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ABSTRACT

A thermodynamic model for chilling of salmon was developed, based on physical parameters. The model result shows the temperature profile, developing through a single fish and can also account for varying boundary conditions, changing heat transfer coefficient and RSW temperature. The model was verified by 4 different chilling experiments in the laboratory, giving an average chilling rate for 10 salmons each.

Different chilling process where evaluated based on the developed model. The influence of the RSW temperature and heat transfer coefficient is well described by the model and comparable to empirical data from earlier tests. The effect of a chilling break is evaluated. The model was also used to compare alive-chilling with slaughtered chilling. The model is evaluating the chilling rate for a standard fish and further work should focus on variation of fish size. Also the physical effects (like agglomeration,...) which occur under industrial applications should be evaluated further and included here. The model can be used to evaluate the overall energy efficiency of the chilling process.

The heat transfer coefficient between the fish and the RSW is an important factor and the investigation showed that the apparent heat transfer coefficient is smaller than calculated values.

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APPENDICES

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1.1 Introduction

Tradisjonell slakteprosess er vist skjematisk i Fig. 1. Fiskens temperatur er 1.0 K høyer enn temperaturen i sløen (Skjervold et al., 2002). Sommerstid kan fisken ha en temperatur på 15-17 °C når den ankommer pakkeriet. Fisken skal da gjennom slakteprosessene og temperaturen skal være lavere enn 4.0 °C før pakking. Helst skulle temperaturen vært 0 °C før pakking i is. Høyt produsjonstemp og tidlig dødsstivhet skaper problemer med å få satt av tilstrekkelig tid til nedkjøling Det har vist seg at dødsstivhet ofte inntreffer allerede 1-2 timer etter bløgging, men det er store individuelle variasjoner og variasjon fra pakkeri til pakkeri. Mulighetene for å forlenge perioden mellom bløgging og tidspunktet for dødsstivhet vil bli undersøkt nærmere i et samarbeidsprosjekt innen SINTEF og NTNU.

Figur 1. *Operasjonene i en slakteprosess vist skjematisk*

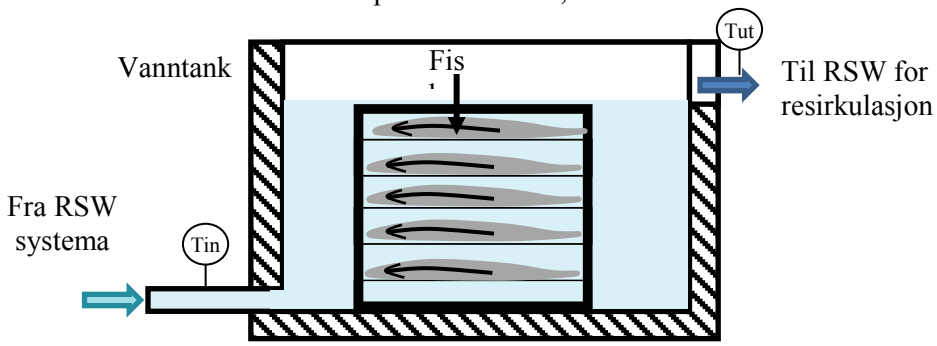
Målet med prosjektet har vært å komme frem til kjølesystem som kjøler store mengder fisk så hurtig som mulig til ønsket temperatur og på en skånsom måte. Kjølesystemet skal videre være driftssikkert, og ha lavest mulige kostnader (og «running costs»).

Kjøling med saltlake (mekanisk kjølt sjøvann) har vært undersøkt i laboratoriet. Det er kjent prinsipp fra kjøling av fisk i slaktefabrikken.

2. Methods of experiments, modelling and materials

2.1. Experimental setup

The setup consist from two main components: refrigerating machine (RSW) to produce chilled sea water in the temperature range from +10.0 to -2.0 °C and chilling tank (approximately 0.8 m^3), Figure 2. The recirculated chilled water flows form the machine to the bottom of the tank with the assistance of water pump. The flow of brine (concentration of *NaCl* 3.5±0.1%) varies in the range between 150 and 600 L min^{-1}. Three levels of brine flow were used in the experiment: 150.0, 300.0 and 600.0 L min^{-1}.



Figur 2. *Experimental setup*

The fish was connected by plastic stripes to the metal stillage, which was placed into the RSW tank. There were 5 shelves by 2 fish on each. The fish parameters were following:

- Weight: 5.9 ±0.1 kg;
- Average maximal thickness: 97.8 ±3.5 mm;
- Average length: 759.0±17.2 mm (from nose to the beginning of tail fin).

2.2. Determination of convective heat transfer coefficient

The convective heat transfer coefficient is essential parameter, which influences the heat exchange rate during cooling. The convective heat transfer coefficient form water to fish (h_c, W m^{-2} K^{-1}) was determined using aluminum cylinder (D=0.04 m; L= 0,758 m; m=2.5525 kg; c_p=0.9 kJ kg^{-1} K^{-1}). This method was applied due to the complicated flow profile of the brine in the chilling tank; the analytical methods were not applicable. As soon as the thermal conductivity of aluminum is relatively high (Bi≈0), the temperature gradient inside the cylinder will negligible, T_{center}=$T_{surface}$. The following equation of energy balance could be applied to measure the convective heat transfer coefficient, eq. 1:

$$m_{cyl}c_{p,cyl}d\left(T_{surf,cyl} - T_\infty\right) = h_c * A * (T_{surf,cyl} - T_\infty)\partial\tau \qquad (1)$$

Derivation of the eq.1 by time and temperature gives the values of h_c for different mass flow of water.
The h_c is also depends on the geometry of the object which is immersed into the cooling media. The following dependence war used to adjust the h_c with respect to the cylinder's diameter, eq 2 (Kerith, 2011):

$$Nu = 0.26Re^{0.6}Pr^{0.36} \qquad (2)$$

The convective heat exchange coefficient and other parameters of cooling media is introduced in the table 1.

Table 1. *Heat transfer coefficients of brine (0.035 % NaCl) at different mass flow of water in the RSW* ***tank.***

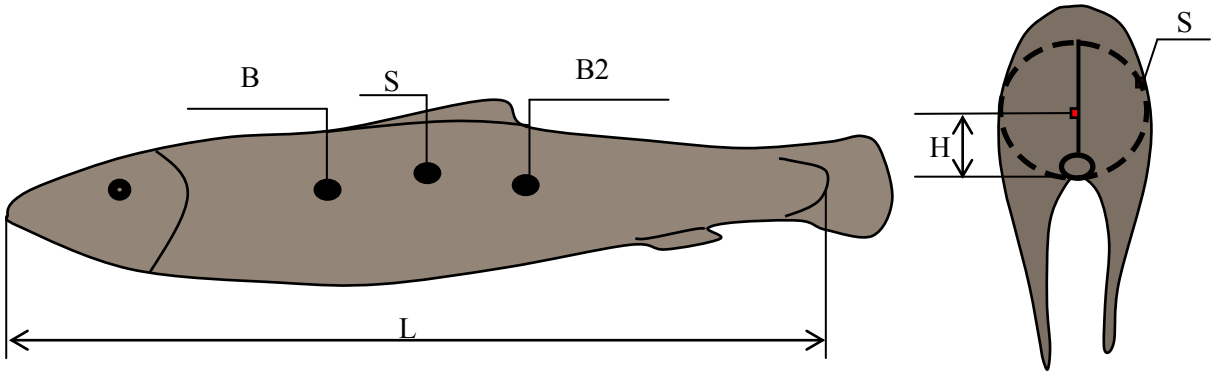
Mass flow of water, L min^{-1}	***Diameter, m***	***Nu, -***	***Re, -***	***Water velocity, U, sm s^{-1}***	***h_c, W m^{-2} K^{-1}***
150	0,04	41.99	977	4.58	575
	0,1	72.77	2444		398
300	0,04	42.2	986	4.62	578
	0,1	73.11	2465		400
600	0,04	83.0	3045	14.29	1137

