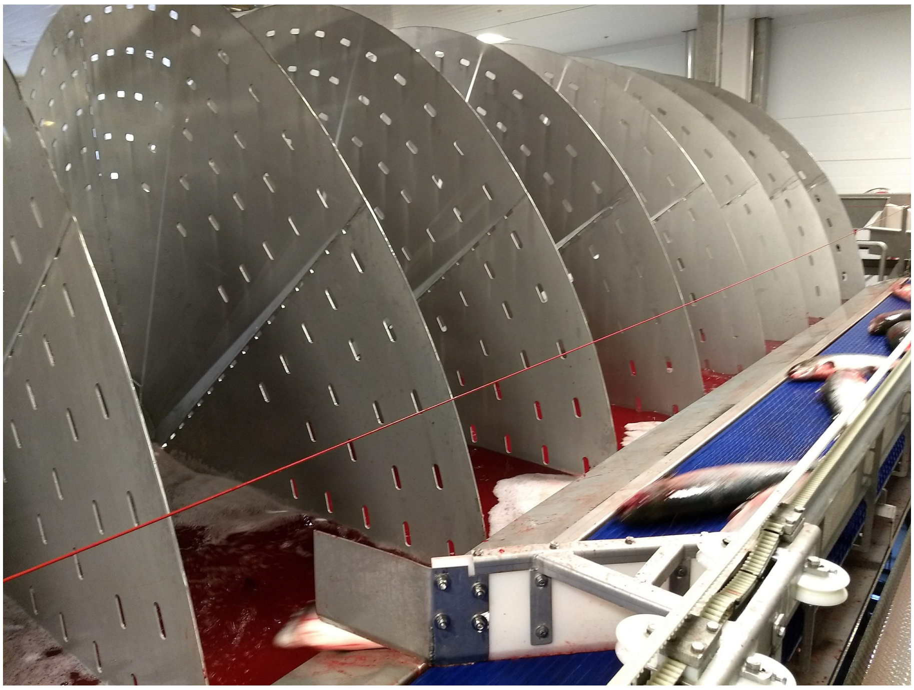
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Rasmus Rørholt Theisen

Optimized industrial cooling of Atlantic salmon

Master's thesis in Mechanical Engineering
Supervisor: Prof. Armin Hafner
June 2019



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Acknowledgements

This master thesis is the result of my work at Department of Energy and Process Engineering at NTNU. It has been an interesting task that have given me knowledge not only about chilling of salmon, but also more general knowledge about working with scientific projects in cooperation with others.

I would like to thank my supervisor, prof. Armin Hafner for giving me this interesting master thesis and helping me whenever needed. I would also like to thank my co-supervisors dr. Kristina Norne Widell and Ignat Tolstorebrov as well as the other participants in the OptiHeliX project. Ignat has been guiding me through the whole semester, answering all my questions and kept an eye on my work, and I want to express extra gratitude for his help. I would also like acknowledge the employees at the slaughtering factory for helping us to perform necessary field experiments. Finally, I want to thank my family and friends for their help, showing their support and motivating me when needed.

Rasmus Rørholt Theisen

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Abstract

When slaughtering salmon, effective and rapid chilling is required to preserve the quality and extend the shelf life. This can be achieved with a HeliX tank where the salmon is both chilled and rinsed for blood.

In this thesis, temperatures and heat flows in a HeliX tank were investigated. Temperature development in salmon being chilled was simulated numerically using PDE Modeler in MATLAB. The simulations showed that for a certain chilling time, the thickness of the salmon is the factor with the biggest influence on the temperature. Because of thermal resistance in the salmon itself, the heat transfer coefficient is of less importance, especially from 200 W/m^2K and higher.

Expressions for an equivalent radius was found so that analytical calculations of temperatures can be performed. Comparison of the results from simulations and analytical calculations revealed minor differences between the two approaches, which were considered acceptable. A chilling index was introduced to measure how well salmon in a real process is chilled compared to an ideal process.

Models were developed to calculate heat flows, temperatures of both salmon and refrigerated sea water (RSW) and a cooling load for the refrigeration system. With EES and MATLAB the models were used to simulate a HeliX tank as continuous, semi-continuous and batch processes. The simulations can be used as a tool to investigate how a tank should be operated to secure sufficient chilling depending on different parameters. A calculated peak cooling load was used for dimensioning the evaporator in a refrigeration vapour-compression cycle.

4 field experiments were performed at a slaughtering factory. Data from a HeliX tank were collected to increase the understanding of the real process and for comparison with the theoretical calculations. It was found quite big variations in temperature after chilling and chilling index between the measured salmon. The average chilling index for the experiments is found to be 64.51 %, 58.68 %, 59.74 % and 67.69 %. This is normal results for a HeliX tank in normal operation, but there are room for improvement. The measured centre temperature of salmon after chilling was 6.68 °C in average, which is clearly higher than what is ideal.

Sammendrag

Når laks slakter er det nødvendig med rask og effektiv kjøling for å bevare kvaliteten og øke varigheten. Dette kan oppnås med en HeliX-tank, der laks kan både kjøles og renses for blod.

Denne masteroppgaven har undersøkt temperaturer og varmestrømmer in en HeliX-tank. Temperaturutviklingen i laks som kjøles ble simulert numerisk med PDE Modeler i MATLAB. Simuleringene viste at tykkelsen på laksen har den største påvirkningen på temperatur, gitt en spesifikk kjøletid. På grunn av termisk motstand inne i selve laksen er ikke varmeoverføringskoeffisienten like viktig, spesielt når den er 200 W/m^{2}K eller høyere.

Uttrykk for en ekvivalent radius ble funnet slik at analytiske beregninger av temperaturer kan utføres. Sammenligning av resultatene fra simuleringer og analytiske beregninger vister små forskjeller mellom de to metodene. Disse forskjellene ble vurdert å være akseptable. En kjøle indeks ble introdusert som et mål på hvordan laks i en ekte prosess kjøles sammenlignet med en ideell prosess.

Modeller for å beregne varmestrømmer, temperatur av laks og RSW (kjølt sjøvann) samt last for et kjølesystem ble utviklet. Modellene ble brukt i EES og MATLAB for å simulere en HeliX-tank som en kontinuerlig, semikontinuerlig og batchprosess. Simuleringene kan brukes som er verktøy for å undersøke hvordan en tank bør styres for å sikre nødvendig kjøling avhengig av forskjellige parametere. En beregnet topplast ble brukt for å dimensjonere fordamperen i en kjølesyklus.

4 forsøk ble utført ved et lakseslakteri. Data fra en HeliX-tank ble samlet for å øke forståelsen av en ekte prosess og sammenligne med de teoretiske beregningene. Det ble funnet relativt store variasjoner i temperatur eller kjøling og kjøleindeks. Den gjennomsnittlige kjøleindeksen fra forsøkene var 64,51 %, 58,68 %, 59,74 % og 67,69 %. Dette er normale resultater for en HeliX-tank i normal drift, men der er rom for forbedring. Sentrumstemperaturen i laksen etter kjøling ble målt til 6,68 °C, noe som er klart over ideell temperatur.

Table of contents

List of figures

List of tables

List of notations

Abbreviations and subscripts

0	Initial value
avg	Average
EES	Engineering Equation Solver
eq	Equivalent
f	Fish
fl	Fluid
RSW	Refrigerated sea water
s	Surface

Symbols

α	Thermal diffusivity	m^2/s
A	Area	m^2
a	Thickness of fish, radius	m
b	Height of fish, radius	m
Bi	Biot number	-
C_n	Constants	-
C_p	Specific heat capacity	J/kgK
Δ	Difference, change	-
$\dot{n}$	Flow rate of n	1/s
Fo	Fourier number	-
h	Heat transfer coefficient	W/m^2K
J_n	Bessel function of first kind, nth order	-
k	Thermal conductivity	W/mK
L	Characteristic length	m
m	Mass	kg
∇	Nabla operator	-
Q	Heat	J
ρ	Density	kg/m^3
r	Radius	m
θ	Dimensionless temperature	-
T	Temperature	°C or K
τ	Time	s
x, y, z	Positions	m
$\bar{x}, \bar{y}, \bar{z}$	Dimensionless positions	-

1 Introduction

Farmed salmon are Norway's third largest export. The total first-hand value of farmed salmon in 2017 was 61,6 billion NOK, and the total production in 2017 was 1 238 354 metric tons (Statistics Norway, 2018). This makes Norway the largest producer of salmon in the world, with a global production share of 53 % in 2016 (Almås & Ratvik, 2017).

Aquaculture salmon are transported alive to slaughterhouses, with a temperature close to the sea temperature. Biological decomposition processes that reduce the quality of the fish begins at the moment of death. Rapid chilling is important in order to slow down these processes as early as possible, preserve the quality of the fish and maximize yield. Bacterial growth is reduced and shelf life will increase (Skjervold et al., 2001). Rapid chilling will also delay the moment of rigor mortis, which limits the time the fish can be processed, as the risk of gapping in the filets is high if fish are treated in the state of rigor mortis (Ola M. Magnussen, Ola Flesland, & Tom S. Nordtvedt, 1991).

When slaughtering salmon, chilling that reduces the temperature in the thermal centre below 4 °C is acceptable, but ideally the temperature should be close to 0 °C (Bantle, Digre, & Tobiassen, 2015) This should be the aim when designing cooling systems in salmon slaughterhouses.

1.1 Methods for chilling salmon

Immersion chilling is widely used in the fish farming industry. These are methods where the fish is chilled by immersing it in a colder liquid. Direct contact between the fluid and the salmon gives a good heat transfer and therefore an effective chilling. Compared to using air as cooling media, the heat transfer coefficient can be up to 20 times higher with liquid (Lucas & Raqoult-Wack, 1998). Also, the liquid will prevent dehydration of the fish, immersion chilling can be combined with washing and bleeding the salmon in the same tank. It is common to use refrigerated sea water, herby referred to as RSW, for immersion chilling, but slurry ice and other aqueous solutions are also be used. Since the slaughtering factories are located by the sea, there is easy access to seawater. Lower freezing temperature prevents undesirable freezing in the refrigeration system and makes seawater preferable compared to pure water. Greater temperature difference between cooling fluid and the fish gives faster chilling. Therefore, adding more salt is sometimes used so that further reduction of the cooling fluid temperature is possible. The initial freezing point of salmon is -2.2 °C (ASHRAE, 2010). To avoid freezing, the RSW temperature should not be significantly lower than this.

Figure 1.1 Slaughtering process

In this thesis, a slaughtering process as shown in Figure 1.1 is considered, with chilling immediately after stunning and gill cutting. Other strategies, which can give a more effective chilling, is also used. For example, it is possible to do some of the chilling while the fish is still alive. Live chilling is faster because of blood circulation that transports heat within the salmon, but issues around fish welfare has strongly reduced the use of live chilling (Bantle et al., 2015). Another strategy is to move the chilling to a later stage in the slaughtering process, so that fish filets are chilled instead of whole fish. This can reduce the energy and time needed for the chilling process, since the filets are smaller and thinner than the whole fish. Drawbacks are increased time form stunning to chilling, possibility of reduced quality and shelf life and that fish filets need much gentler treatment compared to whole fish and this gives limitations for the chilling system.

Immersion chilling can be split into continuous, semi-continuous and batch processes. In continuous processes, the flow of salmon and RSW is constant and it can be modelled as a steady state heat exchanger. Semi-continuous processes have partly constant flow of salmon and RSW, but with regularly changes and/or stops in the flow of salmon. Batch chilling is a simple method of immersion chilling where a batch of salmon enters a chilling tank at the same time, or within a shorter period of time, and after chilling the whole batch exits the tank.

1.2 HeliX tank concept

In this thesis a HeliX tank (also known as spiral tank) as shown in Figure 1.2 is analysed. The tank is filled with circulating RSW of around 0 °C and a screw divides the tank into chambers so that fish entering at different times are separated. The screw is perforated so that RSW can circulate through the tank while the fish is kept in the different chambers. When turning, the screw is pushing salmon to the next chamber. From stunning and gill cutting, the salmon is transported on a conveyor belt to the tank. From the belt, fish can enter the different chambers. Filling starts in the chamber with the highest number, at the exit of the tank, and when a chamber full, filling starts at the next chamber. After filling there is normally a stand still chilling period before the first entering salmon has reached its chilling time. When the salmon is properly chilled the screw starts to move and salmon exits at the end of the tank, while new salmon enters the tank in the other end. From field experiments, it was observed that the time to fill a chamber with salmon, the chamber filling time, was around 5 minutes and normal chilling times were around 90 to 100 minutes. The screw turns until all chambers are filled with new salmon. This normal operation mode is a semi-continuous process, but when looking at only one chamber it is a batch process. There is also a possibility to have a continuous process by eliminating the stand still chilling period. To maintain a sufficient chilling time, the rotational speed of the screw can be decreased, the tank can be made longer and with more chambers or two tanks can be installed in series.

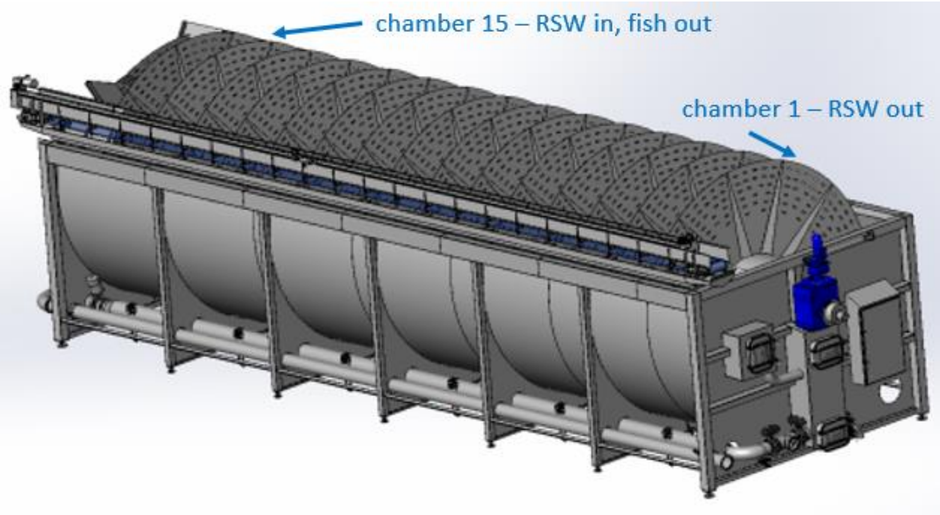

Figure 1.2 HeliX tank for chilling of salmon, provided by Stranda Prolog

As the RSW chills the salmon, its temperature increases through the tank. The RSW is continuously circulated between the tank and a vapour-compression refrigeration system to keep the RSW temperature at a desired level. To reduce accumulation of blood and contamination from the fish, fresh sea water is added to the cycle. The RSW circulates in the opposite direction of the salmon, so that that salmon meets the coldest water at the exit. In theory, this gives slightly better chilling for salmon located in chambers with high numbers during the stand still chilling period. To increase the circulation in the tank, RSW is also injected through nozzles along the tank. This stirs the salmon in the tank and gives a more effective chilling.

Two or more tanks can be put in parallel as shown in Figure 1.3. The flow of salmon alternates between the two tanks. When one tank is filling and emptying, the other tank has its stand still chilling period, and when the first tank is full, the other tank starts filling. This way there can be a constant flow of salmon through the tanks. This setup is used in larger salmon slaughterhouses.

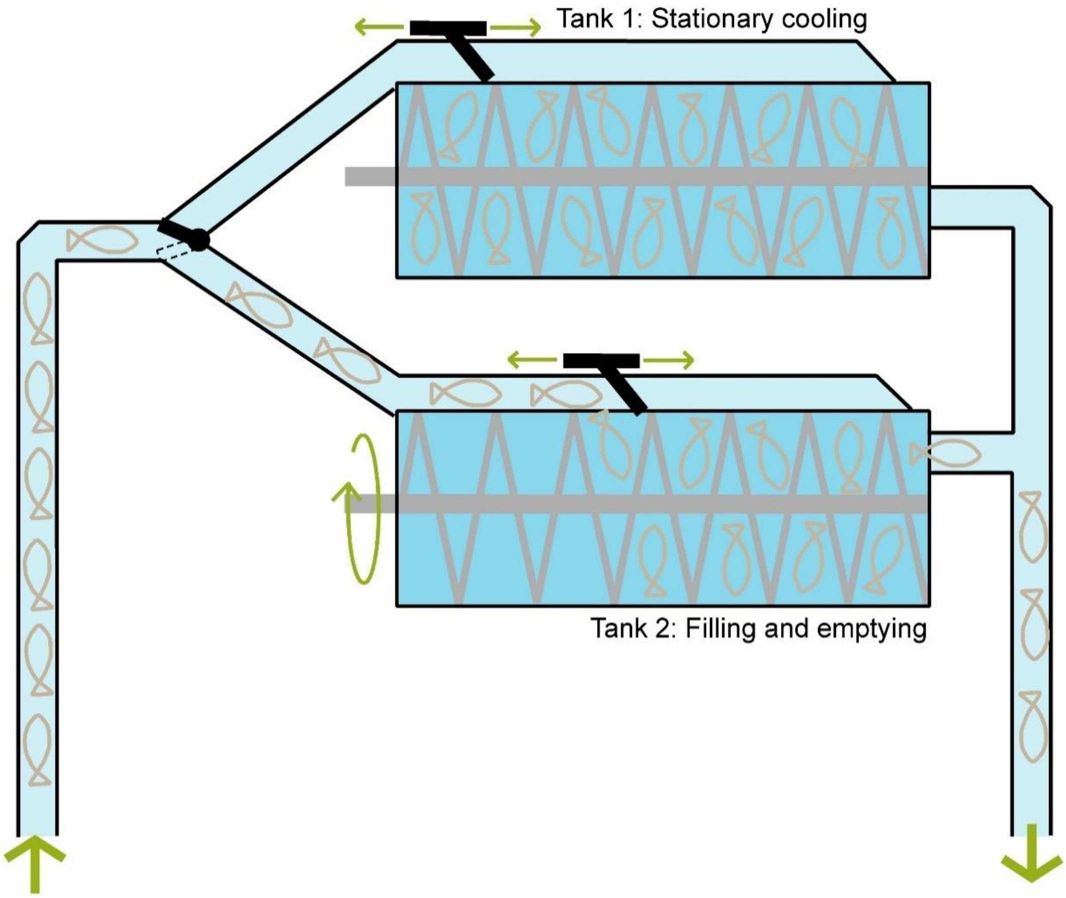

Figure 1.3 HeliX tanks in parallel

1.3 Economic and practical considerations

When operating a HeliX tank in a salmon slaughtering factory, there are practical and economic considerations to be done that might reduce the chilling efficiency and make the chilling process less ideal. By increasing the amount of salmon in the HeliX tank or reducing the chilling time, the total flow of salmon through the HeliX tank can be increased. This way the possible sales and the income can be increased. The drawback is that more salmon will reduce the efficiency and result in salmon out from the tank having a higher temperature, which again can reduce the quality of the salmon. The same happens when reducing the chilling time. Other factors, such as the flow of salmon from the well boats and waiting cages could be different from what is ideal for the chilling process, and the availability of workers or considerations other places in the production line might cause constrains that limit the efficiency of the HeliX tank. The operators in the control room have to consider the total efficiency of the factory, which sometimes causes an operation that is not ideal for the chilling process.

1.4 Background and scope of master thesis

This master thesis is a part of the OptiHeliX project, which is a cooperation between the following project partners:

- Stranda Prolog (project leader)
- SalMar
- Bakkafrost
- SINTEF Ocean
- NTNU

The project aim of OptiHeliX is to further develop the HeliX tank by optimization and documentation. How to operate the tank in order to secure predictable and efficient chilling and gentle treatment of the salmon is investigated, and how the systems perform in slaughtering factories today is documented.

Continuously measuring centre or average temperature of salmon in a slaughtering factory is difficult and costly. The focus of this thesis is how already known parameters such as average weight, RSW flow and chilling time can be used to secure sufficient chilling and to design the chilling process. Also, the report presents documentation and results from measurements on, and related to, a HeliX tank at a slaughtering factory. Figure 1.4 shows parts of Master's Agreement.

Chapter 2 presents theory for numerical and analytical calculations for heat transfer which is used in this thesis. Chapter 3 gives details about the methods used, and how the model is built. A chilling index is introduced as a measure to the chilling efficiency and an indicator for possible improvements. The results are presented and discussed in Chapter 4, before concluding remarks in Chapter 5.

NTNU

Masteravtale

Oppgaven	
Oppstartsdato	**15.01.2019**
Leveringsfrist	**14.06.2019**
Arbeidstittel	**Optimized industrial cooling of Atlantic salmon**
Problembeskrivelse	**Industrial production of aquaculture Atlantic salmon requires gentle control and precise prediction of the chilling process as this influence fish quality, shelf-life and further processing. The desired final temperature in the thermal centre of the fish is in the range between 0.0 and 2.0 C. The market scale Atlantic salmon has relatively high weigh, up to 6 kg. Physical properties such as geometry, heat capacity, density and thermal conductivity influence the heat transfer when chilling the salmon. Several approaches are used in industry for chilling fish. They can be split into continuous, batch and semi-continuous process. Each of the processes has its limitations and optimum operation parameters. Also, the cooling load on the refrigeration system varies significantly with respect to equipment, cooling method and other factors. The objective of this master thesis will be evaluation of available methods for industrial chilling of Atlantic salmon with further optimization and design of refrigeration equipment. The background for this work is the project work Optimized chilling of Atlantic Salmon in HeliX tank, which provides a model developed in EES software for prediction of temperature and chilling time with respect to fish weight and operation mode. Master thesis will include following tasks: - Modelling temperature changes and heat flows when cooling Atlantic salmon. - Compare continuous, semi-continuous and batch processes for industrial cooling and consider the results of different approaches. - Sizing and performance of refrigeration equipment considering the cooling load resulting from different approaches and operation. - Optimizing design, equipment and operation for the different cooling approaches, with respect to energy efficiency and costs. - Master thesis report including a detailed description of the tasks, discussion, conclusion and further work. - Draft version of a scientific paper**

Figure 1.4 Part of Master's Agreement

2 Models and theory

2.1 Modelling salmon with cylindrical slices

Reducing the number of dimensions for heat transfer will drastically decrease the complicity both for analytical calculations and numerical simulations. For a circular infinite cylinder, the heat transfer will be in one dimension, while infinite cylinders of other shapes, like an ellipse, will have heat transfer in two dimensions. This means that there is no heat transfer in the direction of the cylinder axis. It is desirable to model the salmon as an infinite cylinder, because of the simplified calculations. The salmon do not have a uniform cross section, and the height and thickness vary quite a lot along the length of the salmon. The shape and dimensions of the cross section has a large impact on the temperature. Therefore, modelling salmon as a single cylinder is too far from the actual situation. Instead the salmon can be modelled as a series of cylindrical slices with different cross sections, as shown in Figure 2.1. This way the heat transfer can still be modelled as two-dimensional, while the effect of varying cross section is accounted for. In a real situation there will be some heat transfer between the slices, in the direction of the cylinder axis. Since salmon are streamlined with gradual changes in cross sections along the length, this heat transfer will be small, except for at the edges of the fish, the head and the tail. In this thesis this is assumed neglectable, since the effect on the average and centre temperature will be very small.

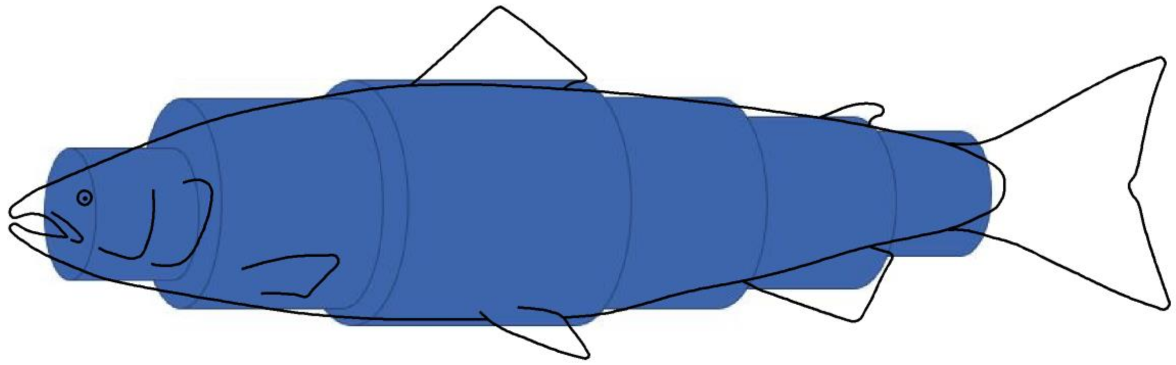

Figure 2.1 Salmon modelled as series of cylindrical slices

2.2 Interpolation of shape from weight

When working with large batches of salmon, the dimensions of each salmon are unknown. Instead, the average weight for salmon in a batch is usually known. If the average dimensions of salmon with respect to the weight are found, this can be used when dimensions of the salmon are estimated. By measuring the dimensions of several salmon with different weight, the average dimensions are found. When salmon are to be modelled as a series of slices, dimensions for corresponding slices of real salmon are measured.

