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# Energy efficient and high quality thawing of cod in large scale

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# MASTER THESIS

for

Student Andreas Wahl

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**Energy efficient and high quality thawing of cod in large scale**

*Energieffektiv tining av torsk i stor skala med vekt på høy kvalitet på råstoff*

## Background and objective

The whitefish industry has a strong political focus in Norway the past few years, due to low profitability. The project "QualiFish" is focusing on the challenges of large volume fluctuations and product quality through the development of market adapted production concepts and novel technology, with research and innovation at its core. The project goal is to develop new knowledge and technology to increase sustainability and profitability of cod production in Norway, enabling actors to meet market demands for safe products with high quality and at sufficient volumes all year round.

In connection to the thawing of the fish, one of the largest challenges is the variation in temperature after the period estimated for the thawing. Pelagic fish and white fish are mainly frozen in blast freezers and plate freezers. The single fish attached to each other, freezes like a block depending on different factors like free water, pressure, packing etc. The geometry make the heat transfer difficult during the thawing process and is one of the reasons that the variation in temperature is large after the thawing period. In industrial thawing process, the product will in a large extent be as a block up to the end of the thawing period is finished. In connection with the introduction of the continuous thawing system the intension is to investigate the possibility to split the block of fishes mechanically at an early stage, to be able to use the thawing period thaw or temper the single fish. An important aspect is to perform the thawing with a minimum of energy input.

The master work will be based on practical experiments and modelling of the thawing system and the single fish and the block of several fishes. A visit to a production facility that will be used as a case for the master thesis work.

**The following tasks are to be considered:**

1. Literature review (published papers) of different thawing systems for fish industry
2. Evaluate thawing procedures for different freezing methods and fish packing
3. Develop models for calculations of the thawing process to evaluate the optimum thawing procedure
4. Evaluate a given case regarding to quality, efficient thawing and energy efficiency
5. Make a draft scientific paper of the main results in the thesis
6. Make proposal for further work

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to "Regulations concerning the supplementary provisions to the technology study program/Master of Science" at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. The final report in Word and PDF format, scientific paper and all other material and documents should be given to the academic supervisor in digital format on a DVD/CD-rom or a memory stick at the time of delivery of the Master Thesis.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2017

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# Summary

Thawing of block frozen cod is the main challenge of the overall industrial process due to the large variation in temperature after processing. The geometry makes the heat transfer slow and further difficult to conduct a precise thawing process. Controlled thawing, however, can give higher yield due to a cleaner cut along the backbone caused by a level of firmness at temperatures just below the initial freezing point. Industrial thawing aim to result in quality comparable to fresh fish for further processing. Yield and energy use influence the profitability whereas bacterial growth determine the shelf life of the resulting product. Hence, the aim is to operate the thawing process in an optimal way with respect to yield, bacterial quality and energy use.

In this work, thawing as a part of industrial processing is introduced. The preliminaries include basic principles of thawing methods and the literature survey of different thawing procedures. The complexity of the block split is yet only investigated for the water thawing process. The investigations on other techniques were mostly conducted with fillet pieces and show a possible thawing time reduction of up to 80%. The producers offer process solutions in various size or in modular build up. Thus, all introduced techniques are availability for large scale thawing.

A two-dimensional model was developed to simulate to thawing process. By a Kirchhoff- and enthalpy transformation, a partial differential system with two mutually related dependent variables was solved to deal with the abrupt changes of the thermophysical material properties. The influence of the process temperature on bacterial quality of the product was evaluated by integration of the temperature distribution.

Basic investigation on single fish thawing delivered a guideline for thawing regarding time, temperature and bacterial growth. The temperature distribution during thawing shows that the surface temperature is reduced within 30 minutes after the transfer to the chill media. The core temperature rises during the chill time due to the enthalpy equalization. Thus, the final core temperature depends on the transferred energy during the bath time. The split times were compared with the time frame to temper the core into the latent heat zone. The results revealed adverse characteristics of high thawing media temperatures at expected split times.

The block thawing model was used to simulate the expected split times at particular temperatures. The temperature range between 7 and 11˚C showed the best performance due to the balance between fast and precise thawing. The split time was varied to investigate the effects of enhancing the block split. The positive effect of the block split acceleration is especially strong for higher temperatures. Thus, fast splitting shifted the recommendations towards higher process temperatures. The quality evaluation showed no significant difference between the different split times and that thawing above 7˚C isn’t increasing the bacterial growth.

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# Nomenclature

| | | |
|---|---|---|
| a | - | Redness |
| b | - | yellowness |
| cp | kJ/kgK | Specific heat |
| E | W/m | Kirchhoff function |
| E‘ | - | Dielectric constant |
| E“ | - | Dielectric loss factor |
| h | $W/m^2K$ | Surface heat transfer coefficient |
| H | $J/m^3$ | Volumetric enthalpy |
| k | W/mK | Thermal conductivity |
| L | - | Lightness |
| m | kg | mass |
| t | s | time |
| T | K/˚C | Temperature |
| x | - | Mass fraction |
| | | |
| greek | | |
| $\Delta$ | | delta |
| $\rho$ | $kg/m^3$ | density |
| $\nabla$ | | Gradient |
| | | |
| Sub/super-scripts | | |
| * | | Reference |
| e | | water |
| f | | freezing |

| | |
|---|---|
| i | index |
| v | volume |

# Abbreviations

| | |
|---|---|
| ABF | Air blast Freezing |
| ABT | Air blast thawed |
| BC | Bacterial count |
| BD | Bacterial deterioration |
| DP | Dielectric properties |
| EC | Electrical conductivity |
| ES | Electrode size |
| LN | Liquid Nitrogen |
| H/G | Headed and gutted |
| HP | High Pressure |
| HPP | High Pressure Processing |
| HPT | High Pressure Thawing |
| MW | Microwave |
| MYO | Myofibrillar protein fraction |
| PAT | Pressure Assisted Thawing |
| PIT | Pressure Induced Thawing |
| PSF | Pressure Shift Freezing |
| RF | Radio frequency |
| RRS | Relative Rate of spoilage |
| RSW | Refrigeration Seawater |
| RT | Room temperature |
| SAR | Sarcoplasmic protein fraction |
| SL | Spoilage level |
| SS | Sample size |
| SSO | Specific spoilage organism |

| | |
|---|---|
| TBA | Thiobarbituric acid |
| TMA | Trimethylamine |
| TMA-N | Trimethylamine nitrogen |
| TVB-N | Total volatile basic nitrogen |
| VBN | Volatile basic nitrogen |
| VC | Vacuum cooling |
| VHT | Vacuum heat thawing |
| WIT | Water immersion thawing |

# 1 Introduction

Supply of fresh raw material often is dependent on seasonal variations, weather conditions, quotas and regulations makes it necessary to use frozen raw fish in the processing industry. A large part of the commercial catch of Atlantic cod (Gadus morhua) is headed and gutted and frozen at sea in plate freezers, typically 1-6 hours after the catching. Before further industrial processing thawing is necessary. Thus, thawing is an important industrial process. If Atlantic cod is correctly frozen, stored and thawed industrially, the quality can be good and of comparable quality to fresh fish (Haugland, 2002).

The methodology and technique used for freezing and thawing processes is important to preserve the quality of frozen foods. It is essential to build up knowledge on various parameter to improve the processes and be able to deliver higher quality product. Many different thawing methods are used for frozen fish but the selection of the method is dependent on factors such as fish size and species (Alizadeh, 2007).

Thawing in room air has been most commonly used in the processing industry due to the relatively small or neglectable need for investments. The low heat transfer coefficients make this method very time consuming and are not recommended from a quality and microbiological point of view. An uncontrolled thawing process can lead to economically losses in several ways: reduced yield and quality, more handling, lack of traceability, capacity reduction and more complex production planning (Haugland, 2002). The most common methods used in industry today are thawing in water vessel and air thawing in tunnels (Archer, 2008).

Thawing of block frozen products is the main challenge of the overall industrial process due to the large variation in temperature after processing. The frozen blocks stick together due to frozen water and will in a large extent be as a block up to the end of the thawing period is finished (Haugland, 2002). The geometry provides an uneven heat transfer during the thawing process. In order to minimize the effect of this, it is important to split the blocks as early as possible, to be able to treat the single fish.

Controlled thawing with an accurate post thawing treatment increase the yield. A tempering towards just below the initial freezing point, with a small amount of internal ice leads to a cleaner cut along the backbone (Haugland, 2002). Thawing equipment, however, most likely does not lead to a controlled process that meets the introduced demands. It is evaluated in this report how controlled thawing can be performed.

# 2 Objectives

The whitefish industry has a strong political focus in Norway the past few years, due to low profitability. The project “QualiFish” is focusing on the challenges of large volume fluctuations and product quality through the development of market adapted production concepts and novel technology, with research and innovation at its core. The project goal is to develop new knowledge and technology to increase sustainability and profitability of cod production in Norway, enabling actors to meet market demands for safe products with high quality and at sufficient volumes all year round. High quality frozen/thawed raw material can contribute to a more continuous production throughout the year, enabling the Norwegian whitefish industry to supply the market with high quality products during the entire year.

In this thesis, the state of the art of different thawing systems for fish industry was evaluated. The literature review of published papers revealed development potential and beneficial application areas for each of the mechanisms.

Furthermore, a numerical model was developed to investigate the thermal characteristics of water thawing. The thawing of single fish was investigated to provide a basic understanding on the interaction of heat transfer and equalization in the fish.

The objective of the work was to deliver recommendations for the block thawing process. The adjustment of process parameters intents to achieve an optimum regarding yield, quality and energy efficiency. It is important for the industry to know how to control the process to deal with market demands.

# 3 Industrial thawing

## 3.1 Introduction

Freezing is an essential part of shelf life extension for fish and its by-products. Fish is frozen as headed and gutted (H/G) on board a trawler and shall be filleted and processed in a factory on shore. In the production chain the raw material cannot be processed if still in frozen state. Therefor gentle and effective thawing techniques are required in order to obtain a high quality product.

To understand the process of thawing it is important to understand the process of freezing, as 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. 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 mixture of water, fat and protein this phase change will take place at a gliding temperature. This is due to the equilibrium between ice and the water solution (Backi, 2015).

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. The temperature of the frozen product in the tempering phase is increased until the melting of ice within the product is accelerated. The rest of the ice melts during the latent zone phase at almost constant temperature of the product. After all the ice has melted, the product enters the heating phase. The temperature increases rapidly as a result of further energy supply.

Thawing is more difficult to carry out with respect to predictability and controllability. The developing water layer results in an increased heat flow resistance as the thawing proceeds. In other words, frozen water is a better conductor of heat than liquid water. It is a practical problem to monitor the core temperature, since the frozen product is hard thus making it difficult to insert a thermocouple with sufficient accuracy. However, it is important to point out that the product temperature is a very important factor for product quality and process yield (Haugland, 2002).

## 3.2 Methods acting through surface

Heat transfer between two objects or across a single object that happens through a material medium and does not involve any fluid motion is called conduction heat transfer. An example of conduction is heat transfer from the warm surface to the cold inner domain of fish during thawing. The heat conductivity varies greatly for different physical conditions.

Heat transfer between an object and the adjacent moving fluid is called convection heat transfer. A necessary condition for convection heat transfer is, that there is a temperature difference between the object and the surrounding fluid. There are two ways that convection heat transfer is created around an object. If the fluid motion is generated by a fan or a pump, it will be called forced convection. An example for forced convection is a warm airflow over the cold surface of fish. On the other hand, if the fluid motion is generated by a density difference due to a temperature difference in it, the convection is called free convection. An example for free convection is the heat transfer mechanism responsible for thawing frozen fish blocks surrounded by still air. Generally, convection heat transfer coefficient in a liquid is a few orders of magnitude larger than that in a gas. Higher velocity fluid has higher convection heat transfer coefficient, due to the fact that heat transfer coefficient in turbulent flows being larger than in similar smooth laminar flows. The heat transfer depends on the thawing media properties, circulation characteristics and the composition and geometric size of the thawing object. Either the energy transfer to the surface from the thawing media or the transfer through the thawed material into the freezing front will determine the speed of the process.

### 3.2.1 Water thawing

Water thawing techniques are widely used in industrial applications. They are often called immersion thawers, as the fish block is immersed inside a water container. The majority of all water-based thawing techniques are notably faster than air thawing methods as the heat exchange rate in heat conduction problems is higher than for heat convection problems.

One method is to use rectangular tanks of varying size (roughly 0.3-1 $m^3$), which are filled with water and fish blocks. This method represents a batch process as it is no continuous operation. The performance of the practical solution depends on many factors. The location, arrangement and water supply of the thawing containers influence the water flow in, through and between the containers. To secure sufficient fluid flow the products have to be stacked equally. This process can be operated in two ways, either by exchanging the thawing medium consistently or by conducting thawing with a fixed amount of water. It is recommended to exchange the thawing medium consistently, due to the fact that the thawing capacity gets reduced as a result of the water being cooled (Backi, 2015).

A water hose is consistently pumping water into the tank and thereby exchanging the water present in the tank. Stacking the containers on top of each other results in water flowing from one and into the next ones. A way to reduce thawing time is to pump small air bubbles into the tank. Agitation assists the separation of single fish from the block leading to an increased area of heat exchange. Control of the thawing media temperature leads to a more accurate thawing time predictability. Accurate post thawing treatment keeps the fish in appropriate condition for further processing.

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 (Haugland, 2002).

### 3.2.2 Air thawing

Air thawing can occur in several configurations. It is either conducted with still air or an air blast. Thawing in still air means that a fish block is thawed only by non-moving air surrounding it. The heat exchange rate is very low and thus takes a long time to thaw the entire fish block. The process can be accelerated by putting the fish block on a grate, such that the surrounding air can act also on the underside of the block. Further acceleration can be achieved by separating single fish from the block leading to a larger area and thus to faster thawing. Thawing in still air can be conducted, either at chill (0-4°C) or ambient temperatures but should not exceed 20°C (Waterman, 2001). Facilities for supplying heat to the room in which the product is laid out to thaw may be required. The seafood is then left for a period of time, usually overnight, until it’s thawed.

Air blast thawing is a common method widely used in industrial applications. It follows the same principle as thawing in still air, but in contrast the air is forced to move over and around the fish’s surface. Compared to thawing in still air, flowing air leads to a higher rate of heat exchange.

In practice, both continuous and batch thawers can be found. An air blast tunnel most commonly comprises a unit containing fans to circulate warm, moist air around a large chamber in which the seafood is placed. A water spray system is used to secure a high moist content in the air. Heat is provided by banks of finned hot water pipes placed in the air stream close to the fan and air temperature is regulated by thermostats.

For batch thawers fish blocks or single fish are put on trays which can easily be stacked on trolleys with enough space in between. This is important in order to have a uniform flow of air inside the chamber into which the trolleys are moved. Not only the space between trays, but also the space between trolleys is important for the air to flow in an optimal way. For a uniform thawing of all blocks inside the batch thawer it is important to have a reversible fan blowing air from both directions along the length of the chamber. A high relative humidity is advantageous in this process. Air blast technique can also operate on a continuous basis. Therefor conveyor belts are used to move the product under the stream of air.

### 3.2.3 Vacuum thawing

Vacuum thawing bases on the principle that the boiling temperature of water is lowered as the pressure is decreased. Thus a thawing temperature can be chosen to transfer latent heat of vaporization into the product. Steam is released in the vacuum chamber at the applied pressure and will condense at the surface of the fish. The technique allows the water vapour to get into air cavities in between single fish. The system can be controlled by regulating the pressure within the chamber.

Vacuum thawing is a batch process. A pump empties the air out of the thawing chamber and water, which is located in the chamber, is heated such that it boils and becomes water vapour (Carver, 1975).

### 3.2.4 Contact thawing

Plate frozen raw material is particularly suitable for contact/plate thawing. Contact thawers typically consist of parallel metal plates which are contacted with the thawing product. These thawers have two advantages: The fish block is not in direct contact to the thawing media and the process is controllable in a better way due to the fact that heat transfer in plate thawers is well understood (Backi, 2015).

## 3.3 Methods acting in the product

There are situations in which there is no medium between two objects that hold different temperatures and somehow face each other. Thus heat transfer happens through the exchange of electromagnetic waves or photons and is known as radiation heat transfer. The second big group acts directly in the inner domain of the fish block.

The heat is generated by the use of microwaves, ultrasound, dielectric methods or electric resistance within the product. The different energy forms are all transformed to thermal energy. Volumetric heating is a term used for technologies that cause heating to occur throughout the whole volume of a material. This can result in significant process and quality benefits when applied to food processing (Maloney, 2016).

### 3.3.1 Dielectric thawing

Dielectric thawing is a collective term for all sorts of thawing methods that use high-frequency waves in order to thaw foodstuff. The commonly used frequencies are either in the range 27 to 100 MHz for radio-frequency (RF) - or 915 to 2450 MHz for microwave (MW) - based methods. To roughly classify dielectric thawing methods one can define RF in MHz and MW in GHz range.

In an oscillating electric field, the molecules start rotating and colliding with other molecules and thus heat is generated inside the fish. The high-frequency waves are mainly absorbed in the boundary layer thus they do not take effect in the inner spatial domain of the object. The boundary layers will heat up faster than the inner layers. The penetration depth of an applied frequency is directly related to the thawing impact of the method.

In microwave heating thermal runaway can occur. This problem is intensified by the fact that liquid water absorbs more energy than ice. Thus parts of an irregular shaped fish can be overheated or cooked while other parts remain frozen. Due to the thermal properties it is not possible to get an even temperature distribution. The penetration depth for microwave oven is not more than a few centimeters. Partial Thawing or tempering to just below the freezing point is a common use for microwave heating in industrial application (James, 2005).

Radio frequency treatments have more promising attributes for processing seafood. At lower frequencies the penetration depth of energy into food is much higher. Thus, the temperature within the product is more equal distributed.

Dielectric properties (DPs) govern the interaction between RF radiation and food. It is necessary to know the properties to adjust the RF treatment. Thus, the availability of DPs of food is important for the industrial application of RF technology. The dielectric behaviour of food can be described by the two factors. The dielectric constant E' quantifies the ability of the product to store electromagnetic energy and the dielectric loss factor E'' the ability to dissipate the electromagnetic energy.

A number of factors affect the DPs of foodstuffs, such as temperature, frequency, chemical composition and the state of moisture as has been reported by (Venkatesh, 2004). The Temperature dependence is quite complex. It may increase or decrease with temperature depending on the material. To solve a practical problem it is not always necessary to understand that complexity. The dependency of chemical composites showed significant influence on different water and salt content (Piyasena, 2007).

### 3.3.2 Electric Resistance thawing

A high frequency alternating voltage is applied to foodstuff through sandwiching the product between electrodes. Heat is generated when an electric current passes through. The thermal properties of a frozen fish block depends on its temperature. As the temperature increases, the rate of heating also increases. The decreasing specific resistance near the thawing temperature makes the process more suitable for removing the latent heat in comparison to tempering the product. For an optimal performance, electric resistance thawing should be combined with a conventional thawing technique.

During ohmic heating there is a conversion of electrical energy into thermal energy. Food with an electrical conductivity in the range of 0.1-10 S/m can always be heated by means of ohmic heating. The voltages used lie between 400 and 4000 V. Field strengths in the range of 20-400 V/cm result when electrode gaps of 10-50 cm are used (Jaeger, 2016).

Based on Ohm's law, this current flow leads to energy input. The technique is characterized by nearly complete conversion of the electrical energy into heat, high energy density and short heating times.

A critical parameter in the design and operation of ohmic heaters is the electric conductivity of the food being processed. Some components increase electrical conductivity and some tend to decrease conductivity. Generally, electric conductivity increases with temperature. At room temperature an estimation using a linear relationship can be made (Maloney, 2016).

The required electrical output can be calculated from the mass flow, temperature increase and specific heat capacity based on the product and taking into consideration the product properties. To achieve the greatest possible uniformity of heating, the electrode geometries used are usually adapted to the product properties. This is important when using ohmic heating as a continuous flow method, since in such a case aspects of the product flow have to be taken into account (Jaeger, 2016).

As with conventional heating, the effectiveness of ohmic heating as a thermal process for inactivating microorganisms depends on the temperature reached at each point of the food and the corresponding holding time.

### 3.3.3 High Pressure thawing

High pressure processing uses the effect of depressing the thawing temperature of water as the pressure rises. It is possible to lower the freezing point to -21°C at a pressure of 210 MPa. Two different methods are used for conducting thawing under high pressure. Pressure Assisted Thawing (PAT) is operated at constant pressure by increasing the temperature. The Heat is transferred between the pressurized chamber and a thawing medium. In Pressure Induced Thawing (PIT) the phase change is initiated by a pressure change. Further heat exchange is conducted at constant pressure (Figure 1).

Pressurization in a thawing process has mainly two advantages. The decrease of the melting point increases the temperature difference between the pressurizing fluid temperature and the thawing object during phase change. This leads to an enhanced heat flux rate. Also the latent heat is reduced with increasing pressure. Both effects result in a faster thawing process when compared to those corresponding to atmospheric pressure.

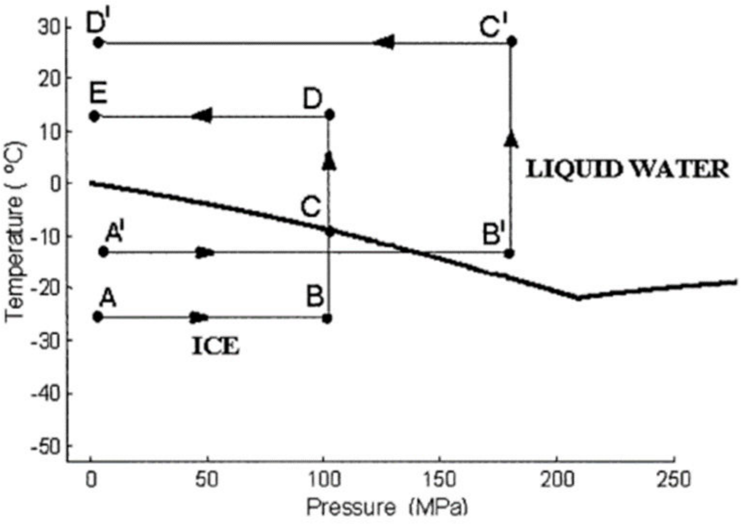


Figure 1: High-pressure thawing processes: ABCDE: pressure assisted thawing, A'B'C'D': pressure induced thawing (Otero, 2003)

Lag time in processing food with high pressure application can lead to non-homogeneous conditions in the volume of the sample and results in a non-homogenous thawing process. Thus phase transition is not conducted under a constant pressure, which results in a pressure induced thawing near the surface and pressure assisted thawing at the centre of the product.

# 4 Evaluation of thawing procedures of frozen fish

## 4.1 Evaluation methods

In general, thawing of fish is evaluated through thawing time and resulting quality. Sensorial analysis can be used to assess the quality of food. Through these analyses the product samples are described by sense impression and physical attributes like structure and colour. However, sensorial analyses are expensive, time consuming and sometimes difficult to run for various reasons. This has put forward a demand to come up with chemical and physical methods for assessing the product quality of fish. Objective parameter that indicate the quality of a fish product are (Lynum, 1997):

- Physical
    - colour
    - texture
    - water holding capacity
    - dry-matter content
    - drip loos
- Chemical
    - pH
    - total volatile basic nitrogen (TVB-N)
    - thiobarbituric acid (TBA)
    - trimethylamine (TMA)
    - myofibrillar and sarcoplasmic protein fraction (MYO + SAR)
    - amount of water/salt soluble proteins
- Microbial
    - total aerobic mesophilic bacteria
    - yeast and mould count

## 4.2 Water immersion thawing

The performance of water thawing varies greatly over the set of process parameters. In general, a water thawing process is affected by these factors:

- Thawing media temperature
- Salt content in the thawing media
- Pre thawing temperature and size of the blocks
- Level of agitation
- Flow system
- Velocity distribution of thawing media

In this chapter water thawing of different fish fillets and cod blocks will be described.

### 4.2.1 Effect of water thawing on salmon filet

(Haugland, 2002) deals with thawing of salmon, mackerel and cod. His work focuses on quality, yield and throughput. With Salmon different aspects of thawing are investigated. The conclusions in this part can help to understand thawing in general and thus helps in the existing issue of thawing cod.

Heat transfer through conduction and convection is compared. It is found out that water thawing is more efficient than contact thawing at the same thawing temperatures of 20˚C. Contact thawing leads to a higher drip loss than thawing in water. Both thawing systems result in fairly good quality because of the very rapid thawing at this temperature.

Further, different principles to end the thawing are compared. Under the chosen methods no significant differences were found. So the easiest to carry through is chosen to conduct thawing experiments. Thawing is being stopped when the core temperature of the coldest sample reaches a temperature 2 K below the thawing media temperature and where chilled in ice prior to the analysis.

The thawing speed and temperature is investigated in regard to colour and weight loss of the raw fish. To reduce the drip loss during thawing it is important to thaw the salmon as fast as possible. Thawing can be accelerated through a high heat transfer coefficient. Therefor a suitable use of thawing media, flow condition and product packaging is required. Regarding colour loos the results can be separated into two temperature areas. Thawing between 0˚C and up to 15˚C does not make any change on filet colour, thawing above 15˚C and up to 30˚C gives significant colour loss. Slow thawing towards high temperatures seems to be more reversible than the faster process

Further (Haugland, 2002) concluded, based on his experiments, that thawing of Atlantic salmon can be conducted with temperatures up to 20˚C. But it is important to cool the fish as soon as possible after the centre of the salmon reached the initial freezing point. For different geometric size of the salmon adjusted thawing media temperature is recommended as well as it should be taken care of a high heat transfer coefficient at high thawing temperatures.

Salmon from Norwegian fish farmers takes a long way to customers around the world. For example to customers in Japan this can be up to 3 months. Different freezing, storing and defrosting methods influent to quality significant in this period of time. Based on (Haugland, 2002)'s study, the reduction of quality can be avoided or minimized by optimal process parameter:

- Freezing to -30˚C within 10-15h
- Storage temperature constant at -50˚C
- Thawing in water between 5-10˚C
- Adequate circulation of thawing media
- Immediate cooling down to 0˚C after thawing

The extensive investigation of water bath thawing with salmon leads to general knowledge of fish thawing. Thawing should be not too slow but higher temperatures must be carefully evaluated. Somewhere between is an ideal temperature for thawing. Immediately after thawing, the fish should be chilled towards the desired temperature.

The ideal temperature for thawing has to be determined for every fish species. For detailed investigation the temperature range for salmon can be used as initial estimation to set test parameter.

### 4.2.2 Effect of water thawing on different fish species

(Ohmori, 1981) investigated the design of water thawing equipment to assess the effects on the thawing rate. The study varies the flow pattern of water, its velocity and temperature and the size of frozen fish block to investigate the resulting freshness of raw fish material. Sand fish (Arctoscopus japonicas), sohachi flat fish (Cleisthenes pinetorum herzensteini) and sardine (Sardinops melanosticta) were frozen to blocks of 44.5x29.5x7.5cm. Several flow patterns are investigated and are compared concerning the flow velocity distribution.

The relationship between thawing water flow velocity (0-2 m/s) and thickness of block (3-10cm) is tested as shown in Figure 2. The flow velocity greatly affects the thawing period. A larger flow velocity leads to a higher thawing rate. With thicker blocks the more intensive the influence.

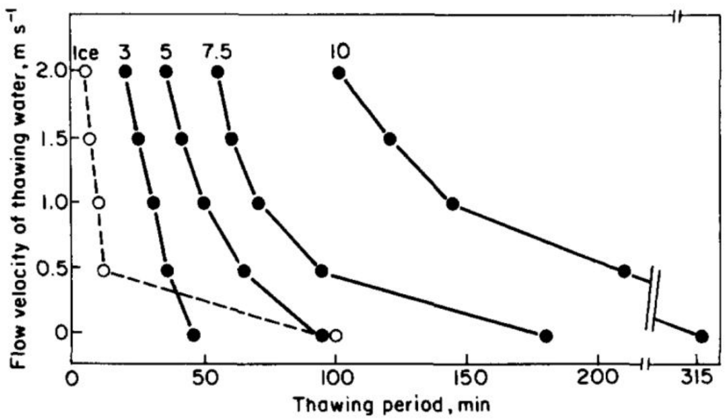


Figure 2: Relationship between thawing period of sohachi flat fish, thawing water flow velocity and fish block thickness (cm) (Ohmori, 1981).

The thawing media temperature has a strong influence on the resulting quality of the thawing process. An increasing water temperature accelerates the thawing but tends to lead to a quality increase due to microbial grow on the surface of the fish. As shown in Figure 3, the freshness decreased with higher thawing water temperature. The trend for sohachi flat fish and sand fish are similar. The freshness of the fish decreased with higher thawing temperature between 10˚C and 25˚C. Sardine reacts different to higher thawing temperatures. The freshness is not affected up to 20˚C. But it shows a rapid decrease at 25˚C. It reveals that every fish is different in his thawing characteristics and therefor every fish has its own optimal thawing temperature. A linear relationship was found between thawing period and resulting freshness (Figure 4). A higher thawing media temperatures leads to a faster thawing as well as an acceleration of physico-chemical changes.

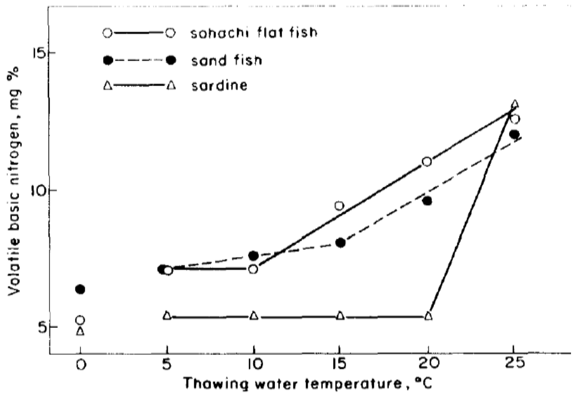


Figure 3: Relationship between thawing water temperature and freshness of thawed fish (Ohmori, 1981)

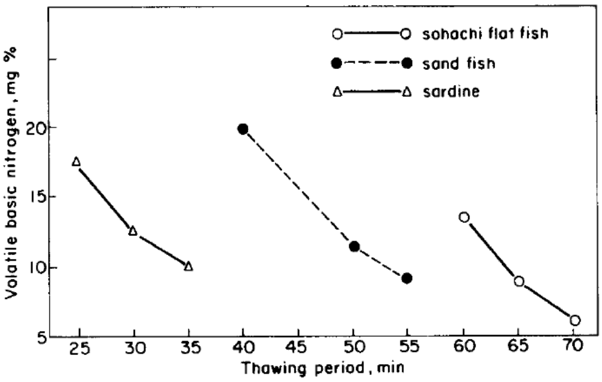


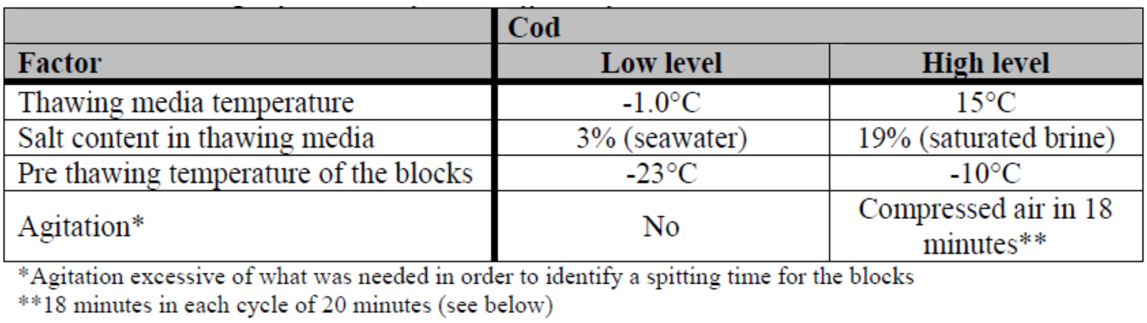
Figure 4: Relationship between freshness of raw fish and thawing period (Ohmori, 1981)

Conclusions about the thawing of cod cannot be drawn from this investigations. But (Ohmori, 1981) experiments led to a general recommendation of a thawing temperature for fish ranging from 10˚C to 15˚C. An optimum in process performance regarding thawing time, freshness and ingress of moisture might be in this range.