	0,1	143.86	7613		788
Pr=14.12; λ_{brine}=0.5479 W $m^{-1}K^{-1}$; $c_{p,brine}$=4029 J $kg^{-1}K^{-1}$; ρ_{brine}=1023 kg m^{-3}; μ_{brine}=0.001921 Pa s					

The small difference between heat transfer values, which were obtained for 150 and 300 L min^{-1}, is explained by the design of the RSW tank which provides significant turbulence of water even at relatively low mass flows. The data, which were obtained for d=0.1 mm was used for simulation of chilling time (Modelica).

2.3. Sensor position

Each fish was equipped with 2 "knappe temperatur sensor", which measures temperature in the range between -50.0 to 150.0 °C. The position of the sensors is introduced on the figure 3. Sensors B1 and B2 were installed inside the fish tissues form the gutt side along backbone on the depth H (approx. 45.0 mm). The sensors were placed from one side on the backbone in such way that they were situated in the geometric middle of the fish before and after the main backfin. Three fishes were equipped with sensor (S) directly under the skin (depth approx. 5.0 mm) with the aim to check the convective heat transfer coefficient during experiments.



Figur 3. *Sensor position in fish (diameter of dashed circle equals to thickness of fish)*

2.4. Description of experiment

Chilled and gutted Atlantic Salmon (Salmo Salar) was delivered by Salmar– The fish were packed in polyester boxes with 10% of ice. When the sensors were installed at the day of slaughtering, the fishes were fixed to the metal shelve by plastic stripes. There were 5 shelves in one metal frame. Afterwards the fish were equilibrated in the climate chamber at 15.0 ±1 °C (relative humidity 90%) for approximately 15 hours. That time was excessive to obtain the constant average temperature of 15.0 ±1 °C in the fish. The temperature deviation was negligible and did not influence on the results of the experiment. Shelve with fish was immersed into the RSW tank for approximately 3 hours. Temperature of the brine was in the range between -1.0 and -0.5 °C.

There was a series of experiment with interrupted cooling, when the fish was removed from the RSW and equilibrated at ambient temperature (20degC) for 30 min.

Parameters of the fish and experiment conditions are introduced in the table 2.

Table 2. *Experiment conditions and parameters of fish.*

Fish number	Thickness of fish in at the location of sensor, mm		Length, mm	Weight, kg	Under skin logger
	Before back fin	After back fin			
Water flow, 150 L min^{-1} and 600 L min^{-1}					

1	97	91	76	5.842	No
2	100	92	78	5.981	No
3	90	85	79	5.824	yes
4	101	93	77	5.836	No
5	98	89	76	5.765	No
6	96	92	78	5.852	yes
7	99	86	79	5.784	No
8	95	89	77	6.050	yes
9	101	96	78	6.113	No
10	101	93	78	5.900	No
Water flow, 300 L min^{-1} and 300 L min^{-1} stopped chilling.					
10	9,1	8,5	71	5,09	
2	8,9	8,4	74	5,159	
7	9,3	8,2	74	5,323	
9	9,4	9	77	5,487	
8	9,8	9,1	75	5,541	
6	9,7	8,9	78	5,591	
4	9,1	8,6	73	5,612	
5	9,3	8,4	72	5,672	
3	10,1	8,6	75	5,756	
1	9,6	8,9	77	5,912	

2.5. Model description

The fish was modeled as a cylinder with radius R divided into N different layers (N=100). The layers have similar length but different radius. The thickness of each layer is R/N. Each layer consists of a heat capacitor with a mass calculated based on the density of the fish and the volume of the layer. The specific heat capacity of the heat capacitor is calculated based on the content of water, protein, fat, and ash and the temperature (recommendation of ASHRAE 2012). Between each layer there is a thermal conductor with a calculated conductivity based on the nutrient content and the temperature. At the surface the heat flow is calculated based on the temperature difference between the outermost layer and the surroundings and a constant coefficient of heat transfer.

The initial temperature of the whole fish was set to a chosen temperature, and the surface temperature of the fish is the same temperature as the outermost layer. The temperature of the surroundings and the heat transfer coefficient is chosen from Table 1. The fish thermal properties were set at following values, Table 3.

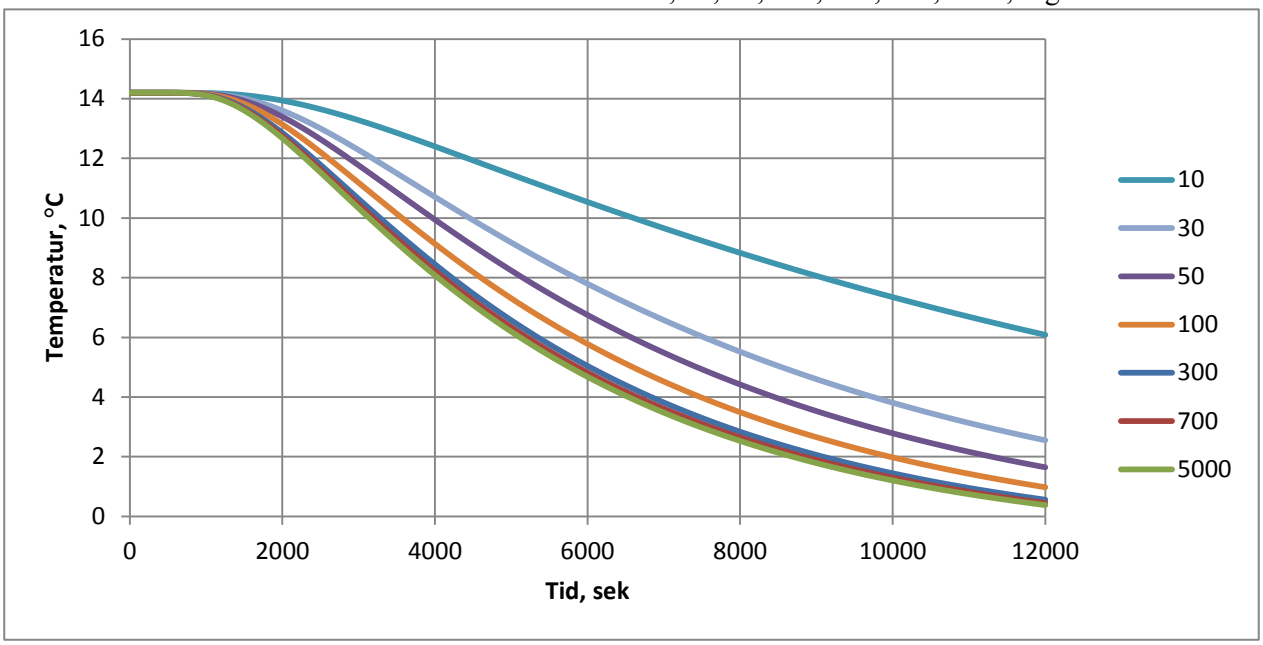
Table 3. *Chemical and physical properties of Atlantic salmon used for simulation.*

