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CFD Modelling and Quality Forecasting for Cooling and Storage of Pelagic Species

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Report Summary

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Titill / Title	**CFD Modelling and Quality Forecasting for Cooling and Storage of Pelagic Species.**		
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Ágrip á íslensku:	Í verkefninu er tölvuvætt varma- og straumfræðilíkan af geymslutönkum uppsjávarafla smíðað. Inntak líkansins er tímaháður umhverfishiti sem aftur skilar hitastigsdreifingu þeirrar blöndu uppsjávarafla og sjós sem geymd er í tönkunum. Það líkan er svo samtvinnað gæðaspálíkani sem segir til um þróun skemmdareinkennandi efna svo sem TMA og NH_3 út frá þeirri hitastigssögu sem fæst úr varmafræðilíkaninu. Meginafrakstur verkefnisins er þróun og beiting tækni sem gerir það mögulegt að spá fyrir um skemmdaferla uppsjávarafla við gefna umhverfishitasögu. Sú tækni gæti reynst gríðarlega notadrjúg í meðhöndlun og vinnslu uppsjávarafla. Samstarfsfyrirtæki í verkefninu eru Síldarvinnslan, Skinney-Þinganes og HB Grandi.		
Lykilorð á íslensku:	Tölvuvædd varma- og straumfræði, uppsjávarfiskur, gæðaspálíkan		
Summary in English:	In this project a thermodynamic model of storage tanks used for cooling and storage of pelagic species is constructed. The input for the model is transient ambient temperature, which gives the temperature and velocity distribution in the mixture of pelagic species and seawater. This model is then coupled with a quality forecast model, which predicts the development of spoilage indicators such as TMA and NH_3 from the temperature time series which are retrieved from the thermodynamic model. The main result of the project was the development and application of a technique which makes it possible to predict the spoilage of pelagic species given only ambient temperature history. This could prove immensely useful in the management and processing of pelagic species. The following companies take part in this project: Síldarvinnslan, Skinney-Þinganes and HB Grandi.		
English keywords:	Computational fluid dynamics, pelagic species, quality forecasting		

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1 Introduction

In this study storage tanks for pelagic species are thermodynamically modelled. The model is based on four tanks located in Höfn, a town in SE-Iceland and are owned and operated by Skinney-Þinganes, a fisheries firm operated from the same location. The layout of the tanks can be seen in Figure 1.

In the thermodynamic modelling a transient temperature load can be applied which then gives the corresponding temperature and velocity distribution of the mixture of seawater and pelagic species.

The thermodynamic model is then coupled with a quality forecasting model where a set of differential equations is constructed based on experimental results about the formation of spoilage indicators such as TMA and NH_3 over time for a given temperature history.

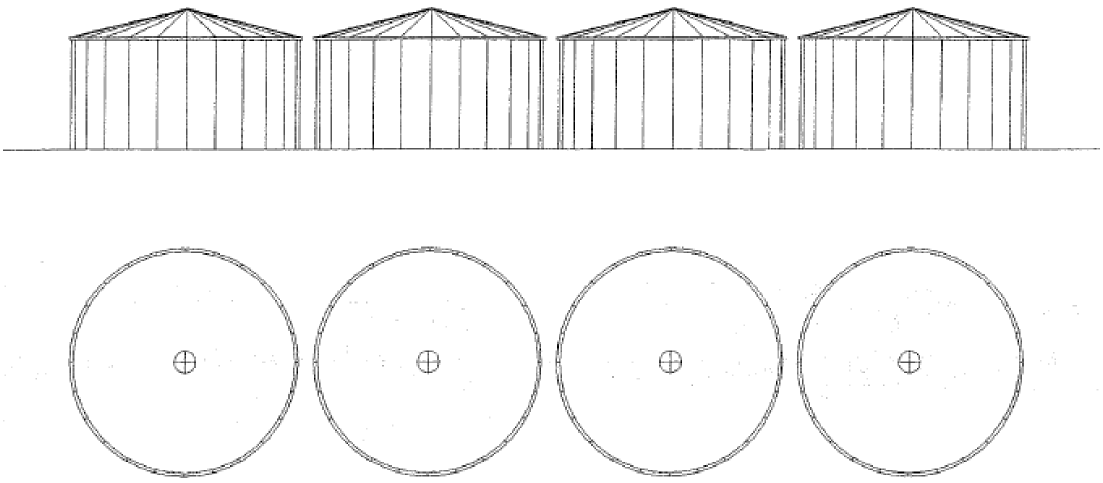

Figure 1: Setup of storage tanks for pelagic species in Höfn.