### 4.2.3 Effect of water thawing on cod block splitting

(Haugland, 2002) further investigated cod based on the knowledge of salmon thawing as described in Chapter 4.2.1. With the intension to speed up thawing it is important to split the blocks as soon as possible. It is investigated how different factors would affect the process time prior to splitting the frozen cod blocks. 25 kg blocks of plate frozen cod blocks were used. The fish size was 1-3 kg. The factors were consider to vary between low and high level (Table 1).

Table 1: The range of variation for the different factors (Haugland, 2002)



| | 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)

The low level of thawing media temperature was chosen to prevent freezing of seawater in the RSW equipment. High level was chosen by the highest imaginable seawater temperature in the parts of Norway where cod production takes place. A full-scale production with fresh water would be too expensive 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. The high level temperature was set to –10°C, since temperature can be used as buffer storage in the production. The low-level temperature was set to –23°C, the typical storage temperature in the fish industry.

To find representative splitting time, a defined manual control of the block strength at given intervals was established. Every 10th minute (First time 10 minutes after start) the cage was turned around (180°), and every 20th minute the cage was opened and the block was tried divided by hand for two minutes.

A statistical experimental design was utilized. 16 experiments with various combinations of low and high levels of the four factors of current interest were chosen. 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.

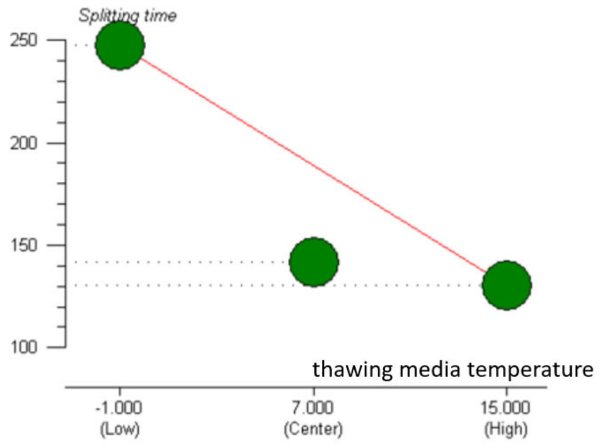


Figure 5: The effect on splitting time for blocks of frozen cod by changing the thawing media temperature (Haugland, 2002)

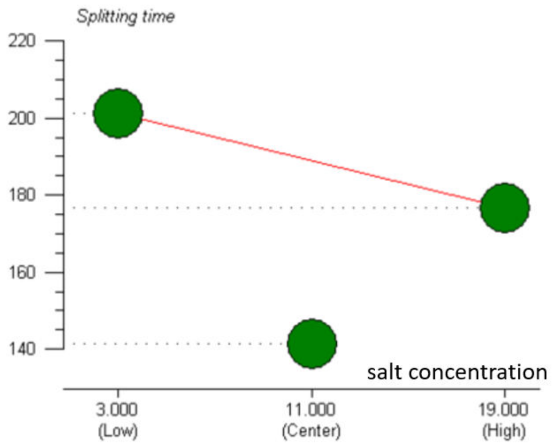


Figure 6: The effect on splitting time for blocks of frozen cod by changing the salt concentration in the thawing media (Haugland, 2002)

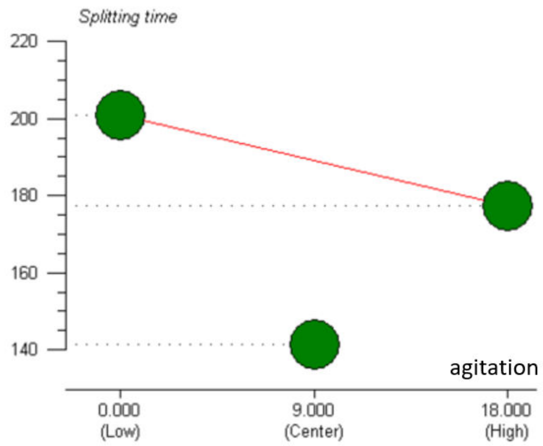


Figure 7: The effect on splitting time for blocks of frozen cod by altering the level of agitation (Haugland, 2002)

Figure 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. It can be assumed that there most likely is curvature on the correlation. However, the curvature cannot be derived due to the number of experiments. Figure 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. Figure 7 shows that if the level of agitation is increased from none to continuously, the cod block will on average split approximately 24 minutes earlier. Also this two figures indicate that there most likely is curvature on the correlation.

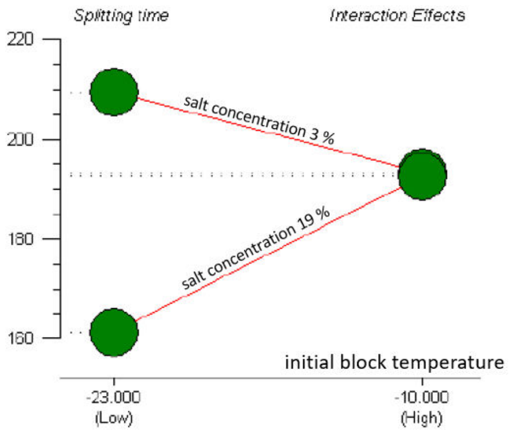


Figure 8: The effect on splitting time for blocks of frozen cod by the interaction between initial block temperature and thawing media salt concentration (Haugland, 2002)

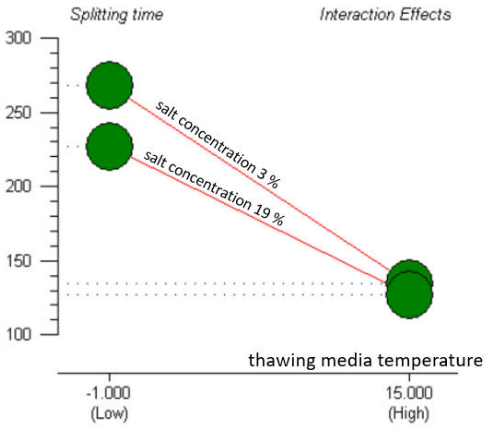


Figure 9: The effect on splitting time for blocks of frozen cod by the interaction between thawing media temperature and thawing media salt concentration (Haugland, 2002)

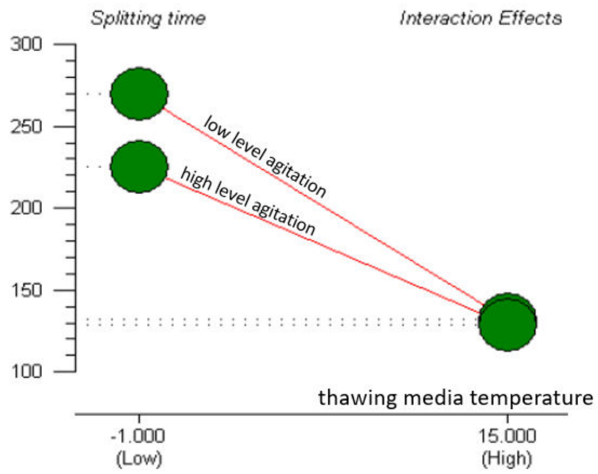


Figure 10: The effect on splitting time for blocks of frozen cod by the interaction between thawing media temperature and level of agitation (Haugland, 2002)

The salt concentration is important when the blocks have an initial temperature of –23°C. It is and not important when the initial temperature is –10°C. This can be due to freezing of the 3% salt brine on the surface of the –23°C cold blocks. None of the 19% salt brine would freeze on the -23°C surface. 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 8).

This interactions (Figure 9, Figure 10) are not significant at a 5% level. They are so close (6.7% and 5.6%) that it should be mentioned. The effect of using 19% salt brine as thawing media, instead of 3%, is 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. The effect of utilizing a high level of 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 by the use of a high level of agitation.

The investigation shows that thawing media temperature is the most important factor for the splitting time of frozen cod blocks. Even for thawing in other media (i.e. air), temperature still play the most important role in splitting of cod block. 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.

### 4.2.4 Effect of water thawing on cod for clip fish production

The study described in this chapter is to see if the product temperature after thawing has any influence on the following processing (Haugland, 2002). 25 kg blocks of plate frozen cod blocks were used. The fish size was 1-3 kg. Thawing was conducted with two different methods.

- Traditionally thawing in 1000 liter vessels with approximately 400 kg fish in each batch. Seawater was supplied through a hose and was running from the afternoon through to the morning.
- Controlled thawing was conducted in the Refrigerated Seawater (RSW) unit. The blocks were thawed at a high temperature. After the block were split manually the media temperature was decreased to a desired end temperature. The total time consumption was the same for both experiments.

Table 2: cod core temperatures after traditional thawing and thawing towards 1˚C, -0.5˚C and -1.0˚C (STDEV = standard derivation) (Haugland, 2002)

| ***Temperature*** | **Traditional Thawing** | **Thawing towards 1,0˚C** | **Thawing towards -0.5˚C** | **Thawing towards -1.0˚C** |
|---|---|---|---|---|
| *Average* | 5.2˚C | 0.6˚C | -0.3˚C | -0.8˚C |
| *STDEV* | 3.4˚C | 0.9˚C | 0.9˚C | 0.2˚C |
| *Maximum* | 7.7˚C | 2.2˚C | 0.8˚C | -0.4˚C |
| *Minimum* | -3.8˚C | -1.3˚C | -1.3˚C | -1.2˚C |

The temperatures of the batches thawed in the RSW unit did not exactly meet the chill temperature. However, the differences are small and the spread is reduced. Especially the batch thawed towards –1°C has a low spread. The temperature distribution for RSW thawing towards 1°C and –0,5°C are similar each other and less spread than the curves for the traditional thawing. The RSW thawing towards -1°C is the less spread distribution (Table 2). The difference is that the thawing aims at a low temperature that could still be in the latent zone. In the latent zone, large change in energy level only lead to small temperature differences. It is likely that the spread of the energy level might be similar for all three experiments.

Further, all batches were processed by the same splitting equipment. The amount of cod that was too cold to get split automatically was recorded and the loss during splitting was calculated. The company itself took over the responsibility after splitting for the batches through the rest of the production process. The final yield and quality were registered. In Figure 11, it becomes clear that it is important to control the product temperature prior to removing the backbone (splitting) of cod.

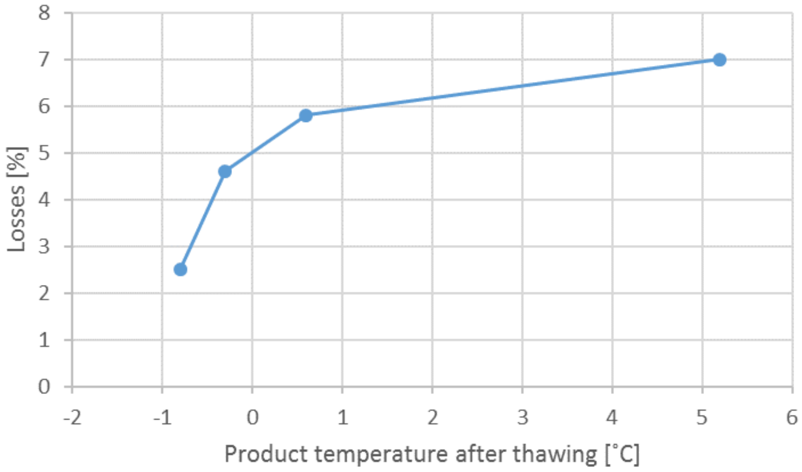
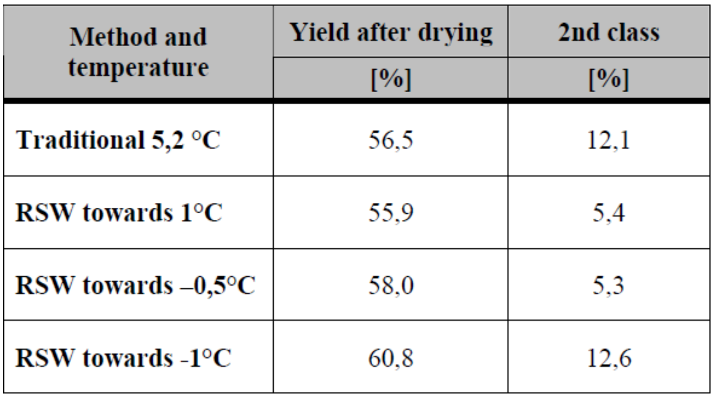


Figure 11: Total losses after the backbone has been removed from the cod in clip fish production, depending on product temperature (Haugland, 2002)

The differences in visual quality are shown in Figure 12. The left fillet is greyer and has much gaping than the right fillet. The left fillet had been traditionally thawed whilst the right fillet was thawed towards –1°C. However, no differences in the final colour of the different batches was found.

Figure 12: Better colour and reduced gaping on the fillet thawed towards –1°C (right) (Haugland, 2002)

Table 3: Final yield and quality on the finished clip fish (Haugland, 2002)



| 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 evaluation of the finished clip fish shows higher yield as the thawing temperature was reduced. This indicates the better cutting ability of colder products with a little amount of ice left in the fish. A cleaner cut along the backbone leaves more fillet on the final product. It is difficult to say why the coldest fish had a higher fraction of 2$^{nd}$ class than the other RSW-batches (Table 3).

The experiments showed the benefits of controlled thawing in terms of higher yield ad better quality. It is recommended to thaw just below the initial freezing point. A better temperature distribution is also recommended and can be achieved by an early block splitting. The possibility of reducing the overall thawing time was not investigated.

### 4.2.5 Effect of water thawing on cod for filet production

Based on the findings of the previous chapter 4.2.4, the goal for this sub-chapter is to as far as possible identify an optimum temperature for a production process for fillets (Haugland, 2002). In addition investigations are made in order to unveil if it is possible to reduce the overall thawing time.

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 after the trimming. The product was not followed further through the production process.

To investigate the optimal processing temperature three different experiments were conducted 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 an air blast tunnel was done.

Table 4: Cod temperatures after RSW thawing towards 1,5°C, -0,8°C and 0,5°C and after thawing in air blast tunnel (Haugland, 2002)

| 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 and –0,8°C are very similar. But measuring the core temperature does not lead to any knowledge of temperature or ice content distribution in spatial domain. The figures for the product thawed towards -0.8°C seem only valid for the product core. The figures seem 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. In the product thawing towards –0,8°C most of the internal ice has melted. Only a little amount of ice is left in the core.

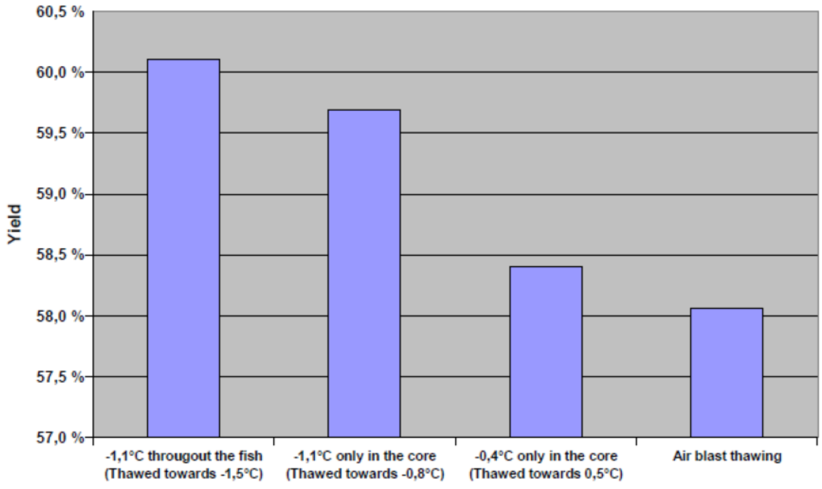


Figure 13: Yield after trimming of thawed Japan cut cod.

It seems like it is possible to increase the yield. Controlled thawing and tempering towards the optimum temperature increases the yield with 2% compared to the air blast thawed samples (Figure 13). The yield increases for lower processing temperatures.

In this case it looks like the optimum value would be close to –1,1°C. The potential profit seems less for fillet production, than for clip fish production (app. +4%).

Figure 14 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 shows only a slight increase of temperature. The temperature change increased for batches thawed towards higher temperature. The batches thawed towards –0,8°C and 0,5°C increases respectively 0,5°C and 1,5°C. In the air thawed batch only small changes take place.

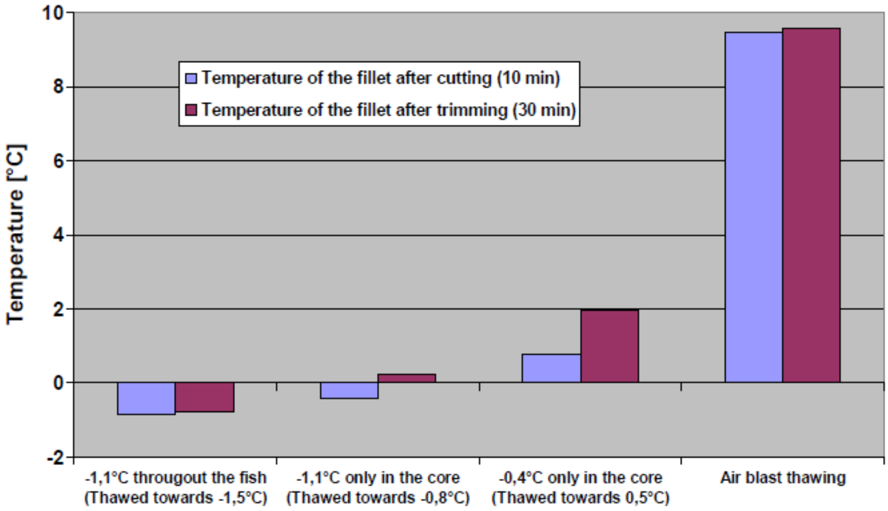


Figure 14: Temperature development during filleting and trimming for RSW thawed and Air blast thawed cod.

In (Haugland, 2002)'s next experiment, a possible reduction of thawing time was conducted while thawing towards the same three temperatures. Respectively 3, 5 and 7 hours after the blocks were split, processed and evaluated.

The previous controlled thawing process (Table 4) was as time consuming as the traditionally methods. This experiment looks into the effects of shortening the total thawing time through reducing the equalizing stage. The indications in the previous chapter showed the optimal processing temperature would be around –1,1°C. Thus, Thawing was conducted towards –1,2°C instead of –1,5°C (Table 5).

Table 5: Cod core temperatures after RSW thawing towards 1,2, -0,8 and 0,5°C depending on how long the product has stayed in the equalizing stage(Haugland, 2002)

| **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 |

The cod core temperatures after the RSW thawing towards –1,2°C, -0,8°C and 0,5°C are given in Table 5. With longer time in the equalizing stage, the derivation decreases for all three experiments. For the product thawed towards –1,2°C and 0,5°C the average temperature is increasing during the equalizing stage, whereas the product thawed towards –0,8°C seems to stabilize at –1,0°C.

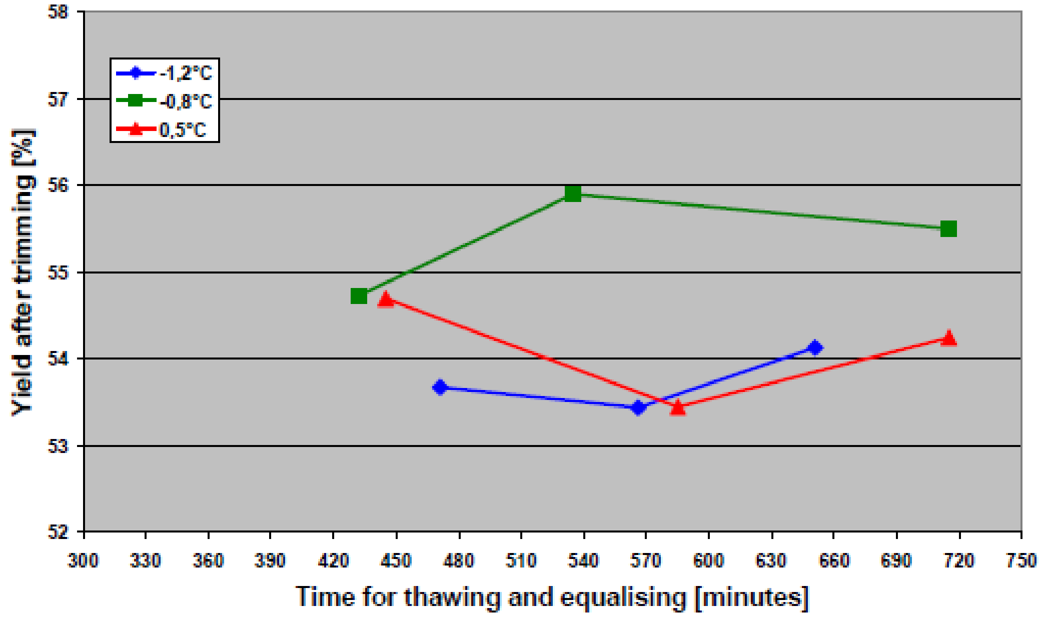


Figure 15: Yield development after trimming, depending on aimed thawing temperature and actual process time. All yields are related to frozen weights(Haugland, 2002)

Figure 15 shows the yield development for the desired thawing temperature and actual process time. The yields are related to the initial frozen weight. The author states that it seems like the overall thawing time should be at least 8 hours to be able to maximize the yield but if the process needs more than 10 hours to achieve this, there is reason to believe that the chosen time and temperature combination during thawing and equalizing is not optimal.

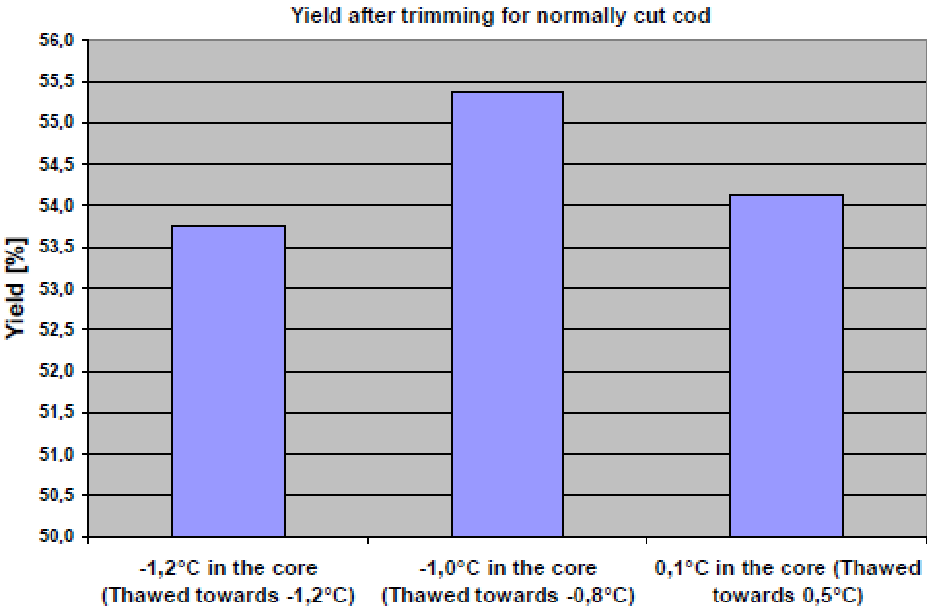


Figure 16: The average yield of the three different temperature levels studied (Haugland, 2002)

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 resulted in the lowest yield. The batch thawed towards –1,2°C gave similar or less yield as the batch thawed towards 0,5°C.

The average yield for the three different temperature levels is studied in Figure 16. The combination of this information with the product temperatures given in Table 5 reveals that 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.

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. The margins are narrow in this temperature region and too low temperatures will reduce the yield. Products containing a small amount of internal ice after thawing, will give higher yields. Additionally, the filets experiences lower temperatures during filleting, trimming and grading. The required energy for refreezing will therefore be reduced. Thus, the economy of the process is increased. The reduced product temperature during processing reduces also the risk for microbial contamination. It seems possible to reduce the overall process time for thawing down to 8 hours without affecting the yield or quality (Haugland, 2002).

## 4.3 Air thawing

Air thawing has two main problems. The thawing media is in direct contact with the fish which leads to drying out of the surface. It is especially a problem for forced convection. Drying results in poor appearance and loss of weight. Also lipid oxidation is an important cause of quality deterioration. It is a disadvantage particularly for fatty fish. Oxidation occurs when unsaturated fats are exposed to heat, light or oxygen (Gurevich, 2014). By use of humid air both disadvantages can be at least reduced. The air should contain a higher fraction of water to improve transfer of heat and prevent drying of the surface

Still air thawing requires considerable space and takes a very long time. However, it has the advantage that little or no equipment is required. A typical block of sea frozen whole cod 100 mm thick, laid out to thaw in still air at about 15°C, can take up to about 20 hours to thaw (Jason, 1965). The air should not be warmer than 20˚C due to the acceleration of microbial growth on the surface of the fish. But thawing in chilled temperatures requires a corresponding longer time. The relatively slow rate of thawing can lead to a high rate of lipid oxidation, as the fish is exposed to air for a long time.

Air blast thawing leads to a higher rate of heat exchange and through this to a faster thawing process. The time taken will depend on the temperature of the air, the speed at which it moves over the fish and the shape and size of the block. The rate of lipid oxidation for the described setup is naturally lower than for thawing in still air, due to the shorter thawing time. According to (Jason, 1965), the speed of air should be at least 6 m/s and as uniform as possible over the whole cross section. The time taken to thaw a block of frozen whole cod 100 mm thick, in humid air at 20°C moving at 8 m/s, is 4-4.5 hours, depending on the size of the individual fish and the compactness of the block.

### 4.3.1 Effect of water thawing on different fish species

The influence of different thawing methods on colour as well as physical, chemical and microbial changes of fish muscle is already reported on several species: eel, sardine, bream, anchovy and meagre. In this chapter the air thawing is compared with other methods used in the investigation. Resulting significant differences between the thawing methods are explained.

Eels (Anguilla anguilla) were thawed in a refrigerator (+4˚C, 4 h), in water (+14˚C, 1.5 h), in air at ambient temperature (+15˚C, 2h) and microwave oven (5 min). The process has a significant effect on the quality. The decrease in TVB-N value of air thawed fish was significant when compared with the fresh control. The Yeast count increased for refrigeration thawing and decreased for air thawing. No significant difference was found for the colour, pH and TBA values. The lowest total aerobic mesophilic bacteria count and yeast count were determined in water thawed samples. Yeast count of the thawed samples under air, water and microwave was reduced. However, the yeast count of the refrigerator–thawed samples increased when compared to the fresh control. The lowest yeast count was found thawed samples under air and water. Therefore, the water thawing method was most suitable for frozen eel (Ersoy, 2007).

Samples included sardine (Sardina pilchardus), gilthead sea bream (Sparus aurata) and anchovy (Engraulis encrasicolus) were thawed using these three methods: refrigeration (+2˚C, 24h), water (+17˚C, 24 min) and microwave (15 min). For sardine and bream the lowest pH-value as for anchovy no difference was observed. The performance in regard to TBA-values depends on the fat content of the species. In average refrigeration thawing resulted in higher values than microwave but lower than water thawing. According to the results of TMA-N the refrigeration thawing showed oppositional performance. For anchovy and sea bream the highest respectively for sardine the lowest values. According to the chemical quality analysis results, tap water thawing method gave better results in anchovy and sea bream samples due to their TMA results. On the other hand no difference was detected between the thawing techniques in TVB-N values of samples. The overall perception of the panellists was that in anchovy the tap water technique was the best. For sardine and sea bream panellists preferred the refrigerator thawing techniques (Dinçer, 2009).

Meagre fillets (Argyrosomus regius) were thawed in the refrigerator (+4ºC, 6h), in air at ambient temperature (+16ºC, 3.5h), in water (+16ºC, 5min) and in microwave oven (15 min, 90 W) at defrost option to avoid from the cooking. Slight differences between the methods were observed for a-values and no significant differences for b- and L-values. Also pH-values showed no significance. The values of TVB-N decreased significantly for all thawed fillets when compared to fresh sample. Air thawed samples showed higher values than refrigeration thawed samples, although not significantly. Hardness was significantly increased in the refrigerator and water thawed fillets. Air thawing showed significant higher mesophilic/psychrophilic bacteria counts than refrigeration thawing. For thawing the meagre fillets, the use of the refrigerator at appropriate power was found the most suitable method of those tested herein (GENÇ, 2015).

The evaluation presented in this chapter showed that the suitability of thawing system varies for different fish species. It can be concluded that refrigeration thawing shows the better results for sardine, bream and meagre whereas water thawing for eel and anchovy. The results show that the time-consuming refrigeration thawing does not necessarily lead to a lower quality. It is beneficial for the economy of fish production to thaw faster while obtaining better quality. In all other cases the reduced processing time has to be compared with the quality decrease. This can still lead to an improvement of economy in the production.

### 4.3.2 Effect of air blast thawing on salmon filet

The investigation of (Alizadeh, 2007) on Atlantic salmon makes it possible to evaluate air-blast thawing. Since no literature is available on air-blast thawing of cod, a general evaluation of fish thawing can be conducted.

Atlantic salmon (Salmo salar) samples were frozen by Pressure-Shift Freezing (PSF, 200 MPa, −18 ˚C) and Air-Blast Freezing (−30 ◦C, 4 m/s). Samples were stored 1 month at −20˚C and then subjected to different thawing treatments: Air-Blast Thawing (4˚C, 4 m/s, 100min), Immersion Thawing (20˚C, 20 min) and Pressure-Assisted Thawing (200 MPa, 20 ˚C, 14 min).

