INDUSTRIAL THAWING OF FISH
- to improve quality, yield and capacity

by

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Foreword

This work has been done at the Department of Refrigeration and Air Conditioning at NTNU in close co-operation with the related department at SINTEF Energy Research. The Norwegian Research Council has funded the first three years of this study, whilst the rest of it has been made possible by the flexible and patient Department of Refrigeration and Air Conditioning at SINTEF Energy Research.

The work has made it possible to get a closer look at an important industry in Norway, and it has been inspiring to meet and work in close co-operation with talented and experienced representatives of this industry.

This work will hopefully act as a basis for new and improved thawing equipment and processes, and be a part of a new and needed revision of the way fish processing are dealt with. This thesis is just a piece of a far larger task.

During this work I have received input and support from many people. Some of you I would like to direct special thanks to (in alphabetical order):

Professor Ola M. Magnussen at NTNU – For your patient and valuable corrections

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Further I would like to thank my friends and family for the support and for not asking me when I'm going to deliver. And finally I thank Kjersti, Camilla, Kristoffer and Kasper for all the things that make it worthwhile.

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Summary and Conclusions

Melting of frozen water in food products is denoted thawing. The phase change requires energy, and takes place at a constant temperature for pure water. For mixtures of water, fat, protein and ashes (i.e. foodstuffs) this phase change will take place at a gliding temperature. Thawing is physically the opposite process to that of freezing. The heat flow is reversed and instead of extracting heat from the product, heat is directed into it. Although opposite processes, thawing is more difficult to carry out with respect to predictability and controllability. This is due mainly to three aspects:

1. Increased heat flow resistance as the thawing proceeds.
2. Reduced temperature difference (ΔT) between product and media.
3. More difficult to monitor the process and product end temperature accurate.

The food processing industry depends on a continuously and safe supply of raw material, in order to utilise process equipment better, improve production planning and to create stable and secure working environment for the employees. The fish industry is very important for Norway, and its export value (NOK 30,6 billion in 2001[1]) is the second highest after oil and higher than gas. The fact that supply of fresh raw material (i.e. fish) often is dependent on seasonal variations, weather conditions, quotes and regulations (governmental and international), has been a great intensive to use frozen raw material in the fish process industry.

A survey amongst 155 fish processing plants throughout Norway showed that 75 % of them used thawing in their production and further 23% claimed that they would do so in the future. 93 % of the companies that thawed did so in an uncontrolled manner. The challenges in industrial thawing are many:

- Block frozen products changes size during thawing and are generally more difficult to handle
- The product texture are temperature dependent
- Size variations – both single fish and batches
- Use of both fresh and frozen raw material
- Company culture

Thawing by heat transfer through the surface has been studied for three different products; Salmon, Cod and Mackerel. A slightly different approach has been used for these products depending on the raw material availability, industrial needs and relevance.

[1] SSB, EFF

To this date, only limited amount of whole frozen salmon is industrially thawed in Norway. In order to realise the announced potential in Norwegian aquaculture it will be necessary to process much more salmon within Norway, in the years to come. Based on this it is also likely that the domestic industrial thawing of salmon will increase. Frozen blocks of cod are today thawed in large quantities and in almost every domestic lean fish processing plant. The trend for this part of the industry is that thawing is increasingly important. Almost all the mackerel landed in Norway is frozen in large facilities on-shore. Only a fraction of this is thawed by the domestic processing industry, the rest of it is thawed and processed closer to the large markets (former east European countries and Asia).

The work has shown that thawing, where relevant, is a very important part of the production process. It strongly affects the quality of the final product, the raw material utilisation and the overall production efficiency. For fish products, based on frozen raw materials, controlled and proper thawing is a condition (not a guarantee) for high quality and efficient and rational production process. For all products, it is important that the thawing process/equipment secure sufficient circulation of the thawing media over all products in each batch all the time.

Thawing of salmon should not be too slow, due to the possibility for increased drip loss, but use of higher thawing temperatures to speed up the thawing must be carefully evaluated. For most practical reason it seems like thawing of salmon should be done in a 5°C – 10°C water bath. Immediately after thawing the salmon should be chilled towards the desired temperature (0°C if no further processing is done). This will give the best possible quality (e.g. colour). The work has also shown that the quality degradation during storage of frozen salmon is significant, if not stored stable at –50°C.

During thawing of block frozen fish (i.e. blocks of cod or mackerel), the physical size and geometry of the blocks introduces a larger spread in temperature distribution during thawing. In order to minimise the effect of this, it is important to split the blocks as early as possible. The most important factor for the splitting time of frozen blocks is thawing media temperature. Salt content in thawing media is increasingly important at lower thawing media temperatures and if the blocks are very cold when they enter the thawing process. Level of agitation is also increasingly important as the thawing media temperature decreases. For thawing processes where the different blocks will have the possibility to freeze together, all these three factors will become increasingly important. For thawing in other media than water/brine (i.e. air) both salt content and level of agitation is out of the question. Thawing media temperature will however still play the most important role in reducing the process time prior to splitting the frozen blocks. In addition; for frozen blocks of mackerel both fat content and the degree of open voids in the blocks (porosity) will also affect the splitting time.

The nature of the rest of the thawing process as soon as the blocks are split, depend on the amount of energy transferred to the product during the splitting stage, and the desired product temperature after thawing. The rest of the thawing process can be heating, cooling or equalising, depending on these other factors.

Controlled thawing applied in clip fish and fillet production offer benefits in terms of higher yield (at least 1,5%), and better quality. The product temperature should be just below the initial freezing point of the product. Normally this means that the product temperature should be approximately –1°C. It is however clear that the margins are narrow in this temperature region and that too low temperatures will reduce the yield. Products containing a small amount of internal ice after thawing will give higher yields and experience lower temperatures during filleting, trimming and grading. The required energy for refreezing will therefore be reduced, thus increasing the capacity on the freezers. The reduced product temperature during processing will also reduce the risk for microbial contamination. It seems possible to reduce the overall process time for thawing down to 8 hours without compromising the yield or quality, at least for blocks of 1-3 kg cod.

For high fat content 500 g mackerels the yield seemed to be highest for the batch tempered towards –2°C, and the capacity of the trimming table was at its peek for the batch tempered towards –3°C, whilst the capacity of the belt freezer increased with decreasing tempering temperature. Temperature level, agitation pattern and lead-time throughout the thawing process should be carefully controlled and regulated. This will secure a better product temperature development, and it is possible to optimise the texture prior to the mechanical filleting. If these aspects are fulfilled the new process will at least give; 1% better yields, less fillet gaping and breakage, more efficient handling during trimming and less necessary time in belt freezer.

For the large sector of the fish processing industry that will make use of thawing as a regular processing step in the future, the most important factor to implement thawing successfully will be knowledge. Knowledge about the logistical, thermal, mechanical and processing aspects of their entire production process, and ability to systematically make use of this to optimise their processes. This thesis has on three different model products shown how thawing affects quality, yield and overall capacity. This knowledge can be used as a basis in the further development of thawing process and new/improved equipment. Depending on the volume to thaw and the relative importance in the overall production, the thawing process should be differently designed and controlled. Large volume and importance will benefit from intelligent automated processes, whilst small volumes should be handled manually by clearly defined routines. Thawing of blocks will require another process than thawing of frozen single fish. Each step during thawing should be taken care of regarding; time, temperature, media flow pattern and mechanical load. The future will further bring water and energy consumption into focus. This might open for use of heat generating thawing methods (alone or in combinations with the traditionally).

Content

Notation

Greek and Latin symbols

α	Heat transfer coefficient [W/m^{2}K]
A	Surface area [m^2]
Bi	Biots Number [-]
C	Volumetric specific heat capacity [J/Km^3]
C_P	Specific heat capacity at constant pressure [kJ/kgK]
c_{water}	Specific heat capacity for water [kJ/kgK]
Δ	Difference [-]
Δh	Latent heat [kJ/kg]
D	Diameter [m]
D_{char}	Characteristic diameter [m]
$dm_{condensate}$	Rate of condensation [kg/m^{2}s]
ε	Emissivity of a surface
Fo	Fourier Number [-]
h	Heat transfer coefficient [W/m^{2}K]
h_{fg}	Latent heat of vaporization [J/kg]
H	Enthalpy [J/m^3]
k	Heat resistance [W/m^{2}K]
λ	Thermal conductivity [W/(mK)]
L	Thickness [m]
L^*, a^*, b^*	Colour components [-]
P, R	Constant depending on geometry [-]
Pk	Planks Number [-]
q	Specific heatflow [W/m^2]
$\dot{q}$	Heat effect generated [W]
ρ	Density [kg/m^3]
σ	Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^{2}K^4]
SS Proteins	Salt soluble proteins
Ste	Stefans Number [-]
T	Temperature [°C]
t	Time [min]
$\overline{T}$	Average temperature [°C]
TS Proteins	Total soluble proteins
V	Volume [m^3]
WS Proteins	Water soluble proteins
X	Cross-section
X	Distance [m]
x,y,z	Co-ordinates defining a 3D object

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C	Core
cond/conv	Conduction/Convection
core-fin	Final core condition
ff	Final freezing point
fi	Initial freezing point
fin	Final condition
Freezingpoint	Freezing point
froz	Frozen product
ice	Pure ice
initial	Initial condition
initial-freez	Initial freezing point
media	Bulk media
media_at_L	Media at a distance L from the product surface
mean	Mean value
Plate	Plate
S	Surface
Surface	Surface
Surrounding	Surrounding (radiation)
thaw	Thawed layer, material or product
w	Pure water
1	Number (time, section)
2	Condition 2, frozen product
2	Number (time, section)
3	Number
-10°C	From –10°C to 0°C

1 Introduction

In order to utilise process equipment better, improve production planning and to create stable and secure working environment for the employees, the food processing industry depends on a continuously and safe supply of raw material. Both the industry's increased focus on high-cost end products, and the fact that supply of fresh raw material (i.e. fish) often is dependent on seasonal variations, weather conditions, quotes and regulations (governmental and international), has been a great intensive to use frozen raw material in the fish processing industry. Transport of frozen products over long distances is also an important aspect. This is mainly chosen to reduce transportation costs due to reduced weight (no ice in the box) and a possibility to choose cheaper freight concepts (container ships in stead of airfreight) and also to improve quality, shelf life and food safety, etc. Thawing has become an important industrial process, and has put forward a demand for more knowledge concerning both the process (logistical aspects, effect on overall capacity, energy considerations, etc.) and its influence on end product quality and yield.

Historically it has been put a large effort in research concerning freezing, at both theoretical and practical levels covering a wide range of subjects (i.e. biochemical, technical, logistically etc.). Research concerning thawing technology and the interaction between the process equipment and the product (i.e. frozen fish) has, however, been very limited. Even though commercial cooling and freezing has been conducted in Norway for more than 150 years, the first thawing equipment for industrial purposes was available as late as the 1950's [1]. Norwegian regulations up to the late 1960 also prohibited refreezing of thawed fish.

Because of relatively small or neglectable need for investments, natural thawing in room air has been most commonly used also in the processing industry. However, low heat transfer coefficients make this method very time consuming (e.g. space demanding) and are not recommended from a quality and microbiological point of view. Since the first commercial thawing unit appeared, several different thawing methods have been investigated, like: thawing of object immersed in water, and thawing based on vacuum, microwave and ultrasound techniques [2-5]. The most frequently used methods in Norway today are thawing in water vessels (size from 400 litres to 1000 litres) and air thawing in tunnels [1, 6].

Uncontrolled thawing process may result in economically losses in several ways: reduced yield and quality, more handling, lack of traceability, capacity reduction, etc. and more complex production planning. Even though the fish processing industry have to deal with these costs themselves, and the fact that they have been aware of the problems connected to the thawing process for a long time, they have found no simple means to solve these problems in a rational way.

This report will deal with fish as raw material and its main focus will be on the industrial needs. For some products it will give some recommendations for new processes, and for others it will present some basic information needed in order to evaluate different future process alternatives. The report will also present some ideas for future thawing equipment, and suggest where further research and development effort in this field should be conducted.

Chapter 2 presents the theoretical background of thawing and combine this with the practical limitations of industrial thawing. The chosen general research approach is presented here.

Chapter 3 deals with challenges and methods that are relevant for at least two sub-chapters.

Chapter 4 deals with thawing of Salmon, and focuses especially on quality aspects related to this. Industrial thawing of Cod is presented in Chapter 5, whilst Chapter 6 deals with industrial thawing of mackerel. The two latter chapters are especially focused on yield and throughput.

Finally the future of industrial thawing is evaluated (Chapter 7) and the thesis are summarised with conclusions (Chapter 8).

2 Industrial thawing

2.1 Introduction

The use of frozen raw material in processing of "ready to eat" products is common in the whole range of food products. Fruit in juices, jams and dairy products, vegetable in "ready to prepare dishes", meat and seafood in frozen products at different processed levels are all products we are familiar with, and where use of frozen raw materials are common.

The fish industry is very important for Norway, and its export value (NOK 30,6 billion in 2001[1]) is the second highest after oil and higher than gas. This part of the food industry did also by far have the most positive respond to the first initiatives towards the food producing industry regarding this project. The fish industry pointed out several areas, and expressed willingness to share its experience and contribute with raw material, labour and in some cases financial support for thawing research. It was therefore at a very early stage of this work decided to focus on industrial thawing of fish.

2.2 Fundamentals of thawing

Melting of frozen water in food products is denoted thawing. The phase change requires energy, and takes place at a constant temperature for pure water. For mixtures of water, fat, protein and ashes (i.e. foodstuffs) this phase change will take place at a gliding temperature (Figure 2.1). This is due to the equilibrium between ice and the water solution.

Figure 2.2 shows a typical enthalpy curve for foodstuffs. It is almost linear below T_2, but in order to further increase the temperature and simultaneously melt the water a considerably amount of energy has to be transferred. As the temperature approaches the initial freezing point (T_{fi}), the melting of water is accelerated and the enthalpy curve becomes steeper. By definition all the ice is melted at T_{fi} and the phase change is completed. Above this temperature the curve is almost linear [7].

[1] SSB, EFF

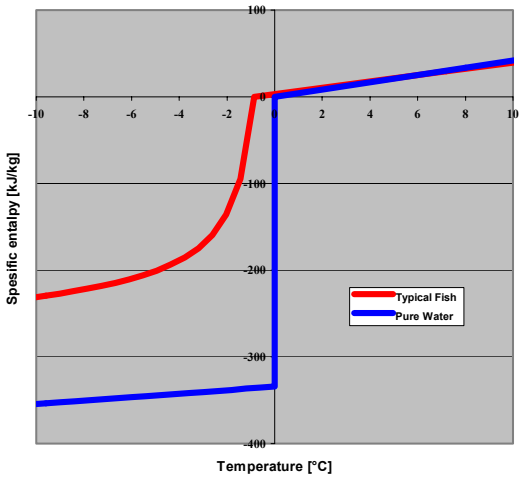


Figure 2.1 *Comparison of the specific enthalpy for a typical fish and pure water* [8]

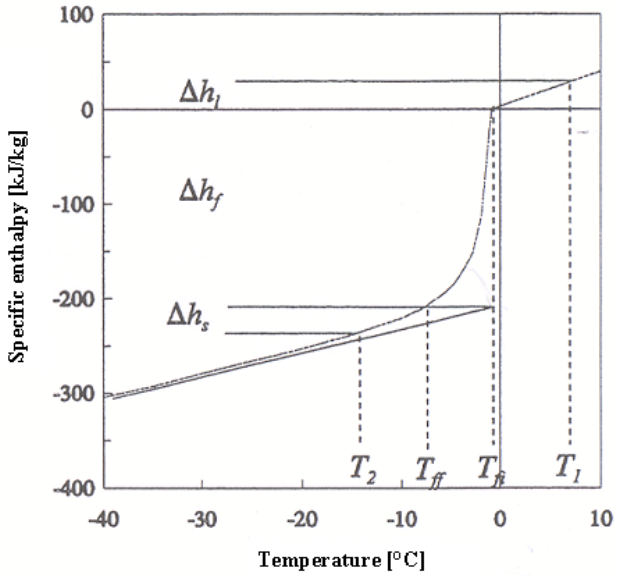


Figure 2.2 *Typical specific enthalpy curve for foodstuff containing water. Temperatures and enthalpy differences of special interest are shown* [7].

Colloquially thawing is referred to as the process of both tempering the product from freezing temperature up to the melting temperature, and the melting itself. Lind [9] divided the process of thawing into three phases (Figure 2.3):

1. The temperature of the frozen product is in **the tempering phase** increased until the melting of the ice within the product is accelerated. $T < T_{ff}$ in Figure 2.2. This phase is short, compared to the next one, due to low specific heat capacity (C_P) and high thermal conductivity in (λ) the ice phase.
2. The rest of the ice melts during the **latent zone phase**. The temperature of the product is almost constant in this phase, due to the fact that the majority of the supplied energy is used to melt the ice. $T_{ff} < T < T_{fi}$ in Figure 2.2.
3. After all the ice has melted, the product enters **the heating phase**. $T > T_{fi}$ in Figure 2.2. In this phase the product thermal capacity is comparatively low. This means that the temperature increases rapidly as a result of further energy supply.

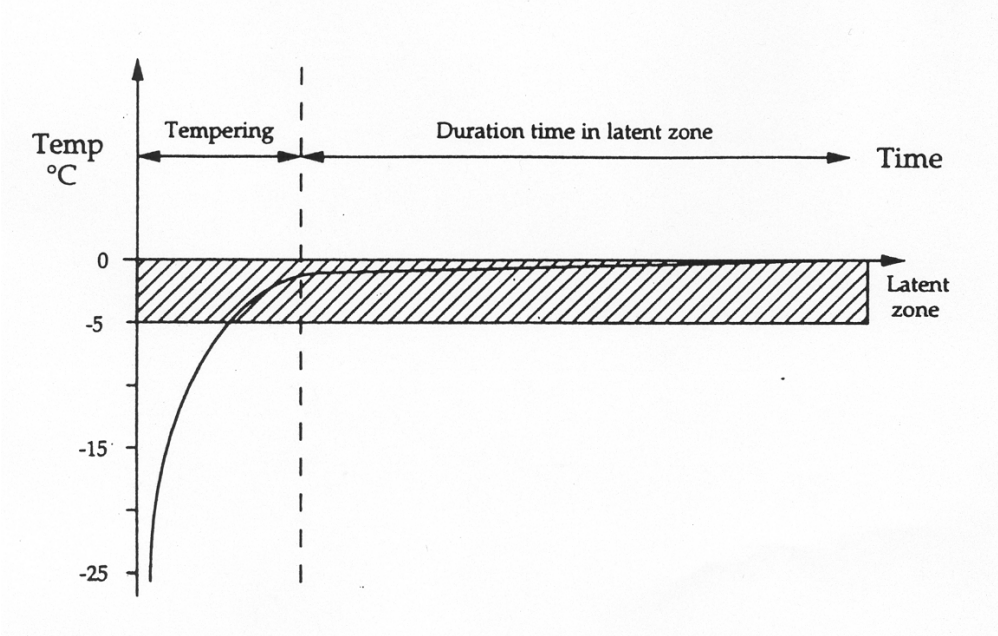


Figure 2.3 *The first two phases of the thawing process; the tempering phase and the latent zone phase* [6].

2.2.1 Thawing – the opposite process of freezing

Thawing is physically the opposite process to that of freezing. The heat flow is reversed and instead of extracting heat from the product, heat is directed into it. Figure 2.4 illustrates the thermal characteristics of the two processes.

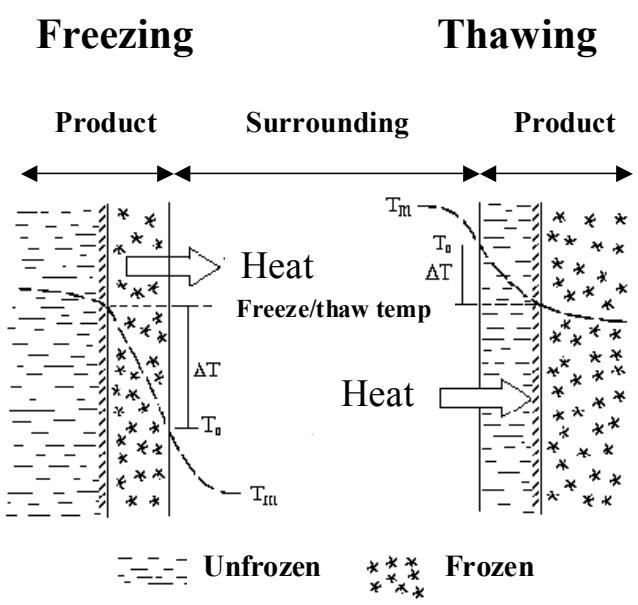


Figure 2.4 *Thermal characteristics of freezing and thawing* [1]

Although opposite processes, thawing is more difficult to carry out with respect to predictability and controllability. This is due mainly to three aspects:

1. Increased heat flow resistance as the thawing proceeds result in a process that runs slower and slower until thawing is completed.
2. During freezing there is "no" quality risk in increasing the temperature difference (ΔT) between product and media (i.e. reduce the media temperature) as long as extreme temperatures are not applied. During thawing the maximum temperature difference (ΔT) is limited by quality considerations. The use of too high media temperature can lead to denaturation of proteins with reduced chemical, visual and sensory quality as a result. Because of this the typical temperature difference (ΔT - the driving force of the process) during thawing is in the range 10°C – 20°C, whilst it for freezing is in the range 30°C – 40°C.
3. If;

   T_C = Product core temperature
   T_{mean} = Product mean temperature
   T_S = Product surface temperature

   During freezing;

   $T_C > T_{mean} > T_S$

T_C can be monitored through simple means and freezing can be defined to be completed when the core temperature has reached a defined value (e.g. –30°C). This temperature will then be the highest temperature in the product, and the product mean temperature T_{mean} will be lower than the defined value. Public regulations regarding freezing is therefore linked to T_C .

During thawing;

$T_C < T_{mean} < T_S$

The thermal core/centre of the product will undergo the slowest thawing process and therefore experience the lowest temperature at any time throughout the thawing process. The product mean temperature T_{mean} will always be higher than T_C (Figure 2.5). It is also a practical problem to monitor T_C , since the frozen product is hard – thus making it difficult to insert a thermocouple with sufficient accuracy. T_S is also very difficult to measure accurate, hence there are no simple temperature indicator that can be used to monitor/control the thawing process. Restraints regarding T_C and T_S will therefore be difficult to follow up. However, it is important to point out that the product temperature never the less is a very important factor for product quality and process yield.

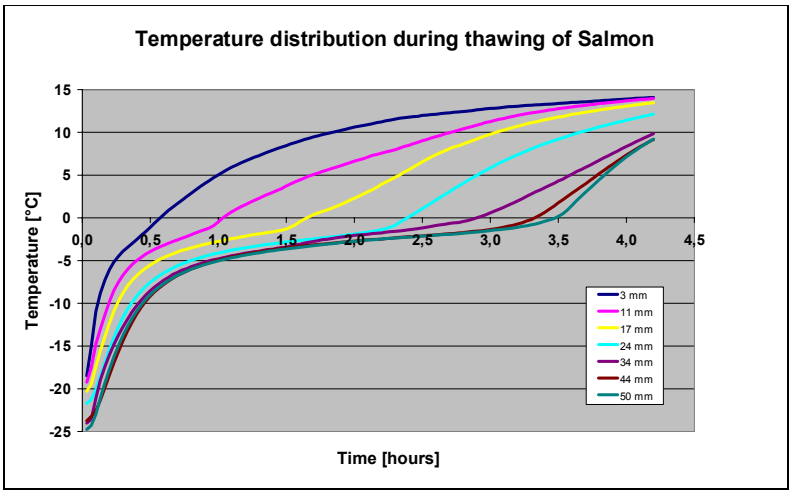


Figure 2.5 *Temperature distribution during thawing in water at 15°C. The product core temperature is the lowest and most stable throughout the process.*

2.2.2 Two principles of heat (energy) transfer

Energy has to be transferred to the frozen product during thawing. This can be done by two different principles:

1. Heat transfer through the surface by;

    - Convection/conduction, where energy is transferred either from a gas, a liquid or by a solid to the product surface.
    - Condensation, where a media (usually water vapour) condensates on the product surface and the condensation energy is transferred to the product.
    - Radiation to the surface.

2. Heat generation in the product, by the use of microwaves, ultrasound, dielectric methods or electric resistant within the product. The different energy forms are all transformed to thermal energy.

After the energy has been transferred to the product, either through the surface or by generation, the energy will align within the product by thermal conduction. Thawing equipment uses different techniques in order to thaw after one or several of the mentioned principles. For instance, thawing in humid air makes advantage of both convection and condensation mechanism.

2.2.3 Heat transfer through the surface

As Figure 2.6 illustrates energy can be transferred to the surface by three mechanisms, alone or in parallel (superposed); conduction/convection to the surface ($q_{cond/conv}$), condensation on the surface ($q_{condensation}$) or radiation to the surface ($q_{radiation}$). If the media is a gas or a liquid, $q_{cond/conv}$ will be dominated by convection, whilst it will be dominated by conduction if the media is a solid. Typical equations for the different settings are given below.

When thawing media is a gas or a liquid:

$$q_{cond/conv} = q_{convection} = h \cdot (T_{media} - T_S) \tag{2.1}$$

When thawing media is a solid:

$$q_{cond/conv} = q_{conduction} = \lambda \cdot \frac{1}{L} \cdot (T_{media\_at\_L} - T_S) \tag{2.2}$$

where:

h – heat transferral coefficient [W/m^{2}K]
λ – thermal conductivity [W/mK]
L – Defined thickness of solid media [m]
T_{media} – Bulk temperature of thawing media [°C]
$T_{media\_at\_L}$ – Temperature of thawing media at a distance L from product surface [°C]
T_S – Product surface temperature [°C]

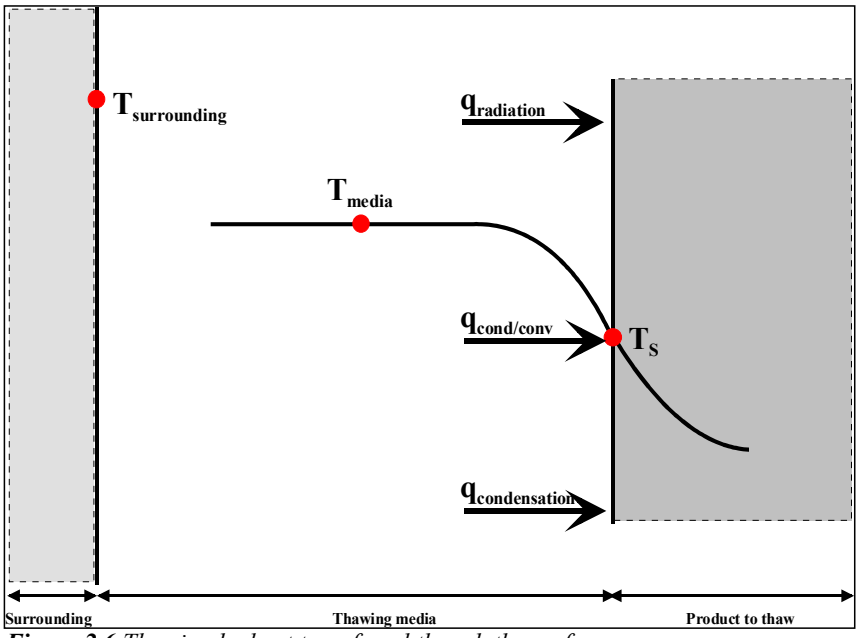


Figure 2.6 *Thawing by heat transferral though the surface*

If the thawing media is an air/gas with water vapour, condensation can occur at the product surface, and the latent heat of the condensate is transferred to the product. The energy transferred to the product ($q_{condensation}$) by this mechanism can be written:

$$q_{condensation} = h_{fg} \cdot dm_{condensate} \tag{2.3}$$

where;

h_{fg} – latent heat of vaporisation [J/kg]
$dm_{condensate}$ – rate of condensation [kg/m^{2}s]

Since this mechanism normally takes place in parallel with convection, the effect is usually incorporated in the heat transfer coefficient h from Equation 2.1.

The energy transferred to the product surface during radiation can be described by:

$$q_{radiation} = \varepsilon \cdot \sigma\left(T^4_{surrounding} - T^4_S\right) \tag{2.4}$$

where;

ε – emissivity of surface
σ – Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^{2}K^4)
Temperatures in Kelvin (K)

Conduction, convection and condensation

If the major mechanisms are conduction, convection or condensation, the object that is going to be thawed is exposed and in direct contact with a warmer media. This media can be gas (dry or humid), liquid or solid. The heat flux into the object will depend on the thermal resistance between the object and the media. For gases and liquids this is connected to the media properties and the boundary layer around the object whilst the media properties and the contact resistant between the two surfaces are crucial if a solid is used. Low thermal resistance results in a small temperature difference between the object and media for a given transport rate.

The most frequently used processes are based on this principle by:

- forced convection by humid air,
- forced convection and/or natural convection by water (freshwater or seawater), or
- steam condensation. Theoretical this is a very elegant solution, since the rate of condensation will be highest at the coldest part of the product surface, hence transferring more energy to the coldest parts. Practical limitation is however a major disadvantage.

Figure 2.7 illustrates how the temperature is distributed through a section of a partly thawed object. The drop in temperature towards the surface of the object is commented above. The heat conduction coefficient of thawed material is about 1/3 of that of frozen material (Figure 2.8), and the total thermal resistance from thawing media into the core will increase as the thawing proceeds.

Depending on the thawing media properties and its circulation characteristics, and the composition and geometric size of the thawing object, either the energy transferral to the surface from the thawing media or the transferral through the thawed material into the freezing front, will be the speed limitation of the process.

In a theoretical convection/conduction thawing process, the heat transfer resistance within the product will increase rapidly and limit the thawing speed. The heat transferral from the thawing media should therefore only limit the thawing speed at the very beginning. This is however not true for most of the traditional industrial methods (See Chapter 2.5).

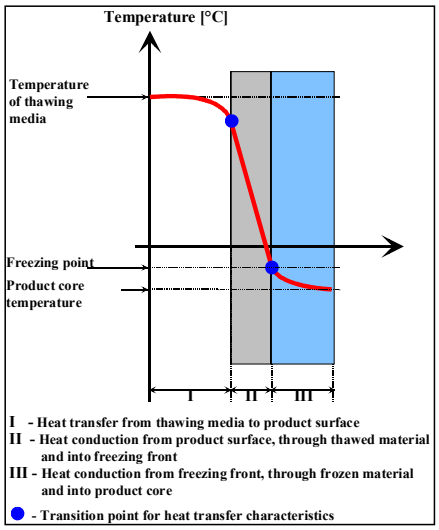


Figure 2.7 *Schematic drawing over the three mechanisms of the Convection/conduction thawing principle.*

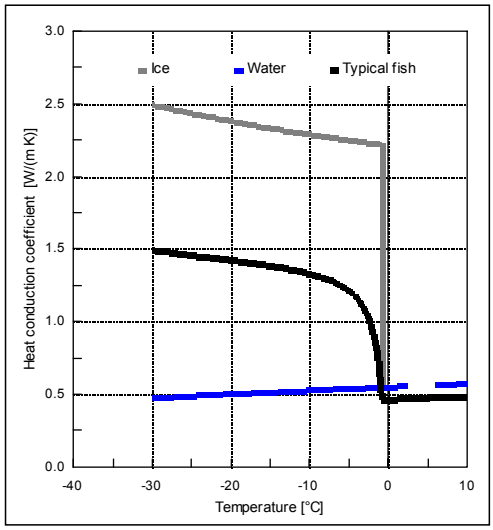


Figure 2.8 *The heat conduction coefficient for a typical fish (regarding chemical composition) as a function of product temperature* [8]

Radiation

Thawing by radiation is accomplished by placing the product to thaw in a room/container/box with heated surfaces. In order to make this system as controllable and effective as possible, the whole product surface should be visible to the heated surfaces (ref Equation 2.4). This is not consistent with the need of large product volumes (i.e. industrial equipment based on this principle will be very space demanding, thus expensive). A short calculation example: During thawing the surface temperature of a product will reach the products freezing point fairly soon. Let's set the product surface temperature to be –1°C and the surrounding surface to be 15°C. If we assume that the product that needs to be thawed is 100% visible for the surroundings, and that the product emissivity ε is 1, Equation 2.4 gives a net heat flux of ~74W/m^2. If forced convection with 15°C air is used to thaw the same product the heat flux will typical be (ref Equation 2.1) 25W//m^{2}K*(287K- 272K) = 400W//m^2. This means that the surrounding surface needs to be kept at high temperatures in order to supply the same amount of energy through radiation, as a simple forced air-thawing unit would do. Because of this, the radiation mechanism is not evaluated further in this work.

2.2.4 Thawing by internal heat generation

Heat generation within the product can be achieved through different techniques. The most commonly referred to in literature are:

1. Dielectric thawing, where the product is placed between two parallel metal plates. A high frequency (10 – 80 MHz) alternating voltage (~5 kV) is applied across these plates. Energy is absorbed in the product every time the voltage is reversed, and heat is generated throughout the product regardless of the contact characteristics between the plates and the product.
2. Microwave thawing, where the product is placed in a chamber and exposed to electromagnetic radiation (1-10 GHz). Energy is generated as the radiation penetrates the surface of the product.
3. Electrical resistance thawing, where an electric current is led through the product and heat is generated due to electrical resistance. The product is placed between two electrodes and good electrical contact is of vital importance. The energy source is typical alternating voltage (50 Hz and 220 V).
4. Ultrasonic thawing, where energy is transferred to the product through vibrations caused by a high frequent sound source (0.2MHz – 4 MHz). Direct contact with the product is not necessary but preferable.

For all these methods electrical energy is transformed to internal energy/heat either directly or through a transformation to either a sound wave or high frequency electromagnetic energy.

Normally, when these methods are referred to, it is claimed that they will secure simultaneously thawing throughout the product. In other words these methods should make it possible to conduct rapid thawing without risking high surface temperatures, and problems with accelerated bacterial growth on the product surface could be avoided. It is however an irrevocable fact that the energy source is placed outside the product, and that the energy "waves" are absorbed as they are moving through the product. This means that there will be less energy to absorb the further into the product the energy "wave" reaches. This is normally dealt with by using several energy sources on opposite sides of the product, but the surface will still be exposed to the highest energy intensity, which can give high surface temperatures [10].

Another fact that also contributes to uneven thawing is the heterogeneity and irregular shape of the food products. For all these techniques apart from the ultrasonic thawing, the product has to have uniform shape and be homogeneous in texture and chemical composition, in order to prevent uneven energy absorption with local heating/cooking as a result. However, the majority of foodstuffs have heterogeneous structure and composition that leads to local overheat and cooking if dielectric, microwave or electrical resistance thawing methods is used throughout the whole thawing process. These thawing methods also suffer from the fact that the energy waves they produce are more attenuated in thawed product than in frozen product [11]. This means that the parts that thaw first also will absorb more and more energy, resulting in runaway heating.

For the ultrasonic thawing the heterogeneity is an advantage in order to spread the energy throughout the whole product. In addition the ultrasound is more highly attenuated in frozen meat than in unfrozen tissue and the attenuation increases markedly with temperatures, reaching a maximum near the initial freezing point of the food. This means that most of the energy should be absorbed at the frozen/thawed boundary. Unfortunately the foodstuffs are not enough heterogeneous to prevent uneven energy absorption with local heating/cooking as a result if this technique is used. And even if the energy should be absorbed at the frozen/thawed boundary, high surface temperatures are difficult to avoid [12].

Thawing by using low frequency acoustics was presented by A. D. Kissam et al. [13]. This method is claimed to stimulate heat transfer rather than aggressively apply energy. The process seemed to be controllable, but required that each block should be exposed in front of a transducer for approximately half an hour, which will be difficult to achieve under practical conditions. In addition the sound (1500 Hz) would be audible, requiring ear protections for the operators.

Even though they are associated with runaway heating and other problems, all the four main methods can be used to temper the product from storage temperature (~-25°C) up to about –6°C, from where more conventional thawing methods can be used. Cost benefit analyses carried out for specific plants and processes will decide upon the future for the internal heat generating thawing methods. How the different factors in such calculations are emphasised will change as time goes by, but an example of how the thawing methods can be compared is given by A.C. Jason [2].

2.2.5 Focus of this work

The state of the art industrial thawing in Norway in the initial phase of this work (Chapter 2.5) together with the known challenges and problems related to thawing by internal heat generating methods, made it clear that the focus in this work had to be on thawing through the surface. In other words: methods described in Chapter 2.2.3.

2.3 Thawing time calculations

Thawing (including tempering and heating) of foodstuff is a non-stationary heat transfer process. The amount of heat transferred will decrease as the driving force ΔT is reduced. Whether the thawing media conditions are constant or not will depend on several factors:

- how heat is supplied to the thawing media,
- regulation means,
- process layout – batch or continuously, and
- thawing media properties as heat capacity.

The heat transfer process is often divided into [14]:

1. Heat transferral from the surrounding media to the product surface.
2. Heat transferral from the product surface towards the product thermal core.

Within the product, this heat transferral takes place through conduction, whilst several mechanisms like conduction, convection and radiation can secure the heat transferral from the surroundings to the product surface.

Due to the phase change of water during thawing, the thermal properties and density of foodstuff will vary during the thawing process.

Analytical mathematical solutions for the heat flux equation for this process exist only for some special cases. In order to estimate the temperature distribution throughout a product, as a function of time and varying boundary condition, computerised algorithms (e.g. Finite Element Methods – FEM) can be used [15].

The equation for conservation of energy[1] or Fourier's law gives the thermal properties of a product that is important during thawing.

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\dot{q}=\frac{\partial\rho c_p T}{\partial t} \tag{2.5}$$

where:

x,y,z – Co-ordinates defining a 3D object
λ - Heat conduction coefficient [W/mK]
$\dot{q}$ – Heat effect generated [W]
ρ – Density [kg/m^3]
c_P – Specific heat capacity [kJ/kgK]
T – Temperature [K]

The heat generation part (q) is typical depending on the product composition and structure, dielectric properties, temperature, and the characteristics regarding how the heat is supplied (i.e. electromagnetic field and product orientation in field). This will be discussed in more detail in Chapter 2.2.5.

Varying thermal properties

The product properties λ, ρ and c_P in real foodstuff are depending on temperature and composition (fat, water, protein and ashes). The variation (spatial, among different fish and during the seasons) is larger for fat fish species than for lean fish. High fat content usually means low water content and vice versa. As an example, composition of farmed Atlantic salmon varies greatly throughout the product. Typical content of water, fat and dry matter in the head and in different parts of the salmon from one cross-section in front of the dorsal fin (Figure 2.9) is given in Table 2.1 [16].

[1] Condition: No internal fluid flow, Isobar conditions

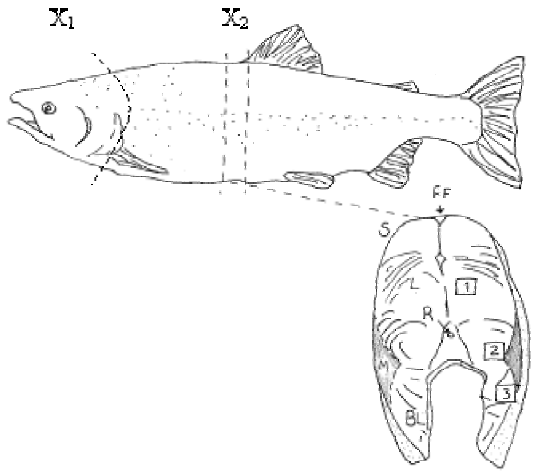


Figure 2.9 *Dissection programme for Atlantic salmon* [16].

Table 2.1 *Content of water, fat and dry matter in the head and in different parts of a salmon at the cross section defined in figure(* [16].

Section in figure 2.9	Part	Water content (% of wet weight)	Fat content (% of wet weight)	Dry matter content (% of wet weight)	Wet weight of tissue fraction (% of total body weight)
X_1	**Head**	62,6	19,3	18,1	9,2
X_2	**Skin, S**	56,3	18,1	25,6	8
X_2	**Belly flap, BL**	55,6	28,1	16,3	7,6
X_2	**Red muscle, M**	56,7	27,2	16,1	4,6
X_2	**White muscle**	68,9	9,6	21,5	56,3
X_2	**Backbone, R**	52,7	22,6	24,7	5,4
X_2	**Dorsal fat region, FF**	48,3	38,4	13,3	0,6

The fat content also varies along the length of the salmon [17]. Figure 2.10 illustrates where the different parts of the salmon, mentioned in Table 2.2 are located.

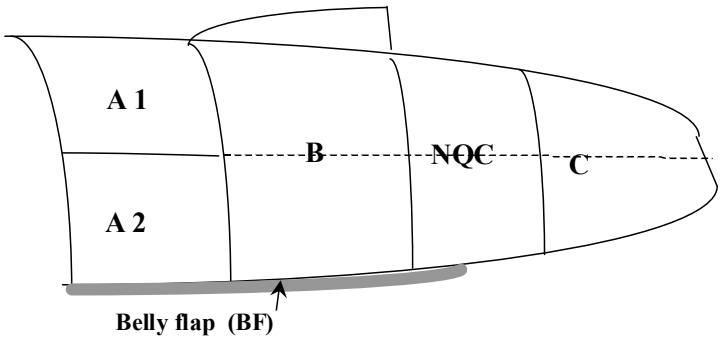


Figure 2.10 *Illustration over the different parts of a typical salmon analysed for fat-content* [17].

Table 2.2 *Fat content depending on where the sample is taken from the salmon* [17].

	A1	A2	B	NQC	C	BF	Whole fillet
Fat content	17,8	22,3	18,3	15,2	9,2	46,4	18,8

In addition to the variation in composition between different regions of the salmon, the fat is unevenly distributed in layers within each region. Between the fibrous muscle tissue there are broad layers of myosepta. The myosepta has a very high fat content (Bæverfjord and Rye [18]) reported a fat content of 54% in the myosepta). Zhou et al. [19] reported that for Atlantic salmon 39,1% of the fat within the white muscle where located in the myosepta, whilst 62,4% of the fat within the dark (red) muscle where located in the myosepta.

Evidently, the composition (fat, protein, water and ashes) of a typical farmed salmon varies severely throughout the geometry. This means that the thermal properties in addition to their temperature dependence also will vary throughout the product (spatial variation). This fact makes an analytical solution of the Equation 2.5 impossible for real products.

Numerical solutions

Numerical solution techniques, such as Finite Element or Finite Difference Methods (FEM or FDM) can be used to solve the equation even for complex geometry and varying thermal properties, but this makes demands for extensive calculation capacity together with detailed knowledge and understanding of the processes the different products undergo. Although very interesting, it has not been a basis or a focal point of my work, so I leave the Numerical solution techniques with this comment.

Simplified calculation methods for thawing time prediction

This sub-chapter takes a closer look at how the equations for thawing time predictions have developed. The heat generative part of Equation 2.5 is not included.

The complexity of the heat transfer calculations even in more uniform food products and also the geometric form requires advanced computer programs. The need for simplified calculations methods is obvious. If the major concern is the thawing time it is possible to develop equations that can be used to find answers with satisfying accuracy for industrial applications. Plank [20] suggested a principle for developing the well-known "Plank's equation".

If we look at the clearly defined case of thawing of water on a hot plate with a temperature of T_{plate}, the temperature will be distributed as in Figure 2.11.

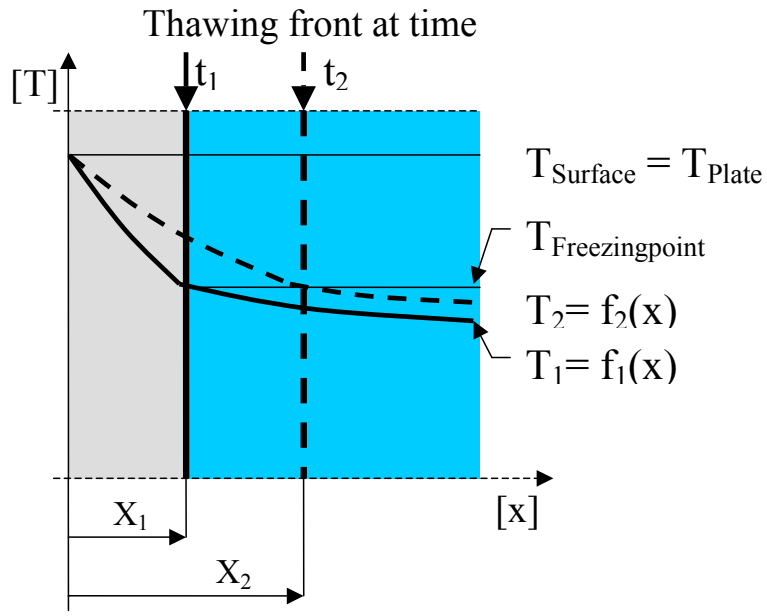


Figure 2.11 *Temperature distribution during thawing of pure ice (H_2O) on a hot plate.*

At time t_1 the temperature distribution is represented by $T_1 = f_1(x)$ and the ice has melted in a depth of X_1. Later, at time t_2, the temperature distribution has become $T_2 = f_2(x)$, and the ice has melted in a depth of X_2. If the considered frozen product is pure water H_2O the $T_{Freezingpoint}$ will be 0°C, if in addition the temperature of the hot plate T_{plate} is fixed, the temperature difference ΔT over the water phase (Thawed ice) will be constant. This means that the heat flux, which is controlled by $\Delta T / \Delta x$ decreases as the thawing proceeds, and also decreases towards the thawing-front since some of the heat transported from the plate is "used" to warm up (increase the temperature) of the product. The energy needed in order to increase the temperature of the water 5°C is given by: $c_{water} \bullet \Delta t$ = 4.2kJ/(kgK)•5K = 21 kJ/kg,

which constitutes to 6.3% of the latent heat of ice (Δh_w ~335 kJ/kg frozen). The effect on thawing time will be less, and it is therefore common to neglect the specific heat capacity of the thawed phase.

If the temperature of the ice is below 0°C, a heat flux from the thawing front towards the ice phase occurs, thus increasing the thawing time. Since the specific heat capacity of ice is approximately half of the one for fluid water, it is also commonly neglected.

The temperature distribution given in Figure 2.12 is based on the assumption that the specific heat capacity of the thawed phase is neglected and that the temperature of the ice is constant at 0°C.

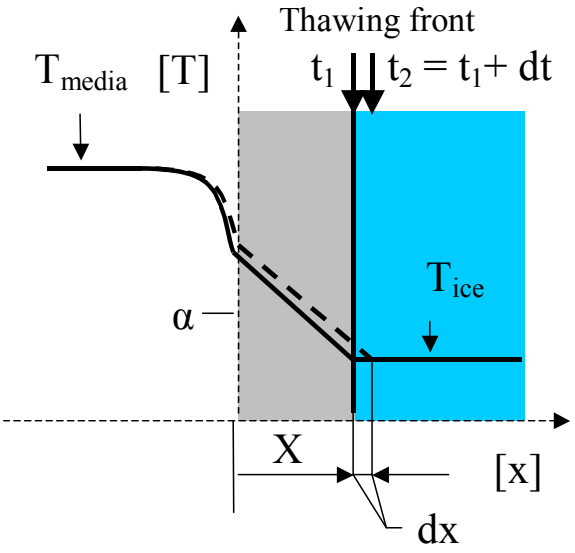


Figure 2.12 *Temperature distribution during thawing of pure water in a hot media*

The heat flow through the thawed layer in Figure 2.12 at instant t_1 (presuming previously mentioned assumption are valid) is equal on the left and right boundary. This heat flow trough the melted layer can be written:

$$\dot{Q} = k \cdot A \cdot (T_{media} - T_{ice}) \tag{2.6}$$

where the heat resistance is;

$$\frac{1}{k} = \frac{1}{\alpha} + \frac{x}{\lambda_{thaw}} \tag{2.7}$$

A – surface area [m]
α – heat transfer coefficient from thawing media to product surface [W/(m^2·K)]
λ_{thaw} – Heat conduction coefficient thawed layer [W/(m·K)]

Neglecting sensible heating of frozen material the heat removed during an infinitesimal time interval dt, Q, equals the latent heat of the melted material during the same period:

$$Q = \Delta h_{ice} \cdot \rho_{ice} \cdot A \cdot dx = k \cdot A \cdot \left(T_{media} - T_{ice}\right) \cdot dt \tag{2.8}$$

which gives;

$$dt = \frac{\Delta h_{ice} \cdot \rho_{ice}}{\Delta T_{thaw}} \cdot \frac{1}{k} \cdot dx = \frac{\Delta h_{ice} \cdot \rho_{ice}}{\Delta T_{thaw}} \cdot \left(\frac{1}{\alpha} + \frac{x}{\lambda_{thaw}}\right) \cdot dx \tag{2.9}$$

If Δh_{ice}, ρ_{ice}, ΔT_{thaw} and α are considered constant, and the equation is integrated from $t = 0$, $x = 0$ to $t = t_{thaw}$ and $x = L$ (the product thickness), the thawing time will be:

$$t_{thaw} = \frac{\Delta h_{ice} \cdot \rho_{ice}}{\Delta T_{thaw}} \cdot \left(\frac{L}{\alpha} + \frac{L^2}{2 \cdot \lambda_{thaw}}\right) \tag{2.10}$$

If the product is not pure water, but consists of water, fat, protein, and ashes (i.e. foodstuff), and the equation is not only solved for the special case of a one-sided thawing of a semi-infinite plate (as Equation 2.10), the equation is usually written in generalized form:

$$t_{thaw} = \frac{\Delta h_{thaw} \cdot \rho_{thaw}}{\Delta \overline{T}_{thaw}} \cdot \left(P \cdot \frac{D_{char}}{\alpha} + R \cdot \frac{D_{char}^2}{\lambda_{thaw}}\right) \tag{2.11}$$

where;

$$\Delta \overline{T}_{thaw} = T_{media} - \overline{T}_{thaw}$$

Δh_{thaw} – Entalpy change during thawing (exclusive tempering and heating phase [J/kg]
ρ_{thaw} – Density of thawed material [kg/m^3]
$\overline{T}_{thaw}$ – Average product temperature during thawing [°C]
D_{char} – Characteristic diameter [m]
P – Constant depending on geometry [-]
R – Constant depending on geometry [-]

Table 2.3 *Values of D_{char}, P and R depending on geometry* [14].

Geometry	D_{char}	P	R = P/4
Semi-infinite plate thawed from two sides with thickness D	D	1/2	1/8
Infinite Cylinder with diameter D	D	1/4	1/16
Sphere with diameter D	D	1/6	1/24

The equation is valid for 1-dimensional problems, and describes the physical relation that dominates during the latent zone phase. It relies, however, on a series of assumptions, which is not often fulfilled.

Several existing methods have been developed specially for freezing time prediction. Where possible the analogous form of the method for thawing has been developed [21]. Cleland et al. [21] compared the prediction accuracy for the best methods as well as for several poorer but well-known methods. The results are summarised in Table 2.4.

Table 2.4 *Summary of percentage difference between experimental thawing times for Tylose slabs, infinite cylinders and spheres, and thawing time calculated by existing simple prediction formulae* [21]

Method	Mean (%)	SD (%)	Min (%)	Max (%)	Corr FDM
Plank, 1913 (thawing at a constant temperature)	6,0	21,4	-28,0	50,5	0,08
Goodman, 1958	13,3	17,6	-15,3	53,7	0,14
Nagaoka et al., 1955	79,1	15,2	45,4	122,6	0,33
Mellor and Seppings, 1976	-4,0	14,4	-36,4	30,7	0,28
Pham, 1984	14,7	7,2	0,6	35,0	0,54
Hung and Thompsen, 1983	92,2	26,6	14,7	134,2	0,23
Calvelo, 1981	0,0	6,0	-12,1	17,1	0,66
Creed and James, 1981	0,2	9,1	-20,0	21,9	0,52

Numerical methods (FDM and FEM) can take into account the temperature variable thermal properties λ, and C (Volumetric heat capacity) and product internal regions with varying product properties (i.e. composition of water, fat, protein and ashes). Consequently these methods can model the physical behaviour of real food material very closely for, and should if correctly formulated and implemented give accurate predictions of thawing times. The Correlation factor compared to a numerical solution based on a Finite Difference Method (FDM) is therefore another way of describing the accuracy in the different simple methods listed in the table.

The version of Plank equation referred to in the table is similar to Equation 2.11, but does not take into account that thawing takes place at a temperature range.

Cleland et al [21] commented that Plank's equation gave a mean prediction error close to zero, but that the spread of predictions were large and that the correlation with the FDM results were poor. The results for the method of Goodman [22] was typical for a large group of methods similar to Plank's equation, except that they take into account the sensible heat

in the thawed phase. This results in a reduced spread than for the method of Plank. A number of methods (here represented by Nagaoka et al. [23]) modify the analytical methods by introducing multiplicative factors in order to account for the sensible heat effects, but they all tended to substantially over-predict and result in high spread. The results using the Meller and Seppings [24] approach were typical for methods based on Plank's equation, but using average thawing temperatures and/or average thermal conductivities as well as sensible heat multiplying factors. The spread of these results were still large due to the lack of physical realistic approach. Other methods divide the phase change process into three stages and try to approximate the heat transfer in each stage with simple formulae. The Pham [25] method was reported to be the most successful of these methods and resulted in a low spread but with a tendency to over-predict the thawing times, due to inaccurate averaging techniques. The empirical formulas (i.e. the Hung and Thompson [26] method) developed for freezing times all tended to over-predict the thawing times, the empirical correction factors were obviously not appropriate for thawing. Empirical methods specially developed for thawing, gave however the best prediction accuracy. The methods of Creed and James [27] and Calvelo [28] are empirical developed formulas based on a fit to numerical prediction methods for beef. They do not take into account differences in thermal properties between foodstuffs, and will therefore most likely introduce a larger error if used for foodstuff with considerably different water content.

Cleland et al. [21] concluded that modifications of the simple equations were necessary in order to make them more valid. They chose to focus their attention to the methods of Calvelo [28], Pham [25], and two different approaches based on Plank's equation [20].

Thawing time calculations have not been an important part of my study; hence the detailed description of the further work of Cleland et al. is given in Appendix I.

Kluza et al [29] showed that Clelands methods from 1986 gave the best results for the regular shapes tested.

For multi-dimensional not complicated shapes, so-called shape factors are used in order to modify the results from basic shapes [30], but when complicated, non-symmetrical shapes are studied the only solution is numerical methods like FEM.

Concluding remarks regarding the calculation methods for thawing time predictions
The analytical methods will introduce even larger errors for real food products, since both the composition and geometry vary a lot (especially for the products dealt with in this work – see Chapter 3.3). The methods are however valuable for estimations and simple evaluations prior to more detailed studies with numerical solutions like FEM. Figure 2.13 shows an example of a model salmon made for detailed FEM calculations in the field of Superchilling.

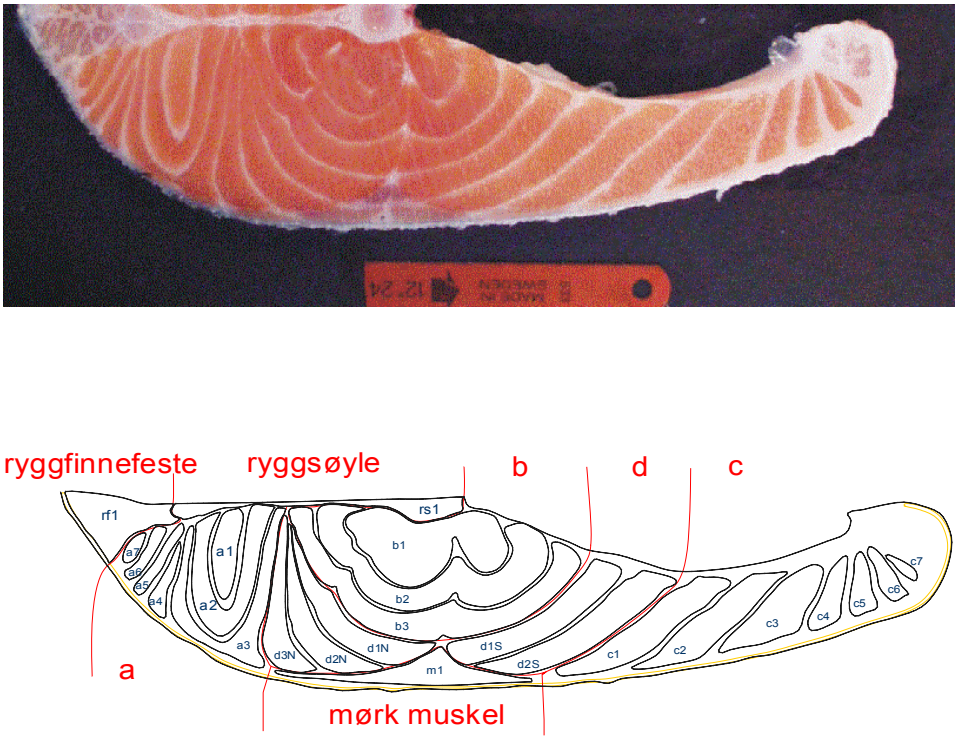


Figure 2.13 *Illustration of the different steps from original salmon to FEM model salmon (Illustartion taken from a project regarding Superchilling at the departments for Refrigeration and Air Condition at NTNU and SINTEF Energy Research)*

2.4 Industrial thawing – one part of the production line

Industrial thawing is usually one part of a processing line. When analysing, designing and implementing a thawing process it is imperative to remember that the goal is to optimise the overall process, and not only the thawing process itself. In this context an optimisation of the overall process means that it is economically optimised over a period of time, typical a year. Assuming that minimising the total costs related to producing the right quality will give the highest long-term profit.

To what extent the overall process is influenced by the thawing process varies, depending on:

- If the thawing is a regular part of the production line every day, or only a backup for periods with lack of fresh raw materials.
- How much of the overall raw material that needs to be thawed.
- The nature of both the raw material and final product itself.

In spite of the varying importance of the thawing process, the by far most used thawing arrangement in the Norwegian fish industry has been batch thawing in 1000 litres containers supplied with running seawater. Air blast tunnels have also been used to a small extent.

2.5 Industrial thawing methods

During the summer of 1997, The Norwegian University of Science and Technology (NTNU) together with the equipment producer MMC Fodema made a survey amongst 155 fish processing plants throughout Norway. 75 % of them used thawing in their production and further 23% claimed that they would do so in the future. 93 % of the companies that thawed did so in an uncontrolled manner, and 94% of them used batch thawing in running water (fresh or seawater). The other 6% thawed their product in air. Figure 2.14 illustrates these numbers.

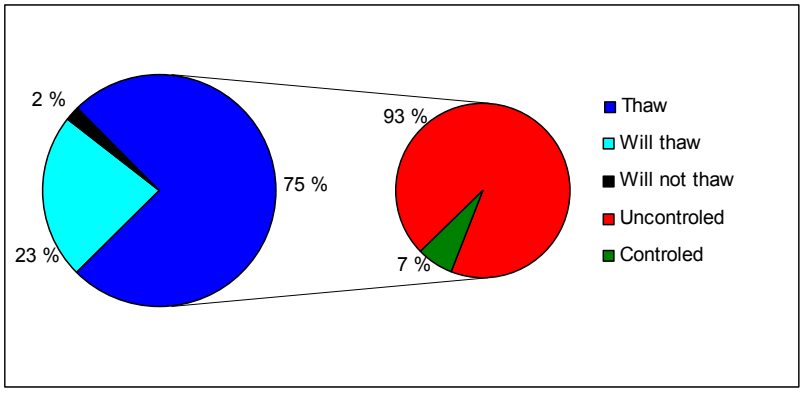


Figure 2.14 *Fish processing companies and their relation to thawing. Based on a survey amongst 155 Norwegian companies.*

Batch thawing in small containers (approximately 1000 litres) has been (during the last two-decades) the most widespread industrial thawing method in the Norwegian fish industry, regardless of product group. Guidelines for this method was developed by NTH (today called NTNU), Department of Refrigeration, and published by the Director of Fishery in 1970 [3]. During the 30 years since then the industry has "developed" a wide range of solutions based on the old principles. The practical solutions are mainly differed by:

- How dense the products are stacked in the containers.
- How the products are arranged in order to secure sufficient fluid flow around each product.
- Location of thawing containers during thawing (indoor or outdoor, with or without roof).
- Water supply. Whether each container is supplied with the same amount of water at any given time and over the whole thawing period. Has each container separate water supply, and how is this done (through one single hose or through a perforated plate in the bottom).
- Arrangement. Whether the containers are stacked on top of each other, resulting in water flowing from one container and into the next ones.
- Post thawing treatment. Whether the thawed product is stored in a mixture of ice and seawater or RSW pending further processing.
- To what extent agitation in the containers is used.
- Thawing media temperature stability during thawing.