2 Methods and materials

2.1 Model parameters

The tanks are modelled two-dimensionally since they are assumed to be fully axi-symmetric. Each tank can hold up to V=400m^3 and has an inner radius of r_i = 5m and height of h_t = 5.1m. The tanks have t_t=15 cm thick concrete walls making the outer radius r_o=5.15m. When modelling the use of ice slurry a certain part of the volume is modelled as solid ice. This is done since it is computationally unfeasible to model each particle in the ice slurry.

2.2 Thermodynamic parameters

In this study both transient temperature and a constant temperature of 15°C is applied to the system. The heat is conducted through a 15cm thick concrete wall. The concrete is assumed to have the following thermodynamic properties: ρ =2300 kg/m^3, c_p = 880 J/kg/°C and k=0.63 W/m/K.

The physical properties of seawater are retrieved from Seton Bennett (2008) assuming 3.5% salinity and are listed in Table 1.

Table 1: Physical properties of seawater

T [°C]	**0**	**10**	**20**
P [kg/m^3]	1028.1	1026.96	1024.75
c_p [J/kg/K]	3985	3989	3993
k [W/m/K]	0.563	0.5795	0.596
μ [kg/m/s]	$1.88 \cdot 10^{-3}$	$1.48 \cdot 10^{-3}$	$1.08 \cdot 10^{-3}$

The physical properties of pelagic species are assumed to be the same as white fish where the heat capacity and conductivity are retrieved from J. Zueco (2003).

Table 2: Physical properties of pelagic fish

T [°C]	**0**	**10**	**20**
P [kg/m^3]	1070	1069.2	1067.7
c_p [J/kg/K]	4144	3683	3222
k [W/m/K]	0.43	0.43	0.43
μ [kg/m/s]	-	-	-

What is probably the largest assumption in this study is to consider the fish and seawater mixture as a homogeneous fluid. This is done in order to spare computational power and thereby speed up the calculations. The physical parameters are weighted in relation to the mass percentage of each material.

Table 3: Physical properties of fish and seawater

T [°C]	0	10	20
P [kg/m^3]	1053.24	1052.31	1050.49
c_p [J/kg/K]	4080	3805	3530
k [W/m/K]	0.4832	0.4898	0.4964
μ [kg/m/s]	$1.88{\cdot}10^{-3}$	$1.48{\cdot}10^{-3}$	$1.08{\cdot}10^{-3}$

The physical parameters displayed in the tables above are interpolated linearly as a function of temperature during the solution of the model.

2.3 Meshing

In this unsteady free convection problem choosing a suitable time-step and grid spacing is essential for a successful meshing strategy. The thickness of the boundary layer for a vertical flat plate in a free convection problem is determined from Holman (2002) as

$$\frac{\delta}{x} = 3.93\ \mathrm{Pr}^{-\frac{1}{2}}(0.952 + \mathrm{Pr})^{1/4}\ \mathrm{Gr_x}^{-1/4}$$

which at *x*=0.5m gives a boundary layer thickness of *δ*=8.1 mm. The cell dimensions at the boundary layer are therefore chosen as Δx=2 .0 mm.

west side

axi-symmetric boundary condition

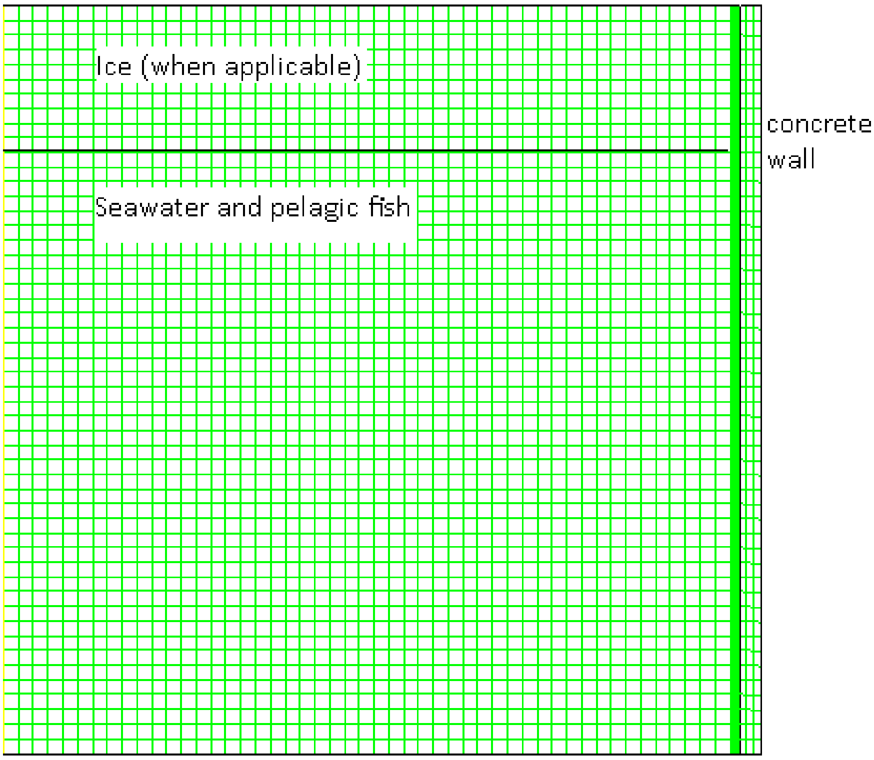

Figure 2: Meshing of the model, where an axi-symmetric boundary condition is used at the west side.