No significant differences in drip loss were found between the different thawing treatments for PSF samples. The Air-Blast Thawing resulted in a higher drip loss irrespective of the thawing process treatments. A reduced drip loss was observed for all the PSF samples irrespective of the thawing process. There was no significant difference among the Air-Blast Frozen and Air-Blast Thawed salmon and the control. But a significant difference in the toughness was noticed among control and PSF samples.

There was no significant difference among the thawing process after PSF for the *L, a*, *b* and *ΔE* values. This result shows that the thawing process had little impact on overall colour change in fish samples. Moreover, a significant difference in the colour was noticed among control and ABF. A decrease in lightness (*L*) and increase in redness (*a*) and yellowness (*b*) were observed after air-blast freezing and immersion/air-blast thawing. The Pressure-shift thawed and Air blast thawed sample shows the opposite trend.

The study showed that the freezing process is a more important factor compared to the thawing process. Whatever the freezing process, ABT leads to a better product in terms of drip loss and colour.

### 4.3.3 Effect of air thawing on cod filet

Air thawing of cod is included in a comparing investigation of thawing, refreezing and storage (Hurling, 1996). The filets were subjected to different thawing and refreezing treatments and compared with the once frozen samples. Thawing was conducted in air (+5˚C, 30 h) or water (+18˚C, 45 min). The analytical assessment of samples took place after frozen storage for 1 week and then after 1, 2, 3, 5, 6 and 9 months (Set of storage time). After the treatments I to V the samples were stored for different durations, transferred to -70˚C and assessed together at the end of the total 9 months storage period. Sensory analysis was carried out in this manner to ensure assessment under the same conditions. The different treatments are visualized in Figure 17.

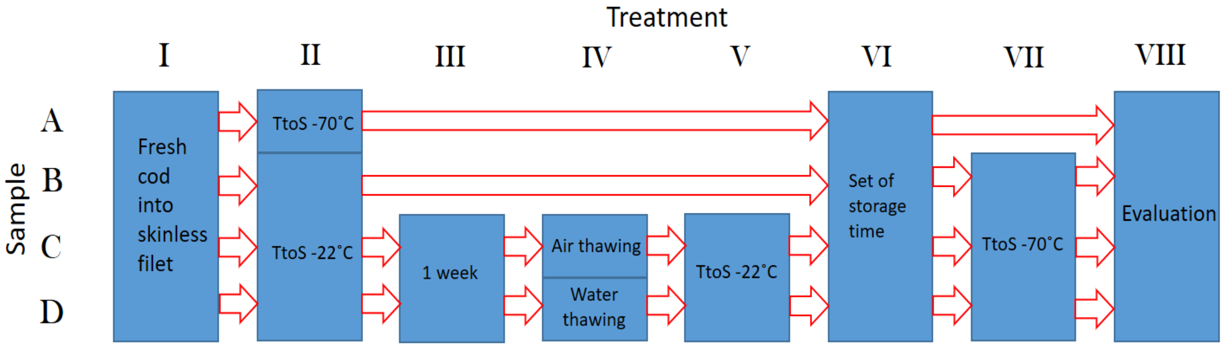


Figure 17: Treatments A, B, C and D for cod filets TtoS=Transfer to storage

The Air-thawed (C) sample can be compared with the water-thawed (D) and untreated samples under different storage conditions (A,B). In the study the amount of protein soluble in potassium chloride buffer represented the solubility of myofibrillar plus sarcoplasmic fractions (MYO + SAR). The amount of protein soluble in distilled water represented the sarcoplasmic solubility alone (SAR). MYO + SAR solubility changed with frozen storage (Figure 19) whereas SAR solubility (Figure 18) did not. The changes in MYO+SAR solubility is caused by a change in solubility of the myofibrillar fraction. The MYO+SAR solubility of the fresh sample had a MYO+SAR solubility of 166 mg/g and showed no significant change over storage at -70˚C (Sample A). The MYO+SAR solubility of the refrozen samples (C,D) greatly decreased from the initial fresh raw material after one week frozen storage and stabilized around 75 mg/g. Sample B was after 1 week similar to Sample A but then fall also to around 75 mg/g.

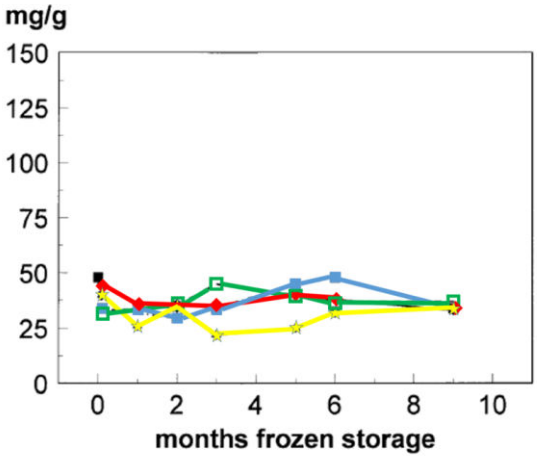


Figure 18: SAR protein fraction of thawed sample (Hurling, 1996)

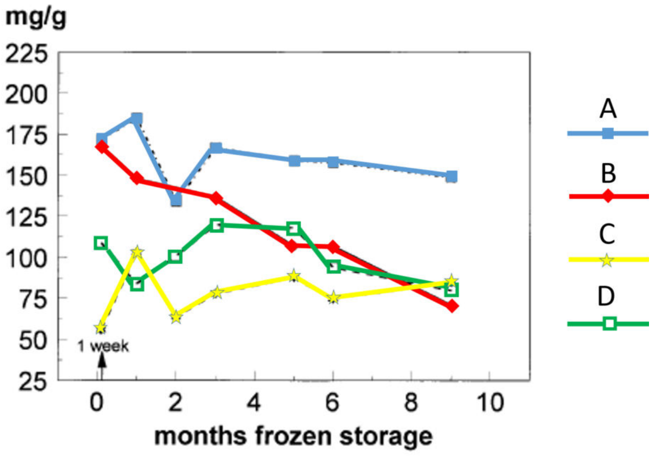


Figure 19: MYO+SAR protein fraction of thawed sample (Hurling, 1996)

Refrozen treatments had a reduced ability to retain water on application of a mild centrifugal force relative to the once frozen control and -70˚C reference, particularly after a few months storage (Figure 20).

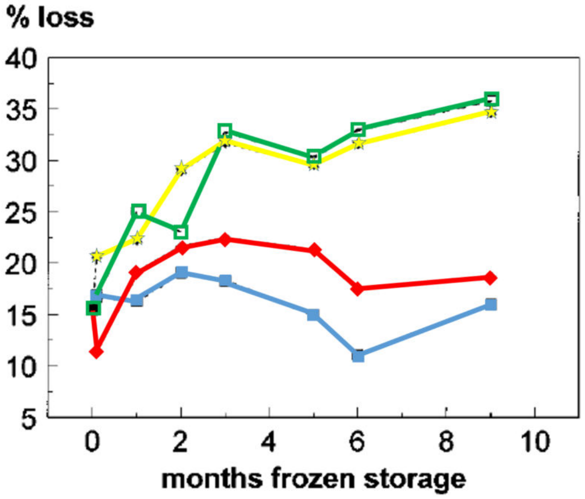


Figure 20: Centrifugal liquid loss from thawed samples (Hurling, 1996)

Samples air thawed and refrozen (Treatment C) were greyer and staler than either the water thawed refrozen sample (Treatment D) or once frozen sample (Treatment B). There were some significant changes in other flavour, firmness and flakiness for treatments B, C and D as a result of storage time but firmness was the only attribute which changed in a consistent manner. For firmness there was a general increase with storage time. Changes in other flavour and flakiness showed no consistent trend.

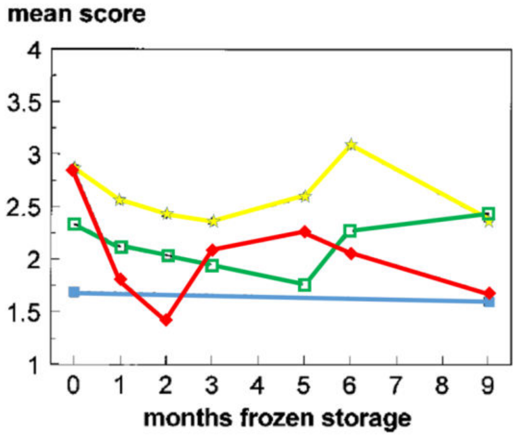


Figure 21: Illustrative plots of sensory attribute: stale flavour (Hurling, 1996)

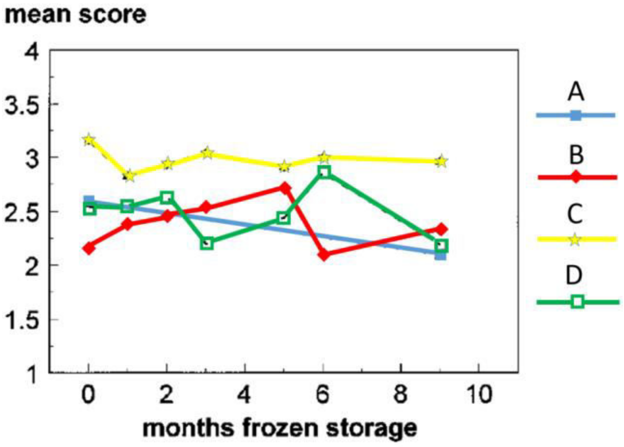


Figure 22: Illustrative plots of sensory attribute: greyness (Hurling, 1996)

The investigation shows that thawing and refreezing does not affect the texture of cod on cooking after frozen storage at -22˚C for up to 9 months. However, there was evidence that thawing slowly (Air) before refreezing resulted in cooked fish that was staler (Figure 21) and greyer (Figure 22) than the once frozen control. Cod thawed rapidly (water) before refreezing was not different from the once frozen control. The use of large blocks and non-optimal heat transfer during factory processing may result in sufficiently slow thawing rates to cause deteriorated flavour attributes.

## 4.4 Vacuum thawing

For vacuum thawing it is required to control the pressure and steam very carefully to avoid heat damage. The method is equal to air or water thawing by means of speed (Backi, 2015). With an appropriate pressure level and steam release, the vacuum technique can thaw the fish without heat damage. Reduction of oxidative changes, inactivation of aerobic spoilage bacteria, and reduction of weight loss due to thaw drip are claimed to be advantages (Carver, 1975).

### 4.4.1 Effect of vacuum thawing on shrimp blocks

In the 1970s, vacuum heat thawing (VHT) tests were conducted on commercially prepared frozen blocks of H&G whiting and shrimp (Carver, 1975).

The vacuum chamber was evacuated (27mbar), steam (5.8 bar) was allowed to expand into the chamber until an absolute pressure of 67 mbar was reached. At this pressure, the surface temperature of the blocks rapidly increased to 38°C. Thus, the use of vacuum cooling (VC) was necessary to recool the surface. It showed the difficulty of the use of relative high pressure in vacuum thawing. The cycled operation mode made the process time-consuming.

Air and ice pockets through the shrimp blocks influenced the thawing process significant due to the ability of steam to enter the air pockets and transfer its heat to an enhanced surface. Thus, the thawing process was much faster for loosely packed and lightly glazed shrimp blocks. When the shrimp blocks were tightly packed and more heavily glazed, the VHT time was significantly longer.

Many pockets of ice and frozen shrimp remained at a centre line temperatures of 6-10°C of the shrimp blocks. Additionally, it was noted that 10-15% ice was remaining when the internal temperature of these shrimp blocks reached 15-23.4°C. In the experiment it was observed to accelerate the thawing process by removing the thawed shrimp on the surface of the block. The thawed shrimp tend to have an insulation effect.

A second test series was conducted with a continuous steam release into the chamber. It can be seen from the results that VHT can be accomplished much faster by a continuous application of steam than by a cycled application.

The study showed that VHT was faster with lower steam pressures than with higher steam pressures. The use of higher pressure steam was more difficult to control whereby the tendency for overheating increased. Thus, there was a need for longer VC time. The greater efficiency of the lower steam pressures also tends to indicate that the major source of heat energy for thawing came from the heat of condensation.

It is doubtful that this process could be used to temper fishery products. Industrial thawing aims to raise frozen product to temperatures near the initial freezing point with a little ice left. A suitable degree of hardness leads to a clean cut at the backbone. However, for a thawing process prior to further processing like cooking and canning the data show that the process is rapid and effective. By the VHT process, different products can be thawed in as little as 10 minutes to 1 hour. The exact processing time depends upon the capacity of the equipment, the size of the load, steam pressures, the application of steam and the presence of extra water or glaze.

Promising results were obtained in VHT blocks of H&G whiting and shrimp. In a refrigerator process 1-2 days is needed to thaw the product. In an 18°C water bath still several hours are needed. The danger of bacterial degradation can occur during these long thawing times. Water can spread the bacterial contamination rapidly. With VHT, these products can be completely thawed within 1 hour. The method does not promote the spread of bacterial contamination. A balance must be struck between thawing time, appearance and bacteriological condition of the product.

### 4.4.2 Effect of vacuum thawing on hole skipjack tuna

In a recent publication the performance of vacuum thawing of frozen skipjack tuna were compared with conventional water thawing (Lee, 2012). The evaluation of the quality, yield and thawing time in tuna canning process identified to advantages and drawbacks of the vacuum technique. The thawing time decreased with increasing pressure. In both, thawing time and maximum temperature difference between core and skin, linearity are detected (Figure 23, Figure 24).

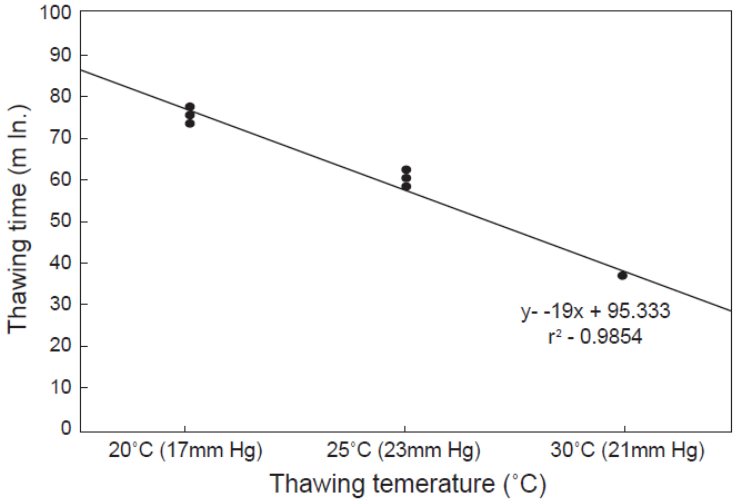


Figure 23: Thawing time against thawing temperature of frozen skipjack tuna (Lee, 2012)

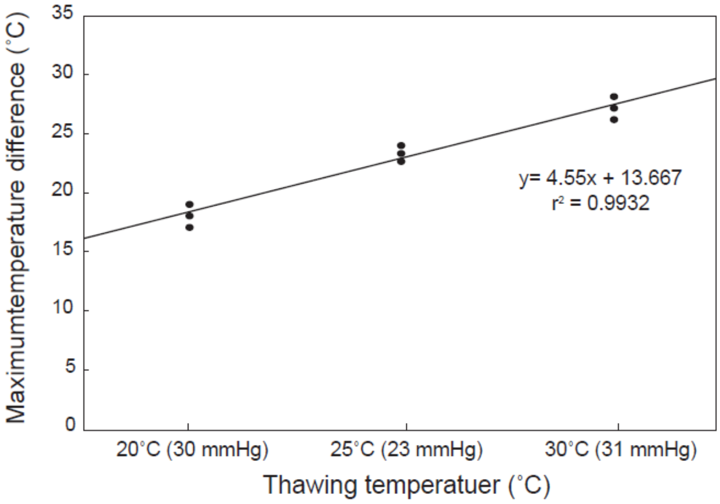


Figure 24: Plot of maximum temperature difference between core and skin of frozen skipjack tuna vacuum (Lee, 2012)

Vacuum thawing shortens the thawing time by 58-80% compared with water immersion thawing at 20°C. The difference between the core and skin temperatures is also increased. No significant change in pH or histamine was observed according to thawing method. The deteriorating effect of biochemical and microbial changes is decreased as the volatile basic nitrogen (VBN) and trimethylamine (TMA) were lower with vacuum thawing than water immersion thawing.

## 4.5 Contact thawing

Contact thawers have two main advantages. The fish block is not in direct contact to the thawing medium and the process is controllable in a better way compared to other thawing techniques. Better ability to monitor and control the process is achievable due to the fact that heat transfer in plate freezers/thawers are well understood (Backi, 2015).

As contact thawing is the reversed process of freezing fish to blocks in plate freezers knowledge can be transferred. Contact refrigeration methods are based on heat transfer by contact between products and metal surfaces. The plates are cooled by refrigerants. Contact cooling offers several advantages over air cooling, such as much better heat transfer and significant energy savings. A desired performance with a fast heat transfer is dependent on several factors: product thickness, good contact and the conductivity of the product. Plate freezers are often limited to a maximum thickness of 50–70 mm. Air spaces in packaging or fouling of the plates can decelerate the process significantly. For example a water droplet frozen on the plate can lengthen the freezing time in the concerned tray by as much as 30–60% (Archer, 2008).

### 4.5.1 Effect of thawing on salmon filet

(Haugland, 2002) investigated the effect of different thawing equipment. With the comparison of contact and immersion thawing the physical principles conduction and convection can be considered. Conclusions can be made regarding the thawing equipment but not regarding the thawing temperature due to the variation in the samples (different fish, different body part).

Figure 25 shows that the thawing time is reduced significant. Thawing time was 95 min and 160 min for thawing at 5°C for respectively plate and brine thawing. With increasing thawing temperatures the thawing time was reduced to approximately 40 min for both equipment. Water thawing gives the faster thawing for temperatures up to 20°C, but for higher temperatures the difference decreases up to almost equal values at 25°C. This shows that for the used sample size (110g –160g) and temperatures the limiting factor is the heat conduction within the sample. The heat transfer from the environment to the sample surface influences the process at low temperatures.

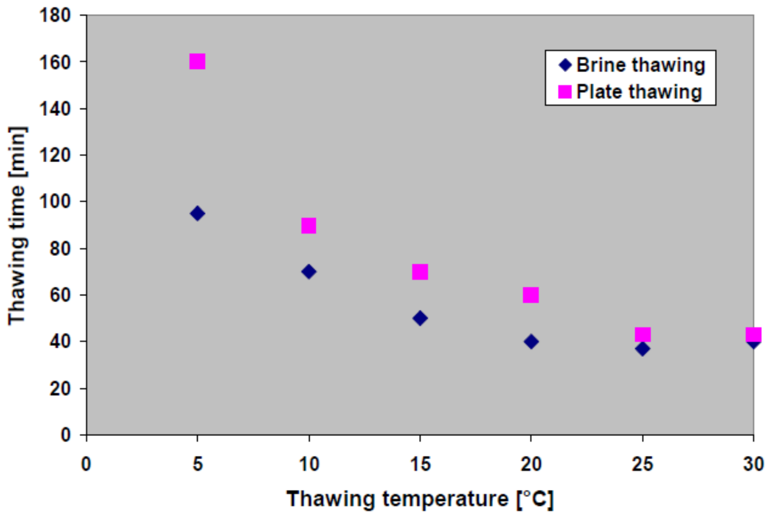
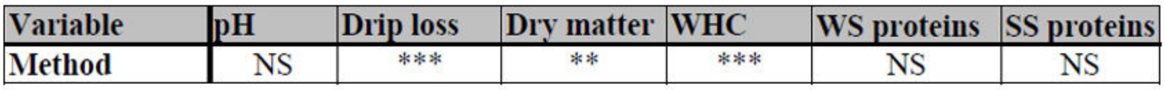


Figure 25: Thawing time depending on equipment and temperature (Haugland, 2002)

The experiment showed significant effects (Table 6). The salmon processed in the plate thawer has a much higher drip loos. The value is almost twice as large (3.8% vs. 2.1%). Higher values of dry matter content and water holding capacity (respectively 1.2% and 2.3%) were detected for the salmon thawed in the plate thawer. 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.

Table 6: Effect overview from the experiments (Haugland, 2002)



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

NS - means Non Significant

** - means that the significant level is 1%

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

Plate thawing is less efficient than water thawing. The difference increases with increased geometrical complexity of the product and decreased thawing temperature. For example thawing of whole fish instead of fillet samples.

Contact thawing However, the quality seemed to be fairly good for all samples even after thawing at high temperatures. This might be caused by a very rapid thawing at these temperatures

## 4.6 Microwave thawing

In the Food industry most recent applications are microwave pasteurization and sterilization. Combined processes like microwave vacuum drying and puffing, but also the combination of microwaves with jet impingement of hot air are used (Schubert, 2001).

Microwave technique in industrial food processing can also be used for the purpose of heating, baking, cooking or, in the present case, tempering. Thawing can be defined as increasing frozen product temperatures up to the unfrozen state while tempering typically means to increase the temperature of a frozen item to approximately -3˚C.

For every application the performance and the connected advantages and drawbacks have to be investigated to evaluate the suitability of the process. Through the varying condition in fish tissue extensive testing is necessary. The time for conventional tempering strongly depends on the low thermal conductivity of the frozen and partly thawed product. By using microwaves the tempering time can be reduced from the order of days to minutes or hours (Edgar, 1986) (Archer, 2008).

However, the application of microwave assisted thawing is constrained by thermal instability. It is possible that parts of frozen food may be cooked whilst the rest is still frozen. This danger exists because the absorption by frozen food of electromagnetic radiation in this frequency range increases as the temperature rises. Any existing temperature difference in the material will increase because more energy will be absorbed in the hotter part. The change of material properties is especially high in the latent zone. Lowering the power density can allow thermal conduction to even out the enthalpy.

Meagre fillets (GENÇ, 2015) were thawed in the refrigerator (+4ºC, 6h), in the air at ambient temperature (+16ºC, 3.5h), in water (+16ºC, 5min) and in microwave oven (15 min, 90 W) at defrost option to avoid from the cooking. The microwave thawing resulted in the lowest L-values. Only slight differences for a-values and no significant difference for b-values. The values for mesophilic and psychrophilic bacteria were comparable with fresh and the refrigerator thawed sample.

The frozen samples (sardine, bream, anchovy) (Dinçer, 2009) were thawed using these three methods: refrigeration (+2ºC, 24h), water (17ºC, 24min) and micro- wave (15 min) thawing methods. The average TBA and TVB-N values were the lowest for the microwave technique. The TMA-N values were higher than the water thawed samples. In the anchovy group thawing with microwave was found to be highest $\Delta E$-values.

The microwave thawing technique was not preferred in all of the three fish species. For sea bream the method even received the lowest scores for each of the attributes.

Eels (Ersoy, 2007) were thawed in a refrigerator (+4ºC, 4 h), in water (14ºC, 1.5h), in air (15ºC, 2h) and microwave oven (for 5 min). The TBA value of thawed fish decreased, except for the microwave thawed sample. TVB-N and pH value showed no significant differences between thawed samples. The highest a-value was found in the water thawed samples while the lowest value was determined in microwave thawed samples.

The microwave thawed sample was not preferred in all of the introduced investigations. A current microwave system might not be suitable for controlled industrial thawing due to the problems of runaway heating. At a controlled thawing process the entire product would be above 0ºC but non over a fixed temperature to avoid quality loss. A heat processing after thawing would these restrictions and microwave thawing could be practical.  However, successful tempering can be achieved in minutes. Tempering systems have many proven advantages. A shorter thawing time, less space requirement and increased flexibility make the technology beneficial.

## 4.7 Radio Frequency thawing

Radio Frequency (RF) processing is a promising technology for food applications. The large penetration depth leads to a rapid and uniform heat distribution. Thus, the process is especially more suitable for large size food packages. RF is applied in drying, pasteurization/sterilization, tempering/defrosting, softening/melting and rapid pre-heating. The spread of applications leads to a wide range of food treated with RF (Stalam inc):

- baked products
- fresh pasta products
- milk, juices, fluidised products
- vegetable and fruit preparations
- raw materials, intermediates
- meat, fish

Baked products are dried to attain the desired final moisture content while the product flavour is preserved and shelf-life is improved. In pasteurization and thermal stabilization of fresh pasta a drastic reduction of microbes at lower processing temperatures in a much shorter time can be achieved. In the pasteurization process for liquids the extremely rapid and uniform heating without noticeable modifications of the product taste is the main advantage.

### 4.7.1 Measurements of dielectric constants on cod

Dielectric properties of cod fish were measured at frequencies from 10 to 200 MHz at temperatures from -25 to 10˚C (Bengtsson, 1963). The results are compared with lean meat (Figure 26). An abrupt change in the dielectric constant was noted in the region of freezing temperatures, which became slightly more gradual as the frequency decreased. At temperatures below the freezing point, dielectric constants increased slightly from values below 10 to values between 10 and 20 before the abrupt increase, on thawing, to values between 60 and 90, depending on the frequency.

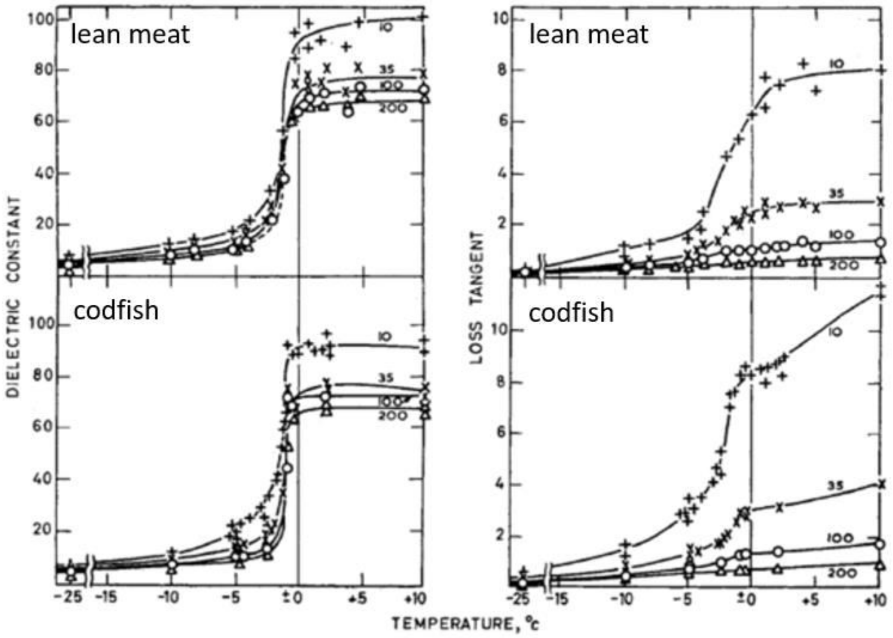


Figure 26: Dielectric constant E‘ and loss tangent E“
as a function of temperature and frequency (Bengtsson, 1963)

### 4.7.2 Dielectric constants and process performance on tuna muscle

Very little data exist on the performance evaluation on RF thawing of fish not to mention of cod. A more general evaluation can still be done with the work of (Llave, 2014). Dielectric properties of frozen tuna and the performance of a radio-frequency system at low frequencies are investigated. Frozen blocks (skinned and boned) of the cephalic parts of tuna were used. Two block sizes were obtained (60x60x25 mm and 60x60x 50 mm) for RF thawing evaluation. The DPs were evaluated from -20 to +10˚C. In the region of -5 to +1˚C the DP conducted a significant change comparable to cod (Figure 26). Higher DP values were found for tuna samples with higher moisture content, especially at lower frequencies.

The RF wave penetration depth significantly decreased with increasing temperature. Values under -5˚C were significant higher than values above -5˚C. In the field of RF defrosting, it is common to use RF power in the range of 50-200 W for each kilogram of sample (Bengtsson, 1963). In the study of (Llave, 2014), the RF performance using 5,10,20,30 and 40 W were compared. Just small differences in thawing time were recorded.

Further the impact of the projection size of the top electrode during RF thawing is investigated. Experimental temperature distributions are shown after RF thawing using different sizes of top electrode projections (Figure 27). The end point was set to -3˚C. With an electrode of the same size as the sample (ES = SS) the thawing had the most beneficial outcome with a greater uniformity. The setting with a larger electrode resulted in higher temperatures at the edges of the sample.

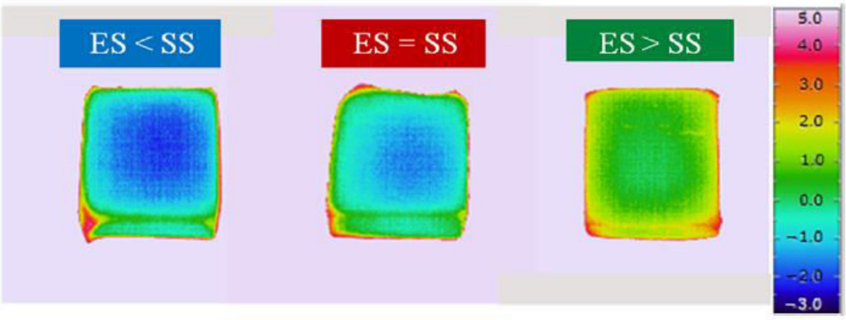


Figure 27: Experimental temperature distributions of tuna after RF thawing captured by an IR camera using different projection size of the top electrode (ES: electrode size, SS: sample size) (Llave, 2014)

The RF system was compared with natural air convection at room temperature (20˚C) whereat a threefold reduction in thawing time was found. The effect of sample composition on the temperature profile is shown in Figure 28. The left sample has a fat content of 1 % as the right a fat content of 11 %. The products were heated at 10W for 8 min. The heating pattern of such a product subjected to RF heating is based on the DPs. The amount of fat rules the temperature rise in the fish. Fat exhibits relatively low DPs and warm up quickly because of their low heat capacities (Piyasena, 2007). The higher the fat contents in the product, the greater the observed temperature difference between the maximum and minimum of the entire temperature distribution.

