SINTEF Energi AS
SINTEF Energy Research
Address:

NO-
NORWAY

Telephone:+47 73597200
Telefax: +47:

energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

Project memo

State of the art: Chilling of salmon in industrial production

Subtitle

VERSION
1

DATE
2014-09-01

AUTHOR(S)
Ignat Tolstorebrov; Michael Bantle

CLIENT(S)
FHF

CLIENTS REF.
Kristian Prytz

PROJECT NO.
502000749

NO. OF PAGES AND APPENDICES:
24 + appendices

ABSTRACT

Methods, requirements and limitations for industrial chilling of Salmon are reviewed. The chilling is influence by several parameters: seasonal variation for temperature, short pre-rigor time, quality requirements, low thermal conductivity of salmon, different heat transfer coefficient for different system, high mass flow, thickness of the salmon, development of a temperature profile during chilling.
Dimensioning parameters are mostly based on experience and experiments, since it is difficult to account for the variations in the process and the product.

PREPARED BY
Ignat Tolstorebrov

SIGNATURE

APPROVED BY
Michael Bantle

SIGNATURE

PROJECT MEMO NO.
TekSlakt SE.1

CLASSIFICATION
Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
1	2014-09-01	State of the art, as presented and discussed at workings-session of the project "TekSlakt"; 01.09.2014

Table of contents

APPENDICES

"[List appendices here]"

1 Introduction

The report is summing up technologies, which can be applied for chilling of Salmon. The report is focused on the efficiency of the heat exchange process and decreasing the chilling time. The last factor is the most important, because high temperature of the fish leads to rapid rigor-mortis changes in the tissues and low quality of the fillet as a result. Sea temperature in the Norwegian water is relatively high during summer and relatively low during winter, Figure 1. Thus the effective and adequate chilling of the fish before packing is an essential question, especially in the summer season.

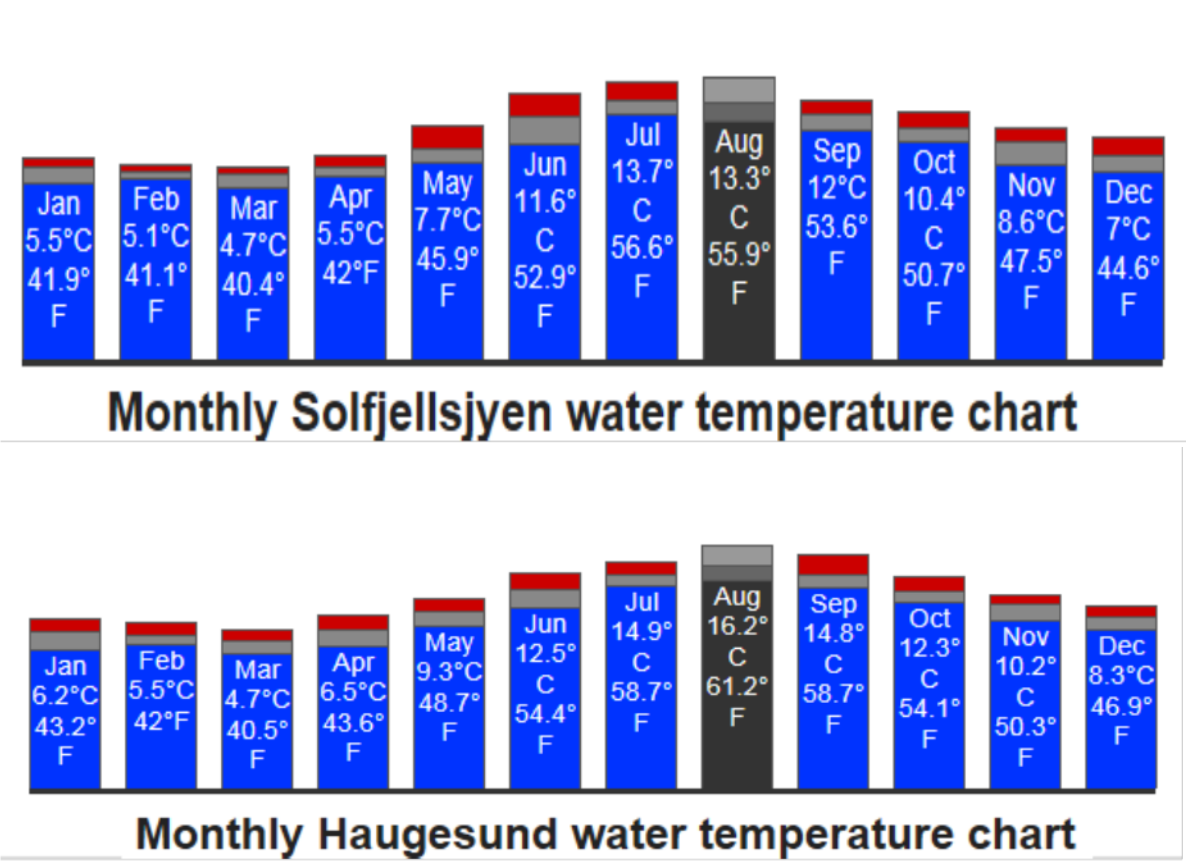

Figure 1. Temperature chart in the Norwegian water during a year. (http://www.seatemperature.org)

It is required that the temperature of the slaughtered salmon before it is packed is between 0-2°C. For filets the requirements can be even lower (between -2°C and 0°C). Hence the capacity of the chilling process is larger in summer compare to winter conditions. If the chilling equipment is designed for summer conditions it will be running at lower capacity in winter. Every chilling system has normally an optimum operational point, where it runs energy efficient. Hence, summer-designed chilling equipment will normally work not energy efficient in winter, even when the fish chilled according to the requirements. On the contrary: if the chilling equipment is designed for winter conditions (or averaged seasonal conditions) it will not have the capacity to fulfil the temperature requirements for summer salmon. The statistics devoted to the quality of the processes salmon during the years shows significant decreasing of the quality of fillets during the summer time, Figure 2.

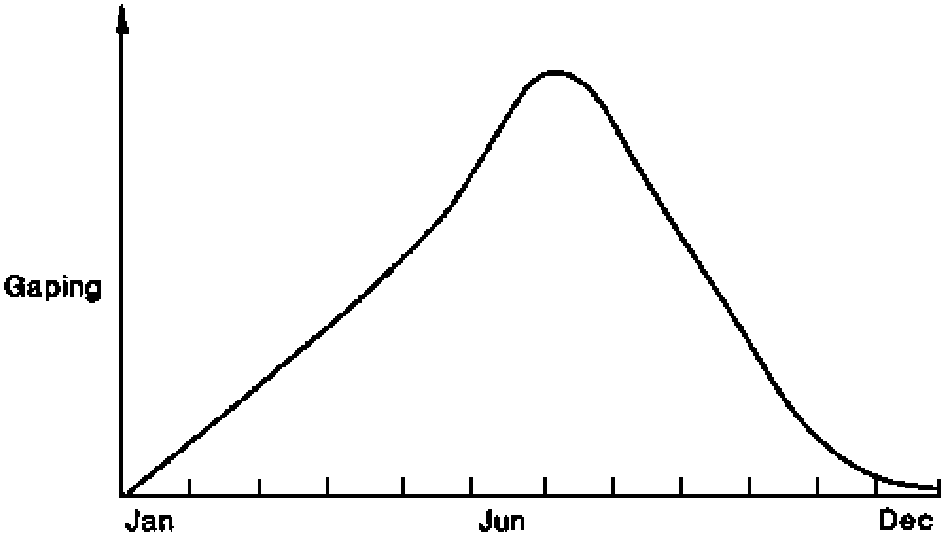

Figure 2. The development of gaping score during the year for Atlantic Salmon (fao.org)

One of the reasons for such increasing of the gaping score can be insufficient chilling of the fish during summer time.