Even though an implicit solution method is used to solve the time dependent problem the time step is chosen such that the resulting Courant number is close to 1 such that

$$\Delta t = \frac{\Delta x}{u} Cu$$

Iterating the model gives a maximum velocity of u_{max}=0.015m/s which results in a time step of$\Delta t = 15s$.

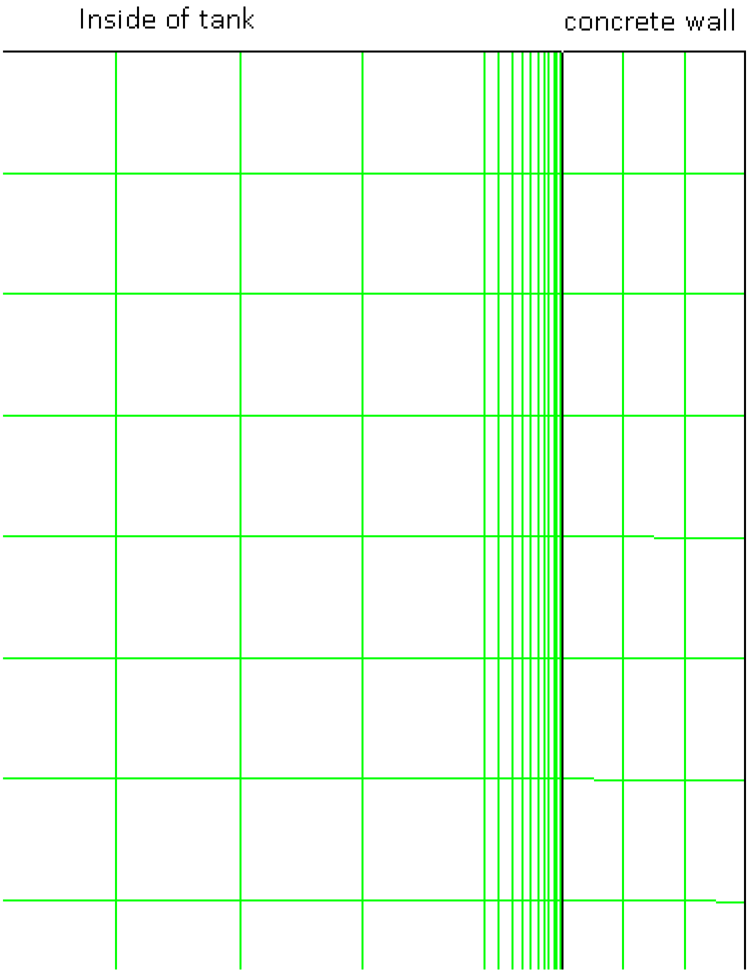

Figure 3: Meshing of the boundary layer at the concrete wall.

2.4 Solver

The problem is solved using Fluent, a general purpose CFD program based on the finite volume method. An unsteady, pressure based axi-symmetric solver is used. Buoyancy is modelled using the Boussinesq approximation where the change in density is assumed to be a linear function of temperature on an interval. A gravitational acceleration of 9.81 m/s^2 and an operating temperature of 273.15 K are used in the Boussinesq approximation. The specific heat and thermal conductivity of fish and seawater is interpolated linearly in the model using the parameters displayed in Table 3.

2.5 Boundary conditions

The surface of the fish-water mixture is assumed to have a constant heat transfer coefficient of *h*=10 W/m^2/°C, which is a reasonable value for the heat transfer between water surface and still air (Williams, 1963). The bottom of the tank is adiabatic. In order to validate the model, a transient temperature load is used as a boundary condition on the sides of the tank.

2.6 Model validation

2.6.1 Measurements

For experimental validation data collected by Ásgeir Gunnarsson, Ásgrímur Ingólfsson and Helgi Örn Kristinsson, as a part of their final project from the Technical school in Reykjavík, was used. The data was collected during five landings from the 22nd of November until December 1st 2007.

Data was collected using eight temperature loggers, four at the side at 0.1, 1.1, 2.1 and 3.1 meters height, and four at the centre at the same heights. Temperature was measured at one minute intervals. Slurry ice was used in four cases, before, during and after landing. In one case no slurry ice was used. Data for ambient temperature was retrieved from the Icelandic Meteorological Office for the weather station at Höfn during the same time period.