2.3 Heat transfer and boundary conditions

When heat is removed from the fish in the HeliX tank, the temperature changes and thus it is a transient process. Transient heating and cooling are described by Fourier's Heat Equation.

$$\frac{\partial T}{\partial \tau} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \alpha \nabla^2 T \tag{2.1}$$

α is the thermal diffusivity and is assumed to be independent of temperature and position. α is found with Equation (2.2).

$$\alpha = \frac{k}{\rho c_p} \tag{2.2}$$

Where k is thermal conductivity.

During cooling, there will be an internal heat flow by conduction from the inner part of the salmon to the surface. The heat flow to the surface can be described by Equation (2.3):

$$\dot{Q} = A_s k \frac{dT}{dx}_{x=0} \tag{2.3}$$

Where x is inward normal to the surface.

From the surface, heat is rejected to the external cooling fluid by convection, as described by Equation (2.4).

$$\dot{Q} = A_s h \left(T_s - T_{fl} \right) \tag{2.4}$$

Where h is the heat transfer coefficient and is dependent on fluid properties and flow regime. h is found experimentally, or from empirical relations based on experiments. The heat transfer coefficient will increase with the Reynold's number, and thus also increase with increased flow velocity.

At the surface, the conductive and convective heat transfer is equal because heat cannot accumulate in a surface with no volume. This can be applied as boundary conditions for the cooling process.

$$h(T_s - T_f) = k \frac{dT}{dx}_{x=0} \tag{2.5}$$

2.4 Dimensionless variables

The initial temperature difference between salmon and RSW can be used to define a dimensionless temperature, θ, so that θ = 1 at the initial conditions, and θ = 0 when the cooling process has reached equilibrium.

$$\theta = \frac{T - T_{RSW}}{T_0 - T_{RSW}} \tag{2.6}$$

To find the geometrical coordinates in a dimensionless form, they are divided by a characteristic length, L.

$$\bar{x} = \frac{x}{L} \tag{2.7}$$

For a cylinder the radius is used as the characteristic length. In this thesis salmon are modelled as a cylinder, but since actual salmon are not completely cylindrical, finding the correct L is not straight forward. How to find this is one of the problems that are investigated in this thesis.

Fourier number is nondimensionalized time and is found by dividing the chilling (or heating) time by the time of thermal wave distribution in the object.

$$Fo = \frac{\alpha \tau}{L^2} \tag{2.8}$$

The Biot number is the ratio between the internal and external thermal resistance.

$$Bi = \frac{hL}{k} \tag{2.9}$$

It gives information about whether conduction or convection is the limiting process to the heat transfer. A small Biot number implies that a low external heat transfer coefficient is reducing the cooling process and the temperature difference between the surface and the fluid is large compared to the internal temperature differences. A large Biot number implies the opposite, with thermal conductivity and size of the object limiting the heat flow. This means that when increasing the heat transfer coefficient in a cooling process, at a certain point the heat flow will start to stagnate and a higher heat transfer coefficient will not reduce the chilling time noticeably. O. M. Magnussen, O. Flesland, & T. S. Nordtvedt, (1991) determined that increasing the heat transfer coefficient above 150 - 200 W/m^2K when chilling salmon in RSW will have little influence on the temperature.

By implementing the dimensionless variables, Fourier's Heat Equation (2.1) and the boundary conditions (2.5) can be written the following way:

$$\frac{\partial \theta}{\partial Fo} = \overline{\nabla^2}\theta \tag{2.10}$$

$$\left(\frac{\partial \theta}{\partial \overline{x}}\right)_{x=0} = -Bi\theta_{x=0} \tag{2.11}$$

2.5 Solution of Fourier's Heat Equation

For simple shapes, the solution of Fourier's Heat Equation can be represented as a sum of infinite series.

$$\theta = \sum_{n=1}^{\infty} C_n \exp(-\mu_n^2 Fo) \tag{2.12}$$

Where C and μ are functions of Bi and the shape of the object. The number of series required to have a sufficiently precise solution varies with Fo. In most cases 2 or 3 series are required, but 1 is sufficient for height Fourier number. For cylinders, only one series is required when Fo ≥ 0,25 (Tolstorebrov, 2016).

For an infinite cylinder the constants in the solution are found with the following expression:

$$C_n = \frac{2J_1(\mu_n)}{\mu_n\left[J_0^2(\mu_n) + J_1^2(\mu_n)\right]} J_0(\mu_n \overline{x}) \tag{2.13}$$

Where J_0 and J_1 are the first kind Bessel function of zero order and first order respectively. μ_n is the nth solution to the following equation:

$$\frac{J_0(\mu)}{J_1(\mu)} = \frac{\mu}{Bi} \tag{2.14}$$

In this thesis both the average and the thermal centre temperature of the salmon are used for description of the cooling process and calculations. For the centre of the cylinder, and thus the thermal centre $\overline{x} = 0$, which gives the centre temperature:

$$\theta = \sum_{n=1}^{\infty} \frac{2J_1(\mu_n)}{\mu_n[J_0^2(\mu_n) + J_1^2(\mu_n)]} exp(-\mu_n^2 Fo) \tag{2.15}$$

The average temperature of an infinite cylinder is (Tolstorebrov, 2016):

$$\theta_{avg} = \sum_{n=1}^{\infty} \frac{4Bi^2}{\mu_n^2(\mu_n^2 + Bi^2)} exp(-\mu_n^2 Fo) \tag{2.16}$$

The average temperature is used for calculations of heat and cooling load. With the thermal capacity and the mass of the salmon, the heat released by salmon that is chilled a certain number of degrees can be found like this:

$$Q_f = \Delta T_{avg} m c_p \tag{2.17}$$

2.6 Numerically solving Fourier's Heat Equation

Analytical solutions for Fourier's Heat Equation exist only for simple shapes. Even if the salmon can be modelled as an infinite cylinder, this does not fully reflect the real geometry, especially for gutted salmon. With numerical simulations, different geometries can be implemented so that analysis of complex shapes can be performed. When a geometry is defined, a network of nodes across the shape is made, and the timespan is divided into smaller time steps. With a discretisation of Fourier's Heat Equation (2.1) and boundary conditions (2.5), one can calculate the temperature change in each node from one timestep to another with the temperatures at the neighbouring nodes. From the initial conditions the temperatures at the nodes can be found for each timestep through the timespan. Finer network of nodes, and smaller timesteps gives more accurate results.

2.7 Equations and dimensioning of Evaporators

The heat released by salmon is part of the cooling load. This is described further in Chapter 3.1.2. When the cooling load is known, it can be used to dimension components of the vapour-compression cycle, such as the evaporator.

The heat exchanged in an evaporator can be calculated with Equation (2.18)

$$\dot{Q} = h_e A \Delta T_{LMTD} \tag{2.18}$$

Where h_e is the overall heat transfer coefficient for the evaporator, A is the area of heat exchange and ΔT is the logarithmic mean temperature difference (LMTD) in the evaporator and can be calculated with Equation (2.19). For a shell and tube heat exchanger with NH_3 as refrigerant, h can be in the range of 200 to 500 W/m^2K (Graneryd et al., 2009).

$$LMTD = \frac{\Delta T_{in} - \Delta T_{out}}{\ln\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)} \tag{2.19}$$

Dimensioning an evaporator is an economic question. For a given required heat transfer, a larger heat exchanger can operate with a higher evaporation temperature, and thus a more effective refrigeration cycle. A larger heat exchanger gives higher investments costs, but lover operation costs. Bäckstöm (1940) treated this question, and even though the analysis is old, it has been shown that his conclusions still hold. For an operation time of 5000 hours per year, a mean temperature difference of 4 °C is suggested for a liquid cooler (Graneryd et al., 2009).

3 Method of calculations and experiments

3.1 Parameters

3.1.1 Temperatures

In the calculations and models, the temperatures of different objects are used, and some simplifications are done. It is assumed that the temperature of RSW is uniform in each chamber of the tank. With good circulation the actual temperature distribution can be close to uniform, but as further discussed in Chapter 4.5.2, this is not always the case.

Both temperature in the thermal centre of the salmon, hereafter referred to as centre temperature, and the average temperature of a salmon is used. Salmons are poikilotherm, and their body has about the same temperature as the sea water. It can therefore be assumed that the temperature of salmon is close to uniform before entering the tank, thus the initial centre and average temperature are about the same. During, and right after chilling, the centre of the salmon is warmer than the outer parts because heat will not flow from the centre before there is a temperature gradient through the fish. After ending the chilling process the centre temperature will continue to decrease because of the temperature gradient in the fish. Without any heat gain to the salmon after chilling, the gradient will equalize, the average temperature will remain constant and the centre temperature will decrease to the same as the average. Therefore, in cases where heat gain to the salmon after chilling is reduced, the chilling requirements can be changed so that only the average should be below 4 °C, and ideally close to 0 °C. In this thesis the aim for the chilling processes is to reach an average temperature of 2 °C.

3.1.2 Cooling load

Heat that is to be removed from the salmon was introduced in Equation (2.17), and together with cooling losses in the HeliX tank, which is described in Chapter 3.1.3, this gives a cooling load to the refrigeration cycle.

$$Q_{load} = Q_f + Q_{loss,HeliX} \tag{3.1}$$

In this thesis, "cooling load" refers to what is described in Equation (3.1). One has to be aware that this is only a part of the "total cooling load" for the refrigeration system. This is because the refrigeration system also chills fresh sea water that is added to the tank. Depending on operation, the energy required for this can be more than 50 % of the total cooling load. It can be calculated the following way:

$$\dot{Q}_{RSW,new} = \Delta T \dot{m} c_p \tag{3.2}$$

Where ΔT is the temperature difference between the sea and RSW in the tank, and $\dot{m}$ is the mass flow of fresh RSW. When dimensioning components for the refrigeration system, $\dot{m}$ is set to 20 m^3/h. During summer, when the temperature of surface sea water is high, sea water can be taken from a depth of 300 m, where it is around 7 to 8 °C (Johnsen & Myksvoll, 2018).

In addition, there are losses in the system, outside the HeliX tank, that increases the total cooling load.

$$Q_{load,tot} = Q_f + Q_{loss,HeliX} + Q_{RSW,new} + Q_{loss,other} \tag{3.3}$$

3.1.3 Losses

There are cooling losses from the HeliX tank because the surroundings are warmer than the content. This gives heat gain through the tank walls, and directly at the RSW surface. The losses can be estimated by measuring the cooling load of the refrigeration system, when running the HeliX tank without any fish. It can also be estimated by calculating the theoretical heat gain by convection and conduction, with Equation (3.4).

$$\dot{Q}_{loss,HeliX} = \frac{A_{wall}\Delta T}{\frac{1}{h_{ext}} + \frac{L}{k} + \frac{1}{h_{int}}} + A_{RSW} h_s \Delta T \tag{3.4}$$

Where A_{wall} and A_{RSW} is the area of the tank wall and the RSW surface, ΔT is temperature difference between RSW and the surroundings, L is the wall thickness, k is the thermal conductivity of the wall, and h_{ext}, h_{int} and h_s are heat transfer coefficient outside and inside the wall and at the RSW surface.

In this thesis, cooling losses of 20 kW is used for a HeliX tank of 100 m^3, which is from 10 to 18 % of the heat released from salmon, depending on the operation of the tank.

When doing calculations for the refrigeration system one also has to consider other losses that normally apply to refrigeration cycles, such as pressure drop in pipes, throttling losses, and losses because compressors are not isentropic. In this thesis only the process in the HeliX tank is considered, so this type of losses is not included in the calculations.

3.2 Software

3.2.1 MATLAB

MATLAB is the main software in this thesis and is used in several stages. PDE modeler in MATLAB is used to numerically calculate theoretical temperatures of salmon in the HeliX tank. With the results from PDE Modeler, a model for calculating temperatures and heat flows in a HeliX tank is made. The model consists of several MATLAB scripts that exchange parameters and variables and calculates different parts of the model.

In PDE modeler, both the centre temperature and the average temperature of an elliptical slice of salmon are calculated. The heat flow is modelled in two dimensions, so there is assumed no heat flow from the neighbouring slices. PDE modeller consist of the following steps:

- Definition of geometry
- Definition of boundary conditions
- Definition of properties
- Generation of mesh grid
- Definition of solving parameters
- Solution and display of results

3 of the steps are shown in Figure 3.1. A mesh grid of up to 15000 nodes is generated and the temperatures are calculated with Fourier’s Heat Equation (2.1), and with Equation (2.5) as Neumann boundary conditions. The output results are lists of temperature varying with time.

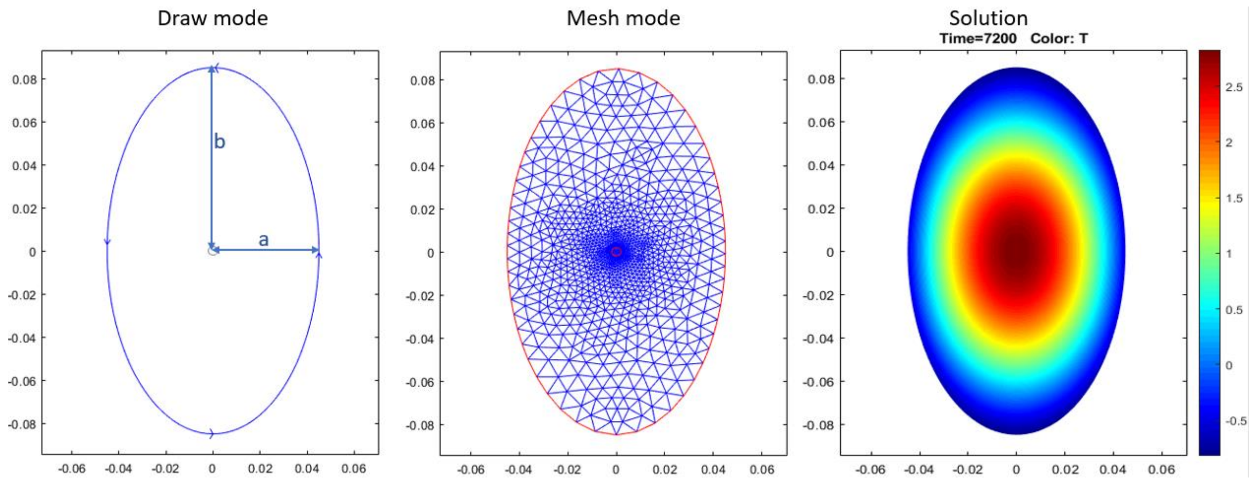

Figure 3.1 Definition of geometry, mesh grid and solution in PDE modeler

3.2.2 DataFit

In this thesis DataFit is used for regression analysis of collected data. Both to check that calculated results are within a certain accuracy and, most importantly, to find mathematical expressions that corresponds to collected data. DataFit can do analysis with one or more variables, perform a regression with a defined type of function or finds the types of functions that gives the most accurate regressions. Additional to functions adapted to the input data, DataFit also gives detailed data about the regression accuracy and plots of the regression.

3.2.3 Excel

All data are collected in Excel sheets: from heat transfer simulations in PDE Modeler, simulations with the final model in MATLAB, regression analysis in DataFit and field measurements with a real HeliX tank. In Excel the data is used for further calculations, comparing data from different sources and visualisation with graphs and diagrams.

3.2.4 EES

With Engineering Equation Solver, a program calculating temperatures of salmon and RSW and the corresponding heat flows is made. Compared to the model of a HeliX tank in MATLAB, the EES program uses the same analytical equations for calculating temperatures, but it assumes a chilling tank that consists of one chamber only. This makes the EES program simpler and faster.

Figure 3.2 shows the data flow in this master thesis.

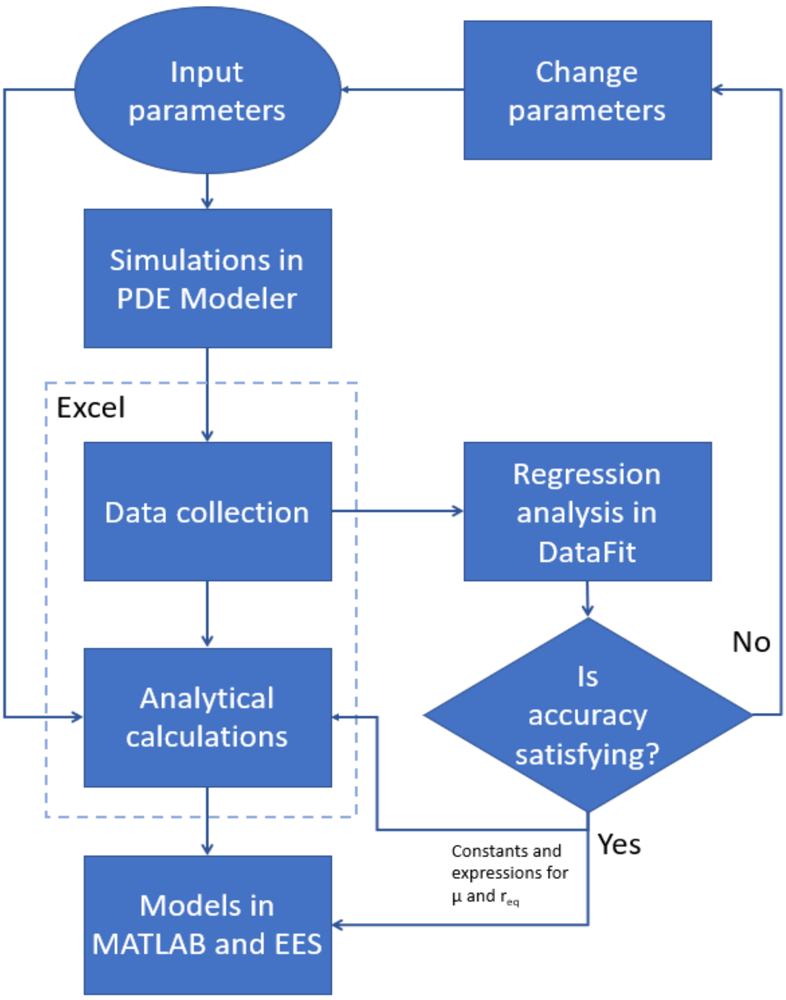

Figure 3.2 Data flow

3.3 Experimentally finding heat transfer coefficient

Earlier in the OptiHeliX project, experiments to find the heat transfer coefficient were performed. A model fish with thermocouples was constructed out of polyurethane. The model fish was sent through the HeliX tank during normal operation and the temperature logged. The temperature development in the model fish was compared to simulations of the same situation in MATLAB. When varying the heat transfer coefficient, it was found that h = 120 W/m^{2}K gave the match of the measured temperatures, as showed in Figure 3.3. This is therefore assumed to be a good estimation (Widell, Nordtvedt, Tolstorebrov, & Fossen, 2018). However, the heat transfer coefficient can vary significant depending on RSW flow and circulation in the tank.

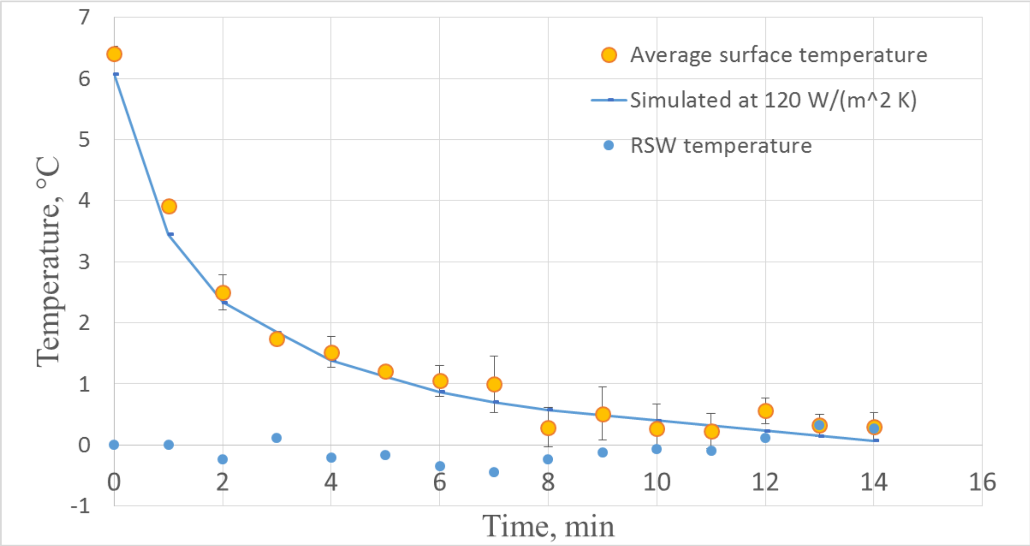

Figure 3.3 Determination of heat transfer coefficient (Widell et al., 2018)

3.4 MATLAB simulations

Simulations of temperature development in elliptical cross sections were performed in MATLAB. Heat transfer coefficient, thickness (a) and height (b) of the ellipse were changed in order to investigate how they influence temperature, and thus get a better understanding of the chilling process. The parameters used are listed in Table 3.1 and Table 3.2. The simulated temperatures were nondimensionalized with Equation (2.6).

Table 3.1 Parameters kept constant during simulations

T_{RSW}	-1	°C
T_0	10	°C
ρ	1050	kg/m^3
c_p	3600	J/kgK
k	0,52	W/mK

Table 3.2 Parameters changed during simulations

h	100, 120, 150, 200, 250, 300, 350, 400	W/m^{2}K
a	3.5, 4.0, 4.5, 5.0, 5.5	cm
b	7, 8, 9, 10	cm
τ	0:60:7200 and 0:60:14400	s

3.5 Finding constants in solution of heat equation

As described in the theory section, the temperature of the salmon can be represented as a sum of infinite series, Equation (2.12), and with Fo > 0.25 only one set is enough to give a good representation of the temperature. Equation (2.12) can be written:

$$\theta = C_1 \exp(C_2 \tau) \qquad (3.5)$$

Where:

$$C_2 = -\mu^2 \frac{a}{L^2} \qquad (3.6)$$

The simulated dimensionless temperatures in timespans where Fo > 0,25 were imported to DataFit for a regression analysis. This way values for C_1 and C_2 in Equation (3.5) were found for each ellipse. Fourier numbers were calculated with a slight overestimation of the characteristic length, to make sure regression was performed within the correct timespan.

For example, with an ellipse where a = 4.5 cm, b = 9 cm and h = 120 W/m^{2}K, then C_1 = 1.5676 and C_2 = 2,0311E-04 for centre temperature and C_1 = 0.7586 and C_2 = 2,054E-04 for average temperature.

3.6 Equivalent radius

A challenge when working with heat transfer of fish is the irregular shape. To do analytical calculations a characteristic length is important because it appears in both the Biot and the Fourier number. The salmon is assumed to have heat transfer like a cylinder, and for cylinders the characteristic length is the radius. Therefor it is necessary find a way to transform the height and thickness of a salmon into an equivalent radius. From the simulations it was found that the dimensions of the salmon have a great impact on the temperatures. This can also be seen in Equation (3.5) and (3.6) which gives that θ is proportional to exp(L^{-2}). It shows that good estimations of the characteristic length are important when accurate calculations are desired.

Simulations were performed in MATLAB with circular shapes instead of ellipses as shown in Figure 3.4. The radius was varied from 4 to 7 cm, with steps of 0.25 cm, and the heat transfer coefficient was set to 120 W/m^{2}K. The other parameters were the same as for simulations of ellipses (Table 3.1 and Table 3.2).

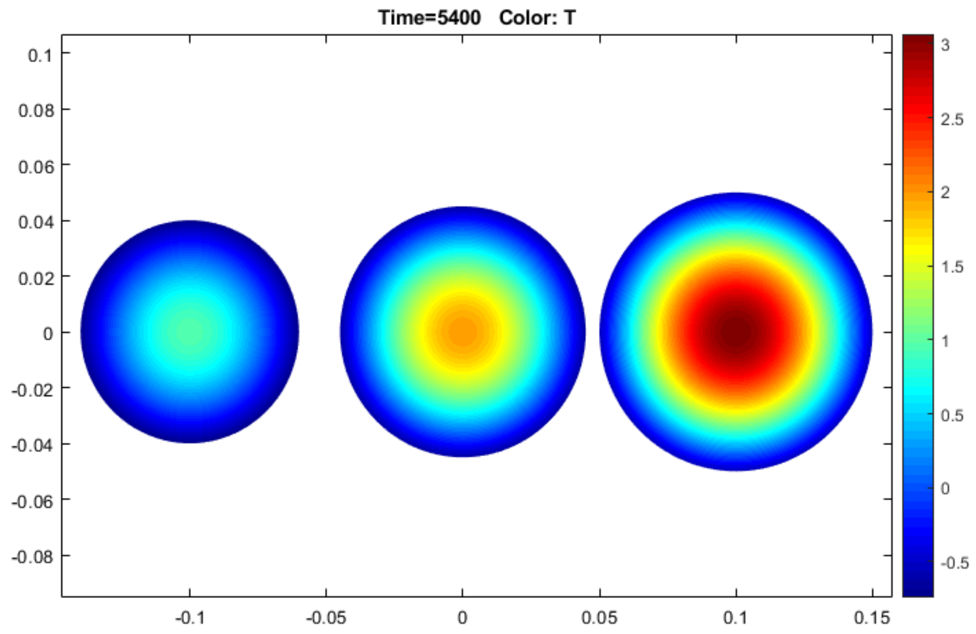

Figure 3.4 Temperatures in circular cylinders after 90 minutes of chilling

Relations for the radius based on either centre or average temperature after 90 min of chilling were found with a regression analysis in DataFit and is shown in Figure 3.5. From the field experiments it was observed that in the HeliX tank salmon are chilled for around 90 to 100 minutes. It is desired to have the calculations as accurate as possible for such chilling times, and therefore 90 minutes is used for finding equivalent radius.