At normal production conditions the alive fish is given time to restitution, after the transportation from the fish farm. However, before the fish is pumped into the processing line for slaughtering the fish is forced into larger crowds, by reducing the free volume for swimming ("trenging"). This causes a significant amount of stress for the fish. Under this condition, the rigor-mortis can appear already after 2-3 hour because fish will be stressed, which gives an additional requirements for rapid (extra-rapid) chilling of fish. Rigor mortis leads to decreasing the fish quality, high gapping score of fillet, high drip losses and low water holding capacity. It is a commonly accepted that the fish should be chilled according to the temperature requirements before pre-rigor, in order to avoid mechanical stress during fish handling and transport due to chilling/packaging. The short pre-rigor time is therefore an important dimensioning factor for chilling.

This report includes immersion and non-immersion methods for slaughtered fish, which are already in use by industry. Additionally current methods for chilling of salmon before slaughtering are described. The Aim is to understand the further investigations in the area of salmon chilling at the conditions of high fish weight (over 5 kg) and high biomass flow during processing (12 tons per hour).

2 Thermodynamic limitations

Chilling (or heating) is a process which is controlled by common thermodynamic physics. Equation 1 shows how the mass (m), the specific heat capacity of the product (c_p) and the temperature difference (ΔT) are defining the heat $\dot{q}$ or (when the mass flow $\dot{m}$ of the product is used) heat flow (Q).

$$\dot{q} = m * c_p * \Delta T \quad [Ws]$$
$$Q = \dot{m} * c_p * \Delta T \quad [W] \qquad [1]$$

This equation can be used to identify the minimum requirement for the chilling capacity for a certain mass flow of salmon. Heat losses, etc. need to be added to this. Based on this equation the chilling capacity cannot be influenced, since the specific heat capacity is defined thermal property and the (adiabatic) temperature difference is the difference between the required salmon temperature at the outlet and the defined temperature of the salmon at the inlet. However, one could influence the mass to be chilled, by gutting the salmon or removing of the head before chilling.

Equation 2 shows the heat between two different media (in or case salmon and a chilling agent) is exchanged.

$$\dot{Q} = k * A * \Delta T$$
$$with \ \frac{1}{k} = \frac{1}{\alpha} + \frac{s}{\lambda} + \cdots \qquad [2]$$

The transferred heat is defined by the temperature difference (ΔT) between the salmon (surface) and the chilling agent. Note: This is not the same the temperature difference from equation 1. Further the area (A) of the salmon through which the heat is exchanged and the summed up heat transfer resistance (k-factor). The k-factor is in the most cases the sum of the heat transfer coefficient (α) between salmon and chilling agent and the thermal conductivity (λ) and the thickness (s) of the salmon through which the heat travels (vertical to the area).
Based on equation 2 several different measures to influence the chilling of salmon can be evaluated, with focus on decreasing the chilling time:

a. The temperature of the chilling agent (air, water, sea-water, ice-slurry,…) can be decreased in order to increase the temperature difference to the product. With this measure it will be possible to transfer more heat in less time. However there is a good chance that the surface of the salmon will freeze (super-chilling =partial freezing of the product). It has to be discussed if this is acceptable with respect to product quality and other requirements.
b. The area for the heat exchange is normally well defined by the geometry of the salmon. However it is possible to increase the specific area (how much m^2 per kg_{salmon}), by e.g. gutting the fish before chilling or filleting. With that also the thickness (s) of the material to be chilled will be reduced

c. Reducing the thickness (s) through which the heat needs to travel, by gutting or fileting the salmon.
d. Increase the external heat transfer coefficient (α) by using chilling technology which result in higher heat transfer coefficient. However, the thermal conductivity (λ) of salmon is a limiting factor the heat transfer as well and is becomes the more dominant factor in the k-factor, when the heat transfer coefficient (α) is increased.

In the following some of these measures are described.

2.1 Chilling alive and dead salmon (apparent thermal conductivity)

The thermal conductivity is a thermal properties and normally constant. However under identical chilling conditions living salmon is chilled faster than salmon which was put to death (Figure 2). This can be explained by blood circulation in the living salmon, which is helping to transport the cold-heat into the fish muscle. The apparent thermal conductivity is therefore increased due to the blood circulation. This is the only way to improve the thermal conductivity of salmon, which is otherwise constant.

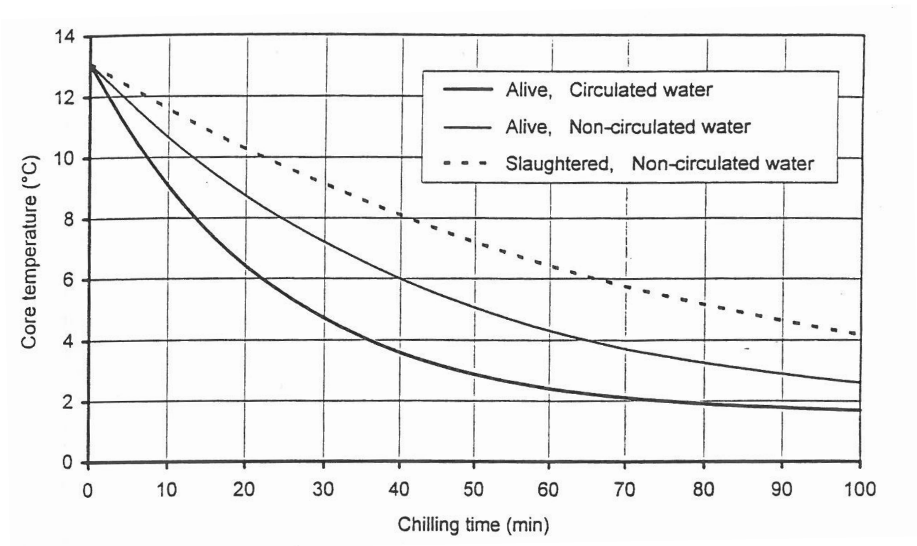

Figure 2: Core temperature of live and slaughtered salmon in different chilling conditions. [Reference]

2.2 Influence of the area for heat exchange

The specific area (in m^2/kg) is in general larger small particles/salmons, hence also the area for heat exchange is larger for the same mass flow of small salmons compare to large salmons. This results in a significant reduction of chilling time for small salmon, as illustrated in Figure 3.