2.6.2 Analytical computation

In a multilayered cylindrical system the heat flow is given by Holman (2002)

$$q = \frac{2\pi k_c h_t (T_1 - T_0)}{\ln\left[\frac{r_0 + t_t}{r_0}\right]} + h\pi r_0^2 (T_1 - T_0)$$

where T_1 is ambient temperature and T_0 is the temperature of the system. The convective heat transfer coefficient is denoted as *h*. The temperature at time step t_i, can then be found from step t_{i-1} such that

$$T_{0,i} = T_{0,i-1} + \frac{q}{c_p \rho V} t_i$$

This gives the temperature development using a lumped heat capacity system. In such systems a uniform temperature distribution throughout the body is assumed. This is of course an idealization since for conduction to occur a temperature gradient must exist inside a material if heat is to be conducted into or out of the material. This assumption can then be used for comparison with the numerical model.

2.7 Description of the formation of TVN and NH_3 at a constant temperature

The development of the spoilage indicator of total volatile nitrogen (TVN) for herring and blue whiting has been measured by Dr. Eyjolf Langmyre at the Sildolje- og Sildemelindustriens Forsknings-institutt (Magnússon, 2009). In that research the environment in a ship hull was simulated at a constant temperature while the formation of TMA and NH_3 were measured. The relationship between temperature and the formation of those compounds was described by constructing equations based on that information.

One of the results of that research was that the formation of TMA in herring and blue whiting stored in sea can be modelled in the following way

$$N(t) = \frac{a}{1 + b \cdot e^{-c \cdot t}}$$

where the coefficients a, b and c are displayed for different temperatures in Table 4 for herring and Table 5 for blue whiting, both in a bulk to simulate the conditions in a ship's hull and in a single fish. The coefficient *a* denotes the initial amount of TMAO-N.

Table 4: Coefficients for the equation of TMA formation in herring at three different temperatures

	TMA in herring (bulk)			TMA in herring (single)		
	a	b	c	a	b	c
0°C	50	79	0.42	30	435	0.67
3.7°C	50	401	0.91	30	10630	1.51
9.5°C	50	22411	2.25	30	376823	3.08

Table 5: Coefficients for the equation of TMA formation in blue whiting at three different temperatures

	TMA in blue whiting (bulk)			TMA in blue whiting (single)		
	a	b	c	a	b	c
0°C	80	32.29	0.448	40	12.64	0.506
3.1°C	80	18.01	0.699	40	43.92	0.986
10°C	80	58.34	1.575	40	59.17	1.764

The formation of NH_3 in the herring itself can be modelled such that

$$N(t) = a \cdot e^{b \cdot t}$$

where the coefficients a and b are displayed in Table 6 for herring and Table 7 for blue whiting.

Table 6: Coefficients for the equation of NH_3 formation in herring at three different temperatures

	NH_3 in herring (bulk)		NH_3 in herring (single)	
	a	b	a	b
0°C	9.4	0.077	9.4	0.081
3.7°C	9.4	0.113	9.4	0.129
9.5°C	9.4	0.205	9.4	0.239

Table 7: Coefficients for the equation of NH_3 formation in blue whiting at three different temperatures

	NH_3 in blue whiting (bulk)		NH_3 in blue whiting (single)	
	a	b	a	b
0°C	9	0.112	9	0.144
3.1°C	9	0.186	9	0.175
10°C	9	0.343	9	0.337

2.8 Quality forecasting model

The equations above cannot be applied directly for temperature modelling as they are only valid for constant temperatures. By using a second order interpolation of the experimental data the following system of equations is retrieved in the case of herring stored in a bulk

$$
\begin{aligned}
&\mathrm{TMA} = c \cdot \mathrm{TMA}_0 - \frac{c}{a} \cdot \mathrm{TMA}_0^2 \\
&c = 79.3687 - 0.8118 \cdot T + 0.0019 \cdot T^2 \\
&a = 30
\end{aligned}
$$

$$
\begin{aligned}
&\mathrm{NH_3} = v \cdot (\mathrm{NH_3})_0 \\
&v = 38.3817 - 0.29219 \cdot T + 0.00056 \cdot T^2
\end{aligned}
$$

$$\mathrm{TVN} = \mathrm{TMA} + \mathrm{NH_3}$$

and for blue whiting in a bulk the formation of TVN as a function of temperature is given as

$$
\begin{aligned}
&\mathrm{TMA} = c \cdot \mathrm{TMA}_0 - \frac{c}{a} \cdot \mathrm{TMA}_0^2 \\
&c = 325.3523 - 2.4457 \cdot T + 0.0046 \cdot T^2 \\
&a = 80
\end{aligned}
$$

$$
\begin{aligned}
&\mathrm{NH_3} = v \cdot (\mathrm{NH_3})_0 \\
&v = -14.83958 - 0.08525 \cdot T + 0.00011 \cdot T^2
\end{aligned}
$$

$$\mathrm{TVN} = \mathrm{TMA} + \mathrm{NH_3}$$

The time dependent problem is then solved by solving the differential equations

$$
\begin{aligned}
&\frac{d}{dt}\mathrm{TMA} = c \cdot \mathrm{TMA} - \frac{c}{a} \cdot \mathrm{TMA}^2 \\
&\frac{d}{dt}\mathrm{NH_3} \; = v \cdot \mathrm{NH_3}
\end{aligned}
$$

using numerical methods such as a fourth order Runge-Kutta solver with temperature history as an input.