The thawing media usually does not undergo any temperature regulation or control prior to its contact with the frozen product. After the thawing media has "done its job" it is led into the outlet where it is mixed with the rest of the waste process water prior to purification. It is also common practice to let the thawing process run a couple of hours longer than what is estimated necessary in order to secure that there is no ice left in any of the products. If there are any products that are too cold to be processed after thawing, they will most likely reduce the capacity in the processing line. The operators very easily detect this, and have therefore naturally developed an "It's better to be safe than sorry" attitude regarding how long the thawing process is run.

In general it can be said that it prevails a widespread insecurity in the industry regarding how the thawing should be carried out, and how optimal conditions can be achieved. The industry resources (especially man-hour and production means) are under great pressure. This has naturally limited the industrial effort and also given limited numbers of tests giving results almost impossible to communicate and/or transfer to other situations/processes.

Figure 2.15 and Figure 2.16 illustrates two different variations of the batch thawing in containers.

Figure 2.15 *Typical batch thawing of Salmon*

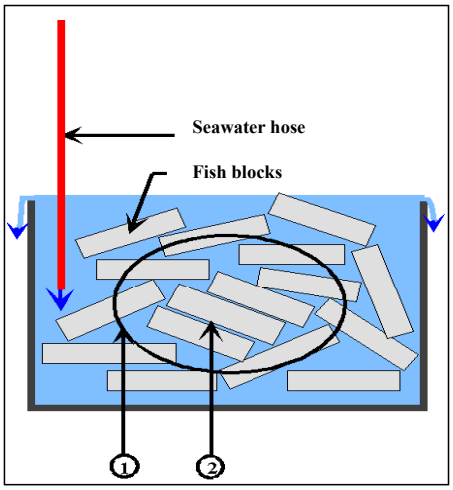


Figure 2.16 *Typical batch thawing of fish blocks*

Figure 2.15 shows typical thawing of Salmon. Seawater is supplied through a hose in the middle of the container, and flows over the edges of the container and into a drain in the floor. Initially some of the Salmons are not even inside the container where the thawing is supposed to take place. As the thawing proceeds the change in density and stiffness for the samples in contact with the thawing media will result in submerging of the samples on top. Figure 2.16 illustrates a typical thawing arrangement for thawing of block frozen fish. Seawater is also in this case supplied through a hose. The thawing media is supposed to be distributed evenly among the frozen blocks, but the water flows where it meets the least obstacles. Subsequently the area marked 1 in the figure will not receive as much water per block as the blocks located close to the seawater inlet or outlet. For some blocks the flow over the thawing surface will be insufficient (area marked 2), leading to blocks freezing together – giving even larger objects to thaw. For large-scale batch-thawing containers like this is stacked on top of each other, and arranged in rows. Water is usually supplied from one or several large pipelines in the ceiling.

The companies that thawed uncontrolled with air (6% of the ones that thawed uncontrolled) did so either by placing the frozen products in a cold store or simply by placing them on shelves in the processing hall. Obviously this does not give a controllable process. It is a very slow process, thus space demanding, with a high risk of dehydration of the product surface. Such methods also require much handling. If the producer is willing to let the process run for a long time, this method will however give any specified “homogeneous” temperature. In the industrial context of this work, I do not find this method an alternative.

The companies that claimed to thaw under controlled condition (7 % of the companies that thawed) did so mainly in batch air blast tunnels. These tunnels are similar to freezing tunnels, but with the use of a water spray to secure a high moist content in the air, and to reduce the surface temperature at the end of the thawing process. The temperature in the thermal centre of a chosen block is often used to control this process. Even with such a feedback from the product, these tunnels have proved to be very difficult to control when used in fish thawing. Some of the major pitfalls related to this thawing arrangement are:

- The facts that make the thawing process more difficult to control than the reversed process; freezing (ref to Chapter 2.2.1).
- The stacking arrangement, and tunnel design tends to give uneven airflow.
- The location of the block where the temperature is measured.
- There is no active chilling of the products when the thawing is finished. There is no control or regulation of the water temperature used in the water spray.
- Extra handling increases the chance for "missing links" in the chill chain.

Figure 2.17 and Figure 2.18 illustrates this kind of thawing equipment.

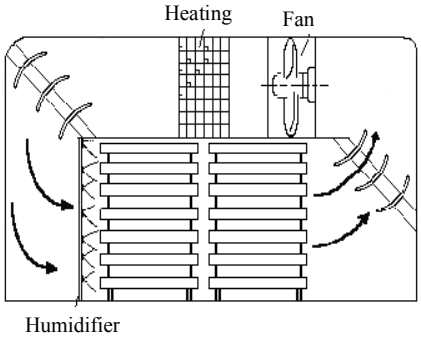


Figure 2.17 *Principal drawing of air blast thawing tunnel*

Figure 2.18 *Air blast thawing tunnel*

Some of the larger companies that process frozen blocks of fish fillets use microwaves to increase the temperature (not completely thaw) of the blocks sufficient to cut them into desired shapes and sizes.

Thawing equipment based on water sprinkling has been the state of the art for continuously sprat thawing lines in the canning industry, and use of water sprinkling in Salmon thawing prior to smoking, has also been reported.

2.6 The perfect thawer

By now it should be quite clear that it is not easy to thaw frozen fish products. The great variety of processing lines in this industry cannot be optimised by the use of one perfect thawer. Each production process will have demands on its own that need to be taken into account in order to give the best possible production means. The perfect thawer is an illusion, and can never be fulfilled in one technical solution. It can however act as guidance when designing and evaluating different possible solutions. The perfect thawer should:

- Give a controllable and predictable process
- Give reproducible thawing runs
- Resulting in a homogeneous end-temperature
- Minimising the losses
- Give optimal and even quality
- Give short thawing time
- Have little or no environmental impact
- Be energy efficient
- Have high capacity
- Be compact - not space demanding.
- Be flexible, regarding the product size and shape
- Be easy to clean, and suitable for hygienic production
- Reliable and safe to operate
- Be simple to run and maintain
- Not be labour intensive
- Demand low investments
- Be run continuously/ semi-continuously
- Be easy to fit into any production plan (not depending or affected by operator breaks and so on)

As already mentioned some of these characteristics are contradictory, thus compromises need to be done in real life.

2.7 Regulations

The Norwegian quality regulation for fish and fish products did until 10th of June 1998 (Appendix) demand that thawing should be done in thawing media with temperature between 14°C and 17°C. The thawing should be finalised as soon as the coldest part of the product reached -1°C, and there should be no delay in the further processing. Each shift should process the fish thawed within the same shift, and thawed fish should if necessary be iced in order to give the product a temperature of 0°C.

This regulation was both hard to follow and not even recommendable for some products. Thawing of thick products would give significantly higher temperature than recommended by following the demands. Figure 2.19 illustrates the mass of the salmon that is warmer than the temperature at a given depth in the salmon during thawing. Figure 2.20 shows what the

average temperature would be if a 4 kg salmon should be thawed in 15°C running water until the coldest part of the salmon reached –1°C.

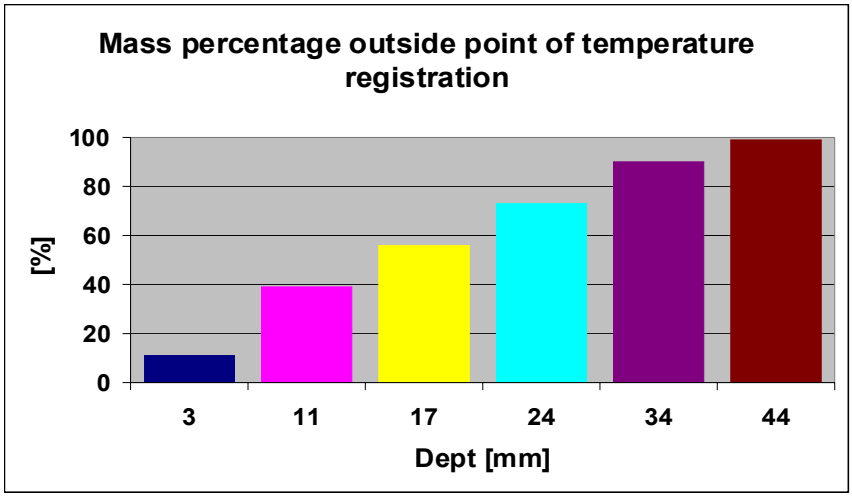


Figure 2.19 *A simplified estimate of how much of the salmon mass that is outside a given depth from the skin. The salmon used here were approximately 4kg and 100mm thick at the selected cross-section.*

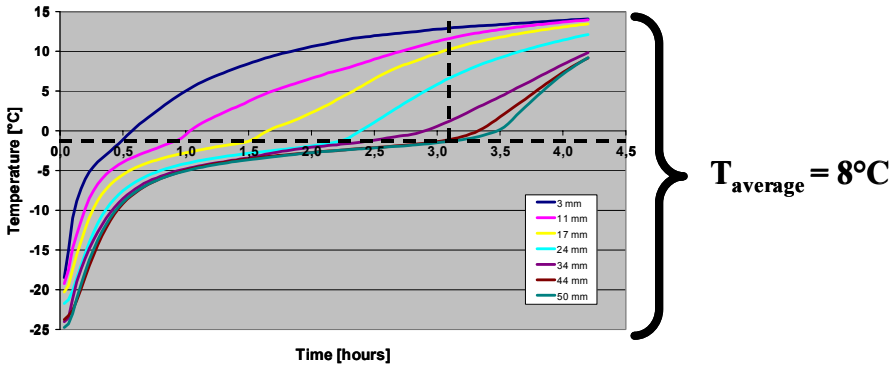


Figure 2.20 *Consequences of following the regulations during thawing of a 4 kg Salmon.*

10th of June 1998, the regulation related to thawing were simplified (Appendix II), most likely because the old regulation was too specific and detailed but not thoroughly based on scientific facts. The new regulations do not say anything about the thawing media temperature, only that the product should be thawed in best possible way to ensure the

product quality. It is still demanded that thawing should be stopped when the coldest part of the product has reached –1°C, and that there should be no delay prior to further processing.

In the future it will most likely also be added (EC regulative that Norway must sign because of the EØS agreement) demands concerning the use and outlet of water in/from thawing processes.

3 Challenges and methods

3.1 Introduction

Chapter 2 described that although thawing is the opposite process from freezing, it is more difficult to calculate, control and carry through. The literature survey shows that very little technology related research has been made public available within the area of industrial thawing.

3.2 Challenges in industrial thawing

In my opinion, even the companies claiming to thaw controlled, most likely do not. Some of the work presented in Chapter 4, 5 and 6 will support this statement. Large amounts of products are thawed, especially within the Norwegian fish industry, every year. There have been literary no development in the technological solutions (If one can use the word technological at all) since frozen raw material was allowed to use in production of frozen consumer products during the end of the 1960's. The different frozen raw material/products are a group of diversity and will most likely need different processes and equipment in order to optimise the overall production processes. Typical industrial thawing processes today process from 2 tons up to 40 tons each shift, depending on type of product.

3.2.1 Block frozen products

Thawing of block frozen products introduces additional challenges to the overall process. One major factor is that the product size changes during thawing, and that geometry **can** change during thawing. The frozen blocks are "glued" together by frozen water, as thawing proceeds the volume of each fish will be slightly reduced, making it possible to split the blocks. A typical block of frozen cod weighs 50 kg and contains 24 single fishes. If one assume conical shape of this product (Headed and gutted) only approximately 35 % of the surface of a single fish is directly exposed to the thawing media. Figure 3.1 illustrates the differences between thawing of a fish within a block and thawing of a single frozen fish.

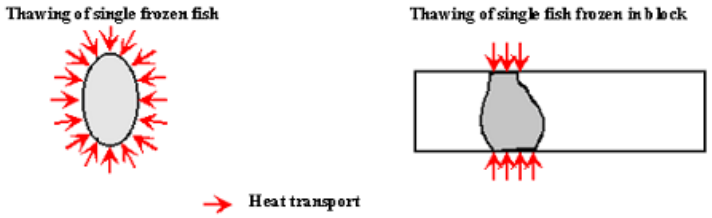


Figure 3.1 *Thawing of single frozen fish compared to thawing of a single fish frozen in a block*

Another way of looking at this is that thawing of a single fish within a block can be compared to 1-dimensional thawing, whilst the thawing of a single fish can be compared to the two dimensional thawing of a cylinder. In Figure 3.2 thawing curves for these two cases are shown.

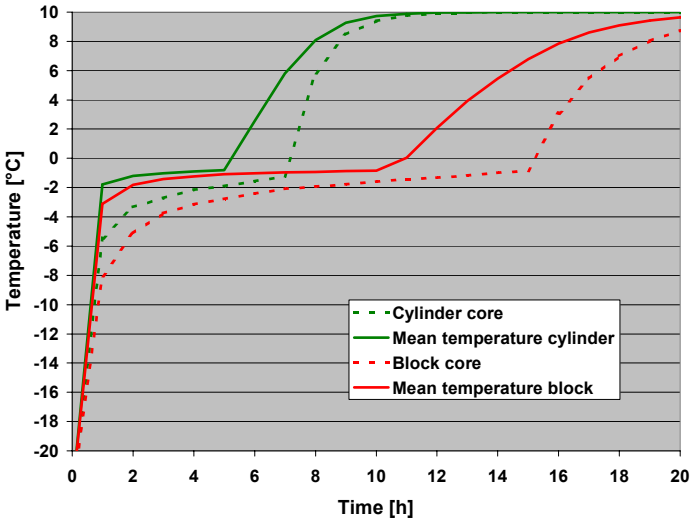


Figure 3.2 *Comparison of thawing time between a 10cm thick block and a cylinder with a 10cm diameter. Calculated with Food Product Modeller software from MIRINZ, New Zealand.*

In both Figure 3.1 and Figure 3.2 the worst located single fish within a frozen block is compared to the single fish itself. It is obvious that the different fish within the block experiences a wide range of temperature development, from the "ideal" to the worst case. This means that thawing of blocks will introduce a wider range of temperature developments than thawing of single fish, as long as time is a critical factor (If a block is thawed slow or long enough the temperature within the block will reach a "homogeneous" temperature in the end).

As obvious from the discussion above the blocks should be split as soon as possible during processing. This way a longer part of the process could be used to ensure equal product temperature between the different fish and within them.

Obviously the rate of how fast the blocks are split depends on what kind of external forces the blocks are exposed to, and the initial "quality" of the blocks themselves. The compactness of the blocks is worth to keep in mind, since the pre-packing/freezing quality of the fish influences on how compact the box is packed. Low quality means soft fish that has a tendency to give more compact blocks. If the fish is exposed for high pressure, e.g. from the box lid, or if the freezing do not start within reasonable time after packing, the fish will be packed more compact. In this situation, water will also get squeezed out of the fish, increasing the strength of the block.

For the most commonly used thawing processes (refer to Chapter 2.5) the products tend to keep their initial block shape throughout the thawing, and do not split until the container is emptied into another container or a production buffer tank.

3.2.2 Temperature dependent texture

The raw material texture must be considered when designing new automated processing lines. At temperatures around the initial freezing point, the texture is very much depending on product temperature. For some products like fat mackerel industrial experience shows that it is almost impossible to cut a first class fillet when the product is completely thawed (contains no ice). This means that temperature control is imperative for these kind of products, and that this fact has to be taken seriously in the process and equipment design.

3.2.3 Volume - weight and number

The process also needs to take into account the production volume. Small volumes and numbers will demand other solutions than large quantities. Variations in supply of raw material and market demands will also have to be taken into account especially for logistical reasons.

3.2.4 Main basis of production – Fresh vs. Frozen

If the production is mainly based on fresh raw material and production from frozen raw material only serves as a back up, it is obvious that an optimisation of the thawing process will have less effect on the overall process. Flexibility, simplicity and low needs for investments and additional space will be important factors for such a process

3.2.5 Company culture

Company culture can also affect what kind of process that will be feasible. Some of the processes/solutions might need to be started/finished outside normal working hours. This is

of course not good, and for some companies located in communities with tight labour market, these processes can be impossible to implement.

3.3 Problem definition – industrial thawing of fish

As shown in Chapter 3.2 the challenges in industrial thawing are many. It is not possible to look into all these in detail, in this thesis. After a round of evaluation of the options, it was decided that this work should deal with industrial thawing of fish. That is thawing of fish for further processing and not for the consumer or catering segment. Obviously some of the results can be used also in these segments, but this is not dealt with here. At a very early stage in this work, it became clear that the work should be focused along two slightly different paths:

1. Laboratory based investigation on the effect of thawing of fish products, and
2. Improvement of thawing processes within the industry.

Ideally work along these paths would be done with the same model products in order to make exchange and comparison of results easier and more effective. However, this was only done to a small extent due to the following facts:

- In order to reveal the effect of thawing it is crucial to have experimental material with the best possible initial quality, that is; high and even quality. In order to make this investigation manageable Salmon was chosen as the first main product for investigations.
- Thawing of salmon was in the industry done in a much smaller scale compared to the lean and pelagic fish thawing. Besides, thawing was in most companies not a daily-integrated part of the production process.
- Companies thawing lean and pelagic fish signalised at an early stage that they had serious problems with their thawing processes, and that they wanted to contribute to the project.

In other words the laboratory approach was concentrated on salmon as raw material; whilst the industrial process improvements aimed at companies using frozen lean (Cod) and pelagic (Mackerel) fish as raw material.

The differences in model product means that the different approaches need to take into account different boundary conditions. Salmon is produced throughout the year, and have relatively small seasonal variation, while lean fish and especially pelagic fish species have large seasonally variations. These variations will greatly affect the operational issues, and therefore also play an important role when discussing equipment and process solutions for the different model products.

3.4 Methods for analysing the thawing processes

The different paths and model products call for different tools to plan, run and evaluate the experiments. In this sub-chapter the general tools used for analysing the thawing process are given. More detailed and exact descriptions of the used methods are given in the respective chapters dealing with the different model products and/or in connection with each group of experiments.

3.4.1 Temperature development

Temperature developments through continuously data logging and stepwise temperature sampling, of both product and thawing media, is one of the major tools for analysing and evaluating the processes. What treatment has induced a given difference in quality, or the other way around: How will the product react on a given temperature development? After all it will always be the actual temperature of experimental material that will have a direct impact on the product quality and yield. The thawing media temperature does not alone control the product temperature, thus only indirectly control the product quality and yield.
The continuously temperature registration was obtained by Fluke 2625A Hydra data loggers, connected to 0,5 mm thermocouples of type T with an overall accuracy of ±0,45°C. All manual temperature measurements were done with handheld ANRITSU Antritherm with an overall accuracy of ±0,5°C. The term "overall accuracy" above does not include the potential error from difficulties in placing the thermocouples exactly as intended.

3.4.2 Quality measurement

Sensorial analysis is by far the best method for assessing the quality of food [48]. Through these analyses the product samples are described by sense impression and physical attributes like structure, colour, and content of specific components (e.g. salt and acids) [31]. Sensorial analyses are expensive, time consuming, and sometimes difficult to run for various reasons. This has put forward a demand especially within the industry to come up with chemical and physical methods for assessing the product quality of fish.

Some objective parameters that indicate the quality of a fish product are [32]:

- Water/dry-matter content
- Amount of water soluble proteins
- Amount of salt soluble proteins
- Fat content
- pH
- Reduction-Oxidation Potential
- Mineral content
- Texture
- Water Holding Capacity
- Storage temperature. Continuously temperature logging can be used as a documentation of the freshness and accumulated quality reduction of the fish products related to cool/cold storage.

3.4.3 Yield and throughput - Capacity

Yield and throughput is very important factors when assessing production facilities in general. Yield in this context means how much of the total raw material is converted to saleable products with as high quality as required, through the entire production process. Throughput simply means how many saleable products are produced by the aid of a specified equipment/process within a given time frame. The thawing processes affect both the yield and the throughput. This will be documented in Chapter 5 and 6. These factors are naturally the ones that are easiest to communicate with the industry, since the numbers are easy to convert into saved costs and/or increased income.

3.5 Experimental design in general

Experimental design is described by CAMO [33] as a plan for experiments where input variables are varied systematically within predefined ranges, so that their effects on the output variables (responses) can be estimated and checked for significance.

For several of the tasks in this work, experimental design has been applied by using a software package from CAMO called Guideline. This package is designed to help product developers in the food industry. Use of this kind of software makes the work more effective, through guidance of:

- Making effective experimental designs.
- Analysing results from the experiments, by applying statistics and multivariate data analysis.
- Illustrating results.

3.5.1 Experimental design

Experimental design is a way to generate experimental data giving maximum information from a minimum number of experiments. It consists in defining a set of experiments which combine a few levels of your input variables in a completely balanced way, so that:

- You can draw conclusions about cause and effect relationships between input and output variables;
- The global conclusions are much more precise than any of the individual results.

Experiments have classically been carried out by varying one parameter at a time, whilst the rest of the potentially influential parameters have been kept fixed. This strategy demands a great number of experiments, and often provides confusing results. If there are interactions between variables, the classical approach will not be able to isolate this from the sole effect of the actual variables, giving sub-optimum solutions.

The main issue regarding experimental design is conduct just enough experiments to be able to describe the effect different variables have on each chosen response variable.

3.5.2 Experimental design in practice

The successive steps of building a new design and interpreting its results are listed below [33].

How to design the experiments:

1. Define which output variables you want to study (responses). The values of these variables are measured for each experiment.
2. Define which input variables you want to investigate (design variables). The values of these variables are chosen and controlled during the experiments.
3. For each design variable, define a range of variation or a list of levels that you wish to investigate.
4. Define how much information you want to gain. The alternatives are:

    - find out which variables are the most important (out of many),
    - study the individual effects and interaction of a rather small number of design variables,
    - find the optimum values of a small number of design variables.

5. Choose the type of design that achieves your objective in the most economical way.

How to analyse the experimental results:

1. Define which model is compatible with your objective. The alternatives are:

    - to find out which variables are most important: a linear model (studies the main effects),
    - to study the individual effects and interaction: a linear model with interaction effects,
    - to find an optimum: a quadratic model (includes main, interactions and square effects).

2. Compute the observed effects based on the chosen model, and conclude on the significance.
3. Interpret the significant effects.

3.5.3 Definition of some relevant statistical terms

A simple definition of some of the most important terms related to experimental design is given hereafter.

High/Low level – defining the range the design variable can vary within. The term level is used in order to also be valid when the design variables are not values but categories (e.g. describing whether a process is applied or not).

Cube samples – any sample that is a combination of high and low levels of the design variables, in experimental design based on two levels of each variable.

Main effects – variations in responses generated by changing the values of the design variables from a high level to a low level.

Interaction – a change in level of one design variable modify the effect on the response by another design variable. This means that the combined effect of the two variables is not equal to the sum of their main effects.

Confounding – some effects cannot be studied independent of each other.

Important variables – the design variables that have significant main effects, and those variables that take part in a significant interaction (even though their main effect is not significant).

Some statistical experimental designs demand so called ***centre samples.*** These samples make it possible to determine whether the correlation is linear or not, and if any experimental errors are likely to be present. They also provide information on the reproducibility, and whether the precision in the measurement of the response variable is acceptable. In some cases, when comparison with existing products is of any interest, ***reference samples*** are included in the design.

3.5.4 Significance testing

In Guideline the significant testing is done as part of Analysis of Variance (ANOVA). The principle of significance testing is very clearly described in the ANOVA [33], and it is therefore repeated here.

Analysis of variance is based on breaking down a response's variation into several parts that can be compared to each other for significance testing.

To test the significance of a particular effect, you have to compare the response's variance accounted for by that effect to the residual variance, which summarise experimental error. If the "structured" variance (due to effect) is no larger than the "random" variance (error), then the effect can be considered negligible. Else it is regarded as significant.

In practice, this is achieved through a series of successive computations:

- First, several **sources of variation** are defined. For instance, if the purpose of the ANOVA model is to study the main effects of all design variables, each design variable is a source of variation. Experimental error is another source of variation.
- Each source of variation has a limited number of independent ways to cause variation in the data. This number is called the **degrees of freedom** (DF).
- Response variation associated to a specific source is measured by a **sum of squares** (SS).
- Response variance associated to the same source is then computed by dividing the sum of squares by the number of degrees of freedom. This ratio is called **mean square** (MS).
- Once mean squares have been determined for all the sources of variation, **F-ratios** associated to every tested effect are computed as the ratio of MS_{effect} to MS_{error}. These ratios, which compare structured variance to residual variance, have a statistical distribution that is used for significance testing. The higher the ratio, the more important effect.
- Under the null hypothesis that an effect's true value is zero, the F-ratio has a Fisher distribution. This makes it possible to estimate the probability of getting such a high F-ratio under the null hypothesis. This probability is called **p-value**; the smaller the p-value, the more likely it is that the null hypothesis is wrong, and that the observed effect is not due to chance. Usually, an effect is declared significant if p-value < 0.05 (significant at the 5% level).

Apart from ANOVA, which tests the significance of the various effects included in the model, using only the cube samples, significance testing can also be done by several other methods. They differ from each other by the way the experimental error is estimated. In Guideline, five different sources of experimental error determine different methods.

Which method that is used to test the significance in the different experiments done in this work, is referred to in each case.

3.5.5 Principal Component Analysis (PCA)

Data = Information + noise (error). Principal Component Analysis (PCA) is used to reveal the information in the data, and at the same time get rid of the background noise that can prevent us from fully understanding the meaning of the raw numbers [33].

PCA summarises multidimensional information by means of small numbers of summary variables called Principal Components (PCs). The samples and the original variables are projected onto those components so that summary plots can be produced. These plots provide the best possible representation of the original data and are easy to interpret.

A graphical explanation of how the PCs are obtained is given hereafter.

Table 3.1 summarises the results from an imagined experimental design with n-samples and j-responses

Table 3.1 *An overview of j-responses on n-samples from the imagined project.*

	Responses			
Sample No	**1**	**2**	**---**	**j**
1	Y_{11}	Y_{12}	---	Y_{1j}
2	Y_{21}	Y_{22}	---	Y_{2j}
---	---	---	---	---
n	Y_{n1}	Y_{n2}	---	Y_{nj}

If these results should be plotted together we would need a system with j-dimensions. If j is a high number this will be hard to imagine, so for describing purposes only, lets look at the case where j =3. Figure 3.3 shows the results plotted in a 3D system.

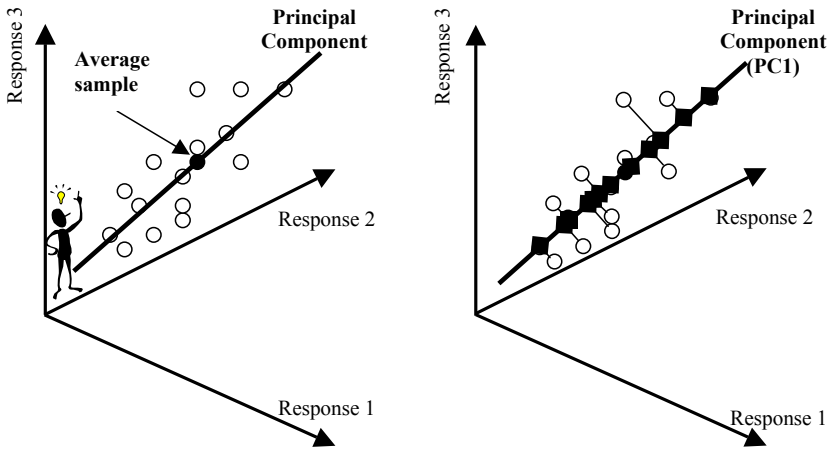


Figure 3.3 *PC1 is the best possible one-dimentional summary of the variations among the samples* [33].

By fitting a straight line through the center of the points, so that it captures the direction of maximum elongation, the variation among the n-samples are summarised. Each sample is projected orthogonally onto the line; the projected points represent approximations of the original samples, and can be used for comparisons. Samples close to each other on the line are similar, whilst samples far away from each other are different.

PC1 is the best possible one-dimensional summary of the variations among the samples. In most cases this is informative and easy to interpret, but it will most likely not take into account all the variations from one sample to another. This is reflected by theresiduals. The

larger the residuals, the more information is not jet described by the PCA. Figure 3.4 shows how the PC2 is build in order to summarise even more of the variation among the samples.

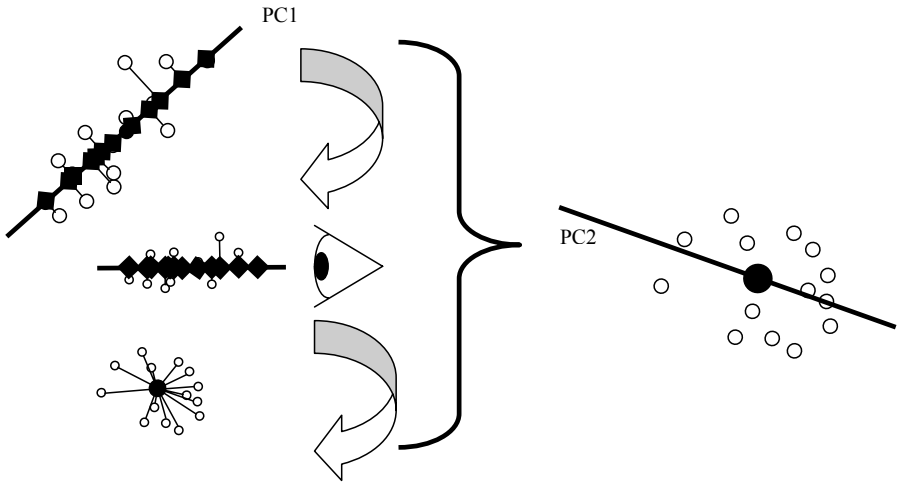


Figure 3.4 *Building PC2* [33].

The figure illustrates how we build PC2 in hyperplane orthogonal to PC1. Here, orthogonal means that the PC2 descibes phenomenon which are independent from those summarised by PC1.

Figure 3.5 illustrates how the two principal components summarise the variaton in the samples. It is possible to continue to describe more and more of the variation by building more prinsipal components (PCs), but it is only interesting as long as there is any meaningful variation to be extracted from the data.

If PC1 and PC2, describe all the meaningful variations, the two PCs will be the best two-dimensional summaries of the variation among the n-samples. The variation beyond the hyperplane build by PC1 and PC2 can be concidered as noise (error).

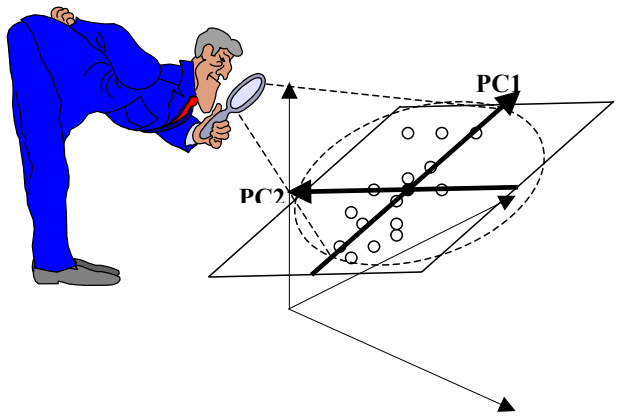


Figure 3.5 *By concidering PC1 and PC2 together, the best two-dimensional summary of the variation among the samples, is obtained* [33].

3.5.6 Response surfaces analysis

The Response surface is modelled by multiple linear regression (MLR) [33]. The model can be linear, or include interactions and/or square effects. The purpose of Response surface analysis is to exploit the results from designed or non-designed experiments as to describe the shape of the variation of a response as a function of variations in the design variables.

The response surface model is an effective tool to identify optimums; that is maximum, minimum or saddle points. The quality of the surface is assessed by using a modified version of the Analysis of Variance (ANOVA) explained in Chapter 3.5.4. Further description of this analysis will be given where appropriate.

3.6 Equipment

During the experiments different types of equipment has been used in order to achieve the desired conditions and temperature developments. In general the different types of equipment and their set-ups are described in connection with the experiments they have been used for. One single equipment has however played a very important role throughout this work, and it is therefore described below.

3.6.1 Refrigerated Sea Water (RSW) equipment

The RSW unit (Figure 3.6) consists of two parts: The refrigeration unit and the water circuit. The refrigeration unit is originally built by the company Aquaterm A/S, and is a one-stage compression system, using a thermostatic expansion valve in order to secure complete evaporation at the outlet of the evaporator. The unit has later been modified with a bypass of the condenser and the thermostatic expansion valve in order to regulate the capacity of the evaporator.

The main components of this system are:

- Compressor: DWM Copeland D3DC1000
- Evaporator: Aquaterm FSV – 25
- Condenser: Helpmann LCX – 10,910
- Throttling valve: Danfoss TEX5 – 3

The water circuit consists of two plastic containers; one 1000 litres and another holding 750 litres. The water/brine is supplied through a perforated plate at the bottom of the largest container. The size of the holes in this plate is dimensioned to secure an even fluid flow over a cross-section of the largest container. The water/brine flows through an overflow and into the second container, which serves as a buffer. From this container the water/brine is pumped through the evaporator where the temperature is adjusted before it again is supplied through the perforated plate in the bottom of the largest container. For some of the experiments the buffer tank was also equipped with a 12 kW electrical heater. The contribution from the heater and the refrigeration system through the evaporator was regulated by a PLS in order to maintain the water/brine temperature at the desired level. Freshwater as well as seawater or stronger brines could be controlled through this equipment.

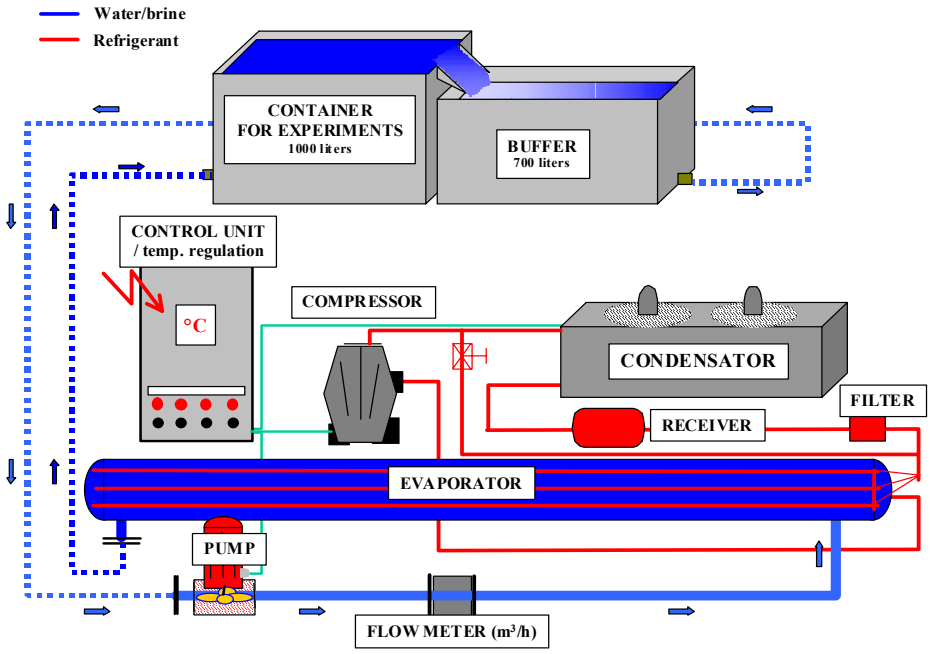


Figure 3.6 *RSW unit used to thaw (split and temper) different products.*

4 Thawing of Salmon

4.1 Introduction – volume and value

In 1999 the production of Atlantic salmon (Salmo salar) in Norway exceeded 420 000 tons. This corresponded to 53% of the world production that year[2]. From this production Norway exported approximately 400 000 tons. By far, most of this export has been iced fresh fish, but the value of frozen salmon products is still considerable (18 %) and increasing especially for the markets in Asia. Round frozen Salmon counted for 10%, whilst frozen fillets counted for 8% of the total export value. 53% of the overall fillet export was frozen products; this is among others due to the increased complexity of transporting fresh fillets vs. whole Salmon.

How much of the frozen products that is thawed industrial is difficult to estimate, but all of it obviously needs to be thawed.

4.2 Domestic vs. export

Due to the fact that the domestic industry is located closer to the farming and slaughter facilities, they have a different motivation for using frozen raw material in their production than the industry abroad (Europe, Asia and North America). In the early nineties Salmon were frozen and stored in Norway in order to avoid collapse in the European salmon market. When producing fillets it is an advantage that the fish either has been stored on ice for a couple of days or frozen and thawed. The pin bones, that are very difficult to remove, immediately after slaughtering are then easy/possible to remove. In other words the reasons for the domestic companies to freeze the products are mainly to regulate the market and to make production planning and operation easier.

In addition to this, some foreign companies prefer frozen products in order to secure that the product they get has the desired quality and to avoid the high prices connected with airfreight. This especially goes for companies situated far away from the production sites in Norway (i.e. USA and Asia).

4.3 Aim of study

As mentioned in Chapter 3.3, the reason for investigating the effects of thawing, on Salmon, is that the product is important for the Norwegian industry and that the product is easy accessible every day throughout the year, thus making a found basis for organised research.

[2] SSB, 2000

The industry involvement in this part has been connected to long distant export of round frozen Salmon. On this basis the focus in this part of the work has been directed towards the effect thawing has on important quality parameters/indicators. The industrial connection is therefore not directly linked to the final refining of Salmon products before it is introduced to the consumers. The study more acts as a universal basis that should be taken into account in every frozen Salmon processing line.

4.4 Structure of approach

The structure of the approach mirrors the fact that results from thawing of Salmon has not been made public available. Probably there has been conducted little or no research within this field. In order to make the different tasks manageable the work has been divided into several smaller projects. Interesting questions like;

- the effect of different thawing equipment,
- the effect of strategy regarding when to end the thawing,
- how to deal with the thawed product, and
- the effect of raw material freshness/quality

constituted the initial focus. Based on this work, several new issues surfaced, and the most interesting where the effect of time in the critical temperature region below the initial freezing point of the product, during thawing. In addition a survey on the effect of temperature level and thawing speed on colour- and drip loss for Salmon were made. These issues are treated in Chapter 4.7.

Following this, a need to investigate the effect of time and temperature after thawing, emerged. This is treated in Chapter 4.8.

In order to put things in perspective, and to reach conclusions that could be used as direct recommendations for Salmon exporters, the effect of thawing was compared to the effects of freezing and storage during long distance transportation. This is presented in detail in Chapter 4.9.

As the work has been carried out, increased knowledge of statistical experimental design and multivariate data analysis has been obtained. The different experiments evidently mirrors this fact, since both the setting (laboratory) and the aim of the study fit these techniques very well.

4.5 Material and methods

Chapter 3 presented an overview of the methods used in the overall work. This sub-chapter deal with the quality measuring methods that are special for the Salmon chapter and that has been used in at least one of the following sub-chapters. In order to investigate the effect on quality by different thawing regimes, it was decided to use dry matter content, extractable amount of salt- and water-soluble proteins, pH, Water holding capacity, drip loss, colour and

texture as parameters for assessing quality. These parameters are commonly used to reveal changes in product quality as a result of freezing and cold storage, and should therefore also be appropriate in connection to the opposite process of freezing, thawing. The dry matter content, proteins, pH and the Water holding capacity, were mainly (where nothing else is mentioned) analysed at the laboratory facilities at the Department of Biotechnology at NTNU, by 8th and 9th semester students under the guidance of Assistant Professor Turid Rustad. A closer description of the chosen quality parameters and measuring methods is given below.

4.5.1 Dry matter content

In order to determine the dry matter content, about 2 g minced fish fillets (two parallels of every sample), was dried at 105°C until constant weight was achieved.

4.5.2 Water holding capacity (WHC)

Water holding capacity (WHC) is one of the functional properties that are used to characterise the fish proteins and fish as raw material for further processing. The WHC is defined as the ability muscle tissue and foodstuff based on muscle tissue has to keep/withhold the original amount of water during a specified treatment [34]. WHC is reduced as the water content increases. WHC of lean fish is therefore lower than for fat fish like Salmon.

For both living organisms and after death, water plays an important role in all physical, chemical and biological processes. WHC is an important factor considering the juiciness and taste of fresh food and for drip loss related to thawing. Reduced WHC leads to economical losses caused by reduced sales weight and trouble during processing. For processing companies that use fish as raw material, it is therefore of great interest to know how much water the tissue contains and how it is bound. For functional properties like texture formation and ability to absorb water or other additives, the interaction between water and proteins are imperative [35].

Measurement of thawing related drip loss and changes in WHC is one of the simplest methods used to assess the product loss in ability to reabsorb water from melting ice crystals. These methods are often used in the industry. The reduction of the fillets ability to absorb water is linked to the hydration of the proteins and the destruction of the ultra structure of the cells [36].

Fennema [34] divided the factors that influence the WHC of tissue into two groups;

1. Factors dealing with the muscle tissue itself:
   - Species, breed, individual, gender, age, type of muscle, fat content, blood vessel size, and which part of the muscle.
   - Fish/animal size.
   - pH, both value and rate of changing.
   - Post mortal physical properties, loss of ATP and formation of actomyosin.

2. External influences:
   - Pre slaughter treatment - feeding and exercise.
   - Season and location.
   - Slaughter method - stress level of fish.
   - Pre rigor procedures like chilling or electrical stimulation.
   - Characteristics of the sample.
   - Conservation methods, heating, drying or freezing.
   - Altering composition, addition of electrolytes.
   - Chosen method for WHC determination.

pH is commonly known to be one of the most important factors to affect the WHC of a product [34, 37-39]. Changes in pH in the range 5 to 6.5 influence the WHC.

The WHC is affected by the changes that take place in muscle tissue post mortem. Changes in force of attraction take place during processing, storage and meal preparation until the product is consumed (i.e. chilling, freezing, storing, thawing, salting, drying and mincing) [35].

There are several methods that can be used in order to determine the WHC. Fennema [34] split them into two groups:

1. Methods solely based on the force of gravitation (determination of free drip, including losses of water as both fluid and gas (evaporation)). These methods can be used for fresh, frozen and thawed, dried and rehydrated or boiled muscle. They are sensitive, but time consuming. [39].
2. Methods that involve additional external forces (determination of expressible moisture and water holding potential). These methods can be based on centrifugal forces, filter-paper and methods where suction is applied.

Honickel [39] introduces thermal force methods (boiling) as another category.

In this work (where nothing else is mentioned) water holding capacity (WHC) has been determined on minced muscle as described by Børresen [40], with the exception that a centrifugal force of 210 x g was used instead of 1500 x g . The WHC is expressed as the percentage of water retained in the mince after centrifugation in 5 minutes.

4.5.3 Protein

Instead of lipid oxidation/ -hydrolyses, protein denaturation is preferred as quality/freshness indicator for salmon. This due to the fact that salmon is relatively stable regarding lipid oxidation [41].

Denaturation of fish proteins leads to reduced amount of soluble proteins. By extracting both water and salt soluble proteins it is possible to tell how the quality of the product has developed during a given treatment. Water-soluble proteins are not much affected by cold

storage, opposed to the salt-soluble proteins. Reduction in the extractable amount of proteins has proven to be well correlated to increased hardness/dryness and drip loss [42, 43].

Mackie [43] and Svensson [44] have stated that the freezing speed has a major impact on the amount of extractable proteins. This was not found by Halvorsen et al. [45].

To what extent the muscle proteins can be extracted both during real processing conditions and under controlled experimental conditions in the laboratory, depends on the extraction conditions like; pH, ionic strength, degree of dilution, homogenisation time etc [46].

The method for protein extraction is not standardised and there is dissension regarding whether one should distinguish between water- and salt-soluble proteins during extraction, or if it is adequate to extract them together in one operation [47]. These facts make comparison of studies using different extraction conditions difficult. However, for assessment of relative changes in quality as a result of different treatments, the protein extraction methods have proven to give valuable results. Significant correlations between reduction of amount of extracted proteins and sensorial evaluations have been found [48].

Many of the methods used to analyse the amount of proteins are based on colour reactions and spectrophotometric measurements: Ninhydrin, Bio-Rad, Biuret and Lowry. These methods only provide relative values and can therefore only be used to estimate soluble proteins. By using a C/N – analysator or "Kjelldals method" one can calculate the total protein content [49].

In this work (except for the experiments described in Chapter 4.8) the amount of extractable water and salt soluble protein was determined after extraction with respectively phosphate buffer and phosphate buffer with KCL, modified method after Anderson and Ravesi [50], and Licciardello *et al.* [51]. For the experiments in Chapter 4.8, 5% Triton was added in both buffers due to findings that this would give higher extraction rates [6]. The extraction of proteins was conducted at 4°C. Two parallels of each sample were analysed. The protein content in the fractions was determined with the Bio-Rad method [52].

4.5.4 pH

pH was determined by mixing minced fish with 0.15 M KCl at a 1:1 ratio [53].

4.5.5 Drip loss

All the sample pieces were weighed before freezing and after thawing (after first removing excess water with an absorbing sheet of paper). The percentage weight loss represented the drip loss.

4.5.6 Colour

One of the most important quality criterions for Salmon is the filet colour. The reddish colour of the fish meat is due to the astaxanthin or canthaxanthin pigment content. This

content can be measured, but the numerical values are badly correlated with the optical impression of the colour. The perception of the colour greatly depends on the temperature and light conditions during viewing. The colour impression also depends on the fat content in the sample [54].

Chemical methods for assessing the colour require the fishmeat to be minced. This has never been an option in this work, since the industry itself almost always assess colour on whole salmon fillets.

Colour can be measured optically by two methods:

- Visually by the use of a LaRoche colour card (Depending on whether the cut is perpendicular or parallel to the backbone the scale is from 1-8 or 11-18) see Figure 4.1, and
- Instrumentally by Minolta Cromometer or X-Rite Spectrocolorimeter where the three colour parameters L*(lightness), a*(redness) and b*(yellowness) are measured. By doing so these instruments imitate the human eye. The Lightness is given, as a value from 0-100 where 0 is black and 100 is white. The values for Redness go from –a (green) through zero (grey) and up to a (red), whilst the Yellowness goes from –b (blue) through zero (grey) and up to b (yellow). The results from measurements made by these instruments will vary from instrument to instrument, and will also be affected by the operator.

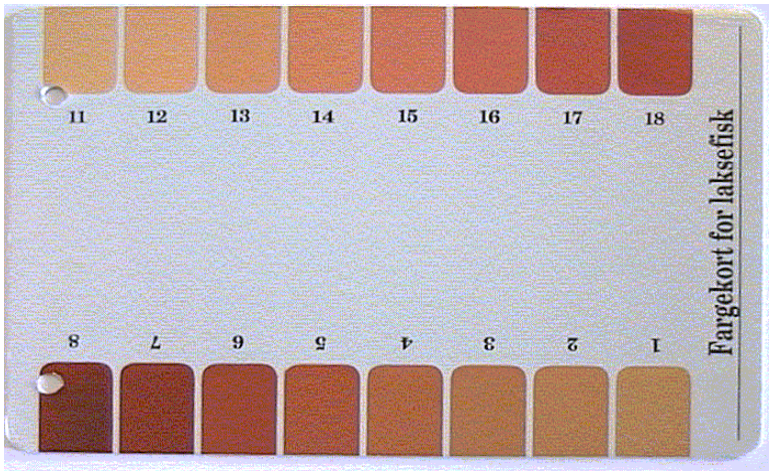


Figure 4.1 *LaRoche Colour card. LaRochew has also a product that is called SalmoFan which has a more detailed scale from 20 - 34*

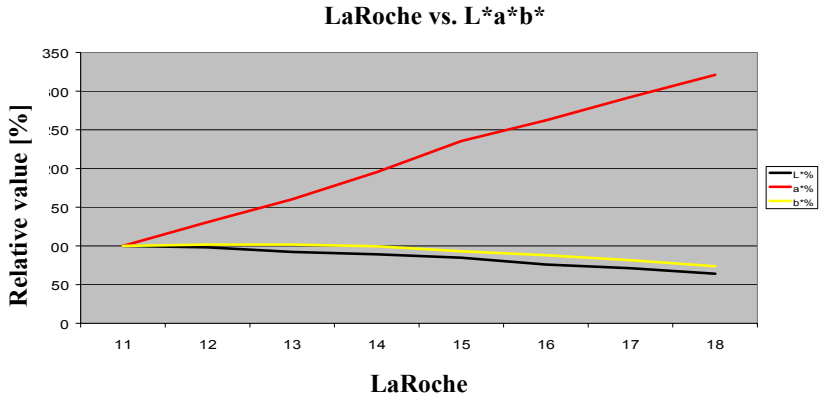


Figure 4.2 *Relation between LaRoche and L*a*b* values measured with a Minolta Chromometer* [55]

The relationship between the LaRoche scale from 11-18 and the corresponding L*a*b* values are given in Figure 4.2. The given relationship is not exact, but the tendency is clear; increased LaRoche values are followed by reduced values of L* and b* and increased values of a* [49, 54, 56].

4.5.7 Texture

The fish meat texture, or in other words the elastic and plastic deformation properties, is a very important quality parameter and it is altered as a result of the product treatment (time and temperature).

According to Torrisen [54] the most important factors that influence the fish meat texture are:

- Autolytic enzymes. These are responsible for the texture change due to storage time and temperature.
- Temperatures exercise and diet. Incubation and hatching at low temperatures give many but small muscle cells, whilst high temperature gives fewer and larger cells. Use of flow regimes that force the salmon to exercise increase the muscle cells. Reduced food access reduces the muscle cells.
- pH, water holding capacity and protein properties.

It has been tried to replace sensorial analysis of the fish texture with various instruments. The heterogeneous nature of fish makes it difficult to find standardised and reproducible methods for sampling and analysing the texture [57]. This makes comparison from fish to fish and between groups hard.

The most common method measures the force needed to push a probe into the sample. Another method is to measure the force needed to cut through the sample. It is also possible to use compression tests that compress the sample until it breaks. From such force measurements it is possible to calculate several parameters like hardness, elasticity and chewing resistance. According to Sigurgísladóttir [58] and Torrisen [54], the cutting based methods tend to give the most reproducible results.

Based on this information it was decided that the texture measurements should be done with a Kramer cell (range: 0-500N), on a 40x40x20mm^3 piece of fillet. The compression/cutting speed was 15mm/minute, and the muscle fibres of the sample were oriented parallel to the edges of the cut. A picture of the Kramer cell is given in Figure 4.3.

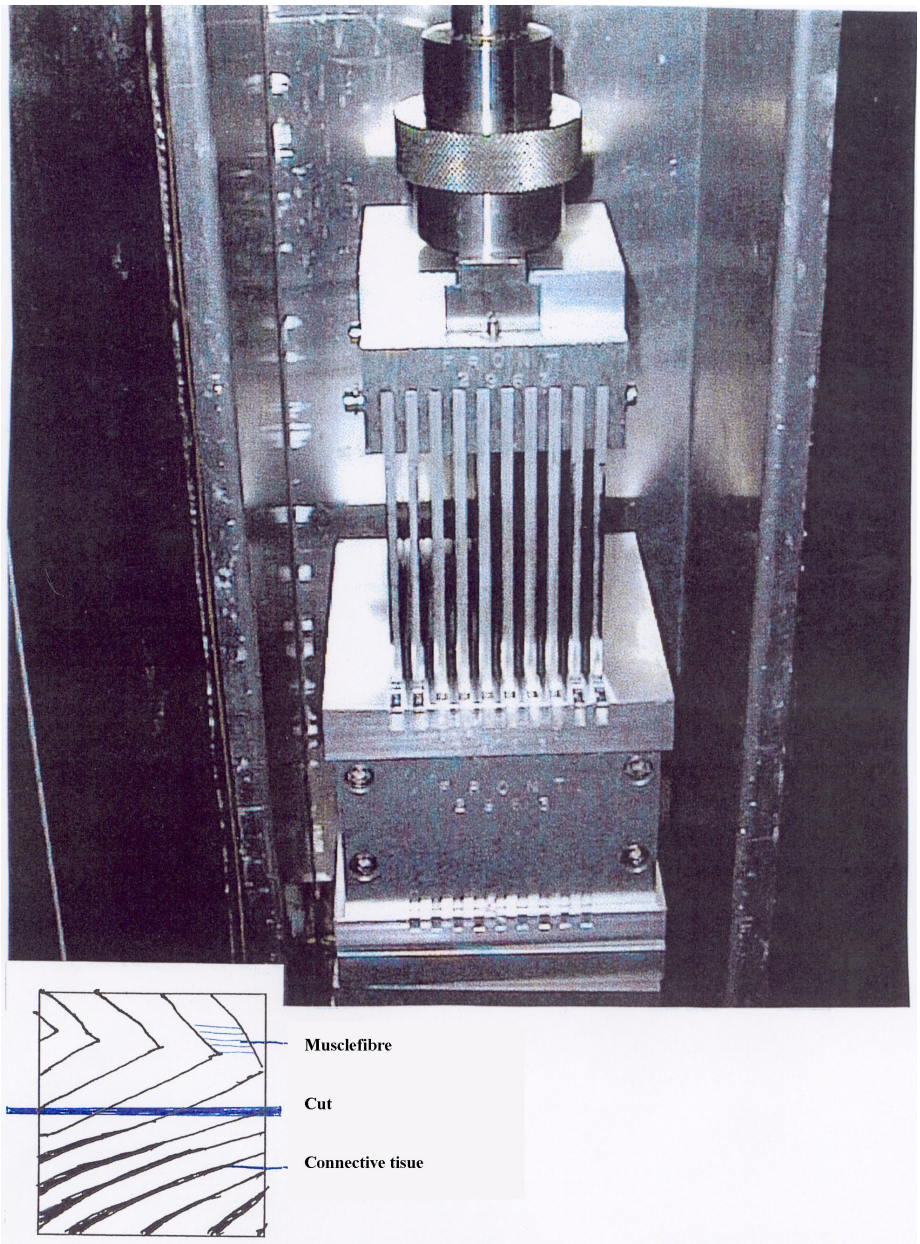


Figure 4.3 *Picture of a Kramer cell, and an illustration of the sample orientation during the tests.*

In this work one of several universal texture measuring instrument, an Instron model 1011, was used. Figure 4.4 illustrates the main characteristics of this instrument.

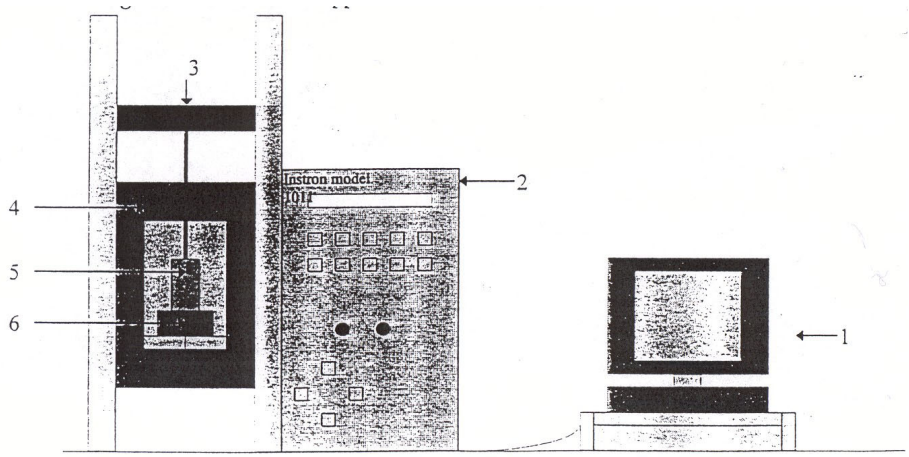


Figure 4.3 *Sketch of the instrument used to measure product texture. 1 - PC used to program 2 and collect the data registered by 2. 2 - The Instron instrument, model 1101, control panel used to calibrate and to run 3 manually. 3 – Load cell (max 500 N). 4 – Cabinet used to control the temperature during sampling. 5 – Kramer cell containing the sample. 6 – Foundation.* [59].

The test procedure was as follows:

A sample was prepared from the thickest par of the fillet (above the backbone), it was cut into a 40x40x20 mm^3 by the aid of a special gauge.

The sample was weighed, and put into the Kramer cell, oriented in such a manner that the muscle fibres were parallel to the Kramer cell knives. Temperature of the sample and temperature within the cabinet have been altered among the different experiments and will be commented when appropriate during the detailed description of each experiment.

The actual compression test could then begin. The top of the Kramer cell (knife piston) was then used to compress the sample at a rate of 15 mm/min. The sample would then be compressed until the cutting would begin. The forces required to compress/cut the specified sample could then be registered. The movement of the knife piston was stopped as soon as max load was registered. From the registered values a destruction curve could be drawn (Figure 4.5). From this curve max force (N), deformation (mm) and steepest slope (N/mm) could be determined.

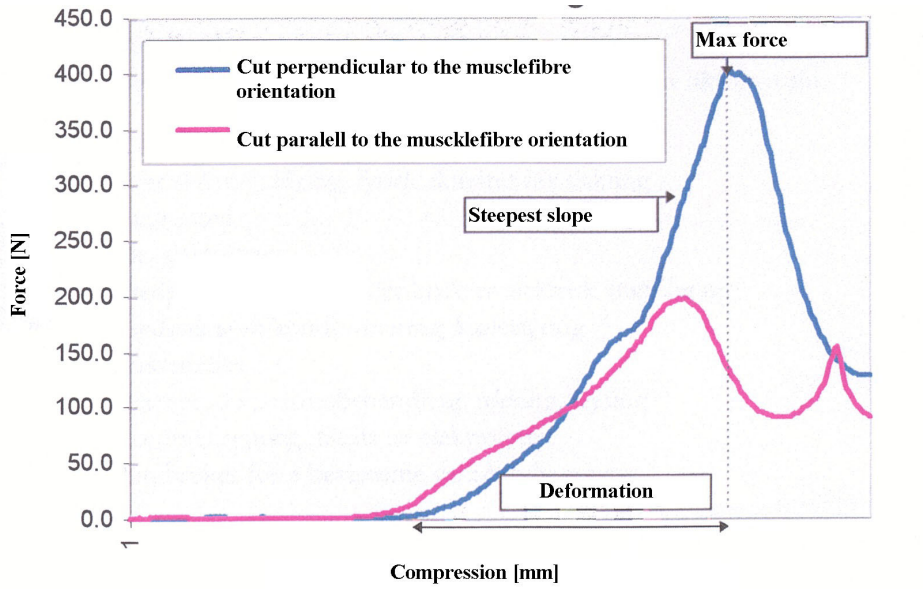


Figure 4.5 *An example on the measured force, and the effect of sample orientation related to the knife piston.*

The figure also illustrates the importance of correct orientation of the sample within the Kramer cell. This proves that the sampling technique used is not very robust.

4.6 Thawing equipment

Equipment for thawing whole fish is described in Chapter 3. For most of the experiments using Salmon as a model product (i.e. this chapter) the sample sizes have been less than 200 g filet, and three or more parallels have been used. With exception of some initial samples, all samples have been vacuum packed, and some of the samples have been equipped with a thermocouple to monitor the sample core temperature. All the samples have been frozen in an air blast freezer. Both thawing by immersing the samples in brine and thawing between two plates have been studied. A brief description of these methods is given hereafter.