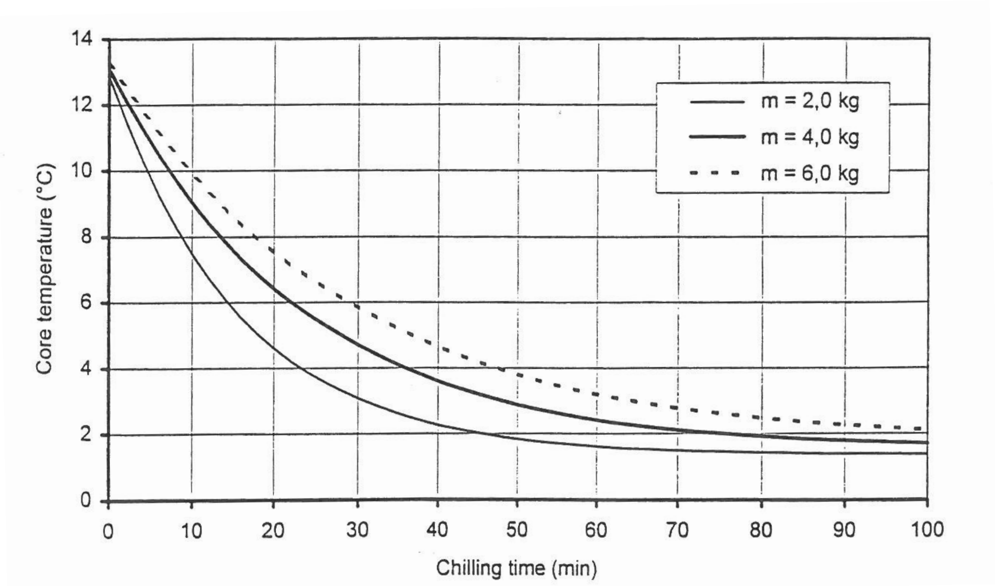

Figure 3. Core temperature of salmon with different weight under identical chilling conditions. [Reference]

2.3 Temperature difference between salmon and chilling agent

The temperature difference between the salmon (surface of the salmon) and the chilling agent is one of the main driving forces for the heat exchange. During chilling a temperature profile develops in the fish filet, as illustrated in Figure 4. When the surface temperature of the fish is almost equal to the temperature of the chilling agent, the heat transfer basically stops. In this situation it is no longer possible to chill the fish further, even when the flow of chilling agent is increased. It is than necessary to give the salmon time to balance its internal temperature profile, before it can be chilled further.

The developed temperature profile in a salmon is also shown for one example in Figure 5. The temperature of the salmon after approximately 2 hours was 3°C. However, the fish was only chilled in seawater for 1 hour, during which a large temperature profile was developed. After this it was no longer possible to remove heat from the fish, due to the not existing temperature difference between the surface and the seawater.

From the energetic point of view it is effective to section the chilling process into active chilling times followed by a certain "resting" time for temperature equilibration. This could be e.g. pre-chilling before slaughtering, main chilling direct after slaughtering and final chilling in storage.

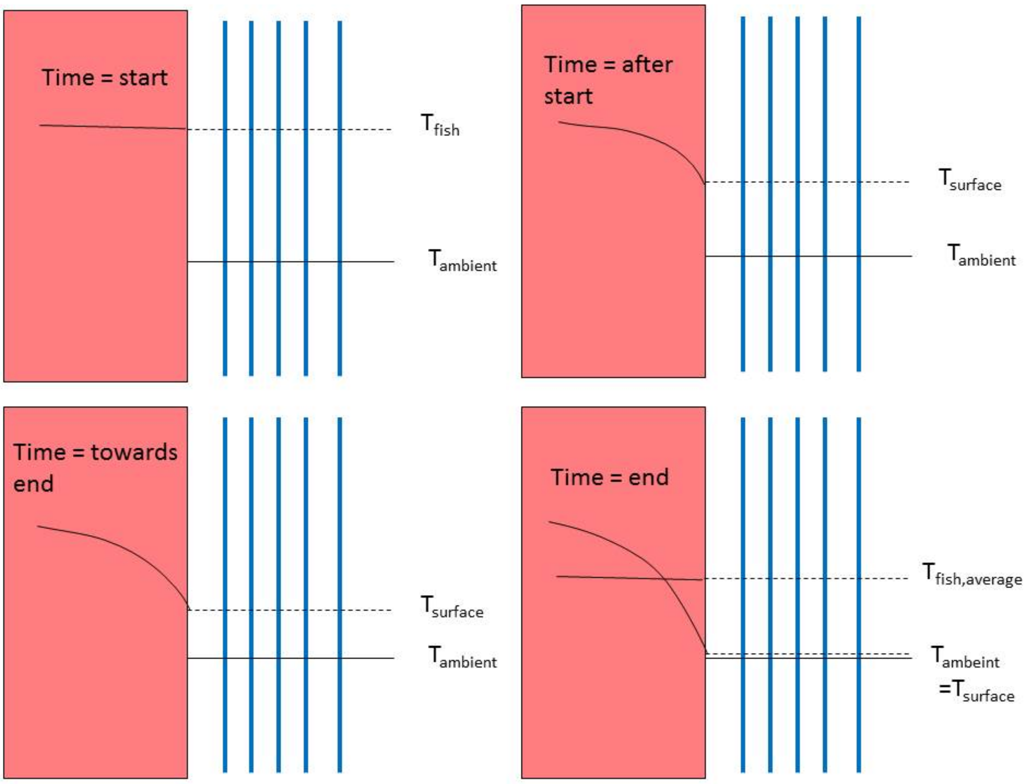

Figure 4. Temperature profile in the fish muscle during chilling.

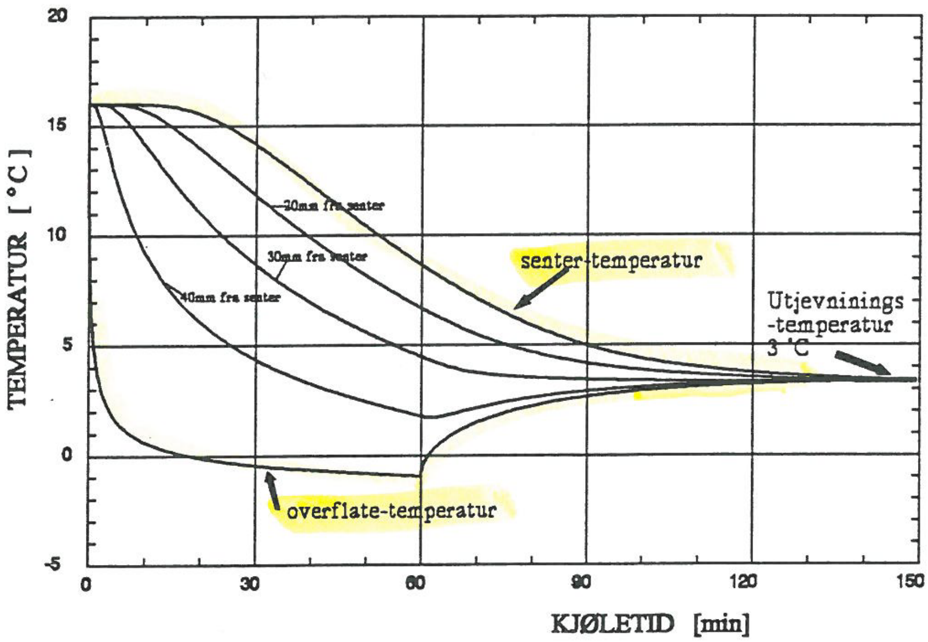

Figure 5. Temperature profile in a salmon while chilling in seawater (-1.5°)

3 Chilling of alive Salmon

As soon as average temperature of sea water in Norway is relatively high (between 14.0 and 20.0 °C), the chilling process begins before slaughtering process. This helps to:

1. decrease refrigeration load during filleting and packaging,
2. immobilize the fish and
3. increases quality of fillet. The decreasing of the fish temperature can postpone rigor-mortis changes in fish tissues up to 24.0 hours, because all natural reactions of fish will be slow down by temperature decreasing. Desirable temperature of fish body should be in the range between 0.0 and +2.0 °C.