3 Results

3.1 Unsteady temperature load

For the unsteady temperature load the temperature history from the 21st of November until the 1st of December at Höfn was used. A layer of 0.5m thick ice is assumed to be on top of the fish and seawater mixture.

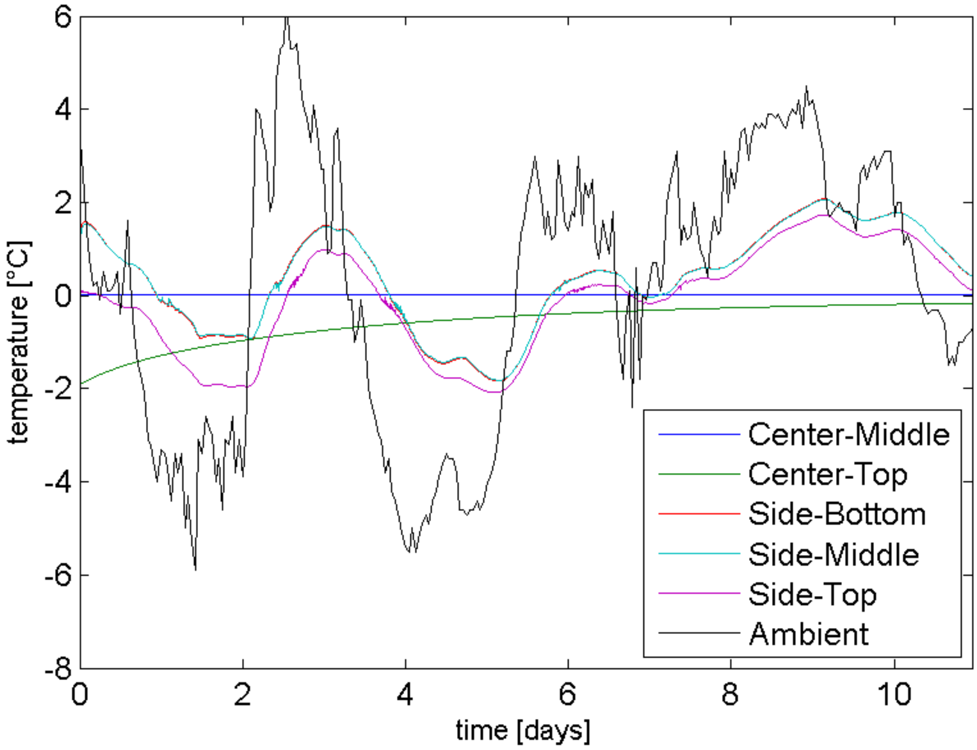

Figure 4: Response of the system to an unsteady temperature load with ice

Figure 4 shows the temperature response to that particular heat load. The lines labelled with 'centre' are located at the axi-symmetric boundary condition, at a height of 2.5m (middle) and 5m (top). The lines labelled as 'side' are located at the boundary between the concrete wall and the fish-seawater mixture at heights 0m (bottom), 2.5m (middle) and 5m (top). In all cases the temperature history is interpolated linearly in three dimensions, height, radius and time. The points at the sides are the fastest to respond since the only thermal barrier between them and the heat load is a 15cm thick concrete wall. When approaching the centre of the storage tank, the temperature distribution becomes more uniform, as the ice melts to compensate for increased heat in the system. The temperature at the centre of the tank remains at 0°C throughout the time period which was observed since the heat load is not enough to fully melt the ice which was put in the tank. The temperature where the ice is located stabilizes at 0°C rather than -1.9°C, which is the melting point for 3.5% brine, since the usage of flake ice is assumed, which is produced without salt. The temperature of the ice layer itself (Centre-Top) steadily increases during the time period and approaches melting point at the end of it.