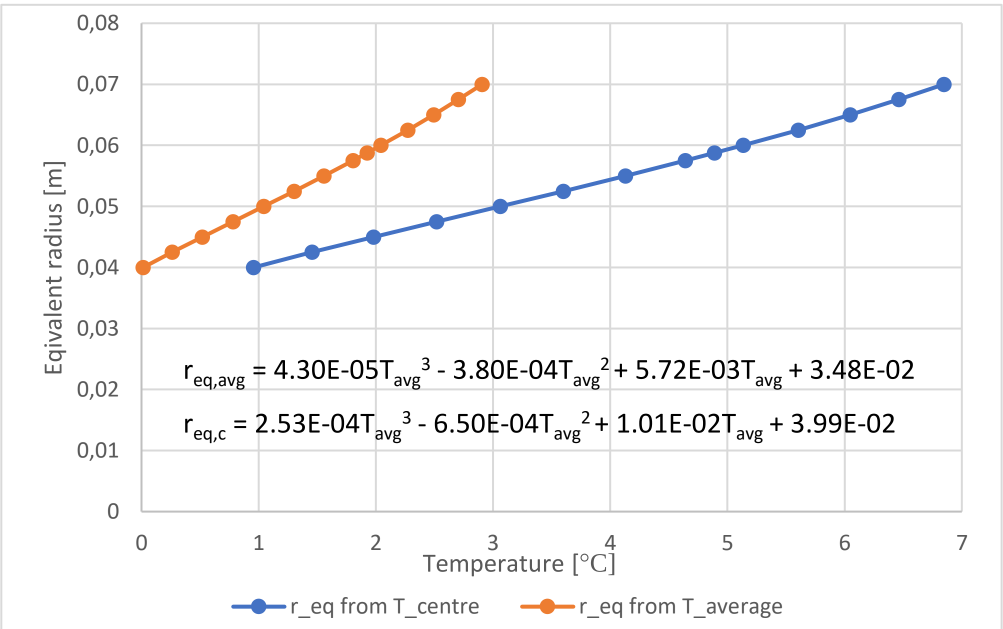

Figure 3.5 Equivalent radius for centre and average temperature after 90 min of chilling

By comparing the simulated temperatures for circular and elliptical shapes it is possible to find an equivalent radius for each elliptical shape. Using· centre or average temperatures gives slightly different equivalent radiuses. The radiuses were imported to DataFit for another regression analysis. This time with the two variables a and b. The following expression was chosen:

$$r_{eq} = Ca^{C_a} b^{C_b} \tag{3.7}$$

To increase the accuracy of the regression the most unrealistic ellipses were removed. The field experiments gave an average ratio of 0.52 between the thickness and the height of salmon. The ellipses with a ratio far below and far above this were removed, so that the accuracy would be increased for the realistic ellipses. The largest deviation from this regression was 0.48 %. This was for the ellipse with radiuses of 4.5 and 7 cm. The average deviation was 0.16 %. This was considered acceptable. The constants that were found are listed in Table 3.3.

Table 3.3 Constant for calculating equivalent radius

For centre temperatures		For average temperatures	
C	0,92904473	C	1,06779567
C_a	0,72247543	C_a	0,76256734
C_b	0,22622743	C_b	0,23376109

With this constants and Equation (3.7) an equivalent radius can be calculated for ellipses, based on the height and the thickness.

Note that there is another possible method to find an equivalent radius. When C_2 is found with regression, and μ is found with Equation (2.14), equivalent radius can be calculated with Equation (3.6). Both methods give some deviations when used to calculate temperatures analytically. In this thesis the first method is used because it is specialized for a chilling time of 90 minutes and gives the smallest deviations in that area.

3.7 Expression for μ

μ is found with Equation (2.14) and is used in solutions of Fourier's Heat Equation. In Excel this is solved with "Problem solver", but this cannot be implemented in Excel's normal equations. Therefore, expressions of μ as a function of radius are found with regression for different heat transfer coefficients. Equation (3.8) and Table 3.4 shows the resulting relations.

$$\mu = a + \frac{b}{r_{eq}} + \frac{c}{r_{eq}^{2}} + \frac{d}{r_{eq}^{3}} + \frac{e}{r_{eq}^{4}} \tag{3.8}$$

Table 3.4 Regression coefficients for μ

h [W/m^{2}K]	a	b	c	d	e
100	2.405	-1.25E-02	3.52E-05	4.48E-07	-5.02E-09
120	2.0405	-1.04E-02	2.37E-05	2.85E-07	-2.74E-09
150	2.405	-8.34E-03	1.49E-05	1.56E-07	-1.24E-09
200	2.405	-6.25E-03	8.19E-06	7.12E-08	-4.57E-10
400	2.405	-3.13E-03	1.99E-06	1.10E-08	-5.87E-11

3.8 Analytical calculations of temperatures

With simple expressions for equivalent radius and μ, the temperatures are calculated analytically. This was done in Excel for the same timesteps as used in the simulations in MATLAB. Summing the first 3 series of Equation (2.15) and (2.16), the centre and average temperatures were calculated for 4 different ellipses and with different heat transfer coefficient.

Table 3.5 shows dimensionless centre and average temperatures after 90 minutes of chilling, calculated analytically in Excel together with the corresponding temperatures from simulations in MATLAB. The table also include mean square error between analytical and simulated temperatures for chilling times between 30 and 240 minutes.

Table 3.5 Simulated and analytically calculated temperatures, 90 minutes of chilling

			Centre temperatures			Average temperatures		
h	a	b	Simulated	Analytical	MSE	Simulated	Analytical	MSE
100	0,035	0,07	0,29170	0,29030	5.5E-05	0,14749	0,14554	2.7E-06
120	0,035	0,07	0,27472	0,27474	6.1E-05	0,13495	0,13363	1.37E-06
150	0,035	0,07	0,25737	0,25895	7.1E-05	0,12258	0,12195	5.7E-07
200	0,035	0,07	0,23973	0,24301	8.4E-05	0,11047	0,11056	4.2E-07
400	0,035	0,07	0,21292	0,21899	1.1E-04	0,09298	0,09421	1.7E-06
100	0,055	0,1	0,69424	0,69507	1.8E-04	0,35690	0,35573	2.4 E-06
120	0,055	0,1	0,68347	0,68459	1.7E-04	0,34361	0,34288	1.5E-06
150	0,055	0,1	0,67206	0,67352	1.6E-04	0,33004	0,32981	8.2E-07
200	0,055	0,1	0,65996	0,66182	1.5E-04	0,31625	0,31657	5.4E-07
400	0,055	0,1	0,64043	0,64305	1.3E-04	0,29518	0,29643	1.4E-06
100	0,04	0,09	0,43723	0,43695	1.7E-04	0,21936	0,22039	7.7E-06
120	0,04	0,09	0,42081	0,42192	1.8E-04	0,20550	0,20733	1.2E-06
150	0,04	0,09	0,40368	0,40638	1.9E.04	0,19156	0,19427	2.7E-06
120	0,045	0,07	0,44552	0,45105	5.1E-05	0,22036	0,22525	1.3E-05

To compare the numerical and analytical approach, the calculated temperatures were plotted together as they changed with time. This is shown in Figure 3.6.

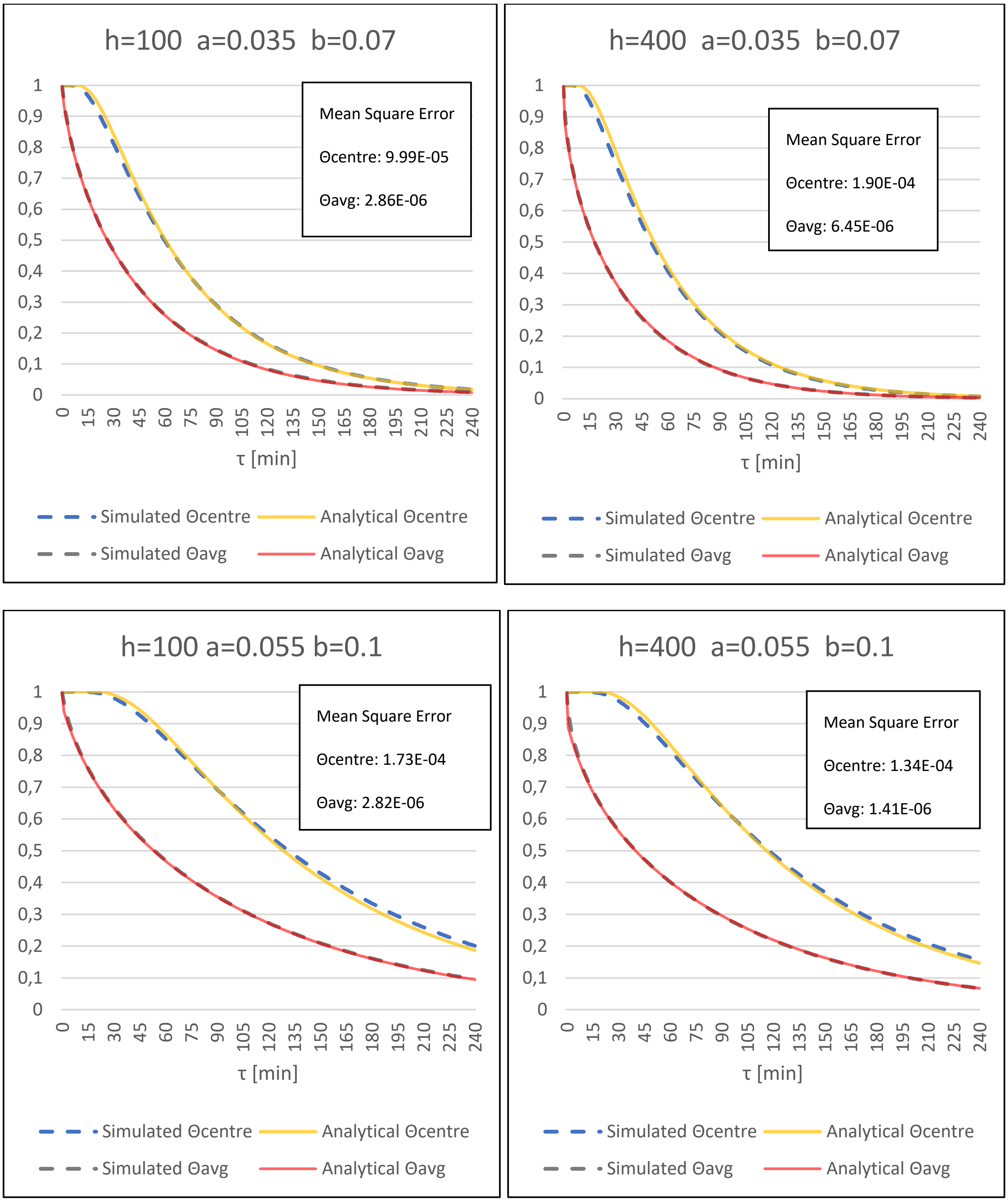

Figure 3.6 Comparison of temperatures simulated and calculated analytically

As can be seen the results for average temperatures matches each other well over the whole timespan. For the centre temperatures, there are some differences especially for the shortest and the longest chilling times where the analytical and numerical temperature developments do not match each other that well. This can also be seen in Table 3.5, where the mean square error is larger for centre temperatures. For chilling times around 90 minutes, the results for centre temperatures are much better. From theses few ellipses, no clear correlation between differences in temperatures and heat transfer coefficient can be found, and it seems like shape of the ellipses are the main factor for the deviations. For all ellipses the temperatures are close to each other for chilling times around 90 minutes.

3.9 Chilling index

To investigate chilling in real processes compared to the ideal chilling in simulations and analytical calculations, a chilling index is introduced. The chilling index uses the centre temperature of the salmon after a certain time of chilling and compares it to the temperature in an ideal chilling process. The chilling index is defined with dimensionless temperatures like this:

$$i_{chill} = \frac{1-\theta_{real}}{1-\theta_{ideal}} \tag{3.9}$$

If using real temperatures, the expression will be:

$$i_{chill} = \frac{T_0 - T_{real}}{T_0 - T_{ideal}} \tag{3.10}$$

The ideal temperature is calculated analytically with an infinite heat transfer coefficient. This makes the chilling index a good tool to see if the chilling process can improve by increasing the heat transfer coefficient. As described in the theory section, increasing the heat transfer coefficient will not always improve the chilling process because the internal thermal resistance can limit the heat flow.

Depending on the initial temperature and the size of the salmon, the required chilling index to reach centre temperatures of 4 °C after 90 minutes of chilling will vary. For small salmon and winter temperatures, the required chilling index can be down to 0.3, while for large salmon in summer temperatures it can be up to 1.5. Since this is impossible to achieve, it means that for the last case, 90 minutes is too short time to reach optimal temperatures.

For a process, the chilling index is connected to the chilling time. The chilling index will change with the chilling time and is most likely to increase with longer chilling times. For a chilling index lower than 1, which is almost always the case, the ideal temperature will get close to the temperature of the RSW faster than the real temperature. When the ideal temperature stagnates, the real temperature has a larger margin for further reduction which can increase the chilling index. Since the chilling index is based on a measured temperature, more experiments have to be done in order to see how different operation of the HeliX tank will affect the chilling index.

3.10 Estimations of fish dimensions

As described in Chapter 2.1, salmon are modelled as a series of cylinders. The dimensions of a salmon are usually not known, unless someone actually measures it. Knowing the weight is more common, and an easier measurement to take. In industrial scale salmon slaughtering, the average weight of a batch of salmon is known. The weight, or the average weight, is therefore used to estimate the dimensions of the salmon. At field experiments, samples of 3 and 3 salmon with a gutted weight of respectively 3,0 kg, 4,9 kg and 8,1 kg were cut in 8 slices and dimensions were measured. The average dimensions that were found are shown in Table 3.6. Because the ungutted weight was not measured, it is estimated with average density of salmon and volume of the elliptical cylinders that model the salmon. These ungutted weights are used to interpolate dimensions of slices when only weight is known.

Table 3.6 Average dimensions of slices

	Gutted weight: 8,1 kg Ungutted weight: 9,7 kg			Gutted weight: 4,9 kg Ungutted weight: 6,25 kg			Gutted weight: 3,0 kg Ungutted weight: 3,8 kg		
	a [cm]	b [cm]	l [cm]	a [cm]	b [cm]	l [cm]	a [cm]	b [cm]	l [cm]
Slice 1	2,5	3,2	4	2	3	3,5	2	3	3,5
Slice 2	4,25	5,5	10	5	6	5,5	5	6	5
Slice 3	5,55	10	14,6	5,3	7,2	8,5	4	7,2	11
Slice 4	5,8	11,75	18,7	5,5	8,75	14	4,3	7,1	10
Slice 5	4,3	9,3	6,5	4,9	7,7	10,6	3,7	6,85	4,8
Slice 6	3,7	8,25	5,5	4	6,55	6,9	3,6	6,85	4,5
Slice 7	3,2	5	5	3,3	4	6,5	3	4,5	6,5
Slice 8	2,45	3,8	9,5	2,1	3,5	6,3	2	3	6,8

The interpolation assumes a linear relation between the weight and the dimensions of the slices. Since this is not true, a small deviation in the dimensions will occur. In a batch of salmon, the size of the salmon can vary a lot, and thus the temperatures in salmon and the heat they reject will vary. It is assumed that these variations will cancel each other, and as long as the average weight provided by the factory is accurate, this will also be the case for calculations of total heat rejection.

3.11 EES script

Two EES scripts are made to model a chilling process as a batch process and a continuous process. Both scripts use average weight of salmon to divide the salmon into 8 slices and estimates dimensions as described in Chapter 3.10. Equation (2.16) is used for calculating the average temperature for each slice. The average temperature for the whole salmon is found by weighting the temperature in each slice with its volume.

$$T_{avg} = \frac{\sum_{i=1}^{n} m_i T_{avg,i}}{\sum_{i=1}^{n} m_i} \tag{3.11}$$

Where n is the number of slices. The heat rejection from salmon to RSW can be calculated with variations of Equation (2.17).

In the continuous process script, the HeliX tank is assumed to operate like a steady state heat exchanger. This is true when all flows are constant over a certain time period so that equilibrium in the heat flows is achieved. The temperature of RSW and the salmon will change as they flow through the tank, but the temperatures in each fixed position are constant. This makes it possible to do calculations on the heat flow and temperature changes without any differential equations. The temperature increase of RSW through the tank can be calculated using a heat balance.

$$\Delta T_{RSW} = \frac{Q_f + Q_{loss,HeliX}}{\dot{m}_{RSW} c_{p,RSW}} \tag{3.12}$$

The batch process script considers one batch of salmon entering a simple tank with only one chamber at $\tau = 0$, while there is a constant flow of RSW through the tank. This is the same as considering only one chamber in a HeliX tank and neglecting the influence from other chambers. The temperatures and heat flows will change with time, so the script uses a differential equation to calculate the temperature of RSW going out from the tank.

$$\frac{dT_{RSW,exit}}{d\tau} = \frac{\dot{Q}_{fish} + \dot{Q}_{loss,HeliX} - \Delta T_{RSW} \dot{m}_{RSW} c_{p,RSW}}{m_{RSW} c_{p,RSW}} \tag{3.13}$$

Where Q_{fish} is found with Equation (2.17), and $\dot{Q}_{losses}$ is the heat gain from the surroundings and is discussed in Chapter 3.1.3. In the scripts, $\dot{Q}_{losses}$ is set to 20 kW.

To solve this, the chilling time is divided into smaller time steps. The temperatures and heat rejection in each step are calculated, and the results from previous steps are used in the calculations for the next step.

3.12 Simulations of HeliX tank

3.12.1 Calculations methods

With MATLAB scripts the chilling conditions in a HeliX tank in normal operation, semi-continuous process, is simulated. Based on input temperatures of RSW and salmon, fish size, RSW flow and chilling time; average and centre temperatures of salmon, temperatures of RSW and cooling load is calculated for every time step. The scripts divide salmon in slices and calculate temperature the same way as the EES batch process script. The difference is that the MATLAB script divides the tank into a specified number of chambers and calculates the temperature of RSW exiting each chamber based on the fish that is chilled there and cooling losses from the surroundings. The calculated temperature is then used as input temperature for the next chamber. This way the effect of increasing RSW temperature through the tank is investigated and differences in fish temperatures in different chambers is found.

The chambers are not filled and emptied at the same time. The temperature increase that happens the first minutes after filling one chamber will not affect the next chamber before that is filled as well. Also, the last period before the fish exits the tank, there are no cambers in front of the fish that will increase the RSW temperature. To account for this, the average RSW temperature increase through a chamber is calculated without the first chamber filling time and with an equal time period added where the temperature increase is set to zero. This average RSW temperature is used in the calculations for the next chamber.

Chilling index for the process is estimated based on the RSW flow. Results from field experiments at two salmon slaughtering factories are used to find the following expression for RSW flow and chilling index:

$$i_{chill} = 0.56 + 0.0017\dot{m}_{RSW} \tag{3.14}$$

Equation (3.14) assumes a tank around 100 m^3 is filled with 33 % salmon and 67 % RSW. This is therefore used as fixed parameters in the simulations, both in MATLAB and EES.

In the MATLAB scripts one of two assumptions for the chilling process can be chosen. The main assumption is a process with constant heat transfer coefficient, and this is what is used in the simulations unless anything else is stated. The scripts find what heat transfer coefficient gives the correct chilling index after 90 minutes of chilling and uses this for its calculations. Another assumption which can be chosen is that the chilling index is constant through the chilling time. With this assumption, ideal temperatures are calculated and the chilling index is used to find real temperatures over the whole chilling period. As discussed in Chapter 3.9, a chilling index cannot be completely constant and this gives some errors. Equation (3.14) is based on centre temperatures and chilling times of 95 and 100 minutes and gives a chilling index which is best adapted to this. While this method gives good results for centre temperatures, the average temperatures will be too high. A chilling index is not the same for centre and average temperatures, and no expressions are made for average temperatures. Since Equation (3.14) is adapted to centre temperatures, using it gives to high average temperatures, and thus the calculated cooling load will be too small (10 – 20 %). Further experiments on chilling index and average temperatures can solve this problem and make the assumption of constant chilling index a better choice than it is today.

3.12.2 Parameters

The simulations were performed with parameters as described in Table 3.7.

Table 3.7 Parameters for simulation of HeliX tank

Parameters that were changed		
Fish weight	3, 5, 8	kg
RSW flow	50, 125, 200	m^3/h
Initial fish temperature	6, 9, 12	°C
Constant parameters		
Number of chambers	14	-
Chamber filling time	5	min
Inlet RSW temperature	-1	°C
Tank volume	100	m^3
Heat from surroundings	20	kW
Filling of fish	33	%

3.12.3 Creating scenarios

The parameters can be used to create a good, a medium and a bad scenario as in Table 3.8. The chilling index is calculated based on RSW flow with Equation (3.14). The good scenario is a winter scenario where the initial fish temperature is low, in addition to high RSW flow and small fish, which give an effective reduction of fish temperature. The bad scenario has low RSW flow and large fish combined with high initial temperature of the fish (late summer).

Table 3.8 Scenario parameters

	Initial fish temperature	Fish weight	RWS flow	Chilling index
Good scenario	6 °C	3 kg	200 m^3/h	0.901
Medium scenario	9 °C	5 kg	125 m^3/h	0.773
Bad scenario	12 °C	8 kg	50 m^3/h	0.645

3.13 Description of field measurements

27th and 28th of September 2018, field measurements were performed at a slaughtering factory, consisting of 4 experiments. The measurements were focused on temperatures of salmon in and out of the tank, and the temperature of RSW in the different chambers. How the HeliX tank was operated and the circulation of RSW and salmon was observed. The activities and observations were documented with pictures and video. Additional to the performed measurements, central data from the factory computer systems were collected.

3.13.1 RSW temperature

iButton temperature loggers were mounted in the chambers of the tank. The setup is shown in Figure 3.7. The loggers registered the RSW temperature every minute throughout the experiments.

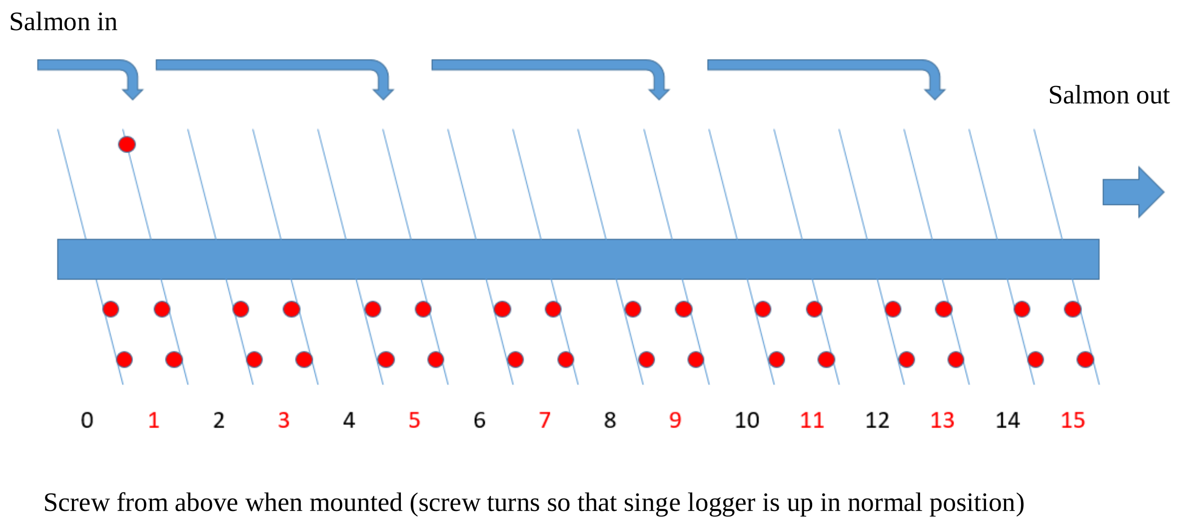

Figure 3.7 Position of temperature loggers (Widell, 2018)

3.13.2 Centre temperature of salmon

In the first experiment, 60 salmon in the production line right before the HeliX tank were marked with a number tag. The centre temperature was measured before entering the tank and again after exiting. A **Testo** temperature measuring instrument with a 23 cm probe was used. Figure 3.8 shows how the centre temperature was measured by sticking the probe down the throat and into the centre of the fish. Thickness and height were also measured, and chilling time and which camber the salmon entered were registered.