However existing technology does not prevent excessive stress of fish during handling, which make positive effect of pre-slaughter and after-slaughter chilling negligible. The reason for that can be crowding of fish, high temperature gradient during alive chilling and large biomass streams (Ulf Erikson, 2008). Thus the analysis of the latest achievements the handling of Salmon before slaughtering is essential.

3.1 European requirements for fish slaughtering

The type of slaughtering is important for understanding the available options for the chilling process. Several methods are used for stunning the fish with the main aim to immobilize it and make slaughtering process more effective: CO2 stunning followed by gill cutting (or gill cutting alone), food-drug anesthesia, percussive and electrical stunning. The first two methods allow to combine both the chilling and anesthesia in the same vessel (Fletcher, Corrigan, Summers, Leonard, Jerrett, & Black, 2003). However some of these method and their derivatives will not satisfy the requirement of animal protection (Van De Vis, Kestin, Robb, Oehlenschläger, Lambooij, Münkner, et al., 2003).

European regulation on the protection of animals at the time of killing (Anonimous, 2009) establishes rules applicable to the killing of animals kept for the production of food, wool, skin, fur, etc. At the same time slaughtering process of fish is not described in this document:

P. 6: "Recommendations on farm fish are not included in this Regulation because there is a need for further scientific opinion and economic evaluation in this field."

Except of short note in Article 3 and 27 of the document:

Article 3 (1) "Animals shall be spared any avoidable pain, distress or suffering during their killing and related operations."

*Article 27(1) "No later **than 8 December 2014**, the Commission shall submit to the European Parliament and to the Council a report on the possibility of introducing certain requirements regarding the protection of fish at the time of killing taking into account animal welfare aspects as well as the socioeconomic and environmental impacts."*

The CO2 stunning of fish is being banned in Norway (Anonimous, 2006), thus the commercial practice in Norway is tending towards percussive and electrical stunning, where a variety of machines and systems do already exist (Lambooij, Grimsbø, de Vis, Reimert, Nortvedt, & Roth, 2010). This requirements decreases methods of chilling which could be applied for Atlantic Salmon.

3.2 Density of the alive fish in the chilling tanks

The density of fish [kg m^{-3}] before slaughtering plays an important role in the fillet production. The reported fish density, which influence positively on fish behavior, depends on the water temperature. Decreasing of temperature permits to increase the fish density in the cage or tank without stressing the fish. The allowable fish density is an important factor when designing the chilling facilities on the factory.

The recommended fish density in the cage is approximately 20.0 kg m^{-3} when the water temperature is around 16.8 °C. This condition is preferable for relaxation of the fish before slaughtering. At the same time water temperature of 1.0 °C allows to increase the fish density in the cage up to 75.0 kg m^{-3} with minor stress. The fish' density over 200.0 kg m^{-3} in the cage is highly stressful for fish (Skjervold, Fjæra, Østby, & Einen, 2001).

3.3 Temperature shock

When the fish is transferred to a tank which has significantly lower temperature "vertical transfer" the so called "cold shock" may appear. It was reported that transfer of the fish from sea water cage with temperature 16.0 to chilling tank with 0.0 °C resulted in resulted in a swift loss of equilibrium followed by death within 1 h (Foss, Grimsbo, Vikingstad, Nortvedt, Slinde, & Roth, 2012). It should be noted that small fish of 0.5 kg were taken for such experiments, the small fish tolerate temperature difference less than big one.

The lower water temperature limit for Atlantic Salmon chilling was proposed by Skjervold (2002). It lies between 0.0 and 0.5 °C, the mild stress response was detected in the temperature range between 0.5 and 1.0 °C. The decreasing of the water temperature to -0.7 °C is lethal for fish (Saunders, 1986).

Seems to be, that temperature of alive fish should be decreased gradually, the Salmon tolerate temperature difference up to 10.0 °C with a mild stress (Wedemeyer, 1997). At the same time fish, which was acclimatized in conditions of 10.0 °C, resist the decreasing of the temperature and thermal anesthesia may not be observed (Iwama & Ackerman, 1994).

When the water temperature is high, the two- or three-step chilling with intermediate relaxation can be applied for Atlantic Salmon. The recovery (conclusion is based on the lactic level in muscles) of the fish appears during 1.0 hour, when the temperature difference is between 8.0 and 12.0 °C. The gradual decreasing of the water temperature from 16.0 to 0.0 °C is also not stressful for fish (Foss, Grimsbo, Vikingstad, Nortvedt, Slinde, & Roth, 2012).

Thus the high rate of heat exchange, probably, is not preferable for alive chilling of Atlantic Salmon.

3.4 Chemical anesthesia

There are two method of chemical anesthesia, which are available today: CO2 and aquatic anesthetic (like AQUI-S), which is permitted for usage in food.

The CO2 is considered to be as not acceptable treatment for fish. At the same time several enhancements were developed to increase the efficiency of this method and decrease the stress for fish. In such case the chilling anesthesia can be increased by CO2. The decreasing of the fish density, aeration of water and mild levels of CO2 can give a positive feedback for the industry (Ulf Erikson, Hultmann, & Erik Steen, 2006). At the same time CO2 stunning which combined with alive chilling becomes less effective, when the large biomasses are processed (Ulf Erikson, 2008).

Aquatic anesthetic is considered to be the same effective as CO2, but it can be consumed by fish directly before slaughtering (Fletcher, Corrigan, Summers, Leonard, Jerrett, & Black, 2003), at the same time it exists high probability that not all the fish will consume it before the processing.

3.5 Prediction of the chilling time for chilling of alive salmon

In general chilling time of the alive fish is faster, when compared with slaughtered one. This is caused by natural circulation of liquids in alive fish. A total of 70–90% of the heat transfer is by conduction directly through the body wall and 10–30% through the gills (Stevens & Sutterlin, 1976). At the same time, the temperature of the alive fish is relatively higher than the water temperature (between 0.1 and 1.0 °C). The values of such difference depends on the body weight (Skjervold, Fjæra, & Snipen, 2002).

The chilling rate depends on the fish body too, but only empirical dependence for gizzard shad (*Dorosoma cepedianum*) was found (Beitinger, Thommes, & Spigarelli, 1977):

$$k = \theta_1 + \theta_2 W^{\theta_3}$$

The chilling time for alive fish can be predicted by the empirical equation developed by Skjervold et al. (2002):

$$t_i = \frac{-1}{\theta_1 + \theta_2 W_i^{\theta_3}} ln\left[\frac{F_i - C_i}{S_i + \theta_4 + C_i}\right] + \epsilon_i$$

	Value	Description
C	-	Chilling water temperature, °C
F	-	Fish temperature, °C
t	-	Time of chilling, sec
S	-	Sea water temperature, °C
ε	$\frac{\sigma^2}{F_i - C_i}$	Residual parameter, which depends on difference between temperature of wish and chilling water, sec
θ_1	$7.79*10^4$	Part of chilling rate independent from body weight
θ_2	$7.12*10^{-5}$	Effect of body weight on chilling rate
θ_3	0.69	Exponent of body wieght
θ_4	1.02	Offset between sea water and initial body temperature
σ	$4.86*10^5$	Residual variation, $°C^{1/2}$ $sec^{1/2}$