Dimensions		Thermal properties		Chemical composition, %	
Geometry	Cylinder	Heat capacity		Water content	
Length	Infinite	Thermal conductivity		Protein content	
Diameter	0.112 m	Density		Fat content	
Number of layers, N	100			Ash	

3. Results and discussion

3.1. Simulation of chilling of salmon at different convective heat transfer coefficients

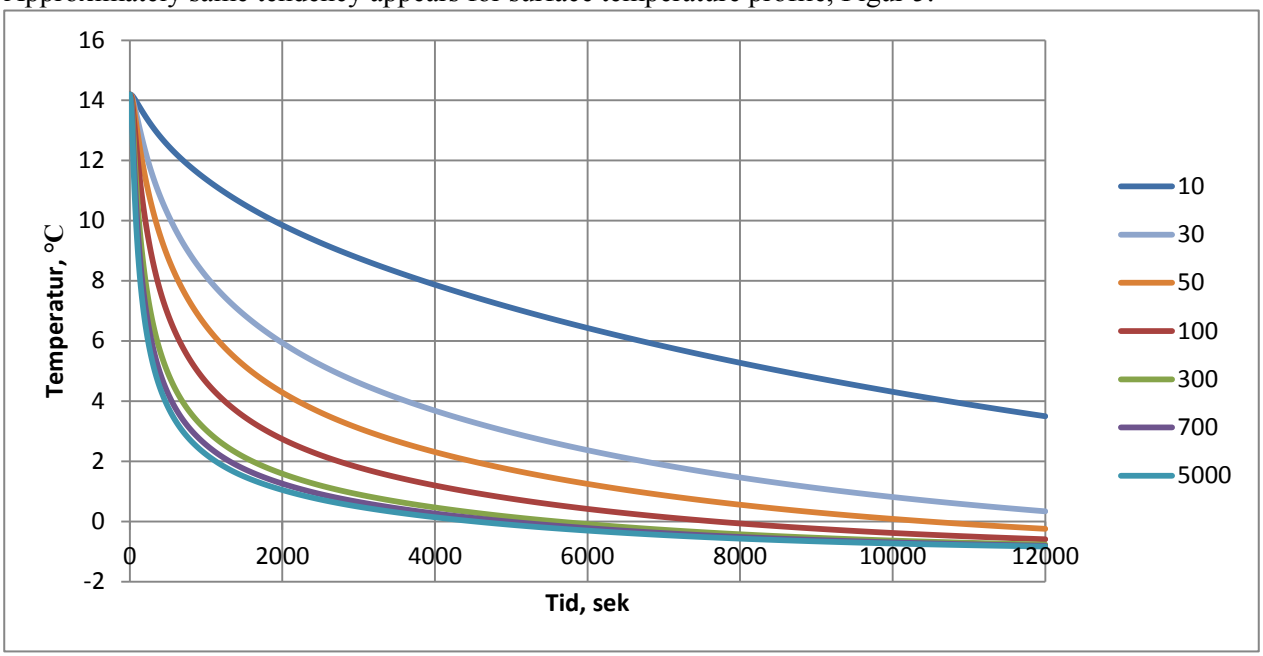
The simulation was done at constant thickness of fish and refers to the thicker part in the middle (0.112 m). Several different heat transfer coefficients were used: 10, 30, 50, 100, 300, 700, 5000, Figur 4.



Figur 4. *Simulation of salmon chilling in seawater (t=-1.0 °C) at different heat transfer coefficients, temperature in the center of the fish (thickness=0.112 m).*

The simulation showed, that the convective heat transfer coefficient influences on the chilling time at its values between 10 and 300 W m^{-2} K^{-1}. The chilling time is decreasing significantly with increasing of h_c. Further increasing of h_c leads to the insignificant decreasing of the cooling time. At such values the thermal conductivity of the fish tissues limits the chilling process.

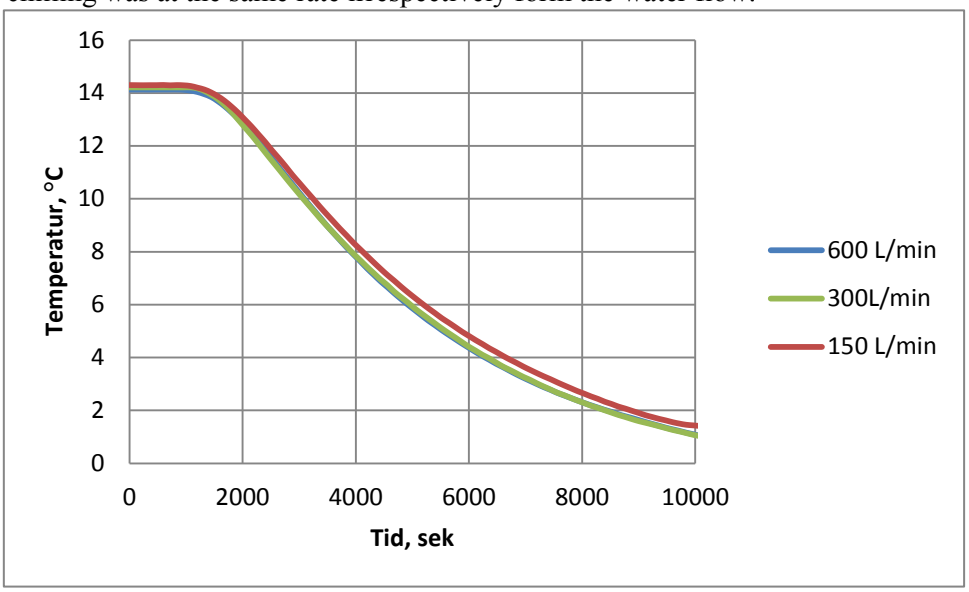
Approximately same tendency appears for surface temperature profile, Figur 5.



Figur 5. *Simulation of salmon chilling in seawater at different heat transfer coefficients, temperature under skin (depth=0.005 m).*

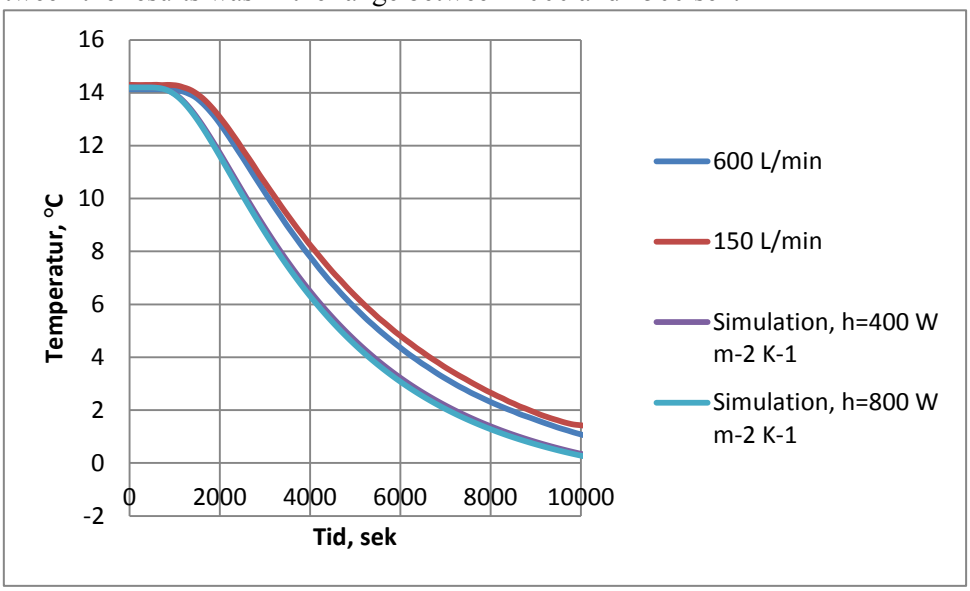
3.2. Experimental chilling of salmon and correction of overall convective heat transfer coefficient