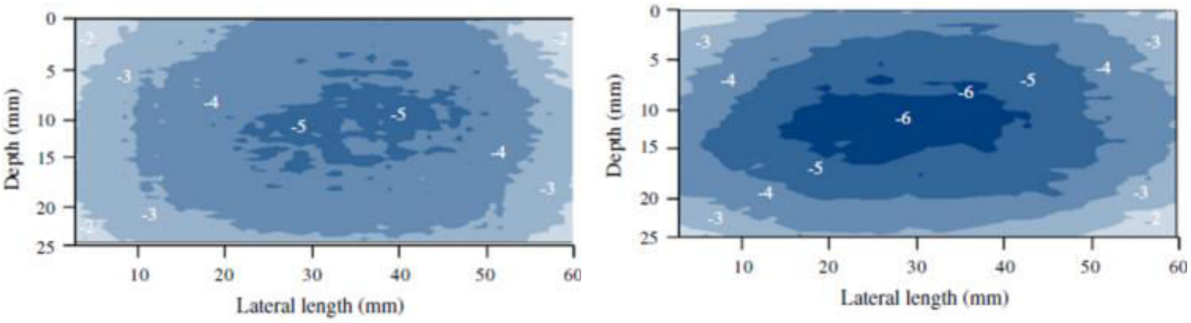


Figure 28: Comparison of RF tempering performance between tuna muscles at the final stage at the internal position (Llave, 2014)

## 4.8 Electric Resistance thawing

The purpose of ohmic heating can be separated into five categories:

- Heating/thawing
- Blanching
- Pasteurization
- Sterilization
- Cell disintegration

Fast thawing rates are however possible if the direct resistance heating method is used. Since heat is generated within the product by the electrical current, the heating rate is effectively independent of the surrounding medium temperature. The advantages of ohmic heating lie in the uniform heating of the product volume. Depending on the configuration, foodstuff can be heated at very low temperature gradients. Another advantage is that the food does not come into contact with hot surfaces (Jaeger, 2016).

A method is to use heated electrodes to ensure that thawing takes by thermal and electrical conduction simultaneously. Another possibility is to use a thawing system in which the electrodes have no direct contact with the product. The product is submerged in an aqueous solution placed between the electrodes. The difficulty in ensuring good contact between the solid and the electrodes without using a carrier fluid limits the applicability of resistance heating in a number of processes. One critical problem is the change in consistence of the material during thawing. It is difficult to process electric heating through the ice-water transition and maintain an even heating rate (Alwis, 1989).

(Jason, 1965) describes a method for thawing frozen fish. Small hole fish in blocks up to 50 mm thick are first immersed in tap water for 15-30 minutes, depending on temperature and type of block, and are then heated electrically for a further 15-20 minutes until they are thawed. Initial preheating is necessary to reduce the very high electrical resistance of frozen fish at normal storage temperatures; the dielectric heating rate was unacceptably low at those temperatures. The specific resistance of frozen fish muscle at - 30°C is $25*10^6$ Ohm/cm and falls to 800 Ohm/cm at 0˚C.

The danger of overheating is present in less than ideal conditions, such as if the blocks are irregularly shaped (Archer, 2008). Based on the limited information on this form of thawing it is not part of his comparisons of thawing systems.

(Liu, 2016) examined ohmic thawing in frozen tuna muscle. The electrical conductivity (EC) values of three tuna muscles (dorsal, lateral, and ventral) were measured between frequencies of 50 Hz and 20 kHz and temperatures of -30˚C to 20˚C and were compared with the composition. No significant differences between the EC-values were observed below -10˚C. The EC values increased rapidly at temperatures above -7˚C, with the highest rate of increase in the range of -3˚C to -1˚C (Figure 29).

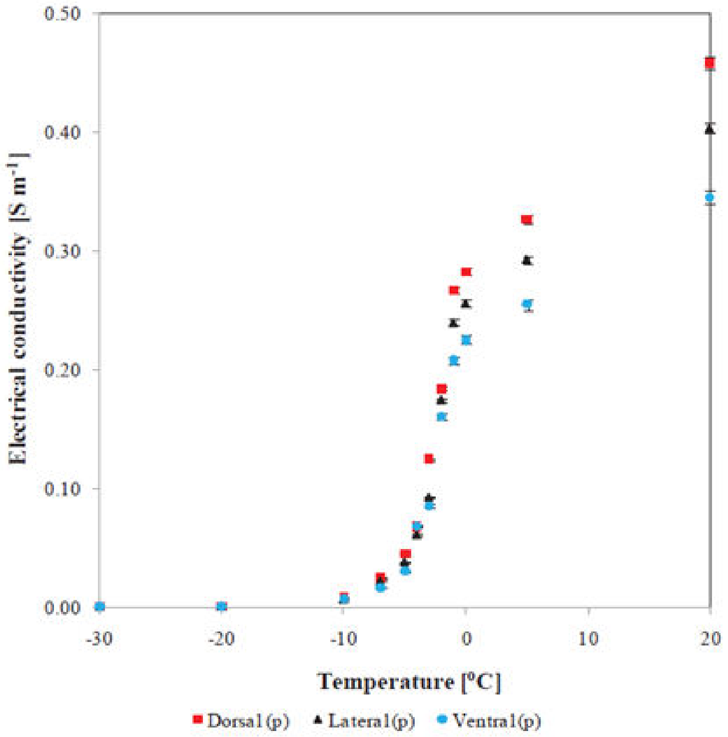


Figure 29: EC of tuna muscles under parallel current direction at 20 kHz (Liu, 2016)

This temperature range coincides with the latent zone of tuna meat (-1.4˚C to -5˚C). Above 0˚C, the EC values increased linearly with temperature. As the temperature of the tuna muscle increased, the rate of heating also increased, and was highest at temperatures above -10˚C (Figure 30). The ES of the tuna muscles directly influence their different ohmic thawing rates. Higher electric conductivity leads to more rapidly heating. The thawing time was the longest and EC the lowest for the muscle with the least moisture content and the highest fat content.

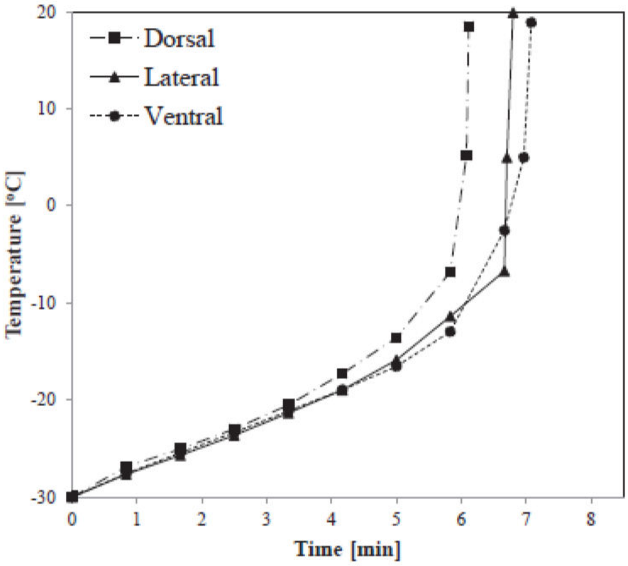


Figure 30: Average temperature profiles of tuna muscle during ohmic thawing (Liu, 2016)

(Roberts, 2002) reported the economically advantageous of ohmic thawing on shrimp blocks whereas the sensory, microbial and quality attributes were compared. Ohmic thawing has been demonstrated to thaw blocks of shrimp in comparable times (to water thawing). Moisture content of large shrimp was not significantly changed. Small shrimp had higher moisture content when conventionally thawed. Total aerobic microbial counts and sensory test showed that there was not a significant difference between conventionally and ohmically thawed shrimp. These results suggest that ohmic thawing can be used to thaw frozen shrimp blocks.

## 4.9 High Pressure thawing

High pressure processing (HPP) is a promising technique for the treatment of fish muscles (Figure 31). The research mainly focuses on three areas. Beside freezing and thawing applications, extension of shelf life and the texturation of fish gel show great potential on improving of fish products (Truong, 2014). In this chapter the main effects, benefits and drawbacks of HPP will be explained.

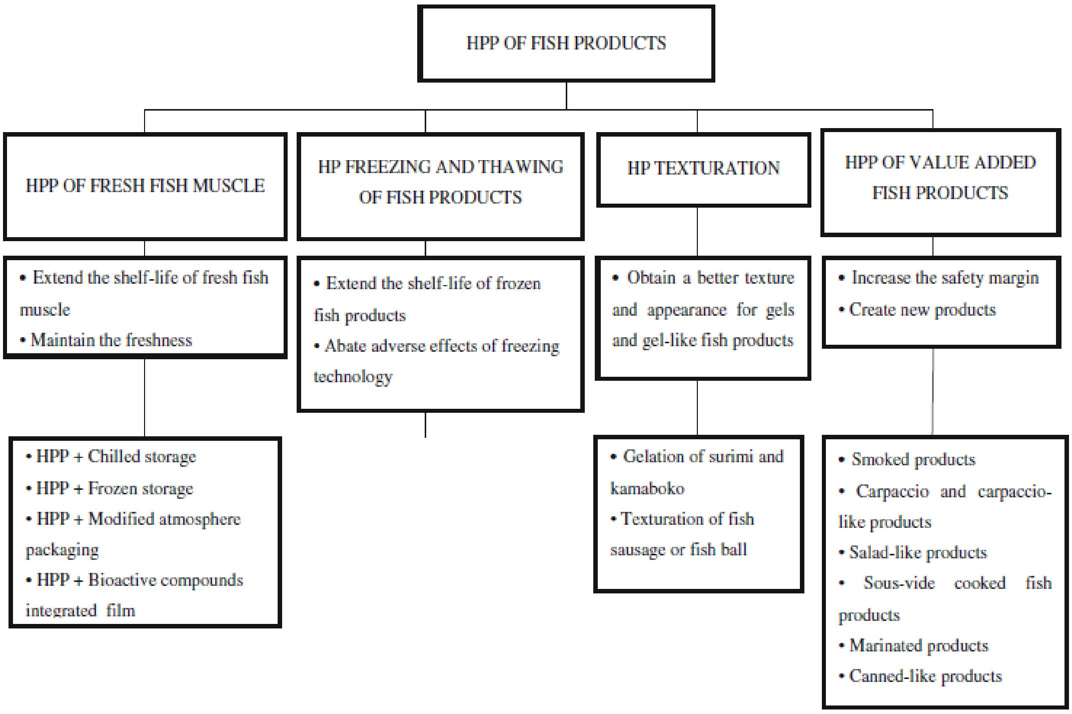


Figure 31: Possibilities of HPP for fish products (Truong, 2014)

The research in HPP is conducted at laboratory scale. High pressure up to 1000MPa can be investigated. Processing temperature can be varied between 0˚C and 100˚C for different purpose. The exposure time ranges between seconds to over an hour. The research on HPP of fish muscle focuses to extend the refrigerated shelf life with a minimal change in overall freshness. The microbial, physicochemical and sensory quality is examined to evaluate the process quality (Truong, 2014).

### 4.9.1 High pressure processing at ambient temperatures

In tuna meat a two log10 reduction of the total microbial count was observed after pressurization at 450MPa and 25˚C for 15 minutes (Ohshima, 1993). In general, application of 300 MPa or higher for a few minutes at room temperature leads to a significant reduction of vegetative micro-organisms in foodstuffs. The magnitude of microbial reduction is strongly dependent of the pressure level and holding time. The influence of the treatment is typically enhanced with the increase in pressure and holding time. Every fish has a different microbial flora with varying characteristics in regard to sensitivity and resistance for HPP.

The microbial spoilage and the autolysis of fish muscles by enzymes is one of the most important factors that can accelerate the deterioration of fish muscle. (Angsupanich, 1997) investigated the activity of proteolytic enzymes in cod muscle under HP treatment. Markedly decrease was stated at different pH-values and especially for a 200 MPa treatment at RT for 20 min. The activity of proteolytic enzymes in tuna samples nearly remains the same during storage after being treated with 150-220 MPa at room temperature for 15-30 minutes. Concurrent, the untreated tuna increased progressively during storage (Zare, 2004).

The change in pH is also frequently used to evaluate the effects of HPP on the overall quality and freshness. The pH of pressurized fish muscle often shows only a marginal increase or stays unchanged. Cod muscle showed an increase from 6.98 to 7.15 for treatment at 200-800 MPa at RT for 20min. The pH increased from 0.14 to 0.25 after 7 days chilled storage at 4˚C. The untreated sample showed an increase of 0.5 pH in the same duration of storage. (Angsupanich, 1997)

Drip loss is an important parameter affecting the quality of fish muscle as well as the yield of processing. Drip loss of fish muscle is increased after HP treatment as observed in tuna, carp and hake (Truong, 2014). However, chilled storage of HP treated fish showed a slower increase in drip loss.

For consumer in retail, colour is one of the most important characteristics in purchase decision. Often the total colour difference is compared. Generally, the values correspond with the visual changes in fish muscle. Cod muscle lost its redness and translucency at pressure level higher than 200 MPa (Angsupanich, 1997). A comparative study of different fish species showed the change of appearance from raw to cooked condition after a HP treatment above 150-200 MPa. Thus, it is suggested that significant denaturation of these fish proteins occurred around 150-200 MPa. (Matser, 2000). In general, the change in the colour values of fish muscle differ drastically from process condition and fish species.

Texture profile analysis includes hardness, springiness, cohesiveness, gumminess, adhesiveness and chewiness. Hardness of fish is appreciated during its consumption. HP treatment induces an increase in the hardness of fish muscles compared to fresh muscles. The observation was made in cod treated at 400 MPa at RT for 20 min (Angsupanich, 1997). Also the close relationship between firmness, springiness and water holding capacity has been showed.

In general, HPP results in a better sensory quality and an acceleration of lipid oxidation for pressurized fish muscles compared to untreated samples after chilled or frozen storage.

In Pressure Shift Freezing (PSF) the phase change temperature of fish is increased rapidly with quick depressurization. Super cooling occurs and produces an ultra-rapid and uniform nucleation. Compared to conventional freezing methods, PSF produces a much smaller, regular and homogeneously distributed intercellular ice crystal texture. During slow freezing, a slower rate of nucleation with few ice nuclei is obtained. It results in a large ice crystal size. The drip loss of PSF turbot muscle was reduced significantly compared to conventionally air-blast freezing (Chevalier, 2000).

### 4.9.2 Effect of high pressure thawing on fish muscle

This process uses the increased temperature difference between the heat source and the phase change temperature. An enhanced heat flux rate is the result. The phase change temperature is shifted to a lower temperature with the increasing pressure up to 210 MPa. The influence of pressure assisted thawing (PAT) on fish muscle was already reported on several species: Carp (Yoshioka, 1999), whiting (Chevalier, 2011) (Schubring, 2003), Atlantic salmon (Zhu, 2003) (Schubring, 2003), cod, redfish and haddock (Schubring, 2003).

PAT maintained a better quality for carp muscle with more elasticity and breaking stress compared to running water-thawed muscle at 15˚C. Whiting fish was thawed between atmospheric pressure and 200 MPa prior to heat treatment (80˚C, 20min). The influence of the pressure level, the freezing rate (0.77 vs. 0.14 K/min), the pressurization rate (100 vs 42 MPa/min) and the pressure holding time was studied. The investigation showed that the drip volume is not significantly different between atmospheric and high pressure thawing. Drip from cooking was not related to the pressure level used for thawing. The differences between the thawing drip volumes according to the rate of freezing are significantly: the thawing drip was lower for the highest freezing rate. Nevertheless, the drip was always greater at high pressure in comparison to atmospheric pressure. The thawing and cooking drips were lower for the highest pressurization rate. The application of 200 MPa reduced the thawing time of whiting fillets with an ambient temperature of 10˚C by a factor of four (60 vs. 15 min).

Atlantic salmon samples were frozen by conventional air freezing, plate freezing and liquid nitrogen (LN) freezing and subjected to different thawing treatments: water immersion thawing (WIT, 4˚C and 20˚C) and high-pressure thawing (HPT) at 100, 150 and 200MPa with water as pressure medium at 20˚C.

The L value of HPT sample at 150 MPa found to be significant higher than that of HPT sample at 100 MPa. HPT samples at 200 MPa looked pale white as in cooked fish and resulted in a very high L-value. The variance in a and b values was much less. The colour degradations obtained were comparable with (Yoshioka, 1999)'s work on carp. The colour change in fish samples resulted mainly from the HPT process rather than the freezing processes. The freezing process was generally much more important than thawing for drip loss. Plate freezing significantly reduced drip loss compared to the other two freezing treatments. Contrary to expectations, the LNF (ultra-rapid freezing) process showed much higher drip loss than other freezing techniques. The HPT process at 200MPa significantly reduced drip loss of the LNF samples. Results showed that freezing process was not an important factor affecting textural quality of the fish samples as compared to the HPT process. Pressure generally caused an increase in the peak force, but only HPT samples at 200MPa showed significantly different.

A comparison between the influence of pressure assisted thawing at 200 MPa and that of conventional thawing in 15˚C water at ambient pressure on the quality of thawed fish fillets has been carried out. Samples from whiting, salmon and cod were affected by pressure assisted thawing and consequently got more demerit points (poorer quality). The assessment of redfish and rainbow trout resulted in equivalent values for the pressure treated and conventionally thawed samples. The parameters affected most by high pressure were taste and texture. For cod fish the influence on odour was more significant while no difference in texture was evaluated. Discoloration as the consequence of pressure treatment was widely observed. These differences indicate a strong influence of high pressure treatment. In raw fillet significant colour changes can be seen. The main effect is a strong increase in lightness (L). After heat treatment, the influence of high pressure on colour was much smaller.

The texture of fish fillet is influenced by high pressure assisted thawing when compared with thawing under atmospheric conditions. Hardness is significantly higher in high pressure, compared to conventionally thawed fillet. The drip loss may be reduced when thawing is assisted by high pressure, compared to thawing at atmospheric pressure, particularly for redfish, haddock and whiting. For salmon and rainbow trout, the same tendency was noted on an insignificant level. The drip loos for cod was slightly lower in conventionally thawed fillets. High pressure assisted thawing was connected with a slight increase in pH value independent of the fish.

The total viable count as well as the number of specific spoilage micro-organisms were significantly decreased in high pressure thawed fillets. The risk of detrimental phenomena and microbial growth is markedly reduced by applying high pressure treatment for thawing. A shelf-life extension of two days was also obtained after high pressure treatment of 150 MPa for 10 min at 5˚C compared to unpressurised, vacuum-packed salmon. Pressure assisted thawing results in a better microbial quality and reduces significantly the thawing time. PAT also induced several adverse effects on thawed products. Loss of transparency together with the increase of lightness and significant denaturation of fish protein was observed.

It has been shown that by applying high pressure at 200 MPa the required phase transition time can be reduced by approximately 50% compared to thawing at atmospheric pressure. The sensory assessment of raw fillet revealed that the high pressure thawed samples were at least comparable to those thawed at ambient pressure.

However, there are several aspects that need the additional investigations such as the influence of the pressure level and pressure-holding time on drip volume, the formation of drip loss during pressure thawing and the optimisation of the process parameters on fish species to reduce the drawbacks and the running cost of PAT.

## 4.10 Conclusion thawing procedures

Water thawing is the most used in industry. The performance of the thaw and block split process was investigated for different fish species. The work of (Haugland, 2002) illustrates the influence of thawing media- and block- temperature, salt content and agitation on the acceleration of the block split of cod. The complexity of water thawing process of cod blocks is already investigated. The literature shows clear trends how to increase yield and quality of the process. Controlled thawing towards a condition with a little ice left can increase the yield with up to 2% for fillet and 4% for clip fish production. The possible shortening of the total thawing time results in a recommendation of 8-10 hours.

Still air thawing is not recommended in regard of an economical point of view due to the required considerable space and the very long process time. Air blast leads to a higher rate of heat exchange and fastens up the thawing process. Investigations show that still air thawing does not necessarily lead to a lower quality. The suitability varies for different fish species. Cod thawed slowly in air before refreezing showed discoloration while the rapid water thawed cod before refreezing was not different from the once frozen control.

Vacuum technique shows promising results in thawing of H&G blocks of whiting and shrimps. The process can completely thaw these products within 1 hour. Hole skipjack tuna could be thawed up to 80% faster with a better microbial quality compared with water thawing at 20˚C while. The adverse influence on the quality is not yet sufficiently investigated.

Contact thawing is less efficient than water thawing. The difference increases with the increased geometrical complexity of a block.

The microwave thawed sample was chosen in none of the introduced studies. A microwave system might not be suitable for controlled industrial thawing due to the problem of runaway heating. However, successful tempering can be achieved in minutes.

Radio frequency has a spread of applications. The thawing depends in large extend on the dielectric properties. Basic investigations on cod and tuna are available to look into the effects of the fat content on penetration depth and resulting temperature difference after thawing.

It is still just a little information available on the ohmic heat treatment of fish products. The electrical conductivity is measured for tuna muscle. The investigation showed relations between fat/moisture content and the thawing time.

Pressure assisted thawing results in a better microbial quality and reduces significantly the thawing time. The sensory assessment of raw fillet revealed that the high pressure thawed samples were at least comparable to those thawed at ambient pressure.

# 5 Industrial application of thawing systems

## 5.1 Water thawing

Many constructive forms of continuous water thawing system can be found. In Figure 32, a large cylindrical tank as build by (Melbu Systems AS, 2017) is shown. The tank is divided into several compartments, which turn around the cylinder's rotation axis. The system is operated to thaw the fish blocks when one full turn is achieved. In an optimal operation the fish will leave the tank separated ready to temper and process.

Figure 32: A cylindrical thawing tank as build by (Melbu Systems AS, 2017)

Other methods work with helical screws in big tanks. The frozen fish gets loaded in the one end and unloaded at the other side. The company (Skanginn 3X, 2017) offers this kind of continuous water thawing systems in industrial scale (Figure 33). The producer claims to provide full control over thawing time, water temperature, throughput per hour and energy consumption. The system is equipped with a patented side injection of water and air to provide the right amount of stress for the product to separate faster. The automatic feeding system ensures that the feeding of frozen products is in sync with the system capacity. The system is available in various sizes and the tank can withhold a product from 2.6-10 tons. The producer also claims that the system is only using a fraction of energy required by MW or RF systems. The water usage is reduced to 0.5 liter per kg of fish by the installed filtering system, which makes it possible to re-use the same water while staying within recommended hygiene standards.

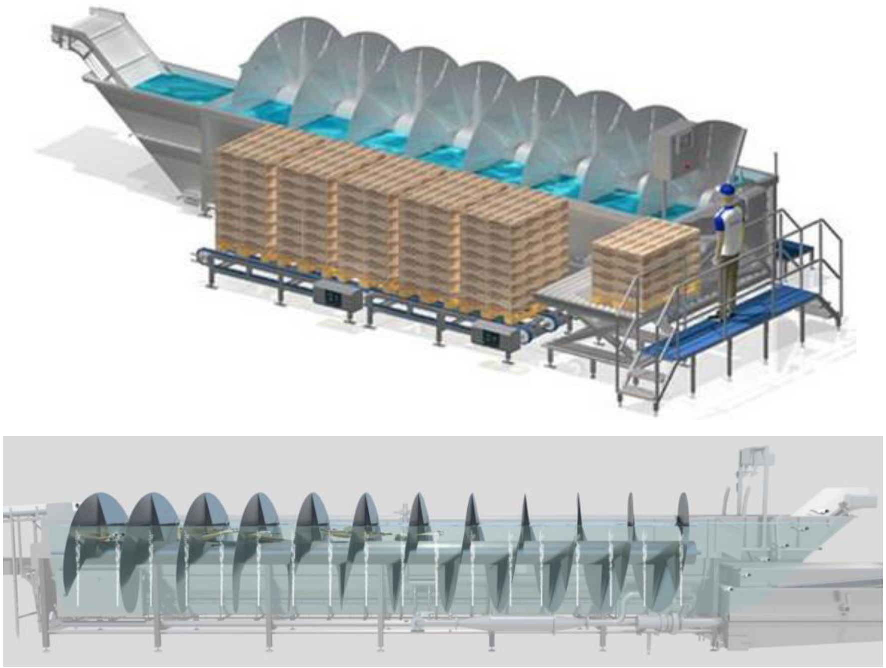


Figure 33: RoteX Thawing® by (Skanginn 3X, 2017)

A further method consists of big tanks with a conveyor belt on the bottom. Thawed fish will sink to the bottom and can be transported out of the tank with the conveyor belt. The company (Traust Technologies, 2017) offers such systems. The thawing process is done in batches. 5-40 ton batches depending on the size of the tank. A conveyor to load the tank can be implemented individually (Figure 34).

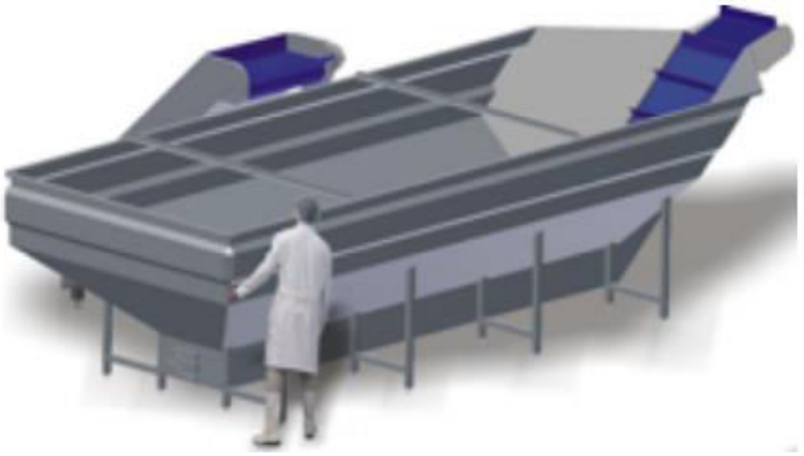


Figure 34: Easy Defrosting System by (Traust Technologies, 2017)

## 5.2 Air thawing

The throughput of thawing is highly depending on the desired temperature change, fish species, density, layer thickness and packing. Thus, companies do not state an exact throughput.

The company (cabinplant, 2017) is offering air thawing units in batch and continuous operation. The batch thawing camber is a modular build-up. Via baffle plates, motorized fans direct a heated air flow into the chamber. The product is placed on trolleys with an average product weight per trolley of 700 kg. Capacity ranges from 700 to 11,200 kg (16 trolleys) per batch. The dimensions range for the 12000kg batch up to 10x3,5x4,1m$^3$ (length, height, width) (Figure 35).

Figure 35: Fully automatic (cabinplant, 2017) thawing

The offered continuous Air thawing is working with a product conveyor, a nozzle system for moistening and fans for air circulation. A cleaning in place system, to ensure to minimize bacteriological problems, as well as large inspection hatches and an optional continuous belt cleaning system are offered. The capacities are stated to be up to 5 tonnes per hour.

## 5.3 Vacuum thawing

In the 1970s, vacuum processing in fish thawing was not commercially utilized caused by the lack of information on these vacuum processes and the high costs to develop the required information (Carver, 1975).

Vacuum thawing is a batch process and the capacity of the largest commercial system is of about 12 tonnes. Relatively thin products, with high surface area to thickness ratios, can be rapidly thawed in these conditions, but efficiency and thawing speed decreases as product thickness increases (Archer, 2008).

The company (GEA, 2017) offers multipurpose systems for food processing. The GEA ScanMidi can be used for high capacity massaging, tumbling, cooling, coating, rinsing and defrosting of pork, beef, poultry and fish (Figure 36). The drum speed, process time, direction, and vacuum are adjustable to provide a very high level of process control. Drum volumes up to 10,000 liters are available.

Figure 36: GEA ScanMidi

## 5.4 Contact

As already mentioned in Chapter 3.2.4, plate freezers are often rebuilt for working with thawing media. The system can be operated with media such as water or glycol-water mixtures. Electric heaters in the plates are also conceivable. The company (Jackstone Freezing Systems Ltd, 2017) offers Plate Freezers in various size. The systems can be manufactured with between 20 and 32 stations and can be suitable for 100mm, 75mm or 50mm blocks (Figure 37).

Figure 37: Vertical Plate Freezer by (Jackstone Freezing Systems Ltd, 2017)

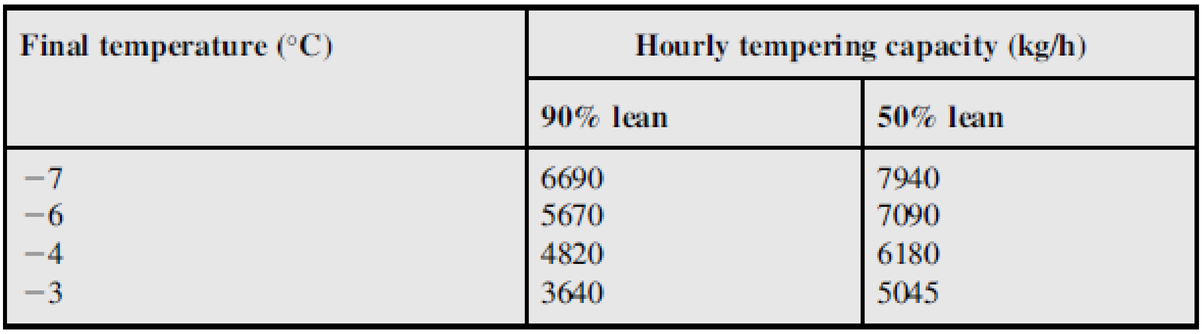
## 5.5 Microwave

The use of microwave oven in household is common. Thus the sale rates are constant on a high level. Also a huge number of microwave ovens are spread all over the industry. Compared to this, microwave processing in food industry was on a much lower quantity (Alwis, 1989). A wide range of batch and continuous commercial microwave systems for thawing and tempering have been developed since the 1970s. In the 1980s tempering was by far the most successful application of microwave technique in food processing. The systems were used to temper meat, fish, butter and berries. Hybrid microwave thawing system were invented to balance the disadvantages of the technology. A microwave/vacuum thawing system was developed. Boiling of surface water at low temperatures was used to cool the surface (James S. J., 1984)

A combination of microwave energy and cold air to avoid runaway heating on the surface was introduced by (Virtanen, 1997). Thawing time was reduced by as much as a factor of seven compared to convective thawing. (Yagi, 2002) found out that thawing under vacuum condition with a relative low microwave power leads to a rate of sublimation at the surface that results in an even product temperature and low weight loss during the process. With a microwave power of 0.7 kW four 2-kilo blocks tuna were raised from -55˚C to -1.5˚C in under 30 minutes.

Industrial systems range in size from catering operations to process one 25kg block at a time to continuous tunnels processing up to 8 tonnes per hour. A typical small batch system is the MIP 4 (Ferrite Microwave Technology, 2017). It is powered by a 40 kW magnetron operating at a frequency of 915 MHz The manufacturer claims that it will temper 680 kg of raw frozen product per hour to a temperature from -2 to -1˚C. A single 25 kg block of frozen meat can be tempered in 65 second.

Table 7: Claimed hourly tempering capacity of MIP 12 for beef at -18˚C with 100kW generator to different final temperature



| Final temperature (°C) | Hourly tempering capacity (kg/h) | |
|---|---|---|
| | 90% lean | 50% lean |
| −7 | 6690 | 7940 |
| −6 | 5670 | 7090 |
| −4 | 4820 | 6180 |
| −3 | 3640 | 5045 |

At the other end of the scale, the same company produces the MIP 12 that they claim will temper up to 7,940 kg of frozen product per hour. Up to four 75 kW generators can be coupled to each 2.5 m long tunnel. However, the throughput is very dependent on the composition of the product and the final temperature achieved after tempering. Table 7 can help the costumer to calculate the throughput of their specific product depending on fat content and final temperature.