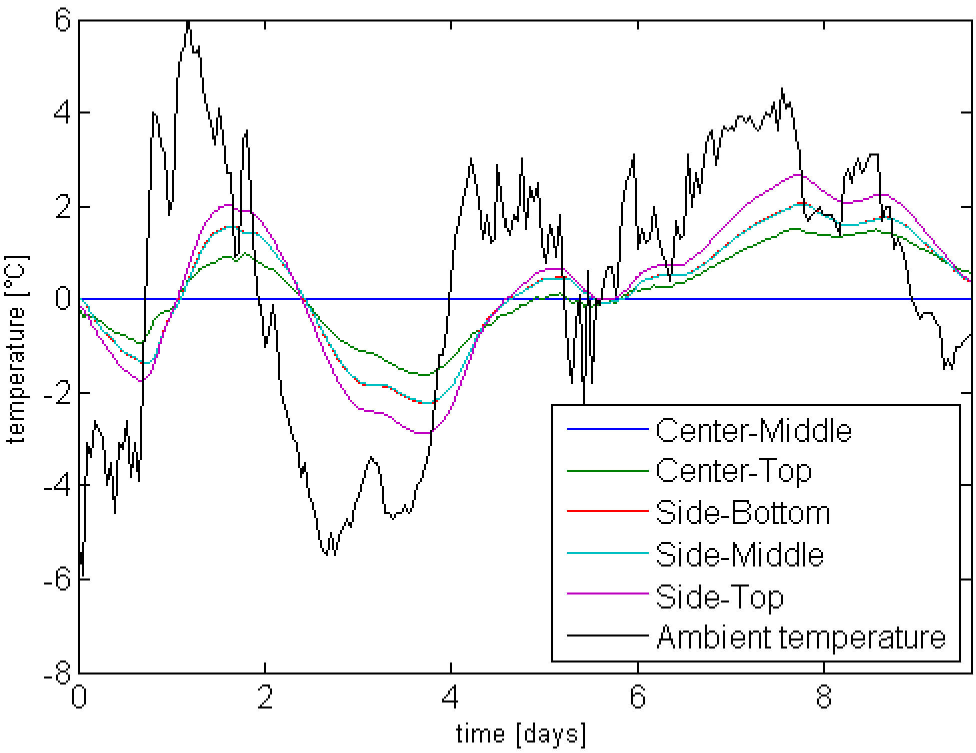

Figure 5: Response of the system to an unsteady temperature load with no ice

Figure 5 shows the temperature response to the heat load from the 22nd of November until the 1st of December without ice in the system. The system seems to respond slightly faster to temperature load than without ice. Had the temperature load during that period been more, a sharper contrast would probably have emerged between the system with ice and without ice.

3.2 Steady temperature load

In the problem with a steady temperature load an initial temperature of 0.3°C was used and a temperature load of 15°C applied.

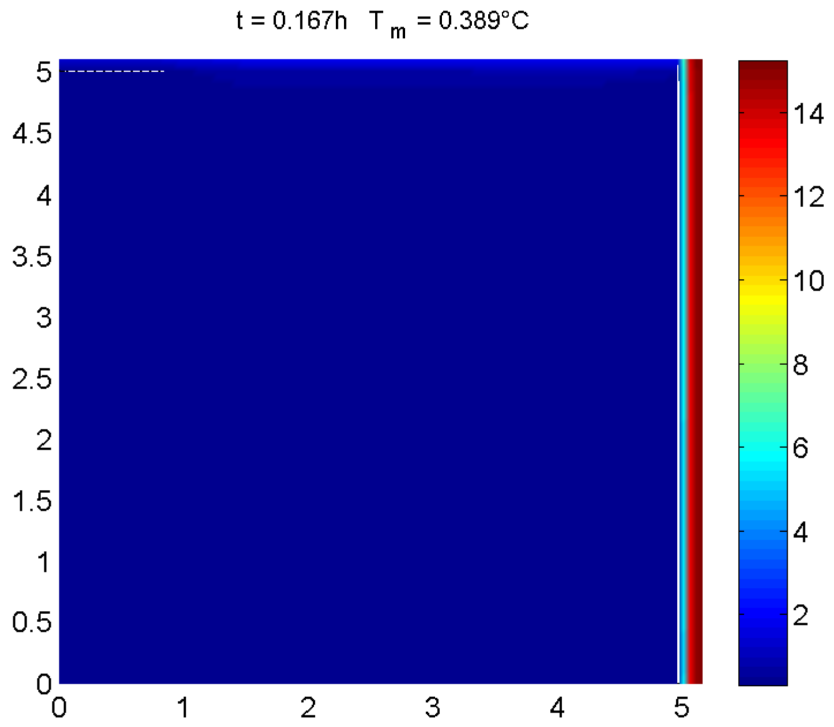

Figure 6: Temperature profile of the tank at 0.167h with a temperature load of 15°C applied.