Figure 3.8 Measuring centre temperature and dimensions of salmon

Experiment 2, 3 and 4 were similar to the first, but they also included measuring the weight of the salmon. Between 38 and 110 salmons were measured going in and out of the tank. Because of restrictions from the factory, these experiments were without number tags. The variation of temperature in salmon entering the tank was small (+/- 0.2 °C). It was concluded that measuring the temperature of the exact same salmon before and after chilling was of less importance since all salmon had almost the same temperature.

3.13.3 Measuring uncertainties

The weight of salmon was measured with a weight from the factory. The weight had an accuracy of +/- 0,1 kg. During experiment 4, a problem with the calibration of the weight was noticed. A salmon that was measured to 6.0 kg was after the recalibration measured again to 5.1 kg. How long there had been a problem with the calibration is unknown. Because of this, the accuracy of the measured weight is uncertain.

The thickness and height of the salmon was measured with a measuring board (Figure 3.8). The accuracy of the thickness is assumed to be +/- 2 mm, while the height is assumed to have an accuracy of +/- 1 cm. Estimating this accuracy is quite difficult, because the shape the salmon will be affected by gravity when lying on the measuring board.

The time was measured with a digital watch on a mobile phone. Only whole minutes were used. There are also some uncertainties because of the time it took from the salmon was measured to it entered the tank, and the time from the outlet of the tank to the measurement. Some salmon had to wait a couple of minutes after the outlet because of the queue at the measuring, but for most of the fish this time was neglectable.

Some of the salmon fell from the transportation band and into the tank before it reached the chamber it was intended to enter. This salmon will stay in the HeliX tank for a longer time because salmon in chambers with lower numbers will exit later. This might have happened to some of the measured salmon.

4 Results and discussion

4.1 Influence of geometry and heat transfer coefficient on T_{avg} and T_{centre}

The simulations of chilling of ellipses in MATLAB resulted in lists of centre and average temperatures changing with time. Figure 4.1 shows the temperature development for one of the simulations.

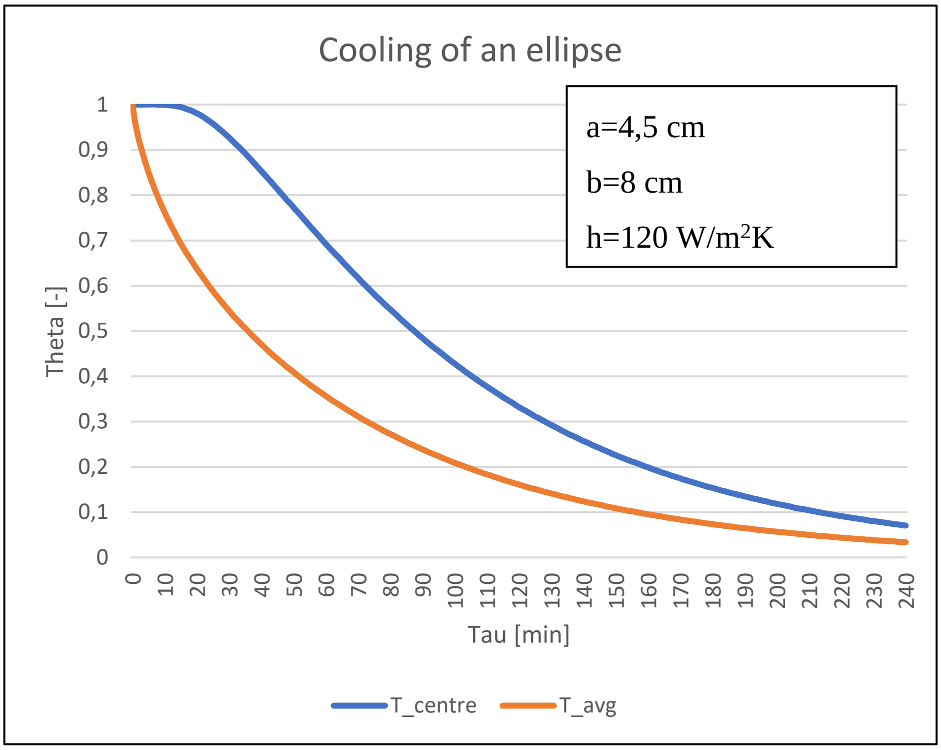

Figure 4.1 Simulated temperature development of an ellipse

By comparing different simulations with different parameters, the influence of the parameters was investigated. Figure 4.2 shows how centre and average temperatures after 90 minutes of chilling changes with heat transfer coefficient, height and thickness. As expected, thickness has the greatest impact on the temperatures, and the effect of increased heat transfer coefficient is small when exceeding 200 W/m^{2}K

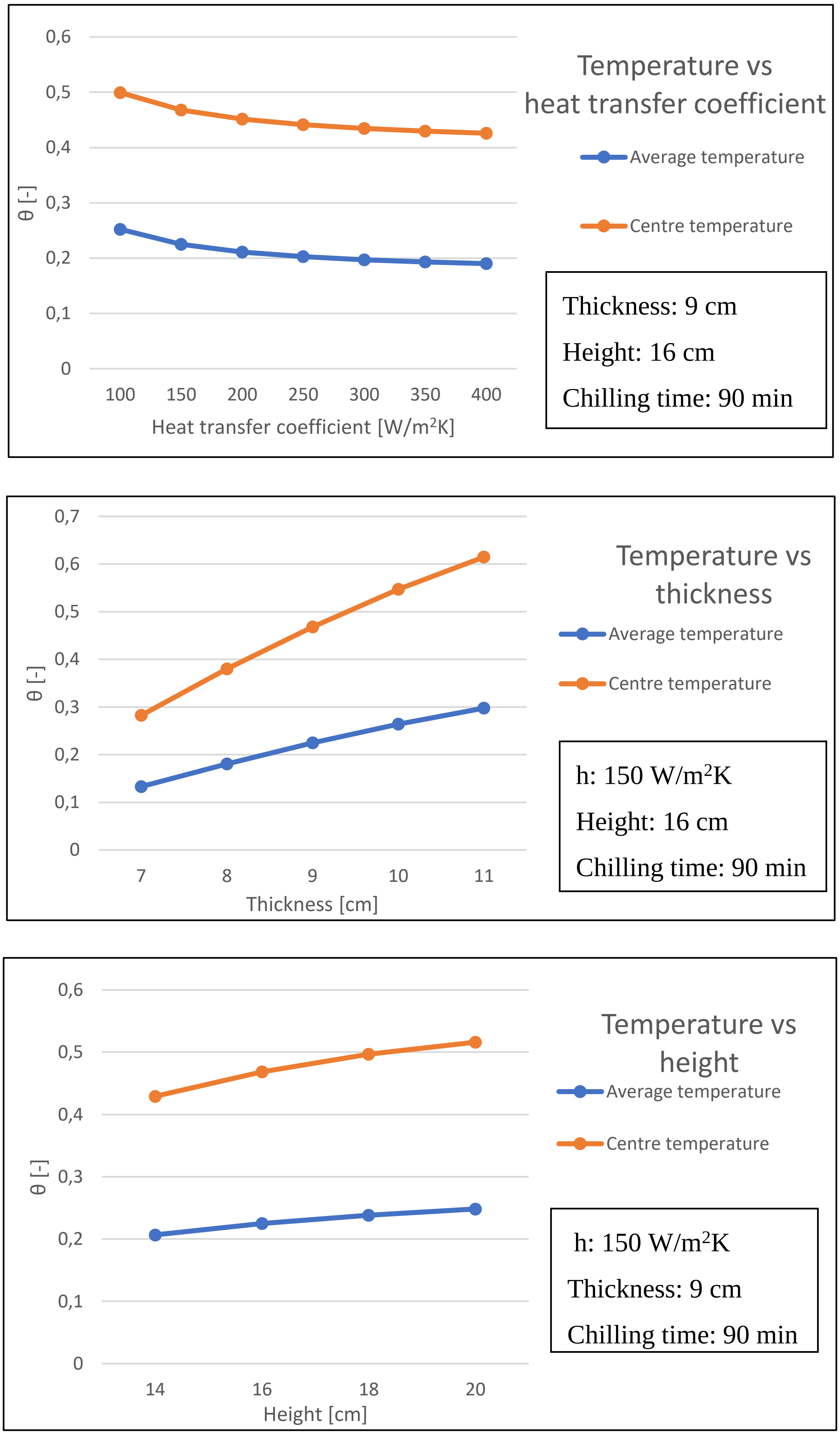

Figure 4.2 Influence of geometry and heat transfer coefficient on Tavg and Tcentre

Centre temperatures changing with time were also plotted for different thicknesses (Figure 4.3).

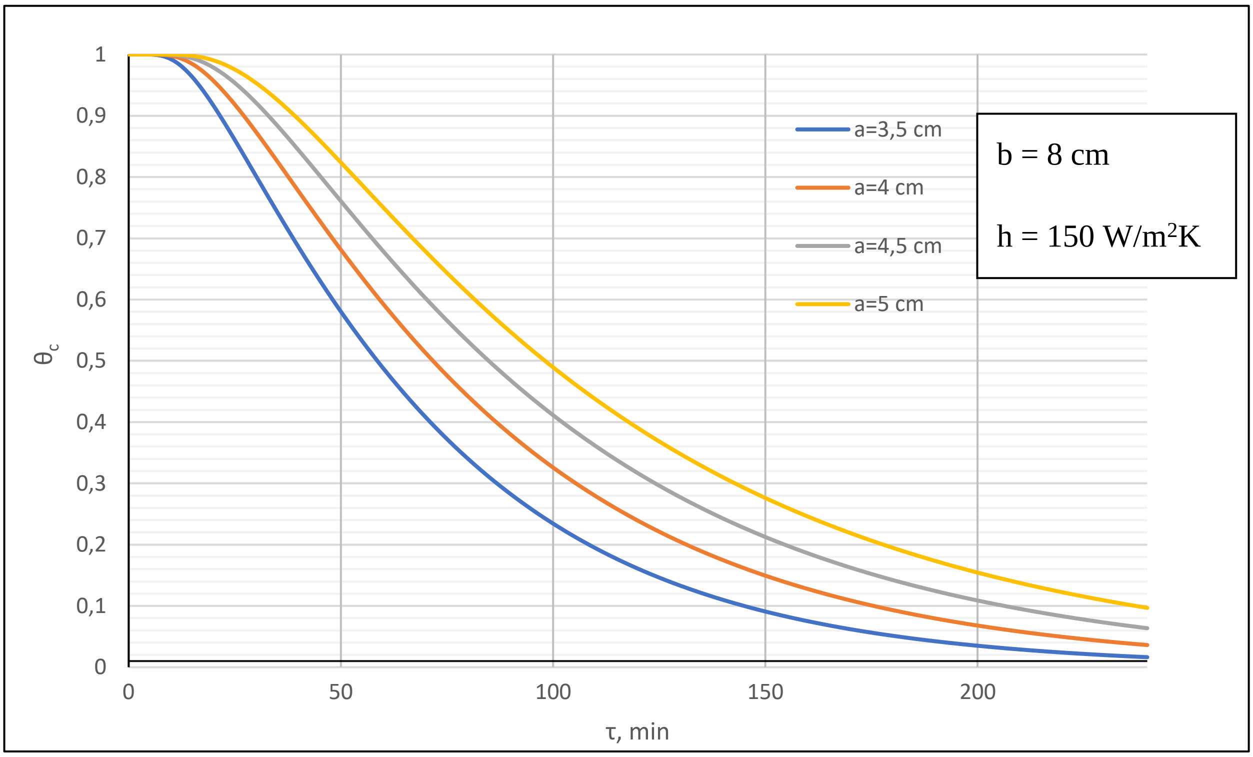

Figure 4.3 Influence of thickness on centre temperature over time

4.2 EES scripts

With two EES scripts, heat rejected from salmon, temperature changes of RSW and cooling load are calculated. Figure 4.4 shows how temperatures and cooling load changes if the tank is filled with 33 metric ton of salmon at τ = 0. Table 4.1 shows results for a continuous process with the same parameters and capacity. Chilling index is assumed constant and calculated with Equation (3.14) in both scripts.

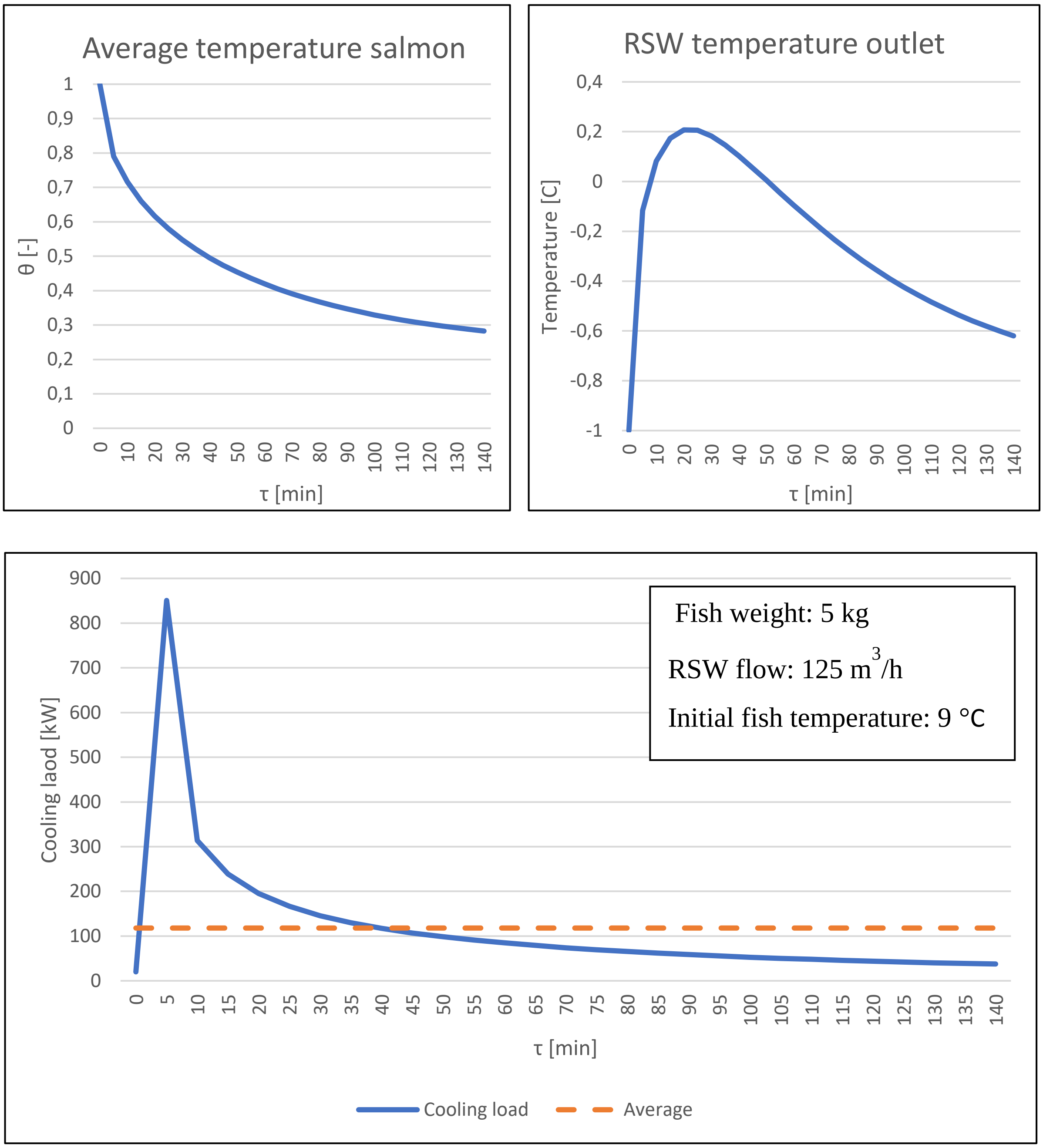

Figure 4.4 Temperatures and cooling load, batch process

Table 4.1 Results continuous process

θ_{avg}	0.2826	[-]
ΔT_{RSW}	0.8745	°C
Cooling load	121.5	kW
Capacity	14.14	tons/h

The scripts give equal final temperature of salmon with a batch process and a continuous process. This is because they use the same chilling index. However, it is easier to have good circulation in a continuous process with a HeliX tank compared to a batch process with the same capacity. Therefore, it can be assumed that the continuous process, to some extent, gives more effective chilling. The average cooling load is the same for both scripts, but while continuous process gives a constant cooling load, batch process gives large variation, with a peak cooling load 7 times larger than the average. This makes continuous processes preferred compared to batch processes. A good solution if a continuous process is to be achieved is to install two HeliX tanks with constant turning screw in series, so that salmon enters the second tank immediately after exiting the first. This gives opportunities to have different circulations of RSW in the two tanks, with different temperatures, and further optimization of the chilling system is possible.

4.3 Simulations of HeliX tank

With the MATLAB model of a HeliX tank, results such as average and centre temperature of salmon, temperature of RSW and the cooling load from the tank are generated. Unless anything else is stated, the resulting temperatures of fish is an average over 14 chambers.

Figure 4.5 shows simulated centre temperature development assuming constant chilling index compared to assuming constant heat transfer coefficient. The heat transfer is set so that the temperatures are equal at 90 minutes, where constant chilling index should give good results.

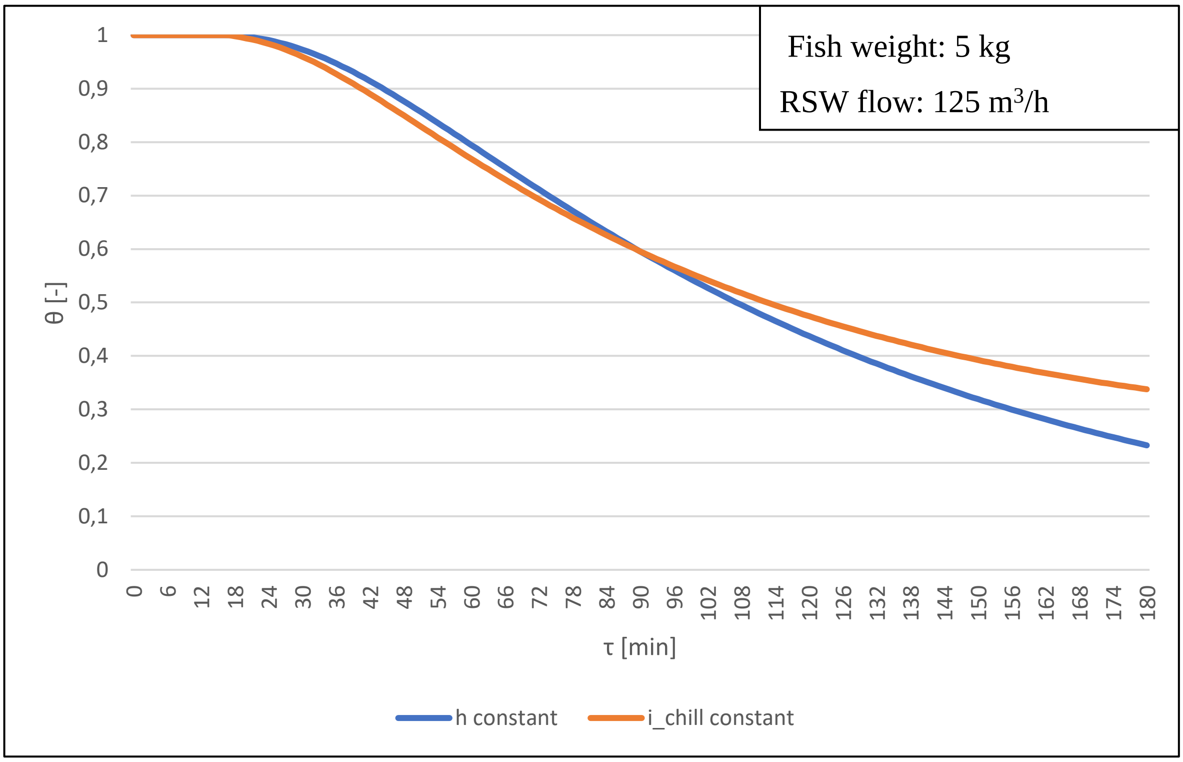

Figure 4.5 Average temperature assuming constant h and i_{chill}

As can be seen, there are some differences. Constant chilling index gives faster temperature decline in the first minutes, while constant heat transfer coefficient gives more decline and lower temperatures for longer chilling times. When only looking at centre temperatures, constant chilling index do not give the same systematic error as for average temperatures, and which assumption gives the results closest to the real temperature depends on the conditions in the tank. For example, bad circulation and high density of salmon give conditions close to constant chilling index, while good circulation and low density of salmon is closer to constant heat transfer coefficient. In real cases the centre temperatures in a HeliX tank is probably somewhere in between the two assumptions.

4.3.1 Scenarios

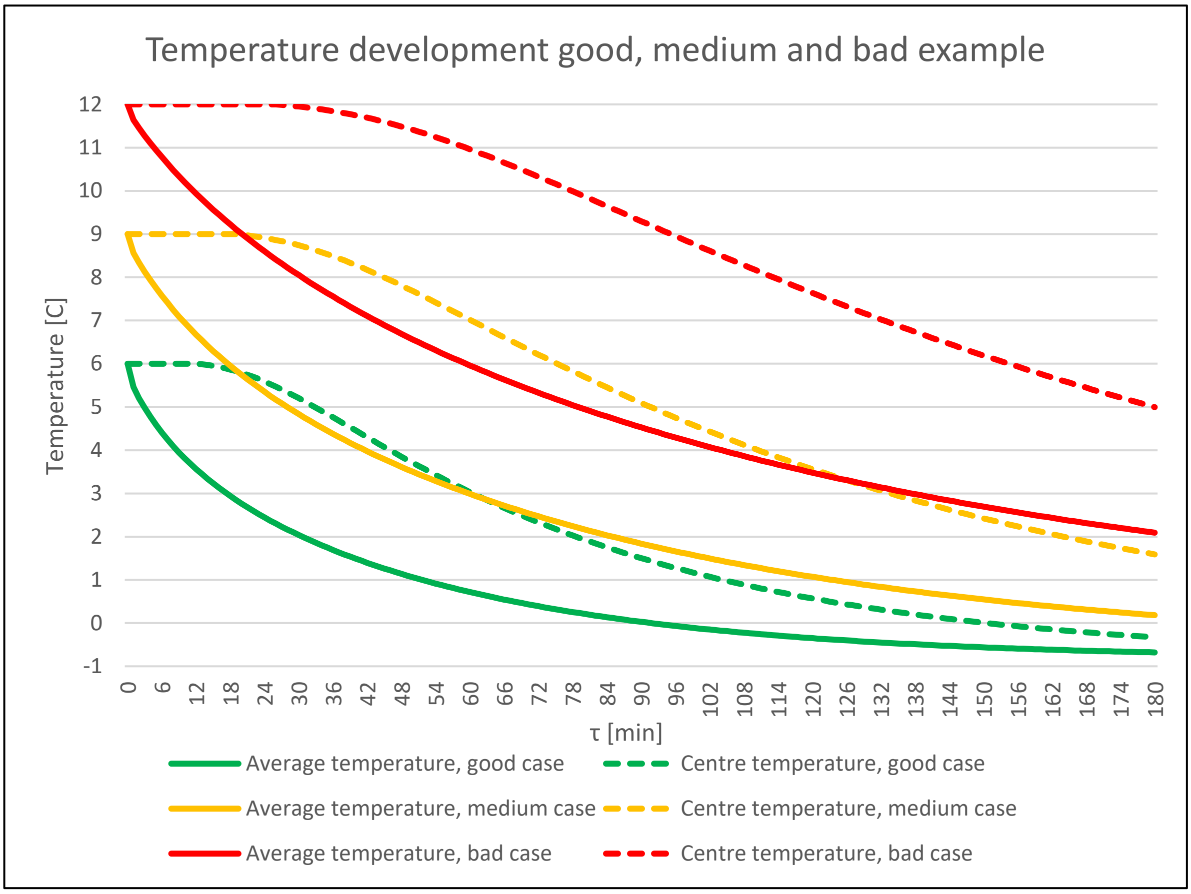

Figure 4.6 Temperature development, scenarios

Figure 4.6 shows the resulting average and centre temperatures for the scenarios over a chilling time of 180 min. As can be seen, when creating scenarios there is a possibility to create very large differences. For the best scenario, average and centre temperature decreases below 2 °C in 28 and 77 minutes respectively, while the worst scenario gives far from satisfying chilling even after 180 min chilling time.