As soon as this is empirical equation, the following limits should be applied in this model:

Type of chilling tank: with carrying forks

Fish weight: 2.5 to 10.8 kg

Fish density: 75 kg m^{-3}

Fish velocity in the tank (due to water flow and moving of the transporter): 0.015 m s^{-1}

Chilling tank volume: 27 m^3

Recirculation of water: 100 m^3 $hour^{-1}$

Amount of fish in the tank at any moment: 2000 kg

Amount of chilled fish: 2500 kg $hour^{-1}$

This means, that the coefficients, which were obtained for the equation are strongly depends on the heat exchange parameters, and can vary significantly form type of chilling equipment. The most interesting is the residual graph of the chilling process, which shows, that the significant error can occur when the fish temperature are close to the chilling water temperature, Figure 6:

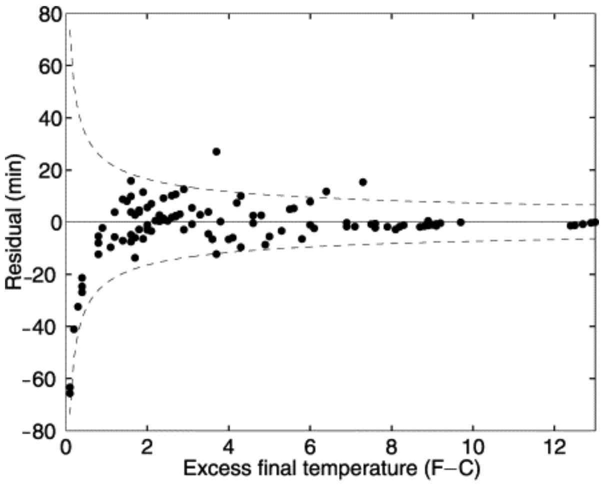

Figure 6. Residuals (dots) of model are plotted against final excess temperature (F−C) (Skjervold, Fjæra, & Snipen, 2002)

It can be noticed, that real physical model is required for effective chilling of alive Salmon. The model should include not only the geometrical parameters of the salmon, but also the characteristics, which are influencing strongly on the heat exchange rate: density of the fish in the tank, water flow parameters, position of the fish in the tank etc.

4 Chilling of slaughtered Salmon by immersion

Several method of food chilling by immersion is applied in industry. The principle of working is simple: the fish is immersed into the vessel with cooling media and expose there until the temperature in the central part of the fish will reach desirable level (between 0 and +3.0 ºC).

4.1 Chilling methods:

- Immersion in sea water
- Immersion in brine solution brine (up to 6 % salt concentration)
- Immersion in fluidized water
- Immersion in binary ice

4.2 Main equipment.

RSW (refrigerated sea water) tank are widely used at processing plants. The design principle of the tank is introduced on the Figure 6. A screw moves fish along the chilling vessel. A feeding belt-transporter allows dropping the fish at different points of the chilling tank. Chilled fish is removed by conveyer to the next stem of operation. Water circulation in the tank is provided by the work of pumps.

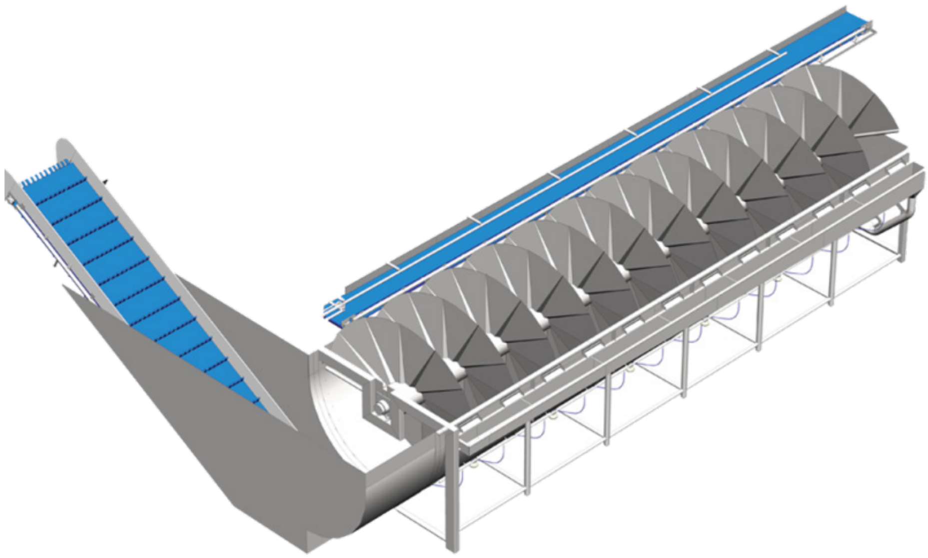

Figure 6. Screw chilling tank for chilling of Atlantic salmon (UNI-FOOD Tecnic AS Danemark)

Energy is required for cooling down water and water circulation (as soon as water pump are energy consuming equipment). The system is or can be designed for simultaneous bleeding and cooling of Salmon. At the same time it is also possible to divide the chilling process in different sections by regulation the seawater flow (and temperature) along the scew.

The seawater temperature can be decreased up to -1.5 ºC (Magnussen et al. 1991), while application of brine is limited by a risk of salting the fish during chilling process, the usual concentration is 6.0 % of salt, brine temperature is -2.5 ºC.

The limiting factors for immersion method are proper temperature difference and good convective heat exchange between the cooling media and fish. Hence the fish ratio and cooling media flow governs the quality and/or time of chilling. Excessive amount of fish will reduce the circulation of water in the tank, while at the same time the fish can be agglomerated in bulks, which is reducing the heat transfer area.

The water flow provides uniform temperature field through the tank and increase the heat exchange rate. However, high biomass flow leads to the decreasing of the chiller's efficiency and the outlet temperature of the Salmon will be higher.

4.3 The renewing of water.

The renewing of cooling media is usually required because the chilling tank is used also for bleeding the fish, after slaughtering. Thus the cooling load will be significantly increased. The recommended water exchange rate (m^3 sec^{-1}) is approximately 63 % from the biomass flow.

Bleeding process. Typical bleeding time is between 15 and 30 minutes and it should be noted that major amount of blood is leaking during first **two minutes** (Ulf Erikson, Misimi, & Fismen, 2010). Low water temperature provides low velocity of coagulation of blood (Olsen, Sorensen, Stormo, & Elvevoll, 2006a). At the same time temperature in the middle of the fish will be relatively high, thus precooling of the fish before slaughtering will be an important factor for fish bleeding. A study revealed that even momenta gutting and filleting without bleeding after stunning will not cause serious decreasing of a fillet's quality (blood spots). Gutting can be described as a part of bleeding in this case (Ulf Erikson, Misimi, & Fismen, 2010; Olsen, Sorensen, Stormo, & Elvevoll, 2006b). **If the data concerning possibility of rapid gutting is correct, this will increase possibilities to rapid chilling of Salmon.**

4.4 Convective heat transfer coefficient.

The convective heat transfer coefficient of sea water is a function of temperature and water flow. The increasing of the water velocity will result in the increasing of the convective heat transfer coefficient; the energy consumption of the water pump will also increase (the increasing depends on the type and model of a pump). Water velocity of 0.01 m sec^{-1} provide convective heat transfer coefficient at 250 W m^{-2} K^{-1}. The same water velocity for brine (6 % salt) provide convective heat transfer coefficient at 180 W m^{-2} K^{-1} (simulated data)(Magnussen O.M., 1991).