4.6.1 Brine thawing

For thawing the samples in a fluid, a water bath containing NaCl brine (concentration depending on experiment) was used. A thermostat controlling a heat sink and a heat source regulated the temperature of the brine. The heat sink was a closed loop where alcohol circulated. The alcohol was kept at –20°C by the aid of a mobile refrigeration unit, type Kryomat. The heat source was an electrical heater that could supply maximum 1 kW. In

addition to this the water brine was equipped with a circulation unit in order to prevent stationary water around the samples.

The frozen samples were carefully placed in a tray that secured fluid flow around the entire samples. The temperature of the water bath was then kept constant or regulated in accordance to a given time-temperature program.

4.6.2 Plate/contact thawing

The equipment used to thaw the samples between two plates consisted of two aluminium plates both containing several electrical sheet heaters. The plates were kept at the same temperature, and the required temperature was regulated by the aid of thermocouples at the plate surface. As long as the plates and its equipment were kept in a 0°C room, the temperature of the plates could be regulated between 0°C and 40°C. For thawing at 0°C the electrical heater was not used.

4.7 Effect of time and temperature during thawing

During thawing, different parts of the salmon will experience a wide range of temperature development. This is illustrated in Figure 2.5. In addition the most common industrial approach will lead to considerable variations amongst the different fish. One of the most important issues related to thawing is therefore how will the quality be affected by the different time-temperature treatments. When this is better understood, it is easier to evaluate different thawing procedures, and to improve the procedures and equipment design. Several different experiments have been set up to get more knowledge about the effect of time and temperature during thawing.

4.7.1 Material

In order to study a given temperature treatment, it is important to reduce the size of the sample as much as possible and still having enough material to perform the chosen quality measurements. Because the different experiments have been conducted with different industrial partners, the samples have had its origin from different locations along the Norwegian coast. Gutted whole salmon on ice were bought directly from the slaughter venue, and transported to the laboratory, and stored in a chilled room at approximately 0°C, for a given time before the samples were prepared. This was done in order to secure that the salmon were post rigor. Figure 4.6 illustrates how the samples have been cut and numbered.

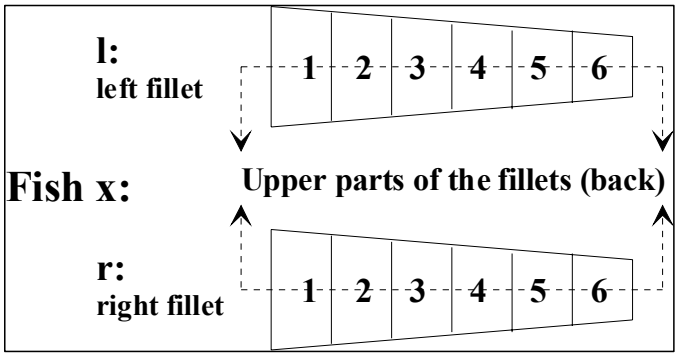


Figure 4.6 *Desiccation scheme and illustration of how the different samples were numbered. For some of the experiments an additional prefix were used to avoid samples being used in the wrong experiments. The third sample of the left fillet in the first fish (salmon) got the number 1-L-3.*

The samples were weighed, vacuum packed and frozen in an air blast tunnel at approximately –30°C with an air velocity of approximately 1.7 m/s. Before vacuum packing a thermocouple was inserted into the sample core to document that the given treatment was as specified.

For some of the experiments, slightly different dissection schemes and sample preparation techniques have been used. This is commented in the ***Condition*** section for the actual experiments. The chosen experimental design does also vary, depending on the purpose of the experiments, the accumulated knowledge and practical limitations. Information concerning this is given in the ***Experimental design*** section for the actual experiments.

4.7.2 Effect of different equipment

The aim of this experiment was to investigate the effect of different thawing equipment. Two different principles were used;

- thawing by conduction – by placing the object to thaw between two heated plates,
- thawing by convection – by immersing the object to thaw in a flow of heated fluid.

Conditions

The samples were prepared as described in chapter 4.7.1, and stored at –40°C until time of analysis.

Experimental design

Three samples were used in each experiment. These samples were cut from the same region in three different fish from the same batch.

The experiments were conducted at the following thawing medium temperatures; 5°C, 10°C, 15°C, 20°C, 25°C and 30°C.

The equipment described in Chapter 4.6 were used, and the thawing were conducted after the following plan. The temperatures of the thawing equipment (T_{thaw}) were kept constant at the different levels given above. The samples were kept in the thawing equipment until all the samples had a core temperature (T_{core}) that exceeded thawing temperature minus 2°C, that is until: $T_{core} > T_{thaw}$-2°C. After this the samples were chilled in ice prior to the analysis.

Comments regarding the experiments

The experiment had two design variables; thawing method and thawing temperature. In addition the samples were taken from different fish and from different part of the fish. These two factors were not controlled (unfortunately), except that the three samples in each experimental run were taken from the same region of the fish. Statistical analysis showed that the sampling programs for these experiment made it impossible to draw conclusion regarding the effect of thawing temperature. These analyses are given in Appendix III.

Results and discussions

Thawing between the heated plates can be said (simplified) to be 1 dimensional heat transferral, whilst the brine thawing will be 3 dimensional. This obviously means that the samples needed a longer residence time in the plate thawing equipment than in the brine thawing equipment. This illustrated in Figure 4.7, where the average time from $T_{core} > -15°C$ until $T_{core} > T_{thaw}$-2°C.

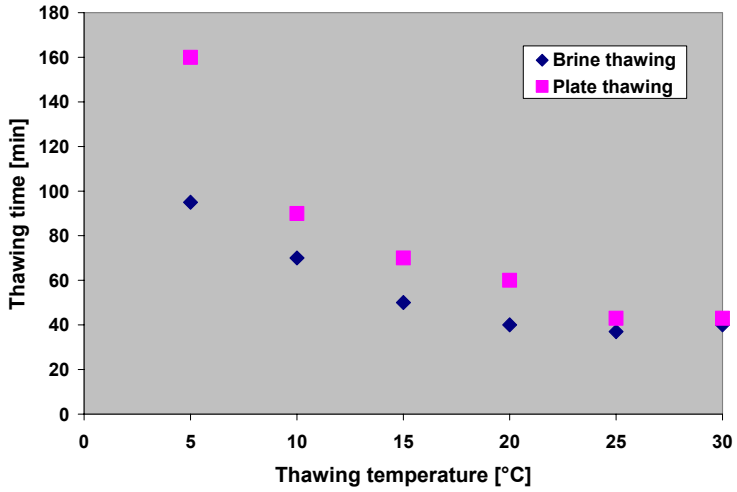


Figure 4.7 *Thawing time depending on equipment and temperature. Time from $T_{core} > -15°C$ until $T_{core} > T_{thaw}$-2°C.*

The figure shows that the thawing time is reduced from between 95 min and 160 min down to approximately 40 min by increasing the thawing temperature from 5°C and up to 25°C. Brine thawing gives the fastest thawing, but the advantage is reduced as the thawing temperature is increased, and for temperatures equal or higher than 25°C the two methods use the same time. This means that for the applied sample size (110g –160g) and these temperatures the limiting mechanism is the heat transferral within the sample and not the heat transferral from the environment to the sample surface.

Initially the experiment had two design variables; thawing method and thawing temperature. Due to reasons discussed above in 'Comments regarding the experiments' only the effect of thawing method is worth while to investigate.

The data from the quality measurements for the different experiments are given in detail in Appendix IV.

Table 4.1 gives an overview on whether the different response variables (pH, drip loss, dry matter, WHC, WS proteins and SS proteins) are influenced by the thawing method.

Table 4.1 *Effect overview from the experiments. NS means Non Significant, whilst the * means that the design variable thawing Method has a significant effect on the response variable (pH, drip loss, dry matter, WHC, WS proteins and SS proteins).*

Variable	pH	Drip loss	Dry matter	WHC	WS proteins	SS proteins
Method	NS	***	**	***	NS	NS

** - means that the significant level is 1%
*** - means that the significant level is 0.1%

The first thing to study is whether there are any significant effects, and secondly to evaluate the relevance of these effects.

Dry matter and WHC are influenced by changes in thawing methods. Figure 4.8 through figure 4.10 illustrate this.

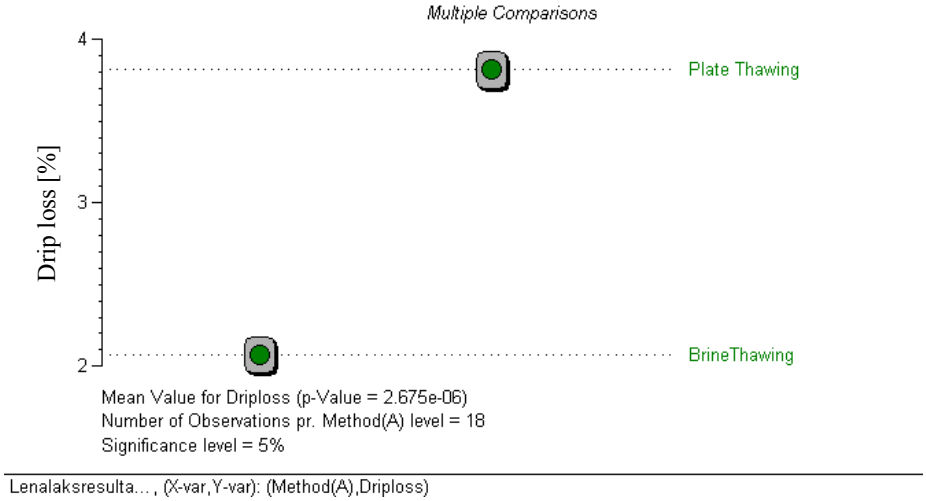


Figure 4.8 *The effect of different thawing methods on drip loss.*

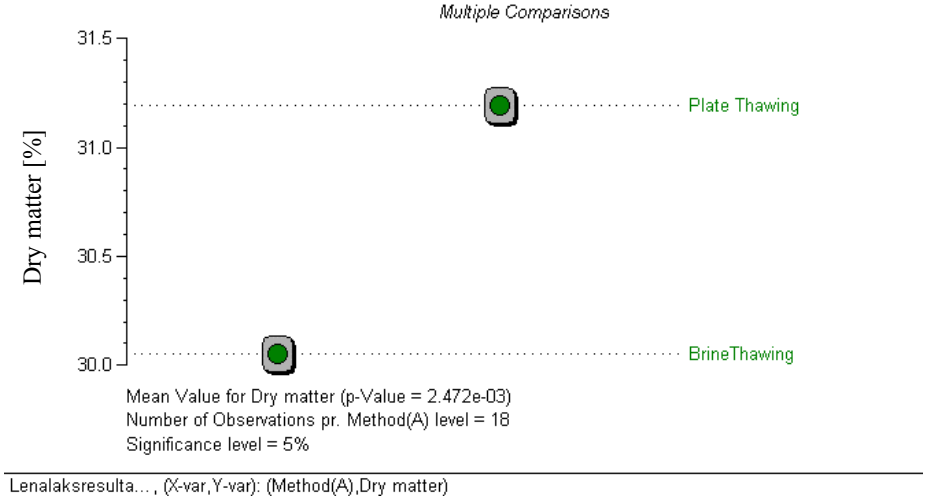


Figure 4.9 *The effect of different thawing methods on dry matter.*

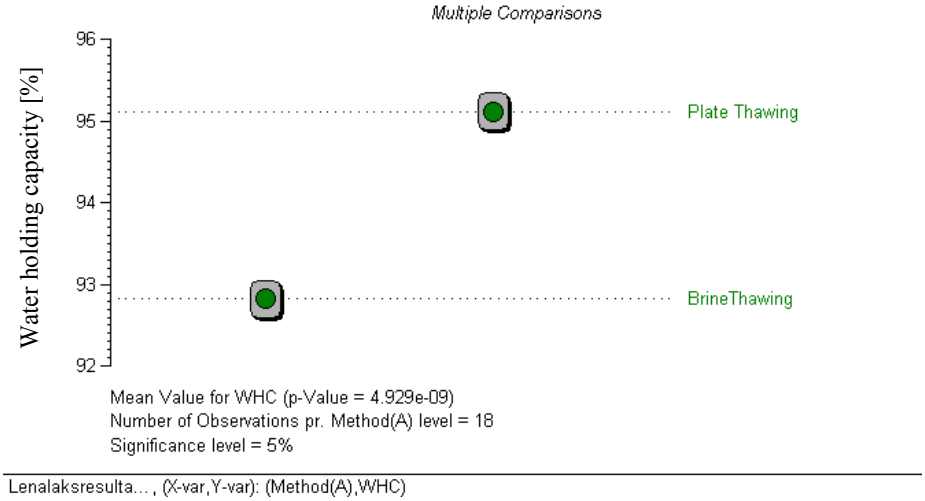


Figure 4.10 *The effect of different thawing methods on WHC.*

The drip loss is almost twice as large for the salmon thawed in the plate thawer than for the salmon thawed in brine (an average drip loss of 3.8% vs. 2.1%). For both dry matter content and Water holding capacity the values are higher (respectively 1.2% and 2.3%) for the salmon thawed in the plate thawer than for the brine thawed. These differences can be connected through the fact that higher drip loss will give a higher dry matter content and result in a higher water holding capacity (the loosest bound water is lost in the drip).

Increased drip loss might be a result from the slower thawing (caused by the plate thawing method), and/or origin from the pressure exercised by the upper heating plate on the samples during this method. The drip loss is however also significant higher for the plate thawing method for thawing at 25°C and 30°C, where no differences in thawing time were found. This probably means that the sample pressure exposure in the plate thawing equipment is the major factor causing the differences in drip loss amongst the two thawing methods.

As mentioned in Chapter 4.5.2, reduced water content will normally give higher WHC. The results in Figure 4.9 (dry matter) and Figure 4.10 (WHC) support this. Increased WHC is however associated with higher quality. The knowledge that the plate thawed samples have suffered a higher drip loss due to pressure exposure contradicts this interpretation. From the literature one would expect that a change in WHC would be accompanied with differences in pH. This is not found in this work. Actually the pH for all the experiments must be considered to be fairly high (average of 6,26) with low spread (0.08). The water loss due to pressure exposure caused by the plate thawing method is most likely the water bound by the weakest mechanisms within the sample. On this basis it is reasonable to assume that the higher dry matter content and WHC is mainly a result of higher loss of loosely bound water caused by the plate thawing method.

Conclusion - effect of thawing equipment

Brine thawing is more efficient than plate thawing, and the difference will increase with increased geometrical complexity of the product (i.e. whole fish instead of fillet samples). Even for the relatively small samples used in these experiments the heat transfer within the product is the limiting mechanism for the overall heat transfer at thawing temperatures above approximately 20°C.

Thawing by conduction as the main heat transferring mechanism, by placing the product between two horizontal plates gives a considerable higher drip loss than thawing in water/brine.

The overall quality seemed to be fairly good for all samples even after thawing at high temperatures; this might be the result of a very rapid thawing at these temperatures, and or an effect of the immediately cooling after thawing before analysing.

4.7.3 Effect of different ways to end the thawing

The aim of these experiments was to find out whether the quality of the thawed product depended on the principle for finalising the thawing. Three different approaches, that seemed to be the extremity under the given experimental set-up, were studied;

- The samples were removed from the thawing equipment when the core temperature of the coldest sample reached 0°C. Before analysing, the samples were put in a small insulated container in order to allow levelling of the temperature within each sample. This method is denoted: **CoreT=0°C**
- The samples were removed from the thawing equipment when the core temperature of the coldest sample reached a temperature 2°C below the thawing media temperature ($T_{core} > T_{thaw}$-2°C). After this the samples were chilled in ice prior to the analysis. This method is denoted: **CoreT=T-2,chill**
- The samples were removed from the thawing equipment when the core temperature of the coldest sample reached a temperature 2°C below the thawing media temperature ($T_{core} > T_{thaw}$-2°C). After this the samples were analysed immediately. This method is denoted: **CoreT=T-2**

Conditions

The samples were prepared as described in chapter 4.7.1, and stored at –40°C until time of experiment.

Experimental design

Three samples were used in each experiment. These samples were cut from the same region in three different fish.

The experiments were conducted at the following temperatures; 10°C, 15°C, 20°C, 25°C and 30°C.

The plate thawing equipment described in Chapter 4.6.2 was used for all the experiments.

Comments regarding the experiments

The experiment had two design variables; End of thawing method and thawing temperature. Unfortunately the same sampling technique as in Chapter 4.7.2 was applied. This made it impossible to study the effect of thawing temperature. The statistical analyses that show this is given in Appendix V.

Results and discussion

Initially the experiment had two design variables; 'end of thawing method' and 'thawing temperature'. Due to reasons discussed above in 'Comments regarding the experiments' only the effect of 'end of thawing method' is worth while to investigate. The results are given in detail in Appendix VI.

Table 4.2 gives an overview on whether the different response variables (pH, drip loss, dry matter, WHC, WS proteins and SS proteins) are influenced by the end of thawing method.

Table 4.2 *Effect overview from the experiments. NS means Non Significant, whilst the * means that the End of thawing method has a significant effect on the response variable (pH, drip loss, dry matter, WHC, WS proteins and SS proteins*

Variable	pH	Drip loss	Dry matter	WHC	WS proteins	SS proteins
End of thawing method	*	NS	NS	NS	NS	NS

The 'end of thawing method' has a small significant effect on pH, but since the effect is as low as 0.06 it is not of any practical value.

It is therefor fair to say that under the chosen experimental setup it was not possible to find any significant differences between the different possibilities for finalising the thawing. It is however important to realise that the 'end of thawing method': **CoreT=T-2** and **CoreT=T-2,chill** had very short resident times (approximately 40 min) at high temperatures, at which one could expect significant effects on quality.

Conclusion – treatment after thawing

Even though no significant differences amongst the different methods for finalising the thawing were found, it will still be necessary to choose one when conducting experiments that involve thawing. The one that is easiest to carry through is the **CoreT=T-2,chill**, where the samples are chilled on ice prior to analysing.

The experiments also put forward a demand for finding out what happens when the resident time at high temperatures increases, and to investigate the effect of different thawing temperatures (As the two previous experiments failed to reveal).

4.7.4 Effect of thawing speed and temperature

The colour is possible the most striking quality parameter for superior Salmon. Exporters know that the colour of Salmon is weakened through freezing, storage, transport and

thawing. This chapter set out to reveal the effects of thawing. The work is based on the assumption that it is the thermal strain that lead to reduce colour impression during thawing. Thermal strain is a function of both time and temperature, hence the experiments have been designed to find how both these factors influence the colour.

Conditions

The samples were taken from region 4 and 5 in Figure 4.6, which corresponded to the Norwegian Quality Cut (ref. page 16). In addition to the procedure described in Chapter 4.7.1, the colour of the samples was measured prior to vacuum packing. After freezing the samples were stored at –45°C until thawing.

Experimental design

Thawing towards 0°C, 15°C and 30°C were done at two different paces; fast and slow.

Fast thawing was achieved by immersing the samples into a circulating brine which was kept at 5°C, 20°C and 35°C for respectively 0°C, 15°C and 30°C end temperature. Measured temperature profiles during fast thawing are given in Figure 4.11. Hence the thermal exposure for these three different runs was unique, and differences in yield and colour could therefore originate from different resident time at any temperature.

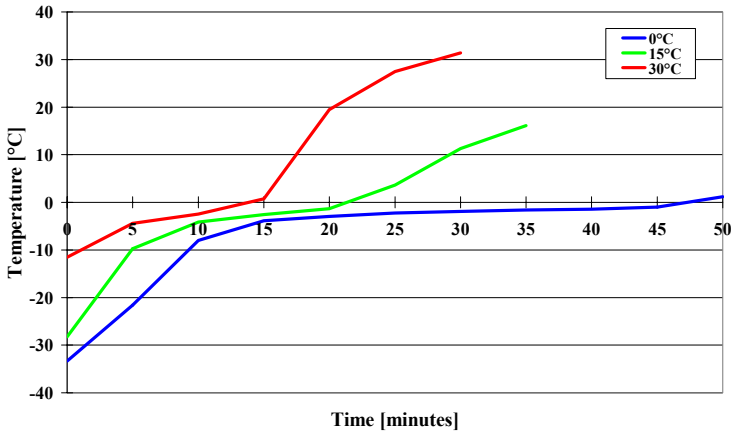


Figure 4.11 *Registered core product temperatures during fast thawing towards 0°C, 15°C and 30°C*

Slow thawing was achieved in the same thawing equipment, by using different time temperature programs. These programs were deduced from actual temperature profiles during thawing of packed whole frozen salmon placed in ambient air at 20°C. The different temperature programs are given in Table 4.3

Table 4.3. *The time-temperature programs that were used in order to achieve slow thawing towards 0°C, 15°C and 30°C in circulating brine.*

Elapsed time [h]	Temperature [°C]	Time at given temperature step [h]	Slow thawing towards [-]
0	-9	5,5	
5,5	-4	9,5	
15	-2	15	
30	5	3	**0°C**
33	10	2	
35	15	2	**15°C**
37	20	1	
38	25	3	
41	30		**30°C**

The temperature programs were identical until the product had reached 0°C. This means that differences between the different temperature levels for the slow thawing will originate from the different thermal exposure above 0°C. 5 samples were used in each experiment. Adjacent right and left samples (ref Figure 4.6) were used in experiments towards the same final temperature but at different speed (fast and slow)

For both thawing speeds the thawing towards 15°C was repeated, in order to validate the experimental error.

Colour (both LaRoche and Minolta[3]) and weight were registered immediately after thawing for all five samples in each of the eight experiments. In addition the colour was re-measured after the samples had been stored dark at ~20°C for five hours. Finally the samples that had been thawed fast towards 0°C and 30°C were measured after being chilled to 0°C.

Results and discussion

For some of the samples used in the slow thawing experiments, leakage occurred around the thermocouples. These samples were excluded from the following presentation. The results could be described in many ways, but the preferred way in this work was to describe the change (absolute or relatively) during the defined treatment. The effect is described as the percentage change of the chosen parameters, except for colour according to LaRoche where an absolute change is preferred[4].

Effects of thawing

Figure 4.12 gives a summary of the changes in the different quality measurements during thawing, for different thawing speeds and temperatures.

[3] Due to malfunction, L*a*b* values was not obtained for the second fast thawing towards 15°C

[4] This because the units in the LaRoche scale is considered to be known to everyone dealing with salmon quality, thus making better sense than after mathematical processing.

The second run for both slow and fast thawing towards 15°C is very similar, and proves that the experiments are reproducible. Figure 4.12 contains a lot of information, and it can seem hard to separate the important effects from more random variations. Combined with statistical analysis (Table 4.4), the effect of the treatment is better described.

Table 4.4 *Effects of thawing. NS means Non Significant, whilst the * means that the design variable (Thawing speed or Thawing temperature) has a significant effect on the response variable (Weightloss, LaRoche, L*, a* and b*)*

Variable	Weight loss	LaRoche	L*	a*	b*
Thawing speed	***	**	NS	***	**
Thawing temperature	***	***	***	***	***

Table 4.4 shows that all the response variables except from L* are significantly influenced by both Thawing speed and temperature. The changes in L* is not influenced by Thawing speed.

Figure 4.12 shows that slow thawing will result in higher weight loss than fast thawing at 15°C or below. Somewhere between 15°C and 30°C the weight loss will increase also during fast thawing and become similar to that of slow thawing at about 30°C.

The colour impression represented by LaRoche is on average 0.5 units lower for the fast thawed samples than for the slow thawed, mainly due to the large difference at thawing towards 30°C.

As for the three colour components L*a*b*; Lightness (L*) is not affected by the thawing speed, whilst redness (a*) and yellowness (b*) respectively on average has increased 20% and 15% more during the slow thawing than the fast thawing. The latter effect is mainly due to differences during thawing towards 30°C. The combined effect from the changes in the three colour components, support the LaRoche findings.

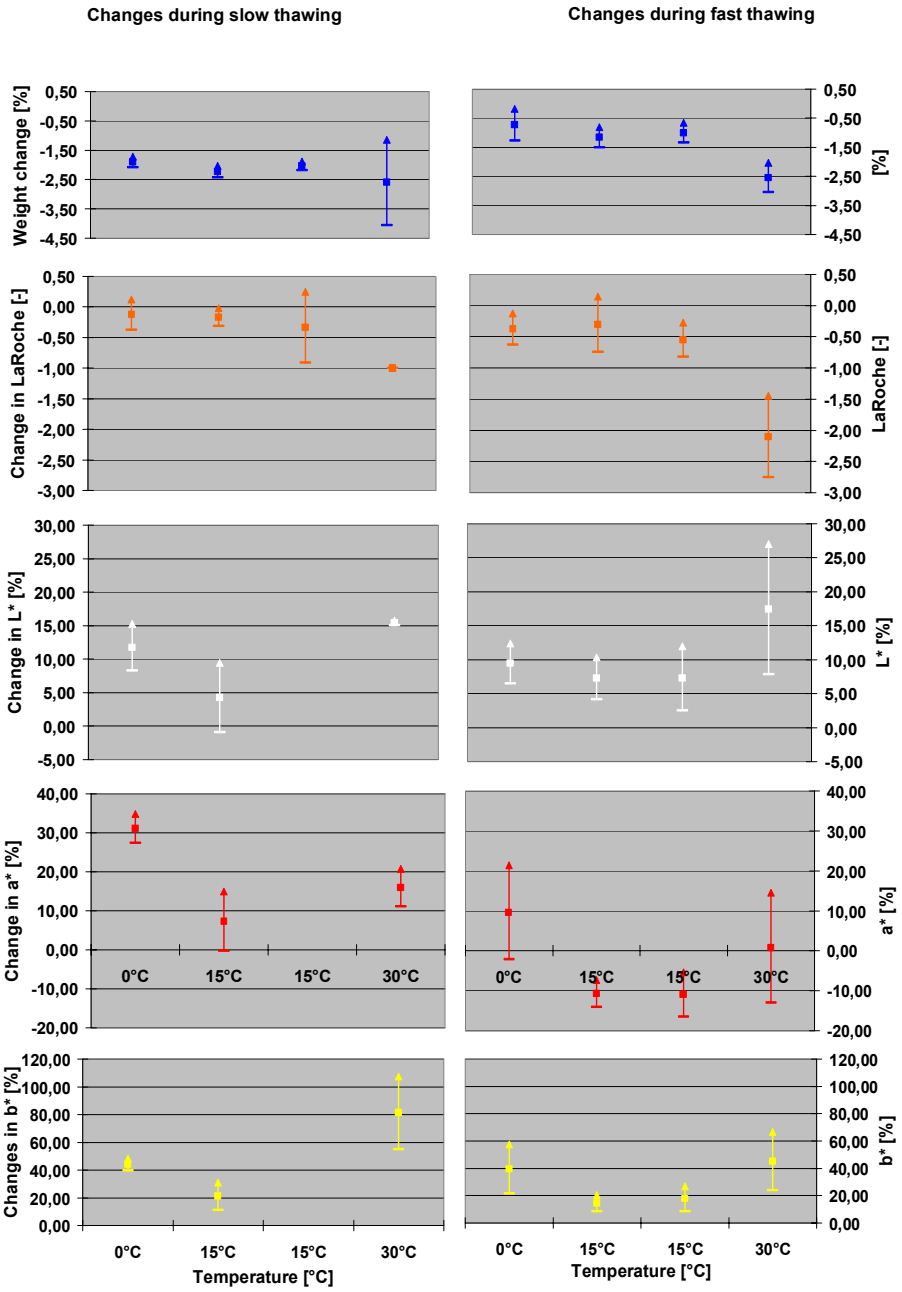


Figure 4.12 *Changes in different quality parameters as a result of the thawing*

Effects of thawing and tempering
After the quality measurements were done, all the samples were wrapped in plastic and stored at ambient condition (ca. 20°C) for 5 hours before the colour was measured again. The result is shown in Figure 4.13. Combined with the result from the statistical analysis (Table 4.5) the effect of the different treatment can be described.

Table 4.5 *Effects of thawing and tempering. NS means Non Significant, whilst the * means that the design variable (Thawing speed or Thawing temperature) has a significant effect on the response variable (LaRoche, L*, a* and b*

Variable	LaRoche	L*	a*	b*
Thawing speed	***	***	***	NS
Thawing temperature	***	***	**	***

Depending on the level of the thawing temperature, the 5 hours in ambient condition will act as a tempering or a cooling. The samples thawed towards 0°C and 15°C were heated and the samples thawed towards 30°C were cooled, during this time.

Table 4.5 shows that all the response variables except from b* are significantly influenced by both Thawing speed and temperature. The changes in b* are not influenced by Thawing speed.

Figure 4.13 shows that for thawing towards 0°C and tempering in ambient condition the increase in L*a*b* values during thawing are reduced during tempering resulting in no net change in the LaRoche value. For thawing towards 15°C followed by tempering in ambient condition the increase in L*a*b* values during thawing is further increased during tempering resulting in a net reduction in the LaRoche value. For slow thawing towards 30°C and cooling in ambient condition the increase of the a* value during thawing is further increased during cooling resulting in a net increment in the LaRoche value. During cooling of the fast thawed samples, the L* and b* values also rise resulting in no net change in the LaRoche value during cooling.

The slow thawed samples generally show less change in lightness (5% less change), more in redness (15% more change) and more in yellowness (for 30°C, that is) than the fast thawed samples.

To summarize; it seems like there is no serious impact on the colour impression over the temperature range 0°C to 15°C, and that the colour impression is affected at some point between 15°C and about 20°C and further towards 30°C. Fast thawing towards high temperatures seems to be less reversible than slow thawing.

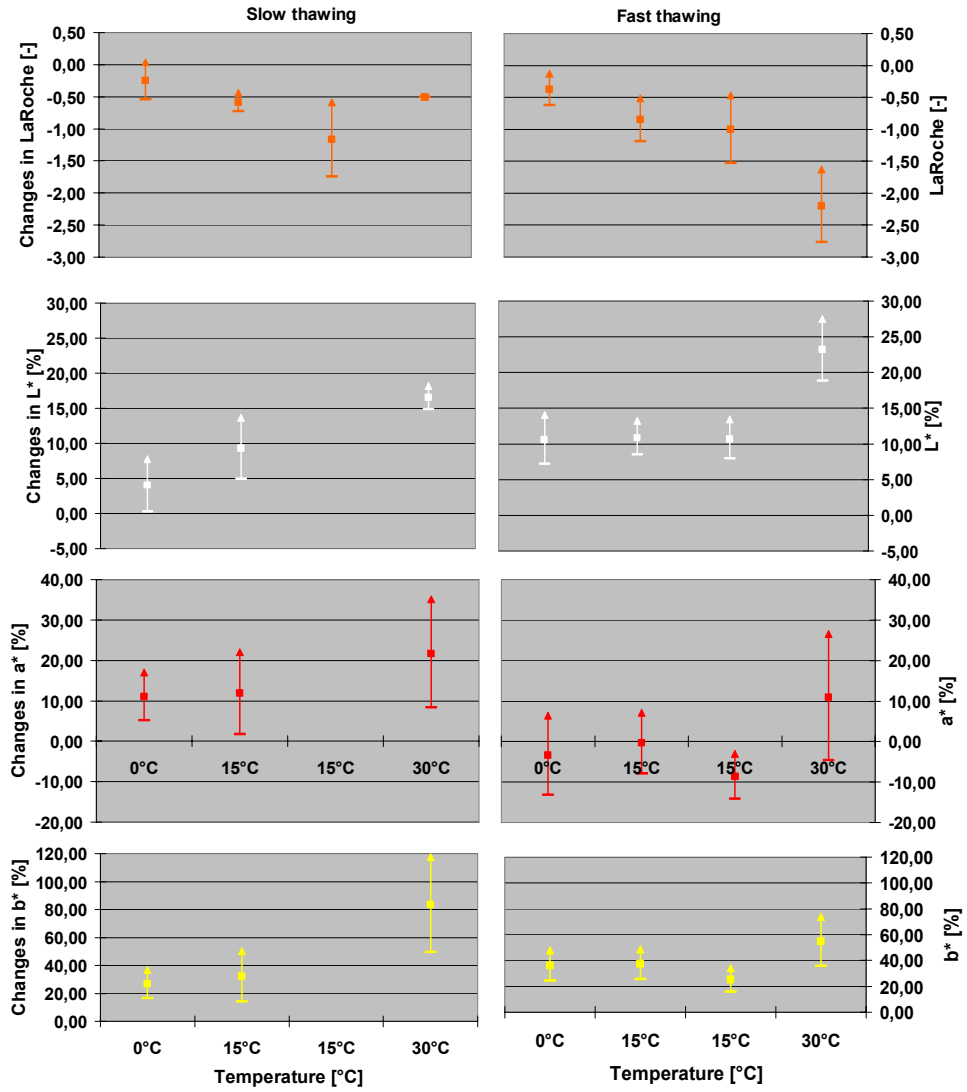


Figure 4.13 *Changes in colour during thawing and 5 hours tempering in ambient conditions*

Effect of thawing, tempering and chilling

In order to check the reversibility of the colour changes, the samples thawed fast towards 0°C and 30°C were chilled on ice after tempering for 5 hours in ambient condition. Figure 4.14 shows the results.

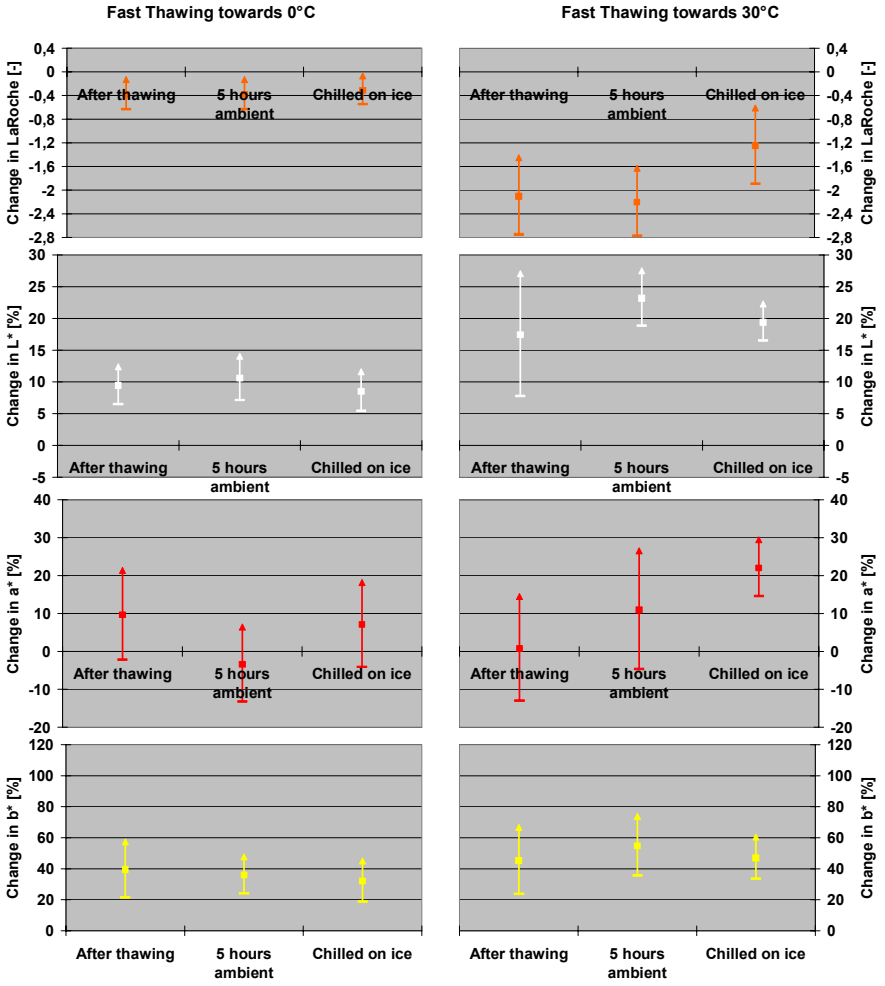


Figure 4.14 *Changes in colour during fast thawing towards 0°C and 30°C, followed by 5 hours tempering in ambient condition and finally chilling on ice*

The colour impression (LaRoche) of the samples thawed fast towards 0°C is reduced very little during thawing, and the successive treatments (heating in ambient conditions for 5 hours followed by chilling to 0°C) do not seem to have any impact at all.

A closer look at the L*a*b* values does not totally support these findings. During thawing L*, a* and b* all are increased, the following heating in ambient condition further increases the lightness (L*) and at the same time reduces the redness (a*) and to a small extent the

yellowness (b*). The final chilling tends to reverse the changes that took place during heating, resulting in L*a*b* values very close to those after thawing. From these findings one should expect that the LaRoche values would be lower for the samples after the 5 hours heating, than finally or directly after thawing. However this was not found, leading to the conclusion that the optical registered changes were not strong enough to make an impact on the colour impression registered by the human eye. Another conclusion is that there is an irreversible colour loss during freezing and thawing that amount to 0,4 units on the LaRoche scale.

During fast thawing towards 30°C an extensive reduction of the colour impression (LaRoche) takes place. This loss is kept through the 5 hours cooling in ambient condition, and is still high after chilling down to 0°C. A closer look at the L*a*b* values support these findings. During thawing the lightness increases significantly (more than for the thawing towards 0°C). Redness is not increased, whilst yellowness is extensively increased. During the following 5 hours cooling in ambient condition the L*,a* and b values are all further increased. The increase of the a* value counteracts the combined effect from increased lightness and yellowness, resulting in no change in the overall colour impression (LaRoche). During the chilling to 0°C the redness (a* value) is increased even further, whilst both lightness (L* value) and yellowness (b* value) are reduced to their post thawing levels.

From this, it seems that fast thawing towards 30°C results in an irreversible colour loss that is approximately 0,8 units (LaRoche scale) larger than the loss caused by the freezing and fast thawing towards 0°C.

Conclusion – thawing speed and temperature

Weight loss:
In order to minimise the weight loss through drip, it is important to thaw the salmon as fast as possible. This means that the heat transfer coefficient during thawing should be high and uniform throughout the thawing equipment. This demands attention towards the chosen thawing media, the actual circulation conditions and product packaging used.

Colour:

- Thawing in the area from 0°C and up to 15°C does not seem to make any major differences on filet colour, but obviously; lower thawing temperatures give higher safety margins during further processing.
- Thawing at temperatures above 15°C and especially up to 30°C can give significant irreversible colour loss.
- Thawing towards high temperature seems to be more reversible when the process is slow than when it is fast. This means that if the product is very thoroughly packed it is possible to increase the thawing temperature to speed up the thawing, but the best alternative if possible is of course to remove the packaging pre thawing. Products that thaw slow because of their size should not be thawed in too high temperatures (~30°C).

Thawing process limitation:
Based on this it seems that thawing in 5°C to 10°C water/seawater, where the whole surface of each fish is kept in contact with sufficient flowing thawing media, is the best way to retain the colour of frozen salmon. The higher thawing temperature used the more important it is to cool the product after thawing, or at the end of the thawing, in order to reduce the potential for further drip loss through handling/processing.

4.7.5 Effect of holding time in the critical temperature region

In Chapter 4.7.4, slow thawing gave considerable higher drip loss than fast thawing. Table 4.3 shows the time-temperature program the samples in the different experiments were thawed after. Evidently all the slow thawing samples experienced identical time-temperature programs during the first phase of thawing, that is until the first 30 hours of the thawing. During this time the weight loss for the samples thawed up to 0°C takes place. It is natural to believe that the samples used for the slow thawing towards 15°C and 30°C had experienced the same drip loss as the samples thawed to 0°C, after 30 hours thawing. In other words; the differences between samples thawed to 0°C and 15°C, have to be explained by the different time-temperature treatment from 0°C to 15°C. The effect from 0°C to 30°C is treated in Chapter 4.8.

The difference in weight loss between fast and slow thawing towards 0°C must relate to the large difference in resident time in the latent-freezing/thawing zone. In terms of temperatures, it is not agreed upon how to define this zone. Products with different composition will experience different time – temperature histories when exposed to identical environment Typical this zone is mentioned to be between 0°C and –10°C . The samples that were thawed fast experienced core temperatures between –10°C and the freezing point no longer than 40 minutes, whilst the slow thawed samples were kept at temperatures within this region for almost 30 hours. The effect of resident time in the latent-freezing/thawing zone is treated in this chapter.

Conditions

The samples were prepared as described in Chapter 4.7.1, and stored at –45°C until time of experiment. Unfortunately during the preparation of the test samples large quality differences between the individuals were discovered. The handling of these fish could not have been appropriate, since there still was some blood left in some fish, indicating insufficient bleeding. In addition both the colour and the texture varied to a large extent from one individual to another. The amounts of water (WS-Proteins) and salt (SS-Proteins) soluble proteins, WHC and drip loss, were analysed. In addition the total amount of extractable proteins (TS-Proteins = WS-Proteins + SS-Proteins) were included in the statistical analyses. The samples were thawed in the brine equipment described in Chapter 4.6.1. During the different experiment, the temperature of the brine was regulated to desired temperature level. The three samples were thawed towards this temperature. The brine temperature was kept constant from the time when all samples had a registered core temperature less than 0,5K below the desired temperature level. This level was kept until desired time (resident time) had elapsed. Following this, the brine temperature was set to

15°C until all samples core temperatures had passed 4°C. The samples were then stored on ice and transported directly to the laboratory for analyses.

Experimental design

The experimental variables considered were thawing temperature (i.e. thawing medium temperature) and holding time (i.e. the time where the entire sample has the same temperature as the ambient thawing medium). The experimental design chosen was an optimisation design, which demands experiment at all combinations of high, low and intermediate level for both design variables, plus two repetitions of the centre experiment (Intermediate level of both design variables). The samples were distributed to the different experiments in a special manner in order to minimise the effects of the large spread in the initial quality.

Table 4.6 *Experimental design for the experiment. Part number is referring to the numbers in Figure 4.6, L means Left fillet and R means Right fillet.*

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">Resident time [h]</th></tr>
<tr><th>1</th><th>4,5</th><th>8</th></tr>
<tr><td rowspan="4">Temperature [°]</td><td>-2</td><td>Fish1-part4-R
Fish7-part6-R
Fish10-part4-R</td><td>Fish1-part3-L
Fish2-part6-L
Fish10-part6-L</td><td>Fish1-part6-L
Fish9-part6-L
Fish12-part5-L</td></tr>
<tr><td rowspan="3">-7</td><td rowspan="3">Fish7-part2-R
Fish3-part4-R
Fish4-part5-R</td><td>Fish4-part2-L
Fish6-part1-L
Fish9-part3-L</td><td rowspan="3">Fish7-part2-L
Fish3-part4-L
Fish4-part5-L</td></tr>
<tr><td>Fish6-part5-L
Fish9-part4-L
Fish12-part2-L</td></tr>
<tr><td>Fish4-part2-R
Fish6-part1-R
Fish9 part3-R</td></tr>
<tr><td>-9</td><td>Fish1-part6-R
Fish9-part6-R
Fish12-part5-R</td><td>Fish1-part3-R
Fish2-part6-R
Fish10-part6-R</td><td>Fish1-part4-L
Fish7-part6-L
Fish10-part4-L</td></tr>
</table>

Comments regarding the experiments

Initially the thawing temperature and holding time should vary continuously within the range from –2°C to –12°C, and from 1 to 8 hours, respectively. Unfortunately the temperature regulating means (Chapter 4.6.1) were unable to secure lower temperatures than –9°C. At the point this was discovered, the centre experiments (average time and temperature) were already carried out. We decided to carry on with the experiments, and to use a slightly different approach during analysing the results (Full factorial design, with two three-levels design variables instead of the optimisation design). The experimental design is outlined in Table 4.6.

Results and discussion

The average results from the different experiments are given in Table 4.7. A Principal Component Analysis was done in order to see if the different responses were interrelated. The results revealed that three principal component explained 97% of the variations. The first component (PC1) explains 57%, whilst PC2 and PC3 respectively explain 24% and 16% of the overall variation. SS-Proteins is explained by PC1 and PC3, WS-Proteins and TS-Proteins is explained by PC1, WHC is explained by PC1, PC2 and PC3, and Drip loss is explained by PC2 and PC3. In figure 4.15 and 4.16 are the interrelationship between the variables illustrated in respectively the PC1/PC2 plane and the PC2/PC3 plane.

Table 4.7 *Overview over the experiments and the average results.*

Temperature [°]	Resident-time [h]	WS-proteins	SS-proteins	TS-proteins	WHC	Drip loss
-9°C	1	6,5	8,4	14,9	96,3	0,87
-7°C	1	6,2	7,5	13,7	93,5	1,24
-2°C	1	7,1	8,3	15,4	95,6	1,57
-9°C	4,5	6,1	7,5	13,6	96,3	1,05
-7°C	4,5	7,3	6,0	13,3	96,7	0,95
-7°C	4,5	7,1	6,4	13,5	96,7	0,88
-7°C	4,5	6,9	6,8	13,7	96,7	0,81
-2°C	4,5	6,8	6,9	13,7	97,3	1,45
-9°C	8	8,5	8,2	16,7	97,6	1,31
-7°C	8	8,7	9,2	17,9	96,7	1,26
-2°C	8	7,3	7,2	14,5	96,6	1,73

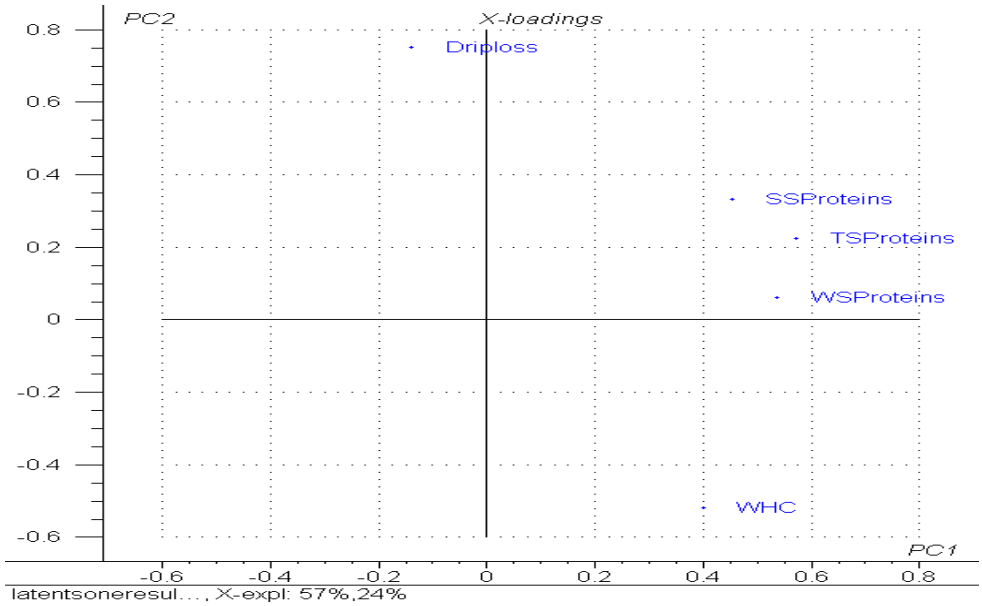


Figure 4.15 *The interrelationship between the response variables in the PC1 and PC2 plane. This plane explains over 80% of the variation in the results.*

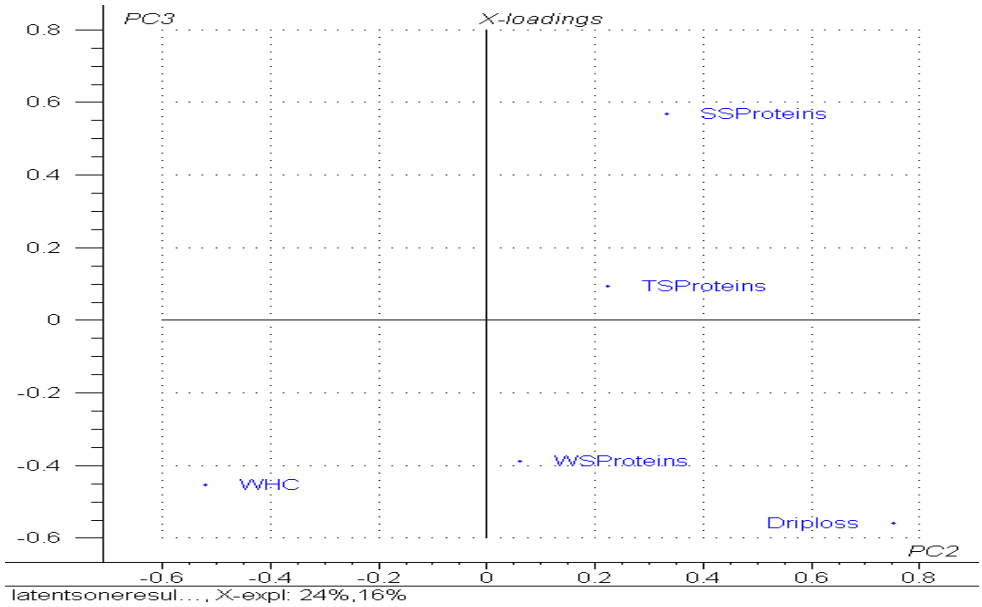


Figure 4.16 *The interrelationship between the responses in the PC2 and PC3 plane.*

PC1 (Figure 4.15) shows that WS-Proteins, SS-Proteins and TS-Proteins are positive correlated. WHC will also normally be high if the amount of extractable proteins is so. PC2 (Figure 4.15and 4.16) shows that high amount of drip loss will lead to reduced WHC. These findings are in line with common knowledge, and describe the normal relationships between important quality factors. If one focuses on PC3 (Figure 4.16) that explains 16% of the variations, some unexpected relationships occur. As drip loss increases, the WHC will also increase. This is not expected, but can be due to the following mechanism:

- During high drip loss, most of the loosest bound water is lost, resulting in high WHC that can be misinterpreted

The fact that amounts of water-soluble proteins and WHC can be high when the amount of salt soluble protein is low and drip loss is high, is more difficult to explain. Johansen and Haugland [60] mentioned possible cross bindings in the structure of the sarcoplasm proteins as an explaination to the negative correlation between WS-Proteins and SS-Proteins.

That the amounts of salt soluble proteins are high while the drip loss is low is in agreement with the theory.

The conclusion of the PCA is that the majority of the variations in the results are in agreement with the theory. Some questions have surfaced, but they can either be explained by special conditions or the fact that the quality of the experimental material had a large spread.

A summary of the analysis of effects is shown in Table 4.8. At first look the chosen temperature levels do not seem to affect the response variables. The p-value for drip loss (5.8%) is however only marginal above the chosen 5% significance level. If we compare the drip loss experienced at different temperatures, regardless resident time (Figure 4.17), it is clear that the results give a strong indication that the drip loss will increase if the Salmon is kept at –2°C for more than 1 hour.

Table 4.8 *Effects of time and temperature in latent zone. NS means Non Significant, whilst the * means that the design variable (Temperature or Time) or the interaction between them (AB) has a significant effect on the response variable (WS-Proteins, SS-Proteins, TS-Proteins, WHC and Drip loss)*

Variable	WS-Proteins	SS-Proteins	TS-Proteins	WHC	Drip loss
Temperature (A)	NS	NS	NS	NS	NS
Time (B)	***	**	***	NS	NS
AB	*	*	**	NS	NS

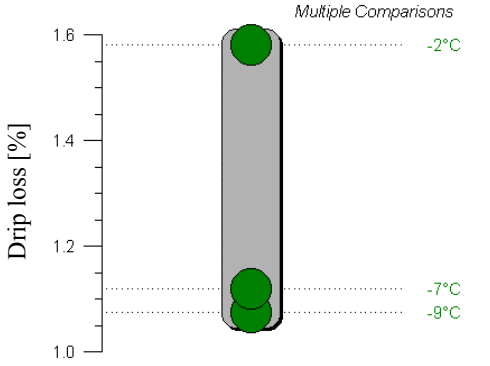


Figure 4.17 *Multiple comparison of the effect of temperature on* ***drip loss*** *in the latent zone*

Resident time has a significant effect on the level of extractable proteins. The fact that also the interaction between **Time** and **Temperature** is significant for these variables reflects that time is important, but that the effects are influenced by the temperature level. Figure 4.18 to 4.20 illustrate how respectively WS-Proteins, SS-Proteins and TS-Proteins are affected by the resident time.

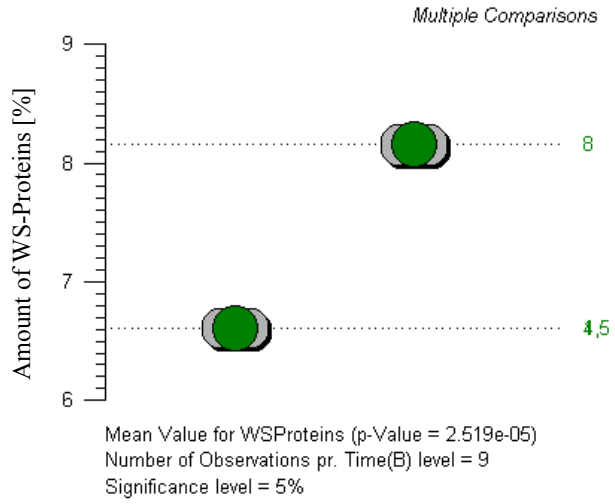
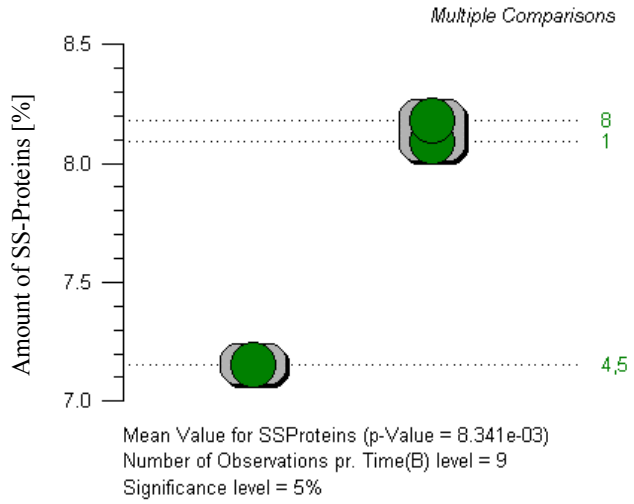
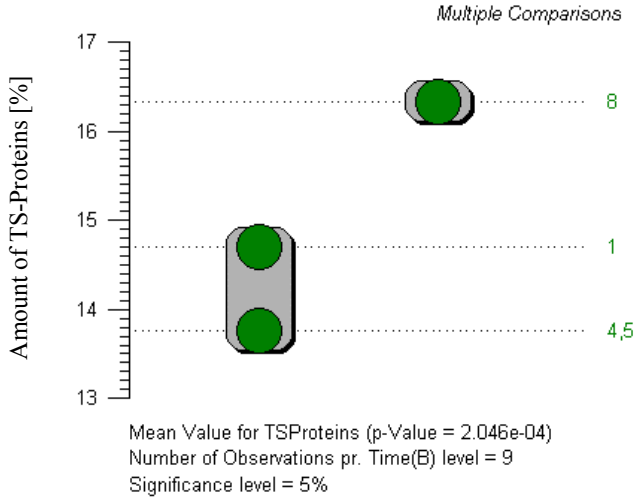


Figure 4.18 *Multiple comparison of the effect of time on* ***the amount of water-soluble proteins*** *in the latent zone.*



latentsoneresul... , (X-var,Y-var): (Time(B),SSProteins)

Figure 4.19 *Multiple comparison of the effect of time on* ***the amount of salt soluble proteins*** *in the latent zone.*



latentsoneresul... , (X-var,Y-var): (Time(B),TSProteins)

Figure 4.20 *Multiple comparison of the effect of time on* ***the total amount of soluble proteins*** *in the latent zone.*

The figures show that the largest amounts of proteins were extracted after the longest resident time within the latent zone. For water soluble proteins (Figure 4.18) and total amount of proteins (Figure 4.20), the amount after respectively 1 and 4,5 hours were significantly lower than for 8 hours resident time. For the salt soluble proteins (Figure 4.19) the amount after 4.5 hours was significant lower than for respectively 1 and 8 hours resident time. This indicates that if the resident time is too short (i.e. changes in temperatures go too fast), the amount of extractable proteins will be reduced. The change in statistical settings mentioned in the section 'Comments regarding the experiments', made a more detailed interpretation of the results difficult. Thus it was not possible to find an exact resident time that will be especially "harmful" for the level of extractable proteins.

WHC was not significantly affected by the design variables and the chosen range for them.

Conclusion – time in latent zone

The relationships between the chosen response variables in these experiments are in agreement with state of the art theory. The results show that the resident time in the latent zone (from –9°C to –2°C) will influence the amount of extractable proteins, and indicates that a certain time will be especially harmful. The results also indicate that the amount of drip loss will increase towards –2°C for all resident times applied in this experiments. For products that are thawed slowly, the different regions of the salmon will experience temperatures around –2°C for longer times than for a product that is thawed fast. These findings might explain the results in Chapter 4.7.2 and 4.7.4.

4.7.6 Evaluation of chapter 4.7

Chapter 4.7 has treated several important issues, and given valuable information about thawing of Salmon. Not surprisingly it has also raised new questions, some of them will be treated in the following chapters and some will not be treated in this work at all.

The results in chapter 4.7.5 show that the resident time at different temperatures in the latent zone influences the quality of the thawed Salmon. Further experiments in this temperature range should be carried out in order to get more detailed information about the effects on all important quality parameters, and to try to find whether the initial quality of the product will affect these effects. This is not done in this work

4.8 Effect of time and temperature on thawed product

Chapter 4.7.4 showed that slow thawing gave considerable higher drip loss than fast thawing. Table 4.3 shows the time-temperature program the samples in the different experiments were thawed after. Evidently all the slow thawing samples experienced identical time-temperature program during the first phase of thawing that is until the first 30 hours of the thawing. During this time the weight loss for the samples thawed up to 0°C takes place. It is natural to believe that the samples used for the slow thawing towards 15°C and 30°C had experienced the same drip loss as the samples thawed to 0°C, after 30 hours thawing. In other words; the differences between samples thawed to 0°C and 15°C, have to be explained by the different time-temperature treatment from 0°C to 15°C.

The effect from resident time in the temperature range from 0°C to 30°C, is treated in this chapter. These experiments represent the parts of the salmon that experience temperatures close to thawing media temperatures for a period of time, while the thawing process is running in order to reach the desired temperature at the thermal center of the object (fish). The temperature range of interest in such an approach covers 0°C through ~30°C. The rest of this chapter describes the experiments, sum up the results, and draw a conclusion on the time-temperature effect on thawed farmed Atlantic salmon.

4.8.1 Material and methods

Because of the individual differences in chemical composition from one fish to another, and the fact that the composition varies along the fish, great care had to be taken in designing the experiments. In order to make the experiment feasible in a practical manner, small pieces of fillets (~100g) from a limited sample size, were used. Only symmetrical fillets (i.e. right and left side fillets) from the same fish located at the same length from the head were assumed to have identical composition and similar properties.

Experimental material

The samples were prepared as described in Chapter 4.7.1, and stored at –50°C until time of experiment.

The upper part of the fillets (back) was used to measure dry matter, water holding capacity and protein content, whilst the lower part (abdominal) was used to colour and texture measurements.

Initially measurements in order to establish a set of reference values and to investigate the original quality of the experimental material together with tests to investigate the effects of the vacuum packaging were done.

Experimental conditions

In order to extract as much information as possible from the experiments and to minimize the effect of natural variation in the experimental material, the experiments were carefully planned by statistically methods (Box *et al*., 1978). The different parameters considered in this work were thawing temperature (i.e. thawing media temperature), holding time (the time where the entire sample piece has the same temperature as the thawing media), and the degree of cooling after thawing. The latter was chosen as an on/off parameter, where either the sample piece was cooled to 0°C before analysing, or it was analysed immediately after thawing. The thawing temperature and holding time varied continuously within the range of 0°C to 30°C and from 0 hours to 8 hours.