The chilling of salmon was made at three different water flows. The flows refer to different convective heat transfer coefficients (between 400 and 800 W m^{-2} K^{-1} according to aluminum cylinder's method of calculation), which were high enough to provide high rate of cooling. The average chilling curves, Figur 6, show that the chilling was at the same rate irrespectively form the water flow.



Figur 6. *Average chilling curves (temperature vs time) of Atlantic Salmon at different sea water flow, temperature in geometric center.*

At the same time comparison of the experimental results with simulation at a predicted convective heat transfer rate (between 400 and 80 W m^{-2} K^{-1}) indicated that time should be significantly shorter, Figur 7. Difference between the results was in the range between 1000 and 1500 sek.



Figur 7. *Comparison between experimental results and simulation of Salmon chilling at different convective heat transfer rates (D of fish was taken at 0.1 m), temperature in center.*

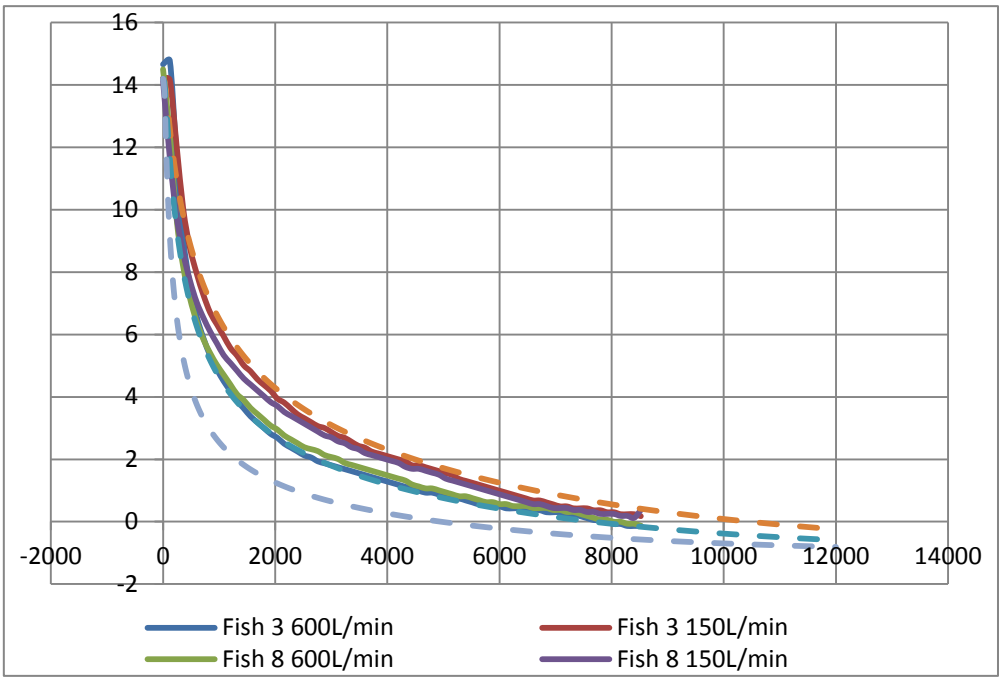
The same trend was observed for temperature decreasing when sensors were installed under the skin of the fish, Figur 8. The high h_c showed higher rate of chilling, when compared with experimental results. Ta the same time the low values of the convective heat transfer coefficients in the range between 50 and 100 W m^{-2} K^{-1} were in agreement with experiments.

The observed events show that the ordinary methods of the convective heat transfer determination could not be used in the case of chilling of Atlantic Salmon. Even at a high water flow the real convective heat transfer coefficient was significantly lower (approx. 8 times), when compared with calculated values (see Table 1.). This could be explained by several factors, which decreases the convective heat transfer:

- The shape of the fish, which is different from the cylinder;
- The sea water flow, which is eddying in the tank and flows at different attack angle to the fish;
- The "jelly" layer on the skin surface, which decreases the heat transfer significantly.

Thus the simulation analysis should be done with respect to empirically observed values. The h_c was set at **75 W m^{-2} K^{-1}** for the simulation analysis to show the average trends during chilling of the fish.

Further work should be done to determine the methodology for calculation the real values of the average convective heat transfer coefficients for different fish species being chilled at different conditions. It can be presented in a form of correlation to the traditional methods of convective heat transfer determination.

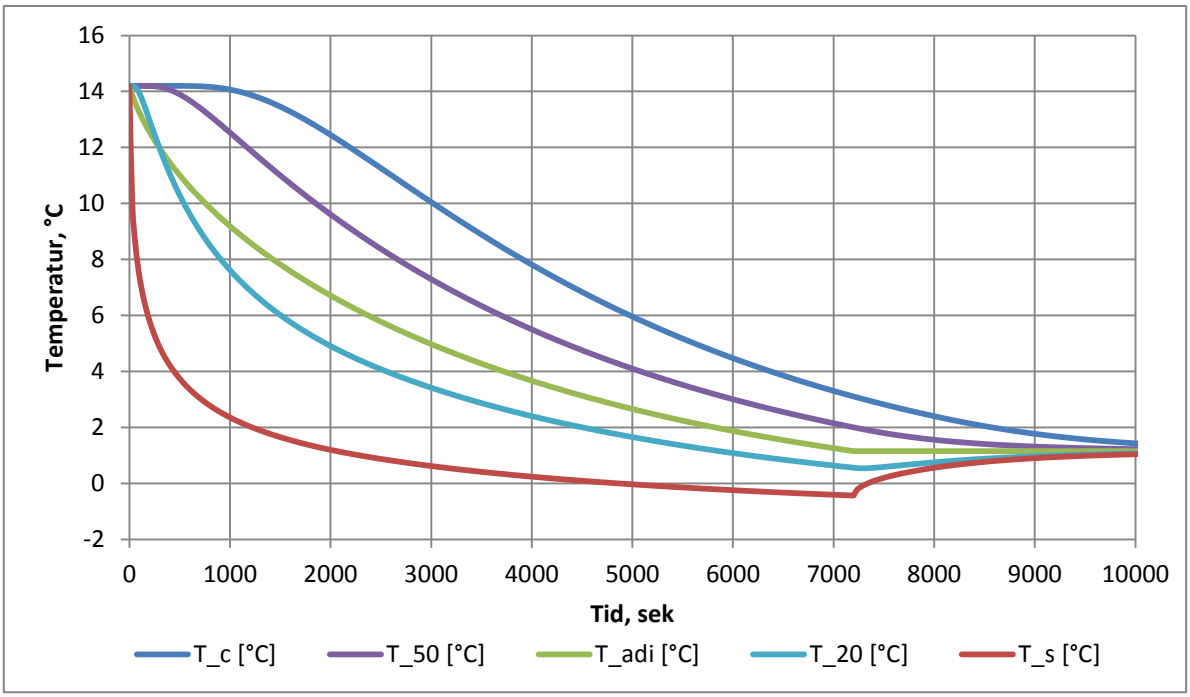


Figur 8. *Decreasing of the temperature under the skin of Atlantic Salmon. Comparison of experiments, when the fish was chilled at different water flow, with simulation at different convective heat transfer coefficients.*