Application of fluidized water system allows increasing the convective heat transfer coefficient because bubbles of cold air will destroy boundary layer on the fish surface. The convective heat transfer coefficients can reach 700 W m^{-2} K^{-1} (when mean velocity of water in water jets is 2 m s^{-1}, turbulent flow) (Fikiin, 1992). The temperature of air, which is passing through the air-jets, is a question of system design and can be decreased to -10 ºC.

The convective heat transfer coefficient of binary ice (slurry ice) depends on the type of the flow (laminar or turbulent) and ice fraction (Meewisse, 2001). At the laminar flow (0.3 m s^{-1}) the convective heat transfer coefficient can reach 1500 W m^{-2} K^{-1}, when the ice fraction is 20 %. The laminar heat transfer is preferable, because it will increase with the increasing of the ice fraction. At the same time circulation and pumping of the binary ice in the vessel is complicated due to higher viscosity (2.5 times higher when compared with fresh water) and high pressure drop (up to 7.3 kPa m^{-1}). This method is also preferable when the sea water temperature is relatively low which means that the driving force for heat transfer (temperature difference between harvested fish and refrigerated seawater (RSW)) is rather small for rapid and effective chilling (U. Erikson, Misimi, & Gallart-Jornet, 2011). The decreasing of the temperature below freezing point will also influence positively on the filleting or skinning process of the fish, the ice crystals may form partially (Stevik & Claussen, 2011).

In the case of sea water refrigerated tanks it was found (Magnussen O.M., 1991) that the convective heat transfer coefficient influences on the heat exchange rate until it reaches a certain value, Figure 7. Simulation of the chilling process of Salmon is presented on the figure. The dimensionless temperature represents the ratio of temperature difference in the middle of the fish (at any time) T_i, and ambient temperature, $T_{ambient}$, to the temperature difference in the beginning of the chilling (time=0), T_0:

$$\Delta T = \frac{T_i - T_{ambient}}{T_0 - T_{ambient}} \qquad [3]$$

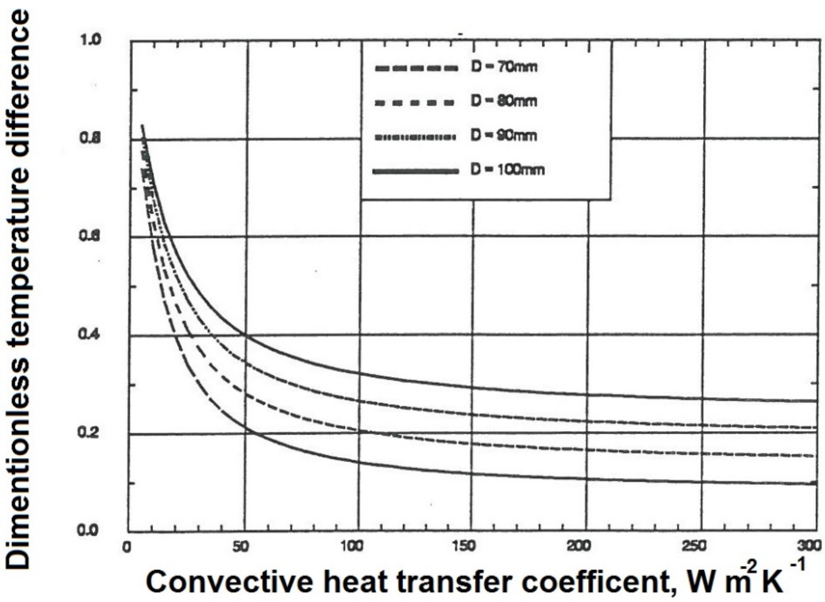

Figure 7. Influence of convective heat transfer coefficient of water (-1.5 ºC) on the temperature decreasing (middle of the Salmon), results are introduced for chilling time of 60 minutes (calculation).

The increasing of the convective heat transfer coefficient over 150 W m^{-2} K^{-1} leads to insignificant decreasing of the temperature in the middle of the fish or in the insignificant decreasing of the chilling time. This is explained by relatively low thermal conductivity of the fish (between 0.45 and 0.55 W m^{-1} K^{-1}) (Magnussen O.M., 1991). Anyway, the required heat transfer coefficient will correlation with the fish:water ratio. It should be noted that this calculations assumed "ideal" conditions.

4.5 Gutting the fish

The chilling process will be faster when the thickness of the product is not high. In some literature sources the term of "apparent surface" (m^2 kg^{-1}) is used; it shows the ratio between the weight of the product and heat(mass)-exchange surface of a fish. It is evident from the Figure 8, that the temperatures in the middle of the fish after 60 minutes of chilling is two times lower for fish with thickness of 70 mm, than for fish with thickness of 100 mm. Figure 4 represents the dependence between the thickness of a product and chilling time more evident.

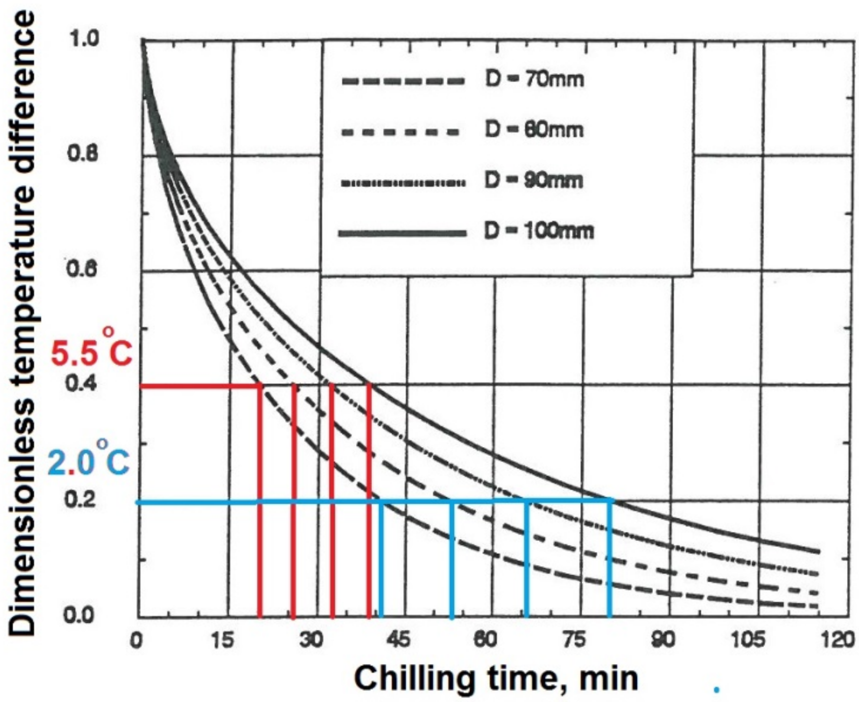

Figure 8. Dependence between thickness of Salmon and chilling time (calculation).

It is evident that the rate of chilling (°C min^{-1}) is falling down at a lower values of the dimensionless temperature, thus the high difference between initial temperature of the fish and ambient temperature is desirable. It can significantly increase the heat exchange rate, the experiments which were done in Sintef Energi showed good results of the chilling of Salmon (5.75 kg) by brine (4.5 % of salt, -2.5 °C). The temperature in the core of the fish dropped down from 10°C to -1°C during 2 hours and 40 minutes the surface of the fish was partly frozen (Nordtvedt T., 1991).