Experimental design

To take full advantage of the statistically method used, the experiments were conducted in two steps. First a screening design (full factorial regarding the three parameters considered) was run. This design resulted in a total of twelve experiments (six experiments with, and six experiments without cooling after thawing) and included four centre experiments (Table 4.9).

Table 4.9 *Experimental design for the screening of main effects and effects of two-factor combinations within the chosen region. Six samples were used in each experiment. The samples are numbered with fish number (e-w), filet side (L = Left and R = Right), and sample number (2-5 ref figure 4.6)*

		Temperature					
		0°C		15°C		30°C	
Residence time	0h	Experiment 7					Experiment 6
		i-l3					e-l3
		l-l3					i-l4
		k-r4					h-r4
		n-r3					o-r4
		p-r4					p-l4
		r-l3					s-l3
			Experiment 9			Experiment 5	
			j-r3			m-r4	
			f-r3			g-r3	
			g-r4			f-l4	
			o-l3			n-r4	
			p-l3			p-r3	
			s-r4			r-l4	
	4h			Experiment 1	Experiment 3		
				h-r3	e-l4		
				k-r3	j-r4		
				m-r3	l-r4		
				t-l3	t-r4		
				u-r4	u-l3		
				w-l4	w-r3		
				Experiment 2	Experiment 4		
				e-r4	h-l3		
				j-l4	k-l3		
				l-l4	m-l3		
				t-r3	t-l4		
				u-l4	u-r3		
				w-r4	w-l3		
	8h		Experiment 10			Experiment 11	
			m-l4			j-l3	
			g-l3			f-l3	
			f-r4			g-l4	
			o-l4			n-l3	
			q-r3			q-l3	
			r-r3			s-r3	
		Experiment 8					Experiment 12
		e-r3					i-r3
		i-r4					l-r3
		h-l4					k-l4
		n-l4					o-r3
		q-r4					q-l4
		s-l4					r-r4
		No Cooling			Cooling		

Each experiment included six samples (fillet pieces). These samples were distributed over the entire experimental region, in such a manner that at least five of the samples in each experiment could be used to estimate the effect of one of the three parameters investigated (i.e. thawing temperature, holding-time and cooling after thawing). Only three of the samples could be used to estimate combinatorial effects of the parameters (e.g. the combinatorial effect of thawing temperature **and** holding-time) (Box *et al*., 1978).

The results from the screening design were used in order to choose which part of the original research region the most interesting effects took place and thus where the focus of the second experimental step should be. An optimisation design was built to gain more detailed information about the chosen effects in this narrowed region (Table 4.10). Three of the experiments from the screening design could be reused, and only seven new experiments had to be conducted (including new centre samples). Each of these experiments included five samples, distributed over the narrowed experimental region; in such a manner that only the main effects (e.g. the effect of the parameters considered) could be found.

Table 4.10 *The experimental design used in the optimalisation experiments. Five samples were used in each experiment. The samples are numbered with fish number (e-x), filet side (L = Left and R = Right), and sample number (2-5 ref Figure 4.6)*

		Temperature			
		15°C	**22.5°C**		**30°C**
Resident time	**0 t**	**Experiment 13**	**Experiment 14**		**Experiment 6**
		i-r2	v-r4		e-l3
		l-r2	x-l3		i-l4
		k-l5	x-r4		h-r4
		o-r2	f-r2		s-l3
		q-l5	k-l5		p-l4
	4 t	**Experiment 3b and 4b**	**Experiment 15**	**Experiment 16**	**Experiment 17**
		t-r4	w-l5	w-r5	t-r5
		u-l3	m-l5	m-r5	u-l2
		w-r3	n-r2	n-l2	w-r2
		t-l4	o-l5	o-r5	t-l5
		u-r3	v-r2	v-l2	u-r2
	8 t	**Experiment 18**	**Experiment 19**		**Experiment 12**
		e-l2	v-l4		i-r3
		i-l5	x-r3		l-r3
		h-r5	x-l4		k-l4
		s-l2	f-l2		o-r3
		p-l5	k-r5		q-l4

Done in screening experiments

Comments regarding the experiments

Unfortunately the colour of the fresh salmon was weak. The values of LaRoche and a* (redness) were low, while the values for L* (lightness) and b*(yellowness) were high compared to the customers demand. This means that the destruction potential in the colour was low (i.e. small changes in colour should be expected). The chosen experimental designs, favour measurement methods that have a very strong reproducibility where few parallels are necessary. The texture measurements are very sensitive to sample size and orientation of the muscle fibres within the Kramer cell, and several parallels should have been used. This was not possible with the experimental design chosen.

4.8.2 Results and discussion

The initially tests indicated no influence by the vacuum packing on the chosen quality parameters [47].

Screening experiments

The results of the screening experiments (statistically treated) are shown in table 4.11. The effect on the chosen quality variables, by the three parameters considered and the combinations of them (combination parameters) are shown in cases where the effect can be described as significant.

Table 4.11 *Significance levels (S) and main effects (Eff) as a result of a change in the parameter levels from low to high; thawing temperature (0°C → 30°C), holding-time (0h → 8h) and cooling after thawing (no cooling → cooling), plus significance levels and effects of two-factor combinations.*

Variable	Temperature (A)		Time (B)		Cooling (C)		AB		AC		BC	
	S	Eff	S	Eff	S	Eff	S	Eff	S	Eff	S	Eff
Drip loss [%]	+++	**3,1**	+++	**3,2**	**NS**		++	2,4	NS		--	-1,9
Dry matter [%]	++	**1,3**	+	**1,1**	**NS**		NS		NS		NS	
WHC [%]	**---**	**-10,2**	**--**	**-2,9**	+++	**9,4**	NS		++	9,0	NS	
WS proteins [%]	**---**	**-0,7**	**---**	**-1,2**	**--**	**-0,4**	--	-0,8	NS		+	0,4
SS proteins [%]	**---**	**-4,5**	**---**	**-3,5**	**NS**		---	-2,0	NS		NS	
TS proteins [%]	**---**	**-5,2**	**---**	**-4,7**	**NS**		---	-2,8	NS		NS	
La Roche [-]	**NS**		**---**	**-0,5**	+++	**0,6**	NS		NS		NS	
L* [-]	++	**2,1**	+	**2,0**	**NS**		++	4,0	NS		+	2,9
a* [-]	**NS**		**NS**		+	**1,2**	++	3,0	NS		NS	
b* [-]	**NS**		+	**1,3**	**NS**		++	3,3	-	-1,2	NS	
Max. force [N]	**NS**		**NS**		**NS**		NS		NS		NS	
Deformation [mm]	**NS**		**NS**		+	**0,7**	-	-0,8	NS		NS	
Steepest slope [N/m]	**NS**		+	**2130**	**--**	**-2560**	NS		NS		NS	

Both the colour and texture variables seem less influenced by the parameters considered. These findings may be explained by the comments made in section 'Comments regarding the experiments'. If the range considered is reduced, one can expect more significant changes in the colour variables, but not for the texture variables. Temperature and holding-

time, and the combinatorial effects of them are the most influential parameters. Cooling after thawing can be described as having no negative effect on the different variables. On the contrary it will increase WHC by 9%, in average, if applied. The screening design assumes linear changes within the chosen experimental region. This is not likely for this physical problem. In Figure 4.21 the average results for the cube experiments (0°C and 30°C) and the centre experiments (15°C) are compared. It is clear that the major effects take place between 15°C and 30°C. If holding time is considered (Figure 4.22), the picture is much more diversified, and changes seem to take place within the whole region (0h to 8h).

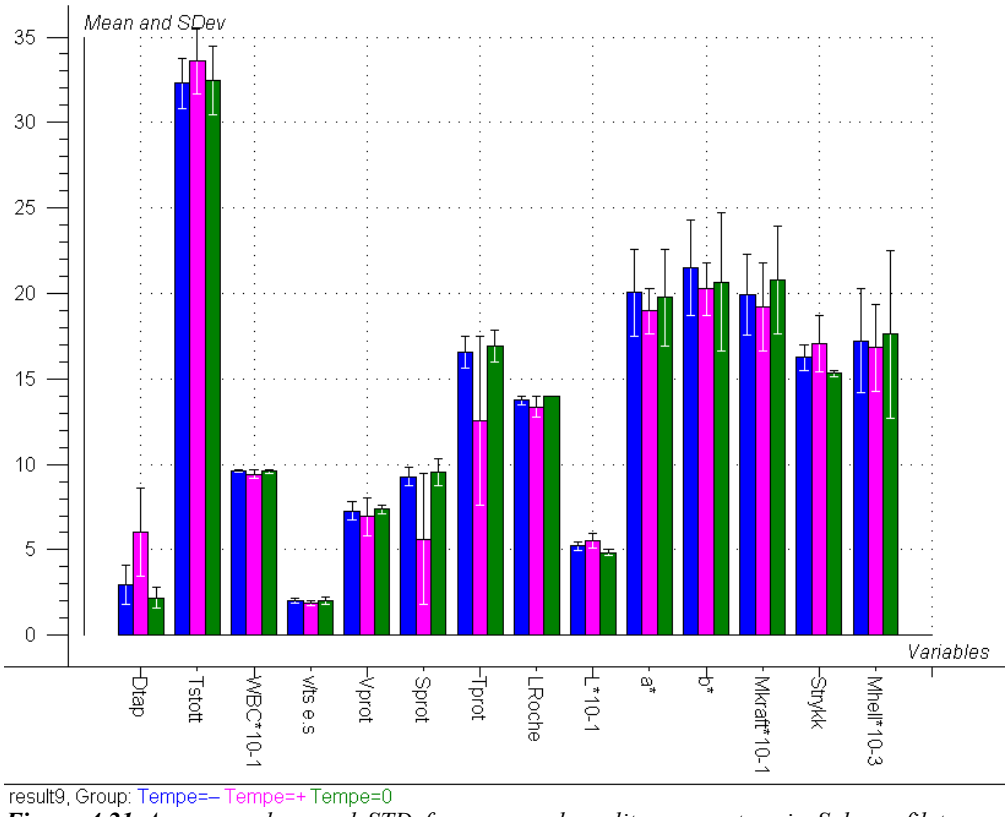


Figure 4.21 *Average values and STD for measured quality parameters in Salmon filets thawed at* ***0°C****,* ***30°C*** *and* ***15°C****. All samples cooled after thawing.*

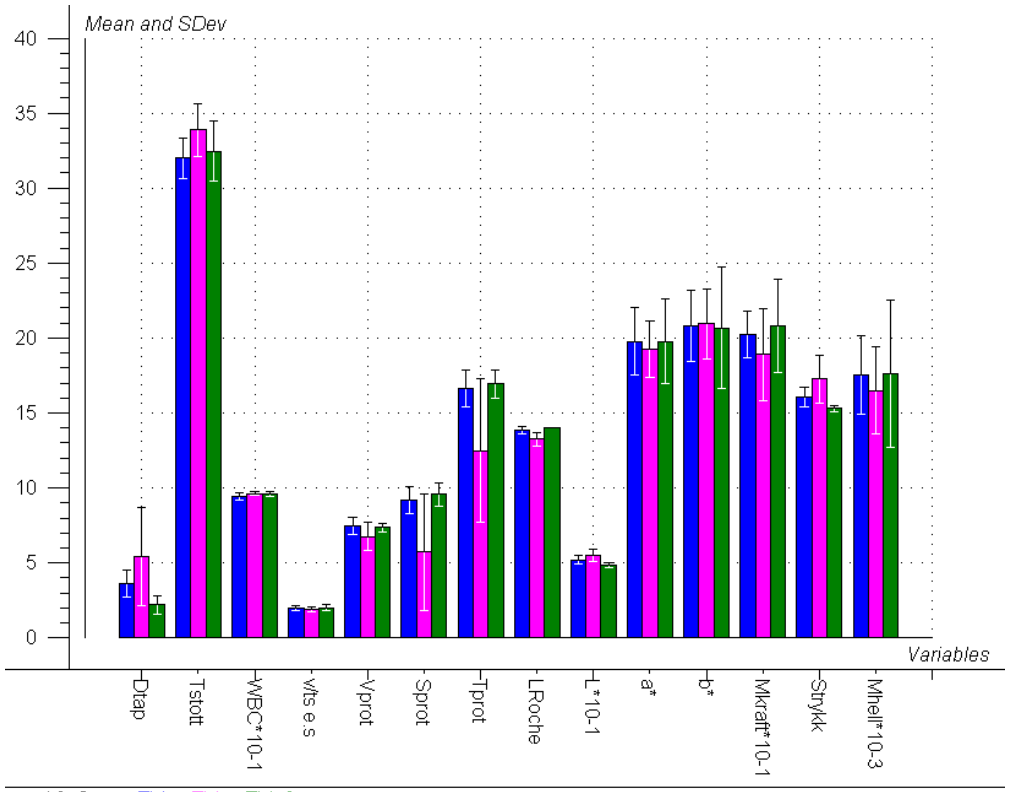


Figure 4.22 *Average values and STD for measured quality parameters in Salmon filets kept at the chosen thawing temperature for;* ***0 hours****,* ***8 hours*** *and* ***4 hours****. All samples cooled after thawing.*

Optimisation design

Based on the findings from the experiments in the screening design, all the experiments in the optimisation design were run with cooling after thawing. Further, the experimental efforts were focused on temperatures from 15°C to 30°C. The holding time range was left unaltered. Due to lack of possibilities for parallel samples in the texture measurements, these were left out in the optimisation experiments. The results of the optimisation experiments (statistically treated) are shown in Table 4.12

Table 4.12 *Significance levels (S) and main effects (Eff) as a result of a change in the parameter levels from low to high; thawing temperature (15°C → 30°C) and holding-time (0h → 8h), with cooling after thawing applied*

Variable	Temperature (A)		Time (B)	
	S	Eff	S	Eff
Drip loss [%]	+++	3,3	+++	3,1
Dry matter [%]	NS		NS	
WHC [%]	--	-1,8	++	-2,0
WS-Proteins [%]	--	-1,0	---	-1,3
SS-Proteins [%]	---	-5,1	---	-3,1
TS-Proteins [%]	---	-6,0	---	-4,5
La Roche [-]	NS		NS	
L* [-]	+	4,7	NS	
a* [-]	++	2,5	NS	
b* [-]	++	3,4	NS	

Table 4.12 shows that drip loss increases with both temperature and holding time, whilst the amount of extractable proteins (WS-Proteins, SS-Proteins and TS-Proteins) is decreasing with increasing temperature and holding time. Water holding capacity decreases with increasing temperature, and **increases** with increasing holding-time. This can be due to the fact that the drip losses at high holding-time, combined with the relative high temperatures, have reached a level where the **remaining water** in the muscle is significantly stronger bounded. Another possibility is that high holding-time, at high temperatures; can result in a gelling of the microstructure, which makes re-absorption of water possible. Dry matter and LaRoche are not significantly affected by changes in temperature and holding-time, whilst the values from the instrumental colour measurements increase with increasing temperature. An increased a* will give a more reddish colour experience, while both L* and b* will weaken this experience, when increased. The net effect on the colour experience might as well be zero, as indicated by the LaRoche measurements. If the colour of the fresh salmon had been better, this would most likely have given significant effects in the overall colour experience within the experimental region (Ref. Chapter 4.7.4 and [61]). A more detailed representation on how drip loss, water holding capacity and the amount of soluble protein varies with changes in temperature and holding time is shown in Figure 4.23 through Figure 4.25.

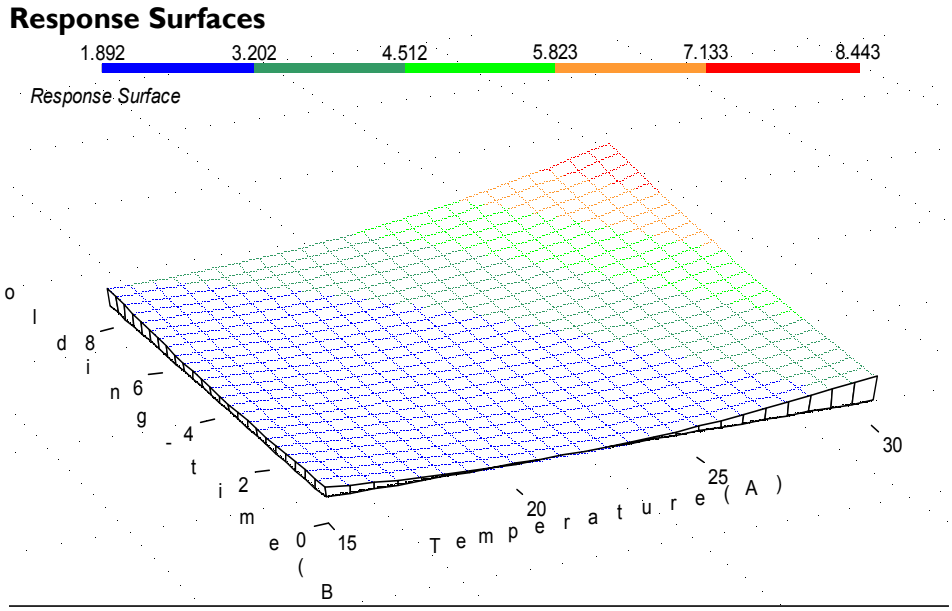


Figure 4.23 *The response surface for* ***Drip loss****, as a function of Holding-time and Temperature.*

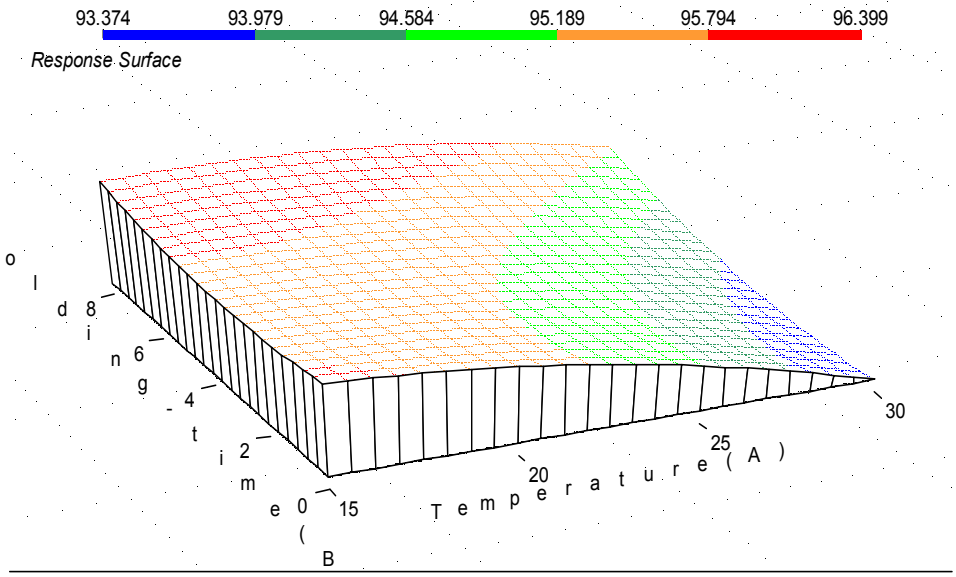


Figure 4.24 *The response surface for* ***WHC****, as a function of Holding-time and Temperature.*

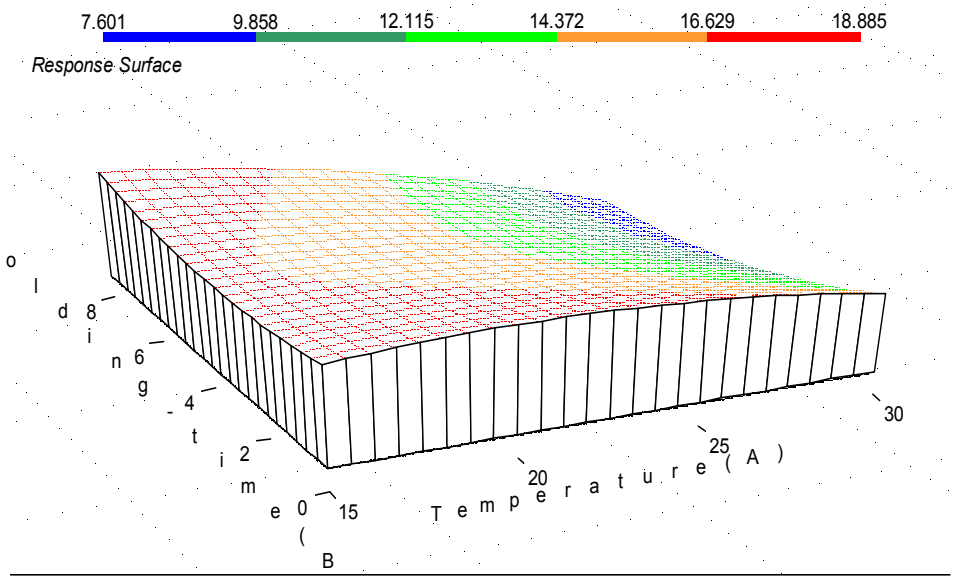


Figure 4.25 *The responce surface for total soluble proteins* ***TS-Proteins.****, as a function of Holding-time and Temperature.*

4.8.3 Conclusion – temperatures after thawing

Based on the quality variables considered in this paper, thawing of Atlantic salmon can be conducted with temperatures up to 20°C, as long as the salmon is cooled down to 0°C as soon as possible after the thermal centre has reached the desired temperature (~0°C). If the geometric size of the salmon results in long thawing times, then reduced thawing temperature should be used in order to prevent gelling of the microstructure. At high thawing temperatures (above 20°C), thawing mediums that secure high heat transfer coefficients should be used (i.e. water instead of air).

Regarding colour and texture variables, no conclusion can be drawn at this point, and further investigations should be done.

4.9 Effect of thawing compared to the effects of freezing and storage during long distance transportation

The basic question in this chapter is directly correlated to a practical problem that a Norwegian company, detected when exporting frozen salmon to a customer in Asia. Based on their own measurements after storage and thawing, the customer claimed that the initial colour of the fresh Salmon had been unsatisfying. While the major part of the colour values in the fish muscle measured by the customer were in the range of 14 to 15 on the La Roche

scale, the customers required 16 as a quality limit. The exporter has verified by in-house measurements that the total loss in colour quality through freezing, storage, transportation and thawing can sum up to 2 units on the La Roche colour scale. However, the exporter has not been able to analyse how the quality loss is distributed through the physical factors, which are important elements in the processing. The aim of this study, therefore, has been to determine the quality loss focusing on the colour parameters in the processes of freezing, storage, transportation and thawing.

Based on simulations of the ordinary transport and alternative transport events, statistical and multivariate data analyses were performed in order to detect the process element(s) where significant improvements in the final product quality could be obtained.

4.9.1 Material and methods

Basic experimental set-up

The different phases of the simulated transport were subdivided in the following factors:

- freezing rate,
- storage temperature and temperature stability,
- storage periods and
- thawing method.

Through statistically planned experiments, the values of these factors were set to two or three levels (Low, Intermediate and High) depending on to what extent the factors could be varied within the defined physical range (Table 4.13).

Table 4.13 *Variations in physical factors in the experimental set-ups*

	Level		
Factors	***Low***	***Intermediate***	***High***
Freezing rate	Fast -30°C in thermal core within 11 h	-	Slow -18°C in thermal core within 24 h
Storage temperature/-Stability	-50°C Stable	-23°C Stable	-23°C/-30°C Not stable
Storage period	3, 8 and 12 weeks	3, 8 and 12 weeks	3, 8 and 12 weeks
Thawing method	In water 5°C in 75 min	-	In air 25°C in 21h

Freezing rate

The freezing rates were defined at two levels, low and high. By using a freezing tunnel and a fast freezing rate, a thermal core temperature at -30°C in the fish was obtained after 11 h (Table 4.13: Low level). The official Norwegian legislation for consumables requires a core

temperature at -18°C, which can be obtained within a period of 24 h using a slow freezing rate (Table 4.13: High level).

Storage temperature and stability
In earlier experiments during which we have tested quality parameters as a function of time, it has been demonstrated that only minor changes can be detected when the storage temperature has been kept below -45°C [62]. Measurements performed by the exporter have demonstrated that freezing containers for transportation of salmon usually are kept at a constant temperature level of -23°C. On this basis the storage test temperatures selected in the present study were -50°C and -23°C at the Low and Intermediate level (Table 4.13). An additional test factor was to determine the effect of storage temperatures varying from -23°C to -30°C and returning to -23°C in 1-2 cycles within a 7 days period (Table 4.13, High level).

Storage period
Normal transportation time between Norway and Japan is 8-12 weeks. Thus the storage period selected was at maximum 12 weeks, with samples taken after 3, 8 and 12 weeks.

Thawing method
In the context of the thawing method, focus was on the effect of thermal stress as a function of temperature and time. Consequently, the major factors were determinations of the ultimate thawing temperature and the measurements of the time used to reach the thermal core temperature in the product. Results presented by Nilsson [6] demonstrate that thawing in water at 5°C gives the best thawing condition for fish. The results from Chapter 4.7 and 4.8 revealed that thawing in water at 5°C – 15°C followed by cooling down to 0°C, apparently gives the minor changes in the fish product. As demonstrated in Table 4.13 thawing in water at 5°C for 75 min was set to a low level, while thawing in air at 25°C for 21 h was set to a high level.

Experimental design

As mentioned earlier these experiments aimed to simulate the whole chain from producer in Norway to customer in Japan. To make this as realistic as possible whole fish samples were handled as long as possible, without compromising the statistical limitation and/or making the experiments impossible to manage because of the size. As a consequence every statistical and multivariate data analysis performed in this study were based on 10 different fish samples in order to clarify if the results were caused by individual variations or the different treatments.

A complete and ideal experimental set-up for the selected factors and the levels of priority, requires 36 different experiments with 10 individuals in each i.e. a total of 360 fish samples. In order to reduce the number of test samples, experiments using a slow freezing rate and storage at -50°C were excluded based on the fact that the latter freezing level represents the ideal transportation conditions. Figure 4.26 illustrates the experimental design, carried out after respectively 3, 8 and 12 weeks.

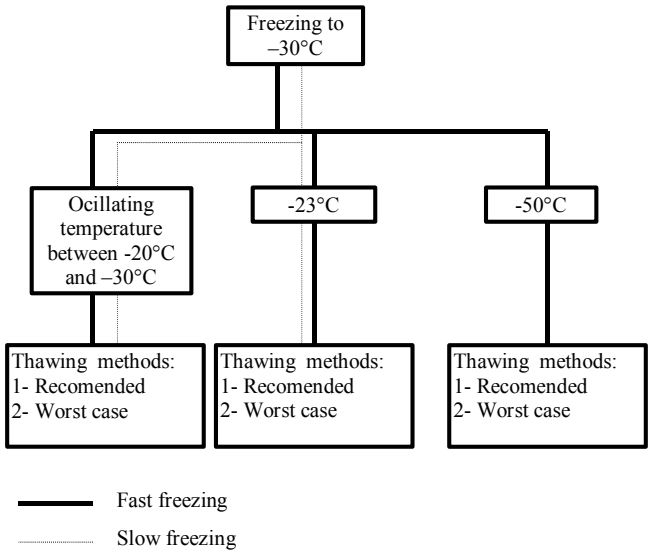


Figure 4.26 *Experimental design as it was carried out after 3, 8 12 weeks of storage.*

Test material

Fish of superior quality with an average weight of 4 -5 kg were killed at the fish farmer and after being packed in ice immediately transported for 8 h to the test laboratory. The single fish samples were labelled, packed in plastic bags and frozen using slow and fast freezing rate. The initial core temperature was approximately 2^{o}C and the temperature changes during the freezing were monitored. As a control of the original quality, 10 fish were repacked in ice instead of being frozen, labelled, and kept at 0^{o}C, for 2 days for rigor development before being analysed.

These same 10 fish were used for sample analyses for each of the five combinations of storage temperature, stability and freezing rate. The samples were prepared by isolating a 4,5 cm thick slice measured from the anal opening towards the major dorsal fin. The fish slice was divided into two equal parts along the backbone, right and left, vacuum-packed, labelled and randomly exposed to the two selected thawing methods. The cut surface on the fish was glazed before the fish were returned to the plastic bags in the boxes under the selected temperature conditions. Before taking a new 4,5 cm fish slice sample, a surface section (thickness 0,5 cm) was removed to avoid the effect of the drying out and the ice accumulation due to the glazing. The size of and the localisation of the fish samples were selected in order to be consistent to the customer's measurements and the optimisation of the different sampling. Figure 4.27 and 4.28 illustrate the sample preparation for the different storage times and thawing methods.

Figure 4.27 *Sample preparation for the different storage times. 3, 8 and 12 weeks from right towards left.*

Figure 4.28 *Sample preparation for the different thawing methods. Upper and lower parts analysed after the same storage time, but randomly exposed to different thawing regimes (ref figure 4.26).*

The chosen experimental design and sampling scheme reduced the need for fish down to 60.

Condition

The equipment used to thaw the samples as recommended (optimal) is described in Chapter 4.6.1. Because of the available space in this thawing equipment, each experiment had to be split into two thawing runs. Five frozen, vacuum-packed fish samples were placed in a holder and exposed to circulating water at 5^{o}C for 75 minutes. This resulted in a sample core temperature in the range from 0°C to 5°C. During the rest of the analysis the test samples were kept on ice.

The hardware for the worst-case air thawing (but certainly not unlikely practice) consisted of a closed drying unit developed on the basis of heat-pump technology. The humidity and temperature were adjustable by regulating the capacity of the evaporator and condenser. The vacuum packing of the samples minimised the immediate potential for a drying out effect. The airflow in the drying unit was adjusted to a minimum (1,22 ms^{-1}), and the temperature was kept at 25^{o}C. The analyses were performed at ambient temperature.

Quality parameters

The fish samples excluding the bones and the dark muscle were used for determinations of the quality analyses. The chosen quality parameters were:

- Colour
  - LaRoche (scale 11-18)
  - L*,a* and b* values
- Water related properties
  - WHC
  - Drip loss
  - Water content
- Texture
  - Maximum force
  - Deformation
  - Steepest slope

Analyses were performed as described in Chapter 4.5 except for the measurements of WHC, where a compression method was used. In this method a cylindrical sample of approximately 5 gram is compressed between two plates, using a weight of 1 kg. Filter paper is placed between the plates and the sample. The samples are weighed initially and after 30 seconds compression. WHC is calculated as the average of three parallel samples.

Drip loss was calculated as the weight difference of the samples before and after thawing. Since the samples were produced with the aid of a band saw, higher drip loss values than normal would be expected.

Comments regarding the experiments

The measurement of LaRoche demands identical light conditions from sample to sample and experiment to experiment. This was unfortunately not so for the analysis of the samples thawed by the recommended method (5°C in 75 minutes) after 8 weeks.

Different persons carried out the WHC measurements after 3, 8 and 12 weeks. Since these analyses require accuracy, it is possible that the person involved can have affected the results. The comparison between the freezing rate, the storage temperature/stability and the thawing methods should be minimal.

4.9.2 Results and discussion

Initial quality – the reference

Two days after the slaughtering 10 fish of high quality, that had been stored on ice, were analysed. This was done in order to get a relevant reference value for the chosen quality parameters. The results are shown in Table 4.14 through Table 4.16.

Table 4.14 *Reference values for the colour related quality parameters*

	Reference values – Colour parameters			
	LaRoche [-]	**L*** [-]	**a*** [-]	**b*** [-]
Average	16,45	33,7	14,1	11,4
STDEV	0,27	1,2	1,0	1,5

Table 4.15 *Reference values for the water related parameters*

	Reference values - Water		
	WHC [%]	**Water content** [%]	**Drip loss** [%]
Average	98,1	68,4	-
STDEV	0,5	2,7	-

Table 4.16 *Reference value for the texture related parameters*

	Reference values - Texture		
	Maximum force [N]	**Deformation** [mm]	**Steepest slope** [N/mm]
Average	389	18,75	27600
STDEV	44	0,86	4000

Obviously drip loss could not be measured. It is relatively low standard deviations (STDEV) for most of the parameters, except for water content, maximum force and steepest slope. This means that it will be more difficult to identify significant effects on these parameters.

Generally the initial quality was considered to be very good, well suited as reference values (with sufficient destruction potential).

Statistical analysis

10 quality parameters on each sample were investigated. The averages from 10 samples from each experiment and for each quality parameter are given in Table 4.17. This table is given in order to show the values that the analyse summarised in Table 4.18 is based on.

All the data were included in statistical analyses in order to find whether the design variables (Freezing rate, Storage condition, Thawing method and Storage time) have a significant effect on the different quality parameters. Table 4.18 presents a summary from these analyses. The interaction between the design variable was significant for several of the quality parameters, but their contribution was so low that it is not commented in this report.

Table 4.17 *Average values from all the experiments for each quality parameter*

Freezing rate	Storage condition	Thawing method	Storage weeks	LaRoche	L*	a*	b*	WHC	Water content	Drip loss	Max. force	Deformation	Steepest slope
Fast	-50°C Stable	5°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	16,25	37,6	16,4	15,4	97,7	68,3	1,1	476	18,5	3,72E+04
			8	15,95	37,3	17,1	16,3	97,0	68,8	6,9	385	19,9	2,49E+04
			12	16,05	39,3	17,3	16,8	96,0	67,5	5,1	340	18,8	2,34E+04
Fast	-50°C Stable	25°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,75	41,7	15,4	15,1	92,0	67,0	3,7	411	17,9	3,28E+04
			8	15,95	39,2	15,0	13,8	92,9	67,5	9,0	366	20,1	2,68E+04
			12	15,6	40,5	15,9	15,1	94,3	63,1	7,8	322	17,5	2,51E+04
Fast	-23°C Stable	5°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	16,05	39,7	17,2	17,1	97,2	68,4	1,5	516	18,9	3,47E+04
			8	15,25	41,9	18,1	18,2	95,4	65,7	5,5	465	20,0	3,19E+04
			12	15,25	44,6	17,7	18,0	93,8	64,6	5,5	405	18,2	3,01E+04
Fast	-23°C Stable	25°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,2	44,5	17,0	17,8	91,0	65,4	5,4	424	17,1	3,53E+04
			8	15,6	42,8	16,4	16,5	89,0	65,1	9,5	394	17,3	3,07E+04
			12	14,75	45,7	17,5	18,3	92,8	60,4	10,3	381	18,3	3,19E+04
Fast	-23°C/-30°C Unstable	5°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	16	40,9	17,7	18,1	96,5	70,4	1,6	475	18,8	3,50E+04
			8	14,8	42,8	18,6	18,8	95,4	69,6	5,6	408	20,4	2,78E+04
			12	15,1	44,2	17,7	18,5	92,7	65,1	5,5	358	18,6	2,53E+04
Fast	-23°C/-30°C Unstable	25°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,25	45,0	17,1	18,0	88,5	65,9	5,7	389	18,2	3,08E+04
			8	15	45,4	17,3	18,3	87,6	68,2	10,3	347	17,6	2,75E+04
			12	14,15	46,8	17,9	19,4	92,8	61,5	11,2	338	17,6	2,72E+04
Slow	-23°C Stable	5°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,9	40,3	17,3	16,9	96,3	68,0	1,4	413	18,8	3,01E+04
			8	15,15	42,6	18,5	18,3	94,5	67,8	5,5	347	19,9	2,33E+04
			12	15,45	43,7	17,6	17,3	92,2	65,0	5,8	332	17,9	2,28E+04
Slow	-23°C Stable	25°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,5	44,4	17,2	17,3	88,5	66,8	5,8	361	17,3	2,90E+04
			8	15,15	44,1	16,8	16,7	85,7	67,9	10,0	318	18,4	2,52E+04
			12	14,65	45,8	18,4	18,7	92,6	61,1	12,4	340	17,0	2,70E+04
Slow	-23°C/-30°C Unstable	5°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,8	41,3	17,3	17,0	96,2	70,7	1,6	425	18,7	3,08E+04
			8	14,1	43,2	18,0	18,2	94,5	67,0	5,5	383	18,8	2,65E+04
			12	15	44,3	17,5	18,1	92,3	65,8	6,7	304	18,2	2,35E+04
Slow	-23°C/-30°C Unstable	25°C	0	16,45	33,7	14,2	11,4	98,1	68,4	0,0	389	18,8	2,76E+04
			3	15,4	44,3	17,2	17,8	88,5	66,7	6,3	375	18,1	3,03E+04
			8	15,25	43,5	17,0	17,5	87,5	66,4	10,4	343	19,4	2,53E+04
			12	14,45	45,5	17,6	18,6	93,6	60,8	12,0	339	18,0	2,58E+04

Table 4.18 *Effects overview from the experiments. S means that the considered design variable (Freezing rate, Storage condition, Thawing method or Storage time) has a significant effect on the quality parameter. No notation means not significant*

Quality parameter		Storage Condition			Thawing method			Freezing rate		
		Storage [weeks]			Storage [weeks]			Storage [weeks]		
		3	8	12	3	8	12	3	8	12
Colour	LaRoche	S	S	S	**S**		**S**			
	L*	S	S	S	**S**	**S**	**S**			
	a*		S	S		**S**				
	b*	S	S	S		**S**				
Water	WHC	S	S		**S**	**S**	**S**	S		
	Water content		S		**S**		**S**			
	Drip loss	S		S	**S**	**S**	**S**	S		S
Texture	Maximum force		S	S	**S**	**S**		S	S	S
	Deformation				**S**		**S**			
	Steepest slope		S	S	**S**			S	S	S

The significant effects for all design variables are shown in Table 4.18, but since this work is focusing on thawing, the detailed analysis will be limited to the findings that are interesting from the thawing perspective.

Colour related parameters
The LaRoche values are significant affected by the thawing method after 3 and 12 weeks. The problems related to lighting after 8 weeks described in the section 'Comments regarding the experiments' most likely caused no significant effects after 8 weeks storage.

For the L* values, the thawing method has a significant effect throughout the storage period, whilst the a* and b* values only are affected after 8 weeks of storage. After 3 and 12 weeks of storage, the b* value (as opposed to the a* value) is far from significant affected by the thawing method, and it is therefore not discussed further.

Water related parameters
All the relevant water related quality parameters are affected by the thawing method. This goes for all the experiments, except for the water content values after 8 weeks storage. This is probably due to the large STDEV introduced by the analyse technique (Ref. sub-chapter about initial quality).

Texture related parameters
All texture parameters are affected by the thawing method after 3 weeks of storage. The thawing method also affects the Maximum force value after 8 weeks storage, whilst the deformation value is respectively almost significant and significant affected after 8 and 12 weeks of storage.

Results after statistical analysis

Colour
Figure 4.29 shows how the LaRoche value is changed by the different condition. At first the thawing method is the most influential variable, but after 12 weeks of storage, the storage condition is more important. The responsibility for the colour loss in the worst-case (~2.0 on the LaRoche scale) is quite evenly distributed (~0.5 on the LaRoche scale each) among Thawing method, Storage temperature and Storage stability. In addition it is a loss of ~0.5 on the LaRoce scale that seems to be impossible to avoid. This unavoidable colour loss can be denoted irreversible colour loss due to freezing and thawing.

Figure 4.30 shows how the lightness (L* value) increases depending on thawing method, storage condition and storage time. For samples stored at –50°C, only small changes occur after the initially jump after 3 weeks storage. For samples stored at –23°C the L* value increases also after the third week, but in a slower manner. The fast thawing at 5°C leads to less change in the L*value than slow thawing towards 25°C. The differences are reduced as the storage temperature and time increase.

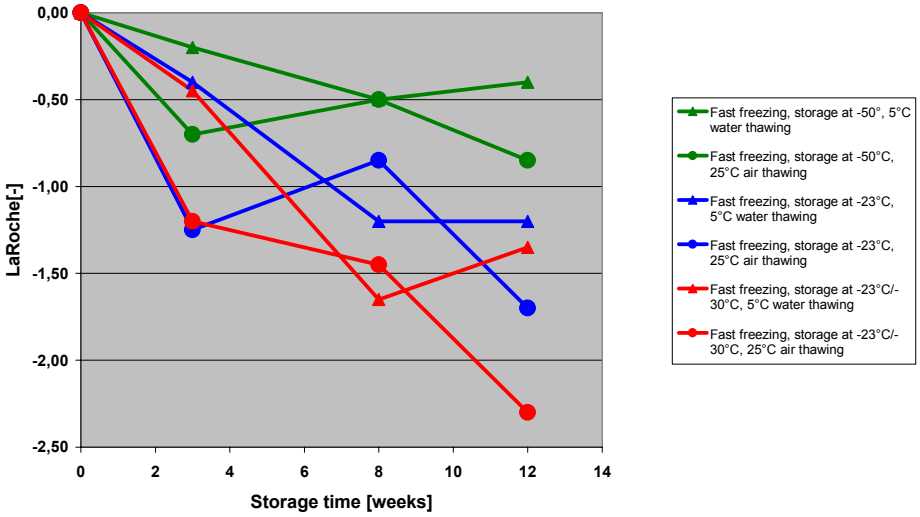


Figure 4.29 *Changes in LaRoche depending on thawing method, storage temperature and stability.*

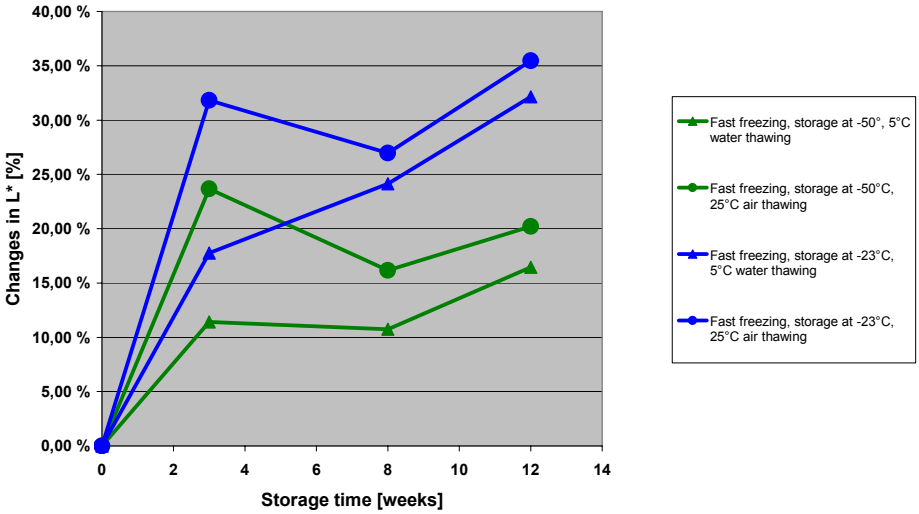


Figure 4.30 *Changes in the lightness (L* value) depending on thawing method and storage temperature.*

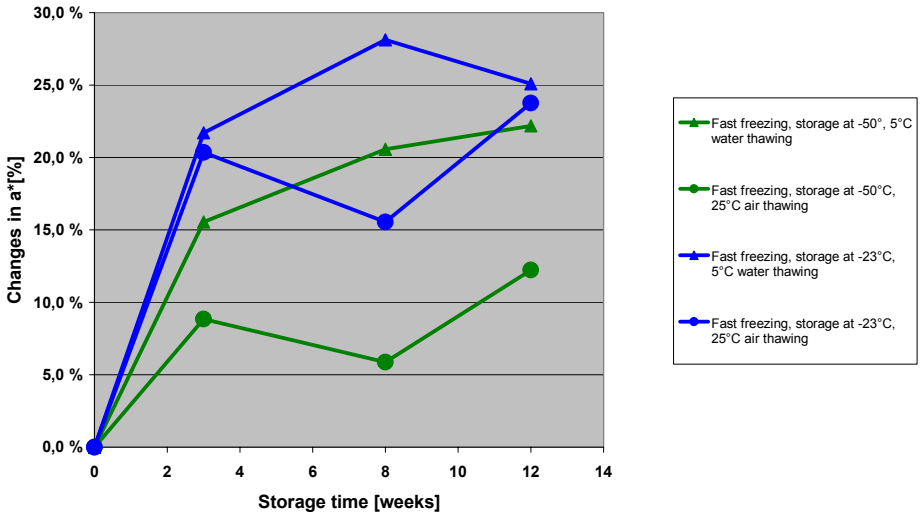


Figure 4.31 *Changes in redness (a* value) depending on thawing method and storage temperature.*

Figure 4.31 shows how the redness (a* value) increases depending on thawing method, storage temperature and time. The largest change takes place in the samples stored at –23°C, and for this temperature the thawing method only affects the redness after 8 weeks. For the samples that have been stored at –50°, the samples thawed fast in a 5°C water bath experience the largest change.

Generally, with respect to the colour, it is preferable to store the salmon at low and stable temperature (-50°C), and to thaw the product effectively at 5°C (e.g. water bath). The freezing rate does not affect the colour.

Water related parameters

Figure 4.32 shows how the WHC depend on freezing rate, thawing method, storage temperature and time. Salmon stored at –50°C has the highest WHC, whilst salmon that is frozen slowly has the lowest WHC. Salmon thawed at 5°C has higher WHC than salmon thawed at 25°C. The strange increase in WHC as time goes by, for samples thawed in 25°C warm air, is due to the very high drip losses for these experiments. (The water that normally would be removed during the WHC analysis is already lost as drip loss.)

Figure 4.33 shows how the water content is depending on thawing method and storage time. The water content is highest for the salmon thawed in 5°C water bath, and it is reduced during storage. The change is especially large for the salmon thawed in 25°C warm air after 12 weeks storage.

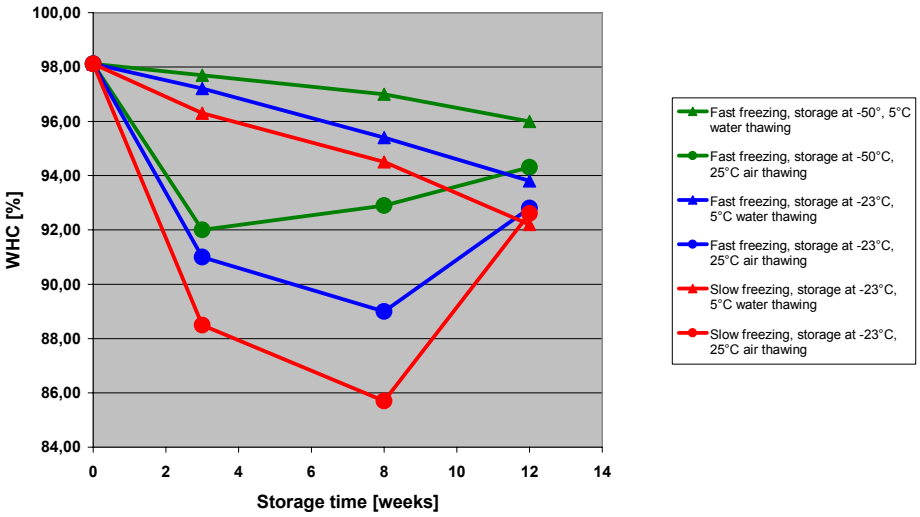


Figure 4.32 *Development in WHC depending on freezing rate, thawing method storage temperature and time.*

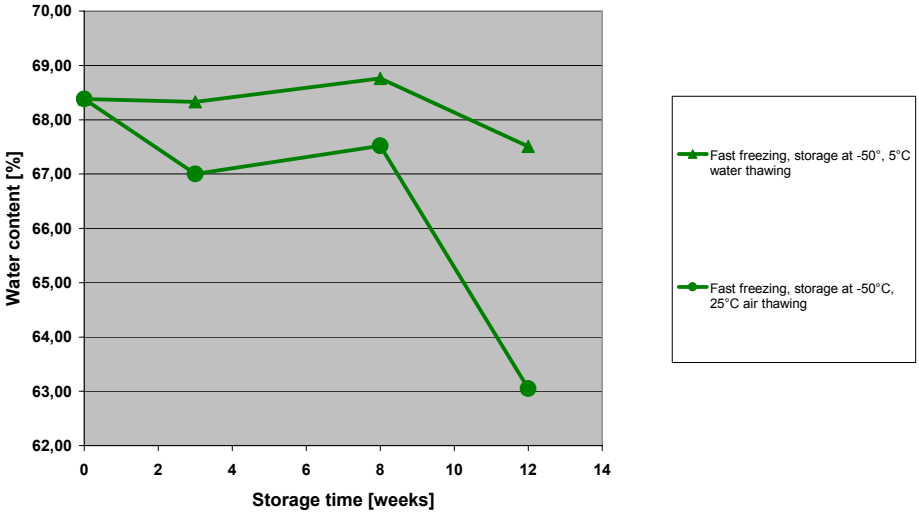


Figure 4.33 *Development of water content depending on thawing method, and storage time.*

Figure 4.34 shows the development of the drip loss depending on freezing rate, thawing method, storage temperature and time. Generally one can claim that the drip loss increases with storage time. The thawing method has a large influence, and thawing in a 5°C water bath gives substantially lower drip loss than thawing in heated air at 25°C, regardless of storage temperature and time. For the samples thawed towards 5°C, the effect of storage temperature and freezing rate is low. For the samples thawed towards 25°C the differences are evident. Slow freezing gives the largest drip loss and salmon stored at –50°C gives the smallest drip loss at this thawing method.

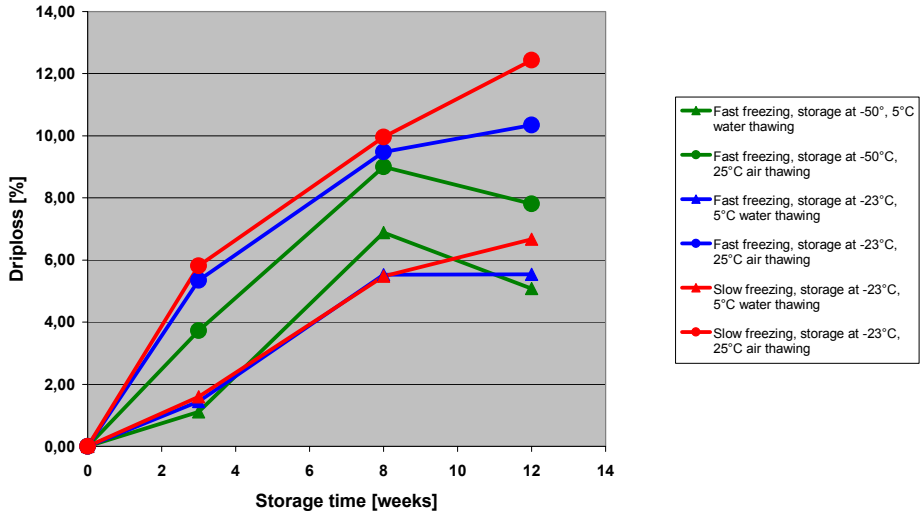


Figure 4.34 *Development of drip loss depending on freezing rate, thawing method, storage temperature and time.*

In order to achieve best possible quality with respect to the water related parameters, the most important factor is to thaw right (i.e. water thawing towards 5°C), followed by storing the salmon at temperatures around –50°C

Texture related parameters

Figure 4.35 shows the development of maximum force depending on freezing speed, thawing method and storage temperature. Thawing towards 5°C in general gives higher values for maximum force. Slow freezing rate reduces the values.

In Figure 4.36 the influence on deformation (represents pliancy) by thawing method is given. For the experiments carried out after 3 and 12 weeks there are no change for the salmon samples thawed towards 5°C, whilst for the samples thawed towards 25°C a reduction of the deformation ability takes place. For the experiments after 8 weeks, the thawing method does not alter the deformation ability.

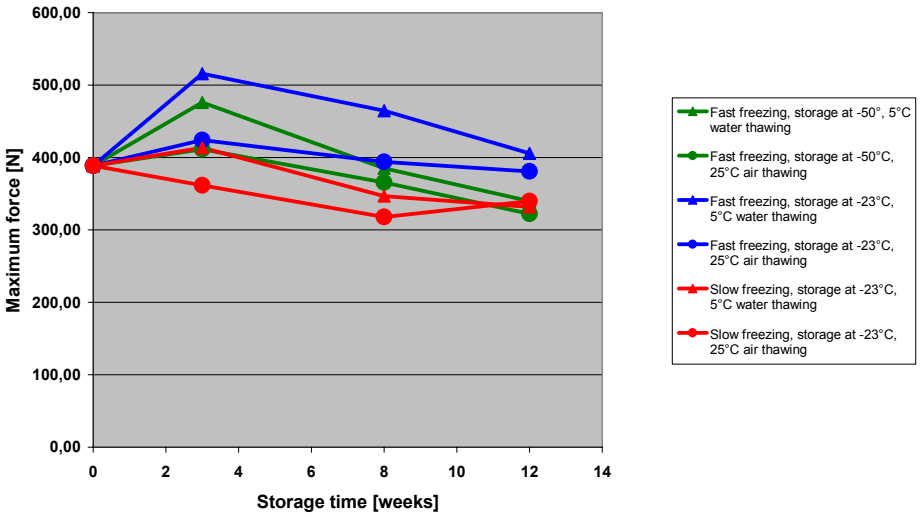


Figure 4.35 *Maximal force as a result of freezing rate, thawing method and storage temperature*

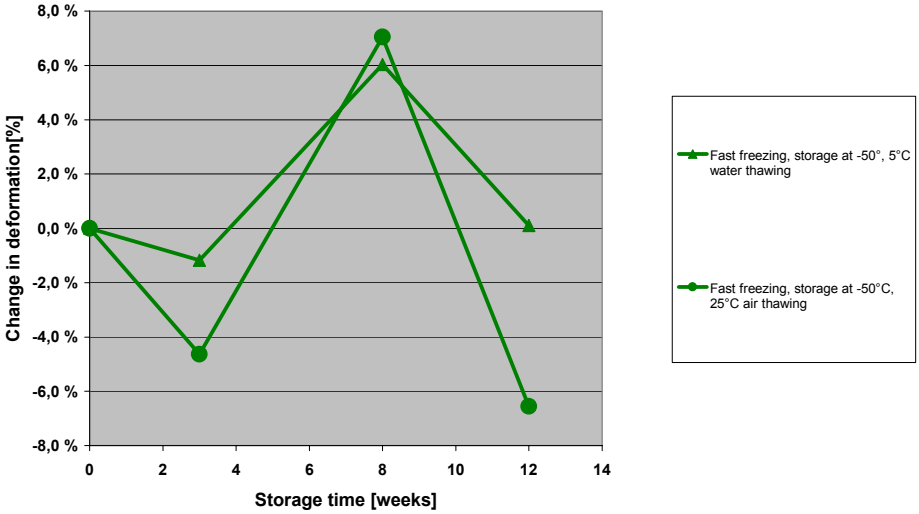


Figure 4.36 *The change in deformation during texture analyses on salmon, depending on thawing method.*

In general, with respect to the texture related parameters, it would be preferable to use a freezing set-up that gives short freezing time. The thawing method is also important, whilst the storage temperature is not.

4.9.3 Conclusion – thawing after long time storage

The total time consumed from the fish farmer in Norway to the customer in Japan, including processing, freezing, cold storage during transportation, intermediate storing, and defrosting, can take up to 3 months. It is a fact that the quality loss is significant, especially regarding the colour and water parameters during this period of time. Based on the results obtained in this study it can be concluded that this reduction of quality can be avoided or minimised, and parallel to that, other quality parameters can be improved. In this context it is suggested that the following physical factors can be improved during the processing:

- Freshly killed salmon should be frozen to -30^{o}C within 10-15 hours
- The storage temperature should be kept constant at -50^{o}C during the distribution period to avoid decrease in colour quality
- The basis for a colour certificate to the customer can be based on the following concept:
    - Thawing in water between 5-10^{o}C. The geometrical size of the product will determine the thawing time.
    - Adequate circulation of the thawing medium around the individual fishes.
    - Immediate cooling down to 0^{o}C after the fish core temperature has reached 0°C.
- This concept ensures that the water content and water binding capacity are maintained at values close to the originals. In this way the drip-loss can be reduced and the texture will also be better preserved.

4.10 Conclusions – thawing of Salmon

To this date, only limited amount of whole frozen salmon is industrially thawed in Norway. In order to realise the announced potential in Norwegian aquaculture it will be necessary to process much more salmon within Norway, in the years to come. Based on this it is also likely that the domestic industrial thawing of salmon will increase.

This work has shown that thawing and the way it might be implemented in industrial processes will affect quality parameters as well as important economical parameters.

Thawing of salmon should not be too slow, due to the possibility for increased drip loss, but use of higher thawing temperatures to speed up the thawing must be carefully evaluated. For most practical reason it seems like thawing of salmon should be done in a 5°C – 10°C water bath. Immediately after thawing, the salmon should be chilled towards the desired temperature. Unfortunately, due to the absence of companies that thaw industrially, this work has not identified what this temperature would be for salmon. In the next chapters examples of such temperatures will be found and evaluated for both Cod and Mackerel.

Some experiments have raised new questions, which will be valuable to explore in the future. Development of new industrial processes for salmon thawing could benefit a lot from this work, and hopefully we will take part in such developments.

5 Thawing of lean fish – Cod

5.1 Introduction – volume and value

Catches of lean fish like Saithe, Haddock and especially Cod together with pelagic species have been the spine of Norwegian fisheries. Lean fish contributed to 32% of the total seafood export from Norway in 1999[5]. Cod constitutes 2/3 of this value. According to the Norwegian Directorate of Fisheries the total catches of Cod, Saithe and Haddock in the North Atlantic were approximately 1.9 million tons in the year 2000. More than 600 000 tons of this were landed in Norway. The share that is landed frozen has increased substantially over the last years. This together with so-called "freeze hotels" that serve as storage until a customer is found for the batch, have given the fishermen an improved flexibility hence a wider market. This, combined with reduced catches, has lead to higher prices.

Inevitably this means that the raw material for the lean fish processing companies more and more often is frozen. Thawing is therefore an increasingly important process in this industry. The survey amongst 155 Norwegian companies (Chapter 2.5) showed that the majority of the companies that thawed stated that they used processes that were difficult to control. All the 103 companies that were into lean fish processing in the survey either thawed or would thaw in the future. Together these companies processed 140 000 tons lean fish in 1997. 10% of those who thawed, used air blast tunnels, and the rest thawed in small water vessels up to 1000 l.

Another effect of the shift towards more freezing at sea is that the domestic fillet industry has got competition from low cost regions like Eastern Europe and China. Companies in these regions use labour intensive processes to produce frozen fillets that can be sold on the world market significantly cheaper than the Norwegian alternative. Two alternative strategies that the domestic fillet industry can follow to survive in this market are;

- Improve the domestic production facilities and processes.
- Focus on fresh raw material in order to make use of the natural benefits of being close to the live raw material in the North Atlantic.

[5] SSB 1999

The first strategy means to optimise all the processes including the thawing process. The second strategy will most likely result in products for niche markets. As the volumes of farmed cod increase, the strategy to focus on fresh cod from the Norwegian coast will result in larger markets.

5.2 Domestic vs. export

Data for distribution between the domestic and international market of the landed quantum have not been looked into in this work. Naturally the domestic market is however just a fraction of the world market. The domestic consumption of frozen fish products (includes all species) according to MarkedsFakta (1999) was about 11 000 tons in 1999, whilst the corresponding export was 1 000 000 tons[1]. Table 5.1 shows the distribution of different types of products for the Norwegian lean fish export[6]

Table 5.1 *Distribution of different types of products for the Norwegian lean fish export (Norwegian Seafood Export Council, 2001)*

	Lean fish product					
	Filet	**Clipfish**	**Stockfish**	**Salted**	**Frozen**	**Fresh**
[%]	**33**	**30**	**8**	**15**	**7**	**7**

Except from production of Stockfish and Fresh lean fish, use of frozen raw material is common for all these preservation methods. Thawing is therefore an important process in production of products that constitutes for 85% of the export value.

5.3 Aim of study

Industrial thawing of lean fish in Norway has traditions back to the late 60's when it was declared by the fishery authorities that double freezing was allowed [3]. Several research programs (e.g. at NTH, Department for Refrigeration) had focused on this aspect, and their conclusion was that use of frozen raw material to produce frozen products was beneficial. The research programs also resulted in procedures for how the thawing process should/could be done. They described mainly two alternatives:

- Thawing in vessels up to 1000 litres by using running seawater as medium.
- Thawing in similar vessels, but by using a certain amount of hot fresh water per unit frozen fish (still water).