4.3.2 Influence of initial fish temperature, fish size and RSW flow

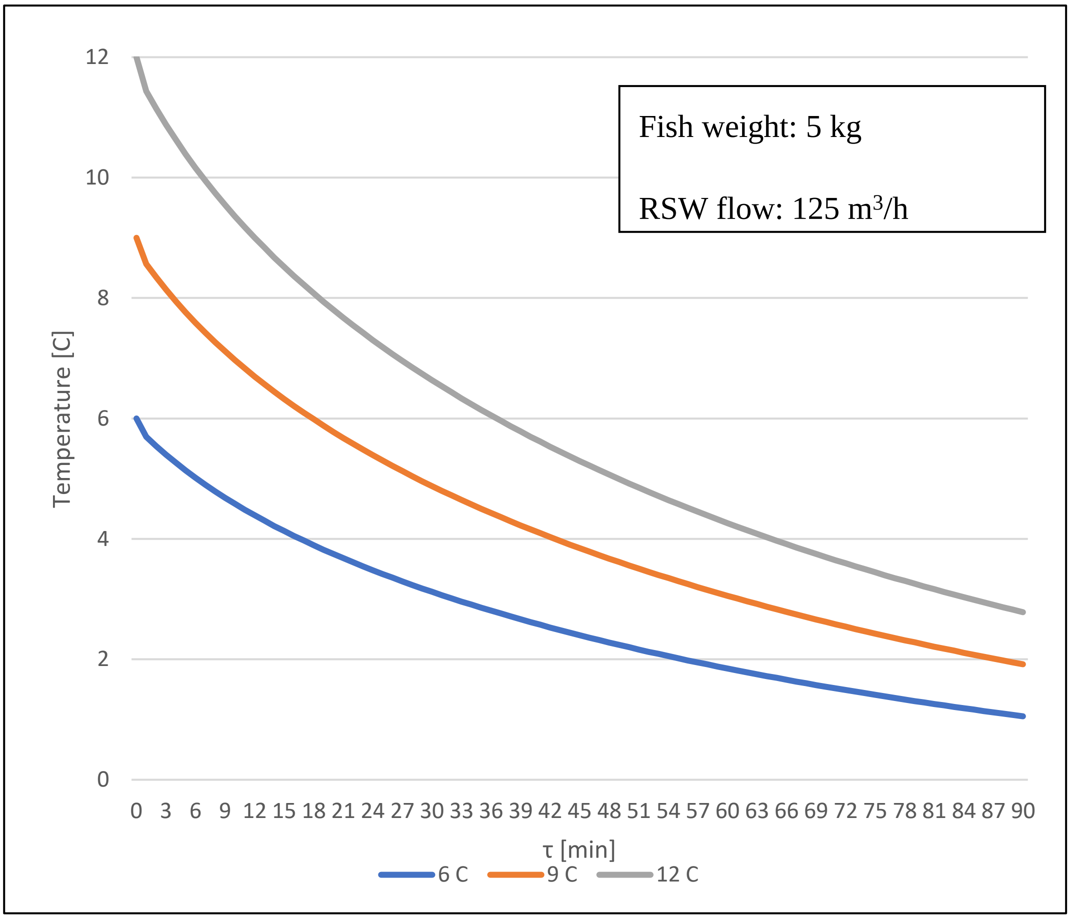

Figure 4.7 Average temperature for different initial fish temperature

Figure 4.7 shows the development of average temperature for fish with different initial temperature. The initial temperature of fish changes with, and is close to, the temperature of the sea water. At Sistranda, Frøya, the average sea surface temperature varies between 4.9 ℃ in March to 14.8 ℃ in August (World Sea Temperatures, 2019). This gives a large variation in chilling required to reach optimal fish temperature of 0 to 2 ℃.

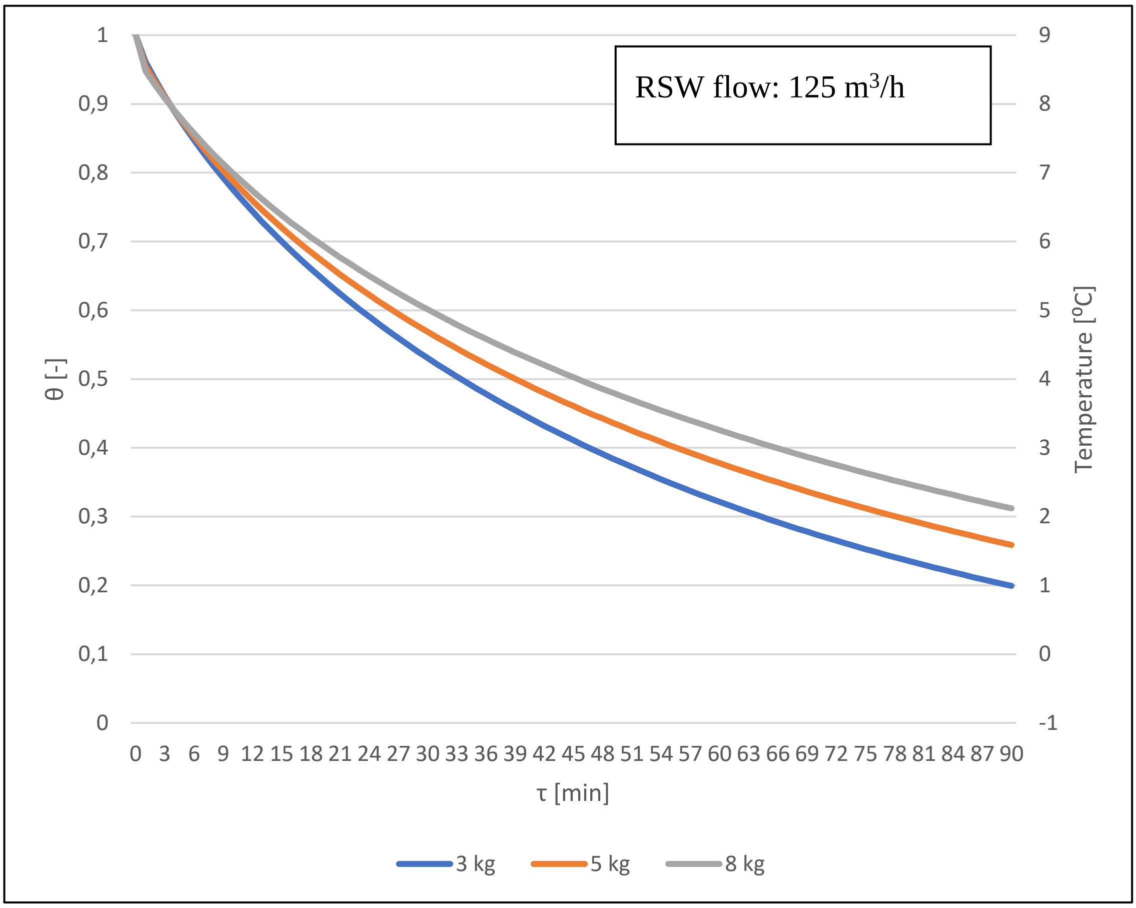

Figure 4.8 Average temperature for different fish weight

Figure 4.8 shows the average temperature of 3 kg, 5 kg and 8 kg salmon, with dimensionless temperature on the left side. The real temperature on the right side assumes an initial fish temperature of 9 °C and RSW temperature of -1 °C. With a chilling time of 90 min, there is a difference of around 1 °C between salmon of 3 and 8 kg. It can be observed that for lower temperatures, the difference in required chilling time increases. It takes double the time to reach θ = 0,4 with salmon of 8 kg compared to 3 kg.

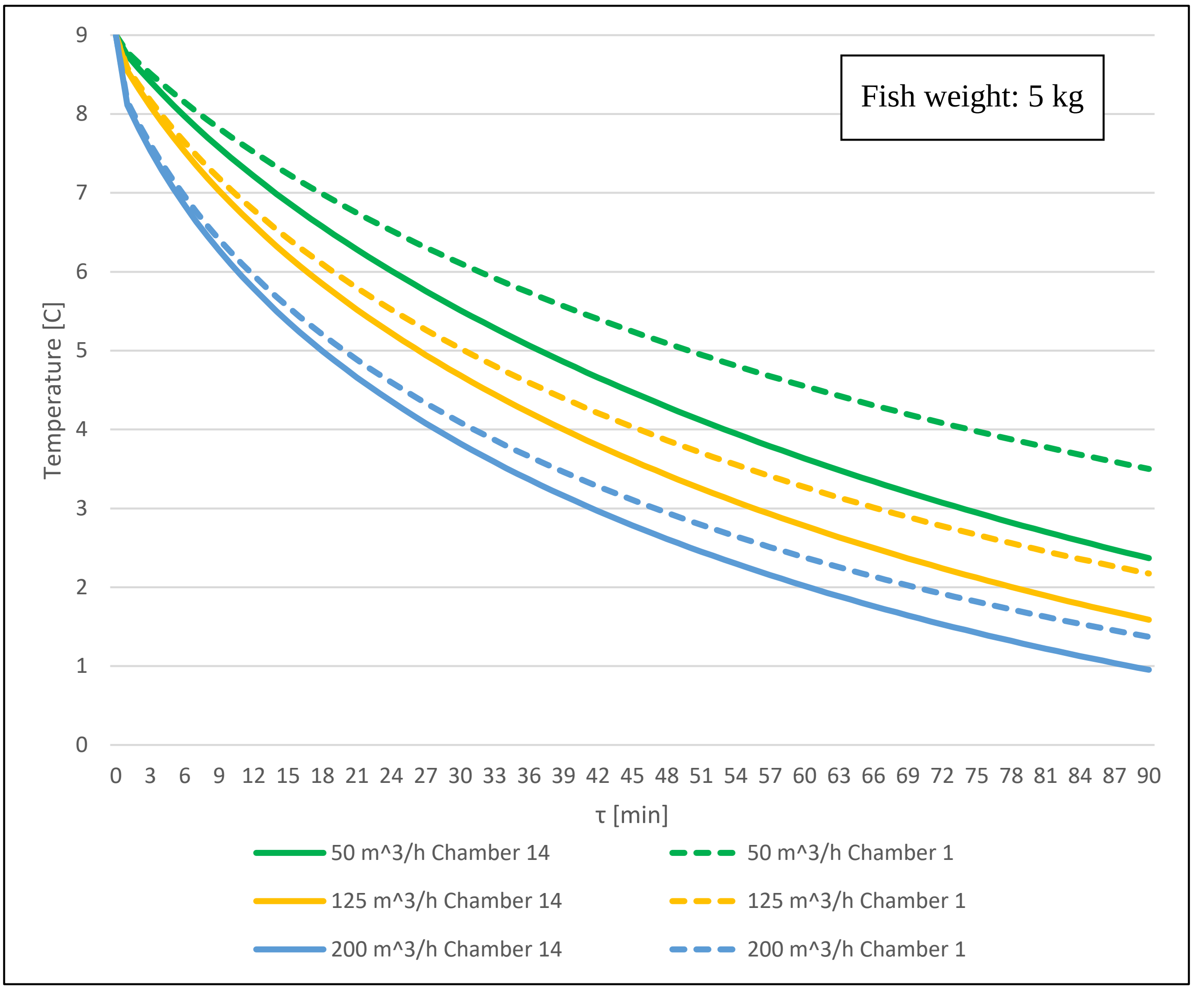

Figure 4.9 Average temperature with different RSW flow

Figure 4.9 shows the average temperature of salmon in chamber 1 and 14 for different RSW flow. Higher RSW flow gives more effective chilling and higher chilling index. We can observe this as the relatively large difference of more than 2 °C after 90 min chilling, between RSW flow of 50 m^3/h and 200 m^3/h. Low RSW flow also results in greater difference between the chambers. This is because the RSW is heated by the salmon and from the surroundings when it flows through the tank. When it reaches the last chambers the RSW temperature has increased so that the chilling in these chambers is decreased. Higher RSW flow gives a lower increase in RSW temperature and thus the chilling is more equal through the tank. Disadvantages with higher RSW flow is more pump work and possibly a slight increase in heat losses.

4.3.3 Operation cycles

A simple cycle of the HeliX tank consists of filling the chambers one by one, the stand still chilling period, and emptying. Chilling the fish in the chambers and heat losses from the environment gives a cooling load which is shown in Figure 4.10.

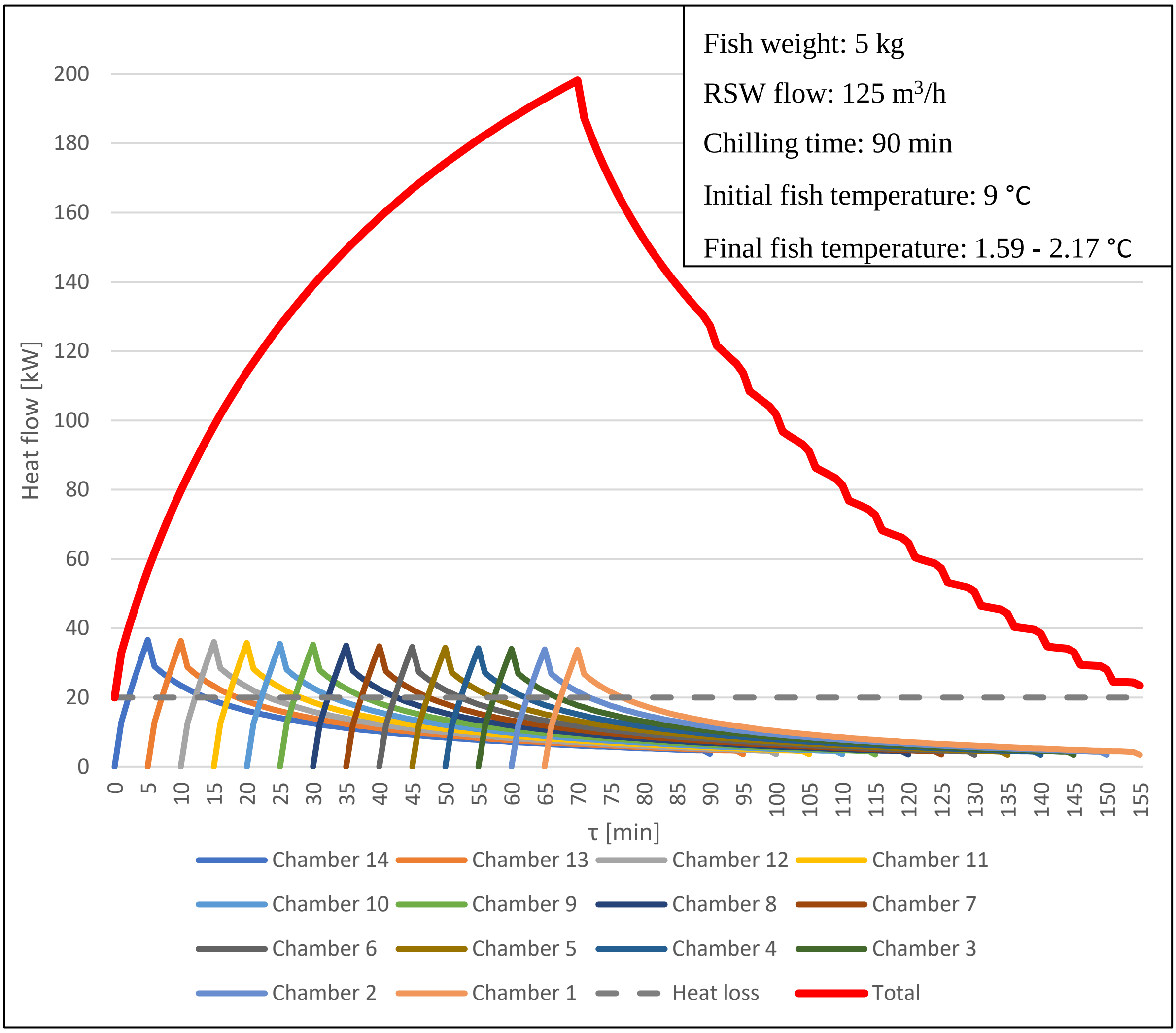

Figure 4.10 Cooling load, simple cycle

Since the heat flow is proportional to the decrease of the average temperature, for each chamber the heat flow is largest immediately after filling, and then decreases as the reduction in temperature gets slower. The total heat flow from the salmon increases as more and more chambers are filled and contributes to the total load. After filling the last chamber, the cooling load rapidly decreases as the temperature reduction in the fish becomes slower. After 90 min emptying the chambers begins and further reduces the cooling load until the tank is empty and only heat losses remain.

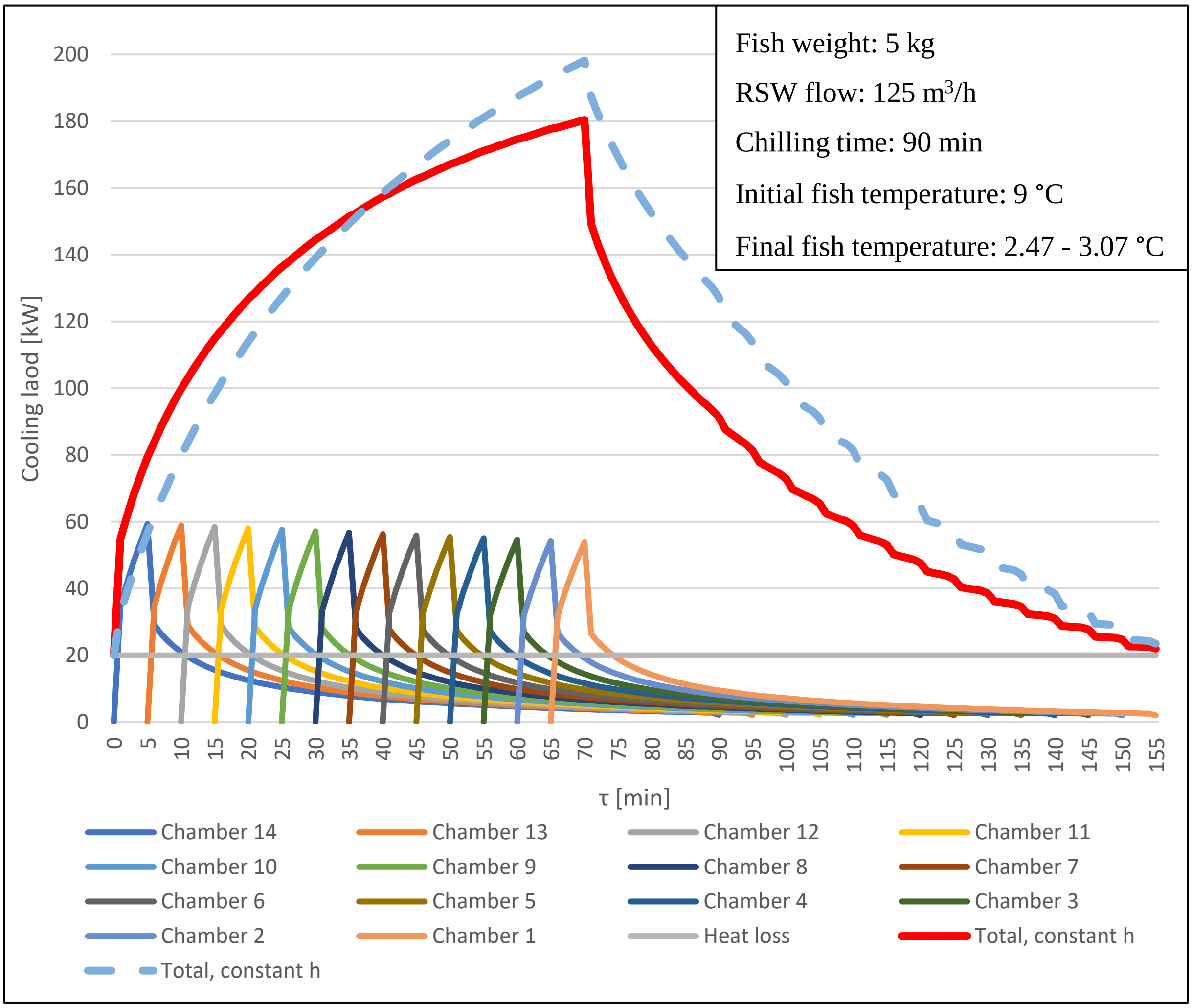

Figure 4.11 Cooling load, constant heat transfer coefficient

Figure 4.11 shows the calculated cooling load when the model assumes constant chilling index, instead of constant heat transfer coefficient. This gives a faster increase in cooling load for the first part of the chilling period, which corresponds to the faster temperature decline this assumption gives. The rapid temperature decline gives a high peak load for the chambers, which is higher than for constant heat transfer coefficient. After the first period, the cooling load with constant chilling index is lower because the final average temperatures are higher, and thus less heat is released by the salmon.

In normal operation the tank is filled with new salmon simultaneous as the emptying. A new cycle begins and the cooling load increases. This is shown in Figure 4.12. With the given conditions, the maximum cooling load is 180 kW, while over many cycles the average is 154 kW. The absolute minimum requirement for the cooling system is to match the average cooling load. This will give some changes in the RSW temperature, and to keep this constant matching the maximum cooling load is necessary.

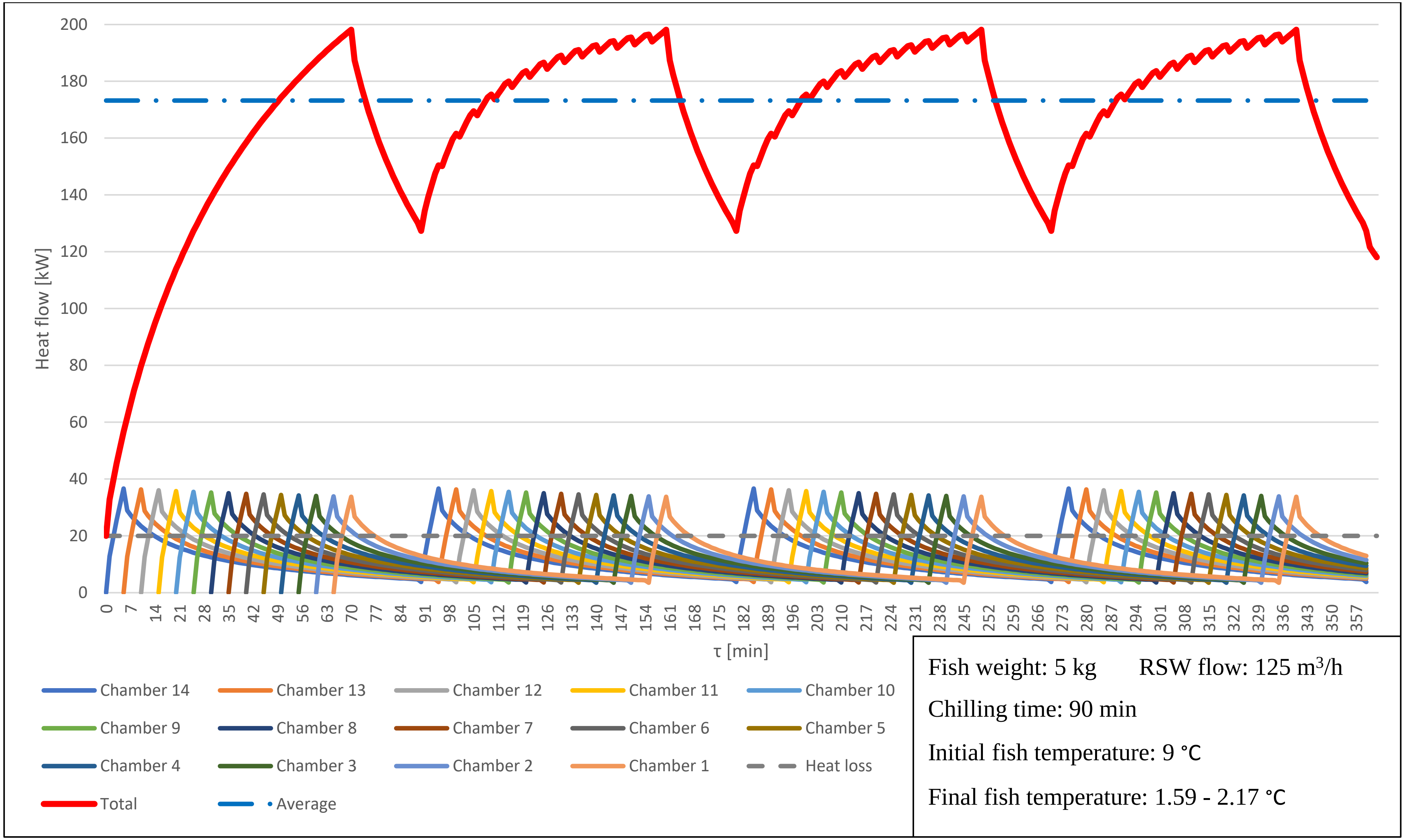

Figure 4.12 Cooling load, cycles in series

For the 3 scenarios, the RSW flow is changed so that chilling is close to ideal, with final average temperature of the salmon between 0 ℃ and 2 ℃. Figure 4.13, Figure 4.14 and Figure 4.15 show the cooling load from the scenarios with two tanks in parallel. When the tanks are in parallel, the stationary chilling period is equal to the filling/emptying time. This gives a total chilling time of 140 min instead of 90 min, which is used in the other simulations. Comparing the simulations behind Figure 4.12 (medium scenario, single tank) and Figure 4.13 (medium scenario, parallel tanks) we see that the increased chilling time gives a final average temperatures from 0.41 °C to 1.01 °C, instead of 1.59 °C to 2.17 °C for the different chamber, and with parallel tanks the capacity increases with 28,6 %, from 14 chambers per 90 min, to 28 chambers per 140 min. The cooling load increases with 57.4 %, from 173.2 kW to 272.7 kW, while cooling load per kg salmon increases with 22.4 %, from 31.2 to 38.2 kJ. Compared to a single tank, parallel tanks give almost constant cooling load after a start-up period. This is ideal for the refrigeration system.