At the same time thermal properties of sea water and brine limits this difference. It should be noted that brine has lower convective heat transfer coefficient, when compared with water at the same conditions, thus the circulation of the brine in the tank should be more intensive.

Gutting of the fish will decrease the effective thickness of the fish and thus the chilling process will be accelerated. The effective diameter will be decreased significantly, thus the chilling time will be also shorter, Figure 9.

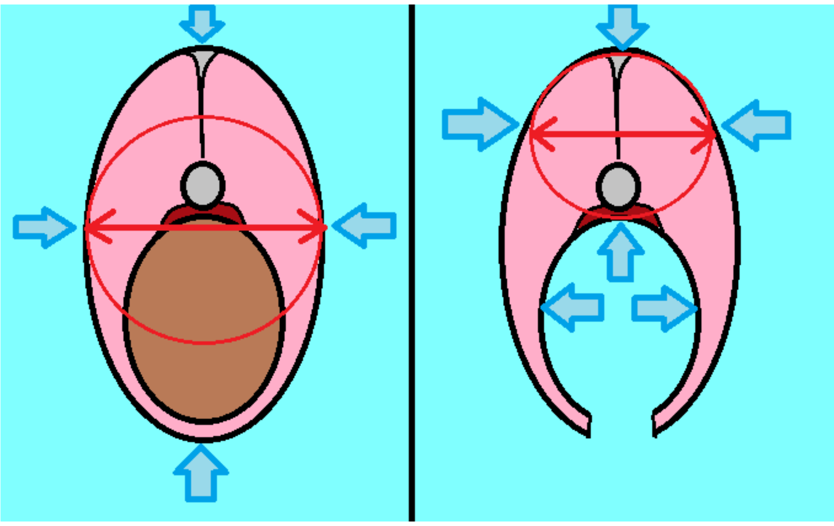

Figure 9. Comparisons between effective diameters for "round" and gutted salmon.

Experiments showed that gutted fish is chilled down 30% faster, when compared with whole fish (Magnussen O.M., 1991). Another experiment of the gutted salmon revealed that gutted Salmon (5.75 kg) chilled up to the required temperature in the core (-1°C) 20 minutes faster, when compared with whole fish (Nordtvedt T., 1991).

5 Non-immersion method for Salmon chilling

The non-immersion methods assume the chilling of the fish on the belt transporter by gases (air, CO2, N2) of mixture of gases and water. The benefit of this method is possibility to control temperature of the fish. The fish can be arranged on the transporter/belt in the best way, which will ensure the effectivity of the chilling process. The disadvantage of this method is excessive mass transfer together with the heat transfer, which will lead to the dewatering of the surface air of the fish. The non-immersion chilling can be applied for chilling of fillets (preferable) and whole or gutted fish. At the same time, the microbial contamination of the fillet depends significantly on the quality of the cooling media.

5.1 Methods of non-immersion chilling

- Gas-chilling/ Super chilling
- Spray-chilling

5.2 Gas chilling/ Super chilling

Several gases can be used for chilling the salmon. The air is the cheapest one. At the same time is air with low relative humidity capable to adsorb moisture from the fish surface (drying). The rate of drying will depend on the air velocity and relative humidity. Evaporative weight losses can exceed 5 % of the fish weight. The convective heat transfer coefficient of gasses is relatively low when compared with liquids, thus the air circulation should be in the range between 3 and 7 m s^{-1}, which provides convective heat exchange coefficient at 100 over 100 W m^{-2} K^{-1} and higher (James, Vincent, de Andrade Lima, & James, 2006). Such velocities will also stimulate drying of the product and can be inappropriate for chilling of fillets.

The temperature decreasing will lead to increasing of the heat exchange rate. The process is called superchilling, when the low enough temperature is applied and partial freezing of the product (surface) takes place. The heat transfer coefficient can be between 200 and 300 W m^{-2} K^{-1} (Kaale, Eikevik, Kolsaker, & Stevik, 2013). This method can be applied to chilling of the fillets before packaging, the short-time formation of the ice crystals will not damage cellular structure of the salmon significantly (Love, 1968). At the same time temperature of the fish will equalize during first hours of the chilled storage of the fish. The long-term storage of the salmon fillets in a superchilled state is also positive. The precise temperature control is important in such case. The required equipment is a blast freezer or an impingement freezer.

5.3 Spay-chilling.

Spray chilling accelerates the heat exchange rate by evaporation of the moisture form the surface of the product, Figure 10. The wet bulb temperature will be lower, when compared with the temperature on the media. The boundary layer will be destroyed in such case by air flow and layer of evaporated water. These factors increase the heat exchange rate.

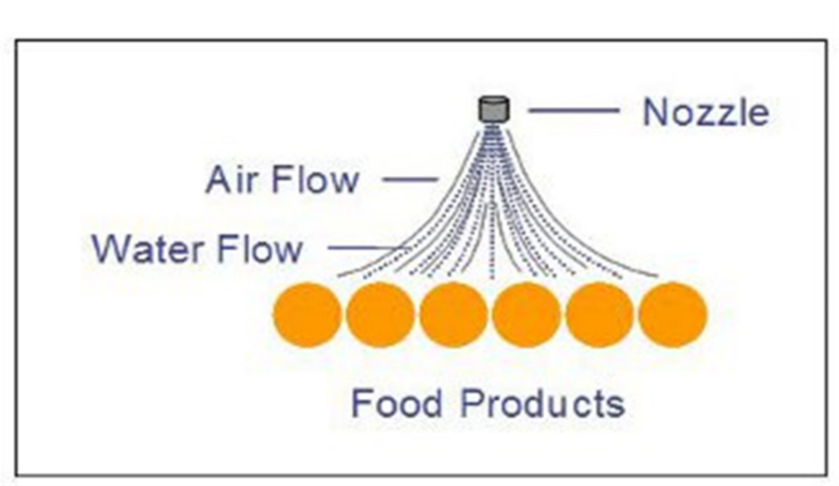

Figure 10. Spray-chilling method.

The factors which will induce the heat exchange are droplet size, ratio of water/air and temperature of the media (Issa, 2009). High water mass flow flux has a detrimental effect on the surface cooling because of the flooding that can occur on the surface. Maximum heat transfer occurs when the spray median droplets size is less than 40 pm (Figure 21). However, surface flooding increases with the increase in droplet size, and when using a large amount of water, the cooling effectiveness of the multiphase spray reduces to that of a forced air jet. Water droplets also make the surface of the fish or fillet wet and the weight decreasing due to drying is relatively low.

The spray-cooling allows to use gases with temperature below freezing point of water. As soon as waster droplet has no centres of crystallization it can be sub-cooled to 15 K below freezing point. The sub-cooled water will have higher temperature difference with the fish body, and rapid chilling will be reached. The possibility exists for partial freezing at the fish surface due to the free moisture for sub-cooling. This should be investigated further.

SINTEF

6 Conclusions

Chilling of salmon in industrial production is limited by several factors:

- Seasonal variation for temperature
- short pre-rigor time
- quality requirements
- low thermal conductivity of salmon
- different heat transfer coefficient for different system
- high mass flow
- thickness of the salmon
- development of a temperature profile during chilling

The optimal convective heat exchange rate can be achieved by several chilling methods, but optimum parameters for several methods (spray chilling, binary ice chilling) are not considered yet. The chilling process should be organized in such way that the maximum allowable temperature difference between the product surface and cooling media will be maintained. Further it should be investigated how the temperature profile in the fish can be equalized during processing.