For both these methods it was recommended to use some kind of aid to prevent the frozen blocks to freeze together in the first stages of thawing – forming even bigger blocks. Estimates on thawing times depending on chosen thawing alternative and media temperature were given.

[6] Norwegian Seafood Export Council 2001

Considering this scientific basis and the long traditions, industrial thawing of lean fish today should be well taken care of. Unfortunately this is not so. Thawing in the lean fish industry has been "neglected". This has allowed a tradition for inaccuracy and aversion for change to grow. The companies have increased their throughput, and only scaled up the original facilities. In order to be able to deal with all these vessels, important elements have been left out (e.g. even water supply and means to secure that the blocks do not freeze together). Instead of curing the origin of their problem, they have treated the symptoms. Based on the initiative taken through the NFR project EXPONOFI, thawing "reappeared" as an important process both for the industry and researchers during the late 90's. This resulted in new products and processes from the equipment producing industry, and major players in the domestic lean fish industry have invested in new equipment. Unfortunately, both the technical installations and the applied processes are not by far good enough.

The main aim of the study regarding thawing of lean fish was to develop new controllable processes that could serve as a found basis for batch or continuously thawing processes. Thawing should be carried out as gentle and effective as possible, and at the same time produce raw material with predictable and even quality, which would lead to better utilisation of raw material and process equipment.

This chapter describe the state of the art in industrial thawing of lean fish in Norway until ca. year 2000, and identifies the critical factors in that practise (Chapter 5.6). Further, means to split the blocks as early as possible have been identified (Chapter 5.7). Chapter 5.8 and 5.9 deal with thawing of frozen raw material in respectively clip fish and fillet production. After this the newest generation of thawing equipment and procedures is described and briefly evaluated (Chapter 5.10).

5.4 Quality evaluation

This work is done in close cooperation with several different Norwegian lean fish companies. The frozen raw material used in the different experiments has varied in origin (season, grounds and boat), Fishing method (trawl, long lining), storage conditions (temperature and time), and fish and block size. This has made it difficult to directly compare results from different experiments. The companies themselves have mainly made the quality evaluations, except from the temperature measurements. In addition to follow product temperature as a quality indicator, our focus has been to investigate yield and overall process capacity. We have tried to build each experiment on the previous, different processes and boundary conditions between the companies have represented a challenge.

5.5 Material and methods

The different companies used different equipment and routines to thaw. The process applied by the investigated company has been used as the reference for each study. This means that the reference has been different amongst the sub-chapters. A short description of the actual procedures behind the reference is given in each sub-chapter.

5.5.1 New thawing processes

In order to control the thawing processes, the RSW equipment described in Chapter 3.6 was used.

5.5.2 Evaluation criteria

Continuously temperature monitoring and supplements of manual measurements have been used to investigate both reference and new processes. The equipment used in these operations is described in Chapter 3.4.1. Definitions of Yield and Throughput – Capacity is given in Chapter 3.4.3

5.6 Industrial Cod thawing - before year 2000

Chapter 2.5 gives an overview on the industrial thawing methods prior to 2000. They have their origin in the recommendations made by the authorities in the late 60's (Chapter 5.3). As described in Chapter 2.5 most of the companies regard their thawing processes to be uncontrolled. What has happened to allow this gap between teaching and doing? First of all the conditions have changed; the use of freezing at sea has increased, the capacity at each facility on shore has increased; large investments demand high capacity. This has lead to an under staffed up scaling of the recommended thawing solutions – Important factors have been let out. Secondly there has been put little or no qualified effort into finding the cause of the problems. One has focused on curing the symptoms.

5.6.1 An example of industrial thawing

For each company that has contributed to this study we have monitored their typical thawing. An example of this monitoring is given in this sub-Chapter. The company normally used over 100 vessels containing approximately 400 kg frozen fish each. Thawing was achieved by supplying running seawater through one tube for each vessel. The tubes were all placed in the upper part of the vessels. Since the vessels were plugged, the water drained over the top of the vessels. Up to four vessels were stocked on top of each other. A timer on the intake pump controlled the water supply, so that the water running time could be adjusted to the actual water inlet temperature. One of the leading workers had as his task to set the timer.

For the monitoring, one of the vessels at the ground was chosen. This vessel contained 8 blocks of frozen Cod. Each block had the approximately size of 100cm*50cm*10cm, and weighed approximately 50 kg. Thermocouples were drilled into the blocks, and into some single fish that fell off when the cardboard wrapping was removed from the frozen blocks. The water temperature in the vessel was also monitored. Figure 5.1 shows the temperature development for the different locations in the vessel.

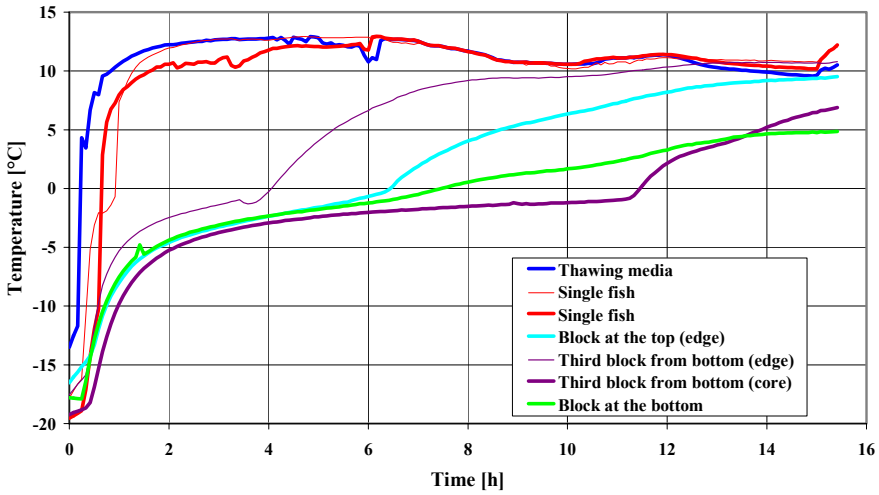


Figure 5.1 *Temperature development for different parts of a 400 kg batch of frozen cod thawed in a 1000 litres water vessel*

The figure shows that there are large differences in thawing speed depending on which part of the batch we are talking about. Parts of the single fish naturally thaw first, but it is likely that either of these curves represent the thermal core of the fish (The thawing went too fast for a 3-4 kg cod). Except for the thermocouple for the 'Block at the bottom', all the thermocouples for the blocks seemed to represent a thermal core. At least they follow the typical pattern of a thermal core; A long resident time in the latent zone, followed by a fast approach to the thawing media temperature. Both the edge and core thermocouple of the 'Third block from bottom' showed thermal core behaviour, but their thawing time differed greatly. The set up for the overall thawing was done so that the inlet pump should supply seawater for 10.5 hours after start (0.5 hours in figure 5.1).

After the thawing was completed, the core temperature of each fish in the monitored batch was registered. Table 5.2 and 5.3 give a summary of the findings.

Table 5.2 *Average temperatures in Cod after thawing.*

	Temperature [°C]
Average (n=109)	9,6
STDEV	3,0
High	11,9
Low	-2,2

Table 5.3 *The percentage of the batch that has a temperature within a different temperature level after thawing.*

Temperature level [°C]	Percentage of batch [%]
< -2	1,8
-2 – 0	1,8
0 – 2	0,9
2 – 4	0,9
4 – 8	10,1
> 8	84,4

The company itself considered a temperature between 0°C and 2°C to be the optimum level after thawing. Table 5.3 illustrates that they did not succeed while we were visiting. Less than 6% of the batch had a temperature below 4°C, whilst over 84% had a temperature more than 8°C. The part of the batch that was colder than –2°C will most likely be considered too cold. This experiment is carried through during summertime, and the seawater was quite warm. According to the company, it was not unusual that 20% of the total thawed volume was too cold during winter when the seawater is at its coldest.

This example illustrates the problems with the traditional practice. The thawing is far from controlled, and the average temperature of the thawed product is high. This will affect the quality, capacity and food safety.

5.6.2 The usual mistakes

This sub-Chapter does naturally not point at all that's wrong with the traditionally thawing, but it identifies some general negative factors and especially factors that are negative in a thermal aspect.

First of all thawing in these water vessels is labour intensive and space consuming. The method represents a safety risk and represents logistic challenges. It generates indirect cost related to trucks.

Stocking of frozen blocks in empty vessels

If we focus on the thermal aspects, it is obvious that the different blocks do not experience the same condition during thawing. This is described in Chapter 2.5 and illustrated in Figure 2.15. When the blocks are put in the vessels, no precautions are made to avoid the blocks from freezing together.

Varying thawing media temperature and pressure

The seawater intake is often at a dept where the temperature changes rapidly as a result of streams or a change in the weather. Equipments elsewhere in the production facilities are also often connected to the same water pump, resulting in varying pressure and thereby flow volume to the containers.

Differences in the water distribution

The high amount of thawing vessels are placed at different length from the inlet pump, resulting in different amount of thawing media per unit time at the different thawing vessels.

Localisation of thawing media tube inside thawing vessel

Usually the thawing media exits the thawing vessel at the vessel top. If the thawing media tube is placed at the top as well, most of the thawing media will exit without ever having encountered the object it was supposed to thaw.

Thawing procedures and routines

The thawing procedures do not set up to deliver an optimum raw material for further processing, but to avoid the product from being too cold. There are no routines that secure the thawing operators to learn as time goes by. Obviously they get experience, but the numerous varying factors and the lack of systematically use of knowledge and experience makes it virtually impossible to improve.

Goal on processing temperature

The industry does not have a clearly defined goal on processing temperature after thawing. They have a vague idea that the product should be processed at not too high temperatures, but have no specific goal to work towards.

5.7 Splitting of frozen cod blocks

As concluded in Chapter 3.2.1, it is important to split the blocks as soon as possible during thawing. This would either make it possible to speed up thawing (for continuously thawing processes), or to ensure that more of the available time for thawing was spent to equalize the temperature levels amongst the single fishes (for batch thawing processes).

The goal of the work described in this sub-Chapter was to investigate how different factors would affect the process time prior to splitting the frozen cod blocks. These factors were:

- Thawing media temperature.
- The content of salt in the thawing media (brine).
- Pre thawing temperature of the blocks.
- Different levels of agitation.

5.7.1 Focus and methods

The raw material

18 boxes, 50 kg each, of frozen cod were used. The fish boxes/ blocks were stored in a cold store at –23°C prior to experiment

The experiments - considered factors

The experiments should unveil the effect of four factors. Use of traditionally experimental design, would require minimum 16 experiments. This would not give any answer regarding the combinatorial effect from the different factors. In order to take full advantage of the 16 experiments, statistical experimental design was chosen. This tool makes it possible by use of statistical methods, to get more information from each experiment.

The experiments followed a plan, where the factors to consider vary between two levels, low and high (Table 5.4). In addition some experiments (centre experiments) were made, where the factors were fixed at intermediate levels.

Table 5.4 *The range of variation for the different factors*

	Cod	
Factor	**Low level**	**High level**
Thawing media temperature	-1.0°C	15°C
Salt content in thawing media	3% (seawater)	19% (saturated brine)
Pre thawing temperature of the blocks	-23°C	-10°C
Agitation*	No	Compressed air in 18 minutes**

*Agitation excessive of what was needed in order to identify a spitting time for the blocks
**18 minutes in each cycle of 20 minutes (see below)

Thawing media temperature

Increased thawing media temperature increases the driving force for heat transport into the product. The low level was chosen in order to prevent freezing of seawater in the evaporator of the RSW equipment. High level was based on the highest imaginable seawater temperature in the parts of Norway where this production takes place.

Salt content in thawing media

As shown in Appendix VII, increasing the salt content from 0% and up to approximately 22% results in decreasing freezing point of the brine. During thawing with water as thawing media, freezing (re-freezing) of water "locked" in voids of the product can occur, especially for non-compact blocks. This phenomenon can be caused by several factors: low product temperature, low thawing media temperature and/or locally insufficient thawing media circulation. High salt content of the thawing media can prevent this re-freezing. This brine could also speed up melting of the frozen water originally contained within the block (as spreading salt on icy roads). For thawing processes in connection to salted cod or clip fish production, the high level of salt could lead to a faster salting process.

According to important players in the industry, full-scale production with fresh water as thawing media would be too expensive to consider - compared to seawater. Low level of salt content in thawing media was therefore set to seawater level (3%). High level was set to 19% salt content.

Pre thawing temperature of the blocks
If the homogenous temperature of the blocks is increased, and the desired final temperature is fixed, it is reasonable to expect that the spread in product temperature during thawing will be reduced.

The high level temperature was set to –10°C, since this is a temperature where the quality of the product will not suffer from for a short period of time (storage at this temperature should also serve as a buffer storage in the production). The low-level temperature was set to –23°C representing the typical storage temperature in the fish industry.

Different levels of agitation
If the fish on the outside of the block is removed as soon as possible, the size of the block will get reduced resulting in quicker thawing, due to the reduced distance the energy needs to be transported (conducted). In order to avoid dilution of the brine, compressed air was chosen as agitation mean.

Low level was represented by no use of forced agitation (i.e. compressed air), beyond what was needed in order to define the splitting time for the blocks. High level was represented by continuously agitation by the use of compressed air.

Experimental set up

The experiments were conducted in the RSW (Refrigerated Sea Water) equipment described in Chapter 3.6.1. The brine entered the test vessel through a perforated plate. The unwrapped frozen block of cod was put into a chicken wire cage and oriented in such a manner that the largest surface of the block was perpendicular to the thawing media stream.

Identification of block splitting time

The thawing media stream around the blocks was not more powerful than that the blocks would be kept in one piece until the entire blocks were thawed. In order to find a representative splitting time, a defined manual control of the block strength at given intervals were done.

The manual control procedures are illustrated in Figure 5.2. Every 10th minute (First time 10 minutes after start) the cage was turned around (180°), and every 20^{th} minute the cage was opened and the block was tried divided by hand for two minutes.

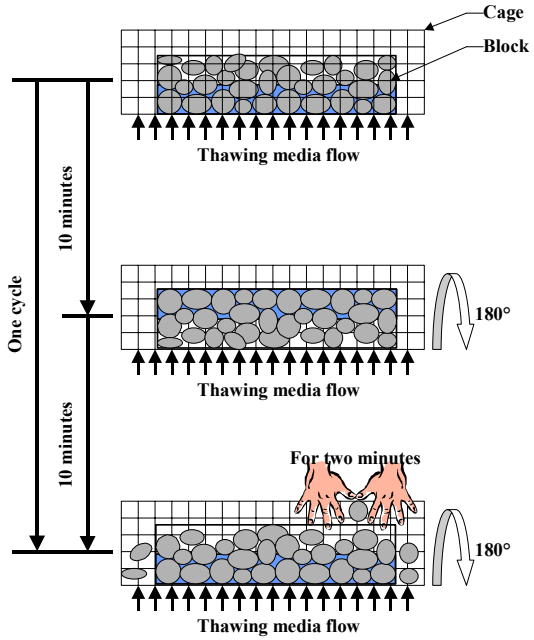


Figure 5.2 *Procedure for identifying the splitting time of the blocks.*

Experiments

As mentioned statistical experimental design was utilised. A full factorial design (2^4 design) consisting of 16 experiments with various combinations of low and high levels of the four factors of current interest were chosen. This specific design gives information about the effects of both the four single factors themselves and on any possible 2-variable interactions (combinatorial effects). In order to check the error of measurement, two centre samples were carried out. This means that a total of 18 experiments (16+2) were used.

Table 5.5 *The different levels of the four variables for the 18 experiments*

Experiment number	Pre thawing temp.	Thawing media temp.	Salt content in thawing media	Agitation
1	-23°C	-1°C	3%	0min
2	-23°C	15°C	3%	0min
3	-23°C	-1°C	19%	0min
4	-23°C	15°C	19%	0min
5	-10°C	-1°C	3%	0min
6	-10°C	15°C	3%	0min
7	-10°C	-1°C	19%	0min
8	-10°C	15°C	19%	0min
9	-23°C	-1°C	3%	18min
10	-23°C	15°C	3%	18min
11	-23°C	-1°C	19%	18min
12	-23°C	15°C	19%	18min
13	-10°C	-1°C	3%	18min
14	-10°C	15°C	3%	18min
15	-10°C	-1°C	19%	18min
16	-10°C	15°C	19%	18min
17	-16,5°C	7°C	11%	9min
18	-16,5°C	7°C	11%	9min

Comments regarding the experiments

The strength of each block varied a lot initially, and the experiments would have benefited from doing parallel trials for each thawing.

The use of pressurised air to increase the level of agitation was unfortunate. The facility for this in the actual laboratory was limited, resulting in small differences between high and low level of agitation.

5.7.2 Results

A set of results that could be used to draw a "splitting curve" was obtained from each of the 18 experiments. Since manual power was used to split the blocks, and get these results, it is inevitable that the blocks have been exposed to a varying force from experiment to experiment. In order to reduce the impact of this fact, a polynomial of second degree ($Y = Ax^2 + Bx + C$) was fitted to the experimental set by the method of least square. Figure 5.3 shows an example of the experimental set and the fitted curve for one of the experiments.

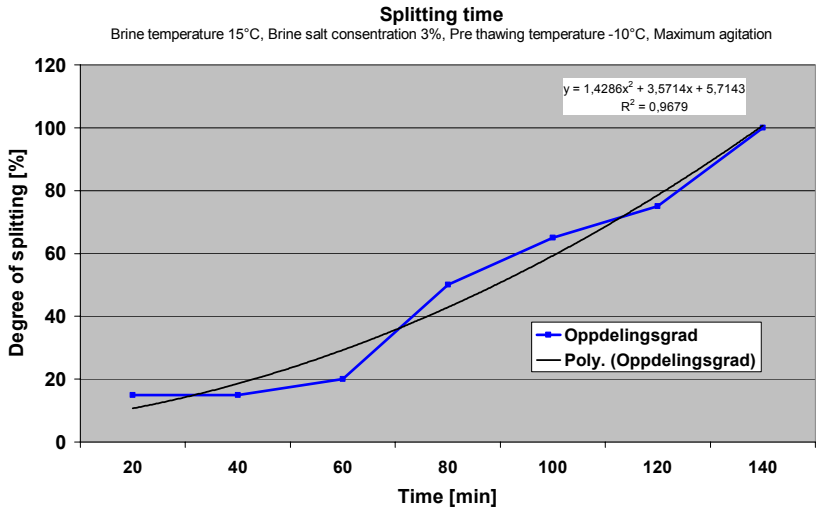


Figure 5.3 *Example of the set of results and how they are utilised in order to identify a splitting time. The conditions are given in the heading of the figure. Experiment number 14.*

Statistical analysis – significant factors

Four different approaches were considered in order to find out whether some of the four chosen factors had significant effect on the splitting of cod blocks:

1. The "Splitting time" from the originally set of results, that is regardless of when within the last 20 minutes cycle (Figure 5.2) the remaining part of the block would have been dividable.
2. "Splitting time" from the fitted curve.
3. To what degree according to the original set of results, the blocks in the different experiments were divided at a given time. This time corresponded to the shortest "Splitting time" experienced in the original set of results.
4. To what degree according to the fitted curves, the blocks in the different experiments were divided at a given time. This time corresponded to the shortest "Splitting time" calculated from the fitted curves.

The results of these different approaches are given in Appendix VIII, whilst the results for the second approach are shown in Table 5.6.

Table 5.6 *Block splitting time for the 18 experiments calculated from fitted curves*

Experiment number	"Splitting time" calculated from fitted curves [Minutes]	Experiment number	"Splitting time" calculated from fitted curves [Minutes]
1	317	**10**	140
2	119	**11**	178
3	217	**12**	116
4	134	**13**	237
5	257	**14**	139
6	140	**15**	226
7	287	**16**	120
8	137	**17**	144
9	262	**18**	139

These results are not straightforward to discuss and analyse, but use of statistical methods make it easier to bring into focus the most interesting factors. Table 5.7 shows the results from this statistical method. The table shows the probability that the four different factors and the combinations of them do not affect the splitting time, and that the variations in the results solely are caused by naturally variations.

Table 5.7 *The probability that the variations in splitting time connected to the different levels of the factors solely is caused by natural variations.*

Factor			Probability for no effect on splitting time
Full name	**Abbreviation**	**Symbol**	**Analysed with data from fitted curve**
Pre thawing temperature	**startTEMP**	**A**	14,7%
Thawing media temperature	**brineTEMP**	**B**	**1,0%**
Salt content in thawing media	**brineCONS**	**C**	**4,6%**
Agitation	**AGITATION**	**D**	**4,7%**
2 VARIABLE INTERACTION		**AB**	74,5%
		AC	**4,7%**
		AD	67,2%
		BC	**6,7%**
		BD	**5,6%**
		CD	11,1%

As the values given in Table 5.7 get lower, the more probable it is that the considered factor has any effect on the response variable (i.e. splitting time). If the probability that the variations connected to a shift in value (from low level to high level) of the considered

factor solely are due to natural variations is less than 5%, it is common to state that the factor has a significant effect on the splitting time. For factors with values higher than this limit it might be possible to discuss tendencies, but as the value increases the more cautious one has to be.

The most important reasons for choosing the second approach (values given in Table 5.7) for analysing the effect of the different factors are:

- The second approach has been compensated (represented by the fitted curve) for differences in exercised manual power from one cycle to another during the experiments.
- The results from the third and fourth approach are based on only a small part (i.e. the beginning) of the result set from several of the experiments.

Table 5.7 shows that three main factors (brineTEMP, brineCONS and AGITATION) and the interaction startTEMP/brineCONS (AC) have a significant effect on the splitting time of the frozen Cod blocks. Furthermore it looks like the 2-variable interactions brineTEMP/brineCONC (BC) and brineTEMP/AGITATION (BD) need to be commented.

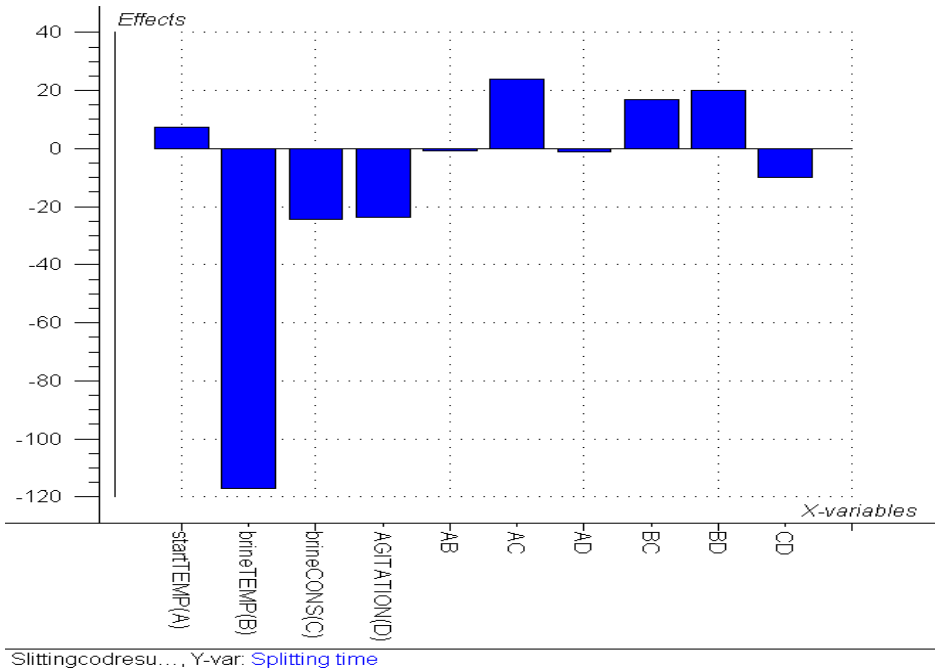


Figure 5.4 *The effect on splitting time by the different factors.*

Statistical analysis - effects

Figure 5.4 shows the effect of all the main factors and their 2-variable interactions. Brine temperature (brineTEMP) is the most effective single factor in order to reduce the process

time prior to splitting of frozen cod blocks. More detailed investigations of the significant factors are given below, where the average scores at the different levels for the factors are compared. It is important to remember that the centre values are based on two experiments carried out under similar condition, whilst both high and low values are based on four experiments each. These four experiments have been carried out under different conditions (except from thawing media temperature). All this means that the absolute values in the following figures should not be compared directly. It is also important to remember that the initial density and strength of the blocks most likely have affected the results, and that the effects that are identified as significant by a narrow margin should not be used to draw absolute conclusions.

The effect by altering the thawing media temperature (brineTEMP)
Figure 5.5 shows that if the brine temperature is increased from –1°C to 15°C, the cod block will on average split 117 minutes earlier. The figure further indicates that there most likely is curvature on the correlation. It is however important to realise that the curvature cannot be derived from this figure. More tests would have had to be done in order to unveil the correlation curvature. This is not done in this work.

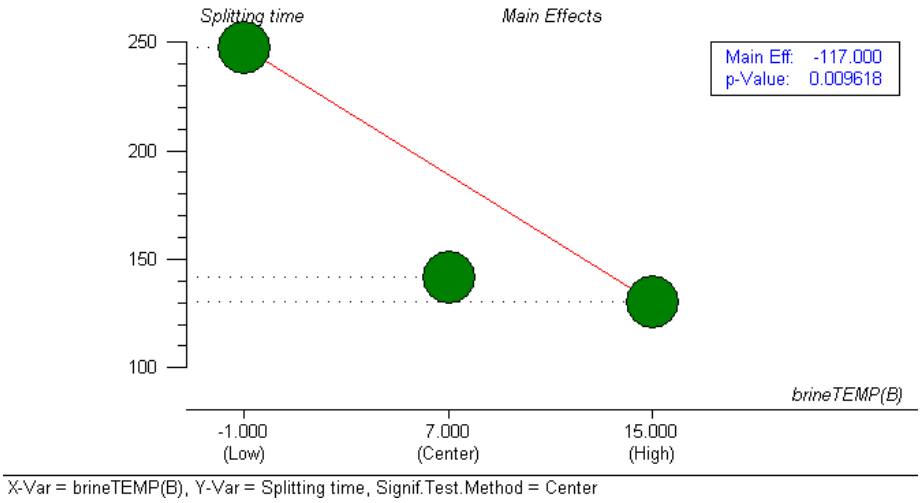


Figure 5.5 *The effect on splitting time for blocks of frozen cod by changing the thawing media temperature (brineTEMP).*

The effect by altering the salt content of the thawing media (brineCONS)
Figure 5.6 shows that if the salt content of the thawing media is increased from 3% to 19%, the cod block will on average split approximately 25 minutes earlier. Also this figure indicates that there most likely is curvature on the correlation.

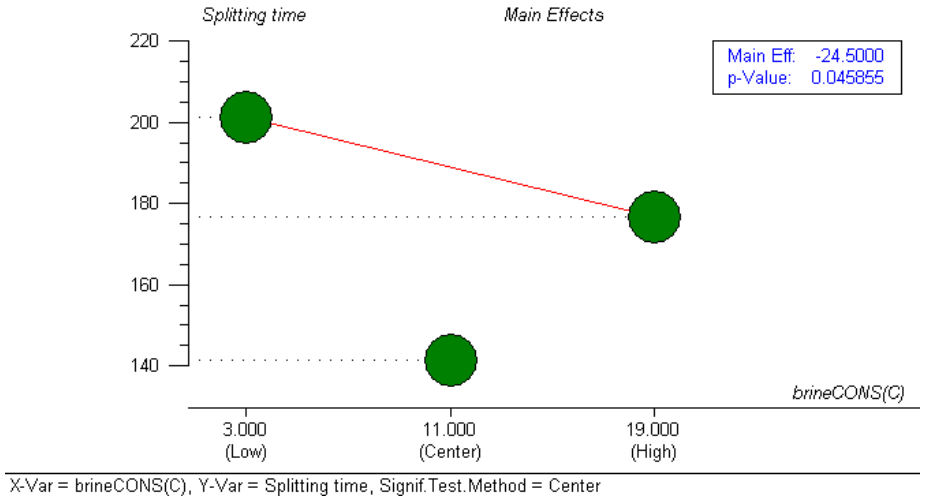


Figure 5.6 *The effect on splitting time for blocks of frozen cod by changing the salt content in the thawing media (brineCONS).*

The effect by altering the level of agitation (AGITATION)

Figure 5.7 shows that if the level of extra agitation is increased from none to continuously, the cod block will on average split approximately 24 minutes earlier. Also this figure indicates that there most likely is curvature on the correlation.

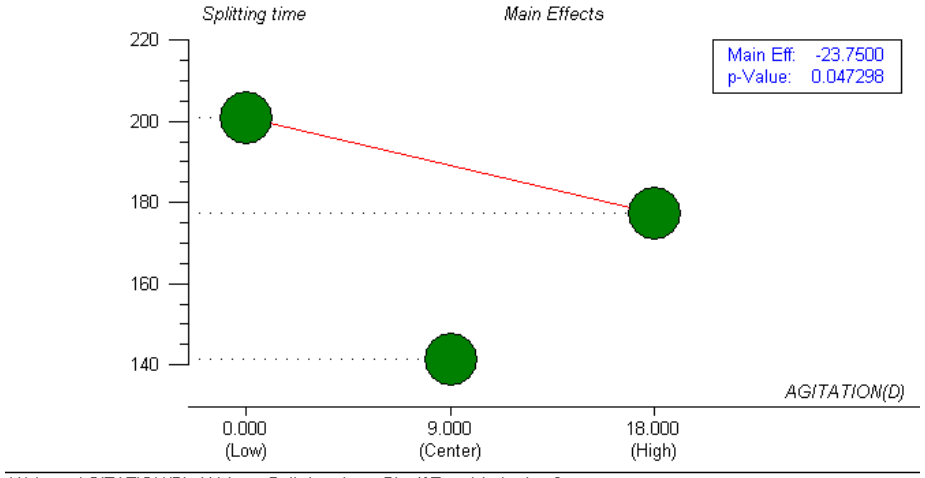


Figure 5.7 *The effect on splitting time for blocks of frozen cod by altering the level of agitation (AGITATION).*

The combined effect by altering the levels of initial block temperature (startTEMP) and the salt content in the thawing media (brineCONS)
Figure 5.8 shows the effect of interactions between the initial block temperature and the salt content in the thawing media. The brine concentration is important when the blocks have an initial temperature of –23°C, and not when the initial temperature is –10°C. This can be due to extensive freezing of the 3% salt brine on the surface of the –23°C cold blocks, whilst virtually none of the 19% salt brine would freeze. For blocks with an initial temperature of –10°C, the energy exchange is not high enough to freeze any of the brines.

Why it takes longer to split the block when the initial temperature is –10°C instead of –23°C and the brine concentration is 19%, is difficult to explain.

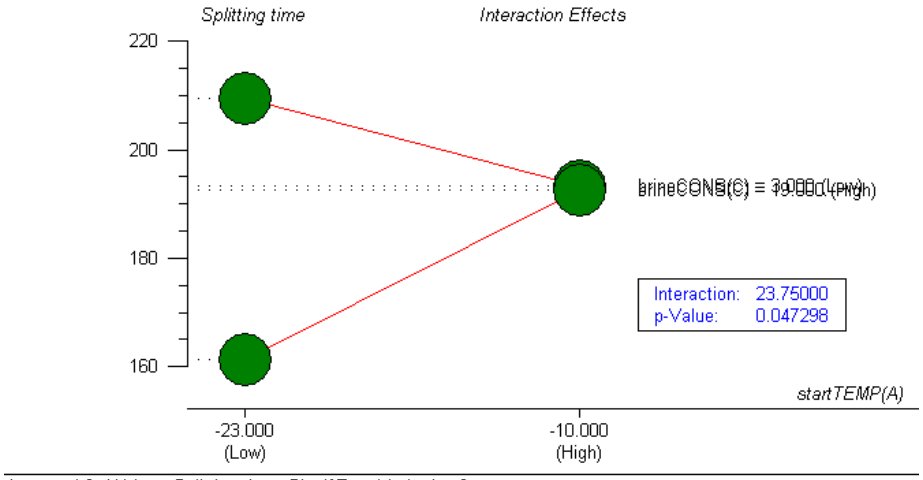


Figure 5.8 *The effect on splitting time for blocks of frozen cod by the interaction between initial block temperature (startTEMP) and thawing media salt concentration (brineCONS). The green dots connected by the upper red line illustrate the effect of changing the initial temperature of the blocks for a fixed brine concentration of 3%, whilst the dots connected by the lower red line represent the same change at a brine concentration of 19%.*

The combined effect by altering the levels of thawing media temperature (brineTEMP) and the salt content in the thawing media (brineCONS)
Figure 5.9 shows the effect of interactions between thawing media temperature and the salt content in the thawing media. This interaction is not significant at a 5% level, but it is so close (6,7%) that it should be commented. The effect of using 19% salt brine as thawing media, instead of 3%, is naturally highest at low thawing media temperatures. At a thawing media temperature of –1°C, the blocks will on average split 40 minutes earlier when using 19% instead of 3% salt brine as thawing media.

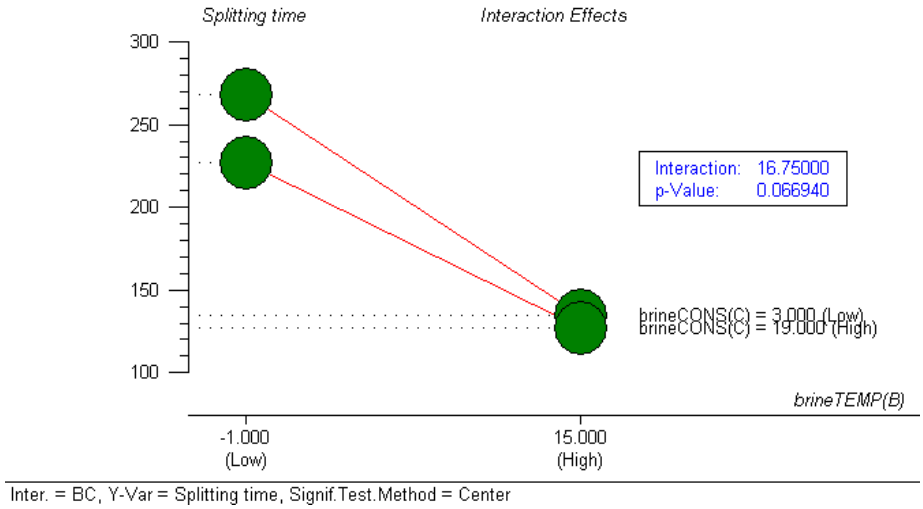


Figure 5.9 *The effect on splitting time for blocks of frozen cod by the interaction between thawing media temperature (brineTEMP) and thawing media salt concentration (brineCONS). The green dots connected by the upper red line illustrate the effect of changing the thawing media temperature for a fixed brine concentration of 3%, whilst the dots connected by the lower red line represens the same change at a brine concentration of 19%.*

The combined effect by altering the level of thawing media temperature (brineTEMP) and the level of agitation (AGITATION)

Figure 5.10 shows the effect of interactions between thawing media temperature and the level of agitation. This interaction is neither significant at a 5% level, but it also is so close (5,6%) that it should be commented. The effect of utilising a high level of agitation, instead of no extra agitation, is highest at low thawing media temperatures. At a thawing media temperature of –1°C, the blocks will on average split 45 minutes earlier utilising a high level of agitation. This mechanism seem logical; agitation at low thawing media temperatures (-1°C) will reduce the chance for freezing of thawing media on at the surface of the frozen block, whilst there will not be any freezing of thawing media at the block surface when the thawing media is 15°C.

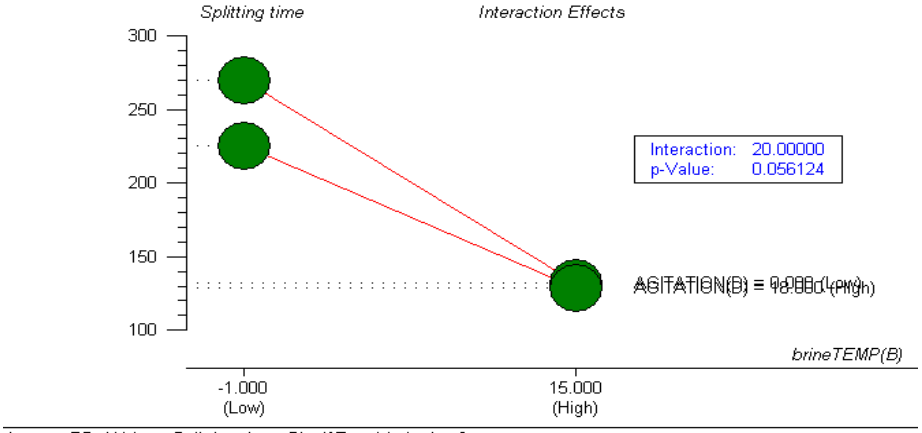


Figure 5.10 *The effect on splitting time for blocks of frozen cod by the interaction between thawing media temperature (brineTEMP) and level of agitation (AGITATION). The green dots connected by the upper red line illustrate the effect of changing the thawing media temperature for a low level of agitation, whilst the dots connected by the lower red line represent the same change utilising a high level of agitation.*

Statistical analysis – response surface

Figure 5.11 and 5.12 show the response surfaces for the splitting time depending on the thawing media temperature (brineTEMP) and respectively thawing media brine concentration (brineCONS) and level of agitation (AGITATION). The coloured lines in the figures illustrate constant splitting times, and the numbers written on them are this time given in minutes. The figures show that both brineCONS and AGITATION are increasingly important as the thawing media temperature decreases.

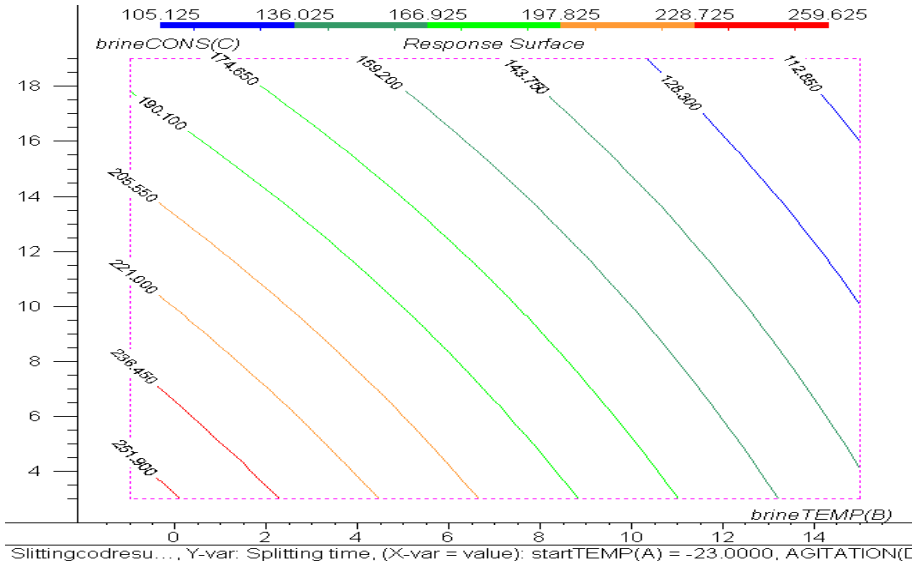


Figure 5.11 *Splitting time (in minutes) as a function of thawing media temperature (brineTEMP) and salt content in thawing media (brineCONS). Initial block temperature is fixed to –23°C and full agitation is utilised.*

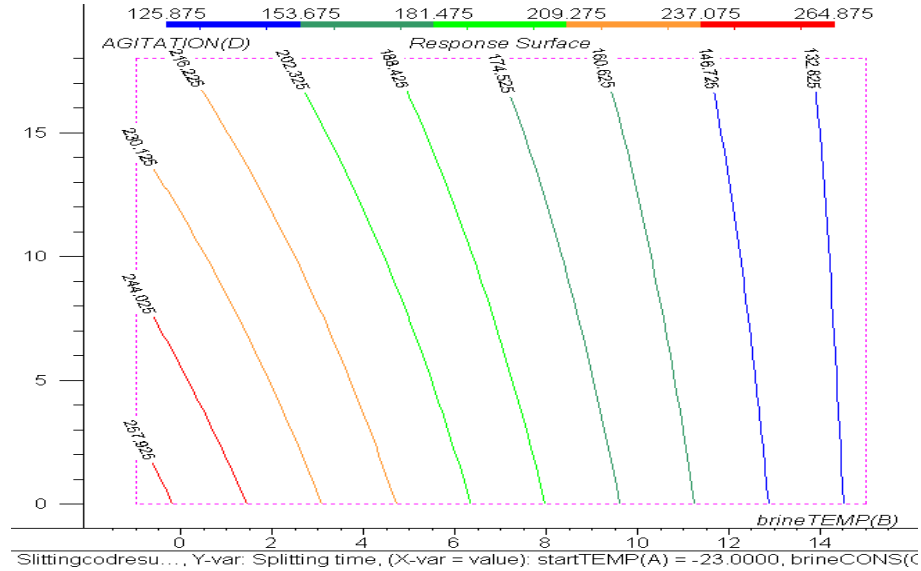


Figure 5.11 *Splitting time (in minutes) as a function of thawing media temperature (brineTEMP) and level of agitation (AGITATION). Initial block temperature is fixed to –23°C and average brine concentration is applied.*

5.7.3 Conclusion – splitting of blocks

The most important factor for the splitting time of frozen cod blocks is thawing media temperature. Salt content in thawing media is increasingly important at lower thawing media temperatures and if the blocks are very cold when they enter the thawing process. Level of agitation is also increasingly important as the thawing media temperature decreases. If a stronger agitation mean had been applied, the effect of agitation would most likely be higher. For thawing processes, where the different blocks will have the possibility to freeze together, all these three factors will become increasingly important. For thawing in other media than water/brine (i.e. air), both salt content and level of agitation are out of the question. Thawing media temperature will however still play the most important role in reducing the process time prior to splitting of the cod blocks.

5.8 Effect of thawing on cod for clip fish production

Clipfish constitutes 30% of the value of Norwegian lean fish export (Table 5.1). Cod is the most important raw material for this product, and frozen raw material has become increasingly important for this industry.

Traditionally this industry has thawed as described in Chapter 5.6. In a new process the frozen blocks should be split as soon as possible without compromising the quality (ref. Chapter 3.2.1). In the previous chapter different means to affect the splitting time were investigated. The most effective method to make an earlier splitting of the blocks possible was the use of relatively high thawing media temperature in the first stage of the thawing. For products where salting is a natural part of the production process, use of a brine with high salt content would also be helpful. This option has not been investigated in this work, because that would also change the salting process itself, and not only the thawing process.

The energy ($\Delta h_{freeze/thaw}$) needed to bring the product from the cold store temperature (typical –23°C) and up to the desired processing temperature is illustrated in Figure 5.13. The desired processing temperature is normally considered to in the area 0°C to 4°C. This characteristic temperature is treated later in this chapter.

At a thawing media temperature of 15°C it is possible to split the blocks after 2-2,5 hours. The inner part of the single fish will then still be frozen. An important aspect with this approach is how much of the energy ($\Delta h_{freeze/thaw}$) needed to increase the temperature of the product to the desired level, is transferred during the block splitting stage. Figure 5.14 illustrates how the thawing media temperature in the block splitting stage influences the further processing.

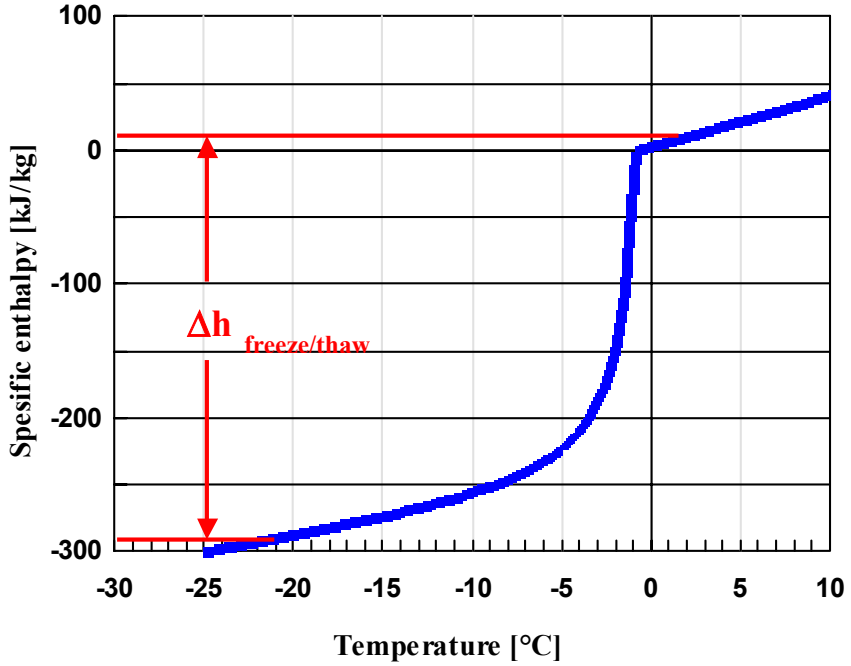


Figure 5.13 *The energy needed in order to increase the product temperature from cold storage level and up to desired process temperature.*

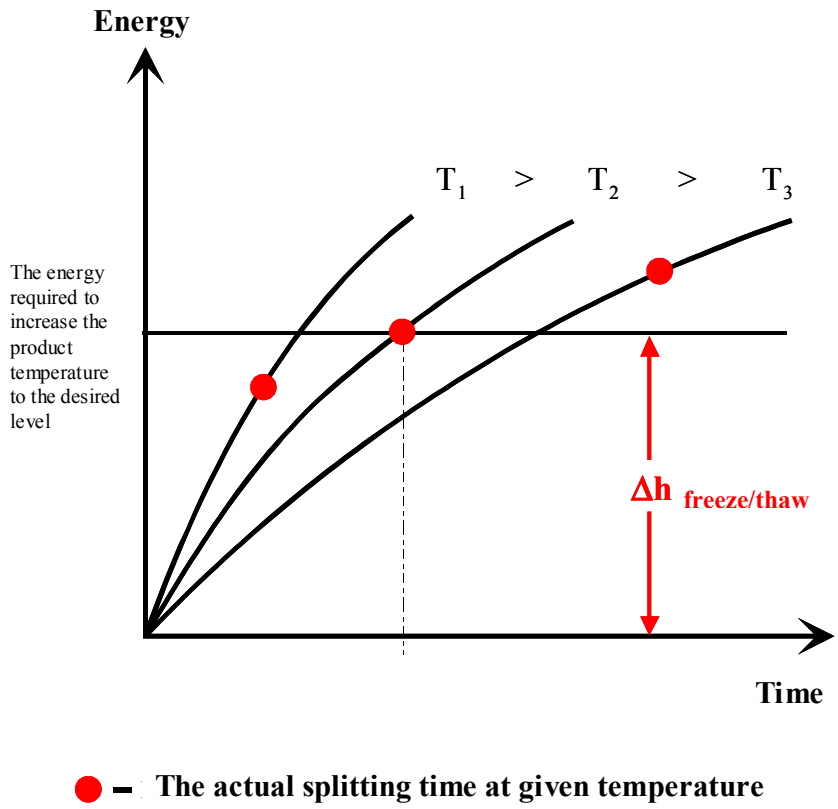


Figure 5.14 *How different temperatures during the block splitting stage can influence the rest of the thawing process.* $\Delta h_{freeze/thaw}$ *is the same as in figure 5.13.*

If the thawing temperature is T_1, the blocks will split before the required energy is transmitted to the product. The rest of the thawing process needs to be designed to further transfer energy to the single fish and to secure that the temperature within and amongst the single fish is equalized.

For a thawing temperature of T_2, all the required energy is transferred as the blocks split. This means that the rest of the process only will have to secure that the temperature within and amongst the single fishes is equalized.

When thawing at a temperature T_3, more energy than required is transferred during the stage of splitting. This means that the next stages of the overall thawing process need to be designed to remove the excess energy and at the same time allow the product temperature to be equalized amongst and within the single fish.

It is obvious that the energy required in order to get a product with the desired temperature prior to further processing is an important factor. In order to find this value, it is necessary to define the optimal processing temperature. The goal of this chapter is to investigate this aspect for the production of clip fish, whilst Chapter 5.9 deals with this aspect for production of frozen fillet.

5.8.1 Focus and methods

The goal of the study described in this sub-Chapter was to see if the product temperature after thawing had any influence on the following processing.

The raw material

80 boxes, 25 kg each, of frozen cod were used. The size of the single fishes was 1-3 kg, and the blocks had been frozen in plate freezers.

The experimental set up

The controlled experiments were conducted in the RSW (Refrigerated Sea Water) equipment described in Chapter 3.6.1, whilst the reference experiments were conducted in 1000 litres vessels (as described in Chapter 5.6). There was no electric heater, to secure high temperatures in the first stage, installed in the RSW unit.

Temperatures were monitored by the means described in Chapter 3.4.1, but the Fluke 2625A Hydra Data logger was equipped with thermocouples of type T1-02-T, 0,2 mm thick and Teflon insulated. Temperatures were recorded every 2 minutes.

All weights were measured by one of the company's own Scan weight (± 1 kg). Initial net weights, and weights after each step were recorded. Fish that was too cold to get split was also weighed.

Experiments

The thawing

Two different thawing methods were applied:

1. Traditionally thawing in 1000 litres vessels as used by the company. Approximately 400 kg fish in each batch. Seawater was supplied through a hose in the upper part of the vessel. A timer could regulate the water supply; however, this was not used during these experiments. The water was running from the afternoon through to the morning. Two experiments were carried through like this.
2. Controlled thawing in the RSW unit. The same amount of fish was placed in the largest vessel (this means that the blocks were stocked as tight as in the traditionally method). The thawing was divided into two stages. In the beginning the blocks were thawed at as high temperature as the RSW unit could maintain. After a while the blocks were split manually, and the RSW unit was programmed to decrease the media temperature down to desired end temperature. The total time consumption during these experiments was similar to thawing time for the traditional method. In other words; the experiments did

not set out for speeding up the process. Three different experiments were carried out this way. We aimed at respectively 1°C, -0.5°C and –1°C as product temperatures after thawing (processing temperature) for these three experiments.

Splitting
After thawing each batch was transferred to a buffer vessel containing 8°C seawater. The same BAADER splitting equipment was used for all the experiments. The amount of cod that was too cold to get split automatically was recorded, and the loss during splitting was calculated.

Salting and drying
After splitting, the company itself took over the responsibility for the batches through the rest of the production process, and final yield and quality were registered.

Comments regarding the experiments

Something went wrong during the weighing procedure (the container used was not identified - hence the weight of it was not available) during the second run with the traditional thawing method, and the result could therefore not be used.

There were some problems with the power supply for the RSW unit. This resulted in several stops during the night, but did most likely not affect the results much.

5.8.2 Results

Temperatures during traditional thawing

The seawater temperature during the traditional thawing is shown in Figure 5.15. The temperatures in the fish after the traditional thawing are given in Table 5.8.

Table 5.8 *Cod core temperatures registered after thawing in the traditional thawed batch*

Temperature	[°C]
Average	5,2
STDEV	3,4
Maximum	7,7
Minimum	-3,8

The average temperature is lower than for the example given in chapter 5.6.1, but the spread in temperature is also here considerable. 7% of the fish in this batch was too cold to be automatically split (Table 5.10).

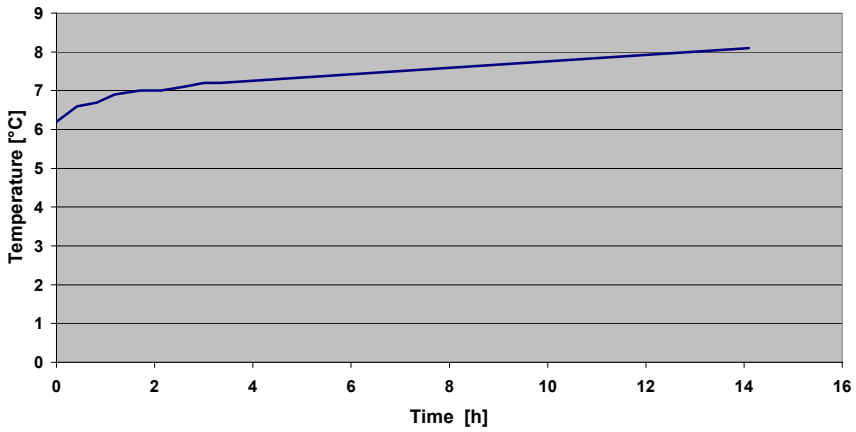


Figure 5.15 *The development in thawing media temperature during traditional thawing of cod.*

Temperatures during RSW thawing

During these runs, the temperatures in some of the blocks were also recorded. After the manual splitting of the blocks, the thermocouples were connected to selected fish. Figure 5.16 shows the temperature development during RSW thawing towards –1°C developed.

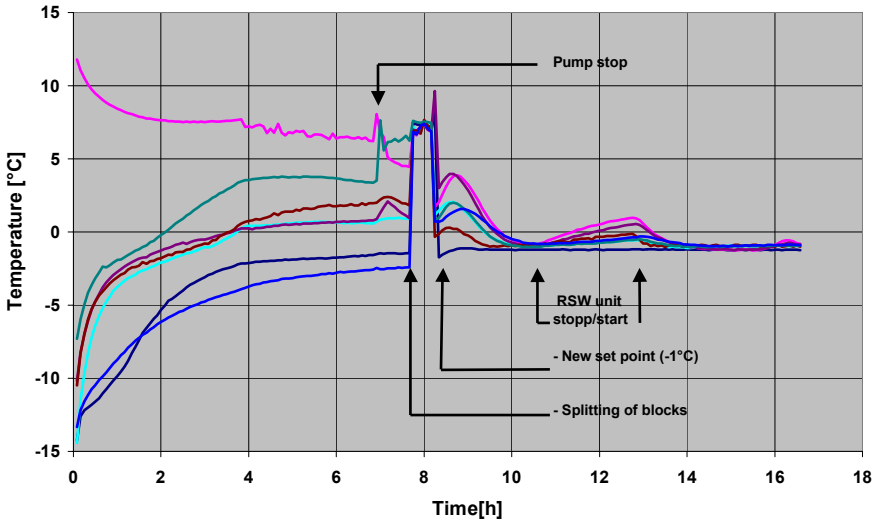


Figure 5.16 *Thawing towards –1°C with the aid of the RSW unit.*

The problems with the power supply to the unit are obvious in the figure. The thawing media temperature in the beginning was kept as high as possible at the present conditions, and was on average ca 7.5°C. After the blocks were split, the thermocouples were inserted to the single fish. This explains the "strange" shifts in temperatures from 7.5 hours and to 8.5 hours.

The temperatures after thawing for all the RSW runs are given in Table 5.9.

Table 5.9 *Cod core temperatures after RSW thawing towards 1°, -0,5°C and –1,0°C*

Temperature	Thawing towards 1,0°C	Thawing towards –0,5°C	Thawing towards –1,0°C
Average	0,6°C	-0,3°C	-0,8°C
STDEV	0,9°C	0,9°C	0,2°C
Maximum	2,2°C	0,8°C	-0,4°C
Minimum	-1,3°C	-1,3°C	-1,2°C

The temperatures of the batches thawed in the RSW unit did not exactly meet the aimed values, but the differences are small, and the spread is reduced considerably compared to the traditional thawing. Especially the batch thawed towards –1°C has a low spread. In order to illustrate the differences in final product temperature, the temperatures are illustrated as normal probability plots in Figure 5.17.

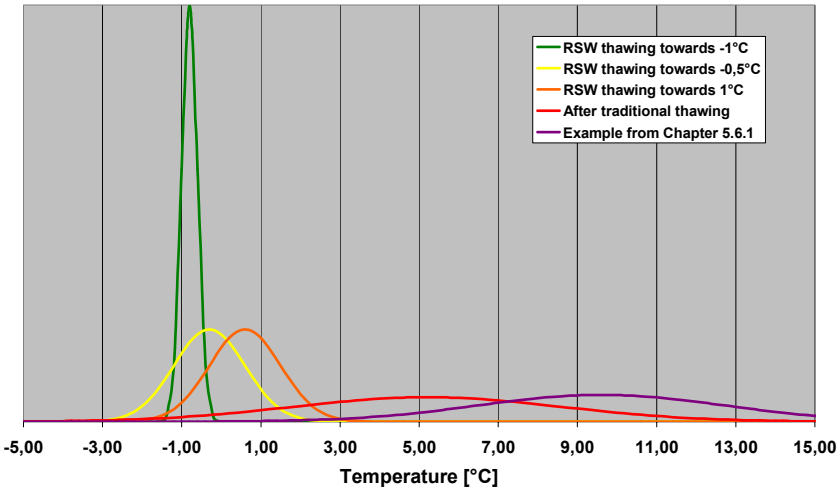


Figure 5.17 *The temperature distribution depending on the thawing method and aimed end temperature.*

The curves for the example given in Chapter 5.6.1 and the traditional thawing are very similar. This is naturally, since both these batches were thawed by the same method. The difference in average value for these two runs is connected to the difference in seawater temperature at time of experiments. The curves for RSW thawing towards 1°C and –0,5°C are also similar each other and less spread than the curves for the traditional thawing, whilst the RSW thawing towards –1°C is the by far least spread distribution. The difference between this experiment and the other two RSW experiments is that the thawing aims at a temperature in the latent zone of the cod. Normally cod has an initial freezing point of –0,7°C. Below this temperature, small changes in product temperature will lead to larger differences in energy levels for the products. If we could have easily measured this energy level, it is likely that the spread of this parameter would had been similar for all three experiments in the RSW unit. The narrowed temperature distributions for the thawing towards 1°C and –0,5°C in the RSW unit, are most likely a result of better thawing media distribution, and the fact that the blocks are split as early as possible.

Yield and quality after the backbone is removed

The different weights during the experiments and the yield after removal of the backbone are given in Table 5.10.

Table 5.10 *Weights during the different stages of the experiment and yield after removal of the backbone.*

	Thawing method			
	Traditional	**RSW- thawing**		
Aimed final temperature	0-2°C	1,0°C	-0,5°C	-1,0°C
Actual final temperature	5,2°C	0,6°C	-0,3°C	-0,8°C
Weights prior to thawing	393 kg	397 kg	388 kg	393 kg
Weights after thawing	402 kg	403 kg	396 kg	399 kg
Water uptake during thawing	2,3 %	1,5 %	2,1 %	1,5 %
Weight on too cold fish	27 kg	14 kg **	-	-
Percentage too cold fish	6,7 %	3,5% **	-	-
Weight that can be split (frozen)*	366,6 kg	383,2 kg	388 kg	393 kg
Weight after splitting	341 kg	361 kg	370 kg	383 kg
Overall yield	**93,0 %**	**94,2 %**	**95,4 %**	**97,5 %**
Losses	**7,0 %**	**5,8 %**	**4,6 %**	**2,5%**

*) – This is the weight of thawed raw material minus the weight of the fish that was too cold to be split, adjusted for the water uptake during thawing. The yield and losses are related to the frozen weight (bought weight).

**) – These 14 kg could not be mechanically split because of weak tales, and not because of wrong temperature.

In figure 5.18 it becomes clear that it is important to control the product temperature prior to removing the backbone (splitting) of cod.