For the good scenario, RSW flow of only 50 m^3/h is necessary to reach well below 2 ℃ with 140 min chilling time, while for the bad scenario 200 m^3/h is needed. Because of different required temperature declines, the cooling load for the summer scenario is larger, 344.2 kW, and smaller for the winter scenario, 189.91 kW.

The medium scenario has the same parameters as EES scripts for continuous and batch processes. When comparing the results one can see that the calculated theoretical temperatures are almost the same, because chilling time and initial conditions are the same, and only smaller differences in calculation method cause differences in the results. The main difference between the chilling methods is distribution of cooling load. Batch process gives the largest changes, while continuous process gives constant cooling load. Semi-continuous processes with HeliX tank can have different set-ups with different cooling load distribution. With two tanks in parallel the operation and cooling load is quite similar to a continuous process.

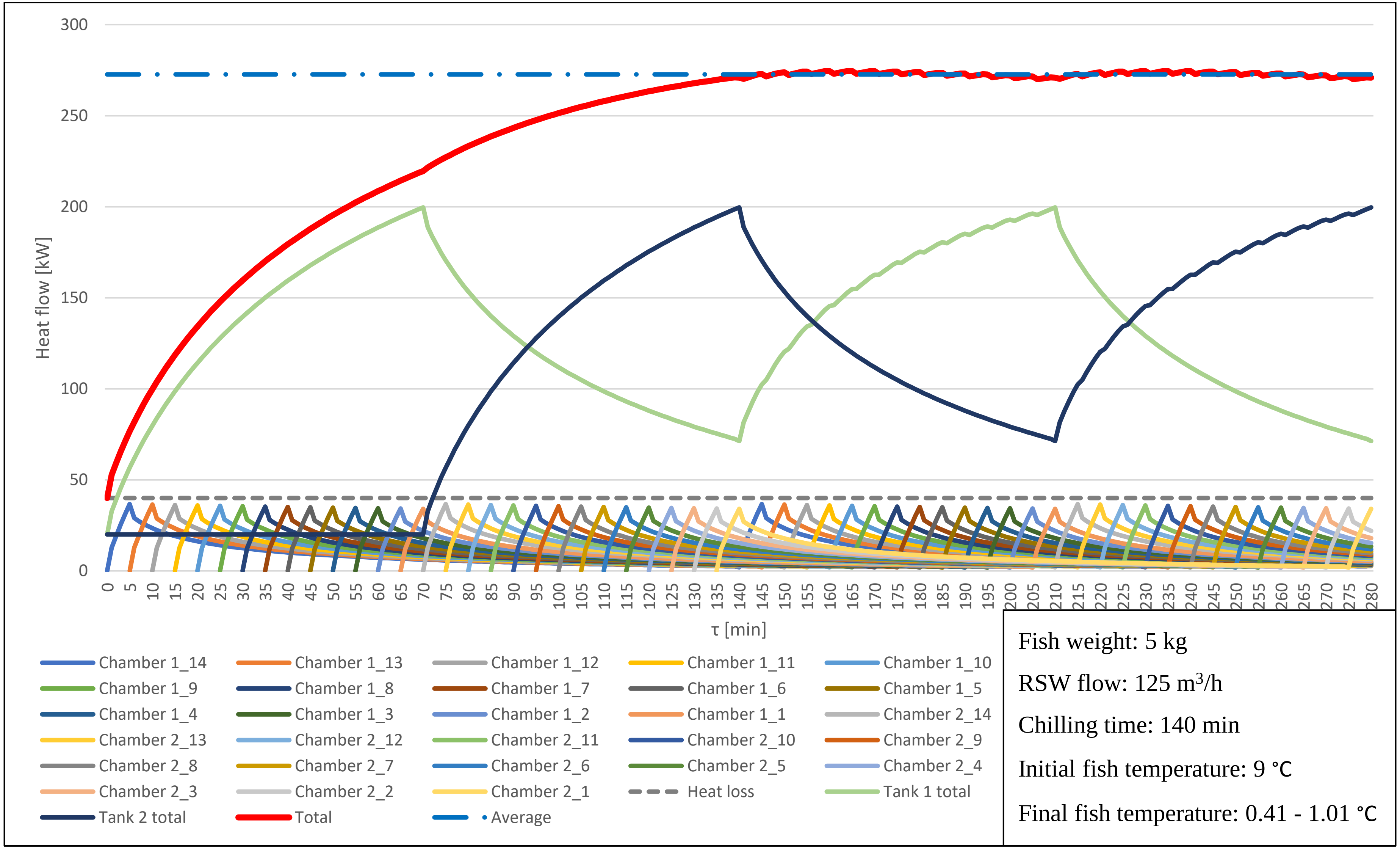

Figure 4.13 Cooling load, parallel tanks, medium scenario

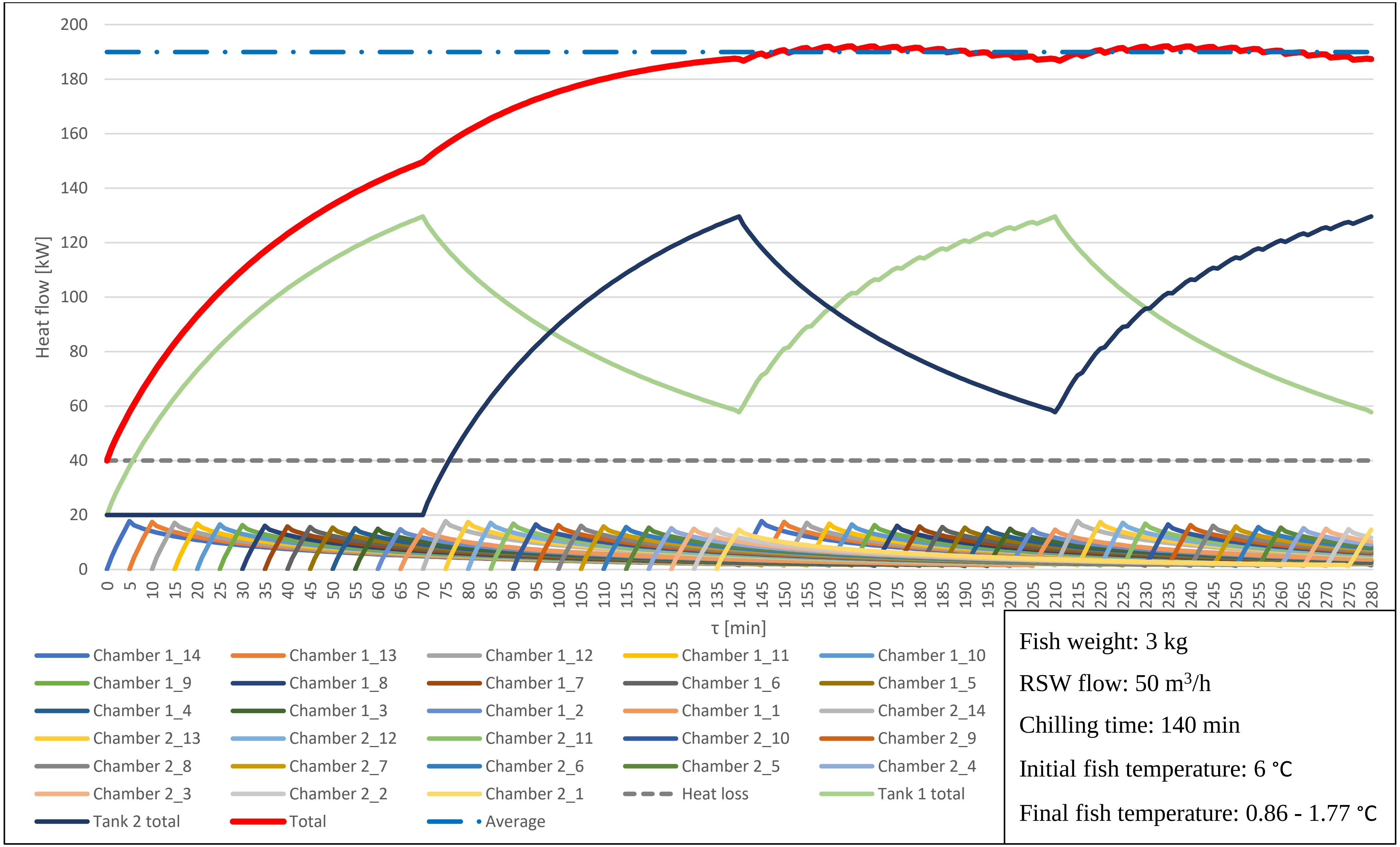

Figure 4.14 Cooling load, parallel tanks, good scenario

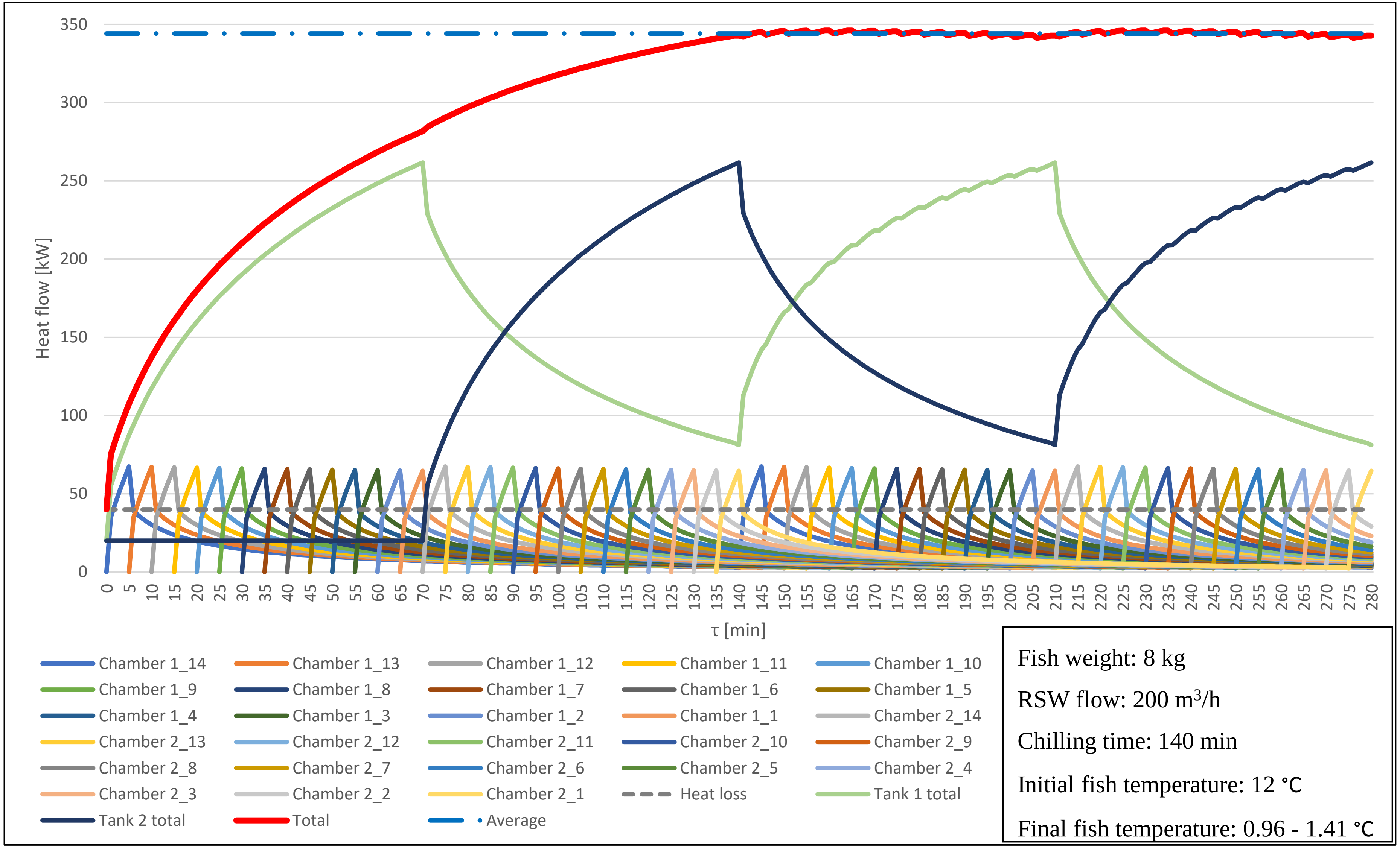

Figure 4.15 Cooling load, parallel tanks, bad scenario

4.4 Dimensioning of evaporator

The refrigeration system should be dimensioned to handle the peak load. It can be assumed that the bad scenario with RSW flow of 200 m^3/h gives the peak load, and with parallel tanks the cooling load is 344.2 kW (Figure 4.15). It is assumed that 20 m^3/h of sea water, taken from at depth of 300 m, with a temperature of 8 °C is added to the circulation of RSW. Equation (3.2) gives $\dot{Q}_{RSW,new}$ = 200 kW, when the sea water is chilled to -1 °C. The cooling load from the HeliX tank is reduced to 309.8 kW, because 20 m^3/h of RSW out of the tank is taken out of circulation and replaced with new RSW. When other losses are neglected, this gives a total cooling load of 509.8 kW. An extra safety margin is added, so that the refrigeration system should deliver 530 kW of cooling.

The RSW temperature increases from -1 to around 0 °C. When mixed with sea water of 8 °C, the temperature of RSW into the evaporator is around 0.8 °C. The evaporator should chill this to -1 °C. A logarithmic mean temperature difference of 4 °C gives an evaporating temperature of -4.17 °C using Equation (2.19). Assuming the overall heat transfer coefficient for the evaporator is 350 W/m^2K, Equation (2.18) gives a heat exchange area of 379 m^2.

4.5 Field measurements

4.5.1 Measurements

4 experiments were performed at a slaughtering factory, where temperatures of salmon and RSW were measured together with weight, dimensions and chilling time. For all experiments the RSW flow where 65 m^3/hour

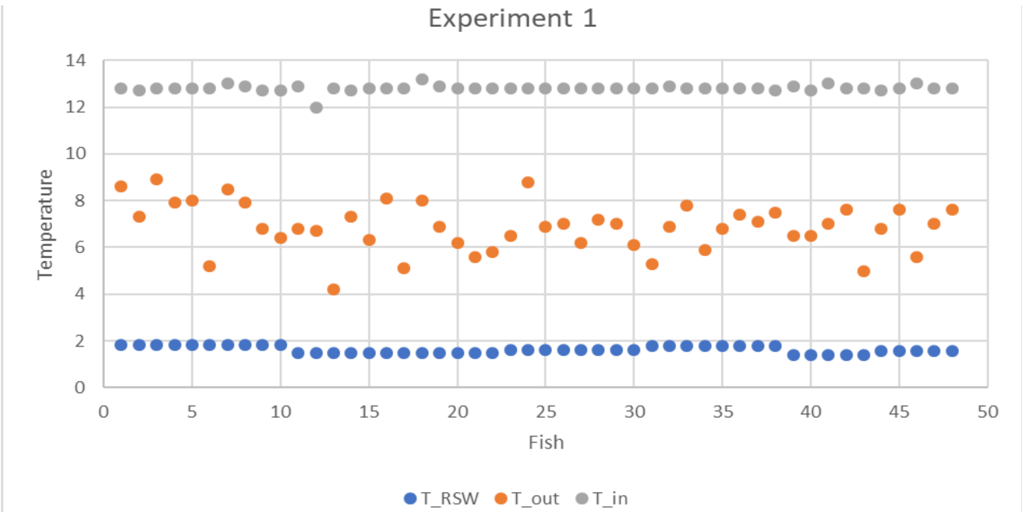

Figure 4.16 Centre temperatures for salmon in and out of tank

Figure 4.16 shows the temperatures of each salmon in experiment 1. As can be seen, the temperatures of salmon out of the tank change quite a lot. This is expected as the salmon varies in size. The variation of RSW temperature is low. The average measured centre temperature for the experiments is shown in Table 4.2. As can be seen, the centre temperatures are clearly above what is ideal.

Table 4.2 Centre temperature, Experiment 1-4

	Centre temperature (Standard deviation)	Chilling time	Height	Thickness
Experiment 1	6.88 °C (1.03)	98 min	16.6 cm (0.80)	8.9 cm (0.54)
Experiment 2	7.05 °C (1.00)	96 min	16.8 cm (1.39)	8.4 cm (0.69)
Experiment 3	6.50 °C (1.34)	96 min	17.1 cm (1.64)	8.8 cm (0.84)
Experiment 4	6.55 °C (1.06)	74 min	15.7 cm (1.47)	8.2 cm (0.70)
Total	6.68 °C (1.13)	88 min	16.4 cm	8.5 cm

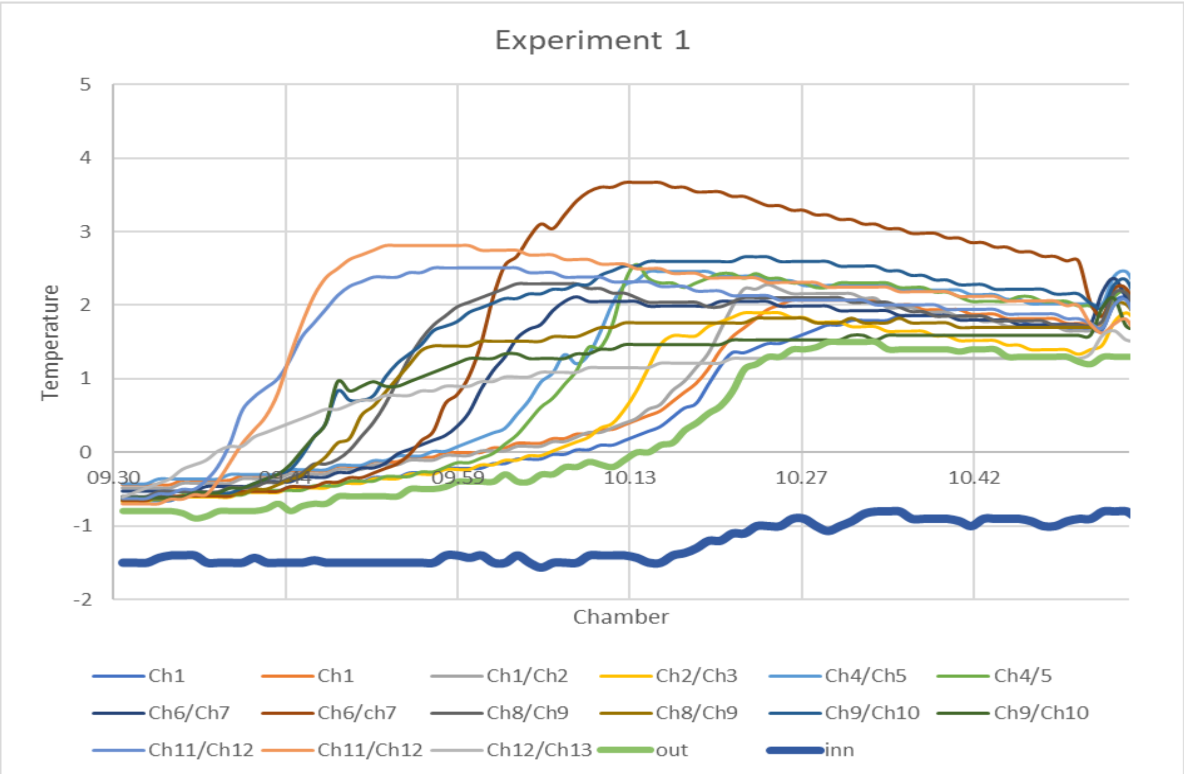

Figure 4.17 RSW temperature for each logger

Figure 4.17 shows how RSW temperature in different chambers starts increasing at different time. As expected, the chambers with the highest numbers, where the salmon enters first, has the first increase in RSW temperature. The temperature of RSW into the tank starts increasing, which indicates that the cooling load is larger than the capacity of the refrigeration system.

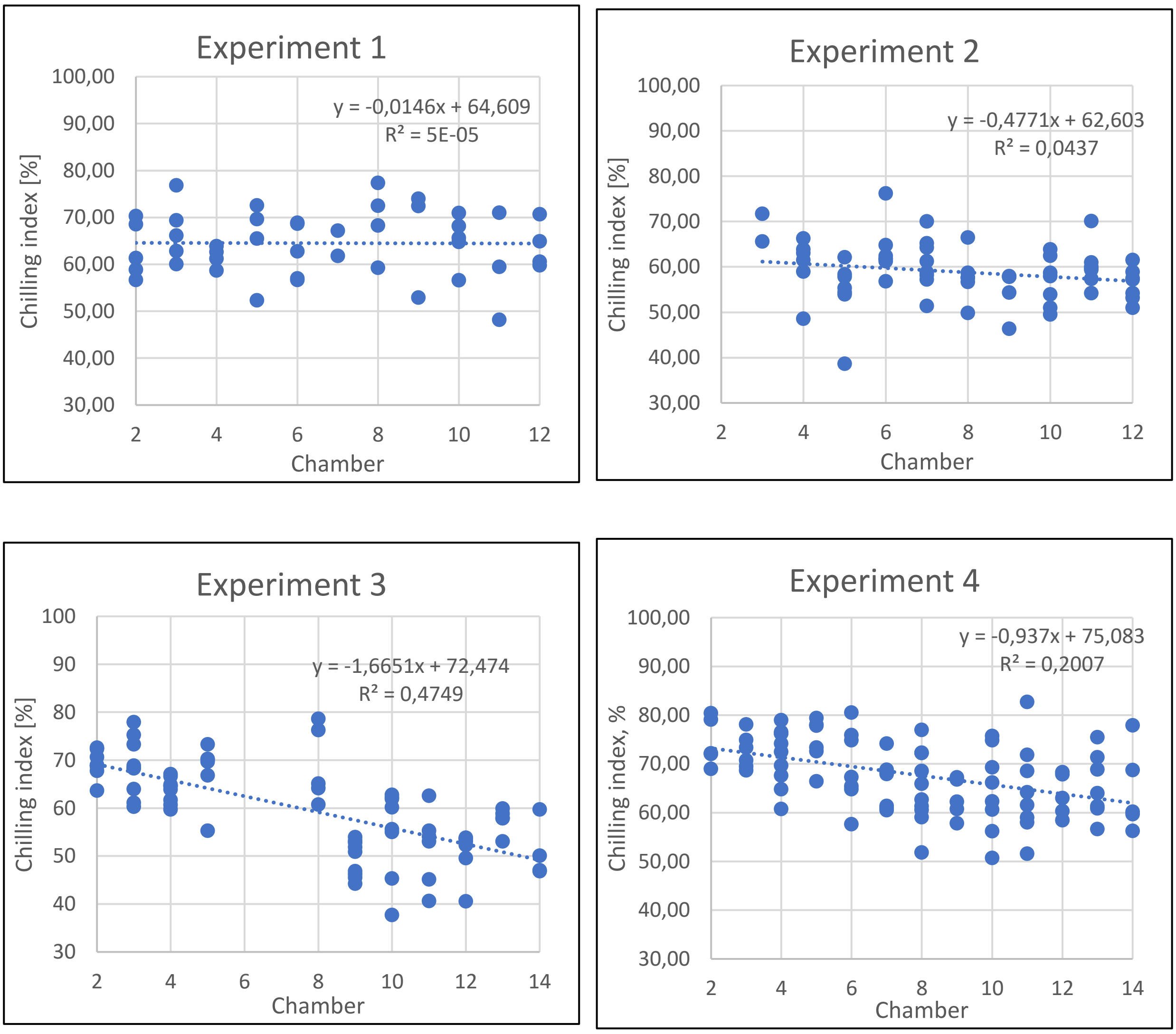

Figure 4.18 Chilling index in chambers

Figure 4.18 shows the chilling index for each salmon, sorted by chamber. As can be seen, there is a trend that salmon in the first chambers have the highest chilling index. The average chilling index for each experiment is:

- Experiment 1: 64.51 %
- Experiment 2: 58.68 %
- Experiment 3: 59.74 % (Chamber 1-5: 67 %, Chamber 8: 69 %, Chamber 9-14: 52 %)
- Experiment 4: 67.69 %

Experiment 3, chamber 8 shows particularly high chilling index. This can be explained by the small amount of salmon in the chamber, which increased the circulation. At experiment 3, there was a change in fish size between chamber 8 and 9, and the larger fish can explain why the chilling index is lower for these chambers. The chilling index at the slaughtering factory is normal for a HeliX tank in normal operation but has potential for improvements. The high density of salmon in the tank limits the circulation and thus also the efficiency of the chilling. The temperatures of salmon exiting the tank is higher than optimal. To come closer to optimal temperatures, the chilling time can be increased, or RSW temperature can be decreased. The last alternative is probably best with respect to economics.