3.3. Interrupted chilling of Atlantic Salmon

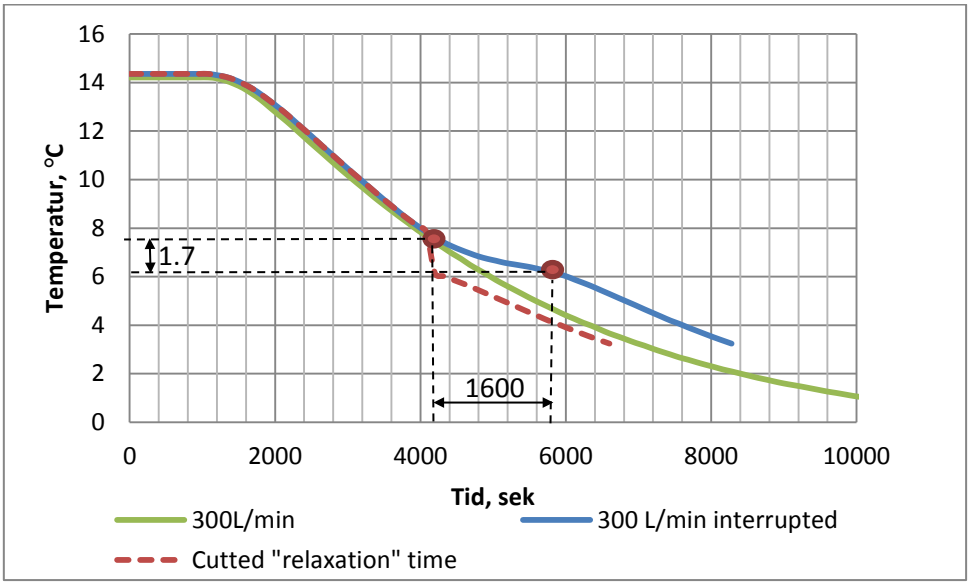
The indicator of a good chilling process is temperature in the geometric center of a fish. The temperature, which is required by most of technical regulations and directives, lay in the range between -1.0 and +4 °C. At the same time, the chilling process is inertial one; as soon as temperature gradient in the fish tissues can be significant due to low conductivity (k is usually in between 0.4 and 0.6 W m^{-1} K^{-1}). This bring the process to such situation, when the temperature in the center of fish is not low enough, but overall (adiabatic) temperature is suitable for further processing steps. The temperature in the center of the fish will continue to fall down, even if the chilling process is stopped, figure 9. The dependence on the figure shows, that when the chilling process was stopped after 2 hours (7200 sec), the center temperature will fall down until

equilibrium will appear. The same trend will be for internal layet T_50 (25 mm from center). In opposite, the temperature of the surface and upper internal layer T_20 (10 mm from surface) will rise up.
It appears that adiabatic temperature is the most important values in such case. The convenient methods of the temperature measurements do not give excessive information about equilibrium (adiabatic) temperature of the product. Because they make measurements of only one point or layer (thermo-scanner).

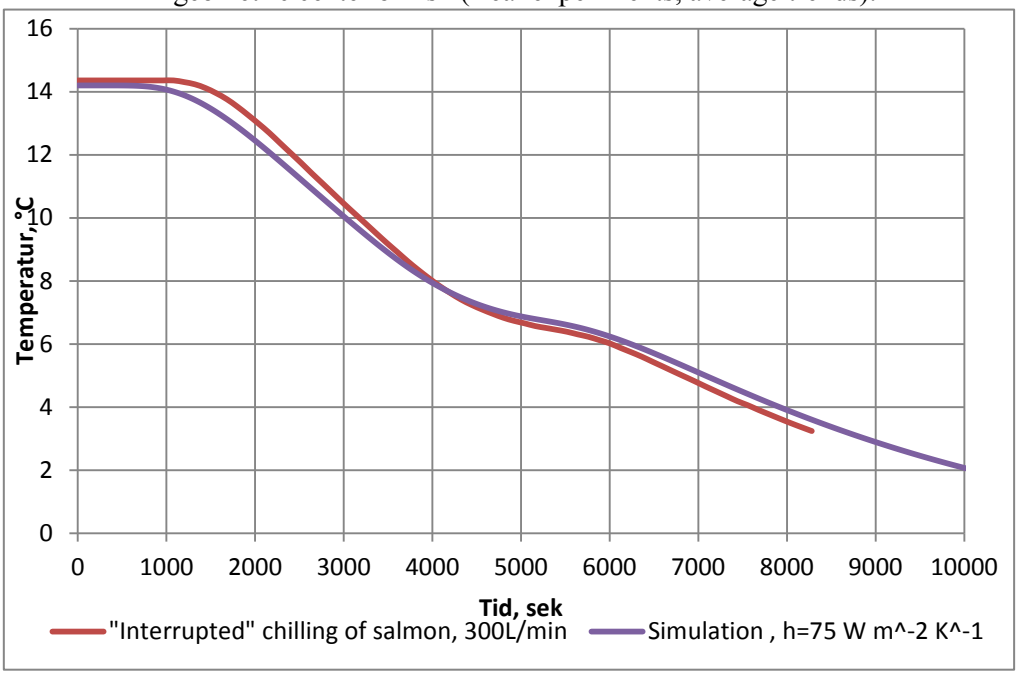


Figur 9. *Simulation of temperature of salmon at different layers during chilling in RSW.*

The pause during chilling can be used to any other processing operation. The comparison of the "interrupted" chilling of Atlantic Salmon is shown on Figur 10. Green line is ordinary chilling in RSW. Blue line shows temperature in center of the fish, when the process was interrupted. Red dashed line represents the "interrupted process" but passive part of pause without chilling is cut.
The model, which was developed, was verified by experimental results, Figur 11. The negligible difference between modelled and simulated values approves the application of this model for designing the chilling process of salmon.