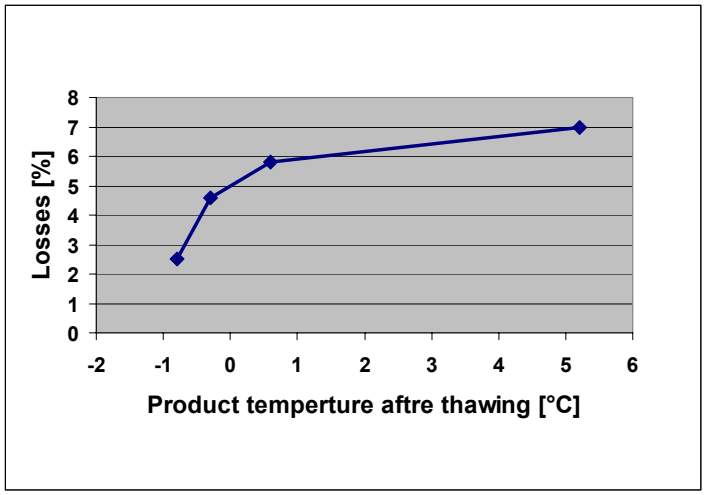


Figure 5.18 *Total losses after the backbone has been removed from the cod in clip fish production, depending on product temperature.*

The company inspected all the batches and concluded that the coldest RSW batch was split as it should (the low loss was not due to remaining parts of the backbone). In addition they judged the visual quality to be best for the fish thawed towards –1°C.

Figure 5.19 *Better colour and reduced gaping on the fillet thawed towards –1°C (right)*

The differences in visual quality are shown in Figure 5.19. The left fillet has much gaping, and seems a bit greyer than the right fillet. The left fillet had been traditionally thawed and had a temperature of 4.2°C when the picture was taken. The right fillet was thawed towards –1°C and had a temperature of –1,1°C.

Yield and quality for final product

As mentioned the company followed the product during the rest of the production process. All the stages from where we left them and until the final product contain sources of error, but the numbers will never the less indicate the effect of different thawing methods and temperatures. The different yield and fraction of 2nd class clip fish are given in Table 5.11.

Table 5.11 *Final yield and quality on the finished clip fish*

Method and temperature	Yield after drying	2nd class
	[%]	[%]
Traditional 5,2 °C	56,5	12,1
RSW towards 1°C	55,9	5,4
RSW towards –0,5°C	58,0	5,3
RSW towards -1°C	60,8	12,6

The yield was higher as the thawing temperature was reduced. This indicates that the increased yield after splitting not only was based on less loss of water during the mechanically load imposed by the splitting equipment. A colder product must also have given a cleaner cut along the backbone, leaving more of the fillet on the final product. Why the coldest fish had a higher fraction of 2nd class than the other RSW-batches is not clear, but it is likely that it has happened somewhere after the splitting process. Whether it has taken place because of the low temperature and ice content in this batch is difficult to say.

There were no differences in the final colour of the different batches.

Other experiments confirming the findings

At a later stage an extensive and confidential research project concerning the effect of the thawing process on the final product in clip fish production was carried through for another company [ref. SINTEF Report TR F5132]. The findings in this project support the results given in this chapter. The RSW thawed cod on average resulted in 1.5% higher yields on the final product, and the visual quality in terms of gaping was improved. There were no differences in colour.

5.8.3 Conclusion – thawing of cod in clip fish production

Controlled thawing in clip fish production offer benefits in terms of higher yield, and better quality. The product temperature should be just below the initial freezing point of the product. Normally this means that the product temperature should be approximately –1°C. A better temperature distribution can be achieved by splitting the blocks as early as possible

and by providing sufficient circulation. The result does not give any answers whether it is possible to reduce the overall thawing time. Even if it was not found in this study, it is likely that if the cod gets too cold, the yield will be reduced as a result of bad cutting. The knives will at some point not work as supposed, and parts of the backbone will be left on the fillets.

5.9 Effect of thawing on cod for filet production

Frozen fillet constitutes for 33% of the value of Norwegian lean fish export (Table 5.1). Cod is the most important raw material for this product.

Also this industry has increased the use of frozen raw material, and the thawing has been done as described in Chapter 5.6 and the previous chapter.

5.9.1 Focus and method

The goal for this sub-Chapter is to as far as possible identify an optimum processing temperature for a production process for fillets. In addition investigations are made in order to unveil if it is possible to reduce the overall thawing time.

The raw material

For identification of optimum processing temperature 24 blocks of Japan cut cod, 25 kg each, were used. Japan cut means that the neck bones are removed prior to freezing, this means that the yield from the production facility on shore will be higher than when normally cut fish is processed. The size of the fish was 1-3 kg.

For evaluating the effect of overall thawing time 48 blocks of normally cut cod, 25 kg each, were used. The size of the fish was 1-3 kg.

The experimental set up

The controlled experiments were conducted in the RSW (Refrigerated Sea Water) equipment described in Chapter 3.6.1, whilst the reference experiments were conducted in air blast thawing tunnel. In order to secure high temperatures in the first stage of thawing, an electrical heater (12 kW) was installed in the RSW unit.

Temperatures were monitored by the means described in Chapter 3.4.1. Temperatures were recorded every 2 minutes.

All weights prior to cutting were measured by one of the company's own pall weight (± 0,5 kg). Weights after cutting and trimming were collected with a Marcell M-2000 Serie (!20 g). Initial net weights, and weights after each step were recorded. BADER 417 and BADER 184 were respectively used for neck cutting and filleting.

Experiments

The RSW thawing was conducted in similar manner for all experiments. During the first stage of thawing, the thawing media temperature was kept at 15°C. This temperature was

kept for 3-4 hours. After this the blocks were split, and the set point for the thawing media was changed to desired levels.

After thawing the product was processed. Weights and temperatures were recorded until after the trimming. The product was not followed further through the production process.

Optimal processing temperature
200 kg raw material were used in each batch. During three different thawing experiments in the RSW unit it was thawed towards –1,5°C, -0,8°C and 0,5°C. The overall thawing time was kept at approximately 8 hours. In addition a reference thawing in the company's own air blast tunnel was done.

Possible reduction of thawing time
There was not made any reference experiments during this study. During three different thawing experiments in the RSW unit it was thawed towards –1,2°C, -0,8°C and 0,5°C. 400 kg raw material were used for each of these temperature levels. Respectively 3, 5 and 7 hours after the blocks were split approximately 135 kg were processed.

Comments regarding the experiments

The experiments were carried through over 2 shifts, making it impossible to use the same operators for filleting and trimming in each experiment.

The nature of the RSW temperature regulating means made it difficult to reach the desired temperatures.

It is also important to be aware that the RSW unit is regulated by feedback from one thermocouple; the continuous temperature recording during thawing is done by another set of thermocouples, and finally the manual temperature measurements were done with yet another thermocouple. All these equipments have an error margin, and might not give the same value, if measuring the same object. It is therefore important not to draw any ambiguous conclusions based on measurements carried out with different equipment.

5.9.2 Results

Optimal processing temperature

The temperatures after thawing for the different experiments are given in Table 5.12

Table 5.12 *Cod core temperatures after RSW thawing towards 1,5°C, -0,8°C and 0,5°C, and after thawing in air blast tunnel*

Temperature	RSW thawing towards - 1,5°C	RSW thawing towards –0,8°C	RSW thawing towards 0,5°C	Thawing in air blast tunnel
Average	-1,1°C	-1,1°C	-0,4°C	13,8°C
STDEV	0,2°C	0,2°C	0,8°C	1,7°C
Maximum	-0,9°C	-0,7°C	0,7°C	16,0°C
Minimum	-1,5°C	-1,5°C	-1,2°C	10,7°C

The core temperatures for RSW thawing towards –1,5°C and –0,8°C are very similar. For the latter, the figures given in Table 5.12 seem only to valid for the product core, whilst the figures seemed valid for the whole product thawed towards –1,5°C. During thawing towards –1,5°C ice has been kept/formed within the whole product, whilst during thawing towards –0,8°C most of the internal ice has melted, leaving some ice left only in the product core. It is natural to assume that the initial freezing point of the raw material used in this study was between –0,8°C and –1,1°C. The temperatures for the batch thawed in the air blast tunnel, speak for themselves.

Figure 5.20 shows the yield after trimming for the different thawing methods and temperatures. The yield is related to the frozen weight.

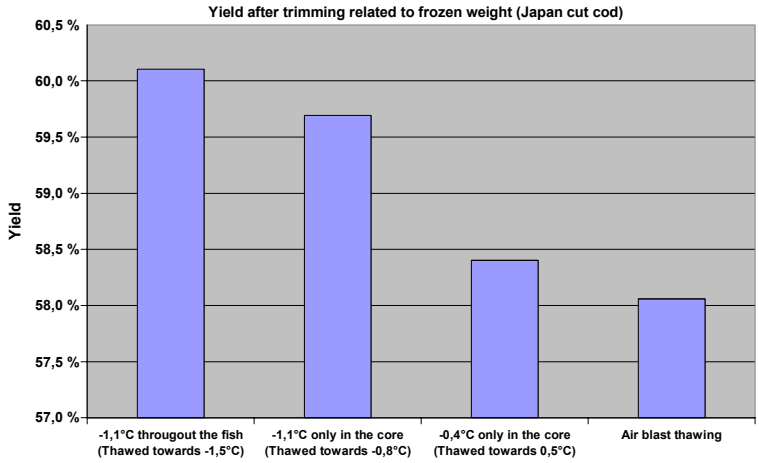


Figure 5.20 *Yield after trimming of thawed Japan cut cod.*

It seems like it is possible to increase the yield after trimming with at least 1,5% if thawing is done controlled and towards the optimum temperature. In this case it looks like the

optimum value would be close to –1,1°C. The potential profit based upon an optimum thawing, seems less for fillet production, than for clip fish (Chapter 5.8) production.

Figure 5.21 shows the development of the product temperature during filleting and trimming. The temperature in the surroundings was approximately 15°C. The batch thawed towards –1,5°C virtually does not change during the 30 minute long processing. The temperature of the batches thawed towards –0,8°C and 0,5°C increases respectively 0,5°C and 1,5°C. For the batch thawed in the air blast tunnel, only small changes take place, since the initial temperature was so high.

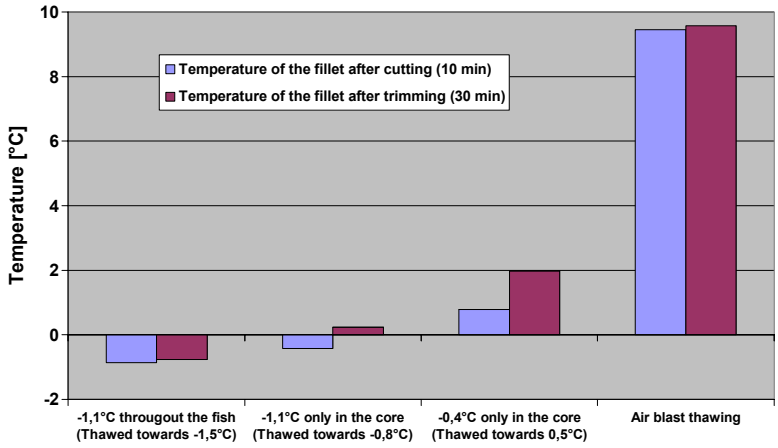


Figure 5.21 *Temperature development during filleting and trimming for RSW thawed and Air blast thawed cod.*

Thawed towards -1,5°C Air thawing

Figure 5.22 *The trimmed fillets after thawing. RSW thawed towards –1,5°C vs. Air blast thawed product.*

Figure 5.22 illustrates the differences in visible quality after trimming depending on different thawing methods.

Possible reduction of thawing time

The controlled thawing process in Chapter 5.8 was as time consuming as the traditionally methods. The RSW thawing process used in the previous sub-chapter used 8 hours less than these methods, that is - the overall thawing time was 8 hours. This was achieved by reducing time both for the block splitting stage (i.e. the thawing media temperature was increased) and for the equalizing stage. This sub-chapter looks into the effects of reducing the equalizing stage.

Due to the indications in the previous sub-chapter, that the optimal processing temperature would be around –1,1°C, we decided to thaw towards –1,2°C instead of –1,5°C. The temperatures during this thawing are shown in Figure 5.23. The curves show the thawing media temperature at various locations in the thawing vessel during the first 200 minutes. From there on they show temperature developments of single fish. During the first 200 minutes the thawing media temperature was supposed to be kept at 15°C, the electrical heater did however not manage to supply enough energy during this stage, and the average temperature for the cod blocks was approximately 10°C. The three different times of processing are also shown.

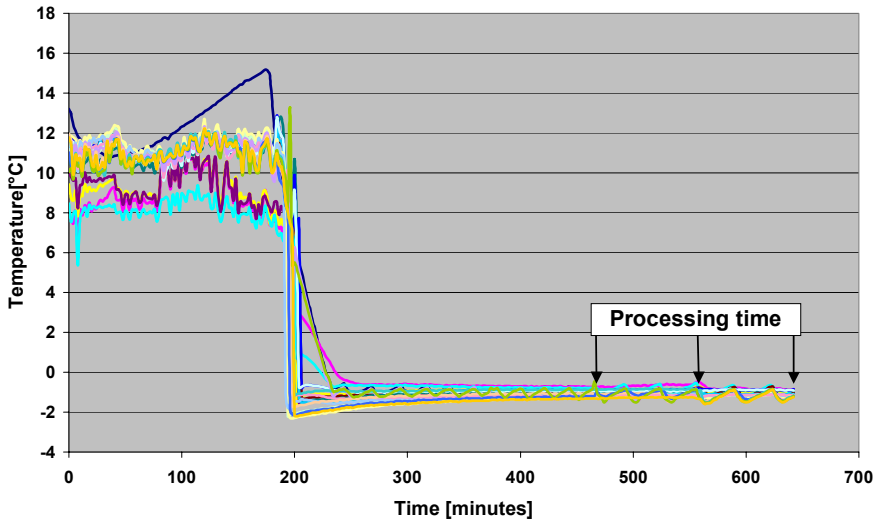


Figure 5.23 *The temperature development during thawing towards –1,2°C. The three different processing times are shown.*

The cod core temperatures after the RSW thawing towards –1,2°C, -0,8°C and 0,5°C are given in Table 5.13. As the time at the equalizing stage increases, the spread decreases for all three experiments. For the product thawed towards –1,2°C the temperature is increasing

towards –1,0°C, whilst the temperature for product thawed towards 0,5°C is increasing towards 0,3°C during the equalizing stage. The product thawed towards –0,8°C seems to stabilize at –1,0°C.

Table 5.13 *Cod core temperatures after RSW thawing towards 1,2°C, -0,8°C and 0,5°C depending on how long the product has stayed in the equalizing stage*

Temperature	RSW thawing towards - 1,2°C [°C]			RSW thawing towards –0,8°C [°C]			RSW thawing towards 0,5°C [°C]		
	Approximate time in equalizing stage								
	3h	5h	7h	3h	5h	7h	3h	5h	7h
Average	-1,4	-1,1	-1,0	-1,0	-0,9	-1,0	-0,2	0,2	0,3
STDEV	0,2	0,2	0,2	0,4	0,3	0,2	0,6	0,4	0,3
Maximum	-1,3	-0,9	-0,9	-0,4	-0,3	-0,7	0,9	0,5	0,5
Minimum	-1,8	-1,4	-1,3	-1,4	-1,3	-1,3	-1,2	-0,8	-0,4

Figure 5.24 shows the yield development for the desired thawing temperature and actual process time. The yields are related to the initial frozen weight. It seems like the overall thawing time should be at least 8 hours, in order to be able to maximize the yield. If the process needs more than 10 hours to achieve this, there is reason to believe that the chosen time/temperature combination during thawing and equalizing is not optimal.

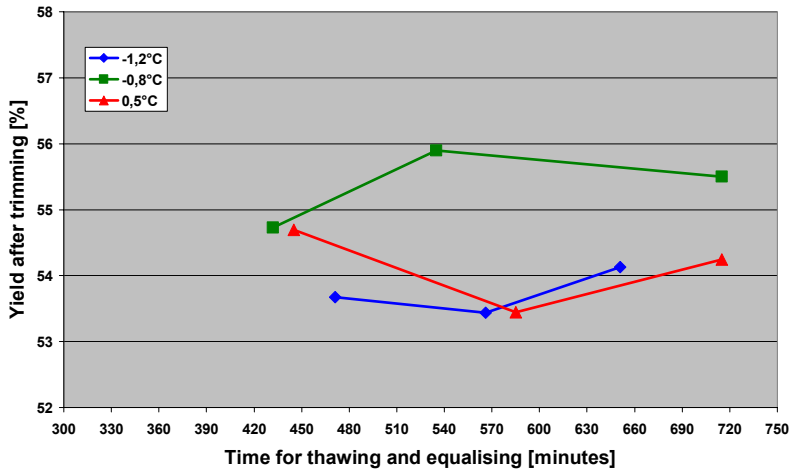


Figure 5.24 *Yield development after trimming, depending on aimed thawing temperature and actual process time. All yields are related to frozen weights.*

The product thawed towards –0,8°C resulted in the highest yields throughout the process. After 9 hours of overall process time, this batch gave approximately 1,5% higher yield than the other two batches. The most surprising result was that the experiment designed to give the highest yield, actually was far from it. The batch thawed towards –1,2°C gave similar or less yield as the batch thawed towards 0,5°C. If the average yield for the three different temperature levels is studied (Figure 5.25), and this information is combined with the product temperatures given in Table 5.13, it can seem like there have been too much ice left in the batch thawed towards –1,2°C. The product was simply too cold. The raw material used in these experiments must have had a slightly higher initial freezing point than the material used in the previous sub-chapter (Optimal processing temperature), or it can be a result of the error margins in the equipment for temperature measurements.

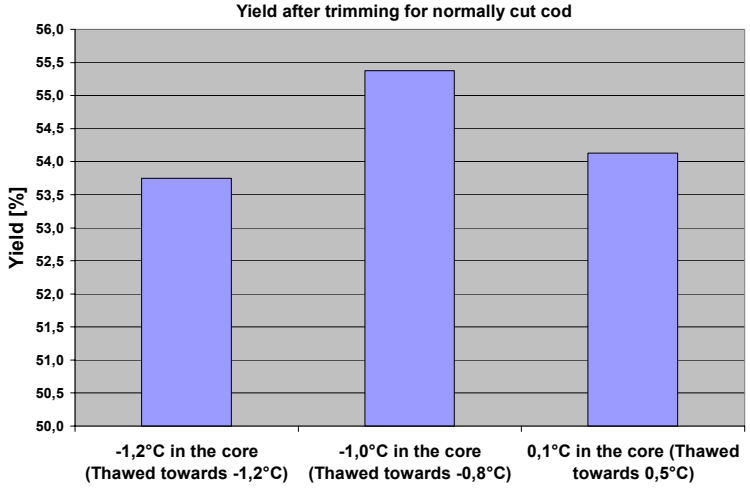


Figure 5.25 *The average yield of the three different temperature levels studied.*

5.9.3 Conclusion – thawing in fillet production

Controlled thawing in fillet production offers benefits in terms of higher yield, and better quality. The product temperature should be just below the initial freezing point of the product. Normally this means that the product temperature should be approximately –1°C. It is however clear that the margins are narrow in this temperature region, and that too low temperatures will reduce the yield. Products containing a small amount of internal ice after thawing, will give higher yields and experience lower temperatures during filleting, trimming and grading. The required energy for refreezing will therefore be reduced, thus increasing the capacity on the freezers. The reduced product temperature during processing will also reduce the risk for microbial contamination. It seems possible to reduce the overall

process time for thawing down to 8 hours without compromising the yield or quality, at least for blocks of 1-3 kg cod.

5.10 Industrial Cod thawing – status

After year 2000 several new thawing solutions/equipments have been introduced by the equipment industry. All these solutions are variations around one principle: One large fixed thawing tank instead of many small. They all differ in the way product is brought to and from the tank, and how the internal transport in the tank is solved. The new solutions all offer reduced running and indirect costs (labour, trucks and space). As far as I know they all represent batch or semi-batch solutions. Unfortunately they do not solve the thermal related problems that limited the traditional thawing methods. The thermal aspect discussed throughout this chapter, will still be valid (with minor modifications) for the new type of equipment.

The greatest challenges related to thawing in these types of equipments are:

- To control and accurate regulate the thawing media temperature.
- To avoid that the blocks are freezing together during the first stage of thawing.
- To secure an effective flow pattern that is suitable for all stages during thawing.
- To avoid wear and tear in handling/thawing.
- To deal with partial load in the thawing tank.
- To deal with the fact that it takes a long time to fill these tanks with frozen product – the first blocks have often been thawing for several hours, when the last block is introduced.
- To secure and take full advantage of the potential in a perfectly thawed product.
- To identify the perfectly thawed product for the overall production process.
- To develop instructions and routines that secure effective thawing and learning.

In other words: The challenges of industrial lean fish thawing are by far solved. The work presented partly in this Chapter, should however find a solid base for meeting the remaining challenges.

5.11 Conclusions – Industrial thawing of Cod

During thawing of block frozen fish, the physical size and geometry of the blocks introduce a larger spread in temperature distribution. In order to minimise the effect of this, it is important to split the blocks as early as possible.

The most important factor for the splitting time of frozen cod blocks is thawing media temperature. Salt content in thawing media is increasingly important at lower thawing media temperatures and if the blocks are very cold when they enter the thawing process. Level of agitation is also increasingly important as the thawing media temperature decreases. For thawing processes where the different blocks will have the possibility to freeze together, all these three factors will become increasingly important. For thawing in other media than water/brine (i.e. air), both salt content and level of agitation is out of the question. Thawing

media temperature will however still play the most important role in reducing the process time prior to splitting of the cod blocks.

The nature of the rest of the thawing process, as soon as the blocks are split, depends on the amount of energy transferred to the product during the splitting stage, and the desired product temperature after thawing. The rest of the thawing process can be heating, cooling or equalising, dependent on these other factors.

Controlled thawing applied in clip fish and fillet production offers benefits in terms of higher yield, and better quality. The product temperature should be just below the initial freezing point of the product. Normally this means that the product temperature should be approximately –1°C. It is however clear that the margins are narrow in this temperature region, and that too low temperatures will reduce the yield. Products containing a small amount of internal ice after thawing, will give higher yields and experience lower temperatures during filleting, trimming and grading. The required energy for refreezing will therefore be reduced, thus increasing the capacity on the freezers. The reduced product temperature during processing will also reduce the risk for microbial contamination. It seems possible to reduce the overall process time for thawing down to 8 hours without compromising the yield or quality, at least for blocks of 1-3 kg cod.

New thawing methods have during the last years been introduced, but do unfortunately not take into account the thermal challenges of the traditional methods. The work carried out in this chapter should therefore still represent a solid basis in order to meet the challenges related to the new thawing solutions.

6 Thawing of pelagic fish – Mackerel

6.1 Introduction – volume and value

Atlantic Mackerel is caught from April to November in the North Sea and Skagerrak. Approximately 340.000[7] tons were landed in Norway in 2001; Norwegian fishers caught approximately half of this. After the catch the mackerel is usually stored in tanks with refrigerated seawater (RSW). These tanks are dimensioned to cool a certain amount of mackerel down to approximately -1°C on the way back into the landing facilities. There are large spread in the quality of catches from the same area, depending on catching method, vessel and crew. This is obviously partly due to differences in the RSW equipment and tank arrangement, and most likely also a result of different practice in how the catch is treated from it is taken out of sea until it is landed. Crucial parameters could be time from handling of catch until the fish is transferred to the RSW tanks, and the actual ratio between fish and RSW in the tanks. At the landing facility the fish is checked, graded and packed in cardboard boxes containing approximately 20 kg mackerel each. The boxes are then frozen in air blast tunnels. Depending on the tunnel arrangement the freezing either starts as soon as one section of the tunnel is filled up or after the entire tunnel is filled. The goal of the freezing plant is usually to fill up, freeze and empty a tunnel during 24 hours. The typical freezing time varies from 16 to 20 hours. These times will for high quality catches be sufficient to preserve the initial excellent quality. The largest problem for the preservation of the quality is the storage temperature and time. Today the temperature in most of the commercial storages is below –30°C. The quality of the product would most likely benefit a lot from being stored at temperatures below –45°C [63]. This is economical and technical possible today.

6.2 Domestic vs. export

The frozen mackerel is mainly exported, but some of it is sold domestic to processing plants that make canned mackerel or fillets for export. In 2001, the overall export value for Mackerel was 2.9 billion NOK, 96% of this was frozen whole mackerel. The domestic processing of mackerel is mostly made from frozen products in order to get a predictable production and to utilise the process equipment better. This means that the thawing process is a very important process in the overall processing lines. The largest markets for frozen mackerel are Japan, China and the eastern European countries. How the thawing of the

[7] SSB

mackerel blocks are conducted vary, depending on what the further processing steps are (mechanical cutting equipment usually demands more control), and in which market it is sold. In general one could say that the thawing is done in batches with little or no control. Thawing in air or by water immersion are the most common techniques.

6.3 Aim of the study

When looked at ideally and from a Norwegian point of view, we should process as much as possible of the mackerel catches in Norway and preferably close to the landing site. This is due to:

- **Higher profit** - if more of the value chain is kept within Norway, it results in a higher cash flow that secures more jobs and higher profit (not necessary higher profit margins).
- **Less transport costs** - the fillets are only approximately 60% of the mackerel.
- **Environmental issues** - savings in transport costs mean reduction in transport environmental impact.
- **Better utilisation of the waste** - instead of spreading the 40% waste all over the world, it can be taken carefully care of as a resource and utilised in feed production (Figure 6.1).

There is however not a large industry for processing mackerel in Norway. If we look at fillet production there are only a few factories. The reason for this is not one single factor, but one very important issue is the risk involved in trying to sell the fillets instead of the well-known whole mackerel. A list of issues in disfavour for processing whole mackerel into fillets, are:

- **Costs** - it is regarded labour intensive.
- **Safety/ Storage life** - once the mackerel has been cut open, it is less protected against dehydration, oxidation, bacterial growth and other kinds of contamination.
- **Flexibility** - the fact that you have fillets on storage reduces the possibilities you have for further processing of the raw material.
- **Technical** - because of its soft texture in unfrozen state it needs special attention/ carefully treatment prior to the mechanical cutting (filleting). Good temperature control is imperative [59].
- **Market** - in all business one has to produce the product in demand.

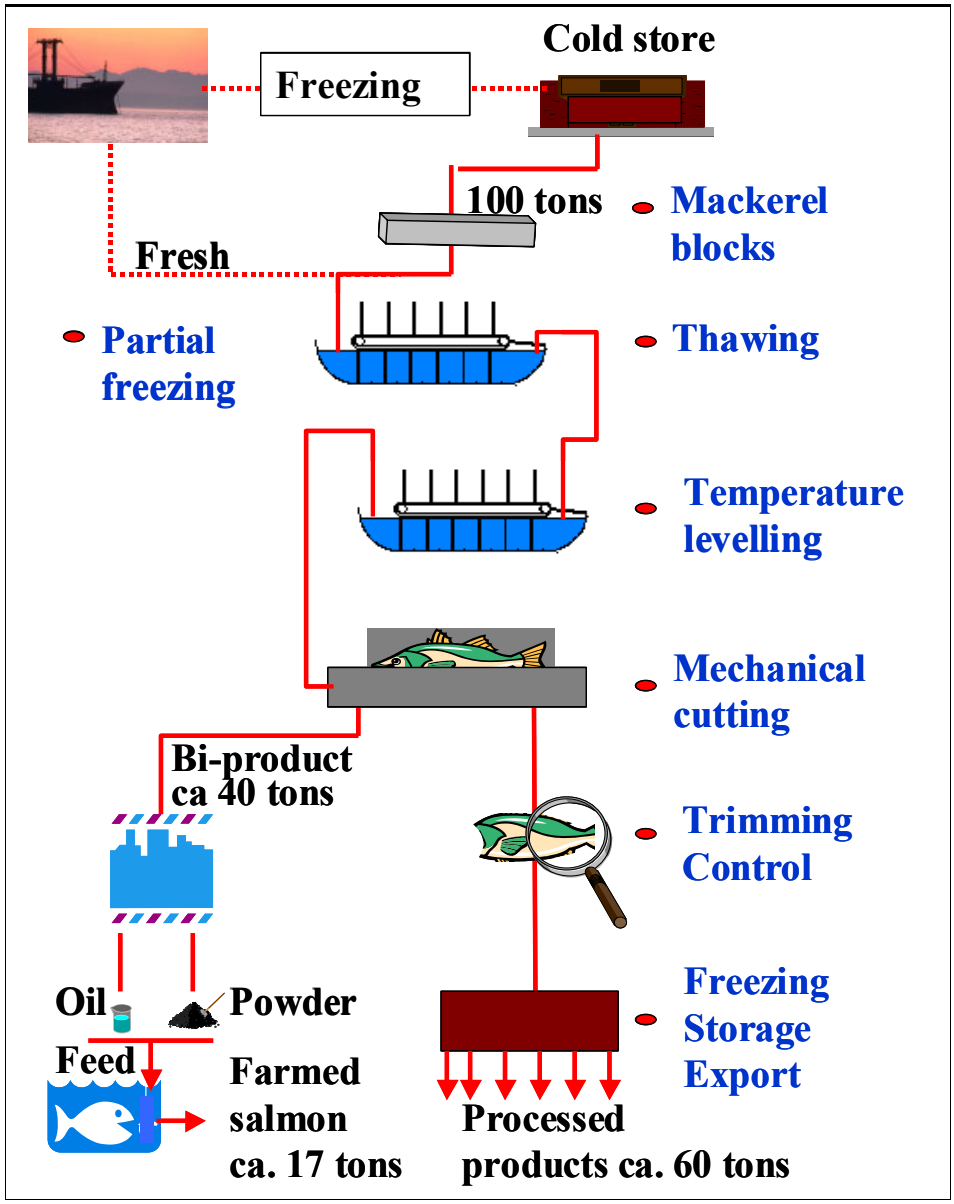


Figure 6.1 *Better utilization of waste in mackerel value chain. Adjusted after* Magnussen [64].

The factories that in spite of all this have chosen to produce fillets must have overcome or found a way around these obstacles. Presumed that the impact on safety/storage life and flexibility are given, and assumed that there is a market for the fillets, the companies have

had to find solutions to the costs and technical issues. The fact that the factories have chosen different strategies in their production planning including technical solutions illustrate that there is not only one way to deal with the challenges. The different strategies have been:

1. **The batch approach**, where mackerel is fed into large tanks filled with refrigerated seawater /brine. The refrigeration/heating (depending on whether the factory is producing from fresh or frozen raw material) capacity is dimensioned in such a way that the temperature of both brine and product very slowly approaches the desired level, and the production can start.
2. **The continuous approach**, where the raw material is continuously fed into the thawing/tempering equipment and meats its desired temperature level just as it reaches the end of this equipment.

Benefits of the batch approach is that it is easier to get a homogeneous temperature in the raw material, and the fact that the thawing/tempering process does not need to be fine tuned to the rest of the production line, since the tank is literally a buffer. Benefits of the continuous approach is that it represents a major reduction of inventory in the production line and thus reduces the economical risks if one has to shut down the production for a longer period. It can also give an improved flexibility. The size of the equipment will also be less than for the batch approach, and the fact that the production time from start of thawing/tempering until the finished product is back in the storage is minimised, also represents an improved safety factor. Labour cost and indirect costs like trucks are usually decreased. However the continuously approach means that the thawing/tempering has to be fine tuned to the rest of the production process, and that it needs to be continuously controlled either automatically or manually.

Considering these issues, it is easy to understand that companies that followed the continuously approach had a need for assistance and great interest in a project that looked into thawing of mackerel blocks in a controlled continuously line. Such a project also represented a bigger challenge for both the equipment producers and the researchers.

The main aim of the study regarding thawing of mackerel was to develop a new continuously and controllable thawing process that provided raw materials with optimised temperature for the further processing steps regarding:

- yield,
- visual quality,
- overall capacity, and
- temperature profile of the product throughout the production process.

The work was divided into five steps:

1. Documentation of temperatures in the present process and identification of critical points. (Chapter 6.4)
2. Evaluation of means to automatically split the blocks as soon as possible - the first stage of the thawing. (Chapter 6.5)
3. Definition of optimum product temperature after thawing - the last step of thawing. (Chapter 6.6)
4. Definition and full scale simulation of new thawing process. (Chapter 6.7)
5. Considerations and results related to a new, implemented process. (Chapter 6.8)

6.4 Documentation of temperatures in a continuously thawing process at a mackerel fillet processing plant

Thawing is one of several necessary operations in a mackerel processing plant. Figure 6.2 gives a schematic overview of these typical operations and in which order they appear. The overview also describes how the production layout was at the industry site involved in this project. The Mackerel is treated as a bulk until the blocks are manually split during the thawing (or until the end of thawing). From that point each mackerel is treated and handled as a single object until the fillets are packed in cardboard boxes and transported to the sales storage. The goal of this chapter is to describe how continuous thawing of mackerel was done until researchers, equipment producers and the industry itself joined their efforts and decided to solve the most important challenges for this production. The chosen thawing process is described and documented.

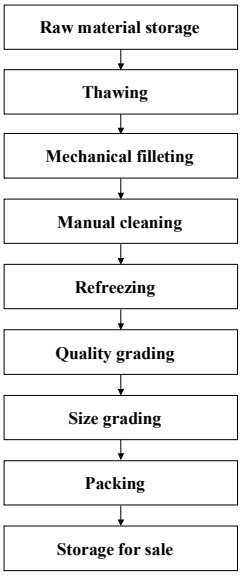


Figure 6.2 *An overview of a typical mackerel processing plant.*

6.4.1 Description of the initial thawing process

The initial thawing process itself is illustrated in more detail in Figure 6.3. Blocks of frozen mackerel were used as raw material for producing the fillets. The nominal weight of the blocks was 20 kg. After removing the cardboard boxes and the plastic sheets, the blocks were fed into the thawing equipment.

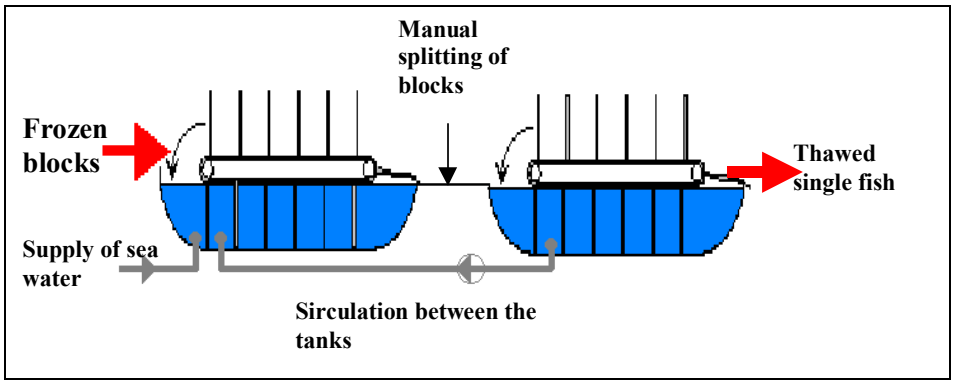


Figure 6.3 *Illustration of the initial thawing process.*

14 blocks of frozen mackerel were normally fed into each chamber. The blocks had an average temperature of -18°C as they were fed into the first chamber, and also contained a significant amount of frozen blood-water (approximately 0.6 kg in each block). The lead-time through the first tank was approximately 70 minutes. The temperature of the thawing water was controlled by the cooling capacity of the blocks and the amount of clean seawater supplied from a dept of 12 meters in the harbour.

The circulation line between the tanks secured equal temperature in both tanks. The blocks were manually split after they were automatically lifted out of the first tank. The second tank had a shorter lead-time, approximately 30 minutes. This means that it was only half as much mackerel in each chamber in the second tank as in the first tank.

The seawater intake was not at a sufficient dept, resulting in a highly varying seawater temperature during the year (even from day to day). This lead to difficulties in regulating the thawing temperature, and blocks freezing together into even bigger blocks was a major problem during the winter.

The desired product temperature after thawing was between -2.5°C and -4.0°C. The total capacity of the production line with this thawing practice was between 7 and 10 tons of raw materials, each day. The refrozen fillets can be divided into two classes: class 1 and 2. Class 1 is fillets of superior quality, while class 2 has one or several characteristics that do not meat the customers' demands for a class 1 fillet. The company stated that class 2 fillets on average constitute for approximately 3% of the net production.

6.4.2 Methods and measurements

The focus of the investigation was to document the thawing media temperature, and the product temperature throughout the production process. The air temperatures in the belt freezer were also recorded.

Thawing media temperature

Thermocouples were attached to the moving chamber wall, at different depths. The temperatures were logged every fifth minute as the chamber wall moved through the tanks. The chamber wall moved one position every twelfth and fifth minute in the first and second tank, respectively. The logger was a Fluke 2625A Hydra data logger (described in Chapter 3.4.2).

Product temperature during thawing

Measurements were conducted manually with an ANRITSU Antritherm with probe (described in Chapter 3.4.2). The probe was placed and the temperatures were recorded both at a depth of approximately 2 cm in the thickest part of the mackerel, and at a depth of approximately 1 cm in the thinnest part of the mackerel (tail). This was done for 10 fishes before start of thawing, in the middle of tank 1, after tank 1, in the middle of tank 2 and after tank 2. The procedure was repeated three times. For the frozen blocks, a drilling machine was used to get the probe into the fish.

Product temperature after thawing:

After filleting, temperatures were measured (same equipment as above) for 20 fillets in three different categories:

- class 1 fillets (Denoted **Class 1**),
- fillets with clear signs of breakage (Denoted **Breakage**) , and
- fillets that were very soft (puree like structure) and had a lot of gaping (Denoted **Soft/Paste**).

The temperatures were measured in both the thickest and thinnest sections of the fillets, at a depth of approximately 5 mm - 8 mm. Measurements were made both directly after the filleting machine and right in front of the belt freezer.

Product temperature during re-freezing:

The belt freezer has two parallel belts. Core temperatures for three fillets on each belt were collected each third minute during the re-freezing. Loggers of the type Tinytalk and Monolog were used. These loggers have one channel and use internal or external probes. They can normally operate down to –30°C with an accuracy of ± 0,6°C.

Air temperatures through the belt freezer:

Three temperature loggers of the type Tinytalk were placed on one of the belts and sent through the freezer.

6.4.3 Results

Thawing media temperature

Thawing media temperatures in the tanks are shown in Figure 6.4 and Figure 6.5. During the first 20 minutes the blocks were fed into the first chamber in tank 1, and the thermocouples had not yet been immersed into the thawing media. The last measurements in tank 1 (after 65 minutes) are made as the chamber wall has lifted the blocks out of the first tank.

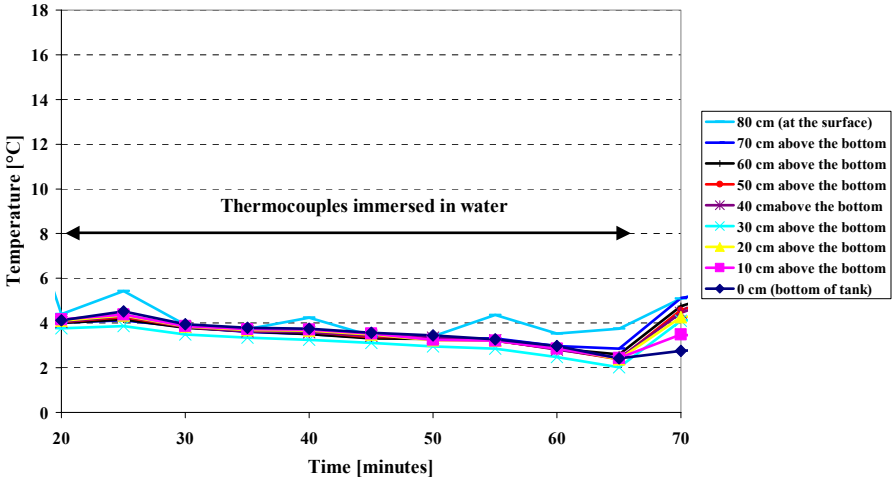


Figure 6.4 *Temperature of water in thawing tank 1 during thawing. The different times represent also different locations through the tank.*

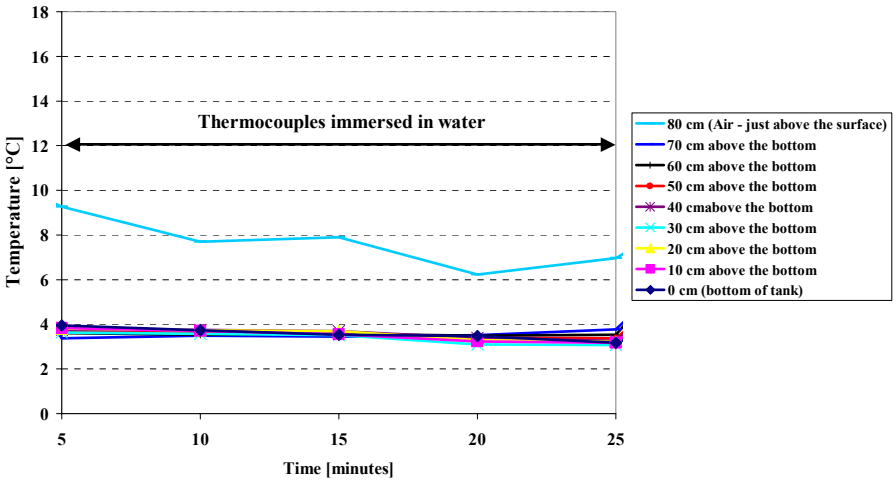


Figure 6.5 *Temperature of water in thawing tank 2 during thawing, after splitting of the blocks. The different times represent also different locations through the tank.*

There are no differences in temperature at different depths (the "surface" temperature in tank 2 is just out of the water and is therefore kept out of the discussion). In tank 1 the

temperature falls from approximately 4°C at the beginning of the tank down to just above 2°C at the end. The blocks are then manually split before they are fed into tank 2. The temperatures in this tank are constant just below 4°C throughout the tank.

Product temperature during the original thawing

The development of the product temperature during thawing is given in Figure 6.6 and Figure 6.7. The temperature increases rapidly immediately after immersion in tank 1, until a major part of the ice content of the product starts to melt. From this point of, the product temperature is rising slowly. From Figure 6.7 we see that most of the ice at a depth of less than 1 cm into the product has melted at the end of the thawing process. A more detailed description of the temperature development during thawing with the initial process is given in Appendix IX.

These data show that when the mackerel blocks are thawed in the initial thawing equipment (described in Chapter 6.4.1) large variations in product temperature within each fish and from fish to fish, will take place. This means that even if the original equipment could be tuned to get the desired average temperature prior to filleting, large parts of the raw material will have unfavourable temperature, resulting in production problems and lower final quality.

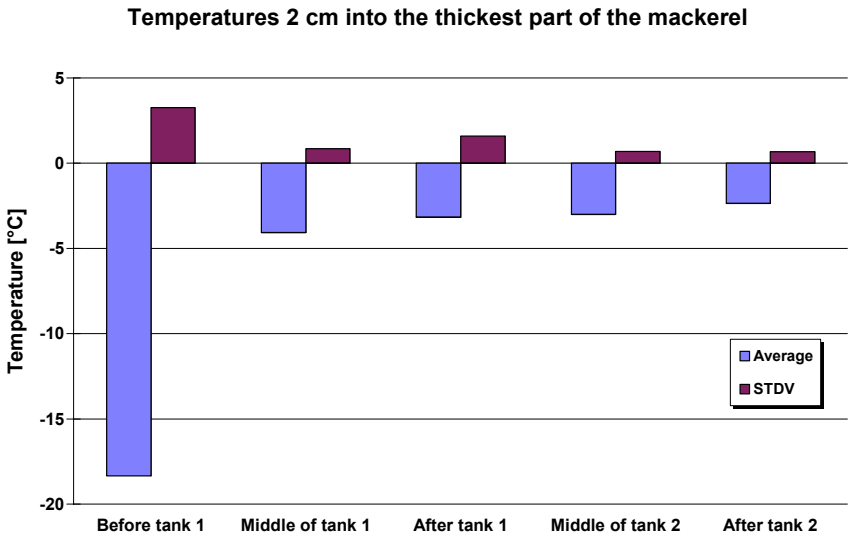


Figure 6.6 *Temperature developement 2 cm into the thickest part of the mackerel during thawing. The average temperature and standard deviation are shown for the different positions throughout the the thawing process.*

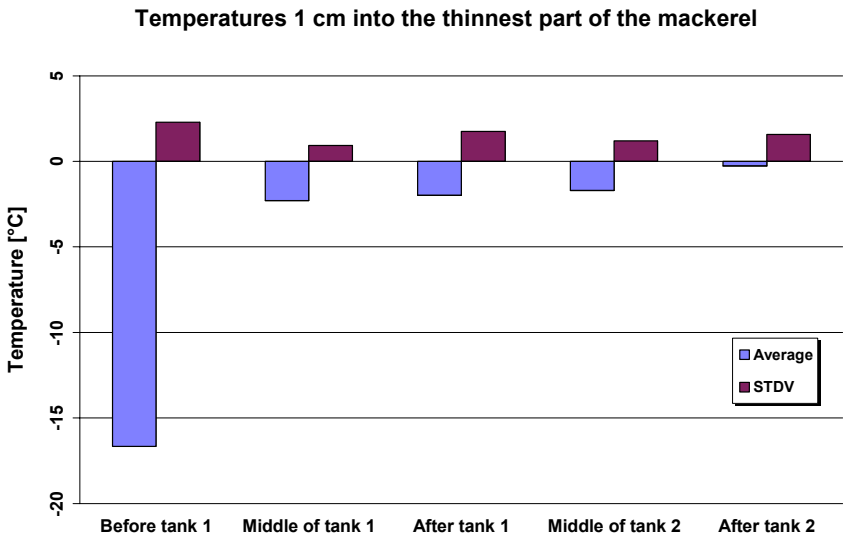


Figure 6.7 *Temperature development 1 cm into the thinnest part (tail) of the mackerel during thawing. The average temperature and standard deviation are shown for the different positions throughout the thawing process.*

Product temperature after thawing

Table 6.1 shows product temperature measured in both the thickest and the thinnest part of the fillets, at two different stages in the processing steps; after mechanical filleting (before manual cleaning) and just in front of the belt freezer (after manual cleaning). The different categories are explained in Chapter 6.4.2. The Class 1 fillets have a lower and more even temperature than fillets with soft/paste like appearance. The data for the 'Breakage' fillets are quite similar to those of the Class 1 fillets, and is probably the result of mackerels with right temperature but bent (banana shaped), and the fact that breakage is more likely to occur in fish with some ice. The measurements of 'After filleting' and 'Before belt freezer' temperatures were not made consecutive on the same fillets, and the measurements can therefore not be used to analyse the temperature change during manual cleaning.

Table 6.1 *Product temperature and quality grading at two different stages after thawing: Straight after the mechanical filleting, and just in front of the Belt freezer. The categories are explained in Chapter 6.4.2.*

		Category					
		Class 1		Breakage		Soft/Puré	
		T_{thick} [°C]	T_{thin} [°C]	T_{thick} [°C]	T_{thin} [°C]	T_{thick} [°C]	T_{thin} [°C]
After filleting	**Average**	-2.0	-1.2	-2.0	-0.7	1.2	2.5
	STDEV	0.3	0.7	0.4	1.5	2.3	1.8
	Maximum	-1.3	-1.3	-1.3	4.2	5.9	5.7
	Minimum	-2.6	-2.4	-2.5	-1.9	-2.7	-0.7
Before belt freezer	**Average**	-1.8	-1.1	-1.8	-1.2	0.1	2.6
	STDEV	0.4	0.3	0.5	0.3	2.0	0.9
	Maximum	-1.0	-0.6	-0.8	-0.7	5.3	4.1
	Minimum	-2.6	-1.6	-2.4	-1.9	-2.6	1.2

It is reasonable to assume that the temperature limits given in Table 6.1 are qualifications the fillets need in order to be judged as '**Class 1**'. This means that if the temperature of a fillet is higher than the maximum temperature for the Class 1 category, the fillet will most likely not be a superb fillet. As an example this means that mackerels with tail temperatures higher than –1.3°C, will not be judged as superb. If the normal probability plot of Figure IX.5 in Appendix IX is studied, it is clear that more than 50% of the mackerels will not lead to superb fillets after filleting. This does not add up to the company's own estimate of 3% class 2 fillets. Many of the soft/pure fillets must have been judged Class 1 after re-freezing (The re-freezing conceals some of the defects).

Product temperature during re-freezing

The plant had two parallel belts. The curves for product temperature given in Figure 6.8 represent different fillet sizes and positions on both belts. All the fillets used exactly the same time on their way through the freezer, and the differences given below in how long the temperature was monitored are only due to the use of too long logging intervals (3 min). It is obvious that the product at the end of the freezer did not meet the desired temperature of –25°C. The result would be that the fillets would have to be given the right temperature after packing, in the intermediate production storage, or even worse in the transport container on its way to the customer. This practice most definitely would affect negatively the product quality experienced by the customer. The temperatures of the fillets were most of the time in the latent zone, this means that the initial fillet temperature was too high (little or non of the

water in the fillets were frozen prior to the freezer), or that the capacity of the freezer was too low. The air velocity inside the air blast belt freezer had been adjusted in such a manner that the fillets should not get blown off the belt; this should mean that maximum practical heat transfer coefficient was used. The air temperature inside the freezer also seemed reasonable low (i.e. typical for such equipment).

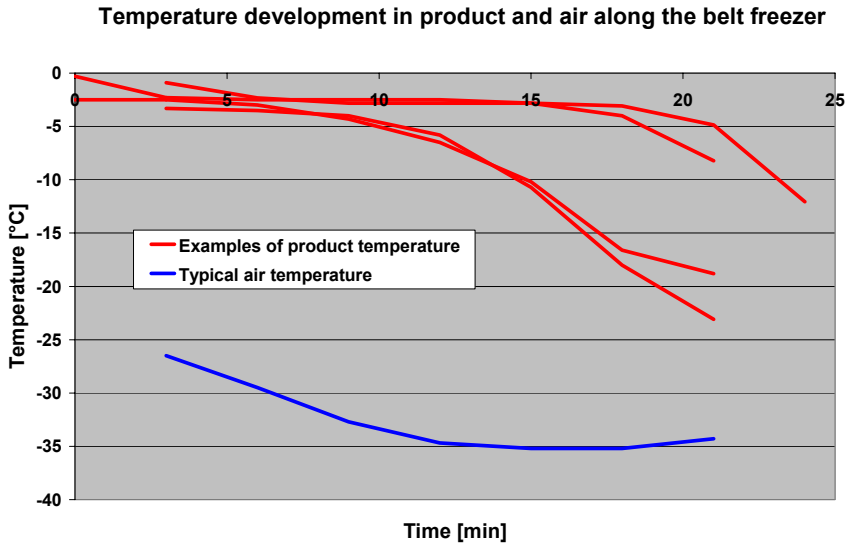


Figure 6.8 *Temperature development in product and air along the belt freezer.*

This leaves us with three options for securing that the fillet temperature meets the requirements:

1. Improve product temperature control (reduce unwanted heating, included over-thawing, of the fillets prior to the freezer).
2. Increase time in belt freezer, which either would mean larger freezer or slower belt.
3. Decrease air temperature within the freezer, in order to increase the driving force for heat transfer.

The two last options would either result in reduced overall capacity of the entire production process, or mean a need for investments. The first option could also lead to needs for investments, but it should at least be evaluated since this option seems to be focusing on the very offspring of the problems regarding quality and capacity.

6.4.4 Conclusion regarding the original process

The thawing process was labour intensive. The splitting of the blocks was done manually, and the process needed to be followed up very thoroughly. The thawed product had an average temperature that seemed reasonable, but the spread was very large, resulting in a

large fraction of fillets with low quality. Too high temperatures seemed to be a problem throughout the process. The thawing process also introduced great risk in the production process. For each unexpected pause in the production, the thawed product would be warmed up getting even further away from its goal temperature.

Based on these findings it was obvious that the thawing process was the bottleneck in the production. Temperature control of the thawing process had to be gained.

6.5 Splitting of Mackerel blocks

As concluded in Chapter 3.2.1, it is important to split the blocks as soon as possible during thawing. This would either make it possible to speed up thawing (for continuously thawing processes), or to ensure that more of the available time for thawing were spent to equalise the temperature levels amongst the single fishes (for batch thawing processes). In Chapter 5, thawing of lean fish, splitting of the blocks seemed very promising.

The work done in this sub-chapter was based on the discussions regarding thawing of blocks presented in Chapter 5.7. Since there are some differences between the blocks of Mackerel and Cod, some extra factors needed to be taken into account in this study.

The goal of this work was to investigate how different factors would affect the process time prior to splitting of the blocks. These factors were:

- Thawing media temperature (described in Chapter 5.7.1).
- The content of salt in the thawing media (brine) (described in Chapter 5.7.1).
- Amount of water in between the single mackerels in the block (described in Chapter 6.5.1).
- Pre thawing temperature of the blocks (described in Chapter 5.7.1).
- Fat content of the mackerel (described in Chapter 6.5.1).
- Different levels of agitation (described in Chapter 5.7.1)

6.5.1 Focus and methods

The raw material

30 boxes, 20 kg each, of frozen mackerel were used. The first half of the fish were from a catch containing approximately 25% fat, and the rest from a catch containing approximately 30% fat. The fish boxes/ blocks were stored in a cold store at –23°C.

The experiments - considered factors

The experiments should unveil the effect of six factors. Use of traditionally experimental design, would require minimum 64 experiments. In order to reduce the costs and time demand, statistical experimental design was chosen. This tool makes it possible by use of

statistical methods, to reduce the number of experiments without compromising the output from the experiments.

The experiments followed a plan, where the factors to consider vary between two levels, low and high (Table 6.2). In addition some experiments (centre experiments) were made, where the factors were fixed at intermediate levels.

Table 6.2 *The range of variation for the different factors.*

	Mackerel	
Factor	**Low level**	**High level**
Thawing media temperature	-1.0°C	15°C
Salt content in thawing media	3% (seawater)	19% (saturated brine)
Amount of water in blocks	No	400 gram
Pre thawing temperature of the blocks	-23°C	-10°C
Fat content of mackerel	25%	30%
Agitation*	No	Compressed air in 18 minutes**

*Agitation excessive of what was needed in order to identify a spitting time for the blocks
**18 minutes in each cycle of 20 minutes (see below)

The discussions leading to the different levels for: **Thawing media temperature, Salt content of thawing media, Pre thawing temperature of the blocks, and Agitation,** are given in Chapter 5.7.

Amount of water in blocks
Frozen blocks of fish always contain water to some extent. This water has either been poured into the packaging along with the fish, or been squeezed out of the fish during packaging, stacking and freezing. The water fills voids between the single fishes and "glue" them together. The freezing point for water can be higher than for the fish itself. This means that the water can be frozen even though the fish is thawed, and make the splitting more difficult.

The blocks of mackerel contained on average 400 gram of water. Those blocks that should get a modified amount of water were thawed in order to remove the water, and then packed, supplied with desired amount of water (0 or 200 gram) and re-frozen.

Fat content of mackerel
The fat content of mackerel naturally varies from 5% and up to 30%, depending on season and fishing ground.

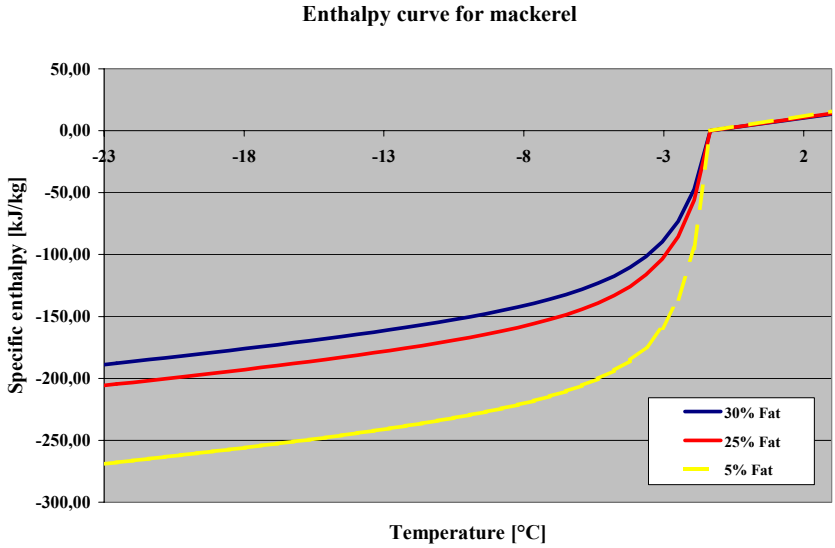


Figure 6.9 Typical s*pecific enthalpy of mackerell depending on temperature and fat content* [8].

Figure 6.9 illustrates the consequences this has on the amount of energy required for changing the temperature of mackerel from –23°C and up to –3°C (Approximately 10% more energy is needed for mackerel with 5% fat than for mackerel with 30%). It is also likely that the texture will be affected both by temperature and fat content. This would mean that optimum homogeneous product temperature prior to mechanical filleting would depend on the product fat content.

The available raw material had a fat-content in the range 25% to 30%, and represented the typical range experienced at the processing plant. As the figure shows, this relatively small range in fat content results in only minor differences in the enthalpy curves.

Experimental set up

The experiments were conducted in the RSW (Refrigerated Sea Water) equipment described in Chapter 3.6.1. The brine entered the test vessel through a perforated plate. The unwrapped block of mackerel was put into a chicken wire cage and oriented in such a manner that the largest surface of the block was perpendicular to the thawing media stream.

Identification of block splitting time

The thawing media steam around the block was not more powerful than the blocks would be kept in one piece until the entire block was thawed. In order to find a representative splitting time, a defined manual control of the block strength at given intervals was done.

The manual control procedures are described in Chapter 5.7.1 and illustrated in Figure 5.2.

Experiments

As mentioned statistical experimental design was utilised. A fractional factorial design (2^{6-2} design) consisting of 16 experiments with various combinations of low and high levels of the six factors of current interest was chosen. This specific design is a 'Resolution IV' design, meaning that it unveils the effect on splitting time, of all the chosen factors, but loses information on 2-variable interactions. In order to check the error of measurement, two centre samples for each fat level were carried out. This means that a total of 20 experiments (16+2+2) were used to unveil the effect of the six factors listed in Table 6.2.

The 20 experiments with the different combinations of the six considered factors are listed in Table 6.3.

Table 6.3 *The different levels of the six variables for the 20 experiments*

Experiment number	Pre thawing temp.	Thawing media temp.	Salt content in thawing media	Amount of water in blocks	Fat content of mackerel	Agitation
1	-23°C	15°C	19%	400g	25%	18min
2	-23°C	-1°C	19%	0g	30%	18min
3	-23°C	15°C	3%	400g	30%	0min
4	-10°C	-1°C	3%	400g	30%	18min
5	-10°C	15°C	19%	0g	30%	0min
6	-10°C	15°C	3%	0g	25%	18min
7	-10°C	-1°C	3%	0g	30%	0min
8	-23°C	-1°C	19%	400g	30%	0min
9	-23°C	-1°C	3%	0g	25%	0min
10	-10°C	-1°C	19%	400g	25%	0min
11	-23°C	-1°C	3%	400g	25%	18min
12	-10°C	-1°C	19%	0g	25%	18min
13	-10°C	15°C	19%	400g	30%	18min
14	-10°C	15°C	3%	400g	25%	0min
15	-23°C	15°C	19%	0g	25%	0min
16	-23°C	15°C	3%	0g	30%	18min
17	-16,5°C	7°C	11%	200g	25%	9min
18	-16,5°C	7°C	11%	200g	25%	9min
19	-16,5°C	7°C	11%	200g	30%	9min
20	-16,5°C	7°C	11%	200g	30%	9min

Comments regarding the experiments

The experiments were carried out as planned, except for a mix-up of the mackerel fat content in experiment 4 and 9.

It was also noticed a freeze out of thawing media on the block surface at the beginning of the experiments combining low thawing media temperature (-1°) with low salt content of

thawing media. This was amplified during experiments with low pre-thawing temperature (-23°). This is in line with the findings in Chapter 5.7.