4.5.2 Circulation

It was observed that some parts of the HeliX tank had good circulation while other parts had almost none. Because the circulation system alternated injection of RSW between the nozzles along the tank, which areas that had good and bad circulation were changing. Some patterns independent of this were observed. Areas in the tank with high density of salmon had worse circulation, and the circulation of RSW was best along the outer wall of the tank.

Since the RSW gets coloured by fish blood, observing the behaviour of the salmon is difficult. Only salmon at the surface can be seen. When the chilling is less effective than expected, an explanation can be that the salmon tends to get packed together in big clusters where the temperature is higher, while the colder RSW flows around the clusters. This is shown in Figure 4.19 and will reduce the chilling because the salmon is mostly in contact with each other and the warmer RSW inside the cluster. This could happen because the clearance between the screw and the walls gives larger flow close the walls, which can push the salmon together in the centre of the chambers. Another reason could be that when the screw moves, salmon that touches the screw are pushed to the side of the chamber, and over time the majority of the salmon are in a large cluster. The observations of the surface could support these two theories. The theories can be confirmed by measuring RSW temperatures in different parts of the tank. It should be possible to see that along the walls and in other areas with good circulation, the RSW temperature is lower than in areas with bad circulation and high density of salmon. Further investigations should to be done on how the salmon behave and how to make the circulation systems more effective.

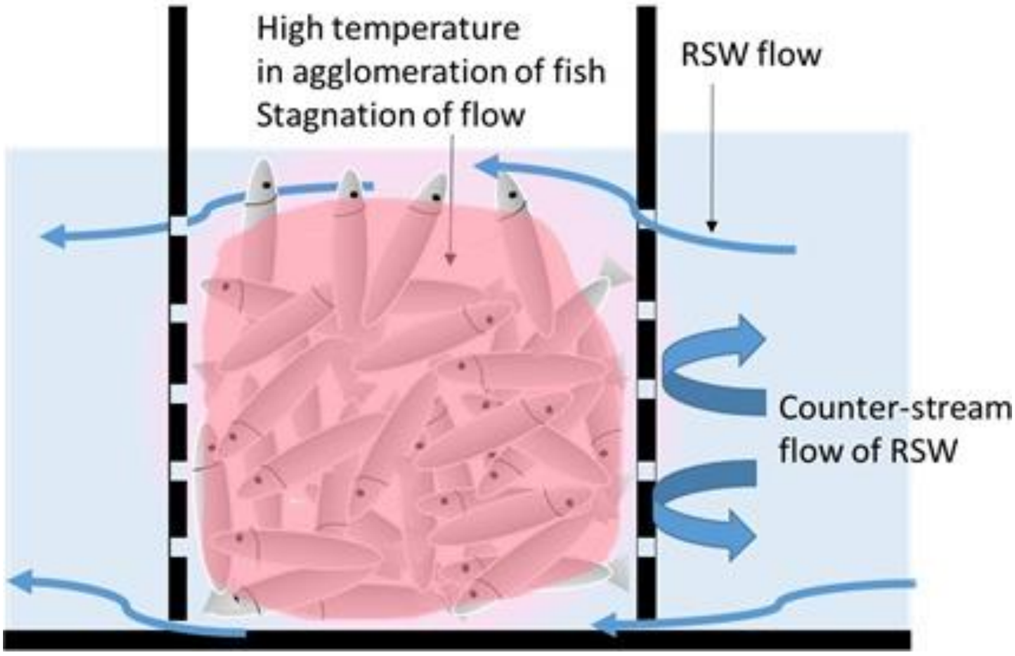

Figure 4.19 Possible result of cluster in chamber (Tolstorebrov & Widell, 2018)

4.6 Comparison of field measurements and simulations

Results from the field measurements are mostly in line with the theoretical calculations. Simulations give the same temperature for all salmon, which the field measurements show is far from the real case. This is because simulations assume every salmon has the same weight and dimensions and that all fish gets the same chilling in the tank. The field measurements showed variation in weight and dimensions, and it is natural that coincidences in the tank gives differences in chilling efficiency as salmon can go through areas of better and worse circulation. Because of the variations, one should make stricter targets for the average salmon, so that a larger share of the salmon reaches sufficient chilling.

5 Conclusion

In this thesis the chilling process of ungutted salmon in a HeliX tank were investigated. Rapid and effective chilling is desired to preserve the quality and extend the shelf life. Many factors affect how long time it takes to chill salmon to the required temperatures, for example circulation in the tank and temperature of RSW. In industry, there is high focus on produced amount of fish, so the chilling must be efficient. Numerical simulations in MATLAB revealed that thickness of the salmon has large impact on temperature development and thus also chilling time, while height and heat transfer coefficient are less important.

With the use of an equivalent radius, it is possible to model the salmon as a series of circular cylinders and analytically calculate temperatures. Because temperatures develop slightly different in circles and ellipses, this can give small errors. To reduce the effect of these errors, a particular chilling time was used to find an equivalent radius that gave a minimum of deviation around this chilling time. A chilling index was introduced as a measure to how effective a chilling process is compared to an ideal process.

Models for simulating continuous, semi-continuous and batch processes with analytical calculations were developed in EES and MATLAB. The simulations gave results for temperature of salmon and RSW, as well as heat flows and cooling load. Such simulations can be used as a tool to find how a tank should be operated to secure sufficient chilling depending on different parameters. Two different assumptions can be used in the models. At the current stage of the research, assuming constant heat transfer coefficient gives the most accurate results, but with more investigations better expressions can be found, which makes assuming constant chilling index a good option. The calculated cooling load was used for dimensioning an evaporator in a vapour-compression refrigeration cycle.

A continuous process is preferred compared to a batch process because of constant cooling load. Semi-continuous processes with parallel tanks have the same advantages, in addition to more flexibility in operation modes. This is the practice today at larger salmon slaughtering factories, and it showed good results in the simulations. Operating HeliX tanks as a continuous process is another good alternative. This can be achieved for example by reducing the rotational speed of the screw, making larger tanks or have two tanks in series.

The field experiments gave results mostly as expected. The variation in temperature and chilling index between each fish is large, which requires big number of measurements to get significant results. There is a distinct increase in RSW temperature when the salmon enters the camber, and chilling index increases with less salmon in a chamber. The average chilling index is normal, but with room for improvements. The centre temperature of salmon exiting the tank is clearly higher than what is ideal. This can be solved by increasing chilling time or decreasing RSW temperature. Since increased chilling time decreases the capacity, increasing the RSW flow is recommended if possible.

Measured RSW temperatures and observations shows that circulations in the tank could be improved. Because of blood in the RSW, observing of the salmon behaviour is difficult, but it seems that the salmon is packed together in clusters with most of the RSW flow going around. When cold RSW flows around warmer clusters of salmon, the heat exchange will be reduced and the chilling will be less efficient. By reducing the amount of salmon in the chambers, circulation will become better.

5.1 Proposal of further work

The proposals for further work are based on the results and observations from working with this thesis.

- **MATLAB simulations with real shapes instead of ellipses.** Since there is a small difference between the real cross section of a salmon and an ellipse, one can investigate how this affects the simulated temperatures. This can then be implemented in the other calculations if the effects are noticeable.
- **Improving the modelling of salmon based on average weight.** With more measurements of dimensions of salmon with different weight, one can come closer to the average salmon shape and have smaller weight spans when interpolating. One can also change from linear interpolations to a more accurate expression of how the weight changes with the dimensions.
- **Improve estimations for chilling index.** One should perform more experiments to investigate what influences the chilling index and improve the expressions used to estimate chilling index. It is especially interesting how different circulation system affect the chilling index, and currently little research has been done here. Expressions for chilling index based on average temperatures, with other filling grades than 33 %, and tanks with different sizes are yet to be done. This will improve the accuracy when simulating a HeliX tank. One can also investigate if temperatures of RSW in and out of tank can be used to calculate chilling index. If better models give good and realistic calculations of RSW temperatures, it is be possible to find a chilling index from measuring the temperature of RSW in and out of the tank. From the temperature

difference one can find heat rejected from the salmon and thus the temperature difference of the salmon. This chilling index has to be based on average temperatures of the salmon. Since the RSW temperature already is measured at HeliX tanks, this could be an easy way to calculate chilling index without any extra measurements.

- **Investigations of how the salmon behave in the tank and how this is affected by circulation systems.** By experimenting with different circulation systems and with different operation of them, one can get more knowledge of how to increase the efficiency of the chilling process. If one can do experiments where the RSW is transparent (without the blood), the behaviour of salmon is easily observed. One should aim to reduce packing of salmon in clusters and have a good mixing of salmon and RWS.
- **Integrate models with refrigeration cycle.** Vapour-compression refrigeration cycles can be modelled, and it is possible to combine such models with models of the HeliX tank. This will make it easier to see the effects of operation modes and different scenarios, not only in the HeliX tank, but also on the refrigeration cycle. It can give a better understanding of the complete refrigeration system and a better basis for deciding operation mode and designing the system.

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Appendix A: EES scripts

Continuous process script

```
"INPUT"
T_rsw=-1 "[C]"
m_dot_rsw_hour=125 "[m^3/h]"
m_dot_rsw=m_dot_rsw_hour/3,6 "[kg/s]"
m_dot_tot=33000/140/60 "[kg/s] 33000 kg in 140min"
m_avg=5 "[kg]"
T_0=9 "[C]"
h_c=10000 "[W/m^2K]"
tau=140 "[min]"
Q_dot_losses=20000 "[W]"
i_chill=m_dot_rsw_hour*0,23/135+0,56

"OTHER FIXED VALUES"
k=0,52 "[W/(m*K)]"
C_p=3600 "[J/(kg*K)]"
rho=1050 "[kg/m^3]"
C_p_rsw=4000 "[J/(kg*K)]"

a=k/(C_p*rho)

"REGRESSION COEFFICIENTS"
r_a=1,067795675
r_b=0,76256734
r_c=0,233761092

"FISH DIMENSIONS"
n=8 "numer of slices"

a_37[1..n]=[4; 8; 8; 8,6; 7,4; 7,2; 6; 4] "[cm]"
b_37[1..n]=[6; 12; 14,4; 14,6; 13,7; 13,7; 8; 6] "[cm]"
t_37[1..n]=[3,5; 5; 11; 10; 4,8; 4,5; 6,5; 6,8] "[cm]"

a_62[1..n]=[4; 10; 10,6; 11; 9,8; 8; 6,6; 4,2] "[cm]"
b_62[1..n]=[6; 12; 14,4; 17,5; 15,4; 13,1; 8; 7] "[cm]"
t_62[1..n]=[3,5; 5,5; 8,5; 14; 10,6; 6,9; 6,5; 6,3] "[cm]"

 f=(m_avg-3,7)/(6,2-3,7)

Duplicate i=1;n
  a[i]=f*(a_62[i]-a_37[i])+a_37[i] "[cm]"
  b[i]=f*(b_62[i]-b_37[i])+b_37[i] "[cm]"
  t[i]=f*(t_62[i]-t_37[i])+t_37[i] "[cm]"
End

x[1]=0
y[1]=0

Duplicate i=1;n

  r_ekv[i]=r_a*(a[i]/200)^r_b*(b[i]/200)^r_c
```

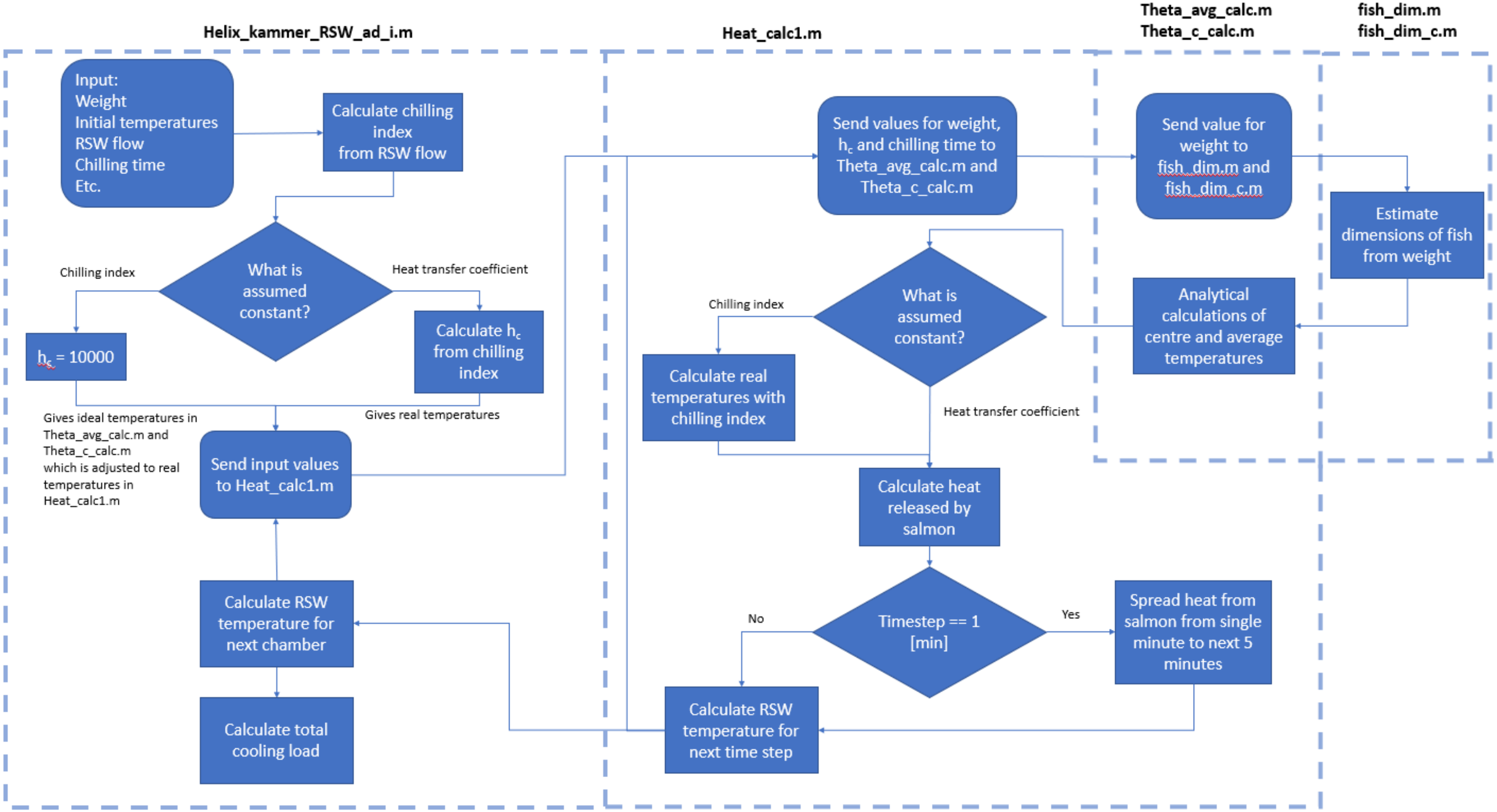
```
  Bi[i]=h_c*r_ekv[i]/k
  Fo[i]=a*tau*60/r_ekv[i]^2

  Duplicate j=1;3
         mu[i;j]=Bi[i]*(Bessel_J0(mu[i;j])/Bessel_J1(mu[i;j]))

Theta_part[i;j]=(4*Bi[i]^2/(mu[i;j]^2*(mu[i;j]^2+Bi[i]^2)))*exp(-
1*(mu[i;j]^2)*Fo[i])

  End

  Theta_slice[i]=sum(Theta_part[i;k]; k=1;3)

  x[i+1]=x[i]+PI*t[i]*a[i]*b[i]*Theta_slice[i]
  y[i+1]=y[i]+PI*t[i]*a[i]*b[i]

End

Theta_total=x[n+1]/y[n+1]
Theta_total_real=1-(1-Theta_total)*i_chill

T_total=Theta_total*(T_0-T_rsw)+T_rsw
T_total_real=Theta_total_real*(T_0-T_rsw)+T_rsw

T_diff=T_0-T_total
T_diff_real=T_0-T_total_real

Q_dot=T_diff*C_p*m_dot_tot+Q_dot_losses
Q_dot_real=T_diff_real*C_p*m_dot_tot+Q_dot_losses

T_rsw_diff=(Q_dot+Q_dot_losses)/m_dot_rsw/C_p_rsw
T_rsw_diff_real=(Q_dot_real+Q_dot_losses)/m_dot_rsw/C_p_rsw
```

Batch process script

```
"INPUT"
T_rsw=-1 "[C]"
m_dot_rsw_hour=125 "[m^3/h]"
m_dot_rsw=m_dot_rsw_hour/3,6 "[kg/s]"
m_rsw=67000 "[kg]"
m_tot=33000 "[kg]"
m_avg=5 "[kg]"
T_0=9 "[C]"
h_c=10000 "[W/m^2K]"
tau=140 "[min]"
step=5 "timestep for solving T_rsw_diff"
i_chill=m_dot_rsw_hour*0,23/135+0,56
Q_dot_loss=20000 "[W]"

"OTHER FIXED VALUES"
k=0,52 "[W/(m*K)]"
c_p=3600 "[J/(kg*K)]"
rho=1050 "[kg/m^3]"
c_p_rsw=4000 "[J/(kg*K)]"

a=k/(c_p*rho)

"REGRESSION COEFFICIENTS"
r_a=1,067795675
r_b=0,76256734
r_c=0,233761092

"FISH DIMENSIONS"
n=8 "numer of slices. If this is changed, remember to set initial
guess value for mu to 3, 5 and 8"

a_37[1..n]=[4; 8; 8; 8,6; 7,4; 7,2; 6; 4] "[cm]"
b_37[1..n]=[6; 12; 14,4; 14,6; 13,7; 13,7; 8; 6] "[cm]"
t_37[1..n]=[3,5; 5; 11; 10; 4,8; 4,5; 6,5; 6,8] "[cm]"

a_62[1..n]=[4; 10; 10,6; 11; 9,8; 8; 6,6; 4,2] "[cm]"
b_62[1..n]=[6; 12; 14,4; 17,5; 15,4; 13,1; 8; 7] "[cm]"
t_62[1..n]=[3,5; 5,5; 8,5; 14; 10,6; 6,9; 6,5; 6,3] "[cm]"

 f=(m_avg-3,7)/(6,2-3,7)

Duplicate i=1;n
  a[i]=f*(a_62[i]-a_37[i])+a_37[i] "[cm]"
  b[i]=f*(b_62[i]-b_37[i])+b_37[i] "[cm]"
  t[i]=f*(t_62[i]-t_37[i])+t_37[i] "[cm]"
End

m=tau/step "number of timesteps"
T_total[0]=T_0
T_total_real[0]=T_0
deltaT_rsw_total[0]=0
deltaT_rsw_total_real[0]=0
C_1=1/(c_p_rsw*m_rsw)
C_2=m_dot_rsw*c_p_rsw*step*60
```

```
Duplicate l=1;m
  x[0;l]=0
  y[0;l]=0

  Duplicate i=1;n

      r_ekv[i;l]=r_a*(a[i]/200)^r_b*(b[i]/200)^r_c
      Bi[i;l]=h_c*r_ekv[i;l]/k
      Fo[i;l]=a*l*step*60/r_ekv[i;l]^2

      Duplicate j=1;3

mu[i;j;l]=Bi[i;l]*(Bessel_J0(mu[i;j;l])/Bessel_J1(mu[i;j;l]))

Theta_part[i;j;l]=(4*Bi[i;l]^2/(mu[i;j;l]^2*(mu[i;j;l]^2+Bi[i;l]^2))
)*exp(-1*(mu[i;j;l]^2)*Fo[i;l])

      End

      Theta_slice[i;l]=sum(Theta_part[i;k;l]; k=1;3)

      x[i;l]=x[i-1;l]+PI*t[i]*a[i]*b[i]*Theta_slice[i;l]
      y[i;l]=y[i-1;l]+PI*t[i]*a[i]*b[i]

  End
Theta_total[l]=x[n;l]/y[n;l]
Theta_total_real[l]=1-(1-Theta_total[l])*i_chill

T_total[l]=Theta_total[l]*(T_0-T_rsw)+T_rsw
T_total_real[l]=Theta_total_real[l]*(T_0-T_rsw)+T_rsw

deltaT_total[l]=T_total[l]-T_0
deltaT_total_real[l]=T_total_real[l]-T_0

deltaT_step[l]=T_total[l]-T_total[l-1]
deltaT_step_real[l]=T_total_real[l]-T_total_real[l-1]

Q_step[l]=m_tot*c_p*(-deltaT_step[l])
Q_step_real[l]=m_tot*c_p*(-deltaT_step_real[l])

Q_tot[l]=m_tot*c_p*(-deltaT_total[l])
Q_tot_real[l]=m_tot*c_p*(-deltaT_total_real[l])

deltaT_rsw_step[l]=C_1*(Q_step[l]+Q_dot_loss*step*60)-
C_1*C_2*(deltaT_rsw_total[l-1]+deltaT_rsw_total[l])/2
deltaT_rsw_step_real[l]=C_1*(Q_step_real[l]+Q_dot_loss*step*60)-
C_1*C_2*(deltaT_rsw_total_real[l-1]+deltaT_rsw_total_real[l])/2

deltaT_rsw_total[l]=deltaT_rsw_total[l-1]+deltaT_rsw_step[l]
deltaT_rsw_total_real[l]=deltaT_rsw_total_real[l-
1]+deltaT_rsw_step_real[l]

T_rsw_out[l]=T_rsw+deltaT_rsw_total[l]
T_rsw_out_real[l]=T_rsw+deltaT_rsw_total_real[l]
End
```