## 5.6 Radio Frequency

Typically, companies make a number a claims about their systems. The company (Stalam S.p.A., 2017) states many advantages in regard to rapid tempering and defrosting of food stuff:

- Very short processing time (minutes rather than hours/days)
- The product can be obtained at the correct temperature needed
- The quality is preserved at best as the drip loss and the deterioration of microbiologic are minimized
- Weather and external ambient conditions do not affect the process
- The product flow can be organized according to “just-in-time” criteria
- Processing costs are reduced drastically

Nowadays, stationary or continuous RF systems are increasingly used in commercial processes to produce food products for retail market. Bottlenecks for a wider spreading of industrial application of RF for seafood thawing are high capital costs and personnel maintenance-related costs (Archer, 2008)

Figure 38: "RF" conveyer system by STALAM

For example, the company (Stalam S.p.A., 2017) claims that they are able to provide systems in a large variety for commercial requirement. The conveyer belt can be up to 180 cm wide to be suitable for even very large dimensions (Figure 38). The modular constructed “STALAM RF” defroster operating at 27.12 MHz is available in sizes from

3 kW to 105kW. Multiple modules can be combined to increase the product capacity. An Example of product capacity is stated in an 85 kW single-module machine: frozen squid, 12kg blocks, from -18˚C to -4/-2 ˚C, up to 1250 kg/h.

## 5.7 Electric resistance

According to (Alwis, 1989) thawing by ohmic heating has not been found attractive due to developments in microwave techniques. Microwave thawing was more energy expensive but still better suited to the task as they involve no direct contact with the food. (Bozkurt, 2010) stated that there is no commercial ohmic thawing system for meat products according to the best of authors' knowledge. In the study resistive thawing experiments were carried out on lean beef samples under different voltage gradients. The effects of sample size, thawing method and voltage gradient on thawing time, drip loss, colour, and temperature homogeneity were investigated. Thawing times ranged from 580 to 650 seconds in the resistive systems compared with up to 4000 seconds in air at 25˚C.

In a recent work, an up to date overview of applications and parameters of ohmic thawing is presented (Jaeger, 2016).The existing scientific investigations show promising results on foodstuff like vegetables, fruits juice, fruits, meat, fish and some miscellaneous items. The author is introducing ohmic thawing as a “new process for heating food”.

For a future implementation of ohmic heating into food industry following aspects need to be investigated (Jaeger, 2016):

- Ensuring uniformity of the heating
- Inactivation kinetics of relevant microorganisms
- Influence of physicochemical product properties
- Studies on process-induced chemical changes
- Design of process and system models
- Development of simulation models
- Evaluation of combined methods

## 5.8 High pressure

Together with the increase in the commercial size of HP systems (up to 2 tonnes or more) and the decrease in total operational cost (around 0.05–0.20 €/kg produced), the application of HPP in food industry has been developed rapidly in recent years with the estimated total market value for HPP food reached 3 billion per year in 2009 (Truong, 2014).

Figure 39: Hiperbaric 525 (Hiperbaric High Pressure Processing, 2017)

Nowadays, HPP systems are available in scale for industrial use. (Hiperbaric High Pressure Processing, 2017) offers equipment for the food industry. The capacities range from a 55 liter vessel up to 525 liter. The 525 liter capacity and 380 mm diameter vessel, shows throughputs of over 3,000 kg of product per hour. The 63 m$^2$ footprint and 460 kW power of the plant are factors in the economy of fish production (Figure 39).

# 6 Numerical investigation

## 6.1 Overview of the work

In this work COMSOL Multiphysics was used to conduct a numerical simulation of the thawing process. The material properties of cod were assumed by the use of the composition data from the USDA Food Composition Database (USDA, 2017) and the temperature-dependent mathematical model by (Choi & Okos, 1986). Thawing of cod was reduced to a two dimensional simulation of the biggest cross section to reduce the computational effort. Cod was cut into cross section, measured and a non-uniform grid system was generated for the simulations. The cross section was scaled to different size by the approximate length-weight ratio (Waterman, 2001). Single fish thawing was investigated to deliver the basics understanding for block thawing. The block thawing simulation was conducted with a set of split time and temperature combinations to look into the possibilities of optimal processing. The yield was evaluated by findings from (Haugland, 2002). The bacterial growth was calculated to evaluate the resulting quality.

## 6.2 Numerical simulation

During a freezing or thawing process, the thermal physical properties undergo abrupt changes. The specific heat, thermal conductivity and density are changing in the latent heat zone due to the phase change between water and ice. The largest challenge in numerical computation of thawing is how to deal with the changes in material properties around the initial freezing point. Beside the change of material properties, the evolution of latent heat has to be taken into account (Pham, 2014).

A traditional method is the use of the apparent specific heat. The sensible heat is merged with the latent heat to produce a specific heat curve with a large peak around the initial freezing point (Santos, 2011). The abrupt change in the apparent specific heat curve usually destabilizes the numerical solution and makes it difficult to obtain convergence with this technique. It is possible to smooth the peak curve to obtain some convergence while maintaining the total heat constant. It is always a chance that the latent heat is underestimated. This happens when a nodal temperature steps over the peak and lead to an overestimation of the temperature change. For this reason, the apparent specific heat method is not recommended (Pham, 2014). In this work it is the aim to temper the fish somewhat under the initial freezing point. Therefor an accurate approach for the thawing/freezing process is necessary.

The rapid change in thermal conductivity around the freezing point contributes to the difficulty in the numerical modelling of phase change. The thermal conductivity is needed to compute the heat flux between two nodes. However it is unclear what values should be used. Two possibilities are the thermal conductivity calculated at the mean temperature $(T_{i+1} + T_i)/2$ or the average thermal conductivity $(k_{i+1} + k_i)/2$ (Pham, 2014). The simultaneous application of the Kirchhoff and the enthalpy transformation avoids the possibility of missing the apparent specific heat capacity peak and the abrupt thermal conductivity change (Scheerlinck, 2001):

$$E(T) = \int_{T^*}^{T} k(T)dT \tag{1}$$

$$H(T) = \int_{T^*}^{T} \rho(T) * Cp(T)dT \tag{2}$$

T* is a reference temperature that corresponds to a zero value of H and E. The non-linearities of phase change are incorporated in a functional relationship with two mutually related dependent variables H (volumetric specific Enthalpy) and E (Kirchhoff function). (Santos, 2011):

$$\frac{\partial H}{\partial t} = \nabla^2 E \tag{3}$$

By combining the boundary condition for heat conduction equation with function (1) and (2) the following equation is obtained:

$$-(\nabla E) * n = h * (T - T_{bath}) \tag{4}$$

$n$ is the nomal outwards vektor component, $T_{bath}$ is the media temperature surrounding the fish and $h$ is the surface heat transfer coefficient.

## 6.3 Material properties

Thermal properties of foods and beverages must be known to perform heat transfer calculations. The design of equipment in refrigeration, freezing, heating and drying operations depends on the properties of the specific food.

The thermal properties of foods and beverages strongly depend on chemical composition. The availability of many types of different food makes it nearly impossible to experimentally determine the thermal properties for all conditions and compositions. The composition data for foods and beverages are available from the USDA Food Composition Database (USDA, 2017). For the numerical investigation in this work the composition off raw Atlantic cod was used (Table 8).

Table 8: Composition of raw Atlantic cod

| | **Mass fraction (%)** |
|---|---|
| *Water* | 81.22 |
| *Protein* | 17.81 |
| *Fat* | 0.67 |
| *Carbohydrate* | 0.0 |
| *Ash* | 1.16 |

Thermal properties of foods can be predicted by using these composition data. (Choi & Okos, 1986) developed a temperature-dependent mathematical models of thermal properties of the individual food constituents. Additionally they developed models for predicting the thermal properties of water and ice. The functions range from -40 to 150˚C.

In general, thermophysical properties of a food or beverage show only small gradients when its temperature is above its initial freezing point. However, the gradients are significant higher below the initial freezing point because of the gradually freezing of water. The initial freezing point of a food is somewhat lower than the freezing point of pure water because of dissolved substances in the moisture in the food (ASHRAE, 2006). The food freezing and thawing proceeds in a temperature range. Food starts to freeze at a specific temperature, named initial freezing point, as some of the water in the food freezes. Thus the remaining solution becomes more concentrated and the freezing point of the unfrozen portion of the food is further reduced. This process continuous with decreasing temperature. Thus, the ice and water fractions in the frozen food is a function of the temperature.

The ice content as a function of the temperature was estimated by using the equation proposed by Tchigeov (1979). The initial freezing point of cod $T_f = -1.1^{\circ}C$ is used.

$$x_{ice} = \frac{1.105 * x_w}{1 + \frac{0.7138}{\ln(T_f - t + 1)}} \tag{5}$$

The Thermal Property Model proposed by (Choi & Okos, 1986) were implemented to estimate the thermal properties. The following equations were used for the density:

$$\rho(T) = \frac{1}{\sum x_i / \rho_i} \tag{6}$$

The thermal conductivity can be calculated by using either parallel or perpendicular models. The parallel model, which is used in this work, is the sum of the thermal conductivities of the food constitutes multiplied by their volume fraction:

$$k(T) = \sum x_i^v * k_i(T) \tag{7}$$

The volume fraction of constituent $i$ can be calculated by the following equation:

$$x_i^v = \frac{x_i / \rho_i}{\sum(x_i / \rho_i)} \tag{8}$$

Specific heat is a value for the energy required to alter the temperature of a food by one degree. Therefor it can be used to calculate required heat loads for heating or refrigeration equipment. At temperatures above the initial freezing point and below the latent heat zone the heat capacity changes only slightly. Thus, constant values above and below freezing can be assumed for coarse estimations. In the freezing zone, both the sensible heat from temperature change and the latent heat from the fusion of water must be considered. An apparent specific heat is used in this model to account the latent heat effect.

$$Cp(T) = \sum x_i * Cp_i(T) - L_w * \frac{\partial x_{ice}}{\partial T}(T) \tag{9}$$

$$L_W = 334 \ \frac{kJ}{kg} \tag{10}$$

Figure 40 a, b and c show the relationships of the thermophysical properties with temperature. The Kirchhoff transformation $E(t)$ (Eq.1) and the enthalpy function $H(T)$ (Eq.2) is shown in Figure 41.a and b. Figure 41.c shows the function$E(H)$.

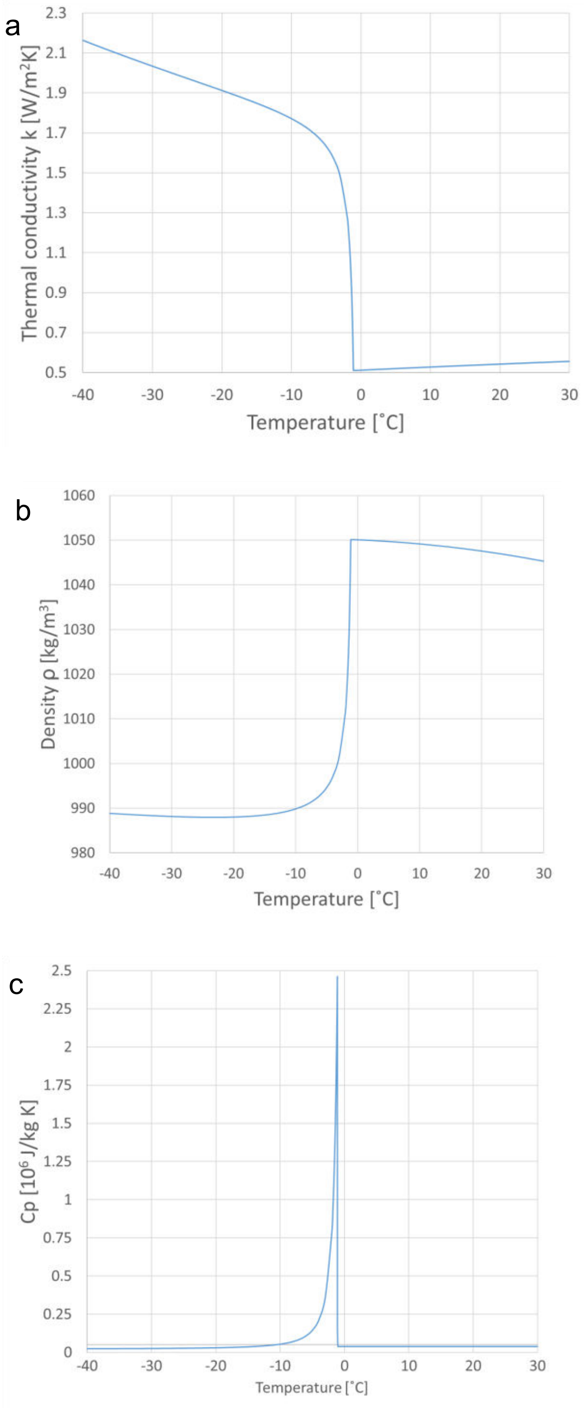


Figure 40: Thermophysical properties of the cod used for the thawing process as a function of temperature

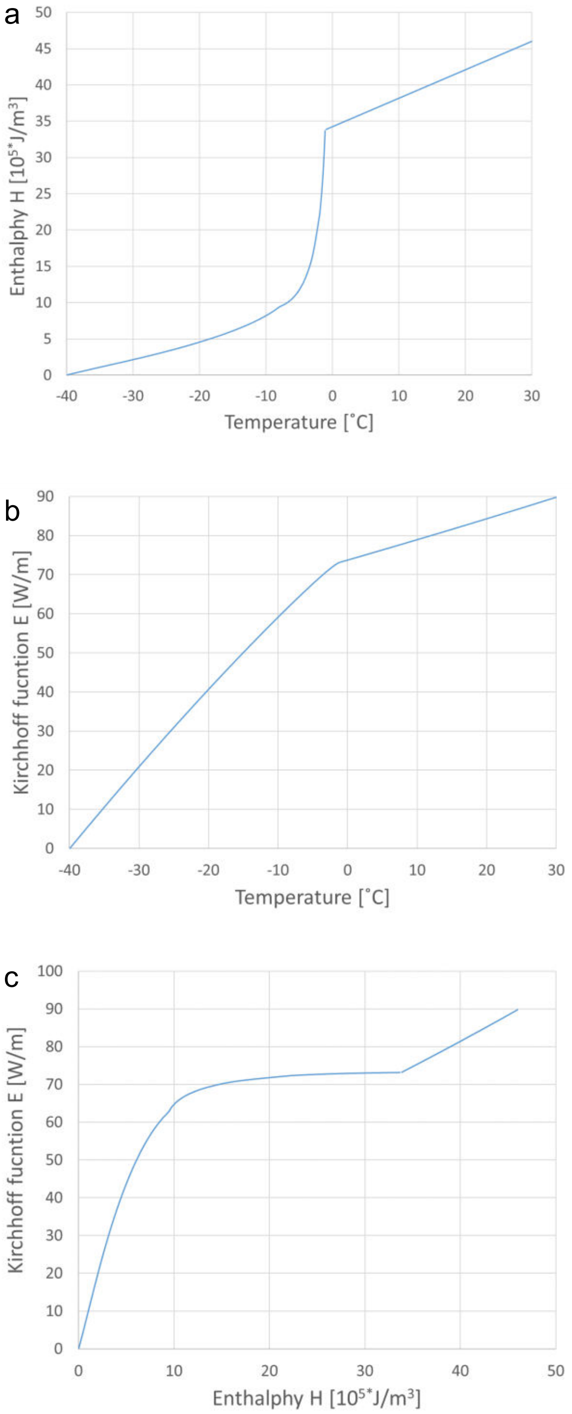


Figure 41: Functional relationships used in the combined formulation of the freezing process

## 6.4 Reconstruction of cod shape and mesh generation

In this work, the geometry of cod was reduced to a number of 2-D cross sections. A 66cm cod with a weight of 2.6 kg was cut into 5cm thick slices (Figure 42). The flap was partially detached in the front 10 cm of fish. The four cuts at $x = 10 - 25cm$ were hollow due to the removed gut. The five cuts in the back $(x = 30 - 50\ cm)$ have the shape of an oval. The actual recorded shape was centred and smoothed to gain a simplified and symmetric curvature to implement into the simulation.

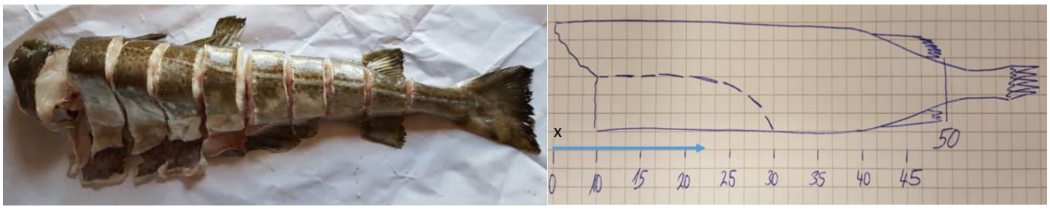


Figure 42: cuts of measured 2.6kg cod

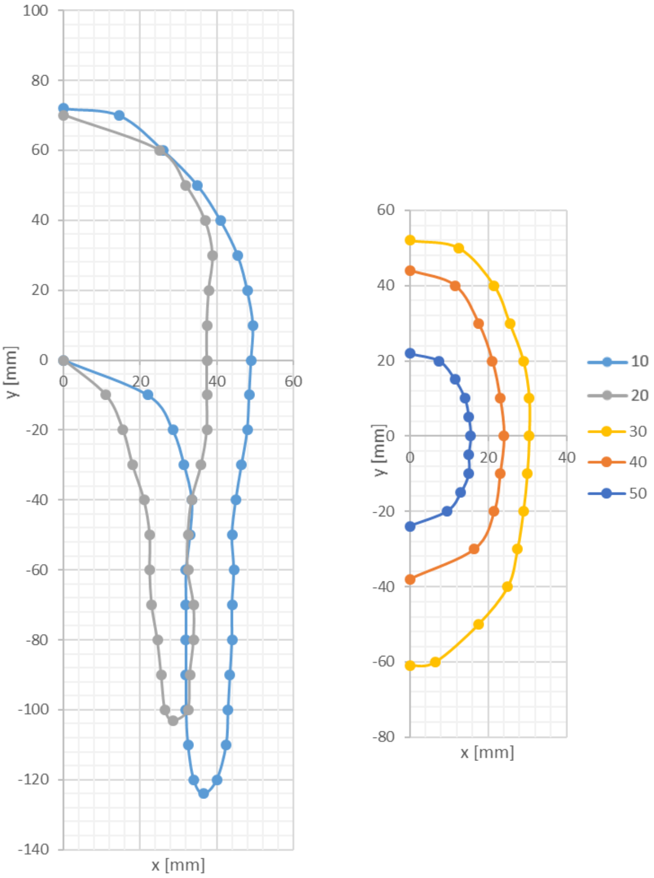


Figure 43: scaled and centred cross sections

In Figure 43, the symmetric shape of the cod for different cross sections is shown. The cross-sections 10cm and 20cm represent the hollow part of the measured cod. The 10cm cut is the the biggest part of the fish. Cross-section at 20cm shows a reduced expansion in the x-direction and a reduced size of the flap whereas the y-axes measure of the center doesn't change. In the backpart, the reduction in x- and y- direction seems to be isometric.

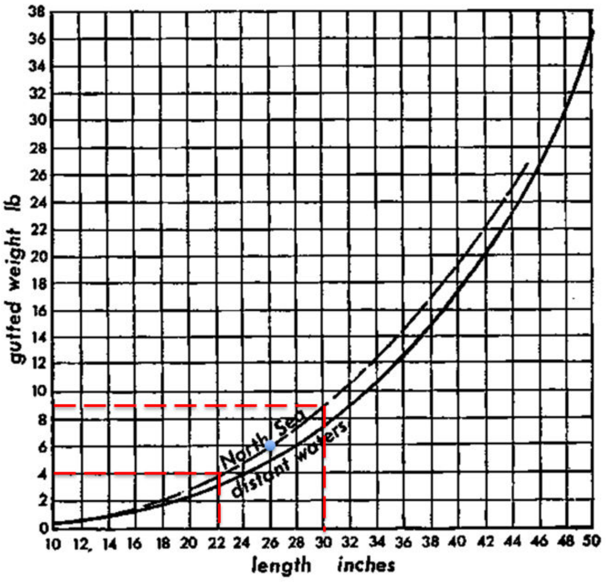


Figure 44: Approximate length-weight ratio of cod (Waterman, 2001)

The measured weight and length fits into the curve of the length-weight ratio of North Sea cod (Figure 44). A linear interpolation was used between the red-marked boundarys.

$$m\ (pound) = \frac{3}{5}\ l\ (inches) - 9.868 \qquad (11)$$

According to the resulting function it is possible to get a length for respectively lighter and heavier cod. The change ratio in x and y- direction was calculated from the total weight change and the change in total length.

$$\Delta x = \Delta y = \sqrt{2{,}737\left(\frac{m(lb)}{m(lb) + 9.868}\right)} \qquad (12)$$

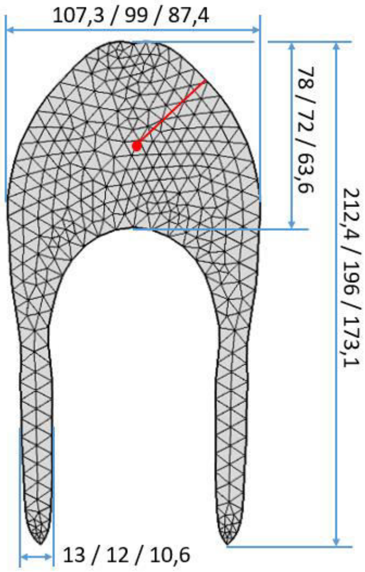


Figure 45: 2D domain discretized into triangular elements, size for different fish:1.8/2.6/3.4kg [mm] and a cutline from core to boundary

The flow in the agitated water bath is estimated with heat transfer coefficients for the outer and inner surface. The h-value in the inside is much smaller due to the obstructing effect of the flap: $h_{outside} = 150\ \frac{W}{m^2K}, h_{inside} = 25\ \frac{W}{m^2K}$. A non-uniform grid system was used in the simulations. The dimensioning show for the three different fish size (Figure 45).An unstructured mesh with 361 nodes and 608 triangular elements was developed for the 2D model. The use of finer mesh showed no significant effect on the accuracy of the solution (Figure 46). In this case, an increase from 608 elements to 1838 elements result in a 0.058 K alternation in average temperature.

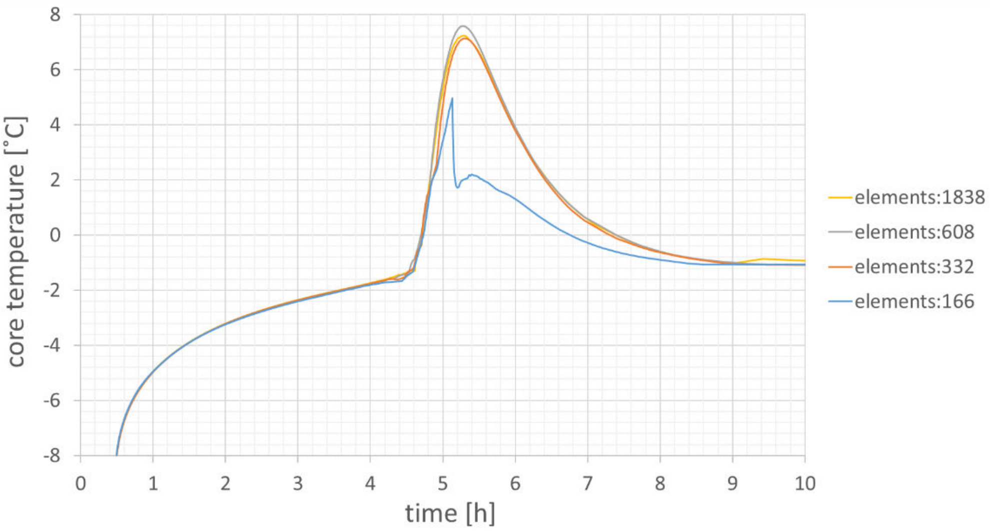


Figure 46: mesh study for single fish: bath: 5h/15˚C chill: 5h/-1.5 ˚C

## 6.5 Model single fish thawing

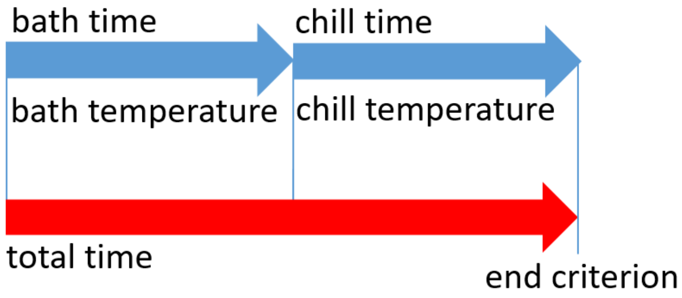


Figure 47: Sequence of the single fish thawing model

The fish is exposed to a high heat transfer in warm thawing media (bath temperature) during the bath time. Then the fish will be transferred to the cold chill media (chill temperature). The fish remains there during the chill time. The total time is made up of bath and chill time (Figure 47). The cutline from core to boundary (Figure 45) is used to show characteristic temperature developments.

Table 9: Parameter values of different simulations for single fish thawing

| | **Bath time [h]** | **Bath temp. [˚C]** | **Chill time [h]** | **Chill temp. [˚C]** | **Total time [h]** | **End criterion (core temp.) [˚C]** |
|---|---|---|---|---|---|---|
| *1* | 0.5/0.75/1/1.25/ 1.5/1.75/2/2.25 | 3/7/11/15 | **RESULT** | -1.5 | **RESULT** | -3 |
| *2* | **RESULT** | 7/11/15 | **RESULT** | -1.5 | 10 | -1.1/-1.5/-1.9 |
| *3* | 0.5/1.5/2.5 | 15 | 9.5/8.5/7.5 | -1.2/-1.5/-2 | 10 | **RESULT** |

Three different simulations were conducted. Table 9 shows the used parameter values for the simulations. The first simulation investigated the time necessary to heat the core temperate up to -3˚C. The thawing time was compared to the resulting quality (explained in chapter 6.7).

The second simulation revealed the bath time to reach a particular core temperatures after the total time of 10 hours. The temperature distribution on the cutline was visualized at five different times during processing (Figure 48).

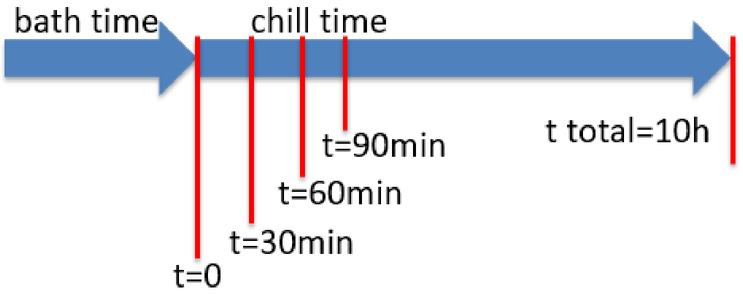


Figure 48: Time to visualize the temperature distribution during processing

The third simulation shows the effect of chill temperature on the resulting core temperature. The initial temperature was set to $T_{int}$ = -23˚C representing the typical storage temperature in the fish industry. Single fish thawing was investigated with different sizes: 1.8kg, 2.6kg and 3.4kg.

## 6.6 Model cod block thawing

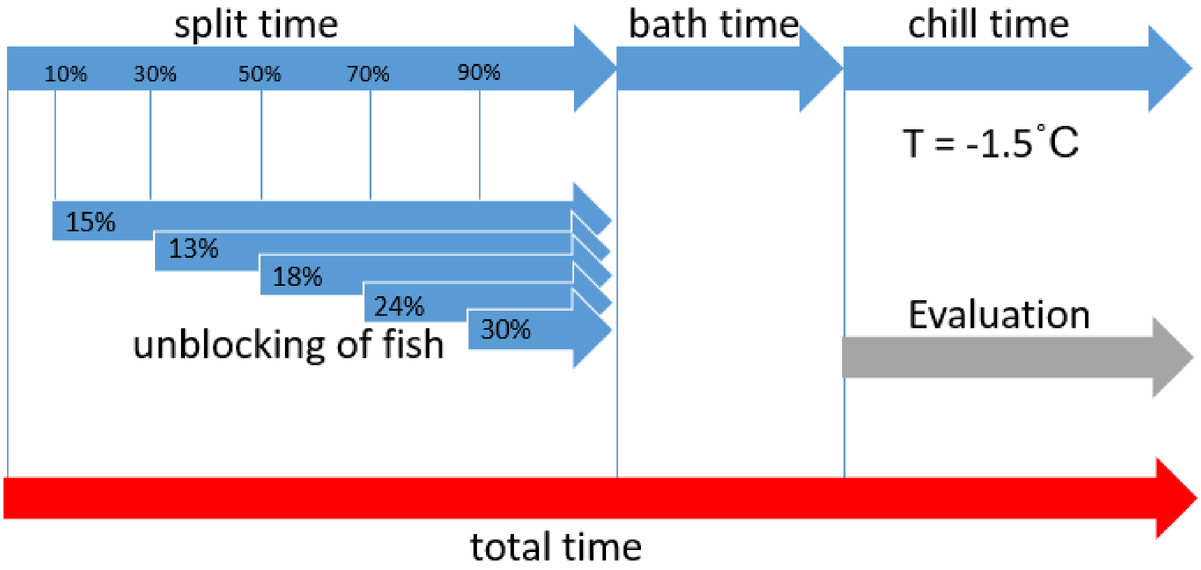


Figure 49: Sequence of the complete block thawing process model

The block thawing process is devided into three sections. During the split time, five groups of fish are getting unblocked to be exposed to heat transfer for the remaining split time (Figure 49). The splitting curve (Figure 50) obtained by (Haugland, 2002) is used to quantify the groups (Table 10).

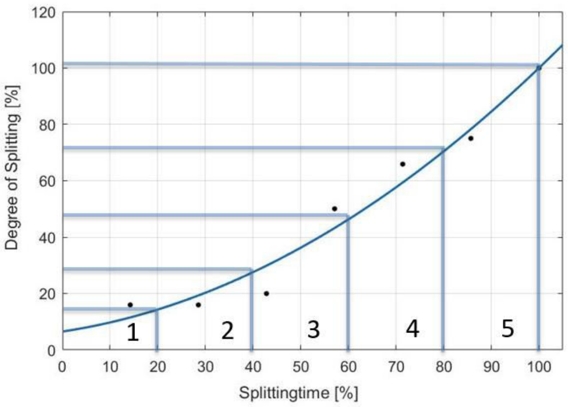


Figure 50: fitted splitting curve (Haugland, 2002)

Table 10: Overview on different fish groups

| | Time of single fish in thawing media [%] | Amount of fish [%] |
|---|---|---|
| *1* | 90 | 15 |
| *2* | 70 | 13 |
| *3* | 50 | 18 |
| *4* | 30 | 24 |
| *5* | 10 | 30 |

When the split time ends every fish is separated in the thawing media. The fish stays in the media for the remaining bath time. The temperature of the chill media was -1.5˚C. During the chill time, the temperature equalizes in the fish. The evaluation was conducted during the chill time. The variety of fish size in the blocks is considered with three different sizes in the model: 1.8, 2.6 and 3.4kg. The initial temperature is set to $T_{int}$ = -23˚C representing the typical storage temperature in the fish industry

## 6.7 Quality evaluation

A high quality product has a long shelf life due to a low spoilage level after processing. The bacterial deterioration (Equation 16) was used to evaluate the performance of thawing in chapter 7.1, 7.4 and 7.5.