The boxes/blocks that should have modified water content were by mistake packed more compact than originally. This resulted in an increased contact surface between the single fishes during the experiments involving 0g or 200 g of excess water. Consequently this led to blocks that were more difficult to split than originally. It is quite reasonable that the blocks containing a reduced amount of water would be easier to split (no estimates of magnitude given), given similar compactness of blocks.

6.5.2 Results

A set of results that could be used to draw a "splitting curve" were obtained from each of the 20 experiments. Since manual power was used to split the blocks, and get these results, it is inevitable that the blocks have been exposed to a varying force from experiment to experiment. In order to reduce the impact of this fact, a polynomial of second degree ($Y = Ax^2 + Bx + C$) was fitted to the experimental set by the method of least square. Figure 6.10 shows an example of the experimental set and the fitted curve for one of the experiments.

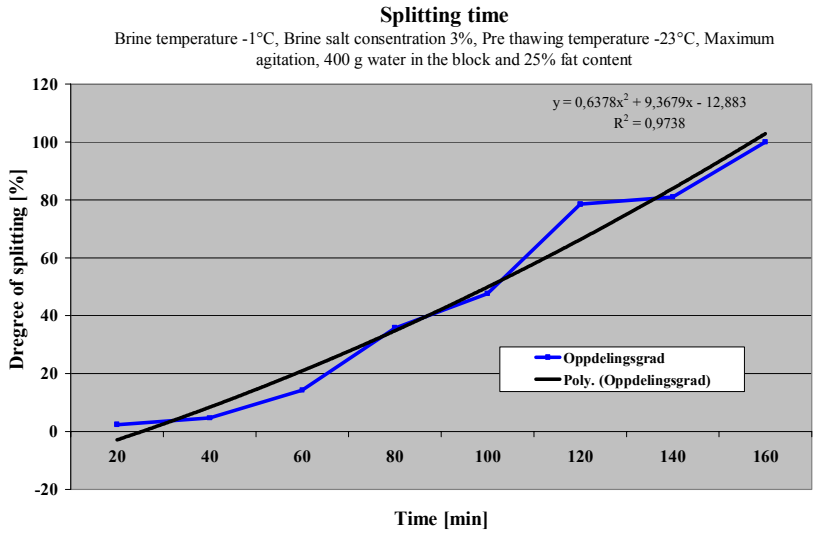


Figure 6.10 *An example of the set of results and how they are utilised in order to identify a splitting time.*

Statistical analysis – significant factors

Four different approaches were considered in order to find whether some of the six chosen factors had significant effect on the splitting of mackerel blocks:

5. The "Splitting time" from the originally set of results, that is regardless of when within the last 20 minutes cycle (Figure 5.2) the remaining part of the block would have been dividable.
6. "Splitting time" from the fitted curve.
7. To what degree, according to the original set of results, the blocks in the different experiments were divided at a given time. This time corresponded to the shortest "Splitting time" experienced in the original set of results.
8. To what degree, according to the fitted curves, the blocks in the different experiments were divided at a given time. This time corresponded to the shortest "Splitting time" calculated from the fitted curves.

The results of these different approaches are given in Appendix X, whilst the results for the second approach are shown in Table 6.4.

Table 6.4 *Block splitting time for the 20 experiments calculated from fitted curves.*

Experiment number	"Splitting time" calculated from fitted curves [minutes]	Experiment number	"Splitting time" calculated from fitted curves [minutes]
1	40	**11**	157
2	80	**12**	97
3	40	**13**	36
4	101	**14**	40
5	40	**15**	60
6	40	**16**	60
7	138	**17**	96
8	61	**18**	99
9	176	**19**	81
10	60	**20**	76

These results are not straightforward to discuss and analyse, but use of statistical methods make it easier to bring into focus the most interesting factors. Table 6.5 shows the results from this statistical method. The table shows the probability for the six different factors not to affect the splitting time, and that the variations in the results solely are caused by naturally variations.

Table 6.5 *The probability for the variations in splitting time connected to the different levels of the factors solely to be caused by natural variations. The 2-levels centre samples are used for significant testing.*

Factor			Probability for no effect on splitting time Analysed with data from fitted curve [2]
Full name	**Abbreviation**	**Symbol**	
Pre thawing temperature	**startTEMP**	**A**	**0,9%**
Thawing media temperature	**brineTEMP**	**B**	**0,05%**
Salt content in thawing media	**brineCONS**	**C**	**0,2%**
Amount of water in mackerel blocks	**blockWATER**	**D**	**0,6%**
Fat content of mackerel	**FATcontent**	**E**	**1,0%**
Agitation	**AGITATION**	**F**	**76,4%**

As the values given in Table 6.5 gets lower, the more probable it is that the considered factor has any effect on the response variable (i.e. splitting time). If the probability that the variations connected to a shift in value (from low level to high level) of the considered factor solely are due to natural variations is less than 5%, it is common to state that the factor has a significant effect on the splitting time. For factors with values higher than this limit it might be possible to discuss tendencies, but as the value increases the more cautious one has to be.

The most important reasons for choosing the second approach (values given in Table 6.5) for analysing the effect of the different factors are:

- The second approach has been compensated (represented by the fitted curve) for differences in exercised manual power from one cycle to another during the experiments.
- The results from the third and fourth approach are based on only a small part (i.e. the beginning) of the result set from several of the experiments.

As mentioned the experiments are of resolution IV that means that the 2-variable interaction cannot be distinguished from each other and the significance of these interactions are therefore not given in the table.

Table 6.5 shows that all main factors except AGITATION have a significant effect on the splitting time of the mackerel blocks.

Statistical analysis – effects

Figure 6.11 shows the effect of all the main factors. Brine temperature (brineTEMP) is the most effective single factor in order to reduce the process time prior to splitting of frozen cod blocks.

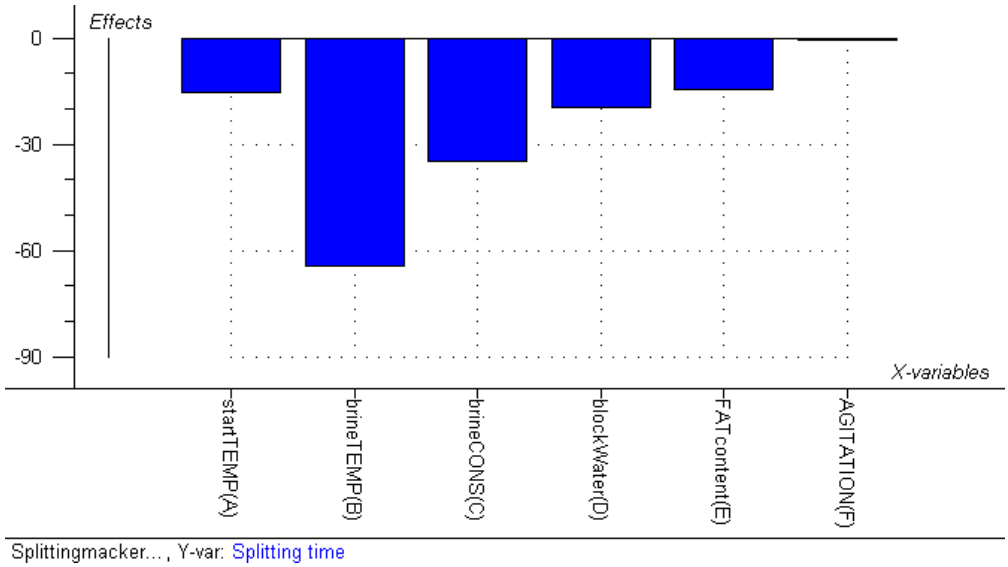
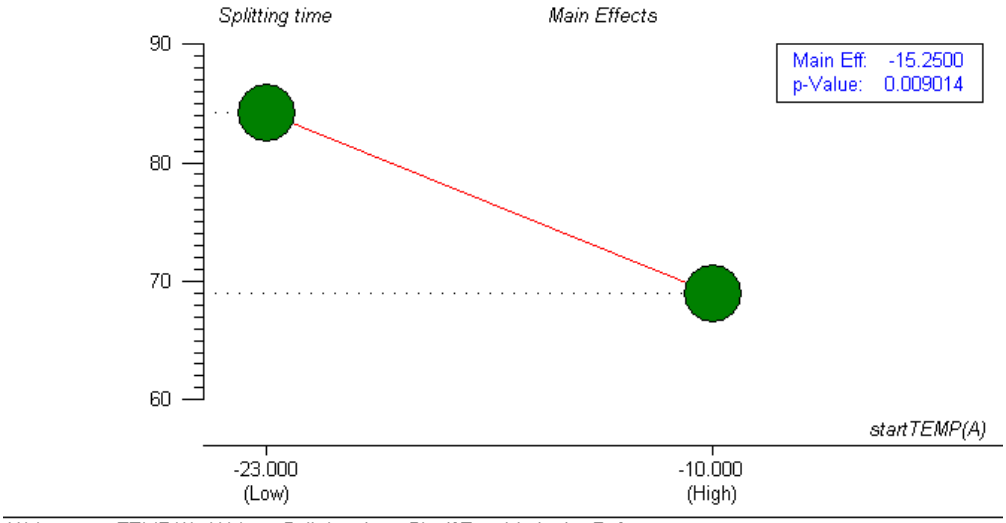


Figure 6.11 *The effect on splitting time by the different factors.*

More detailed investigations of the significant factors are given below, where the average scores at the different levels of the factors are compared. From Table 6.4 it can be calculated that the centre samples for 25% and 30% fat were split after respectively 97.5 minutes and 78,5 minutes. For all the main factors (except for FATcontent) these values represent two different levels of the centre sample. If both of these levels are below or above a straight line between the low and high level splitting time for the considered factor, it is reason to believe that the relationship is not linear. It is however important to remember that the two sets of centre samples are based on two experiments carried out under similar conditions, whilst both high and low values are based on eight experiments each. These eight experiments have been carried out under different conditions (except from the considered factor). All this means that the absolute values in Figure 6.12 through Figure 6.15 should not be compared directly.

The effect by altering the pre thawing temperature (startTEMP)

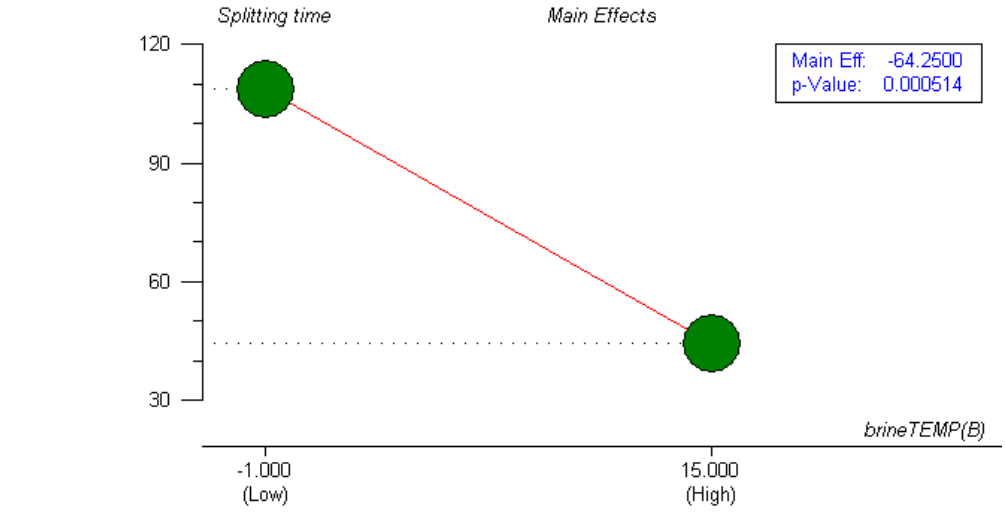
Figure 6.12 shows that if the initial temperature of the blocks are increased from –23°C to –10°C prior to thawing, the mackerel block will split approximately 15 minutes earlier.



X-Var = startTEMP(A), Y-Var = Splitting time, Signif.Test.Method = Reference

Figure 6.12 *The effect on splitting time for blocks of frozen mackerel by changing the temperature of the block prior to thawing (startTEMP).*

Both centre sample values would be higher than the line connecting the Low and High levels, suggesting a curvature in the relationship.



X-Var = brineTEMP(B), Y-Var = Splitting time, Signif.Test.Method = Reference

Figure 6.13 *The effect on splitting time for blocks of frozen mackerel by changing the thawing media temperature (brineTEMP).*

The effect by altering the thawing media temperature (brineTEMP)
Figure 6.13 shows that the effect of increasing the thawing media temperature (brineTEMP) from -1°C up to 15°C will reduce the splitting time of the mackerel block with 64 minutes. Also here would the centresamples lay above the connecting line, indicating a curved correlation.

The effect by altering the salt content of the thawing media (brineCONS)
Figure 6.14 shows that an increase from 3% up to 19% salt content in thawing media (brineCONS) will reduce the splitting time with 35 minutes. Also this finding suggests correlation curvature.

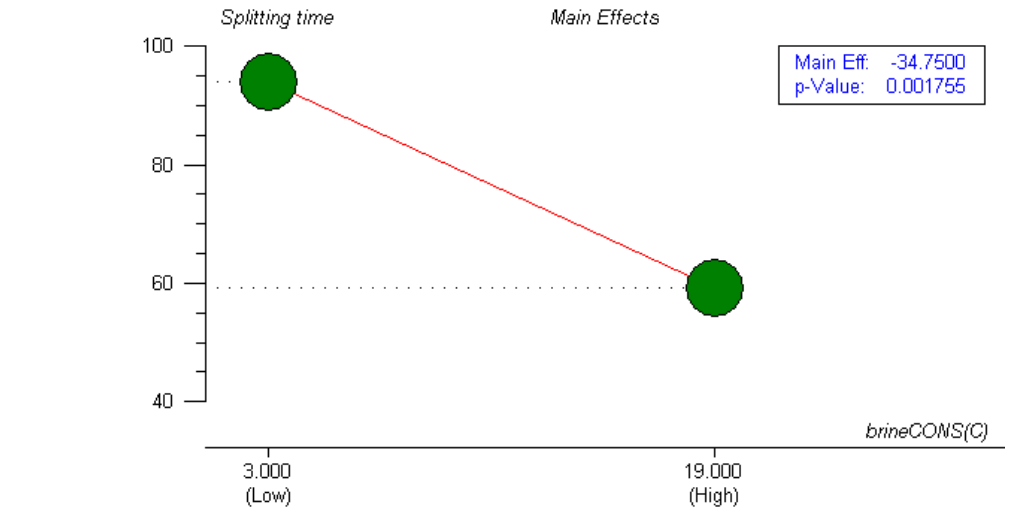


Figure 6.14 *The effect on splitting time for blocks of frozen mackerel by changing the salt content in the thawing media (brineCONS).*

The effect of different amount of water in the blocks (blockWATER)
As mentioned the effect of water amount in the blocks (blockWATER) is distorted due to differences in the compactness of the blocks. Thus there is no meaning in analysing the factor blockWATER further. However it is important to recognise that this factor will be very dependent on the sorting, packing and freezing process and thus dependent on where (at which factory) the mackerel block is produced.

The effect of different fat content of the mackerel (FATcontent)
Figure 6.15 shows that if the fat content increases from 25% to 30% the mackerel blocks will split 14 minutes earlier. There were not conducted any experiments at intermediate level of the fat content, and it is therefore not possible to indicate anything regarding linear or curved relationship. It is reasonable to believe that the differences would be larger if the low level had been closer to 5% fat (The physical low limit of fat content in mackerel).

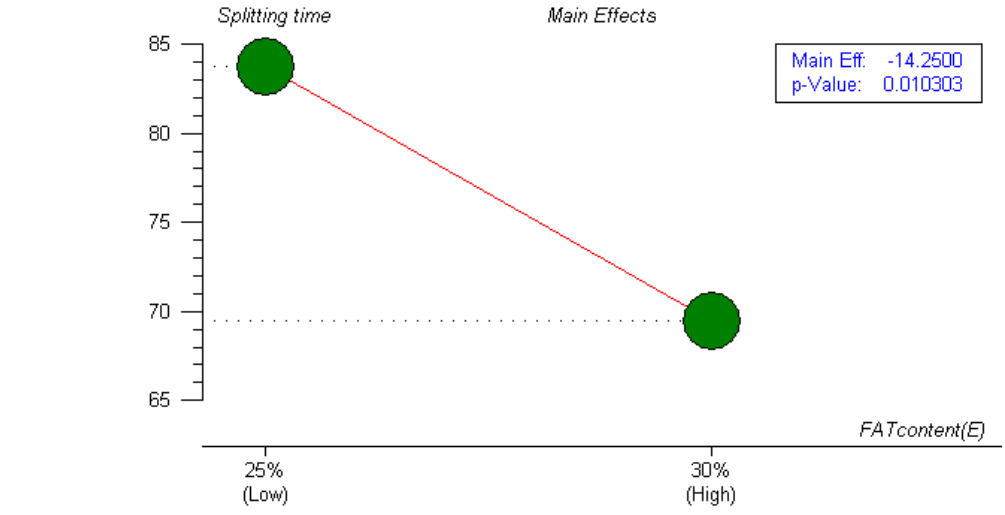


Figure 6.15 *The effect on splitting time for blocks of frozen mackerel by different fat content (FATcontent).*

The effect by different levels of agitation (AGITATION)
In Chapter 5.7 AGITATION did have a significant effect on the splitting time of frozen cod blocks. For splitting of mackerel blocks use of agitation does not seem to reduce the splitting time. This is probably due to an insufficient extra momentum caused by the compressed air agitation. Another way to put it is that the difference between the low and high level for this factor was too small.

Statistical analysis – response surface

In order to reflect reality as well as possible, the factors that either did not affect the response or could not be analysed due to experimental error are fixed. Agitation is set to zero, whilst the amount of water in the blocks is set to the normal value; 400 g in each block.

Figure 6.16 and 6.17 show the response surfaces for the splitting time depending on the thawing media temperature (brineTEMP) and respectively pre thawing temperature (startTEMP) and thawing media brine concentration (brineCONS), for 25% fat content. The coloured lines in the figures illustrate constant splitting times, and the numbers written on them are this time given in minutes.

These figures can be used to find the ideal combination of thawing media temperature and pre thawing temperature of the block or salt content of the thawing media, that secure splitting within a desired time. It can also be used as a help to choose the most favourable approach in order to adjust the splitting time in any desired direction.

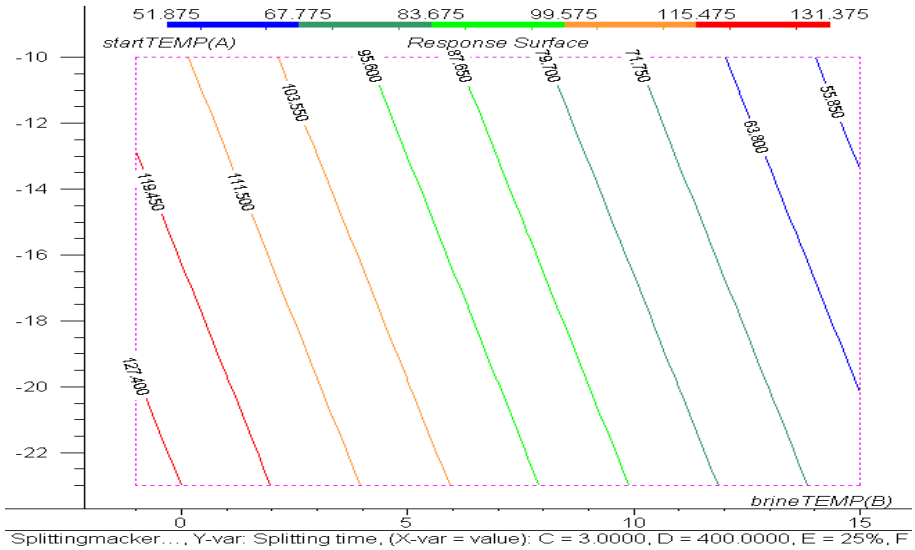


Figure 6.16 *Splitting time (in minutes) as a function of thawing media temperature (brineTEMP) and pre thawing block temperature (startTEMP), valid for 25% fat content, 400 g of water in the block and 3% salt content in thawing media.*

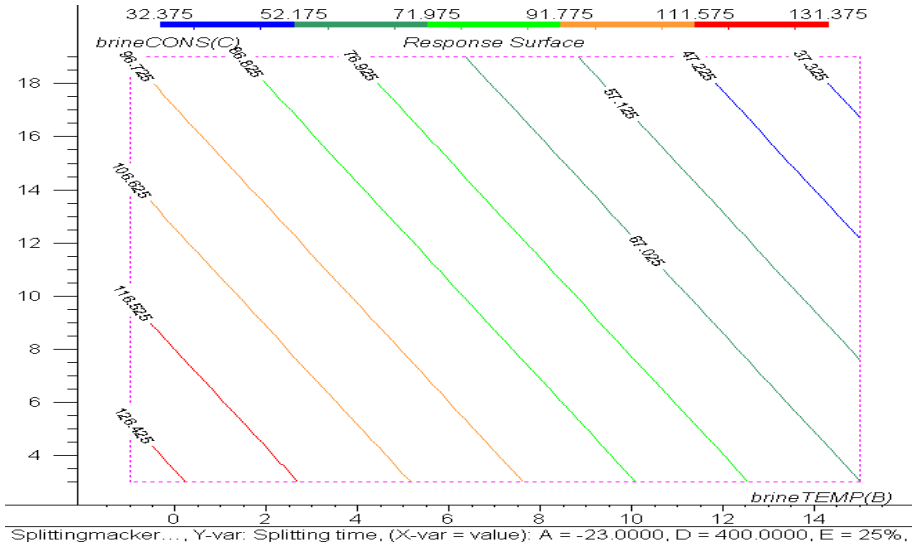


Figure 6.17 *Splitting time (in minutes) as a function of thawing media temperature (brineTEMP) and the thawing media salt content (brineCONS), valid for 25% fat content, 400 g of water in the block and an initial block temperature of –23C.*

6.5.3 Conclusion – splitting of mackerel blocks

The splitting time and consequently the spread in post thawing temperature and/or the thawing time for the mackerel blocks can be reduced, by manipulation of thawing media temperature and/or salt content. Also pre thawing block temperature can be altered to adjust the splitting time, but it would need new routines and the potential effect is lower than for the first two methods. It is of course important that the quality is closely monitored in order to prevent damages from too high thermal impact or too much salinity in the splitting phase.

Both fat content and amount of water/blood in the blocks will influence the splitting time. If the fat content of the raw material varies in another/wider range than applied in this survey (i.e. 25% - 30%), then the effect of fat content should be re-evaluated, in order to be able to fit the process to the new raw material.

Due to experimental errors (described in the "Comments regarding." section), the effect of variations in water content was distorted in this survey, but the factor should be kept in mind and it will be important to note whether the blocks of raw material vary in compactness and have different amount of visible water.

Agitation does not show any effect in these experiments. However it did so in Chapter 5.7 regarding splitting of frozen cod blocks. If the agitation source had been stronger, it is likely that also this parameter would be an important factor for the splitting time. The low mechanical strength of mackerel will restrict the levels of agitation.

Another possibility to split the blocks early would be if the blocks were "glued" together with a media with significant lower freezing point (e.g. a mixture of antioxidants) than the fish itself. This way the block would be split while the single fish still was frozen.

6.6 Effect of thawing on mackerel for fillet production

Chapter 6.4 pointed out that the product temperature after thawing needed to be improved (both average and spread). The goal of this sub-chapter is to identify an optimum post-thawing temperature.

6.6.1 Focus and methods

In order to find the optimum post-thawing temperature, different batches of thawed mackerel were tempered to different temperatures. After this the batches were processed as usual, whilst temperature, yield and quality were monitored.

The experimental set up

The raw material for these experiments was taken from the last stage of the thawing equipment illustrated in Figure 6.3. The RSW unit described in Chapter 3.6.1 was used to obtain the desired brine/product temperatures. A tempering media containing 10% NaCl was used for all experiments in order to have similar conditions. This level was chosen to prevent freezing of the RSW unit evaporator.

Temperatures were monitored by the means described in Chapter 3.4.1, but the Fluke 2625A Hydra Data logger was equipped with thermocouples of type T1-02-T, 0.2 mm thick and Teflon (±0,45°C). Temperatures were recorded every 2 minutes. Core temperatures were measured by inserting a thermocouple along the backbone through the gatt opening.

Weights were registered by a Mettler PM34 weight (± 0,5 g).

Experiments

Five batches were tempered to respectively –1°C, -2°C, -3°C, -4°C and –5°C. During this tempering skin and core temperatures were continuously monitored for 10 whole mackerels. When skin and core temperature were equal, tempering was completed. Each batch consisted of three parallel series of 50 whole mackerels each. After tempering, the core temperatures of all 50 mackerels in each series were measured. The 10 whole mackerels used for the continuously temperature monitoring were not included in either of the series. The series were followed though filleting, trimming and refreezing, and weighing was done after each of these stages.

Comments regarding the experiments

The batch tempered to –1°C was originally designed to produce a batch of 0°C. 8 of the 10 control fishes showed approximately 0°C after 7,5 hours tempering, but the batch itself had an average temperature of –0,9°C, thus represented a post thawing temperature of –1°C. The reason for this mismatch between control temperatures is obviously uncertainties in the measurements and the fact that the RSW unit was not able to produce a more stable brine temperature. The quality of the fillets after filleting at this temperature were very low (referring to the presentation given below), and there was no need to run another 0°C experiment.

During the experiments where the batches should be tempered towards –2°C and –3°C the same 10 mackerels were used for temperature control. This was done to save time, and unfortunately introduced another uncertainty factor (the 10 control mackerels had not been exposed to the same temperatures as the 150 mackerels in the three series of the –3°C batch).

The combination of the relatively strong NaCl brine and different tempering times and temperatures, might have had an effect on the water uptake.

All experiments were conducted during the regular shifts with full production. The test batches were run in between the normal production. One of the three parallel series in the tempering towards –5°C was by a mistake mixed with the rest of the production after filleting. Because of this, all data from this experiment after filleting relates to the average from two series of 50 mackerels each.

6.6.2 Results

The results are given as average temperatures and yields for each batch, and general quality evaluations are done. The detailed results for each batch and series are given in Appendix XI.

Temperatures during tempering

Tempering towards –1°C

The average fish weight (n=150) after thawing and before tempering was 504 gram. During the 7.5 hour tempering the batch added 1,2% water to its weight. Figure 6.18 shows the temperature development for the control fish during the tempering. The core temperatures are represented by the most stable curves, whilst the fluctuating curves show the skin temperatures. The curves indicate that the core of the thawed mackerels (taken after the second thawing tank) needs to be slightly heated during tempering in order to reach –1°C, whilst the skin needs to be chilled.

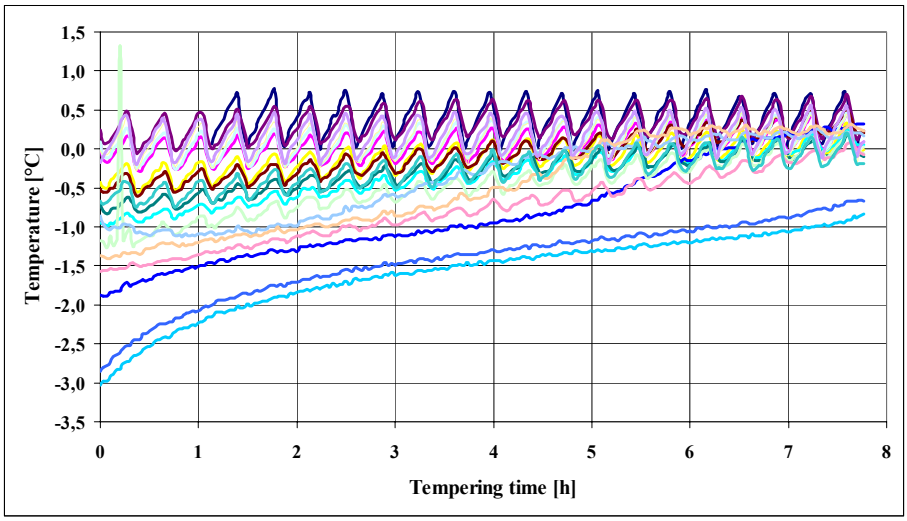


Figure 6.18 *Temperature developments for the 10 control fish during tempering towards –1°C.*

The manual measurements of all the mackerels after tempering showed that their core temperature was –0,9°C ± 0,7°C. After tempering the mackerels that had been frozen bent (banana shaped) had straighten up, which is a benefit during the mechanical filleting. During filleting the product temperature increased rapidly, and after filleting the temperature of the thickest part of the fillet had increased to 4,8°C, whilst the thinnest part had a temperature of 5.2°C. All the fillets were soft/puré like and were difficult to handle during the manual trimming.

Tempering towards –2°C
Average weight of the mackerels in this experiment was 495 g (n=150), and the average core temperature after the 4 hour tempering was –2,1°C ± 0,3°C. The batch gained 0,5% weight during tempering. Figure 6.19 shows the temperature development for the 10 control fish during tempering, and it is obvious that the skin needed to be chilled, whilst the core needed to be heated.

After tempering the batch was kept in three plastic boxes at ambient conditions (~10°C) for approximately 30 minutes prior to the filleting. After filleting the temperature in the thickest and thinnest (tale) part were respectively –1,4°C and –1,1°C. The visual quality was varying from firm to soft/pure like, but overall this batch had far better visual quality than the batch tempered towards –1°C.

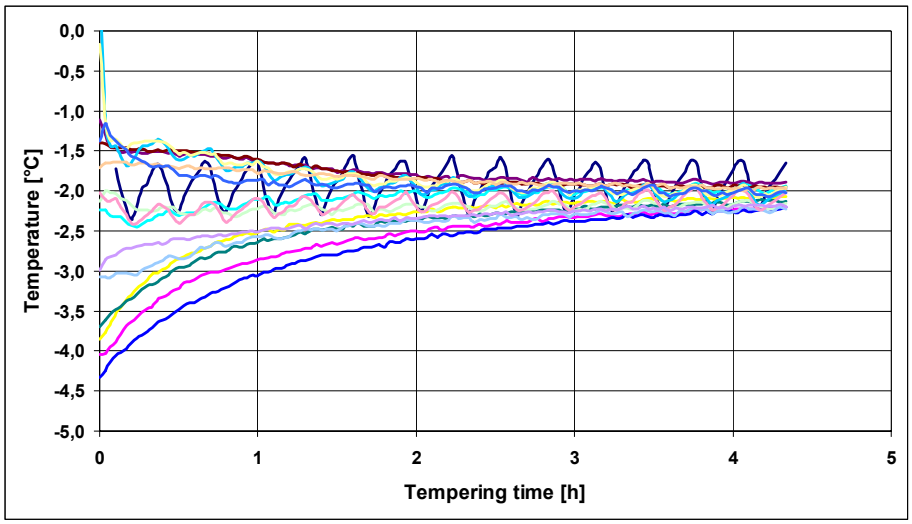


Figure 6.19 *Temperature developments for the 10 control fish during tempering towards –2°C.*

Tempering towards –3°C
As explained in the 'Comments regarding the experiments' section the 10 control fish from the last experiment were also used here.

Figure 6.20 shows the temperature development for both experiments and the preparation phase between them.

Average weight of the mackerels in this experiment was 505 g (n=150), and the average core temperature after the 6 hours tempering was –2,7°C ± 0,4°C. The batch gained 0,3% weight during tempering

After tempering the batch was kept in three plastic boxes at ambient conditions (~10°C) for approximately 30 minutes prior to the filleting. After filleting the temperature in both the thickest and thinnest (tale) part was –2,1°C. The visual quality was very good both directly after the filleting and after refreezing. The fillets were also easy to handle during the manual trimming.

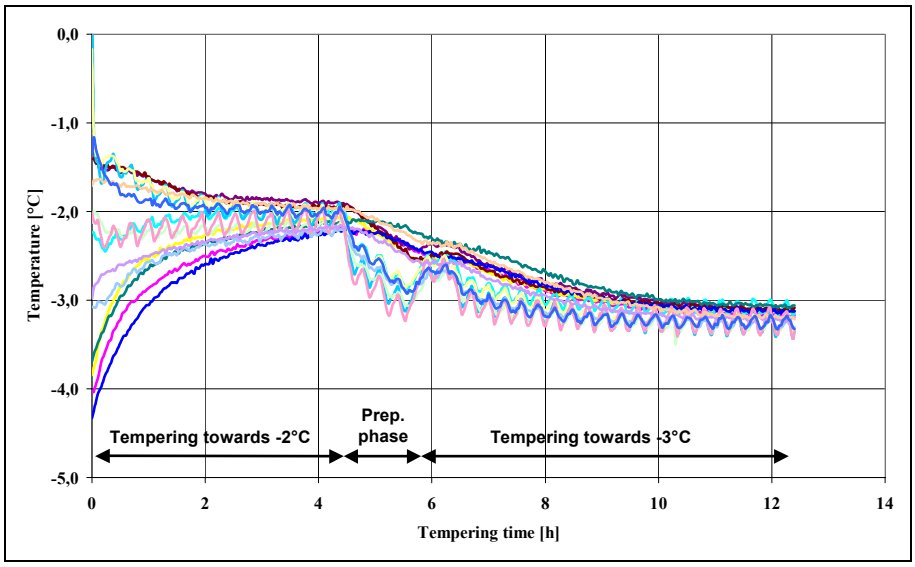


Figure 6.20 *Temperature developments for the 10 control fish during tempering towards –2°C, followed by a preparation phase, and finally the tempering towards –3°C.*

Tempering towards –4°C

Average weight of the mackerels in this experiment was 525 g (n=150), and the average core temperature after the 4,5 hours tempering was –3,5°C ± 0,4°C. The batch gained 0,1% weight during tempering. Figure 6.21 shows the temperature development for the 10 control fish during tempering, and the fact that this experiment was a cooling process.

After tempering the batch was kept in three plastic boxes at ambient conditions (~10°C) for approximately 15 minutes prior to the filleting. After filleting the temperature in both the thickest and thinnest (tale) part was -2,4°C. The visual quality was good, but 1-2 cm of the backbone was left on most of the fillets, demanding more manual trimming. The workers that performed the trimming stated that the trimming was more difficult because of the relatively hard fillets. The refrozen fillets had very high visual quality.

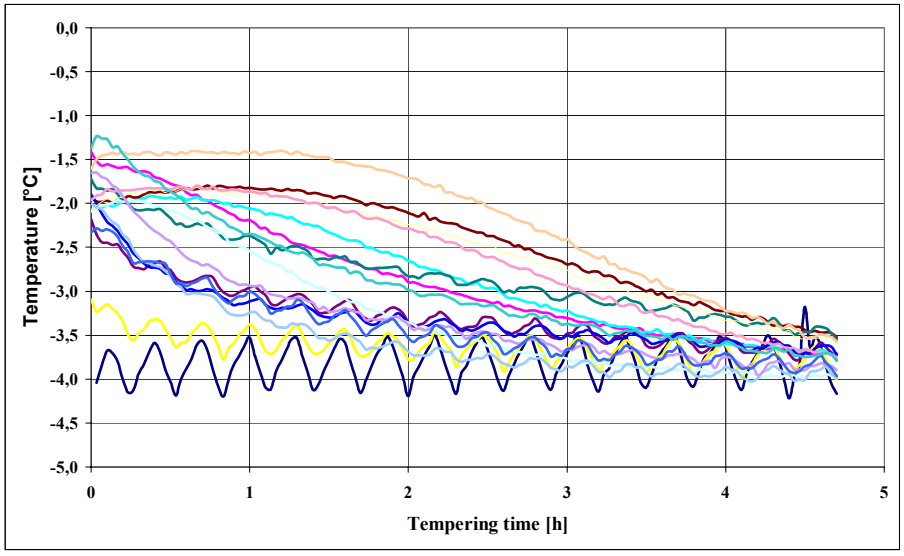


Figure 6.21 *Temperature developments for the 10 control fish during tempering towards –4°C.*

Tempering towards –5°C

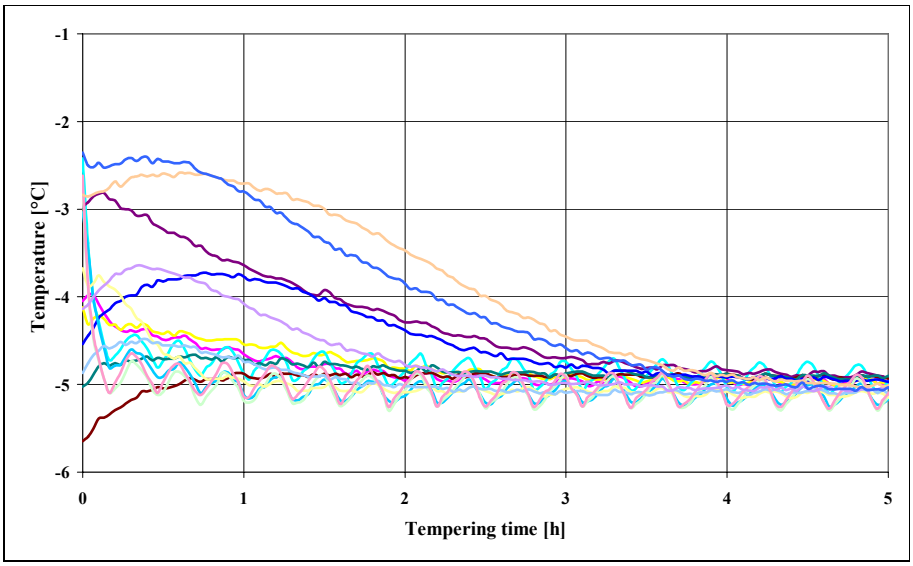


Figure 6.22 *Temperature developments for the 10 control fish during tempering towards –5°C.*

Average weight of the mackerels in this experiment was 512 g (n=100), and the average core temperature after the 4 hours tempering was –4,8°C ± 0,3°C. The batch did not gain weight during tempering. Figure 6.22 shows the temperature development for the 10 control fish during tempering, and the fact that this experiment was a cooling process.

The batch was filleted immediately after the tempering. After filleting the temperature in the thickest and thinnest (tale) part were respectively -3,4°C and –3,2°C. Some of the gut and 3 - 5 cm of the backbone was left on many of the fillets, demanding more manual trimming. Fillets with breakage were also observed.

Yield

Table 6.6 gives an overview of the average yields after each production process. All values are related to the initial weight prior to the tempering, except for 'Loss during refreezing' where the loss relates to the net weight before the belt freezer.

Table 6.6 *The effect on yield of different pre processing temperatures.*

		Tempering towards				
		-1°C	**-2°C**	**-3°C**	**-4°C**	**-5°C**
Water uptake [%]		1,2	0,5	0,3	0,1	0,0
Yields after [%]	**Filleting**	65,6	76,0	67,5	70,4	66,0[1)]
	Trimming	61,7	65,8	64,1	63,6	62,4[1)]
	Refreezing	59,7	63,7	61,3	61,4	61,3[1)]
Loss during refreezing [%]		2,1	2,3	2,9	2,1	1,2[1)]

n = 150 for all data, except for [1)] where n=100.

Depending on resident time and temperature during tempering, the mackerels will take up water. For these experiments the uptake decreases with decreasing temperature from 1,2% for –1°C down to 0% for –5°C. This is natural since the mobility of water will decrease as the temperature of the fillet is decreased.

Table 6.6 shows that the loss during filleting is largest for the batch tempered towards –1°C and –5°C. The reason for this has to be the fact that both batches have a texture that is far from ideal for the equipment used in these experiments. The –1°C batch was too soft, whilst the –5°C batch was too hard. It seems like low losses during filleting means larger loss during trimming. This indicates that the equipment efficiency is varying depending on product size and temperature. The filleting and trimming should for most purposes be looked upon as one process. After trimming it seems like the yield will be at its best for mackerel tempered towards –2°C, and that the yield decreases fastest if the temperature is increased.

The losses during refreezing seem to be highest for the batch tempered towards –3°C, and it is decreases fastest for decreasing temperature. That the losses during freezing is reduced

with decreasing temperature could be expected, since a colder fillet would mean that the normally loosest bound water would be thermal bound (as ice). But it is not easy to understand why the fillet tempered towards –3°C results in the highest losses during refreezing. One reason might be different conditions in the belt freezer. Unfortunately these conditions were not documented during our stay. It is outside the scope of this work to dig further into this question.

The final yield after refreezing is around 61,5% for the batches tempered towards –3°C, -4°C and –5°C, whilst the batch tempered towards –1° only gave a 59,7% yield. The highest yield (63,7%) was achieved for the batch tempered towards –2°C.

The evaluation of the fillets after refreezing seemed to be very dependent on the actual person doing it. Unfortunately we did not secure that the same person did this for all batches. This makes detailed comparisons between the different batches useless; it was however a clear trend that the visual quality improved as the tempering temperature decreased.

6.6.3 Conclusion – thawing of mackerel for fillet production

It is important to bear in mind that even if this work has showed that the post-thawing temperature strongly affects both;

- yield,
- trimming capacity and
- final product quality,

it does not provide one temperature that will be optimum for all frozen mackerels. Both size and initial quality and other process parameters might affect the optimum temperature.

The yield seemed to be highest for the batch tempered towards –2°C, and the capacity of the trimming table was at its peek for the batch tempered towards –3°C, whilst the capacity of the belt freezer increased with decreasing tempering temperature. What temperature or range of temperatures a company decides to strive against will depend on their production facilities and how they range quality, yield and capacity.

6.7 Full scale simulation of the new process

The intention of the chosen approach described in Chapter 6 was to improve the existing processing plant. The work presented in Chapter 6.5 and Chapter 6.6 outline what a new continuously thawing process for frozen mackerel could look like. Fast splitting of the frozen blocks by the aid of “high temperatures” and “strong agitation”, followed by a tempering phase where the temperature of the single mackerels should be evened out to a chosen value within the range –2°C to –4°C. As a final test before changes were agreed upon, and investments were made, a full-scale simulation of the suggested process was made. This chapter describes this simulation.

6.7.1 Focus and method

The aim of this work was to compare the new simulated process with the original process as described in Chapter 6.4.

The raw material

18 20 kg blocks of frozen mackerel blocks that were going to be processed the following day, were used in the simulation of the new process.

The experimental setup

The original process used as reference in this experiment, has been described in Chapter 6.4.1. The only difference was that the circulating pump supplied the water through jets at the bottom of the first tank. Under each chamber four parallel jets were placed, these could be shut or opened by a manual valve.

The splitting of the blocks during the simulation of the new process was carried out in the first tank in the original equipment described in Chapter 6.4.1 with modification described above. The tempering of the fish was carried out in the RSW equipment described in Chapter 3.6.1. The tempering media in the RSW unit contained 10% of NaCl.

Temperatures and weights were measured as described in Chapter 6.6.1.

Experiments

After the second shift had ended, and the thawing equipment (Figure 6.3) was empty, fresh seawater was continuously supplied to the thawing equipment, after a while a thawing media temperature of 10°C was achieved. The 18 blocks were fed to one of the chambers; while fresh seawater still was added in order to prevent the temperature in the thawing media to decrease. No more fish was added into the tank. The normal lead-time in the first tank was used. As the chamber with the blocks moved, the parallel jets under the chamber were opened, and the ones not directed towards the actual test chamber were shut. This way maximum agitation was achieved in the test chamber throughout the splitting stage. As the chamber moved, the temperatures in single mackerels were measured.

When the blocks were split, 3*50 mackerels were transferred to the RSW unit and tempered towards –2,7°C for approximately 6 hours. After this the three parallel series were processed. The results were compared to a similar batch from the original process, produced approximately three hours later.

Comments regarding the experiments

After the blocks in the simulated process were split, they remained in the relatively hot thawing media for several minutes, while the test chamber was moved to the end of the tank. This means that the mackerels had a higher temperature than necessary when they entered the tempering stage (RSW unit).

6.7.2 Results

Temperatures for the original process are given in details in Chapter 6.4, and only some control measurements after thawing and filleting were therefore made during the reference experiments. The temperatures during the simulation of the new possible process are given in the following sub-chapter.

Temperatures during the simulated new process

Temperatures during splitting of the blocks

Figure 6.23 shows the temperature development of single mackerels during the splitting stage of the new process. The thawing media temperature is stable throughout the splitting stage, this means that the heat of the supplied seawater is more effectively compensating for the heat sink, the 18 frozen blocks represent. Both core and skin temperature increases fast the first 10 minutes, but from then on the core temperature is stable at –5°C, whilst the skin temperature increases further towards the thawing media temperature. After 40 minutes at approximately 10°C all the blocks are split. If the same equipment was used to split the blocks in a full production, the temperature would most likely get reduced because of the refrigeration capacity of the frozen blocks, and the splitting time would increase due to both the decreased temperature and reduced agitation in each chamber.

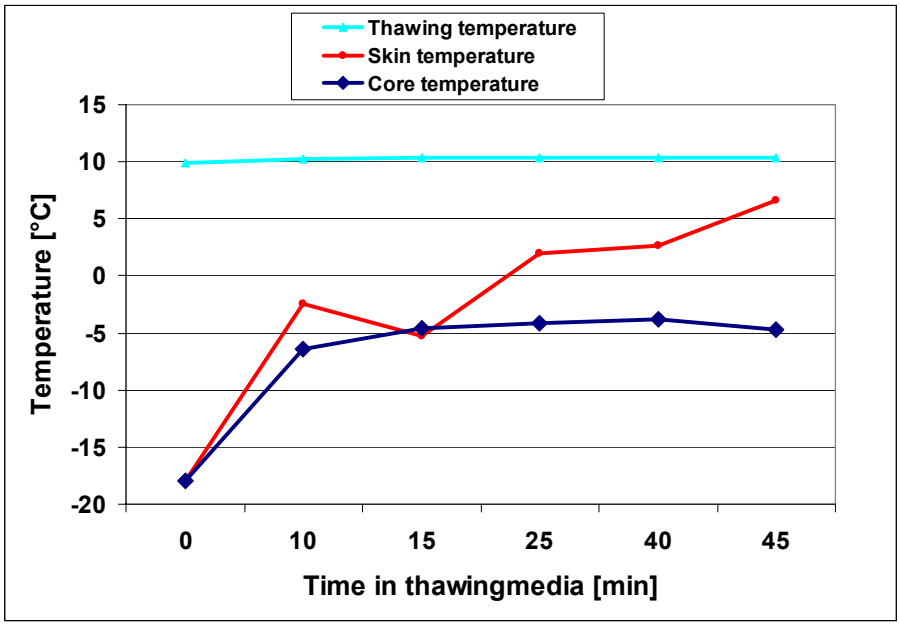


Figure 6.23 *Temperature of some single fish during the splitting phase in the simulated new thawing process.*

A summary of the temperatures after the splitting stage and before tempering is given in Table 6.7. There are large variations in the product temperature both between different fishes and internal.

Table 6.7 *Overview of the product temperature after splitting of the blocks.*

	Temperature [°C]	
	Core	**Skin**
Average (n=150)	-2,1	2,1
STDEV	0,5	1,6
Maximum	-1,2	5,9
Minimum	-4,1	-3,3

The average core temperature is –2,1°C, which is substantially higher than the value expected from Figure 6.23. The excess time the batch was kept in the chamber (described in the 'Comments regarding the experiment' section) might have resulted in this.

Temperatures during tempering

Figure 6.24 shows the temperature development for the 10 control fish during tempering, and the fact that this experiment was a cooling process. Average weight of the mackerels in this experiment was 533 g (n=150), and the average core temperature after the 6,5 hours tempering was –2,2°C ± 0,2°C. The batch gained 1,2% weight during tempering.

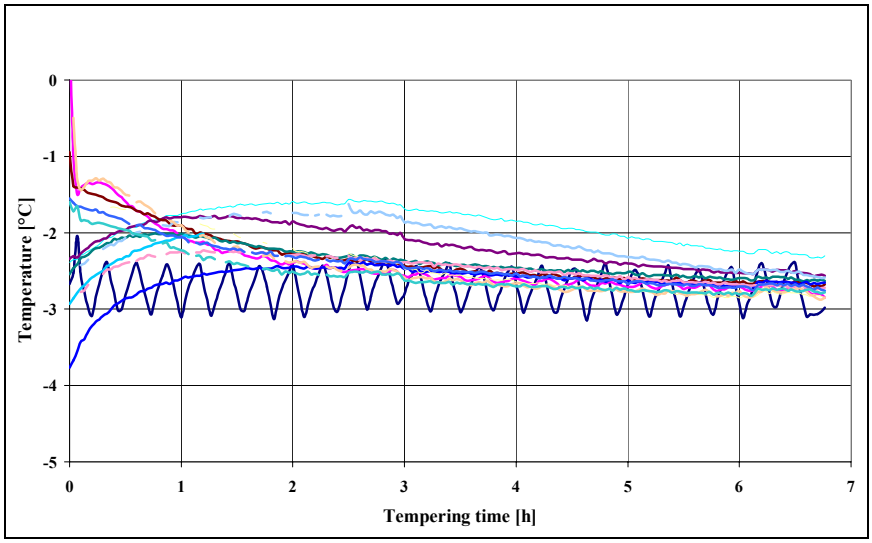


Figure 6.24 *Temperature development for the 10 control fish during tempering towards –2,7°C.*

The batch was 0,5°C warmer than we wanted, even after 6,5 hours tempering time. Explanations, could be:

- The thermal energy transferred to the fish during splitting was larger than necessary
- The temperature in the RSW unit was too fluctuating throughout the tempering
- The temperature in the RSW unit was too high
- Experimental error

After tempering the batch was filleted directly. Some fillet gaping was observed, but the overall impression was that the fillets had high visual quality.

Yields

The average weight of the mackerels in the batch representing the original process was 510 g (n=150), and the average core temperature was –2,7°C. In this case it is important to remember that the original process gives large spread in temperature within the fish (ref Chapter 6.4), whilst the tempered fish in the simulated new process will have almost uniform temperature.

Table 6.8 gives an overview of the average yields after each process step. The detailed values are given in Appendix XII. The large loss during refreezing of the batch with fish from the simulated new process is difficult to understand. No fillets had been lost, and all three parallel series showed the same tendency. The most likely explanation is that the belt freezer might not have been operating under the same conditions for both batches (The batch from the original process was frozen 3 hours after the batch form the simulation of the new process).

Table 6.8 *The effect on yield of different thawing method.*

		Thawing method	
		New process with uniform temperature of –2,2°C (low spread)	**Original process with core temperature of –2,7°C (larger spread)**
Water uptake [%]		1,2	-*
Yields after [%]	**Filleting**	70,9	65,1
	Trimming	66,7	63,3
	Refreezing	61,6	60,6
Loss during refreezing [%]		5,1	2,7

*) This value was not registered, since the single fish selection to this batch was done just before filleting

If the losses during refreezing had been as usual (i.e. 2-3%), then the yield would have been 63-64% for the batch from the simulated new process. This would be in agreement with the findings in Chapter 6.6.

6.7.3 Conclusion – full scale new process simulation

The simulation of the possible new process shows that it is possible to increase the number of blocks in each Chamber, and that the blocks can automatically become split after 40 minutes in 10°C seawater if the agitation is sufficient. From Chapter 6.5 it is clear that if the temperature of the splitting stage increases, the splitting time will be decreased and vice versa.

In order to prevent too high surface temperatures it is important that the single fish is transferred to a chilling/tempering tank immediately after block splitting is completed. Depending on what post thawing temperature the process gets designed for, the stage after splitting should be designed to remove or supply the energy required reaching the desired temperature.

A third stage where the energy is evened out, giving as uniform temperature as possible throughout the fish should be implemented. In this particular factory it also seemed like they should pay attention to the belt freezer, which most likely can be further optimized.

The new process will at least give 1% better yields, more efficient handling during trimming, less time in belt freezer and better visual quality. All this adds up to increased capacity and better quality.

6.8 The new process, considerations and results

The work described in Chapter 6.4 through Chapter 6.7 has been carried through in close cooperation with one equipment producer and one mackerel processing plant. Depending on (among other aspects) production facilities and main product, different companies will range improved quality, increased yield and capacity different. There is therefore not only one optimum solution regarding how frozen blocks of mackerels should be thawed. The companies and researchers involved in this work evaluated the results described in these Chapters and designed new equipment and processes together. The documentation of this process shows that we succeeded, but it would not be appropriate to reveal the choices and experience in detail.

The new process takes advantage of splitting the blocks automatically by use of “hot” seawater and agitation. An automatically regulated RSW unit secures the temperatures pre filleting. Agitation, temperatures and lead-times are regulated automatically in a continuously process. As the benefits of the new process surfaced, it became clearer that a stable, controllable thawing process is an absolute condition for running a mackerel fillet production line.

The new thawing process resulted in;

- 1% higher yield,
- better quality and
- made it possible to increase the production line capacity with more than 50%.

Their production could be further optimised, and as an example the lead-time could have been significantly reduced and at the same time improve quality, capacity and yield.

6.9 Conclusion – industrial thawing of mackerel

The initial thawing process in the company's plant was labour intensive and resulted in very large spread in the product temperature prior to filleting. Unforeseen delays due to production problems would give too high temperatures in the thawing tanks.

Thawing - the bottleneck in the production process

Based on these findings it was obvious that the thawing process was the bottleneck in the production. Temperature control of the thawing process had to be gained. The frozen blocks should be automatically split as soon as possible. This would either make it possible to speed up thawing (for continuously thawing processes), or to ensure that more of the available time for thawing was spent to equalise the temperature levels amongst the single fishes (for batch thawing processes).

Fast splitting of blocks

The splitting time and consequently the spread in post thawing temperature and/or the thawing time for the mackerel blocks can be reduced, by manipulation of thawing media temperature and/or salt content. Also pre thawing block temperature can be altered to adjust the splitting time, but it would need new routines and the potential effect is lower than for the first two methods. Agitation can also most likely be used to speed up splitting.

Another possibility to split the blocks early would be if the blocks were "glued" together with a media with significant lower freezing point (e.g. a mixture of antioxidants) than the fish itself. This way the block would be split while the single fish still was frozen.

Both fat content and the degree of open voids in the blocks (porosity) will affect the splitting time, and the companies should bare this in mind, and if possible control the different batches when they are bought. In order to make use of this info, new experiments to reveal the detailed effects of these two factors should be carried out.

Tempering towards optimum production temperature

After the blocks are split the surface temperature should be reduced, followed by a temperature equalising stage. The post thawing temperature strongly affects both yield, trimming capacity and final product quality, but most likely one temperature that will be optimum for all frozen mackerel does not exist. Both size and initial quality and other process parameters might affect the optimum temperature. For high fat content 500 g mackerels the yield seemed to be highest for the batch tempered towards –2°C, and the capacity of the trimming table was at its peek for the batch tempered towards –3°C, whilst the capacity of the belt freezer increased with decreasing tempering temperature.

Temperature level, agitation pattern and lead-time throughout the thawing process should be carefully controlled and regulated. This will secure a better product temperature development, and it is possible to optimise the texture prior to the mechanical filleting.

The results

If these aspects are fulfilled the new process will at least give;

- 1% better yields,
- less fillet gaping and breakage,
- more efficient handling during trimming and
- less necessary time in belt freezer.

All this adds up to increased capacity and better quality.

7 Industrial thawing of fish in the future

7.1 Introduction

Norway will need to relay more on our sustainable marine resources as our income from oil and gas related activity is expected to decrease. In order to do so, we will need to produce a wider range of products. For the fish- and aquaculture industry this means that new species will be farmed, and more refining of these and traditionally products will need to be done. There is no reason to believe that thawing will reduce its importance as a result of this trend. The companies that are going to succeed with production from frozen raw material will have to do long term investments in both knowledge and technology.

7.2 Status

The status of industrial thawing today, as seen in many plants, is intimidating. The traditional solutions are generally uncontrolled and ineffective and the produced thawed material has low and varied quality. The new generation of thawing equipment and solutions from some suppliers seem not to have dealt well enough with the thermal aspects of thawing. Neither the equipment producers nor the users have succeeded in making these equipments function satisfactory under different conditions.

7.3 Action needed

There are of course not one single group to blame for the state of the art. Both equipment producers and processing companies have failed. Also the researchers have failed to communicate their knowledge to the industry. Researchers, equipment producers and the users should cooperate at a much earlier stage than today. The thawing equipment should be followed by a knowledge package. This package could include systematically modules regarding: information to the employees in general and to all potential operators, realistic thawing programs, maintenance instruction and service intervals, interactive database for every thawing run. In addition the interface between operators and process control should be improved.

7.4 Other aspects

As more knowledge around thawing is gained, more advanced equipment will be further developed. In addition to logistical, capacity and quality aspects, these will focus on water and energy consumption. The processes will also be increasingly automated.

The trend with processing the frozen raw material in low cost countries will most likely grow stronger. International companies will invest in production facilities in these countries, and the thawing will still be of increasing importance. To compete the Norwegian processors have to have the best equipment and the best knowledge about how to use this under varying conditions (e.g. varying ambient conditions, frozen material, product size/geometry, process equipment etc.).

8 Summary and Conclusions

8.1 Background

This Chapter aim to summarise the most important aspects of industrial thawing in general and to present the different conclusions from the three product chapters regarding industrial thawing of Salmon, Cod and Mackerel.

8.2 Thawing

Melting of frozen water in food products is denoted thawing. The phase change requires energy, and takes place at a constant temperature for pure water. For mixtures of water, fat, protein and ashes (i.e. foodstuffs) this phase change will take place at a gliding temperature.

Thawing is physically the opposite process to that of freezing. The heat flow is reversed and instead of extracting heat from the product, heat is directed into it. Although opposite processes, thawing is more difficult to carry out with respect to predictability and controllability. This is due mainly to three aspects:

4. Increased heat flow resistance as the thawing proceeds.
5. Reduced temperature difference (ΔT) between product and media.
6. More difficult to monitor the process and product end temperature accurate.

8.3 Industrial thawing of fish

The use of frozen raw material in processing of ready to eat products is common in the whole range of food products. Fruit in juices, jams and dairy products, vegetable in "ready to prepare dishes", meat and seafood in frozen products at different processed levels are all products we are familiar with, and where use of frozen raw materials are common.

The food processing industry depends on a continuously and safe supply of raw material, in order to utilise process equipment better, improve production planning and to create stabile and secure working environment for the employees. The fish industry is very important for Norway, and its export value (NOK 30,6 billion in 2001[1]) is the second highest after oil and higher than gas. The fact that supply of fresh raw material (i.e. fish) often is dependent on

[1] SSB, EFF

seasonal variations, weather conditions, quotes and regulations (governmental and international), has been a great intensive to use frozen raw material in the fish process industry.

A survey amongst 155 fish processing plants throughout Norway showed that 75 % of them used thawing in their production and further 23% claimed that they would do so in the future. 93 % of the companies that thawed did so in an uncontrolled manner, and 94% of them used batch thawing in running water (fresh or seawater). The other 6% thawed their product in air. All these methods are based on the same principle: Heat transfer through the surface. Theoretically these methods are more flexible and controllable than the heat generation methods. Because of all this, this work focuses on industrial thawing of fish by heat transfer through the surface.

The challenges in industrial thawing are many:

- Block frozen products change size during thawing and are generally more difficult to handle
- The product texture is temperature dependent
- Size variations – both single fish and batches
- Use of both fresh and frozen raw material
- Company culture

At a very early stage in this work, it became clear that the work should be focused along two slightly different paths:

1. Laboratory based investigation on the effect of thawing of fish products, and
2. Improvement of thawing processes within the industry.

Ideally work along these paths would be done with the same model products in order to make exchange and comparison of result easier and more effective. However this was only done to a small extent due to the following facts:

- In order to reveal the effect of thawing it is crucial to have experimental material with the best possible initial quality (high and even). In order to make this investigation manageable Salmon was chosen as the first main product for investigation.
- Thawing of salmon was in the industry done in a much smaller scale compared to the lean and pelagic fish thawing. Besides, thawing was in most companies not a daily-integrated part of the production process.
- Companies thawing lean and pelagic fish signalised at an early stage that they had serious problems with their thawing processes, and that they wanted to contribute to the project.