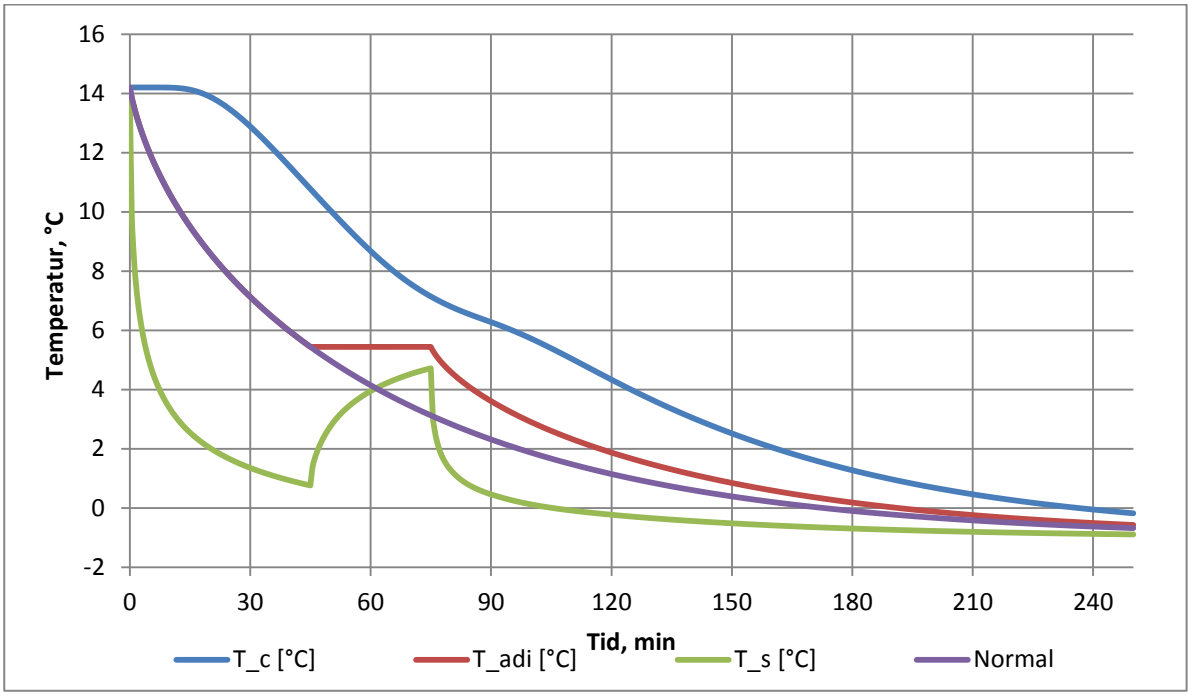


Figur 10. A comparison of "interrupted" chilling with normal chilling of Salmon in sea water, temperature in geometric center of fish (Real experiments, average trends).



Figur 11. *Verification of model for salmon chilling by experiments*

Adiabatic temperature of fish remains constant during the pause, while the surface temperature is increasing and center temperature is decreasing simultaneously, Figur 12. This is valid under assumption that heat exchange between fish and environment if negligible small, for example, bulk of fish in storage tank before gutting. Thus the knowledge of correct adiabatic temperature gives an opportunity to decrease the chilling time before or between different processing operations.



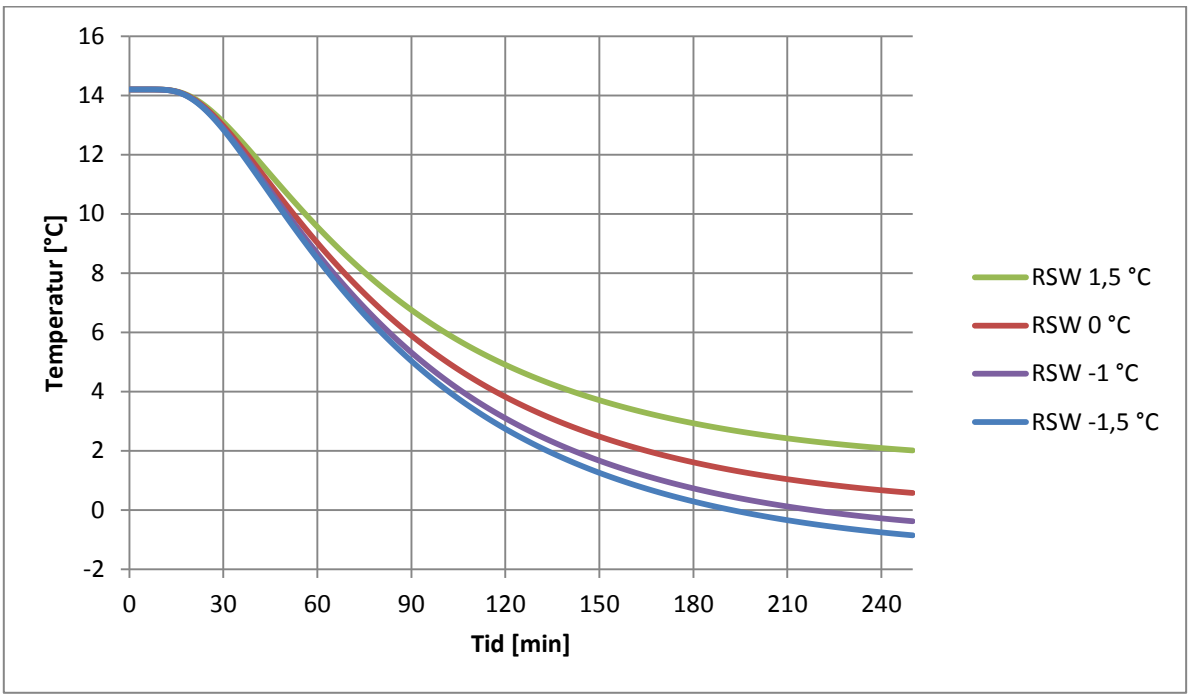
Figur 12. *Simulation of temperature profile in fish during "interrupted" chilling. T_c – temperature in center of fish, T_s – temperature under the skin of fish, T_adi – adiabatic temperature of the fish.*

3.4. Influence of different factors on chilling process of salmon

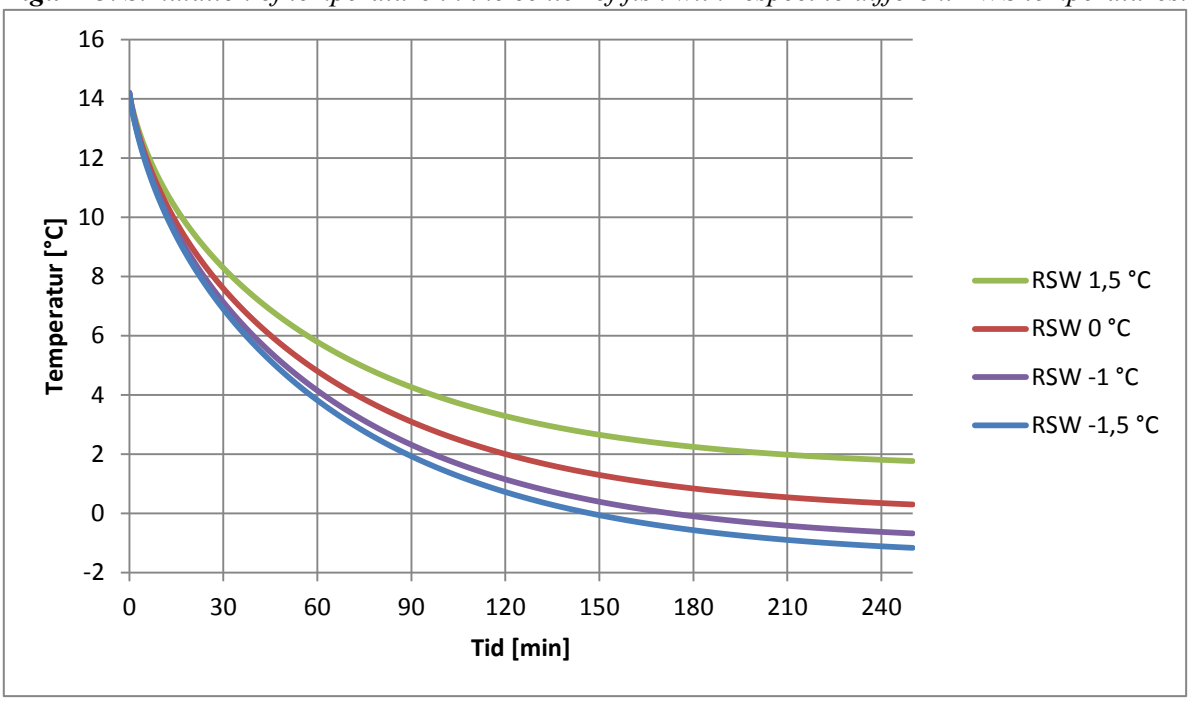
The influences of several factors were simulated by use of the verified model:

- Temperature of seawater were varied in the range between -1.5 and 1.5 °C;
- Convective heat transfer coefficient was changed from 75 to 25 W m^{-2} K^{-1};

The RSW temperature is the most important parameter, because temperature different accelerates heat transfer rate. This is an important parameter when thermal conductivity of the fish is relatively low (all food products). Figures 13 and 14 illustrate the chilling process at different RWs temperatures. The influence of RSW temperature is more detectable, when the deference between cooling media temperature and center/adiabatic temperature is exceeded 8 °C. Thus the lower temperature of RSW is preferable on the final stage of cooling, when the higher temperature of RWS will be suitable at the beginning of the precess.

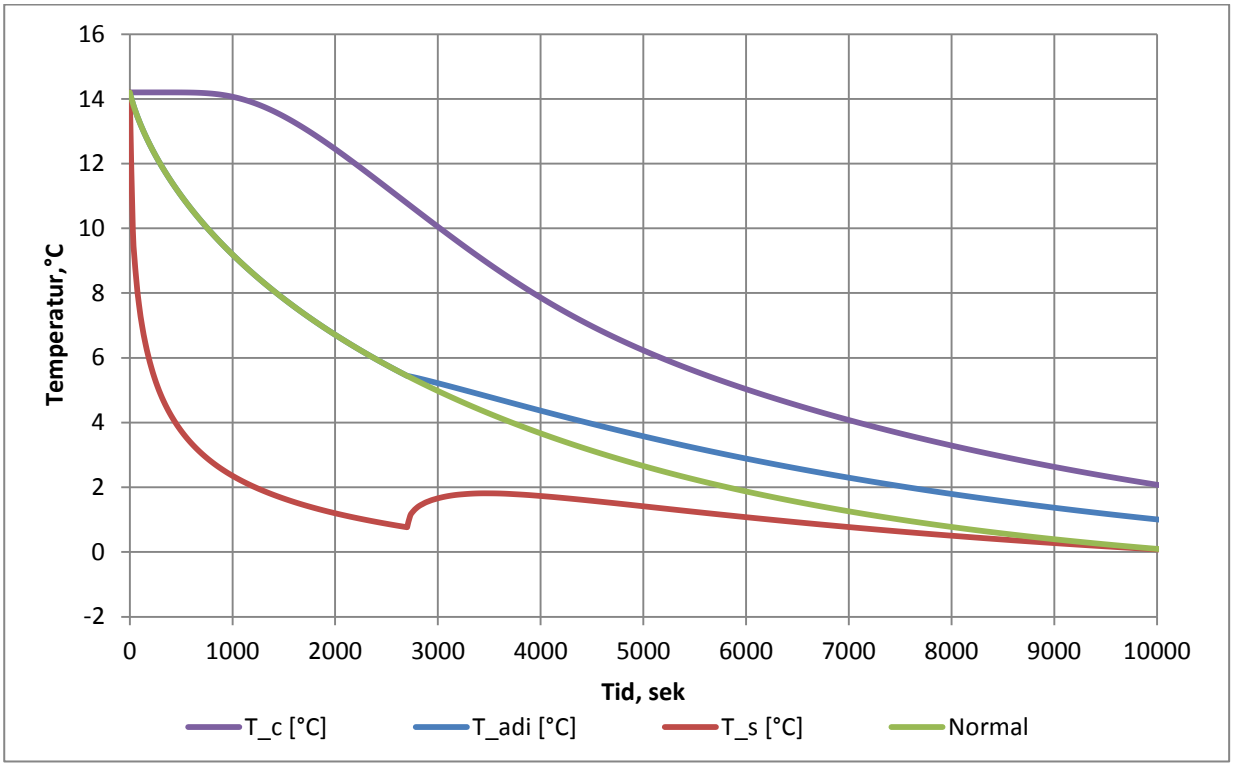


***Figur 13**. Simulation of temperature in the center of fish with respect to different RWS temperatures.*



***Figur 14.** Simulation of adiabatic temperature of fish with respect to different RWS temperatures.*

The decreasing of the h_c in the end of the chilling process increases the chilling time significantly, Figure 15.



Figur 15. *Simulation Salmon chilling when h_c was changed from 75 to 25 W m^{-2} K^{-1} after 45 minutes from the beginning of the chilling process.*

3.5. Comparison between chilling of gutted fish and alive fish

Prediction of the chilling time of live salmon was not investigated in an excessive way during the last period. The following factors make this chilling preferable:

- High heat exchange rate due to blood circulation in alive fish;
- The process can be held in a special tanks simultaneously with "resting" of fish;
- The temperature of fish before slaughtering can vary, which decreases refrigeration loads during processing.

The following dependence was obtained before to predict the chilling time of alive Salmon:

The chilling dynamics of the alive fish was described by Skjervold (2002).

The fish body temperature response after a sudden shift from one constant temperature to another was described by eq. 3:

$$F(t) = (F(0) - C)\exp[-kt] + C \qquad (3)$$

where $F(t)$: fish body temperature, C: constant temperature of the chilling water, $k>0$: the rate of chilling, and $F(0)$: fish body temperature as it enters the chilling water ($t=0$).

The chilling rate from Eq. (3) is likely to depend on fish body weight, W, and such results have also been reported (Beitinger et al., 1977):

$$k = \theta_1 + \theta_2 W^{\theta_3} \qquad (4)$$

In a practical situation, sea temperature S is measured instead of initial fish body temperature F(0). Since the fish has been in this water for a long time prior to chilling, we may assume that its body temperature is very well reflected by this temperature:

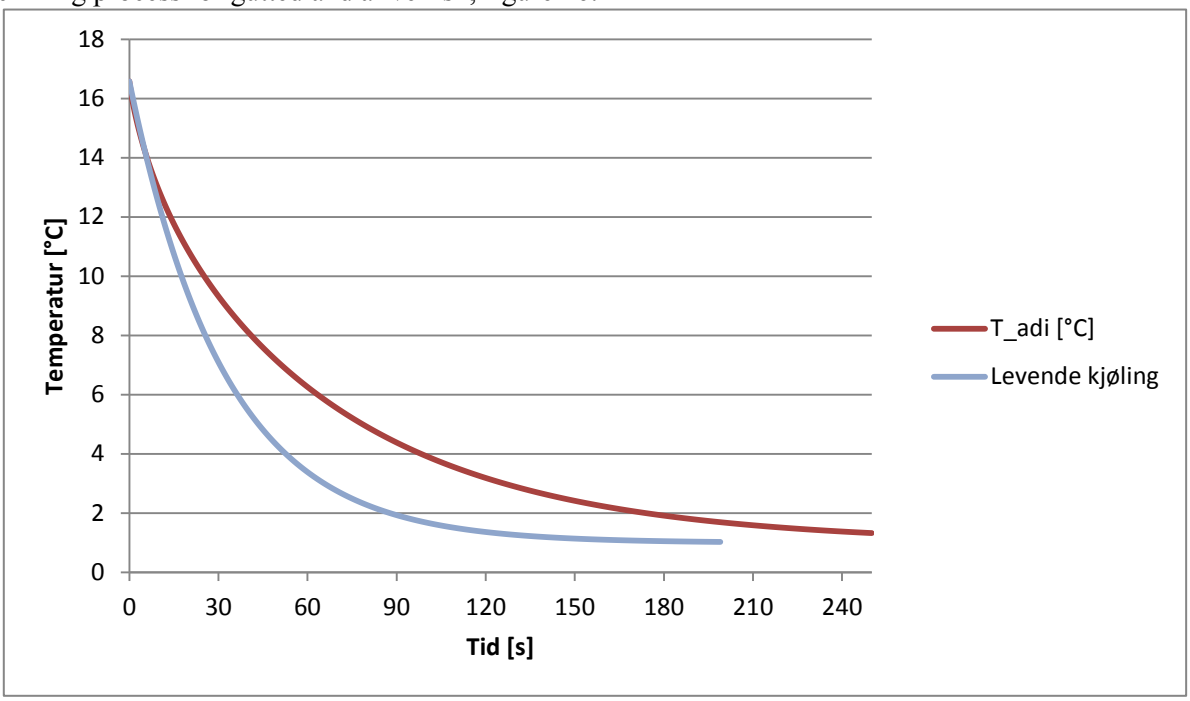
$$F(0) = S + \theta_4 + \theta_5 W \qquad (5)$$

where θ4 - constant offset and θ5 - effect of fish body weight on the difference between sea water and fish body temperature at steady state.

Thus Eq. 3 can be introduces like this:

$$F(t) = (S + \theta_4 + \theta_5 W - C)\exp[-(\theta_1 + \theta_2 W^{\theta_3})t] + C. \qquad (6)$$

The eq. 6 is empirical, the heat transfer is introduced through the empirical values and limitation of this method is not clear. However, knowledge of coefficients for this equation gives an opportunity to compare the chilling process for gutted and alive fish, figure 16.



Figur 16. *Comparison between chilling of alive fish and gutted fish at the same RSW temperature.*

Definitely, the chilling time of alive fish is significantly lower, when compared with gutted fish. At the same time this method has some limitation:

Crowding

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 et al., 2001).

Temperature difference

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 et al., 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 and 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 et al., 2012). Thus the high rate of heat exchange, probably, is not preferable for alive chilling of Atlantic Salmon.

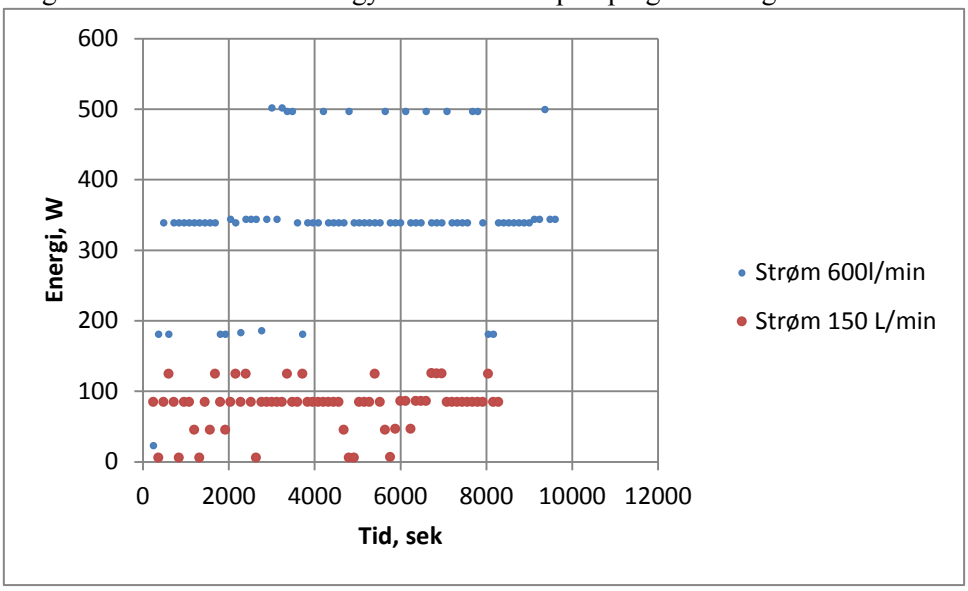
3.6. Energy efficiency on the chilling process in RWS tank

The main energy losses appear through excessive heat exchange rates between the walls of the RWS tank and environment. For conditions, which were maintained in the experiment, the air temperature was in between 18 and 21 °C. The consumption of energy was measured using following equation 7:

$$W = m * c_p \Delta t$$

Where m – water flow, kg s^{-1}; c_p – heat capacity of water at 0 °C, Δt - temperature difference inlet/outlet.

The energy consumption of energy for water refrigeration was significantly higher for high water flow, figure 17. This figure does not include energy consumed for pumping the refrigerated water.



Figur 17. *Energy consumption of RWS system for different water flows.*

It should be noted that for this experiment water flow did not influence on the chilling time, thus the the energy losses were even unnecessary.

3. References

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A Appendix

Determination of convective heart transfer coefficients at different mass flow of water

Time, sek	Water flow, 150 L min^{-1}		Water flow, 300 L min^{-1}		Water flow, 150 L min^{-1}	
	$T_{cylinder, average}$	$T_{ambient}$	$T_{cylinder, average}$	$T_{ambient}$	$T_{cylinder, average}$	$T_{ambient}$
0	18,48	-0,93	19,42	-0,65	16,77	-0,81
10	14,04	-0,90	18,38	-0,65	10,55	-0,86
20	10,40	-0,92	12,96	-0,68	5,95	-0,81
30	7,89	-0,91	9,74	-0,68	3,31	-0,83
40	6,10	-0,92	7,38	-0,70	1,81	-0,79
50	4,73	-0,91	5,52	-0,68	0,91	-0,79
60	3,70	-0,90	4,26	-0,66	0,34	-0,81
70	2,83	-0,92	3,19	-0,65	-0,05	-0,83
80	2,15	-0,90	2,42	-0,65	-0,34	-0,78
90	1,63	-0,87	1,81	-0,65	-0,51	-0,81
100	1,16	-0,90	1,25	-0,67	-0,63	-0,79
110	0,77	-0,89	0,81	-0,67	-0,69	-0,81
120	0,45	-0,92	0,50	-0,65	-0,77	-0,80
130	0,18	-0,90	0,26	-0,65	-0,79	-0,81
140	-0,05	-0,90	0,08	-0,66	-0,82	-0,78
150	-0,19	-0,90	-0,10	-0,64		
160	-0,40	-0,92	-0,26	-0,62		
170	-0,47	-0,92	-0,37	-0,66		
180	-0,60	-0,89	-0,45	-0,69		
190	-0,67	-0,92	-0,54	-0,66		
200	-0,74	-0,94	-0,58	-0,67		
210	-0,79	-0,94	-0,62	-0,70		
220			-0,67	-0,68		
230			-0,71	-0,66		

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