Appendix B: MATLAB flow chart



Appendix C: Results, field experiment 1

	(+/- 2 min)	(+/- 0,1C)	(+/- 2 mm)	(+/- 1 cm)		(+/- 2 min)	(+/- 0,1C)							
Nr	Kl _inn	T_inn [C]	Bredde [cm]	Høyde [cm]	Kammer	Kl_ut	T_ut [C]	Tau [min]	T_RSW	Theta_real	r_ekv [m]	Fo	Theta_ideal	i_chill
1	09:32	12,8	10,3	18	12	11:03	8,6	91	1,82894382	0,61717451	0,0632077	1,88E-01	0,53518042	0,8236002
2	09:33	12,7	9,5	17	12	11:02	7,3	89	1,82894382	0,50326814	0,05885528	0,21207129	0,46682677	0,93165192
3	09:34	12,8	10,4	18	12	11:04	8,9	90	1,82894382	0,64451918	0,06365046	0,18335898	0,54935296	0,78882314
4	09:34	12,8	10,3	18	12	11:15	7,9	101	1,82894382	0,55337026	0,0632077	0,20866242	0,47599563	0,85233972
5	09:35	12,8	9,9	17	12	11:06	8	91	1,82894382	0,56248515	0,06063539	0,20429225	0,48799418	0,85451148
6	09:37	12,8	8,5	17	11	11:24	5,2	107	1,82894382	0,30726815	0,05431084	0,29941499	0,28223124	0,96511842
7	09:38	13,0	8,5	17	11	11:10	8,5	92	1,82894382	0,59717327	0,05431084	0,25744092	0,35971913	0,62914066
8	09:39	12,9	9,1	17	11	11:11	7,9	92	1,82894382	0,54837191	0,05705425	0,23327843	0,4134182	0,769932
9	09:39	12,7	8,8	17	11	11:08	6,8	89	1,82894382	0,45727444	0,05568904	0,23687182	0,40496708	0,91209332
10	09:40	12,7	8,8	17	11	11:18	6,4	98	1,82894382	0,42047949	0,05568904	0,26082515	0,35276299	0,89537604
11	09:42	12,9	8,8	17	10	11:19	6,8	97	1,49755	0,46502725	0,05568904	0,25816367	0,35822237	0,83357961
12	09:42	12,0	8,8	16	10	11:17	6,7	95	1,49755	0,49535585	0,05493048	0,25987209	0,35470851	0,78204062
13	09:43	12,8	8,6	16	10	11:54	4,2	131	1,49755	0,23910303	0,05402565	0,37045379	0,1870207	0,93593647
14	09:44	12,7	8,6	16	10	11:20	7,3	96	1,49755	0,51796259	0,05402565	0,27147759	0,33171808	0,72130847
15	09:44	12,8	8,7	16	10	11:16	6,3	92	1,49755	0,42490345	0,05447879	0,25585609	0,36302269	0,90285249
17	09:46	12,8	9,6	18	9	11:26	8,1	100	1,49755	0,58416096	0,06007403	0,22871214	0,42440211	0,72244712
18	09:47	12,8	8,4	16	9	11:31	5,1	104	1,49755	0,31873178	0,05311497	0,3042722	0,2744073	0,93891273
20	09:48	13,2	8,7	16	9	11:25	8	97	1,49755	0,5556486	0,05447879	0,26976132	0,33502329	0,66822099
21	09:50	12,9	8,5	15,5	8	11:29	6,9	99	1,48947403	0,47416973	0,05318766	0,28885254	0,30001728	0,75120465
22	09:50	12,8	8,8	16	8	11:30	6,2	100	1,48947403	0,41647276	0,05493048	0,27354957	0,3277706	0,86804779
24	09:51	12,8	8,8	17	8	11:29	5,6	98	1,48947403	0,36342483	0,05568904	0,26082515	0,35276299	0,98352715
25	09:51	12,8	8,7	17	8	11:32	5,8	101	1,48947403	0,38110747	0,05523111	0,27328554	0,32827104	0,92134263
26	09:54	12,8	8,3	16	7	11:33	6,5	99	1,60036765	0,43748153	0,05265737	0,29469964	0,29003837	0,79232234
28	09:55	12,8	9,5	18	7	11:34	8,8	99	1,60036765	0,64284542	0,05962127	0,229877	0,42157385	0,61745925
29	09:56	12,8	9,1	17	7	11:32	6,9	96	1,60036765	0,47319699	0,05705425	0,24342097	0,38999143	0,86359935
31	09:59	12,8	8,2	16	6	11:36	7	97	1,60036765	0,48212586	0,05219825	0,29384798	0,29147111	0,73091464
32	09:59	12,8	8,9	16	6	11:40	6,2	101	1,60036765	0,41069494	0,05538075	0,2718107	0,33108029	0,88098026
33	10:00	12,8	8,5	16	6	11:38	7,2	98	1,60036765	0,49998359	0,05357105	0,28185678	0,31240403	0,72719509
34	10:00	12,8	9,0	16,5	6	11:39	7	99	1,60036765	0,48212586	0,05621962	0,25853668	0,35745227	0,80596992
35	10:01	12,8	8,5	16	6	11:37	6,1	96	1,60036765	0,40176608	0,05357105	0,2761046	0,32296656	0,8836106
36	10:03	12,8	7,9	14,5	5	11:39	5,3	96	1,77055085	0,32000231	0,04969237	0,32088885	0,24923625	0,90574124
37	10:03	12,9	9,1	17	5	11:43	6,9	100	1,77055085	0,46088976	0,05705425	0,25356351	0,36785411	0,85282566
38	10:04	12,8	8,7	16	5	11:41	7,8	97	1,77055085	0,5466682	0,05447879	0,26976132	0,33502329	0,68172583
40	10:05	12,8	8,8	16	5	11:43	5,9	98	1,77055085	0,37440212	0,05493048	0,26807858	0,33829539	0,94543376
41	10:08	12,8	8,5	16	4	11:45	6,8	97	1,77055085	0,45600184	0,05357105	0,27898069	0,31764194	0,7972327
42	10:09	12,8	8,7	17	4	11:44	7,4	95	1,77055085	0,51040166	0,05523111	0,25705076	0,36052969	0,76563107
43	10:09	12,8	9,1	17	4	11:49	7,1	100	1,77055085	0,48320175	0,05705425	0,25356351	0,36785411	0,81753002
45	10:10	12,7	9,5	17,5	4	11:46	7,5	96	1,77055085	0,52422122	0,05924251	0,22577045	0,43162546	0,83708673
46	10:12	12,9	8,6	16	3	11:55	6,5	103	1,3875098	0,44408205	0,05402565	0,29127283	0,29584609	0,78948359
47	10:13	12,7	9,2	16,5	3	11:52	6,5	99	1,3875098	0,45193323	0,05711947	0,25045496	0,37450547	0,87621354
48	10:13	13,0	9,1	17	3	11:51	7	98	1,3875098	0,48331496	0,05705425	0,24849224	0,37876537	0,83170676
49	10:14	12,8	9,3	18	3	11:54	7,6	100	1,3875098	0,54435886	0,05871176	0,23944877	0,39900927	0,75815003
50	10:14	12,8	8,3	15,5	3	11:51	5	97	1,3875098	0,3165383	0,05228052	0,29292384	0,29303372	0,96675291
51	10:16	12,7	8,5	16	2	11:57	6,8	101	1,5547234	0,47062776	0,05357105	0,29048505	0,29719742	0,75323036
52	10:17	12,8	9,1	17	2	11:58	7,6	101	1,5547234	0,53758363	0,05705425	0,25609914	0,36251414	0,7253751
53	10:17	13,0	8,4	15,5	2	11:59	5,6	102	1,5547234	0,35344507	0,05273484	0,30273852	0,27685418	0,89408652
54	10:18	12,8	9,5	17	2	11:56	7	98	1,5547234	0,48422789	0,05885528	0,2335167	0,4128526	0,87843719
55	10:18	12,8	9,4	17,5	2	11:56	7,6	98	1,5547234	0,53758363	0,05879131	0,23402517	0,41164812	0,78595206

Appendix D: Draft of scientific paper

Introduction of chilling index

1 Abstract

When slaughtering salmon, effective and rapid chilling is required to preserve the quality and extend shelf life. As a measure to the efficiency of a chilling process, a chilling index is introduced. It compares the temperature reduction in a real chilling process to the temperature reduction in an ideal process with the same parameters. The ideal temperature is calculated analytically with an infinite heat transfer coefficient. This makes the chilling index a good tool to see if a chilling process can be improved by increasing the heat transfer coefficient.

The chilling index is influence by many factors. For a given chilling process, the chilling index will change with time, and the chilling index is different if calculated with centre temperature or average temperatures. When the heat transfer coefficient is low, it can have a large influence on the chilling index, but when exceeding 200 W/m^2K, the influence is almost neglectable.

In a chilling tank the RSW temperature can vary. It is important to know what RSW temperature is used for calculating the chilling index, because this affects the chilling index. If the RSW temperature used in the calculations is different from the RSW at the position of the salmon, there may be errors in the calculations.

2 Introduction

Farmed salmon are Norway's third largest export article. The total first-hand value of farmed salmon in 2017 was 61,6 billion NOK, and the total production in 2017 was 1 238 354 metric tons (Statistics Norway, 2018). This makes Norway the largest producer of salmon in the world, with a global production share of 53 % in 2016 (Almås & Ratvik, 2017).

Aquaculture salmon are live transported to slaughterhouses, with a temperature close to the sea temperature. Biological decomposition processes that reduces the quality of the fish begins at the moment of death. Rapid chilling is important in order to slow down these processes as early as possible, perceive the quality of the fish and maximize yield. Bacterial growth is reduced and shelf life will increase (Skjervold et al., 2001). When slaughtering salmon, chilling that reduces the temperature in the thermal centre below 4ºC are acceptable, but ideally the temperature should be close to 0ºC (Bantle, Digre, & Tobiassen, 2015)

Many factors affect how long time it takes to chill salmon to the required temperatures, for example, size of the salmon, circulation in the chilling tank and temperature of the cooling media, RSW. In industry, there is high focus on produced amount of fish, so the chilling must be efficient. Chilling processes for salmon can have great variations in parameters such as initial temperature, RSW flow and fish size. These parameters strongly influence the final temperature. To compare different chilling processes, and give a measure to their efficiency, dimensionless temperatures is used, and a chilling index is developed. It compares the temperature reduction in a real chilling process to the temperature reduction in an ideal process with the same parameters.

3 Methods

3.1 Formulas

The initial temperature difference between salmon and RSW can be used to define a dimensionless temperature, θ, so that θ = 1 at the initial conditions, and θ = 0 when the chilling process has reached equilibrium.

$$\theta = \frac{T - T_{RSW}}{T_0 - T_{RSW}} \tag{3.1}$$

Where T and T_0 is current and initial temperature of the salmon.

The dimensionless temperature is, for å given chilling process, independent on the real temperatures. When found, it is a good tool to find what initial temperature is required to reach a specified final temperature.

Due to large variations in parameters influencing the result of a chilling process, both real and dimensionless temperatures, it is necessary to find another measure to be able to compare different processes. Therefore, a chilling index is developed using the temperature in the thermal centre of a salmon. The chilling index is the ratio of the temperature decline in a chilling process to the temperature decline in a corresponding ideal process, and is defined with dimensionless centre temperatures like this:

$$i_{chill} = \frac{1 - \theta_{real}}{1 - \theta_{ideal}} \tag{3.2}$$

If using real temperatures, the expression will be:

$$i_{chill} = \frac{T_0 - T_{real}}{T_0 - T_{ideal}} \tag{3.3}$$

This way, i_{chill} = 1 if the real centre temperature is equal to the ideal centre temperature, and i_{chill} = 0 if there is no chilling at all.

3.2 Ideal chilling process

Chilling of salmon in RSW consists of convective heat transfer between the RSW and the surface of the salmon, and conductive heat transfer within the salmon itself. The conductive heat transfer is decided by the thermal conductivity of the fish, k, which in many cases can be considered constant and unchangeable.

$$\dot{Q} = Ak\frac{-dT}{dx} \tag{3.4}$$

Where A is an area normal to the heat flow and x is the direction of the heat flow

Convective heat transfer is described by Equation (3.5):

$$\dot{Q} = A_{surface}h\left(T_{surface} - T_{RSW}\right) \tag{3.5}$$

Where h is the heat transfer coefficient and is dependent on fluid properties and flow regime and can vary significant for different chilling processes. (insert references to values and changes of heat transfer coefficient). It has been shown that for a heat transfer coefficient larger that 200 W/m^2K, (Take scentence from master thesis) because the chilling will be limited by resistance in the internal heat transfer.

The ideal temperature used for calculating chilling index is defined to be the resulting temperature from a chilling process where the heat transfer coefficient is infinite, and the other parameters equal to that of the real chilling process. This makes the chilling index a good tool to see if a chilling process can improve by increasing the heat transfer coefficient. A chilling index close to 1 indicates that a chilling will not improve with higher heat transfer coefficient, and that other parameters, such as RSW temperature and chilling time, has to be changed in order to reduce temperature of salmon after chilling.

The ideal temperature can be calculated with numerical simulations of a chilling process, or analytically. Analytical calculations require that salmon is modelled as a geometry where formulas are known, for example infinite cylinder.

3.3 Chilling time

For a process, the chilling index is connected to the chilling time. The chilling index will change with the chilling time and is most likely to increase with longer chilling times. This is shown with Figure 3.1, where a constant chilling index of 0.6 is assumed. This leads to a stagnation of temperature at Θ = 0.4. The temperature difference compared to RSW cannot be sustain over time, since the temperatures eventually will equalize. When average and centre temperatures are reduced compared to what is shown in Figure 3.1, the chilling index will increase.

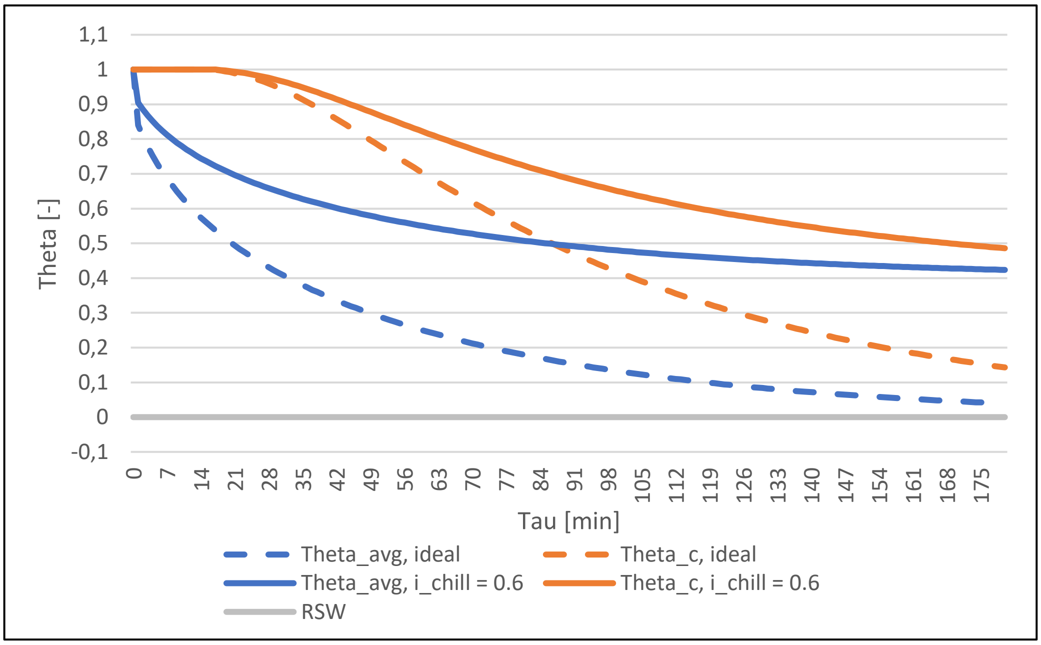


Figure 3.1 Centre and average temperature with constant chilling index

3.4 Temperatures

Chilling index is originally defined with centre temperatures, but also average temperature of salmon can be used. This is useful when heat and heat flows are to be quantified, because the total heat released by a fish is proportional to the difference in average temperature. Centre temperatures are closer to the initial temperature for a given time. This makes the relative difference between numerator and denominator in Equation (3.2) and (3.3) larger than compared to average temperatures, and thus using centre temperatures gives a smaller chilling index.

A challenge when working with chilling index is that RSW temperature can change, both with time and position of measurement. Calculations of ideal temperature is usually based on a constant RSW temperature, while this might not be the case in real processes. Using lower a lower RSW temperature when calculating gives a lower chilling index. For example, the temperature of RSW into a chilling tank is lower than for RSW exiting. In a HeliX tank in normal operation it was measured a RSW temperature difference up to 2.5 °C between inlet and outlet, and in some chambers it was measured temperatures 3.5 °C higher than at RSW intlet. What RSW temperature to use is often decided by what measurements is available. Because of the influence this can have on the chilling index, it is important to be aware of what temperature is used.

4 Results and discussion

Depending on the initial temperature and the size of the salmon, the required chilling index to reach centre temperatures of 4 ºC after 90 minutes of chilling can vary a lot. For small salmons and winter temperatures, the required chilling index is down to 0.3, while it can be up to 1.5 for large salmons in summer temperatures. It means that for the last case, 90 minutes is too short time to reach optimal temperatures.

4.1 Influence of heat transfer coefficient on chilling index

One of the factors that affect the chilling index is the heat transfer coefficient. As stated in Chapter 3.2, the heat transfer coefficient is dependent on the RSW flow regime. Higher velocity of RSW over the salmon surface increases the heat transfer coefficient. The RSW velocity varies a lot in a chilling tank, but higher RSW flow through the tank will in general increase the velocity. Injecting high velocity RSW through nozzles along the tank is another measure. This will stir the salmon so that clusters are broken and the salmon gets more exposed to the RSW flow.

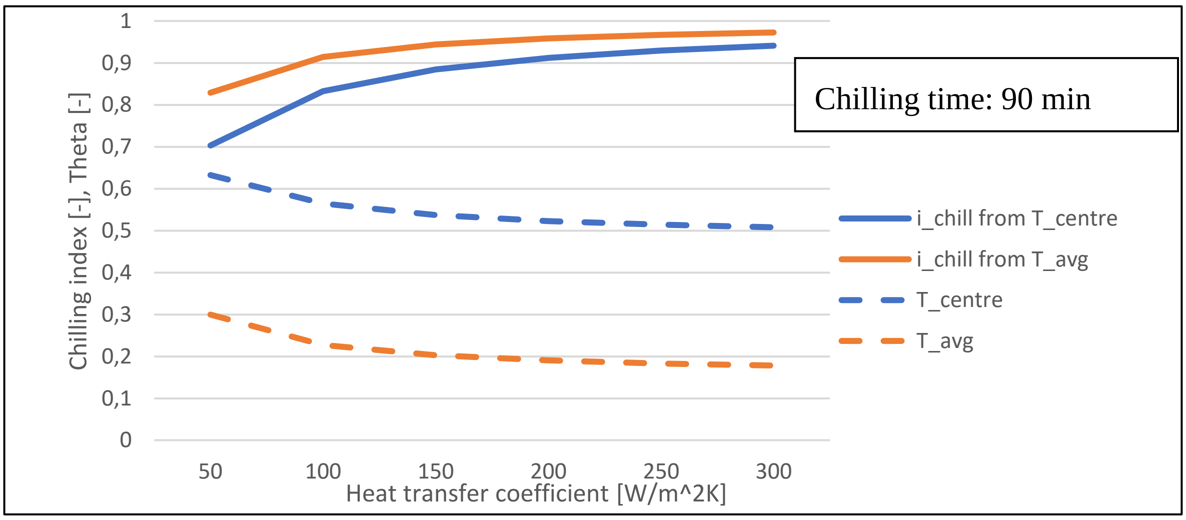


Figure 4.1 Influence of heat transfer coefficient

Figure 4.1 shows how temperatures and chilling indexes changes with the heat transfer coefficient. As can be seen, the influence of the heat transfer coefficient is greater for lower values, and when it exceeds 200 W/m^2K the influence is almost neglectable. As the chilling indexes are close to 1, they cannot increase much, no matter how grate the heat transfer coefficient becomes.

4.2 Influence of RSW temperature on chilling index

Figure 4.2 shows how a chilling index changes depending on what RSW temperatures is used in the calculations. In a chilling tank, the temperature of RSW can change depending on position and time, and the chilling index will change depending on what RSW temperature is used. As the figure show, if a high RSW temperature is used, it is possible to calculate a chilling index higher than 1. This should be impossible, and indicates that the real RSW temperature where the salmon is chilled is lower than what is used for the calculations.

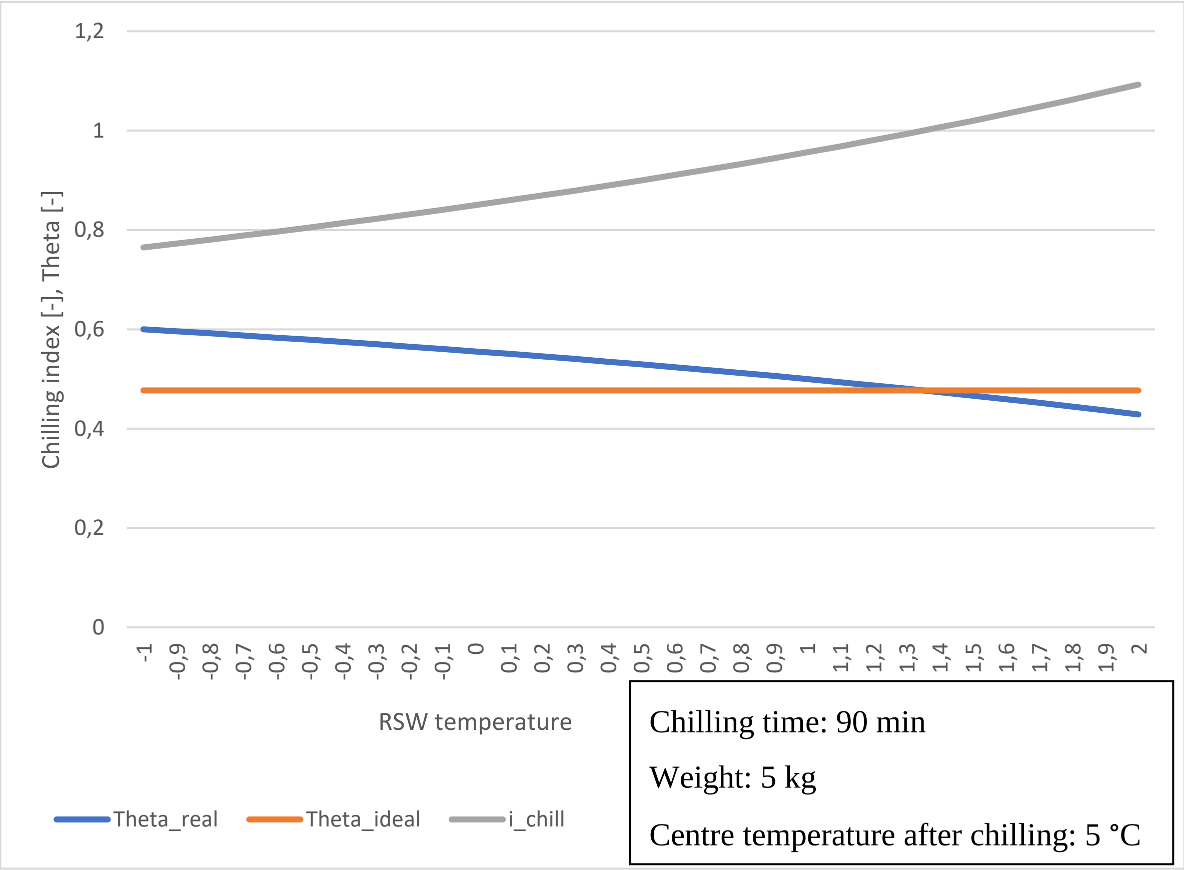


Figure 4.2 RSW temperature influence on chilling index

4.3 Influence of chilling time on chilling index

Figure 4.3 shows the temperature development in a process where the chilling index is constant, compared to a process with constant heat transfer coefficient. If one assumes that constant heat transfer coefficient gives correct results, one can see that constant chilling index gives too low temperatures in the beginning of the process, and too high temperatures at the end. This means that the constant chilling index is too high at first, and later becomes too low. This means that the real chilling index will increase through the chilling time.

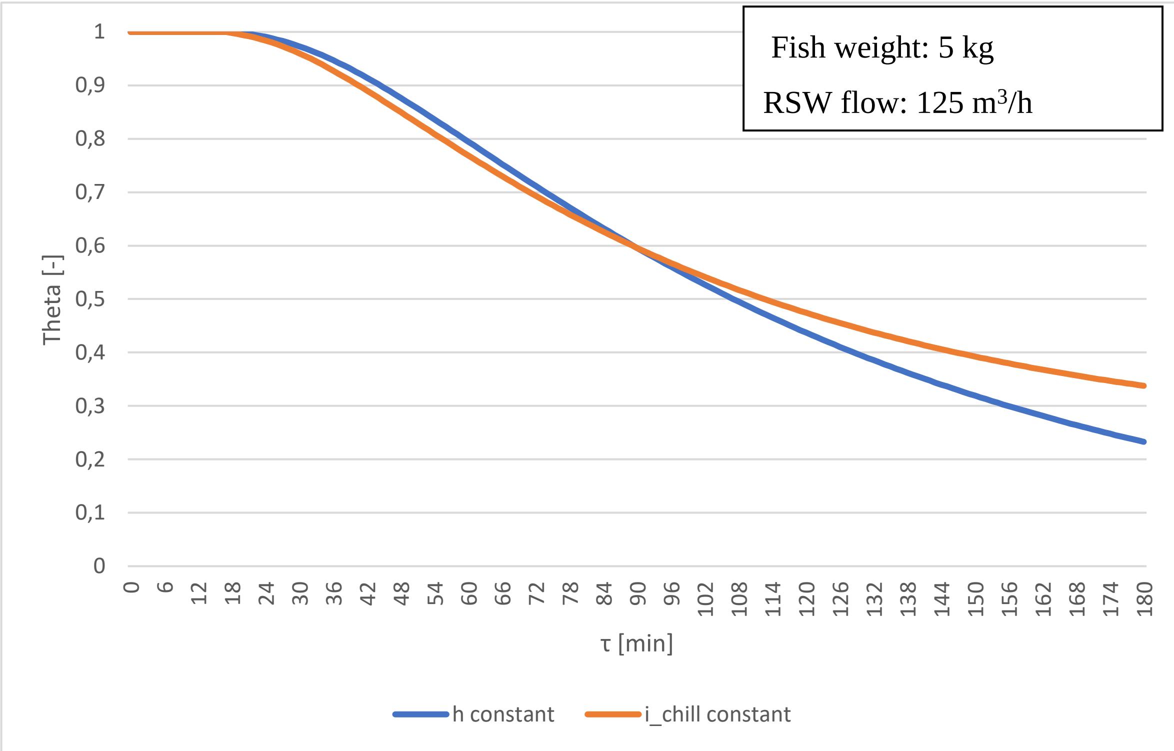


Figure 4.3 Average temperature assuming constant h and i_{chill}

5 Conclusions

The chilling index is introduced to measure the efficiency of a chilling process. Since effective and rapid chilling is important when slaughtering salmon, the chilling index can be a tool to investigate possibilities to improve the chilling process. The chilling index is different if calculated with centre or average temperatures, and for a given cooling process it will increase with time.

At low values, the heat transfer coefficient has a significant influence on the chilling index. The influence decreases with increasing heat transfer coefficients and is almost neglectable for values over 200 W/m^2K. Choosing the correct RSW temperature can be a challenge when calculating a chilling index, but it is essential when accurate results are desired. If correct RSW temperature is not known, it is important to be aware of what RSW temperature is used, to have in idea of how this might have influenced the results.

This paper present results based on simulations in MATLAB. Since the chilling index is based on a measured temperature, the results should be compared to experiments with a real cooling tank. This can confirm these results or show a mismatch between simulations and real measurements. A mismatch would indicate the need of improving the simulations.

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