The main problem of the todays chilling methods, that the models, which are used for chilling time estimation, are strongly empirical. It means that they can be applied with several assumptions and at a certain conditions. In other conditions, they will, probably, give a high error. Thus the development of the physical model of the chilling of salmon alive and slaughtered is required. The main focus should be on the factors, which have are influencing the overall heat exchange rate.

Dimensioning a chilling process for fish is restricted by the appearance of the rigor-mortis state, which gives the requirement that the core temperature of the salmon should be reduced below 2°C within 2-3 hours after slaughtering. However, industry partners reported a longer pre-rigor time, so that the strict time limit for chilling might be not necessary.

7 Reference list

Anonimous. (2006). Forskrift om slakterier og tilvirkingsanlegg for akvakulturdyr. In *Fiskeri- og kystdepartementet*). Oslo.

Anonimous. (2009). Council Regulation (EC) No 1099/2009 of 24 September 2009 on the protection of animals at the time of killing (1). *Official Journal of the European Union, L 303*, 1-31.

Beitinger, T. L., Thommes, M. M., & Spigarelli, S. A. (1977). Relative roles of conduction and convection in the body temperature change of gizzard shad, Dorosoma cepedianum. *Comparative Biochemistry and Physiology Part A: Physiology, 57*(2), 275-279.

Erikson, U. (2008). Live Chilling and Carbon Dioxide Sedation at Slaughter of Farmed Atlantic Salmon: A Description of a Number of Commercial Case Studies. *Journal of Applied Aquaculture, 20*(1), 38-61.

Erikson, U., Hultmann, L., & Erik Steen, J. (2006). Live chilling of Atlantic salmon (Salmo salar) combined with mild carbon dioxide anaesthesia: I. Establishing a method for large-scale processing of farmed fish. *Aquaculture, 252*(2–4), 183-198.

Erikson, U., Misimi, E., & Fismen, B. (2010). Bleeding of anaesthetized and exhausted Atlantic salmon: body cavity inspection and residual blood in pre-rigor and smoked fillets as determined by various analytical methods. *Aquaculture Research, 41*(4), 496-510.

Erikson, U., Misimi, E., & Gallart-Jornet, L. (2011). Superchilling of rested Atlantic salmon: Different chilling strategies and effects on fish and fillet quality. *Food Chemistry, 127*(4), 1427-1437.

Fikiin, A. G. (1992). New method and fluidized water system for intensive chilling and freezing of fish. *Food Control, 3*(3), 153-160.

Fletcher, G. C., Corrigan, V. K., Summers, G., Leonard, M. J., Jerrett, A. R., & Black, S. E. (2003). Spoilage of Rested Harvested King Salmon (Oncorhynchus tshawytscha). *Journal of Food Science, 68*(9), 2810-2816.

Foss, A., Grimsbo, E., Vikingstad, E., Nortvedt, R., Slinde, E., & Roth, B. (2012). Live chilling of Atlantic salmon: physiological response to handling and temperature decrease on welfare. *Fish Physiol Biochem, 38*(2), 565-571.

Issa, R. J. (2009). Multiphase Spray Cooling Technology in Industry In K. Jayanthakumaran (Ed.), *Advanced Technologies*): InTech.

Iwama, G. K., & Ackerman, P. A. (1994). CHAPTER 1 - Anaesthetics. In P. W. Hochachka & T. P. Mommsen (Eds.), *Biochemistry and Molecular Biology of Fishes*, vol. Volume 3 (pp. 1-15): Elsevier.

James, C., Vincent, C., de Andrade Lima, T. I., & James, S. J. (2006). The primary chilling of poultry carcasses—a review. *International Journal of Refrigeration, 29*(6), 847-862.

Kaale, L. D., Eikevik, T. M., Kolsaker, K., & Stevik, A. M. (2013). Modeling and Simulation of Food Products in Superchilling Technology. *Journal of Aquatic Food Product Technology, 23*(4), 409-420.

Lambooij, E., Grimsbø, E., de Vis, J. W. v., Reimert, H. G. M., Nortvedt, R., & Roth, B. (2010). Percussion and electrical stunning of Atlantic salmon (Salmo salar) after dewatering and subsequent effect on brain and heart activities. *Aquaculture, 300*(1–4), 107-112.

Love, R. M. (1968). Ice formation in frozen muscle. In J. Hawthorn & E. Rolfe, J. (Eds.), *Low temperature biology of foodstuffs*, (pp. xii, 458 s.). Oxford: Pergamon.

Magnussen O.M., F. O., Nordtvedt T.S.. (1991). Nedkjøling og transportsystem for oppdrettsfisk. In). Trondheim, Norway: SINTEF Energy.

Meewisse, J., W., Ferreira, C.,A. (2001). Freezing Point Depression of Various Ice Slurries. In *IIF – IIR*, vol. Commission B1). Paderborn, Germany.

Nordtvedt T., S. (1991). Nedkjøling I kjølelake. In). Trondheim, Norway: SINTEF Energy.

Olsen, S. H., Sorensen, N. K., Stormo, S. K., & Elvevoll, E. O. (2006a). Effect of slaughter methods on blood spotting and residual blood in fillets of Atlantic salmon (Salmo salar). *Aquaculture, 258*(1-4), 462-469.

Olsen, S. H., Sorensen, N. K., Stormo, S. K., & Elvevoll, E. O. (2006b). Effect of slaughter methods on blood spotting and residual blood in fillets of Atlantic salmon (Salmo salar). *Aquaculture, 258*(1–4), 462-469.

Saunders, R. L. (1986). The thermal biology of Atlantic salmon: influence of temperature on salmon culture with particular reference to constraints imposed by low temperature [Salmo salar] In): Institute of freshwater research, Drottningholm.

Skjervold, P. O., Fjæra, S. O., & Snipen, L. (2002). Predicting live-chilling dynamics of Atlantic salmon (Salmo salar). *Aquaculture, 209*(1–4), 185-195.

Skjervold, P. O., Fjæra, S. O., Østby, P. B., & Einen, O. (2001). Live-chilling and crowding stress before slaughter of Atlantic salmon (Salmo salar). *Aquaculture, 192*(2–4), 265-280.

Stevens, E., & Sutterlin, A. (1976). Heat transfer between fish and ambient water. *J Exp Biol, 65*(1), 131-145.

Stevik, A. M., & Claussen, I. C. (2011). Industrial superchilling, a practical approach. *Procedia Food Science, 1*(0), 1265-1271.

Van De Vis, H., Kestin, S., Robb, D., Oehlenschläger, J., Lambooij, B., Münkner, W., Kuhlmann, H., Kloosterboer, K., Tejada, M., Huidobro, A., Otterå, H., Roth, B., Sørensen, N. K., Akse, L., Byrne, H., & Nesvadba, P. (2003). Is humane slaughter of fish possible for industry? *Aquaculture Research, 34*(3), 211-220.

Wedemeyer, G. A. (1997). Effects of rearing conditions on the health and physiological quality of fish in intensive culture In G. K. Iwama (Ed.), *Fish stress and health in aquaculture*). Cambridge [England]: Cambridge University Press.

http://www.fao.org/wairdocs/tan/x5958e/x5958e01.htm

SINTEF

Technology for a better society

www.sintef.no