8.4 Thawing of Salmon

To this date, only limited amount of whole frozen salmon is industrially thawed in Norway. In order to realise the announced potential in Norwegian aquaculture it will be necessary to process much more salmon within Norway, in the years to come. Based on this it is also likely that the domestic industrial thawing of salmon will increase.

This work has shown that thawing and the way it might be implemented in industrial processes will affect quality parameters as well as important economical parameters.

Thawing of salmon should not be too slow, due to the possibility for increased drip loss, but use of higher thawing temperatures to speed up the thawing must be carefully evaluated. For most practical reason it seems like thawing of salmon should be done in a 5°C – 10°C water bath. Immediately after thawing the salmon should be chilled towards the desired temperature. Unfortunately, due to the absence of companies that thaw industrially, this work has not identified what this temperature would be for salmon.

Some experiments have raised new questions, which will be valuable to investigate further in the future. Development of new industrial processes for salmon thawing could benefit a lot from this work, and hopefully we will take part in such developments.

8.5 Industrial thawing of Cod

During thawing of block frozen fish, the physical size and geometry of the blocks introduces a larger spread in temperature distribution during thawing. In order to minimise the effect of this, it is important to split the blocks as early as possible.

The most important factor for the splitting time of frozen cod blocks is thawing media temperature. Salt content in thawing media is increasingly important at lower thawing media temperatures and if the blocks are very cold when they enter the thawing process. Level of agitation is also increasingly important as the thawing media temperature decreases. For thawing processes where the different blocks will have the possibility to freeze together, all these three factors will become increasingly important. For thawing in other media than water/brine (i.e. air) both salt content and level of agitation is out of the question. Thawing media temperature will however still play the most important role in reducing the process time prior to splitting of the cod blocks.

The nature of the rest of the thawing process as soon as the blocks are split, depends on the amount of energy transferred to the product during the splitting stage, and the desired product temperature after thawing. The rest of the thawing process can be heating, cooling or equalising, dependent on these other factors.

Controlled thawing applied in clip fish and fillet production offer benefits in terms of higher yield, and better quality. The product temperature should be just below the initial freezing point of the product. Normally this means that the product temperature should be approximately –1°C. It is however clear that the margins are narrow in this temperature

region, and that too low temperatures will reduce the yield. Products containing a small amount of internal ice after thawing, will give higher yields and experience lower temperatures during filleting, trimming and grading. The required energy for refreezing will therefore be reduced, thus increasing the capacity on the freezers. The reduced product temperature during processing will also reduce the risk for microbial contamination. It seems possible to reduce the overall process time for thawing down to 8 hours without compromising the yield or quality, at least for blocks of 1-3 kg cod.

New thawing methods have during the last years been introduced, but do unfortunately not take into account the thermal challenges of the traditional methods. The work carried out in this chapter should therefore still represent a solid basis in order to meet the challenges related to the new thawing solutions.

8.6 Industrial thawing of Mackerel

The initial thawing process in the company's plant was labour intensive and resulted in very large spread in the product temperature prior to filleting. Unforeseen delays due to production problems would give too high temperatures in the thawing tanks.

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- less fillet gaping and breakage,
- more efficient handling during trimming and
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All this adds up to increased capacity and better quality.

8.7 Industrial thawing in the future

First of all: Industrial thawing of fish will still be important in the future. As today there will be used many different solutions. For the large sector of the fish processing industry that will make use of thawing as a regular processing step, the most important factor to implement thawing successfully is knowledge. Knowledge about the logistical, thermal, mechanical and processing aspects of their entire production process, and ability to systematically make use of this to optimise their processes. This thesis has on three different model products shown how thawing affects quality, yield and overall capacity. This knowledge can be used as a basis in the further development of thawing process and new/improved equipment. Depending on the volume to thaw and the relative importance in the overall production, the thawing process should be differently designed and controlled. Large volume and importance will benefit from intelligent automated processes, whilst small volumes should be handled manually by clearly defined routines. Thawing of blocks will require another process than thawing of frozen single fish. Each step during thawing should be taken care of regarding; time, temperature, media flow pattern and mechanical load. The raw material and the available post thawing process equipment will be of importance for the optimum temperature of the product after thawing. The future will further bring water and energy consumption into focus. This might open for use of heat generating thawing methods (alone or in combinations with the traditionally).

9 References

[1] O. M. Magnussen and J. Slettedahl, Fag 67171 Næringsmiddelteknologi. Norges tekniske høgskole, Institutt for kuldeteknikk, Trondheim, Norway, 1994.

[2] A. C. Jason, Torry Research Station, Aberdeen, 1974.

[3] K. Sunnanå, Fiskeridirektoratets småskrifter. **7**Fiskeridirektøren, Bergen, 1970.

[4] W. Vyncke, Quality aspects of thawed fish, *Agricult* **31**(1978), 541-547.

[5] G. Londahl, Thawing of frozen meat and fish for further industrial processing, *Z Lebensm Technol Verfarenstech* **31**(1980), 163-166.

[6] K. Nilsson, Quality of Frozen Rainbow Trout. Effects of Different Freezing and Thawing Treatments. Department of Food Science, Chalmars University of technology and SIK, Gøteborg, Sweden, 1994.

[7] V. Hardarson, Matvarers termofysiske egenskaper og deres betydning ved dimensjonering av frysetunneler. Universitetet i Trondheim, Norges tekniske høgskole, Institutt for klima- og kuldeteknikk. 1995pp 141.

[8] V. Hardarson, TermFys-Lotus spreadsheet program for calculating thermal properties, (1997),

[9] I. Lind, Convective Thawing of Foodstuffs in Humid Air. **1 ed**Department of Food Engineering Lund University, Lund, Sweden, 1990.

[10] A. C. Jason, Torry Reasearch Station. 1974?pp 4331-4337.

[11] X. Zeng and A. Faghir, Experimental an d Numerical Study of Microwave Thawing Heat Transfer for Food Materials, *Journal of Heat Transfer* **116**(1994), 446-455.

[12] C. A. Miles, M. J. Morley and M. Rendell, High power ultrasonic thawing of frozen foods, *Journal of Food Engineering* **39**(1999), 151-159.

[13] A. D. Kissam, R. W. Nelson, J. Ngao and P. Hunter, Water-Thawing of Fish Using Low Frecuency Acoustics, *Journal of Food Science* **47**(1981), 71-75.

[14] O. M. Magnussen and V. Hardarson, Fag 67171 Næringsmiddelteknologi. Norges tekniske høgskole, Institutt for kuldeteknikk, Trondheim, Norway, 1994.

[15] S. V. Patankar, Numerical heat transfer and fluid flow. Taylor and Francis. 1980.

[16] M. Aursand, B. Bleivik, J. R. Rainuzzo, L. Jørgensen and V. Mohr, Lipid Distribution and Composition of Commercially Farmed Atlantic Salmon (Salmo salar), *J Sci Food Agric* **64**(1994), 239-248.

[17] O. Einen, B. Waagan and M. S. Thomassen, Starvation prior to slaughter in Atlantic salmon (Salmo salar). Effects on weight loss, body shape, slaughter- and fillet-yield, proximate and fatty acid composition, *Aquacult* **166**(1998), 85-104.

[18] G. Bæverfjord and M. Rye, Hvor lagrer laksen fettet, *Norsk Fiskeoppdrett* **11A**(1994), 35-36.

[19] S. Zhou, R. G. Ackman and C. Morrison, Storage of lipids in the myosepta of Atlantic salmon (Salmo salar), *Fish Physiology and Biochemestry* **14**(1995), 171-178.

[20] R. Plank, Die gefrierdauer von eisblocken, *Zeitschrift fur die gesamte Kalte-Industrie* **20**(1913), 109-114.

[21] D. J. Cleland, A. C. Cleland, R. L. Earle and S. J. Byrne, Prediction of thawing times for foods of simple shape, *International Journal of Refrigeration* **9**(1986), 220-228.
[22] T. R. Goodman, The heat balance integral and its application to problems involving a change of phase, *Trans ASME* **80**(1958), 335-342.
[23] J. Nagaoka, S. Takaji and S. Hohani, Experiments of the freezing of fish in an air blast freezer, *Proc 9th Int Congr Refrig* **4**(1955), 105-110.
[24] J. D. Mellor and A. H. Seppings, Thermophysical data for designing a refrigerated food chain, *Bull IIR Annexe - 1* (1976), 349-359.
[25] Q. T. Pham, An extension to Plank's equation for predicting freezing times of foodstuffs with simple shape, *International Journal of Refrigeration* **7**(1984), 377-383.
[26] Y. C. Hung and D. R. Thompson, Freezing time prediction for slab shape foodstuffs by an improved analytical method, *Journal of Food Science* **48**(1983), 555-560.
[27] P. G. Creed and S. J. James, Predicting thawing times of frozen boneless beef blocks, *International Journal of Refrigeration* **4**(1981), 355-358.
[28] A. Calvelo, Developments in Meat Science - 2. Applied Science Publishers Ltd, London, UK, 1981pp 125-158.
[29] F. Kluza, W. E. L. Spiess and D. Goral, Procedings of the 7th International Congress on Engineeering and Food. Sheffield Acadeic Press, Sheffield, 1997pp SF1-SF4.
[30] C. Ilicali, T. H. Teik and L. P. Shian, Improved Formulations of Shape Factors for the Freezing and Thawing Time Prediction of Foods, *Lebensm-Wiss u-Technol* **32**(1999), 312-315.
[31] T. Rustad, Kompendium i fag 54042 Næringsmiddelkjemi, grunnlag. NTH, Institutt for bioteknologi, Trondheim, 1994.
[32] L. Lynum, Fisk som råstoff. **2**Tapir forlag, Trondheim, 1997.
[33] CAMO, The Guideline Methodology; User Manual A. CAMO, Trondheim, 1998pp 43-137.
[34] O. R. Fennema, Comperative water holding properties of various muscle foods. Critical review relating to definitions, methods of measurement, governing factors,comparative data and mechanistic matters, *Journal of Muscle Foods* **1**(1990), 363-381.
[35] T. Rustad, E. Padget and J. Halvorsen, Forskningsprosjekt 1902-301.033. NTH, Institutt for bioteknologi, Trondheim, 1993.
[36] S. Y. K. Shenouda, Theories of protein denaturation during frozen storage of fish flesh, *Adv Food Res* **26**(1980), 275-275.
[37] R. Hamm, The effect of water on the quality of meat and meat products: Problems and research needs, in *Properties of water in foods*. (D. Simatos and J. L. Multon, eds.), M. Nijhoff, Dordrecht, Nederland, 1985, pp. 591-602.
[38] R. Hamm, Functional properties of the myofibrillar system and their measurement, in *Muscle as food*. (P. J. Bechtel, ed.), Academic Press. 1986, pp. 135-199.
[39] K. O. Honickel, The meat aspects of water and food quality, in *Water and food quality*. (T. M. Hardman, ed.), Elssevier Appl. Sci., London, 1989, pp. 277-304.
[40] T. Børresen, Nyutviklete metoder for bestemmelse av vannbindingsevne,saltbindingsevne og koketap i fiskemuskel. **663**FTFI, Tromsø, 1980pp 26.
[41] N. K. Sørensen, 23rd annual WEFTA meeting. , Gøteborg, Sweeden, 1993.

[42] H. O. Quarranta and S. S. Perez, Chemical Methods for Measuring Changes in Freeze Stored Fish: A Review, *Food Chemistry* **11**(1983), 79-85.
[43] I. M. Mackie, The effect of freezing on flesh proteins, *Food Reviews International* **9**(1993), 575-610.
[44] S. Svensson, Vad hander med fisk under fryselagring, *Livsmedes teknikk* **24**(1982), 16-19.
[45] J. Halvorsen, V. Mohr, E. Padget and T. Rustad, Raport II, NFFR prosjekt III 301.10. NTH, Institutt for bioteknologi, Trondheim, 1987.
[46] Y. H. Lan, J. Novakofski, T. R. Carr and F. K. McKeith, Assay and storage conditions affect yield of salt soluble proteins from muscle, *Journal of Food Science* **58**(1993), 963-967.
[47] A. M. Grøtli, Hovedoppgave høsten 1997. NTNU, Institutt for bioteknologi, Trondheim, 1997.
[48] H. Hellebust and T. Rustad, Rapport I, NFFR prosjekt III 301.10. NTH, Institutt for teknisk biokjemi, Trondheim, 1985.
[49] T. P. Coultate, Royal Society of Chemistry Paperbacks. 1996pp 108-111.
[50] M. L. Anderson and E. M. Ravesi, Relation between protein extractability and free fatty acid production in cod muscle aged in ice, *JFish Res Bd Can* **25**(1968), 2059-2069.
[51] J. J. Licciardello, E. M. Ravesi, R. C. Lundstrøm, K. A. Wilhelm, F. F. Correia and M. G. Allsup, Time - temperature tolerance and physical-quality tests in frozen red hake, *Journal of Food Quality* **5**(1982), 215-234.
[52] M. M. Bradford, A rapid and sensitive Method for the Quantitation of Microgram Quantities of Protein Utiliizing the principle of Protein-Dye Binding, *Anal Biochem* **72**(1976), 248-254.
[53] J. R. Bendall, The structure and function of muscle. **2**Academic Press, New York, 1973pp 243-309.
[54] O. J. Torrisen, Havbruksrapport 1997, *Fisken og Havet* **3**(1997),
[55] A. Haugland and S. Johansen, Kartlegging av ulike faktorers innflytelse på fargen i tint laks TR F4698. SINTEF Energiforskning. 1998.
[56] O. Ringdal and T. Skåra, Norconserv, Institutt for Fiskeforedling og Konserveringsteknologi, Stavanger, Norway, 1988.
[57] H. S. Jensen, Objektiv konsistensmåling på fiskekød. Fiskeriministerens forsøgslaboratorium, Lyngby, Danmark, 1985.
[58] S. Sigurgísladóttir, H. Hafsteinsson, A. Jonsson, Ø. Lie, R. Nordtvedt, M. Thomassen and O. Torrisen, Textural Properties of Raw Salmon Fillets. Nordfood project. . 1977.
[59] T. K. Heskestad, Tining og temperering av pelagisk fisk, produksjon av delvis frossen filet - Prosjektoppgave ved siv.ing. studiet. NTNU, Institutt for Klima- og kuldeteknikk, Trondheim, Norway, 1996.
[60] S. Johansen and H. Haugland, Effects of the thawing media temperature and holding time in the latennt zone during thawing of fish. SINTEF Energy Research, Trondheim, Norway, 1999.
[61] A. Haugland and S. Johansen, Temperaturnivåets og tinehastighetens innflytelse på farge i laks. Confidential SINTEF report TR4697, ISBN/ISSN 82-594-1248-9, Trondheim, Norway, 1997.

[62] S. Johansen, O. Jonassen, I. Larssen, T. S. Nordtvedt, J. Pettersen and J. Aalvik, Super freezing of fish. SINTEF Report, STF11 A94019, SINTEF Energy Research, Refrigeration and Air Conditioning, Trondheim, Norway, 1995.
[63] O. M. Magnussen and S. Johansen, Procedings from 19th International Congress of Refrigeration. IRR, Hague, 1995pp 249-257.
[64] O. M. Magnussen, Videreforedling av makrell - et innlegg på 50.års jubileet til Institutt for Klima- og kuldeteknikkk. . 2001.
[65] A. C. Cleland and R. L. Earle, Freezing time prediction for foods - a simplified procedure, *International Journal of Refrigeration* **5**(1982), 134-140.

Appendix

I Improved mathematical methods for thawing time prediction as done by Cleland et al. [21]

The equation of Calvelo [28] was rewritten in dimensionless form, including the thermal properties, so it would take into account the differences among food. The experimental data were analysed using multiple non-linear regression and resulted in:

$$Fo \cdot \frac{S \cdot D}{2 \cdot V} = 1.4291 \cdot \left(\frac{0.5}{Bi \cdot Ste} + \frac{0.125}{Ste} \right)^{1.0248} \cdot Ste^{0.2712} \cdot Pk^{0.0610} \qquad \text{(I.1)}$$

where;

$$Fo = \frac{\lambda_{thaw} \cdot t_{thaw}}{C_{thaw} \cdot D^2} \qquad \text{(Fourier Number)} \qquad \text{(I.2)}$$

$$Bi = \frac{\alpha \cdot D}{\lambda_{thaw}} \qquad \text{(Biot Number)} \qquad \text{(I.3)}$$

$$Ste = C_{thaw} \cdot \frac{T_{media} - T_{thaw}}{\Delta H_{-10°C}} \qquad \text{(Stefan Number)} \qquad \text{(I.4)}$$

$$Pk = C_{froz} \cdot \frac{T_{thaw} - T_{initial}}{\Delta H_{-10°C}} \qquad \text{(Plank Number)} \qquad \text{(I.5)}$$

V – Volume [m^3]
D – Thickness or diameter [m]
C_{thaw} – Volumetric specific heat capacity of thawed product [J/(C·m^3)]
C_{froz} – Volumetric specific heat capacity of frozen product [J/(C·m^3)]
$\Delta H_{-10°C}$ – Change in enthalpy from –10°C to 0°C [J/m^3]
$T_{initial}$ – Initial product temperature [°C]

Plank's equation (1913) was modified in a similar manner as to that used by Cleland and Earle [65] to predict freezing times, by the use of weighted multiple linear regression:

$$Fo \cdot \frac{S \cdot D}{2 \cdot V} = \frac{P}{Bi \cdot Ste} + \frac{R}{Ste} \tag{I.6}$$

where;

$P = 0.5 \cdot (0.7754 + 2.2828 \cdot Ste \cdot Pk)$
$R = 0.125 \cdot (0.4271 + 2.1220 \cdot Ste - 1.4847 \cdot Ste^2)$

The method of Pham [25], where the freezing time is calculated as the sum of the three phases; pre-cooling time, the phase-change time and the tempering time, was developed:

$$t_{thaw} \cdot \frac{S \cdot D}{2 \cdot V} = \sum_{i=1}^{3} \frac{\Delta H_i \cdot D}{\Delta T_i \cdot 2 \cdot \alpha} \cdot \left(1 + \frac{\alpha \cdot D}{4 \cdot \lambda_i}\right) \tag{I.7}$$

where;

$$\Delta H_1 = C_{froz} \cdot (\overline{T}_{thaw} - T_{initial}) \tag{I.8}$$

$$\Delta T_1 = T_{media} - \frac{\left(T_{initial} - \overline{T}_{thaw}\right)}{2} \tag{I.9}$$

$\lambda_1 = \lambda_{froz}$

ΔH_2 = Latent heat [J/m^2]

$$\Delta T_2 = T_{media} - \overline{T}_{thaw} \tag{I.10}$$

$$\lambda_2 = 0.25 \cdot \lambda_{froz} + 0.75 \cdot \lambda_{thaw} \tag{I.11}$$

$$\Delta H_3 = C_{thaw} \cdot \left(\overline{T}_{fin} - \overline{T}_{thaw}\right) \tag{I.12}$$

$$\Delta T_3 = T_{media} - \frac{\left(\overline{T}_{fin} + \overline{T}_{thaw}\right)}{2} \tag{I.13}$$

$$\lambda_3 = \lambda_{thaw}$$

$$\overline{T}_{fin} = T_{core-fin} - \frac{\left(T_{core-fin} - T_{media}\right)}{\left(2 + \frac{4}{Bi}\right)} \tag{I.14}$$

$$\overline{T}_{thaw} = T_{initial-freez} - 1.5°C \tag{I.15}$$

T_{fin} – Average final temperature throughout the product
$T_{core\text{-}fin}$ – Final product core temperature
$T_{initial\text{-}freez}$ – Initial freezing point of product

Cleland et al. [21] stated that due to the arbitrary choice of the weighting factor for λ through the three phases, the method should be considered as an empirical modification of Plank's equation. The procedure to find the average driving temperature difference ΔT_i for the three phases is also somewhat arbitrary chosen. The statement that $\overline{T}_{thaw} = T_{initial-freez} - 1.5°C$ is based on Pham's $\overline{T}_{freeze} = T_{initial-freez} - 1.5°C$ for his freezing time predictions [25], and has no physical basis apart from convenience. In 1995 Hardarson [7] introduced a mathematical method that identified the temperature at which the freezing entered the third phase, thus giving a more physical founded definition of the average driving temperature difference ΔT_i. Hardarson [7] also suggested a slightly modification of Pham's procedures to determine the λ_i . The method of Hardarson resulted in a slightly over-prediction of the freezing times, but delivered results with far less spread than any of the other methods investigated [20, 25, 26, 65]. It would have been interesting to improve the Cleland et al. (1986) modifications of Pham's method for prediction of thawing times in a similar manner as Hardarson's modification of Pham's method for prediction of freezing times, but this lies outside the scope of this work.

Cleland et al. [21] also made a direct fit of a correction to Plank's equation using an approach for freezing time prediction proposed by Pham:

$$Fo \cdot \frac{S \cdot D}{2 \cdot V} = \left(\frac{0.5}{Bi \cdot Ste} + \frac{0.125}{Ste}\right) \cdot \left(0.8941 - \frac{0.0244}{Ste} + 0.6192 \cdot \frac{Pk}{Bi}\right) \cdot \left(1 + \frac{C_{thaw} \cdot \left(\overline{T}_{fin} - T_{core-fin}\right)}{\Delta H_{-10°C}}\right) \tag{I.16}$$

Equations (I.1, I.6, I.7 and I.16) are claimed to predict thawing times for slabs of minced, lean, beef with an error between –5.4% and –7.2%, within a standard deviation of up to 8.5 compared to experiments, under the following thawing condition ranges:

$0.6 < Bi < 57.3$

$0.085 < Ste < 0.768$
$0.065 < Pk < 0.272$

The methods can also be used to predict thawing times of products with similar thermal properties (i.e. product composition) as the Tylose mix used in the referred papers.

II Thawing regulations

Kvalitetsforskrift for fisk og fiskevarer

§ 8-6. *Tining*

1. Tining av dypfryste fiskevarer er bare tillatt når det skjer i forbindelse med videre bearbeiding eller foredling.

2. Temperering og tining skal utføres på en måte som i minst mulig grad reduserer varenes kvalitet. Forurensning skal unngås og det skal sørges for effektivt avløp av eventuelt smeltevann.

3. Uansett tinemetode skal tiningen avbrytes når temperaturen i tinegodsets kaldeste punkt er -1°C. Tint fisk skal videreproduseres uten avbrudd. Det må ikke tines mer fisk enn det som kan opparbeides på samme skift som tiningen er avsluttet. Om nødvendig må tint fisk påises for å holdes ved 0°C.
[0] Endret 10 juni 1998 nr. 575.

III Analysis whether the sampling could have influenced the results of the experiments in Chapter 4.7.2

The experiment had two design variables; thawing method and thawing temperature. In addition the samples were taken from different fish and from different parts of the fish. These two factors were not controlled (unfortunately), except that the three samples in each experimental run were taken from the same region of the fish. Therefore the variables Filet sample and Fish were included in the data analysis in order to investigate whether any systematically differences in the sample preparation had occurred.

Table III.1 shows that the Filet samples do not appear to be evenly distributed among the different experiments. There are significant differences from which region of the fish the sample has been prepared for both the thawing method and thawing temperature. The fact that the properties of the salmon (ref Chapter 2.3) vary along the fillet makes this finding very unsatisfying. This is a typical example of lack of knowledge regarding how it is possible to avoid that the results are influenced by natural variation within the raw material used for sampling.

Table III.1 *Effects overview from the experiments. NS means Non Significant, whilst the * means that the uncontrolled variable (Filet sample or Fish) is badly distributed in the experimental design, thus making it difficult to draw conclusions regarding the design variables (thawing Method and Temperature).*

Variable	Filet sample	Fish
Method	***	NS
Temperature	***	NS

*** - means that the significant level is 0.1%

The first thing to study is whether the sampling is badly distributed, and secondly to evaluate the relevance of this.

Figure III.1 and Figure III.2 give a more detailed view on these effects. The fact that the green circles are not combined in one grey box means that the effect is significant at the significant level given in the figure.

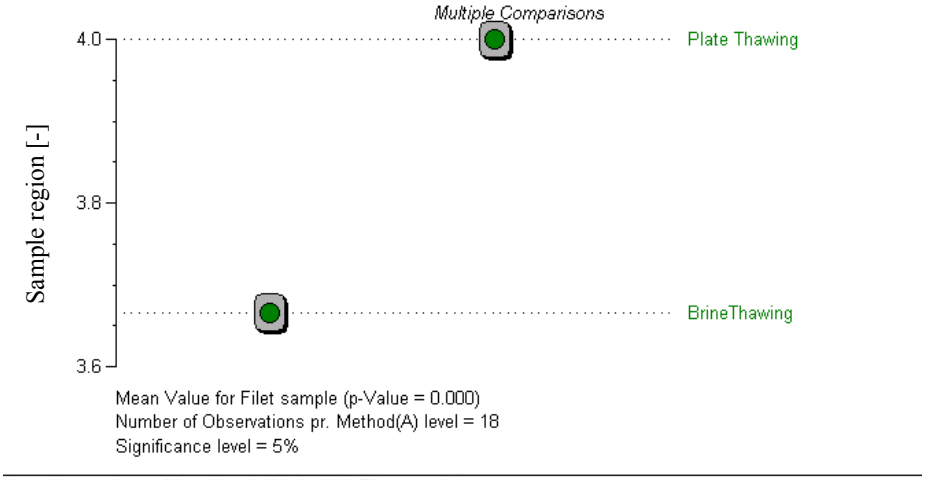


Figure III.1 *The difference in sample origin (region of the fillet) depending on thawing method.*

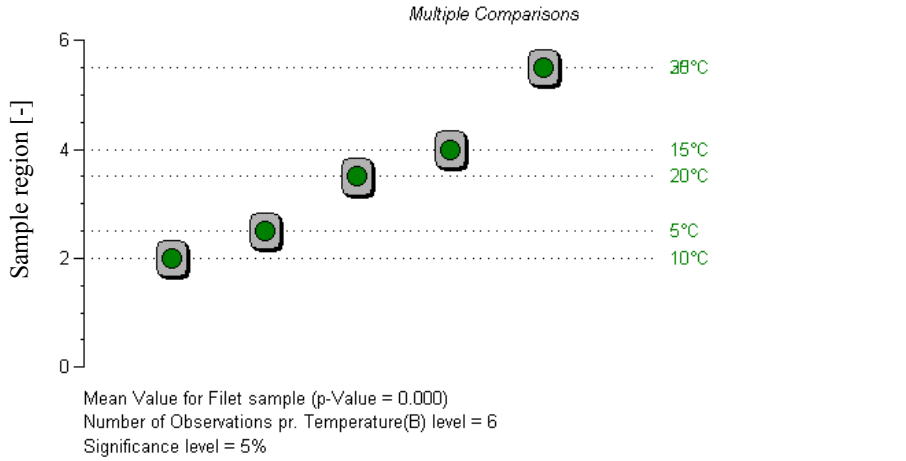


Figure III.2 *The differnce in sample origin (region of the fillet) depending on the thawing temperature.*

Figure III.1 shows that the differences is quite small 4.0 vs. 3.67, for all practical reasons this difference must be concidered small. The experiments for both thawing method are conducted with samples prepared from the area in the vicinity of region IV.

This interpretation is unfortunately not possible to make for the identified difference in sample origin connected to the different thawing temperatures used. Figure III.2 shows that only thawing at 25°C and 30°C have been conducted with samples from the same region. This means that the identified significant effects of varying thawing temperature on the response variable, is a product of the variations in initial sample properties. It is therefore not worth while to interpret the effects of this design variable.

IV Results for the experiments related to Chapter 4.7.2

IV.1 Brine thawing

Table IV.1 *Results from brine thawing*

Thawing temperature [°C]	Sample nr. [-]	WS-Proteins [%]	SS-Proteins [%]	Dry-matter [%]	WHC [%]	Drip loss [%]	pH
5	5-H-I	5,7	6,9	31,6	93,9	2,3	6,30
	6-H-I	5,9	6,6	31,1	94,4	1,2	6,32
	16-H-I	5,1	7,3	31,0	94,3	2,4	6,35
10	5-H-II	6,1	7,2	31,5	93,8	2,1	6,26
	6-H-II	6,1	7,4	31,5	94,6	1,4	6,26
	19-H-II	6,0	6,8	32,2	92,5	1,3	6,26
15	1-H-V	6,3	7,4	31,0	91,2	2,4	6,17
	2-H-V	6,6	6,7	28,5	90,5	3,1	6,20
	12-H-V	6,0	7,4	29,3	91,7	1,7	6,23
20	5-H-III	6,2	7,4	31,2	93,5	2,9	6,23
	6-H-III	6,1	7,0	31,2	94,3	1,9	6,25
	20-H-III	6,0	6,7	29,2	94,4	2,1	6,26
25	5-H-VI	6,5	7,1	28,6	91,8	1,48	6,23
	9-H-VI	6,1	6,7	27,4	92,6	2,0	6,30
	17-H-VI	6,4	6,7	28,1	94,2	1,7	6,26
30	5-H-V	5,4	6,9	29,5	90,8	3,1	6,20
	6-H-V	5,9	7,4	29,4	91,8	1,9	6,22
	18-H-V	6,1	6,3	28,6	90,5	2,4	6,15

IV.2 Plate thawing

Table IV.2 *Results from plate thawing (Also named as* ***CoreT=T-2,chill*** *in Chapter 4.7.3)*

Thawing temperature [°C]	Sample nr. [-]	WS-Proteins [%]	SS-Proteins [%]	Dry-matter [%]	WHC [%]	Drip loss [%]	pH
5	5-H-IV	6,1	7,7	31,9	95,9	4,5	6,22
	6-H-IV	6,3	8,0	30,5	96,1	2,6	6,23
	20-H-IV	5,3	8,1	29,6	95,5	6,8	6,22
10	7-H-II	5,9	7,3	32,8	94,7	4,6	6,20
	8-H-II	6,0	6,3	34,7	92,9	4,0	6,22
	9-H-II	5,3	6,3	30,7	94,3	4,6	6,29
15	I-H-III	5,9	6,1	33,4	93,8	3,2	6,18
	4-H-III	6,0	6,5	32,2	94,9	4,0	6,25
	11-H-III	6,4	5,9	32,8	94,9	2,6	6,25
20	3-H-IV	5,9	7,0	31,6	95,9	4,3	6,46
	4-H-IV	6,0	6,6	31,8	95,3	3,8	6,26
	11-H-IV	6,5	7,6	30,4	96,0	2,6	6,25
25	3-H-V	6,3	6,4	31,2	96,3	3,6	6,43
	4-H-V	6,4	7,1	30,6	93,9	3,8	6,24
	11-H-V	7,2	7,6	28,5	94,1	2,7	6,24
30	3-H-VI	5,3	6,0	29,8	95,4	4,1	6,48
	4-H-VI	5,2	7,4	29,0	94,6	3,9	6,26
	11-H-VI	5,8	7,3	28,1	93,7	2,8	6,25

V Analysis whether the sampling could have influenced the results of the experiments in Chapter 4.7.3

The experiment had two design variables; End of thawing method and thawing temperature. In addition the samples were taken from different fish and from different parts of the fish. These two factors were not controlled (unfortunately), except that the three samples in each experimental run were taken from the same region of the fish. Therefore the variables Filet sample and Fish were included in order to investigate whether any systematically differences in the sample preparation had occurred.

Table V.1 shows that the Filet samples do not appear to be evenly distributed among the different experiments. There are significant differences from which region of the fish the sample has been prepared for both the 'end of thawing method' and 'thawing temperature'.

Table V.1 *Effects overview from the experiments. NS means Non Significant, whilst the * means that the uncontrolled variable (Filet sample or Fish) is badly distributed in the experimental design, thus making it difficult to draw conclusions regarding the design variables (end of thawing Method and Temperature).*

Variable	Filet sample	Fish
End of thawing method	*	NS
Temperature	***	NS

* - means that the significant level is 5%
*** - means that the significant level is 0.1%

Figure V.1 and Figure V.2 give a more detailed view on these effects.

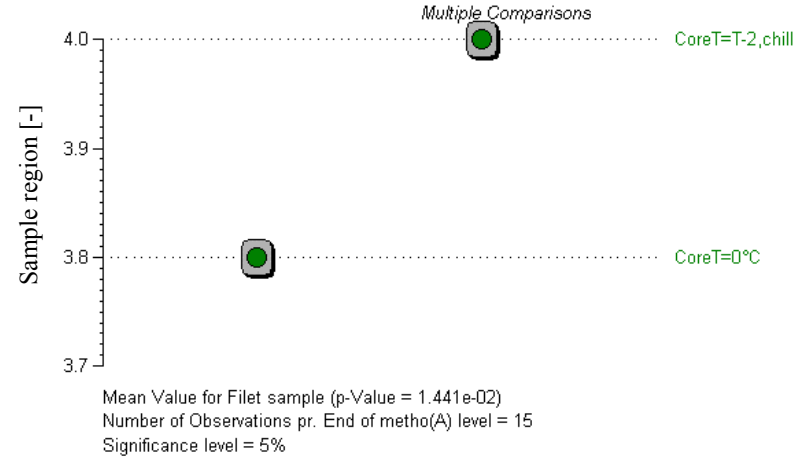


Figure V.1 *The difference in sample origin (region of the fillet) depending on the 'end of thawing method'.*

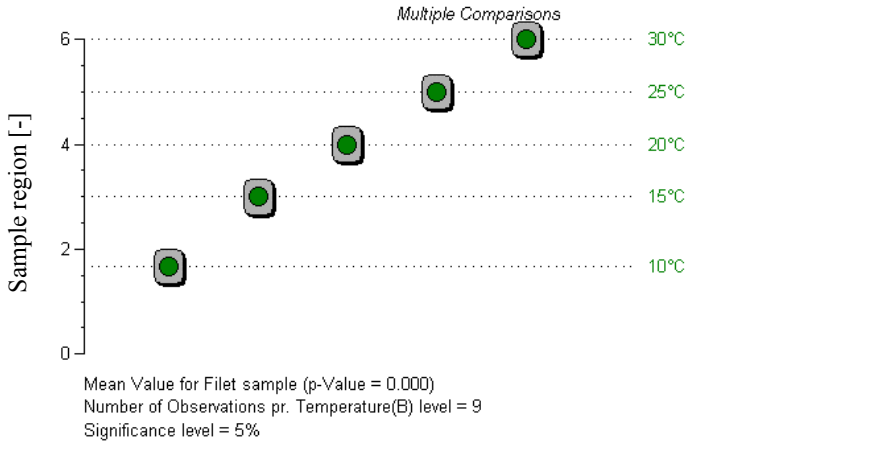


Figure V.2 *The differnce in sample origin (region of the fillet) depending on the 'thawing temperature'.*

Figure V.1 shows that the differences are quite small 4.0 (for both **CoreT=T-2,chill**, and **CoreT=T-2**) vs. 3.8 (for **CoreT=0°C**), for all practical reasons this difference must be concidered small. The experiments for all three 'end of thawing method' approaches are conducted with samples prepared from the area in the vicinity of region IV.

This interpretation unfortunately is not possible to make for the identified difference in sample origin connected to the different thawing temperatures used. Figure V.2 shows that none of the experiments with different temperature have been conducted with samples from the same region. This means that the identified significant effects of varying thawing temperature on the response variable, can be a product of the variations in initial sample properties. It is therefore not worth while to interpret the effects of this design variable.

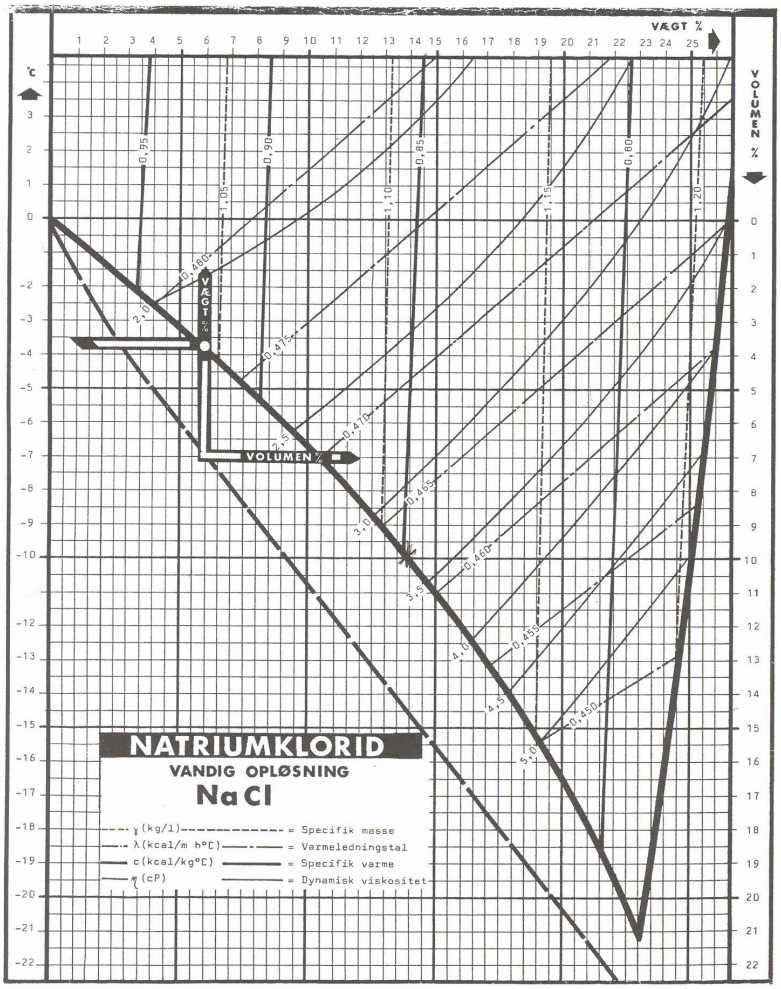
VI Results for the experiments related to Chapter 4.7.3

Results from the experiments with **CoreT = T-2,chill** are given in Table IV.2. Results for the **CoreT = T-2** and **CoreT = 0°C** are given in Table VI.1

Table VI.1 *Results from the experiments with* ***CoreT=T-2*** *and* ***CoreT=0°C.***

Thawing temperature [°C]	Sample nr. [-]	WS-Proteins [%]	SS-Proteins [%]	Dry-matter [%]	WHC [%]	Drip loss [%]	pH
CoreT=T-2							
10	7-H-II	5,9	7,3	32,8	94,7	4,6	6,20
	8-H-II	6,0	6,3	34,7	92,9	4,0	6,22
	9-H-II	5,3	6,3	30,7	94,3	4,6	6,29
15	7-H-III	5,9	8,1	32,3	95,5	4,4	6,20
	8-H-III	6,0	7,2	33,0	94,2	5,3	6,22
	10-H-III	6,1	7,1	30,1	95,2	3,1	6,25
20	7-H-IV	5,7	6,5	32,5	95,0	3,8	6,22
	8-H-IV	5,3	5,9	31,9	95,1	3,8	6,24
	10-H-IV	5,3	5,9	29,8	95,1	4,1	6,26
25	7-H-V	6,0	7,3	31,0	95,8	4,0	6,12
	8-H-V	6,4	7,1	31,7	95,5	4,6	6,22
	10-H-V	6,2	7,6	28,6	94,5	3,6	6,24
30	7-H-VI	5,8	7,0	29,9	95,4	3,4	6,21
	8-H-VI	5,8	7,3	30,4	94,8	3,6	6,23
	10-H-VI	5,8	6,8	27,0	94,5	2,9	6,24
CoreT=0°C							
10	7-H-I	4,9	6,5	32,0	95,8	2,7	6,23
	8-H-I	5,1	5,8	33,4	94,9	3,0	6,23
	9-H-I	4,4	4,3	30,7	95,1	3,2	6,31
15	2-H-III	5,1	6,1	29,7	94,7	3,7	6,21
	3-H-III	4,9	5,6	32,2	95,8	3,0	6,40
	12-H-III	5,1	62	31,9	94,5	1,6	6,21
20	1-H-IV	6,4	7,6	33,0	93,6	4,1	6,18
	2-H-IV	6,1	7,8	30,7	94,7	5,7	6,23
	12-H-IV	6,4	7,6	31,7	94,5	1,5	6,24
25	1-H-V	6,1	7,2	33,3	94,5	1,8	6,16
	2-H-V	6,7	6,4	30,2	95,5	4,6	6,24
	12-H-V	6,2	6,2	30,5	95,6	4,0	6,23
30	1-H-VI	5,7	6,3	31,1	94,4	3,7	6,14
	2-H-VI	6,2	7,4	28,8	93,6	5,4	6,19
	12-H-VI	5,8	6,7	28,6	95,7	1,7	6,20

VII Freezing point depression by the use of NaCl-brine



FigureVII.1 *NaCl brine freezing point depression.*

VIII Splitting of frozen Cod blocks

Table VIII.1 *The results according to the three approaches left out in Chapter 5.7.*

Experiment number	"Splitting time" original results (Approach 1 in Chapter 5.7.2) [Minutes]	"Degree of splitting" after a certain period - original results (Approach 3 in Chapter 5.7.2) [%]	"Degree of splitting" after a certain period - from fitted curves (Approach 4 in Chapter 5.7.2) [%]
1	345	4,6	16,5
2	120	100,0	95,9
3	220	50,0	42,4
4	140	90,5	82,3
5	260	14,3	16,5
6	140	67,7	65,2
7	300	4,4	12,6
8	140	83,3	74,8
9	260	13,6	10,8
10	140	68,2	61,6
11	180	36,4	41,2
12	120	100,0	100,0
13	240	33,3	31,0
14	140	75,0	74,9
15	220	45,8	41,9
16	120	100,0	94,8
17	140	86,4	95,9
18	140	75,0	72,7

IX Detailed temperature development during initial thawing of Mackerel

Figure IX.1 through Figure IX.5 give more detailed descriptions of the temperature distributions in the product at different stages during the thawing in the initial process. Curves that describe the probability of finding a specified temperature at the different stages of thawing, given that the temperature distribution can be described with a normal distribution function, are also shown.

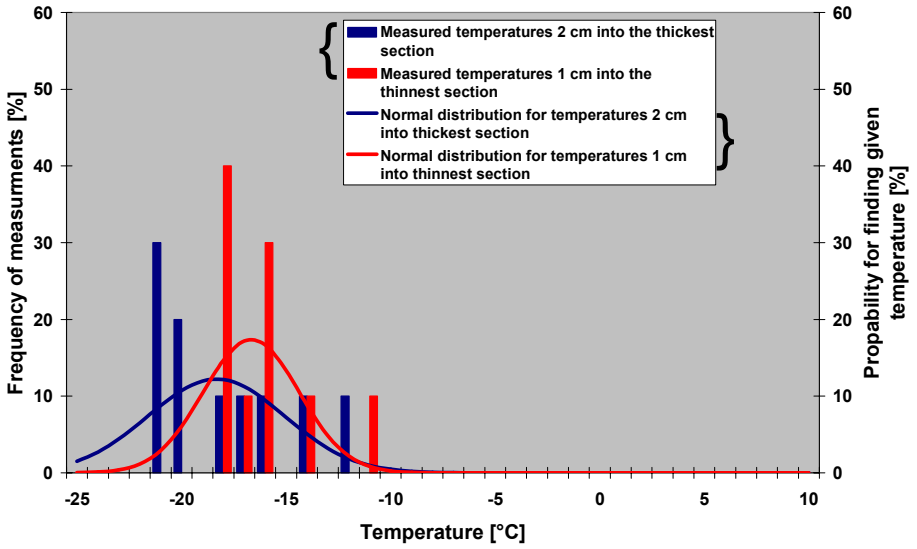


Figure IX.1 *Temperature distribution (bars) and propability for finding given temperature (curves) in the Mackerel* ***imidiately before thawing****.*

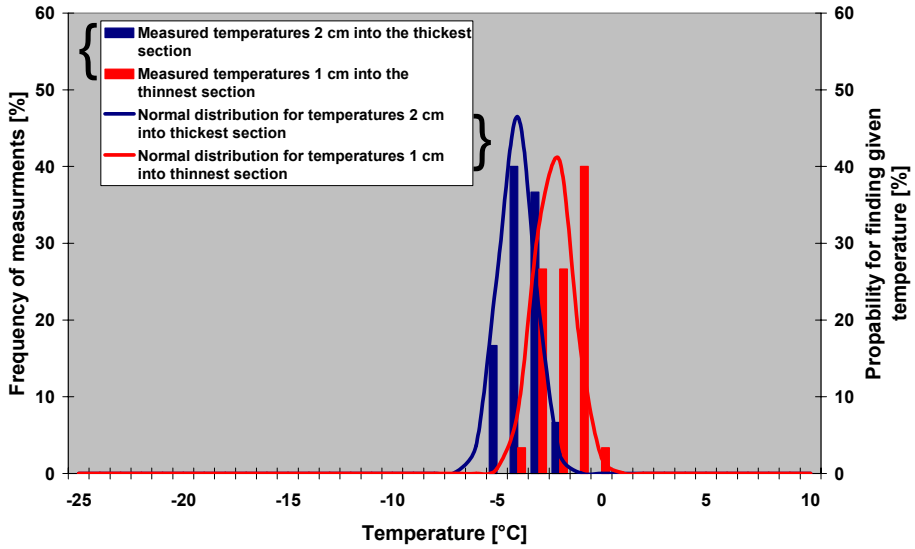


Figure IX.2 *Temperature distribution (bars) and propability for finding given temperature (curves) in the Mackerel* ***in the middle of tank 1****.*

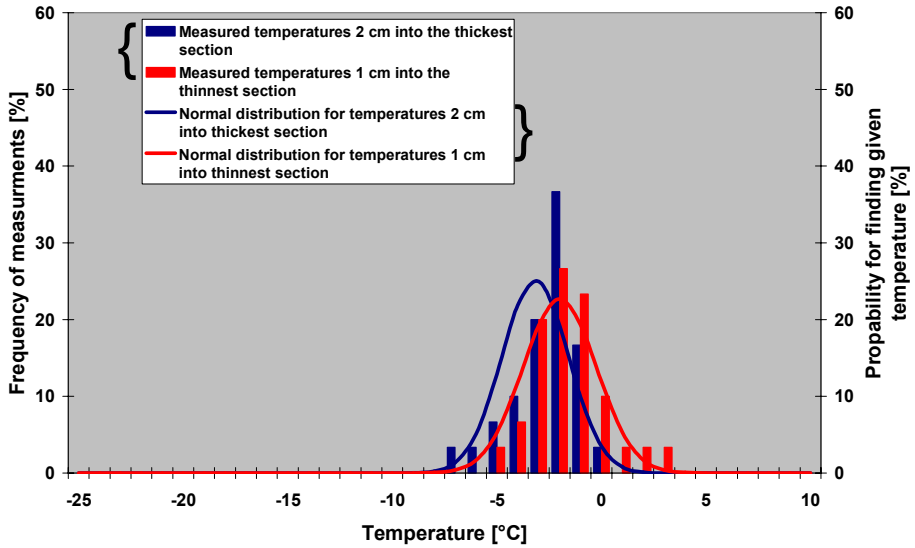


Figure IX.3 *Temperature distribution (bars) and propability for finding given temperature (curves) in the Mackerel imidiately after manual splitting of blocks* ***(between tank 1 and tank 2)****.*

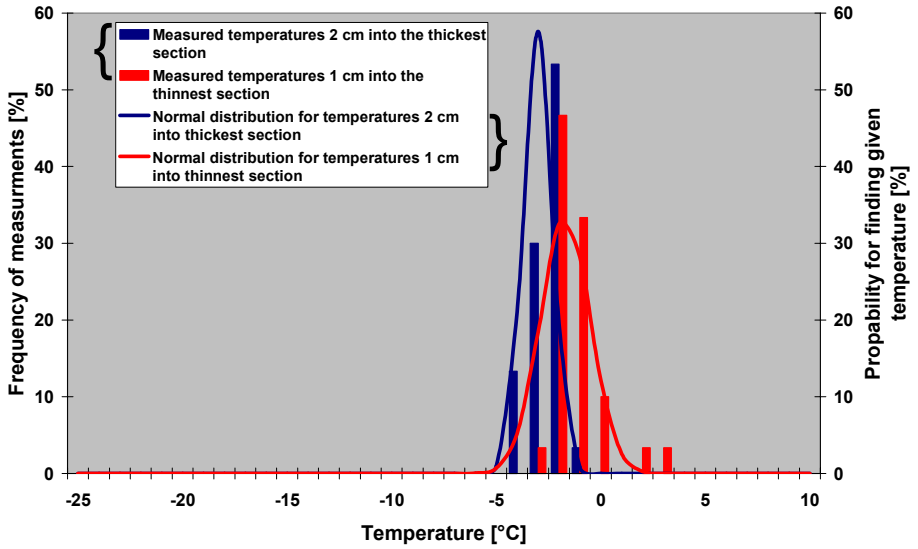


Figure IX.4 *Temperature distribution (bars) and propability for finding given temperature (curves) in the Mackerel* ***in the middle of tank 2****.*

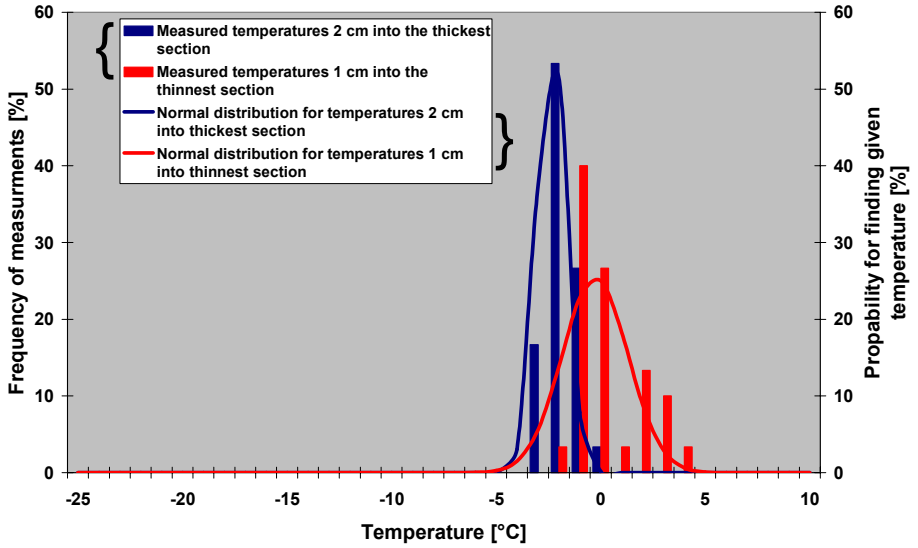


Figure IX.5 *Temperature distribution (bars) and propability for finding given temperature (curves) in the Mackerel* ***imidiately after thawing*** *(and before start of filleting).*

X Splitting of frozen Mackerel blocks

Table X.1 *The results according to the three approaches left out in Chapter 6.5.*

Experiment number	"Splitting time" original results (Approach 1 in Chapter 6.5.2) [Minutes]	"Degree of splitting" after a certain period - original results (Approach 3 in Chapter 6.5.2) [%]	"Degree of splitting" after a certain period - from fitted curves (Approach 4 in Chapter 6.5.2) [%]
1	40	100	87,8
2	80	16,7	10,7
3	40	100,0	88,2
4	100	14,9	9,2
5	40	100,0	76,1
6	40	100,0	80,4
7	140	6,8	7,6
8	60	74,4	70,6
9	180	2,3	3,1
10	60	61,3	52,1
11	160	4,8	5,8
12	100	18,2	20,5
13	40	100,0	100,0
14	40	100,0	94,0
15	60	46,5	35,5
16	60	58,1	87,8
17	100	12,2	11,7
18	100	16,7	14,4
19	80	36,4	26,3
20	80	40,9	40,6

XI Detailed temperatures and yields for Chapter 6.6 – Effect of thawing on mackerel for fillet production

XI.1 Temperatures

Table XI.1 gives a more detailed view of the mackerel core temperatures after thawing (prior filleting). The core temperature is generally higher than what we aimed at. For –2°C or below, the STDEV must be regarded low.

Table XI.1 *Fish core temperature after thawing.*

		Tempering towards				
		1°C	**2°C**	**3°C**	**4°C**	**5°C**
Temperature [°C]	**Average (n=150)**	**-0,9**	**-2,1**	**-2,7**	**-3,5**	**-4,8**
	STDEV	**0,7**	**0,3**	**0,4**	**0,4**	**0,3**
	Maximum	1,1	-1,2	-1,2	-1,4	-2,3
	Minimum	-2,0	-2,6	-3,3	-4,0	-5,1

For the experiment with tempering towards –1°C, the fish was filleted directly after tempering. The rest of the experiments, the batch was kept in boxes for some minutes before filleting. The ambient temperature was 8-10°C. Table XI.2 shows the core temperature in the thickest part of the fillets directly after filleting, whilst Table XI.3 shows the core temperature of the thinnest part of the fillets directly after filleting.

Table XI.2 *Core temperature in the fillets, measured* ***in the thickest*** *part of the fillet after tempering and filleting.*

		Tempering towards				
		1°C	**2°C**	**3°C**	**4°C**	**5°C**
Temperature [°C]	**Average (n=45)**	**4,8**	**-1,4**	**-2,1**	**-2,4**	**-3,4**
	STDEV	**0,2**	**0,5**	**0,1**	**0,0**	**0,1**
	Maximum	6,3	2,7	-0,9	-2,0	-2,2
	Minimum	1,1	-2,2	-2,7	-2,9	-4,0

Table XI.3 *Core temperature in the fillets, measured* ***in the thinnest*** *part of the fillet after tempering and filleting.*

		Tempering towards				
		1°C	**2°C**	**3°C**	**4°C**	**5°C**
Temperature [°C]	**Average (n=45)**	**5,2**	**-1,1**	**-2,1**	**-2,4**	**-3,2**
	STDEV	**0,0**	**0,5**	**0,1**	**0,0**	**0,1**
	Maximum	6,7	2,6	-0,9	-1,9	-2,6
	Minimum	3,6	-1,8	-2,6	-2,8	-3,7

XI.2 Yields

Table XI.4 *Yields related to tempering towards –1°C (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL**
Weight prior filleting [kg]	25,923	24,601	25,072	75,596
Weight after tempering [kg]	26,345	24,785	25,365	76,495
% Water uptake	1,6 %	0,7 %	1,2 %	1,2 %
Weight after filleting [kg]	17,474	15,723	16,423	49,621
% Yield after filleting	67,4 %	63,9 %	65,5 %	65,6 %
Weight after trimming [kg]	16,090	14,276	16,297	46,665
% Yield after trimming	62,1 %	58,0 %	65,0 %	61,7 %
Weight after refreezing [kg]	15,548	14,714	14,832	45,094
Overall yield	60,0 %	59,8 %	59,2 %	59,7 %
Losses during refreezing [%]	2,1 %	-1,8 %	5,8 %	2,1 %

Table XI.5 *Yields related to tempering towards –2°C (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL**
Weight prior filleting [kg]	25,291	23,961	24,965	74,217
Weight after tempering [kg]	25,410	24,108	25,058	74,576
% Water uptake	0,5 %	0,6 %	0,4 %	0,5 %
Weight after filleting [kg]	18,741	18,668	19,005	56,414
% Yield after filleting	74,1 %	77,9 %	76,1 %	76,0 %
Weight after trimming [kg]	16,541	15,946	16,357	48,844
% Yield after trimming	65,4 %	66,5 %	65,5 %	65,8 %
Weight after refreezing [kg]	16,165	15,237	15,895	47,297
Overall yield	63,9 %	63,6 %	63,7 %	63,7 %
Losses during refreezing [%]	1,5 %	3,0 %	1,9 %	2,3 %

Table XI.6 *Yields related to tempering towards –3°C (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL**
Weight prior filleting [kg]	25,515	25,746	24,462	75,723
Weight after tempering [kg]	25,459	25,921	24,557	75,937
% Water uptake	-0,2 %	0,7 %	0,4 %	0,3 %
Weight after filleting [kg]	17,212	17,365	16,533	51,110
% Yield after filleting	67,5 %	67,4 %	67,6 %	67,5 %
Weight after trimming [kg]	16,535	16,567	15,471	48,573
% Yield after trimming	64,8 %	64,3 %	63,2 %	64,1 %
Weight after refreezing [kg]	15,630	15,835	14,945	46,410
Overall yield	61,3 %	61,5 %	61,1 %	61,3 %
Losses during refreezing [%]	3,5 %	2,8 %	2,2 %	2,9 %

Table XI.7 *Yields related to tempering towards –4°C (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL**
Weight prior filleting [kg]	26,868	25,601	26,211	78,680
Weight after tempering [kg]	26,845	25,658	26,252	78,755
% Water uptake	-0,1 %	0,2 %	0,2 %	0,1 %
Weight after filleting [kg]	18,942	17,908	18,522	55,372
% yield after filleting	70,5 %	70,0 %	70,7 %	70,4 %
Weight after trimming [kg]	17,012	16,296	16,706	50,014
% Yield after trimming	63,3 %	63,7 %	63,7 %	63,6 %
*) Weight after trimming [kg]	16,790	16,174	16,632	49,596
*)% Yield after trimming	62,5 %	63,2 %	63,5 %	63,0 %
Weight after refreezing [kg]	15,870	16,040	16,430	48,340
Overall yield	59,1 %	62,7 %	62,7 %	61,4 %
Losses during refreezing [%]	4,3 %	1,0 %	1,1 %	2,1 %

***** The fish were weighed once more after the process water had had a chance to drain from the box. This was done to investigate the effect of the process water. The procedure was not repeated for any of the other experiments.

Table XI.8 *Yields related to tempering towards –5°C (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL N=3**	**TOTAL N=2**
Weight prior filleting [kg]	26,441	25,681	24,742	76,864	50,423
Weight after tempering [kg]	26,611	25,315	24,917	76,843	50,232
% Water uptake	0,6 %	-1,4 %	0,7 %	0,0 %	-0,4 %
Weight after filleting [kg]	17,717	16,993	16,278	50,,988	33,271
% Yield after filleting	67,0 %	66,2 %	65,8 %	66,3 %	66,0 %
Weight after trimming [kg]		15,996	15,484		31,480
% Yield after trimming		62,3 %	62,6 %		62,4 %
Weight after refreezing [kg]		15,788	15,097		30,885
Overall yield		61,5 %	61,0 %		61,3 %
Losses during refreezing [%]		0,8 %	1,6 %		1,2 %

XII Detailed yields for Chapter 6.7 – Full scale simulation of the new process

Table XII.1 *Yields related to tempering towards –2.7°C (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL**
Weight prior filleting [kg]	26,451	26,738	26,722	79,911
Weight after tempering [kg]	26,808	27,156	26,934	80,898
% Water uptake	1,3 %	1,6 %	0,8 %	1,2 %
Weight after filleting [kg]	18,955	19,128	18,984	57,067
% Yield after filleting	71,7 %	71,5 %	71,0 %	71,4 %
Weight after trimming [kg]	18,006	18,102	17,219	53,327
% Yield after trimming	68,1 %	67,7 %	64,4 %	66,7 %
Weight after refreezing [kg]	16,665	16,145	16,434	49,244
Overall yield	63,0 %	60,4 %	61,5 %	61,6 %
Losses during refreezing [%]	5,1 %	7,3 %	5,3 %	5,1 %

Table XII.2 *Yields related regular production (n=50 in each parallel).*

	Parallel 1	**Parallel 2**	**Parallel 3**	**TOTAL**
Weight prior filleting [kg]	25,359	24,858	26,284	76,501
Weight after tempering [kg]				
% Water uptake				
Weight after filleting [kg]	16,458	16,125	17,242	49,825
% Yield after filleting	64,9 %	64,9 %	65,6 %	65,1 %
Weight after trimming [kg]	15,837	15,894	16,698	48,429
% Yield after trimming	62,5 %	63,9 %	63,5 %	63,3 %
Weight after refreezing [kg]	14,954	15,270	16,130	46,354
Overall yield	59,0 %	61,4 %	61,4 %	60,6 %
Losses during refreezing [%]	3,5 %	2,5 %	2,2 %	2,7 %