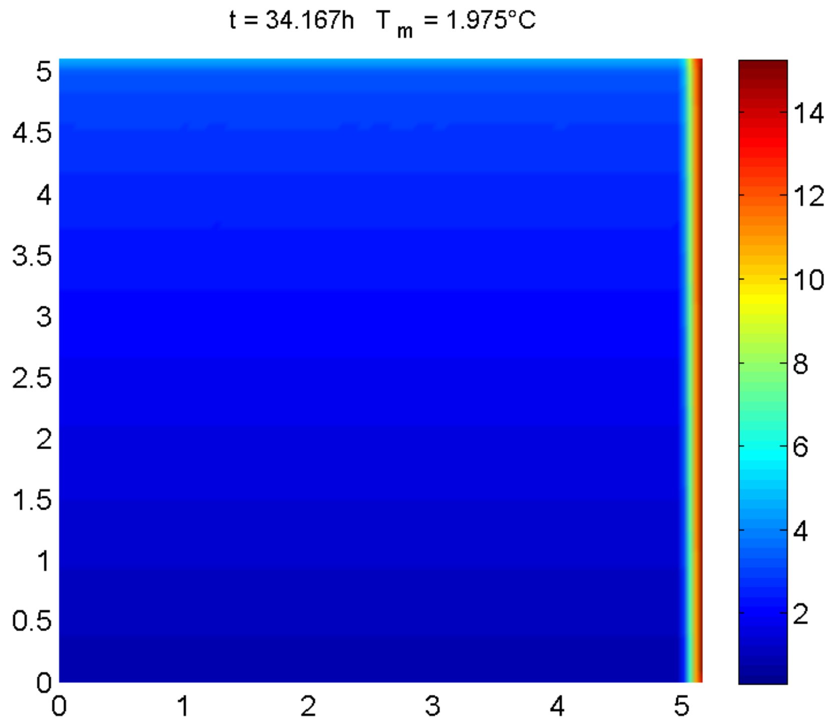

Figure 7: Temperature profile of the tank at 34.167h with a temperature load of 15°C applied.

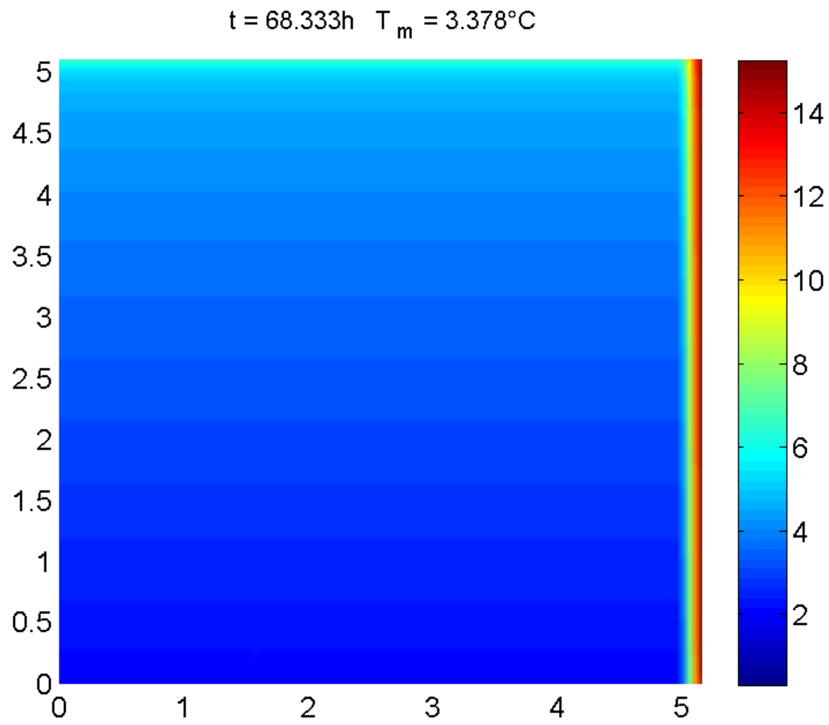

Figure 8: Temperature profile of the tank at 68.333h with a temperature load of 15°C applied.