Enzymatic and microbiological activity are greatly influenced by temperature. In the temperature range from 0 to 25°C, temperature changes have greater impact on microbiological growth than on enzymatic activity. Thus, microbiological activity is relatively more important (Koutsoumanis, 2000).

Microbial activity is responsible for spoilage of most fresh fish products. The shelf life of fish products is extended when products are stored at low temperatures. It is common practice to store fresh fish on ice (at 0°C) (Huss, 1995). The shelf life at different storage temperatures has been expressed by the relative rate of spoilage (RRS), defined as shown in following equation (Nixon, 1971):

$$RRS\ at\ t°\mathrm{C} = \frac{keeping\ time\ at\ 0°\mathrm{C}}{keeping\ time\ at\ t°\mathrm{C}} \tag{13}$$

The relationship between shelf life and temperature has been thoroughly studied. Based on data from the literature they found that the relationship between temperature and RRS can be expressed as an S-shaped general spoilage curve (Figure 51). (Spencer, 1964) found a straight line relationship between RRS and the storage temperatures of cod from the North Sea:

$$RRS(T) = 1 + 0.336 * T \tag{14}$$

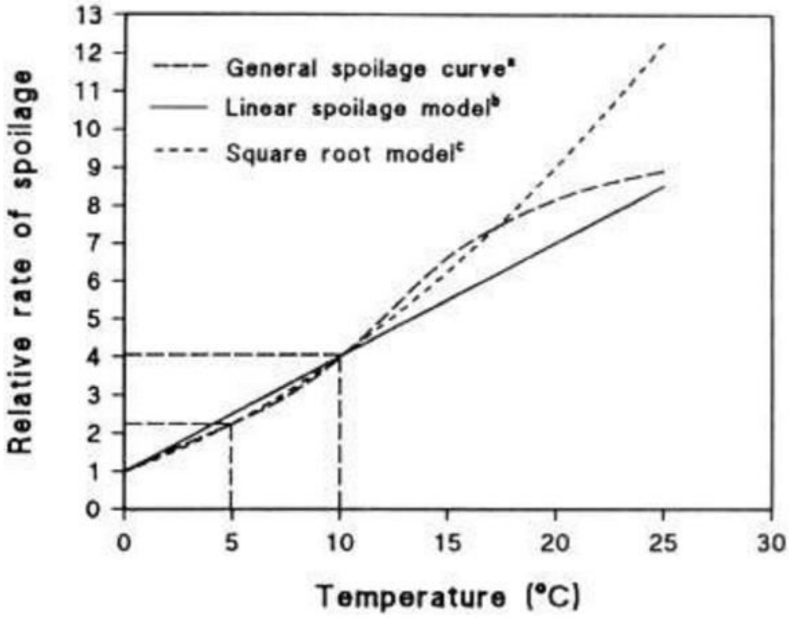


Figure 51: Effect of temperature on the relative rate of spoilage of fresh fish products

The effect of time/temperature storage conditions on product shelf life has been shown to be cumulative (Charm, 1972). In this thesis the relative rate of spoilage is used to evaluate the microbial growth in the fish. The temperature dependent RRS is integrated over the area and total time of the model:

$$Bacterial\ count\ (BC) = \iint RRS(T)\ dA\ dt \tag{15}$$

As a reference value the shelf life at 0˚C (RRS=1) of 10days is used:

$$Bacterial\ Deterioration\ (BD) = \frac{BC}{BC_{Ref}} * 100\% \tag{16}$$

## 6.8 Yield evaluation

The Yield was evaluated by the core temperature. According to a desired amount of ice in the fish, the chill temperature was set to -1.5˚C. The yield at this temperature is 60%. A deviation from this temperature is related to a yield decrease. No ice is left at -1.1˚C and too much ice is left at -1.9˚C. The Yield at this temperatures is set to 58%. The Yield isn't decreasing any further towards higher or lower temperatures (Figure 52). The evaluation is based on the findings of (Haugland, 2002) mentioned in chapter 4.2.5.

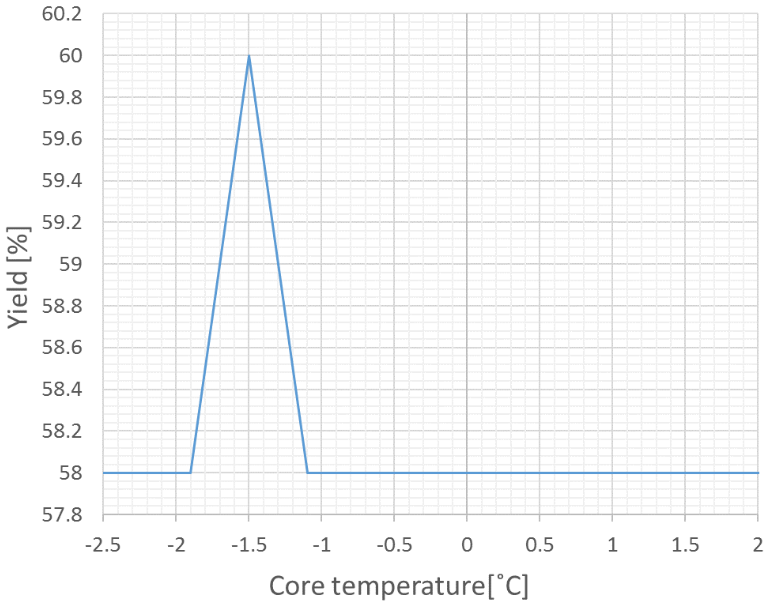


Figure 52: expected yield depending on the core temperature

The average yield was evaluated during the chill time. For different quality levels were elected to quantify the process. The Values were 58.3%, 58.6%, 58.9% and 59.1%. (Haugland, 2002) identified that the overall thawing process should be between 8 and 10 hours as described in Chapter 4.2.5. Most of the processes reached 59.1% yield in this timeframe. Thus, this yield level was used to quantify the processes.

## 6.9 Split Time

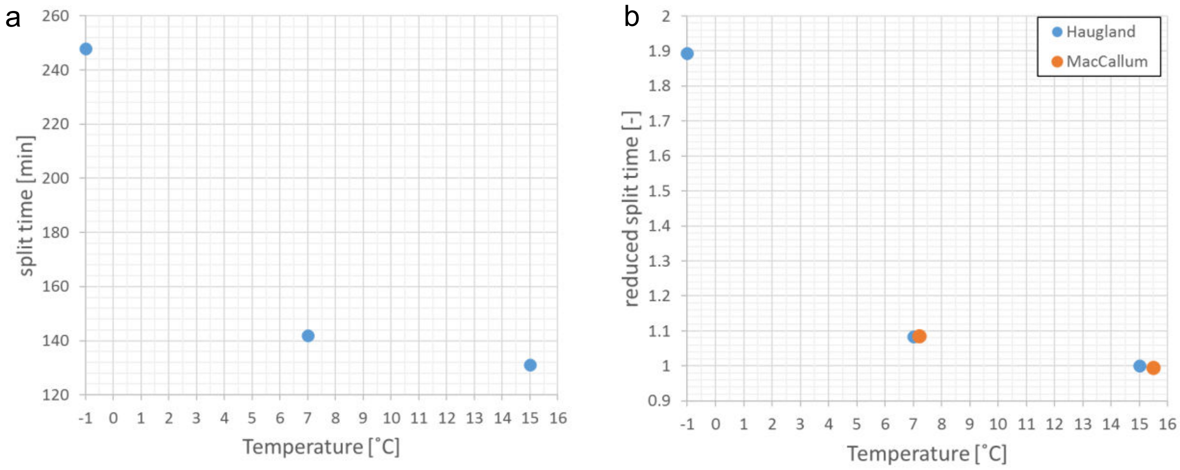


Figure 53: split time of cod blocks from different literatures

The blue dots in Figure 53.a show the data obtained by (Haugland, 2002). If the thawing media temperature is increased from –1°C to 15°C, the cod block will on average split 117 minutes earlier.From the data it can only be assumed that there is most likely curvature on the correlation. The curvature cannot be derived due to the number of experiments.

(MacCallum, 1964) investigated splitting of cod blocks at 7.2°C and 15.5°C. The absolut values of both sources can’t be compared due to the varying test conditions. However, the data can be compared by reducing the values with its reference time at 15°C (Figure 53.b). Thus, the marginal alternation between 7°C and 15°C can be confirmed. The curvature between -1°C and 7°C is still unknown.

Table 11: Overview of split time data

| | Tempera-ture [˚C] | Split time [min] | Reduced split time [-] |
|---|---|---|---|
| *Haugland* | -1 | 248 | 1.893 |
| | 7 | 142 | 1.084 |
| | 15 | 131 | 1 |
| *MacCallum* | 7.2 | 288 | 1.085 |
| | 15 | - | 1 |
| | 15.5 | 264 | 0.995 |

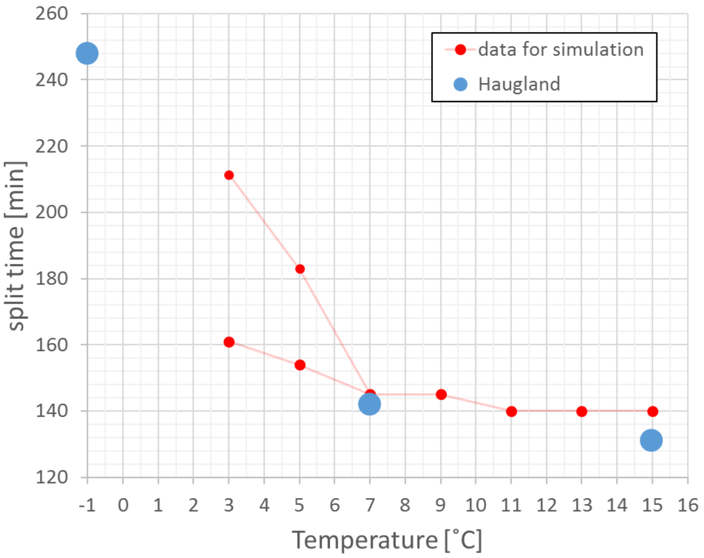


Figure 54: Split time at different temperatures (connected red dots) for the implementation in the model

For the numerical investigation the absolute values from (Haugland, 2002) were utilized. The red dots are the values implemented into the model (Figure 54) following the expected curvature of Figure 53. Below 7˚C, two different assumptions were made. The lower line shows an optimistic estimation with a slight increase of the split time between 3˚C and 7˚C. In this case the main part of the curvature would take place below 3˚C. The upper line is an assumption with a strong curvature between 3 and 7˚C. Both assumptions at 3 and 5˚C were compared.

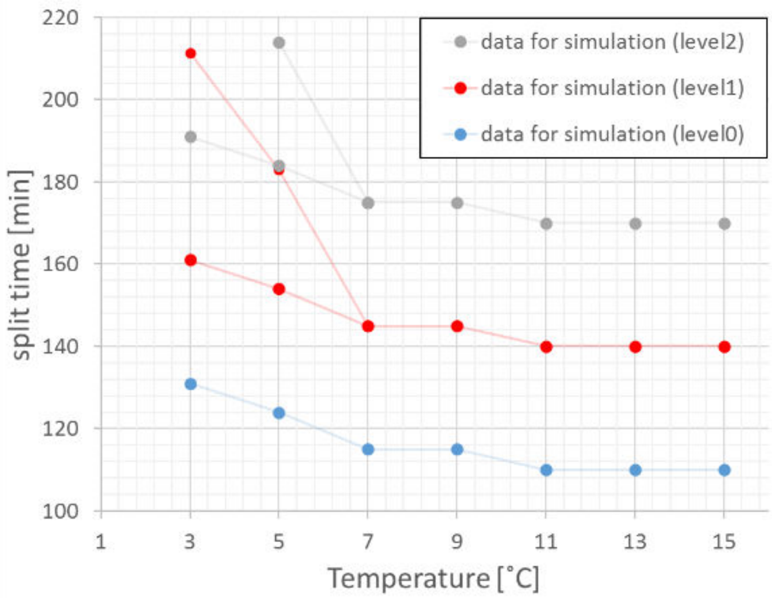


Figure 55: Different split time levels used in the investigation

Furthermore, different levels of split times were used to investigate both the effect of changing the process temperature and enhancing the block splitting. The variation by 30 minutes was a theoretical assumption to detect significant trends. Level2 was an extension of the split time of 30 minutes. Level0 was a reduction of the splitting time of 30 minutes (Figure 55).

# 7 Results

## 7.1 Effect of time and temperature on single fish thawing

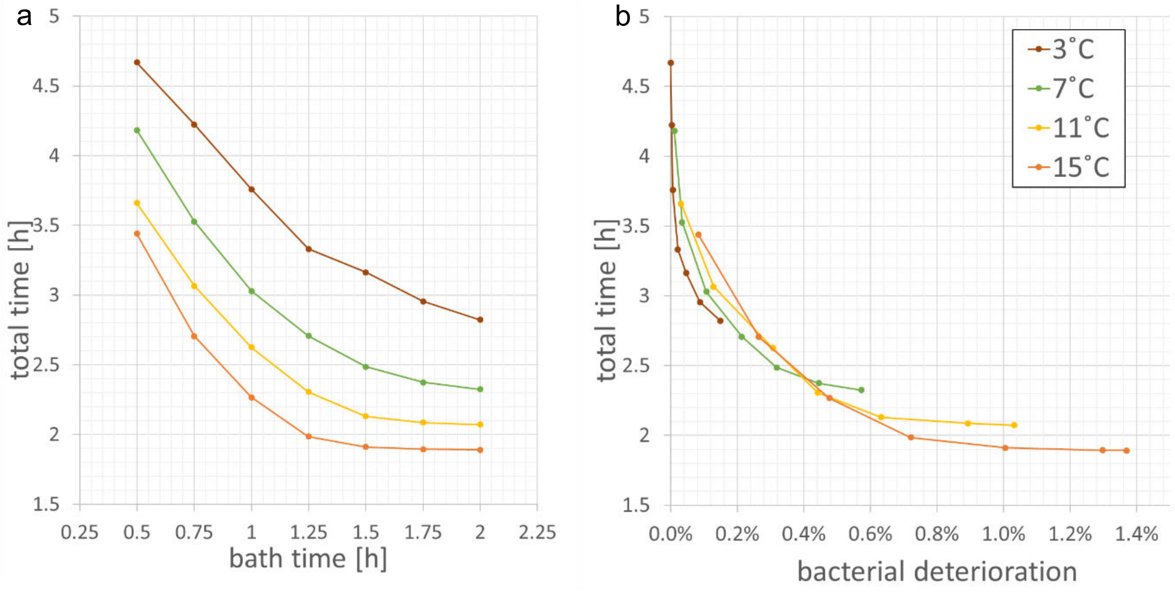


Figure 56: (a) total time to reach a core temperature of -3˚C at different media temperatures and (b) comparison of thawing time and bacterial deterioration for a 1.8kg cod

Figure 56 shows that the thawing time can be reduced by increasing the bath time or bath temperature. The curve for 15˚C media temperature shows no significant change above 1.25h bath time. The same can be seen at 13˚C above 1.5h bath time.

The curve confirm the explained findings in chapter 4.2.1, that the heat conduction in the muscle is the limiting factor of thawing. At 15˚C media temperature and a bath time above 1.25h the fish is exposed to high temperatures without a reduction in total thawing time. Figure 56.b shows the balance between fast thawing and bacterial growth (chapter 6.7). Higher temperatures lead to a faster thawing, but also higher bacterial growth. It's the opposite at lower temperatures with a slower thawing with lower bacterial growth. It can be seen that an effective thawing of the 1.8 kg fish can be done in between 2 and 3 hours. It exists approximately a linear relation between the two factors in this region. The results can be compared with those in Figure 4. Figure 57and Figure 58 show the results of thawing on 2.6 and 3.4kg cod.

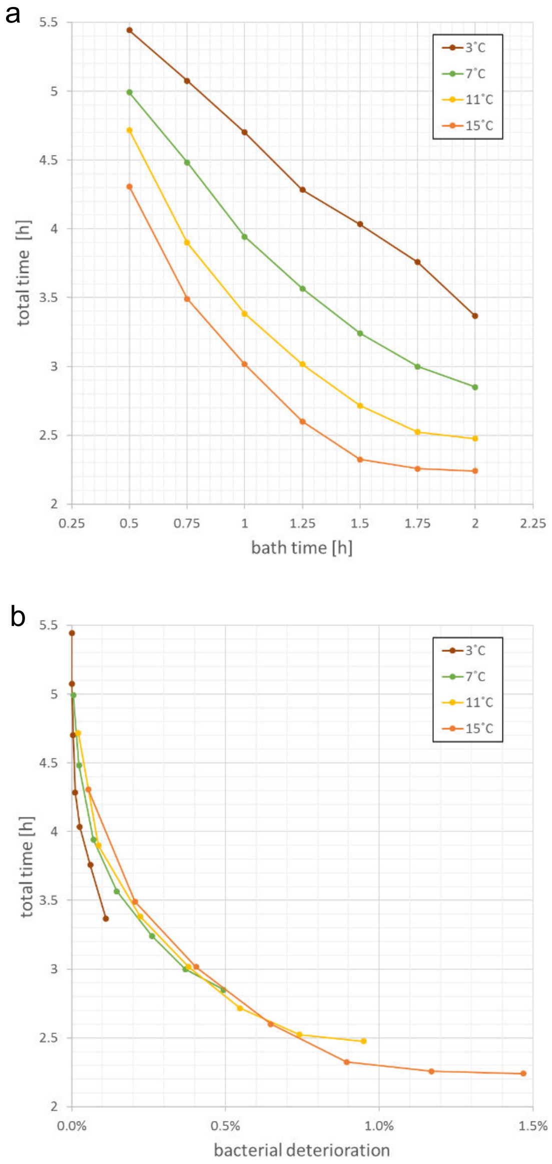


Figure 57: Thawing of 2.6 kg single fish

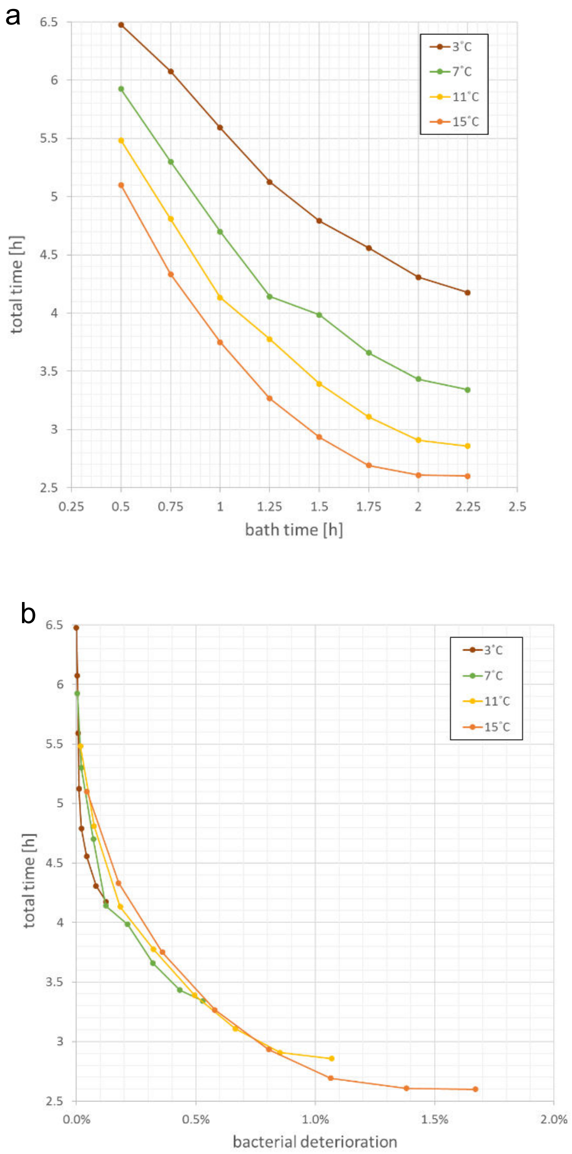


Figure 58: Thawing of 3.4 kg single fish

The thawing performance of a fish can be summed up into one curve. The curve is a combination of most efficient thawing at different temperatures and bath times. Figure 59 shows that bigger fish tends to require a longer thawing time combined with a higher bacterial growth.

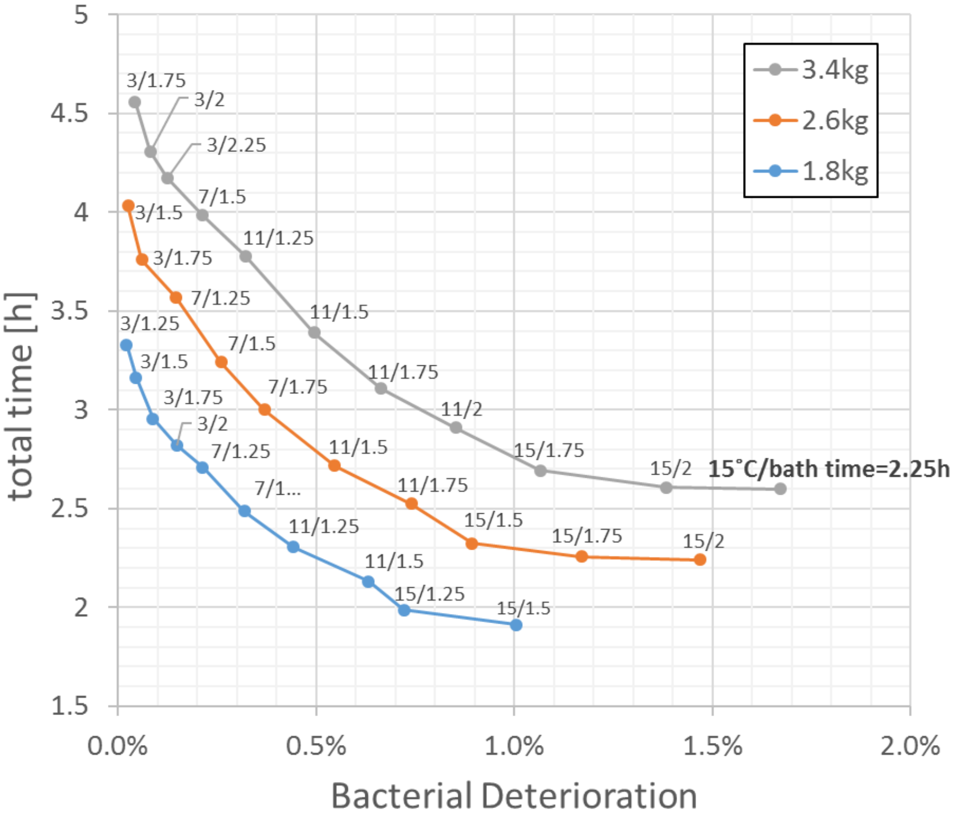


Figure 59: Summary of the performances of the most efficient thawing parameters for different size of fish

## 7.2 Characteristics of the temperature distribution during thawing

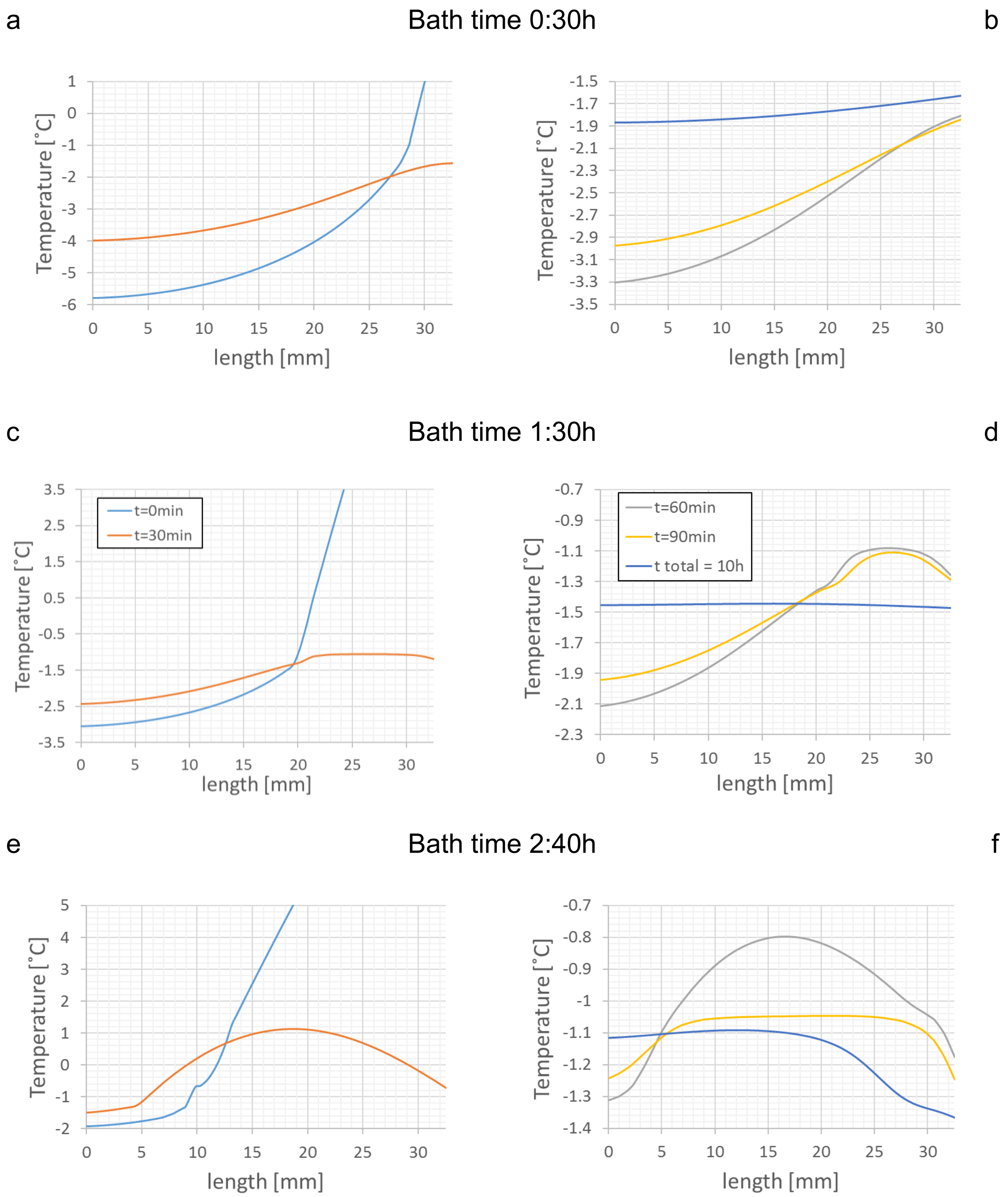


Figure 60: Comparison of temperature equalization on a 1.8kg cobath temperature 15˚C and different bath times

In this chapter the thawing of a 1.8 kg cod with a bath temperature of 15˚C is used to show characteristic temperature distributions. Three different bath times were chosen to show conditions following conditions:

- Too cold (core temperature -1.9˚C)

At Figure 60.a/b, the core temperature at t=0min (length=0mm) is still very low and outside the latent heat zone wheras the surface temperature is 4˚C. In the first 30 minutes of the chill time the surface temperature is reduced to the chill media temperature. The core temperature rises by about 2K. Between 30 and 90 minutes the core temperature keeps rising slowly. At the end of the process time of 10h, the temperature is equalized between -1.9˚C at the core and -1.7˚C at the surface. The very low temperature gradient in the chill media combined with a huge enthalpy difference requires an extensive time period to achieve the desired condition. The bath time was too short. Thus too little energy was transferred and the result is too much ice.

- Ideal tempering (core temperature = chill media temperature = -1.5˚C)

Figure 60.c/d shows an ideal tempered fish. In the first 30 minutes of the chill time the surface is decreases while the core temperature rises. At this point, ice exists from 0 to 20mm. The outer layer (20-30mm) is cooled down to the initial freezing point (-1.1˚C). At 60 and 90 minutes, the core temperature rises slowly and on the surface ice is formed again. After 10h the fish is equalized at -1.5˚C. The temperature gradient is neglectable at this point. The exact bath time was found to provide a sufficient energy transfer. The equalizing leads to the desired amount of ice all over the muscle.

- Too warm (core temperature = initial freezing point = -1.1˚C)

Figure 60.e/f shows completely thawed fish. During chill time ice melts slowly in the core. At the start of the chill time, 10 mm ice is left in the core. After 30 minutes only 5 mm is left. Ice is formed again at the surface after 60 minutes. The surface ice is 10 mm thick after 10 hours process time but in the core no ice is left due to the enthalpy equalizing. The ice would keep moving towards the core to be in the desired condition after an extensive time period. The bath time was too long. Too much energy was transferred and resulted in a completely thawed muscle.

In all three cases can be seen that the surface temperature was reduced within 30 minutes after the transfer to the chill media. The average enthalpy of the elements on the cutline changes only slowly (Figure 61), due to the small temperature gradient.

However, the core temperature rises during the chill time due to the enthalpy equalization. Thus, the final core temperature depends on the transferred energy during the bath time.

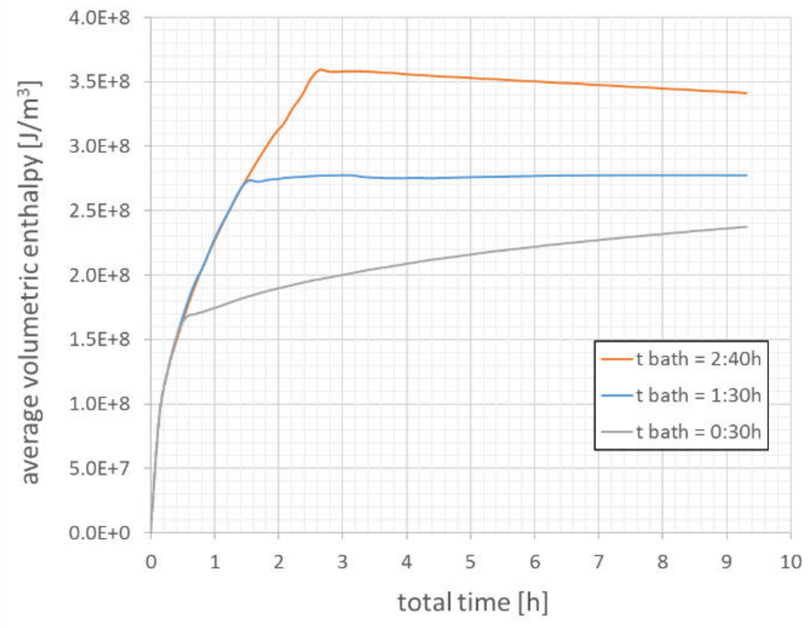


Figure 61: Average enthalpy on the cut line for different bath time

The comparison of the three cases in Figure 60 reveals the reason of different conditioned fish even after an appropriate in the equalizing stage. The acceleration of splitting reduces the timelag between early and late unblocked fish. The difference in transferred energy is smaller and thus, the resulting temperature after a adequat chill time is more equal.

Table 12: Overview of bath times for different size and temperature:
too cold/**time lag in between**/completely thawed [min]

| | **7˚C** | **11 ˚C** | **15 ˚C** |
|---|---|---|---|
| *1.8kg* | 30/**240**/270 | 20/**190**/310 | 20/**140**/160 |
| *2.6kg* | 70/**280**/350 | 50/**200**/250 | 40/**160**/200 |
| *3.4kg* | 90/**310**/400 | 70/**230**/300 | 60/**170**/230 |

The same procedure was conducted for all three fish size at 7, 11 and 15˚C. Table 12 shows three values each weight/temperature couple. The first is the bath time to reach the “too cold” condition, the bold one is the timedifference between “too cold” and “too warm” and the third is the bath time for to reach “too cold”. All three values decreases towards lighter fish and warmer bath temperature.

(Haugland, 2002) stated that it is important to cool the fish as soon as possible after the center of the salmon reached the initial freezing point. The simulation results reveal that this would lead to a completely thawed fish. It can be recommended to cool (transfer to chill media) the fish when the core reached a temperature 2K below the initial freezing point.

At higher temperatures the heat transfer is faster. Thus, the time needed to transfer the ideal amount of energy is shorter. But also the time lag between the two unwanted conditions „too cold“ and „too warm“ is shorter. In Figure 62 the split time (level 0-1-2) is compared with the described time lag for the different weights (Table 12). The data quantifies the adverse characteristics of warm temperatures at a slower split. The time lag, especially for lighter fish, is shorter than the split time. The heat transfer is fast but the early unblocked fish will be completely thawed whereas the late unblocked fish will be too cold. For split level 0, the split time is shorter than the time lag. At lower temperatures, the core temperature rises with constant small gradient towards to desired end temperature. The heat transfer is slow but all fish will be tempered into the latent heat zone.

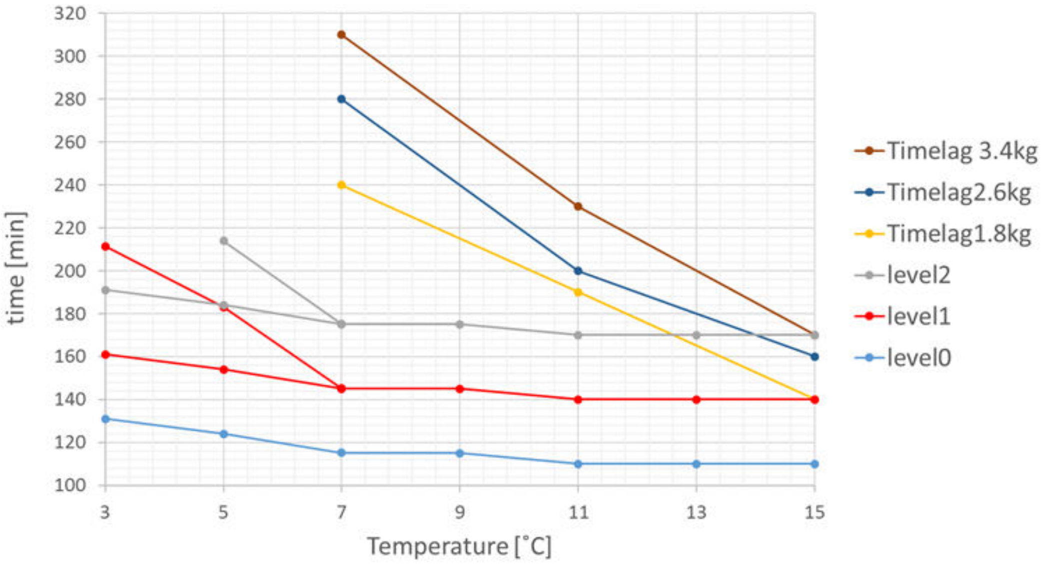


Figure 62: Comparison of the split time and the time lag between "too cold" and "too warm"

## 7.3 Effect of chill media temperature on single fish thawing

The data in Table 13 shows the relevance of the process parameter and the knowledge of the heat conduction in the fish msucle. The 1.8kg cod is thawed in 15˚C water bath for respectively 30, 90 and 150 minutes, then transferred to -1.2, -1.5 or -2˚C for a total process time of 10 hours. The final core temperature after 10 hours of processing strongly extent dependant on the bath time. The average temperature is significant different whereas the influence of the chill media (ΔT) is minor (Figure 63). ΔT decreases towards longer bath times.The data shows that it is not possible to temper the fish towards an desired end temperature without an appropriate energy transfer during the bath time.

Table 13: core temperature after 10 hours of processing with different chill media temperature and bath time [˚C]

| | **30 min** | **90 min** | **150 min** |
|---|---|---|---|
| *-1.2˚C* | -1.85 | -1.53 | -1.24 |
| *-1.5˚C* | -1.97 | -1.59 | -1.29 |
| *-2˚C* | -2.25 | -1.77 | -1.33 |
| *Average* | -2.02 | -1.63 | -1.29 |
| *ΔT* | 0.40 | 0.24 | 0.09 |

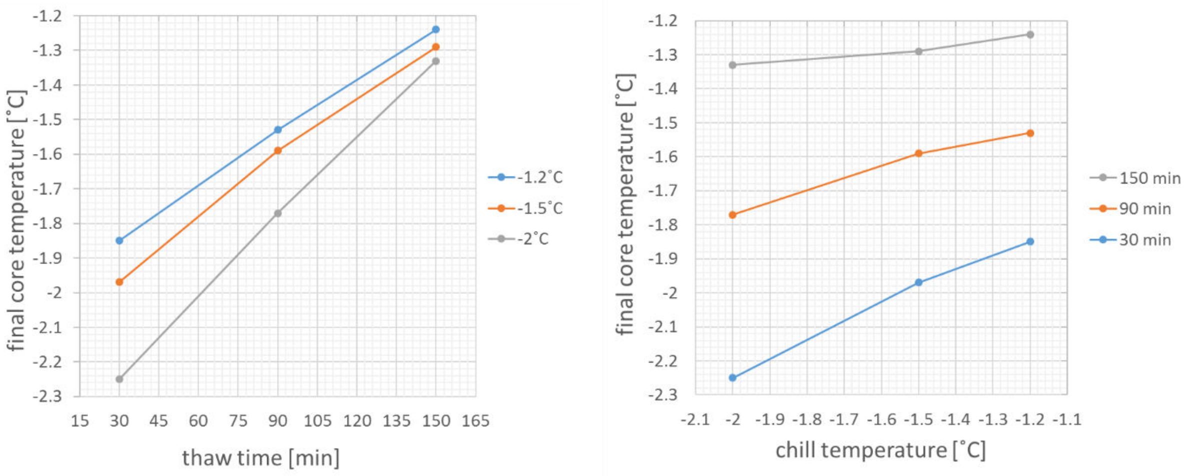


Figure 63: The effect of thaw time and chill temperature on the core temperature after 10 hours processing

## 7.4 Results of block thawing with expected split time (level1)

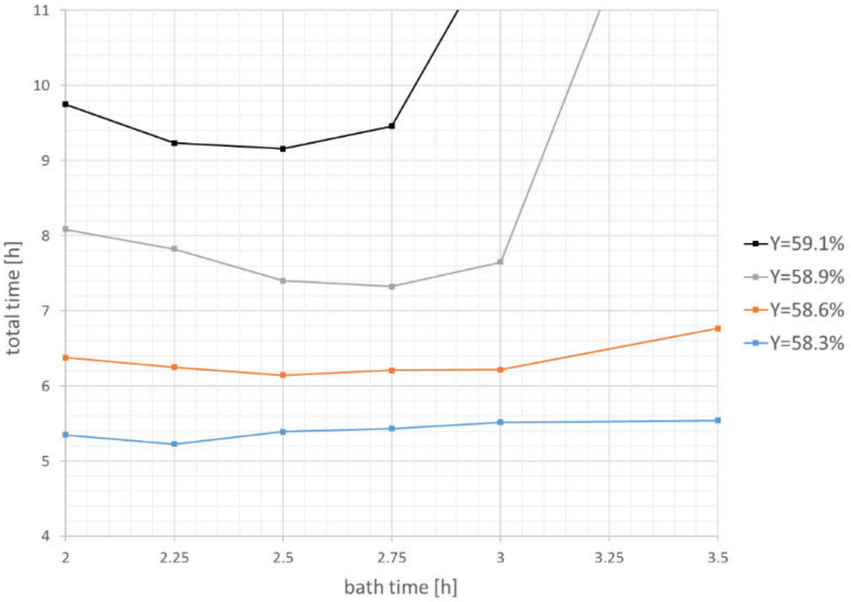


Figure 64: Performance of different bath times at splittimelevel1 with 11˚C

For each couple of thawing temperature and split time a set of bath times was tested. The performance was compared by the use of 4 different average yield levels. The yield level 58.3% and 58.6% in general doesn't show significant differences. In Figure 64, yield level 58.9% as well as 59.1% shows significant differences between the chosen configurations. The peak performance is chosen by yield level 59.1%. It is resulting optimal bath time and a recommended total process time. In this case 2.5h was chosen. For longer bath times it can be seen that the two highest yield levels couldn't be reached in acceptable time. By overstepping a critical bath time the performance decreases drastically. In this case it is over the bath time of 2.75h. Towards shorter bath times the performance decreases more gradually. Each bath temperature result in a recommended bath time (Table 14).

Table 14: Overview of the process configuration at split level 1

| ***Temperature [˚C]*** | **3** | **5** | **7** | **9** | **11** | **13** | **15** |
|---|---|---|---|---|---|---|---|
| *Bath time at the Best performance [h]* | 5 | 4.5 | 4 | 3 | 2.5 | 2 | 1.75 |

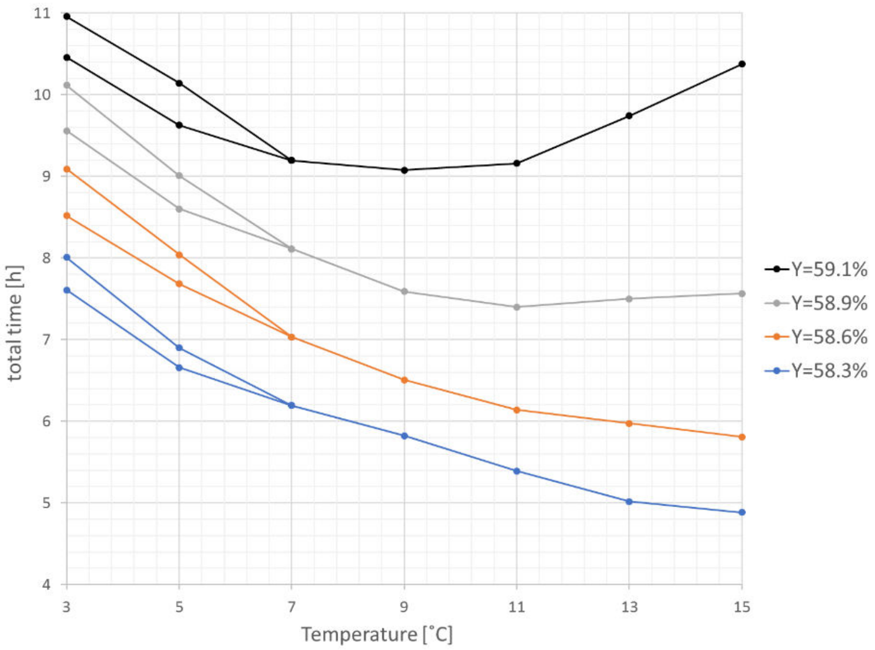


Figure 65: Comparison of the best performance at different process temperatures at splittlevel1

The best performance for each temperature can then be compared (Figure 65). The yield levels 58.3% and 58.6% are reached much faster at higher temperatures. Both lines show similar curvature with a decrease of about 3 hours between the lowest and highest temperature. The lag time between the lines is constant at approximately 1 hour. The yield level 58.9% shows up to 9˚C a similar curvature as the two lower levels. Above 9˚C, the time stays approximately the same. The steady trend towards shorter times, as in the two lower levels, doesn't exist anymore. The time difference between the recommended process time at the highest and the lowest temperature decreases to approximately 2.5h. The yield level 59.1% shows the adverse properties of thawing at high temperatures. From 3 to 7˚C the time decreases from maximum 11 to 9 hours. Between 7 and 11˚C the process time stays approximately the same. Above 11˚C, the process time increases again up to values comparable to them at 3˚C. Both assumptions show the same trend. The actual performance might be somewhere in between the points. Even for the optimistic assumption, 3˚C and 5˚C show a clear trend towards longer process times. The yield level 59.1% shows that the pros and cons of both low (3-5˚C) and high (13-15˚C) temperatures balance each other to result in the same expected quality after 10 hours. The balance between fast and precise thawing might be found between 7 and 11˚C.

The best performance in matter of a fast processing can be expected between 7 and 11˚C. The data shows the potential reduction of process time through a change of the thawing temperature. For thawing at low temperatures it can be worth it to enhance the media temperature towards 7˚C. Thus, it is possible to increase the throughput of the production by an increased energy input to the thawing media. Between 7 and 11˚C only a slight difference in process time can be seen. A decrease to 7˚C could preserve energy expenses at same throughput. The performance decreases towards even higher temperatures above 11˚C. Thus, this temperature range cannot be recommended.

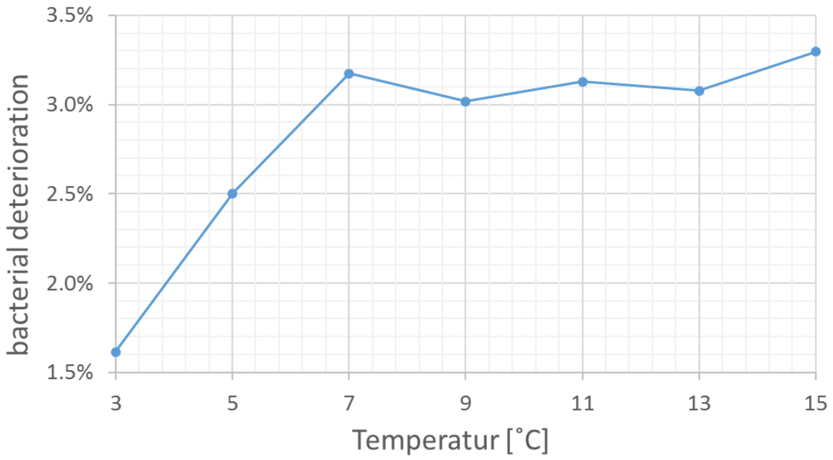


Figure 66: Bacterial deterioration at different temperatures to reach Y=59.1%

The resulting bacterial deterioration for the set of process configurations (Table 14) helps further to rate the total quality of cod filets (Figure 66). The graph shows that above 7˚C the bacterial growth doesn’t change significant. In this area the effect of the higher temperature is balanced by a shorter bath time (Table 14). 3% deterioration is equal to 7.2 hours of the equivalent 10 days storage at 0˚C. The temperatures below 7˚C show benefits regarding the bacterial growth. Between 7˚C and 3˚C the bacterial load is reduced by half.

## 7.5 Effect of a split time variation on block thawing

The split time variation makes it possible to show both the trend of changing process temperature and split time.

The comparison of the different coloured dots at a particular temperature show the potential of faster splitting (Figure 67). For each process temperature the recommended process time decreases for a faster splitting and increases for a slower splitting. The process time reduction strongly depends on the temperature. The split time reduction of 30 minutes at 15˚C leads to a process time reduction of about 2 hours. Thus, the resulting curvature and the temperature of the fastest processing are different.

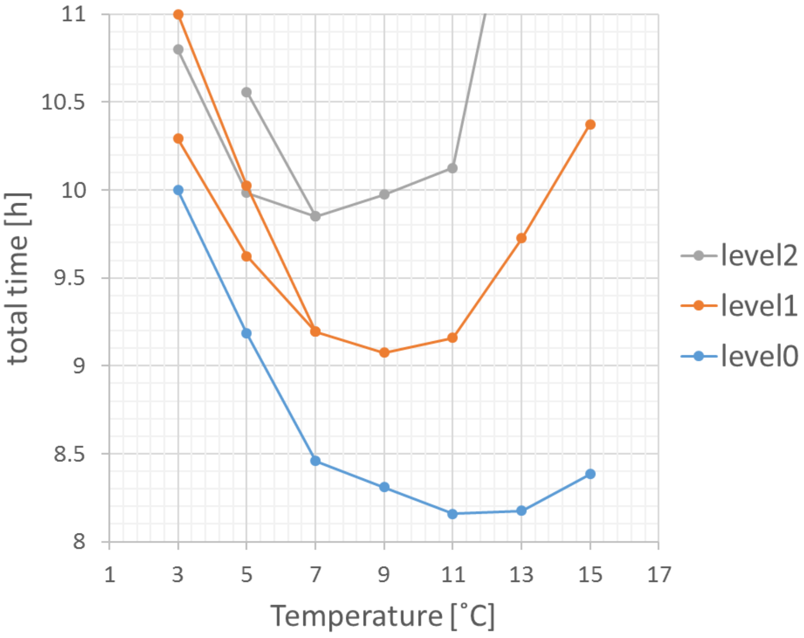


Figure 67: Total time to reach Y=59.1% for different split level depending on the temperature

The fastest possible processing, independent from temperature, decreases from 9:06h (9˚C) to 8:10h (11˚C) for faster split (level0). The curvature shows a strong gradient below 7˚C. Between 7 and 15˚C the value changes only slightly. However, the lowest point can be stated at 11˚C. The data shows that for a faster split higher temperatures are more attractive. The increase towards 15˚C can be neglected. The slower split (level2) shows the opposite trend. The fastest processing can be stated at 7˚C with only a slight difference for the values between 5 and 11˚C. The value for 13 and 15˚C is outside the considered maximal process time. In this case, the optimistic assumption at 5˚C would be a recommended processing.

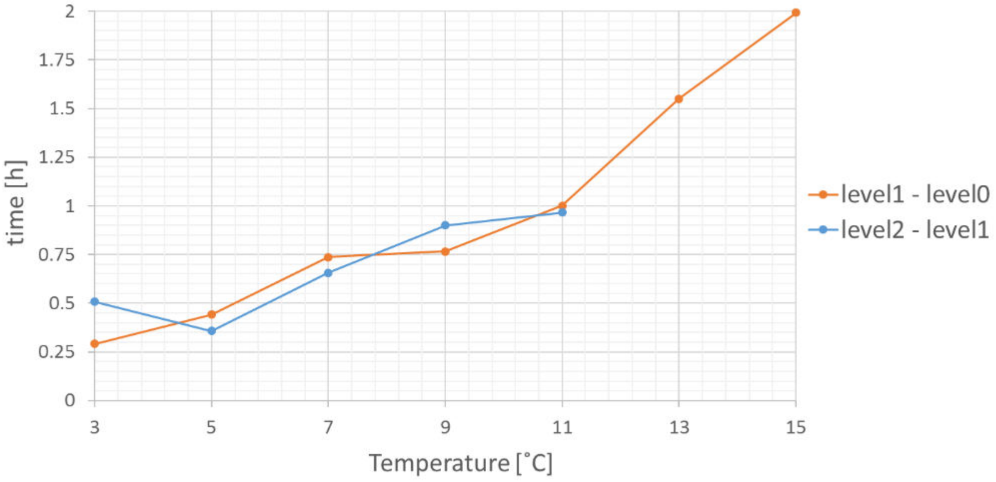


Figure 68: Time difference between the split levels depending on the temperature

The reduction of the process time is approximately linear (Figure 68). The reduction of the split time of 30 minutes leads to a reduction of the process time of up to 2 hours at 15˚C. The bacterial deterioration (Figure 69) of the three curves show no significant difference. Thus, bacterial deterioration is independent from split time.

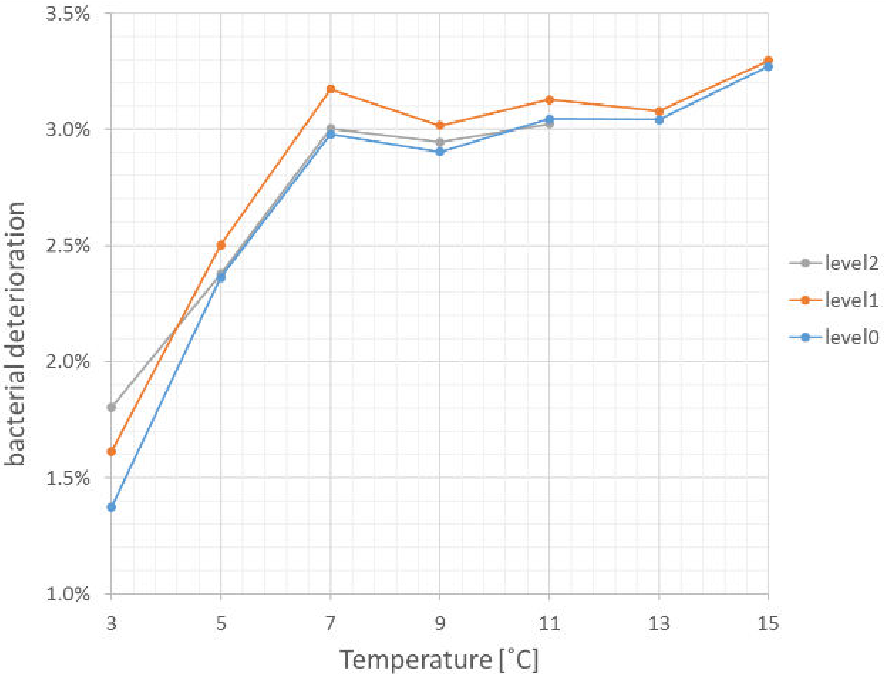


Figure 69: Bacterial deterioration of the three splitlevel

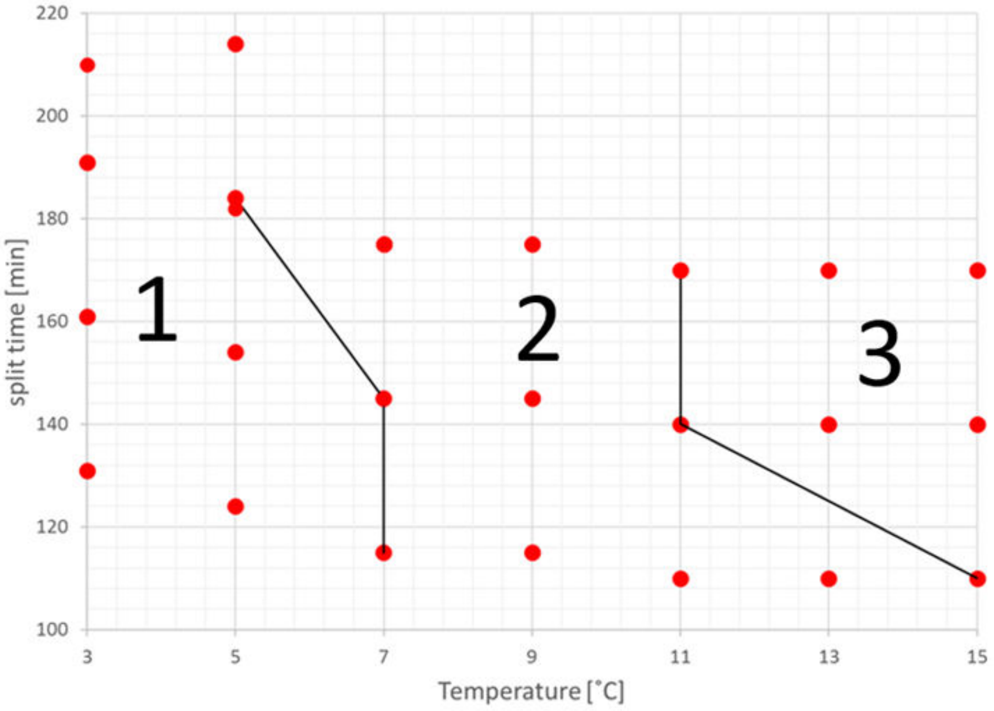


Figure 70: Classification of split times into three areas

The data of investigated temperature/split time combinations can be separated into three areas. For each area a recommendation for the process can be done.

1. The process time can be reduced by increasing the thawing media temperature. The throughput of the plant is increased by an additional energy input.
2. The temperature change has only a minor influence on the process time.
3. The process time can be reduced by reducing the thawing media temperature.

The seawater intake is often at a depth where the temperature changes rapidly as a result of streams or a change in the weather. The temperature of the thawing water can be controlled by the cooling capacity of the blocks and the amount of fresh seawater supplied from a depth of 12 meters in the harbour. (Haugland, 2002). That means, recommendation 2 and 3 can be applied through the adjustment of the seawater pump in the production facility.

# 8 Conclusion

Thawing of frozen raw fish has become an important industrial process due to the market demands for safe products with high quality and at sufficient volumes all year round. Appropriate freezing and thawing of Atlantic cod can result in quality comparable to fresh fish for further processing.

The literature survey shows that the complexity of the block split is yet only investigated for the water thawing process. The investigations on other techniques were mostly conducted with fillet pieces and show a possible reductions of the thawing time of up to 80%. For electric resistance- and radio frequency thawing, research is needed to better understand the effecting material properties. Vacuum-, microwave- and high pressure thawing demands research on the process parameter. The different techniques are wide spread in the food industry. That makes the availability independent from the suitability at thawing. The producers offer process solutions in various size or in modular build up. Thus, all introduced techniques are availability for large scale thawing.

The objective was to find a numerical way of describing the complex process of thawing. The model can be used to better understand thawing to predict thawing times for certain size and type of fish. The basic thermic of thawing was investigated with a 2-D cross section. A 1.8kg cod can be thawed within 2 to 3 hours depending on the thawing media temperature. The resulting linear relation between thawing time and quality (bacterial growth) was confirmed with literature data. At the same bath time, thawing can be conducted in 3h at 3˚C or in 2h at 15˚C. This acceleration is connected with the increase of bacterial deterioration from 0.1% to 0.7%. Heavier fish requires a longer time and results in a higher bacterial growth.

The model was used to investigate block thawing of cod. The goal was to develop a concept for precise block thawing to meet market demands for safe products with high quality. As the research has demonstrated the process efficiency depends on the mutually dependent variables temperature and the time needed to split the block. The potential process time reduction induced by a faster block split rises linear towards higher temperatures. In other words, high temperatures shows adverse characteristics for a slow split. This can be explained by the huge enthalpy difference due to the fast energy transfer. Thus, the resulting curve of the investigated split levels are different.

The performance of high temperatures up to 15˚C can only be recommended for a splitting faster than 2 hours. Slower splitting makes lower temperatures more recommendable.

A temperature variation of 2K leads to a reduction of the recommended process time of up to 20%. The bacterial growth of the process does not depend on the split time. The bacterial growth is constant for a processing above 7˚C due to the balancing of higher temperatures with shorter duration. The resulting data can be classified in three groups of recommendations. In the average, the temperature between 7 and 11˚C can be recommended due the balance between fast and accurate thawing.

# 9 Proposal for further work

The scientific investigation on most of the introduced techniques are still sparse. It is not possible yet to estimate the performances on cod block thawing. There are numerous possibilities to go further in the research of the particular technique.

The model shows clear trends in regard to parameter settings to run an optimal process. However, the particular circumstances might be different for each production facility. To make specific recommendations further testing is necessary. The measurement and monitoring of the exact split time-temperature curve makes it possible to adjust the guidelines. It is essential to identify the possibilities to measure the parameter and further influence the system to vary those. The influence of the process temperature on the bacterial growth can also be different. An energy analysis would delivers data to estimate the practicability and economy of a possible parameter change.

However, the model is still just a simplified imitation of the actual complexity. The block split might be the biggest inaccuracy in the model. The block split can be conducted with more than five steps to correlate the splitting curve. Up to the unblocking, the cod isn’t exposed to any heat transfer in the model. In the actual process, the cod is at least partially exposed to a heat transfer. The investigation of the block structure before and during the split stage might lead to ideas how to implement this heat transfer. Recording and implementing of the splitting curve and weight distribution of a block leads to a more precise analysis of the actual process. The model should be validated to demonstrate the significance.

(Haugland, 2002) delivers the fundamentals for this work. He showed that the yield can be increased by processing at temperatures near the initial freezing point with a little ice left. On the other hand, completely thawed and too cold fish lead to reduced yield. However, the exact temperature range should be investigated because it can be different for different fish type or end products.

Faster splitting shows a great potential at higher temperatures. Thus, further work on speeding up the block split might be only reasonable if high temperatures are used in industry. Beside a maximum level of agitation, it is possible to influence the splitting by adjusting the salt content of the thawing media. Agitation and the salt content can accelerate the block split and thus lead to the possibility for faster processing. The investigation showed that this isn’t related to an enhanced bacterial quality.

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# 11 Appendix- draft paper

# Energy efficient and high quality thawing of cod in large scale

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## ABSTRACT

A two-dimensional model is developed to simulate to thawing process. The abrupt changes of the thermophysical material properties in the melting zone leads to a highly non-linear mathematical problem. By a Kirchhoff- and enthalpy transformation, a partial differential system with two mutually related dependent variables can be solved. The influence of process temperature on the bacterial quality and the resulting shelf life of the product is evaluated by integration of the temperature distribution. Basic investigation on single fish thawing delivers a guideline for thawing regarding time, temperature and bacterial growth. The model delivers data to optimize the thawing process depending on the circumstances of the particular application. The positive effect of a faster split is especially strong for higher temperatures. Thus, a fast split leads to recommendation of higher temperatures.

## 1. INTRODUCTION

The fact that supply of fresh raw material often is dependent on seasonal variations, weather conditions, quotes and regulations makes it necessary to use frozen raw fish in the processing industry. A large part of the commercial catch of Atlantic cod (Gadus morhua) is frozen at sea in plate freezers, typically 1-6 hours after the catching. Thus, thawing is an important industrial process. If Atlantic cod is correctly frozen stored and thawed, the quality can be good and of comparable quality to fresh fish **(Haugland, 2002)**. The methodology and technique used for freezing and thawing process play an important role in the preservation of the quality of frozen foods. To deliver a high quality product it is essential to build up knowledge on various parameter of the process. Many different thawing methods are established for frozen fish but the selection of the method is dependent on factors such as fish size and species **(Alizadeh, 2007)**. Thawing in room air has been most commonly used in the processing industry due to the relatively small or neglectable need for investments. However, the low heat transfer coefficients make this method very time consuming and are not recommended from a quality and microbiological point of view. Uncontrolled thawing process leads to economically losses in several ways: reduced yield and quality, more handling, lack of traceability, capacity reduction and more complex production planning **(Haugland, 2002)**. Thawing of block frozen products is the main challenge of the overall industrial process due to the introduced large spread in temperature distribution during thawing. The frozen blocks are “glued” together by frozen water and will in a large extent be as a block up to the end of the thawing period is finished. The geometry make the heat transfer difficult during the thawing process and is one of the reasons that the variation in temperature is large after the thawing period. In order to minimize the effect of this, it is important to split the blocks as early as possible, to be able to use the thawing period thaw or temper the single fish. Controlled thawing with an accurate post thawing treatment increase the yield. Tempering towards just below the initial freezing point with a small amount of internal ice leads to a cleaner cut along the backbone. Thawing equipment, however, most likely does not lead to a controlled process that meets the introduced demands **(Haugland, 2002)**. Thus, it is important to evaluate how controlled thawing can be performed. During a freezing or thawing process, the thermophysical properties undergo abrupt changes. The specific heat, thermal conductivity and density are changing in the latent heat zone due to the phase change between water and ice. The biggest problem in the numerical computation of thawing is how to deal with the sudden changes in material properties around the freezing point. Beside the change of material properties, the evolution of latent heat has to be taken into account **(Pham, 2014)**. One of the traditional methods is the use of the apparent specific heat, where the sensible heat is merged with the latent heat to produce a specific heat curve with a large peak around the freezing point **(Santos, 2011)**.The abrupt change in the apparent specific heat curve usually destabilizes the numerical solution and makes it difficult to obtain convergence with this technique. Many authors have done approximations by ''softening'' the peak curve in order to obtain some convergence of the method, modifying the shape of the apparent specific heat curve while maintaining the total latent heat constant. However, this softening method is not recommended, because the actual temperature range around the freezing zone, is altered becoming wider than the actual temperature freezing range **(Santos, 2011)**.It is always a chance that the latent heat is underestimated. This happens when a nodal temperature steps over the peak in the apparent specific heat curve. The mean specific heat between the initial and final temperature is then always less than the peak and the temperature change will be overestimated. For this reason, the apparent specific heat method is not recommended. In this work it is the aim to temper the fish somewhat under the initial freezing point. Therefor an accurate approach for the thawing/freezing process is necessary.

The whitefish industry has a strong political focus in Norway the past few years, due to low profitability. The project "QualiFish" is focusing on the challenges of large volume fluctuations and product quality through the development of market adapted production concepts and novel technology, with research and innovation at its core. The project goal is to develop new knowledge and technology to increase sustainability and profitability of cod production in Norway, enabling actors to meet market demands for safe products with high quality and at sufficient volumes all year round. High quality frozen/thawed raw material can contribute to a more continuous production throughout the year, enabling the Norwegian whitefish industry to supply the market with high quality products during the entire year. In this thesis, the up-to-date technology status of different thawing systems for fish industry will be evaluated. The literature review of published papers will reveal development potential and beneficial application areas for each of the mechanisms. Furthermore, a numerical model will be developed to investigate the thermal characteristics of water thawing. The thawing of single fish will be investigated to provide a basic understanding on the interaction of warm thawing- and cold chill media and the resulting temperature distribution in the spatial domain. The objective of the resulting data is to deliver recommendations depending on the conditions of particular applications. Adjusting of process parameter time and temperature intents to achieve an optimum regarding yield, quality and energy efficiency. It is important for the industry to know how to accelerate the process to increase the throughput to deal with higher market demands.

## 2. Material and methods

### 2.1. Numeric simulation

The rapid change in thermal conductivity around the freezing point contributes to the difficulty in the numerical modelling of phase change. A more rigorous formulation is obtained by using the Kirchhoff transformation:

$$\boldsymbol{E(T) = \int_{T^*}^{T} k(T)dT} \tag{1}$$

The simultanious application of the Kirchhoff and the enthalpy transformation avoids the possibility of missing the apparent specific heat capacity peak and the abrupt thermal conductivity change **(Scheerlinck, 2001)**:

$$\boldsymbol{H(T) = \int_{T^*}^{T} \rho(T) * Cp(T)dT} \tag{2}$$

$\boldsymbol{T^*}$ is a reference temperature that corresponds to a zero value of $\boldsymbol{H}$ and $\boldsymbol{E}$. The non-linearities of phase change are incorporated in a functional relationship with two mutually related dependent variables $\boldsymbol{H}$ (volumetric specific Enthalpy) and $\boldsymbol{E}$ (Kirchhoff function). Combining both transformations helps to avoid inaccuracies and/or divergence of the numerical method **(Santos, 2011)**:

$$\frac{\partial \boldsymbol{H}}{\partial \boldsymbol{t}} = \nabla^2 \boldsymbol{E} \tag{3}$$

By combining the boundary condition for heat conduction equation with function (1) and (2) the following equation is obtained:

$$-(\nabla \boldsymbol{E}) * \boldsymbol{n} = \boldsymbol{h} * (\boldsymbol{T} - \boldsymbol{T_{bath}}) \tag{4}$$

$\boldsymbol{n}$ is the normal outwards vector component, $\boldsymbol{T_{bath}}$is the media temperature sourrounding the fish and $\boldsymbol{h}$ is the surface heat transfer coefficient. The flow in the agitated water bath is estimated with heat transfer coefficient for the outer and inner surface.

### 2.2 material properties

The typical composition of atlantic cod (Gadus morhua) considered to estimate the thermal properties were: 81.22% moisture content, 0% carbohydrates, 0.67% fat, 17.81% protein, and 1.16% ash **(USDA, 2017)**. The model proposed by Choi and Okos **(Choi, 1986)** were implemented to estimate the thermal properties as a function of temperature and composition of the foodstuff. The thermal conductivity was:

$$\boldsymbol{k}(\boldsymbol{T}) = \sum \boldsymbol{x_i^v} * \boldsymbol{k_i}(\boldsymbol{T}) \tag{5}$$

Where $\boldsymbol{k}$ is the global conductivity, $\boldsymbol{k_i}$ is the thermal conductivity of the component $\boldsymbol{i}$ (where $\boldsymbol{i}$ corresponds to thedifferent components: water, ice, carbohydrate, fat, etc.), $\boldsymbol{x_i^v}$ corresponds to the volumetric fraction of each component. The density of the product was calculated using:

$$\boldsymbol{\rho}(\boldsymbol{T}) = \frac{\boldsymbol{1}}{\sum x_i/\rho_i} \tag{6}$$

Where $\boldsymbol{\rho}(\boldsymbol{T})$ is the global density and $\boldsymbol{\rho_i}$ is the density of the component $\boldsymbol{i}$. The fractions $\boldsymbol{x_i}$ corresponds to the mass fraction of each component. The specific heat of the mushroom was estimated using the following Equation:

$$\boldsymbol{Cp}(\boldsymbol{T}) = \sum \boldsymbol{x_i} * \boldsymbol{Cp_i}(\boldsymbol{T}) - \boldsymbol{L_w} * \frac{\partial \boldsymbol{x_{ice}}}{\partial \boldsymbol{T}}(\boldsymbol{T}) \tag{7}$$

The ice content as a function temperature (at $\boldsymbol{T} > \boldsymbol{T_f}$) was estimated using the equation proposed by Tchigeov **(Tchigeov, 1979)**:

$$\boldsymbol{x_{ice}} = \frac{\boldsymbol{1.105} * \boldsymbol{x_w}}{1 + \frac{0.7138}{\ln(\boldsymbol{T_f} - \boldsymbol{t} + 1)}} \tag{8}$$

The initial freezing point of cod $\boldsymbol{T_f} = -\boldsymbol{1.1}°\boldsymbol{C}$ is used.

### 2.2. Reconstruction of cod shape and mesh generation

In this work, the geometry of cod was reduced to a number of 2-D cross sections. The 66cm/2.6kg cod was cutted into 5cm thick slices. The actual recorded shape was centered and smoothed to gain a simplified and symmetric curvature to implement into the simulation. The variety of fish size was considered with three different weights: 1.8, 2.6 and 3.4kg. Isometric scaling was conducted by the approximate length-weight ratio **(WATERMAN, 2001)**. As shown in Figure 1 a non-uniform grid system was used in the simulation. An unstructured mesh with 361 nodes and 608 triangular elements was developed for the 2-D model. The use of finer mesh showed no significant effect on the accuracy of the solution.

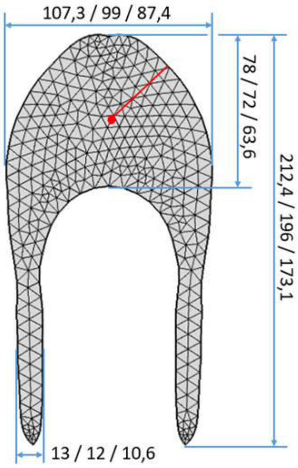

Figure 1: 2D domain discretized into triangular elements, size for different fish:1.8/2.6/3.4kg and a cut-line from core to boundary

### 2.3. Model single fish

Table 1: Parameter values of the simulations for single fish thawing

| | Bath time [h] | Bath temp. [˚C] | Chill time [h] | Chill temp. [˚C] | Total time [h] | End criterion (core temp.) [˚C] |
|---|---|---|---|---|---|---|
| 1 | 0.5/0.75/1/1.25/ 1.5/1.75/2/2.25 | 3/7/11/15 | **RESULT** | -1.5 | **RESULT** | -3 |
| 2 | **RESULT** | 7/11/15 | **RESULT** | -1.5 | 10 | -1.1/-1.5/-1.9 |
| 3 | 0.5/1.5/2.5 | 15 | 9.5/8.5/7.5 | -1.2/-1.5/-2 | 10 | **RESULT** |

The fish is exposed to a strong heat transfer in warm thawing media (bath temperature) during the bath time. Then the fish will be transferred to the cold chill media (chill temperature). The fish remains there during the chill time. The total time is made up of bath and chill time. The cutline from core to boundary (Figure 1) is used to show characteristic temperature developments.

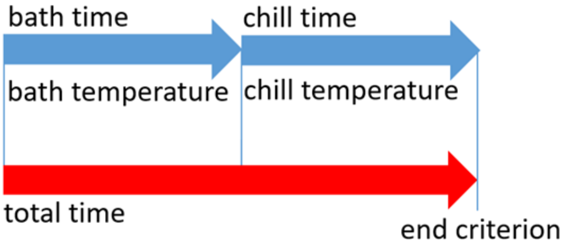

Figure 2: Sequence of the single fish thawing model

Three different simulations will be conducted. Table 9 shows the used parameter values for the simulations. The first simulation investigates the time need to transfer the core temperate to -3˚C. The total time can be compared with the resulting quality. The second simulation will reveal the bath time to reach a particular core temperatures after the total time of 10 hours. The temperature distribution on the cutline will be visualized to look into the characteristics of the temperature distribution. The third simulation shows the effect of chill temperature on the resulting core temperature. The initial temperature is set to $T_{\text{int}} = -23°\text{C}$ representing the typical storage temperature in the fish industry. The calculations will be conducted with three different size of fish: 1.8, 2.6 and 3.4kg.

### 2.4. Model cod block thawing

The thawing process is divided into three sections. During the split time, five groups of fish are getting unblocked and exposed to heat transfer for the remaining split time. The splitting curve obtained by Haugland (Haugland, 2002) is used to quantify the groups. Most of the fish stays in the block up to the end of the split time (group4: 24%, group5: 30%). When the split time ends every fish is separated in the thawing media. The fish stays in the media for the remaining bath time. During the chill time the fish is in -1.5˚C media to be able to equalize the temperature distribution. The temperature distribution in the fish muscle is supervised during the chill time for a permanent evaluation. The variety of fish size in the blocks is considered with three different sizes in the model: 1.8, 2.6 and 3.4kg.

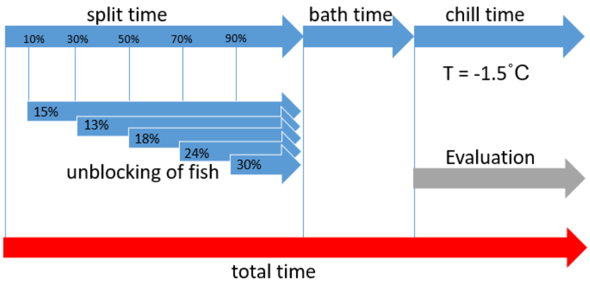

Figure 3: Sequence of the block thawing model

### 2.5. Quality and yield evaluation

The effect of time/temperature storage conditions on product shelf life has been shown to be cumulative (Charm, 1972). The shelf life at different storage temperatures has been expressed by the relative rate of spoilage (RRS) (Nixon, 1971)

$$RRS\ at\ t°\text{C} = \frac{keeping\ time\ at\ 0°\text{C}}{keeping\ time\ at\ t°\text{C}} \tag{9}$$

The relationship between RRS and the storage temperatures of cod from the North Sea is linear (Baines, 1964).

$$RRS(T) = 1 + 0.336 * T \tag{10}$$

The temperature dependent RRS was integrated over the area and total time of the model. As a reference value the shelf life at 0˚C (RRS=1) of 10 days is used:

$$Bacterial\ Deterioration\ (BD) = \frac{\iint RRS(T)\, dA\, dt}{BC_{Ref}} * 100\% \tag{11}$$

Controlled thawing and tempering on cod for filet production increases the yield with 2% (60.1% vs 58.1%) compared to the air blast thawed samples (core temperature -1.1 vs +13.8˚C). Further experiments revealed that the batch thawed towards –1,2°C gave similar or less yield as the batch thawed towards 0,5°C. The reason might be that there have been too much ice left in the batch thawed towards –1,2°C. It is however clear that the margins are narrow in this temperature region and that too low temperatures will reduce the yield. In this work the yield was evaluated by the core temperature (Figure 4). According to a desired amount of ice in the fish, the chill temperature was set to -1.5˚C with a peak yield of is 60%. The Yield is decreasing towards 58%

for higher and lower temperatures respectively with the same gradient: no ice at -1.1˚C and too much ice at -1.9˚C. To quantify the process, the time needed to reach the average Yield of 59.1% was used.

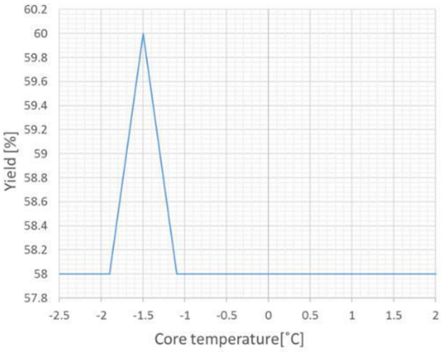

Figure 4: expected yield depending on the core temperature.

## 2.6. Split time

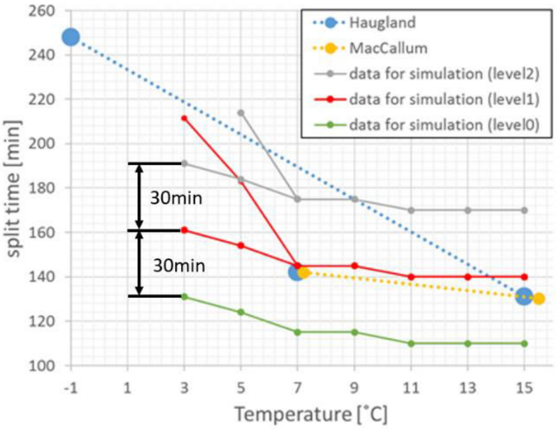

Figure 5: Split time depending on temperature by Haugland confirmed with the relative alternation by MacCallum and the three used split time levels

Haugland (Haugland, 2002) showed that if the thawing media temperature is increase from –1°C to 15°C, the cod block will on average split 117 minutes earlier (Figure 5). The center experiment at 7°C indicates that there is most likely curvature on the correlation. However, the curvature cannot be derived due to the number of experiments. MacCallum (MacCallum, 1964) investigated splitting of cod blocks at 7.2 and 15.5°C. The absolute values of both data sets are different due to the test conditions, however, the marginal alternation between 7°C and 15°C can be confirmed. The unknown curvature below 7°C is assumed by two different values (level1). The time level of the split is altered by 30 minutes to investigate the potential of a faster split (level 0 and 2).

# 3. Results

## 3.1. Effect of time and temperature on single fish thawing

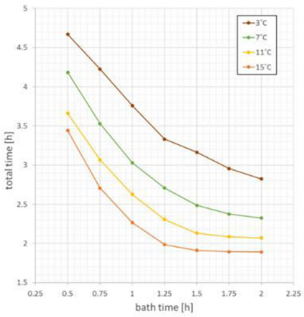

Figure 6: total time to reach a core temperature of -3˚C of 1.8kg cod at differrent bath temperatures

*Figure 6* shows that the thawing time can be reduced by increasing the bath time or bath temperature. The curvature for 15˚C media temperature shows no significant change above 1.25h bath time. The same can be seen at 13˚C above 1.5h bath time. The curvature confirms that the heat conduction in the muscle is the limiting factor of thawing.

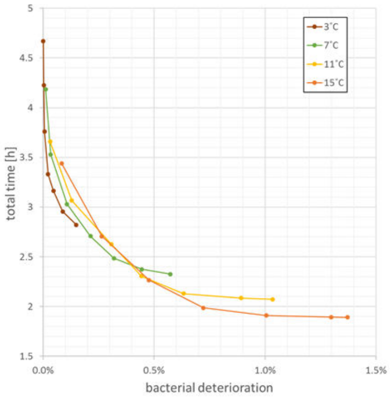

Figure 7: comparison of thawing time and bacterial deterioration of 1.8kg cod

*Figure 7* shows the trade-off between fast thawing and bacterial growth. Higher temperatures leads to a faster thawing with a higher bacterial growth. Effective thawing of 1.8 kg fish can be done in between two and three hours. It exists approximately a linear relation between the two factors in this region. Experimental results confirm that findings (Ohmori, 1981). The thawing performance of single fish can be summed up into one curve. The curve is a combination of most efficient thawing at different temperatures and bath times. Figure 61 shows that bigger fish tends to require a longer thawing time combined with a higher bacterial growth.

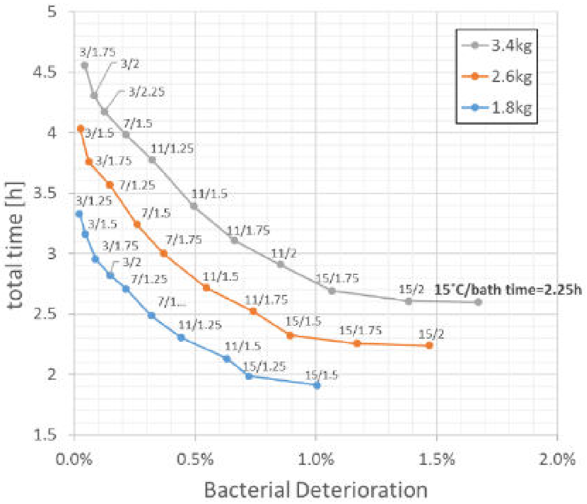

Figure 8: Summary of most efficient thawing for different cod size

### 3.2. Characteristics of the spatial temperature distribution during thawing

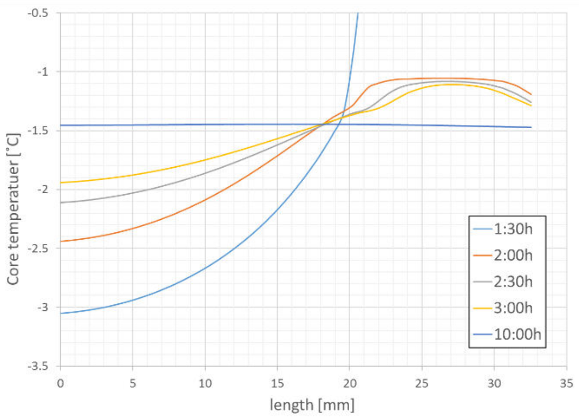

Figure 9: Temperature on the cutline at different times: 1.8kg cod, bathtime 1:30h, bath temperature 15˚C

Figure 9 shows the temperature profile at different moments during processing. After 10 hours processing, the temperature is equalized at the desired chill temperature of -1.5˚C. It can be derived from the data that the surface should be cooled when the core reached a temperature 1.5K below the initial freezing point. From 0(core) to 18mm, the ice is kept whereas on the outer layer the ice is melted and formed again due the enthalpy equalization in the muscle and the heat transfer between surface and chill media. The time lag between the too unwanted conditions, quantified with core temperature -1.1˚C (completely thawed) and -1.9˚C (too much ice), helps to understand the complexity of block thawing. The comparison of the lag time with the split times reveals especially for temperatures up to 15˚C dificulties to temper every fish into the latent heat zone.

Table 2: Time lag between the bath times to reach a core temperature of -1.1 ˚C and -1.9 ˚C after 10h processing

| | 7˚C | 11 ˚C | 15 ˚C |
|---|---|---|---|
| 1.8kg | **4:00** | **3:10** | **2:20** |
| 2.6kg | **4:40** | **3:20** | **2:40** |
| 3.4kg | **5:10** | **3:50** | **2:50** |

At higher temperatures the heat transfer is faster. Thus, the time needed to transfer the ideal amount of enthalpy is shorter. But also the time lag between the two un-wanted conditions „too cold“ and „too warm“ is shorter. In Figure 70 the split time (level 0-1-2) is compared with the described time lag for the different weights (Table 12). The data quantifies the adverse characteristics of warm temperatures at a slower split. The time lag, especially for lighter fish, is shorter than the split time. The heat transfer is fast but the early unblocked fish will be completely thawed whereas the late unblocked fish will be too cold. For split level 0, the split time is shorter than the time lag.

### 3.3. Effect of chill media temperature on single fish thawing

The final core temperature after 10 hours of processing is in large extent dependant on the bath time. The average temperature are significant different whereas the influence of the chill media (ΔT) is minor. ΔT decreases towards longer bath times.The data shows that it is not possible to temper the fish towards an end temperature without an appropriate enthalpy transfer during the bath time.

Table 3: core temperature after 10 hours of processing with different chill media temperature and bath time [˚C]

| | **30 min** | **90 min** | **150 min** |
|---|---|---|---|
| *-1.2˚C* | -1.85 | -1.53 | -1.24 |
| *-1.5˚C* | -1.97 | -1.59 | -1.29 |

|  |  |  |  |
|---|---|---|---|
| *-2˚C* | -2.25 | -1.77 | -1.33 |
| *Average* | -2.02 | -1.63 | -1.29 |
| *ΔT* | 0.40 | 0.24 | 0.09 |

### 3.4. Effect of split time and temperature on block thawing

The split time variation makes it possible to show both the trend of changing process temperature and split time. The comparison of the different colored dots at a particular temperature show the potential of faster splitting (Figure 67). For each process temperature the recommended process time decreases for a faster splitting and increases for a slower splitting**.** It exists a linear relation between the process time reduction and the media temperature. The split time reduction of 30 minutes at 15˚C leads to a process time reduction of about 2 hours. Thus, the resulting curvature and the temperature of the fastest processing are different.

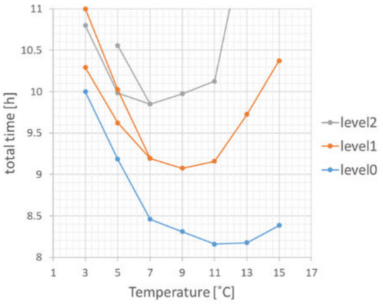

Figure 10: Total time to reach Y=59.1% for different split level depending on the temperature

The fastest possible processing, independent from temperature, decreases from 9:06h (9˚C) to 8:10h (11˚C) for faster split (level0). The curvature shows a strong gradient below 7˚C. Between 7 and 15˚C the value changes only slightly. However, the lowest point can be stated at 11˚C. The data shows that for a faster split higher temperatures are more attractive. The increase towards the highest temperatures can be neglected. The slower split (level2) shows the opposite trend. The fastest processing can be stated at 7˚C with only a slight difference for the values between 5 and 11˚C. The value for 13 and 15˚C is outside the considered maximal process time. In this case, the optimistic assumption at 5˚C would be a recommended processing.

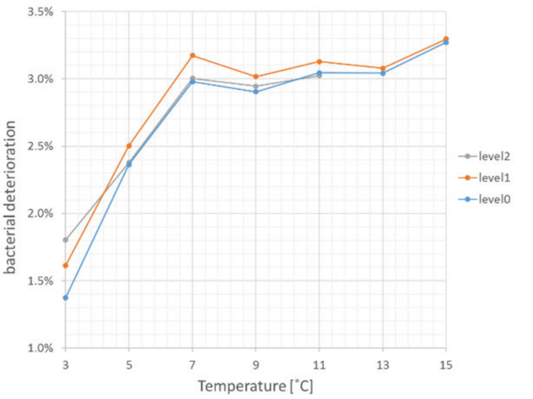

Figure 11: bacterial deterioration of the three splitlevel

The resulting bacterial deterioration for the set of process configurations helps further to rate the total quality of cod filets. The temperatures below 7˚C show benefits regarding the bacterial growth. Above 7˚C the bacterial growth doesn't change significant due to the balancing effect of higher temperature and shorter bath time (Table 13). Between 7 and 3˚C the bacterial load is reduced by half. The similar progress for different splitlevels can be explained by longer bath times at shorter splitting. 3% deterioration is equal to 7.2 hours of the equivalent 10 days storage at 0˚C.

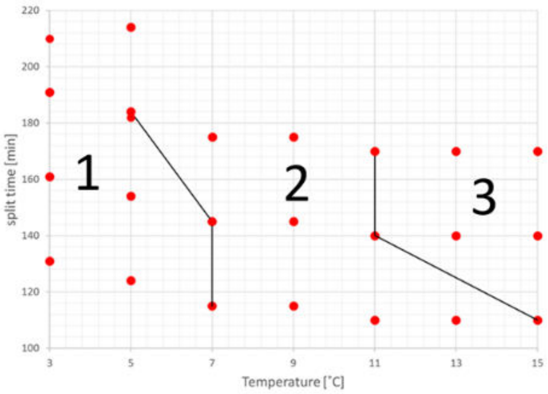

Figure 12: classification of split times into three areas

The data of investigated temperature/split time combinations can be separated into three areas. For each area a recommendation for the process can be done.

1 The process time can be reduced by increasing the thawing media temperature. The throughput of the plant is increased by an additional energy input.
2 The temperature change has only a minor influence on the process time.
3 The process time can be reduced by reducing the thawing media temperature.

The seawater intake is often at a depth where the temperature changes rapidly as a result of streams or a change in the weather. The temperature of the thawing water can be controlled by the cooling capacity of the blocks and the amount of fresh seawater supplied from a depth of 12 meters in the harbour (Haugland, 2002). That means, recommendation 2 and 3 can be applied through the adjustment of the seawater pump in the production facility.

## 4. Conclusion

Thawing of frozen raw fish has become an important industrial process due to the market demands for safe products with high quality and at sufficient volumes all year round. Appropriate freezing and thawing of Atlantic cod can deliver quality comparable to fresh fish.

The complexity of the block split is yet only investigated for the water thawing pro-cess. The investigations on other techniques were mostly conducted with fillet pieces and show a possible reductions of the thawing time of up to 80%. For electric resistance- and radio frequency thawing, research is needed to better understand the effecting material properties. Vacuum-, microwave- and high pressure thawing demands research on the process parameter. The different techniques are wide spread in the food industry. That makes the availability independent from the suitability at thawing. The producers offer process solutions in various size or in modular build up. Thus, all introduced techniques are availability for large scale production. The main objective of the thesis was to develop a time- and energy efficient concept to meet market demands for safe products with high quality. The basic thermic of thawing was investigated with a 2-D cross section. A single fish of 2.8 kg can be thawed within 2 to 3 hours depending on the thawing media temperature. The result-ing linear relation between thawing time and quality (bacterial growth) can be con-firmed with literature data. At the same bath time, thawing can be conducted in 3h at 3˚C or in 2h at 15˚C. This acceleration is connected with the increase of bacterial deterioration from 0.1% to 0.7%. Heavier fish requires a longer time and results in a higher bacterial growth. As the research has demonstrated the process efficiency depends on the mutually dependent variables temperature and the time needed to split the block. The potential process time reduction induced by a faster block split rises linear towards higher temperatures. In other words, high temperatures shows adverse characteristics for a slow split. This can be explained by the huge enthalpy difference due to the fast energy transfer. Thus, the resulting curvature of the investigated split levels are different. The performance of high temperatures up to 15˚C can only be recommended for a splitting faster than 2 hours. Slower splitting makes lower temperatures more recommendable. A temperature variation of 2K leads to a reduction of the

recommended process time of up to 20%. The bacterial growth of the process does not depend on the split time. The bacterial growth is constant for a processing above 7˚C due to the balancing of higher temperatures with shorter duration. The resulting data can be classified in three groups of recommendations. In the average, the temperature between 7 and 11˚C can be recommended due the balance between fast and accurate thawing. The scientific investigation on most of the introduced techniques are still sparse. It is not possible yet to estimate the performances on cod block thawing. There are numerous possibilities to go further in the research of the particular technique. The mod-el shows clear trends and leads to recommendations for the process parameters to run an optimal process. However, it is still just a simplified imitation of the actual complexity.
The block split might be the biggest inaccuracy in the model. The block split can be conducted with more than five steps to correlate the splitting curve. Up to the unblocking, the fish isn't exposed to any heat transfer in the model. In the actual process, the fish is at least partially exposed to a heat transfer. The investigation of the block structure before and during the split stage might lead to ideas how to implement this heat transfer. Recording and implementing of the splitting curve and weight distribution of a block leads to a more precise analysis of the actual process. A mesh refinement is connected to an increased computing effort but leads to more accurate results. Additionally, the model should be validated to demonstrate the significance. The energy aspect wasn't considered in this work. The particular circumstances might be different for each production facility. The measurement and monitoring of the relevant process parameter enables to utilize the presented trends of this thesis. It is essential to identify the possibilities to measure the parameter and further influence the system to vary those. An energy analysis would delivers data to estimate the practicability and economy of a possible parameter change. Faster splitting shows a great potential at higher temperatures. Thus, further work on speeding up the block split might be only reasonable if high temperatures are used in the production. Beside a maximum level of agitation, it is possible to influence the splitting by adjusting the salt content of the thawing media

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