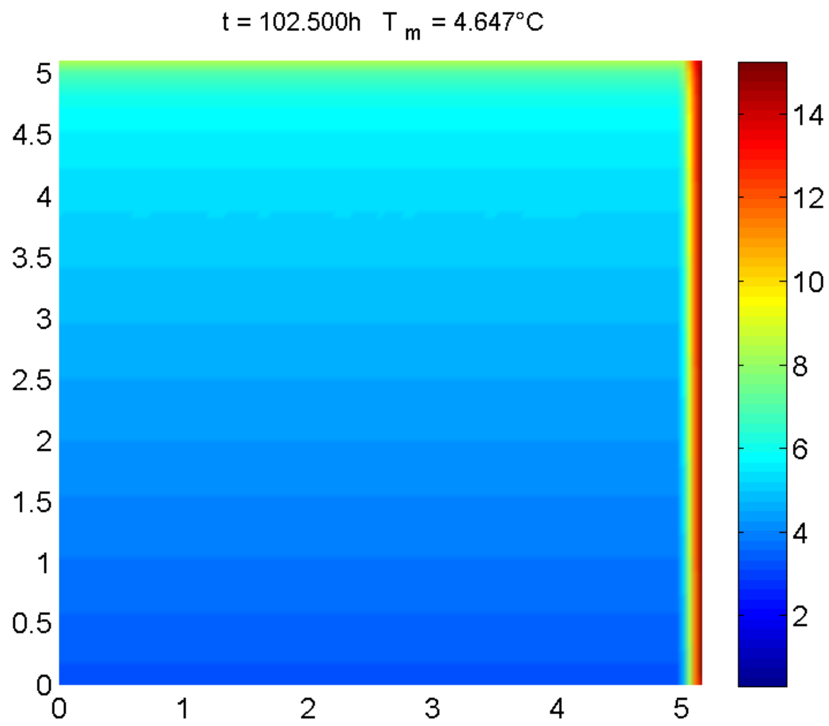

Figure 9: Temperature profile of the tank at 102.500h with a temperature load of 15°C applied.

Figure 6-Figure 9 show the development of the temperature profile in the system when a stable temperature load of 15°C is applied. The temperature at points closest to the top and sides increases

fastest, but the temperature change decreases in the deeper parts of the tank. The mean temperature (T_m) goes from 0.4°C to 4.6°C the 102.5 hours which are observed. The vertical-gradient of the temperature seems to be dominant, as the Boussinesq approximation gives buoyancy to warmer water.

A small boundary layer can also be seen at the boundary between the concrete wall and the fish and seawater mixture. In fact, the heat input there creates a circulation in the system, where warm fluid rises to the top, mixes with colder fluid, and falls to the bottom close to the axi-symmetric boundary at the centre of the tank.

3.2.1 Comparison with analytical results

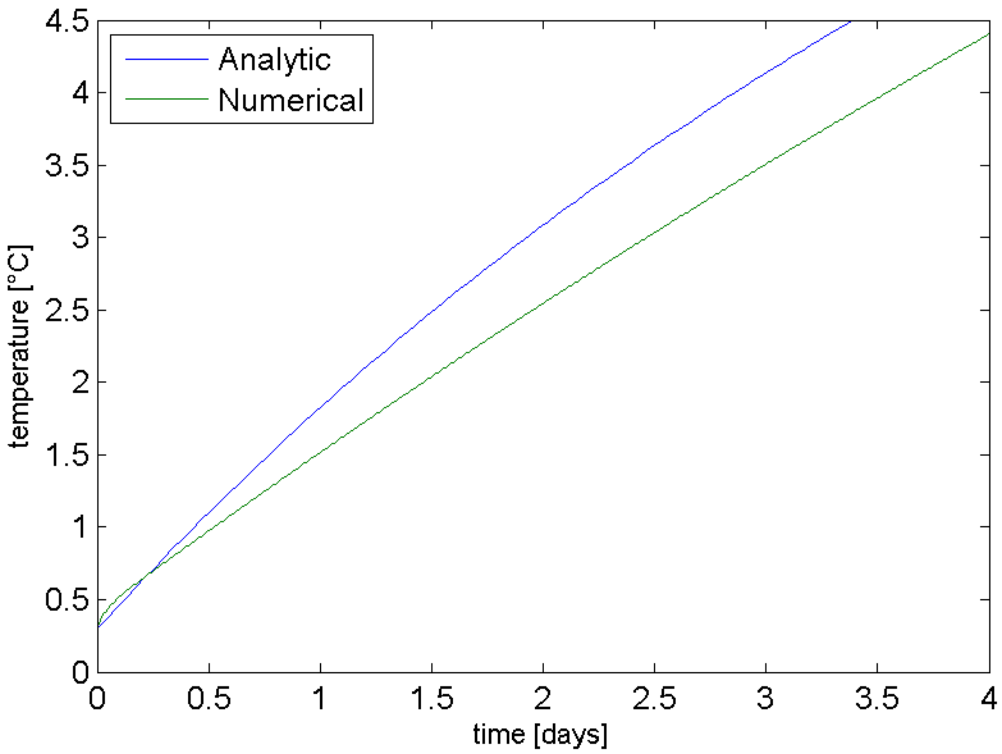

Figure 10: Comparison of an analytic method using lumped heat capacity system and the numerical method applied in other calculations.

Figure 10 shows the temperature development assuming a steady ambient temperature of 15°C and an initial temperature of fish and seawater of 0.3°C. Using the numerical method the average temperature of the fish-seawater mixture is found over the temperature distribution in the entire tank displayed in Figure 6-Figure 9. The temperature profiles seem to follow each other rather closely. However, the temperature found using the lumped heat capacity model seems to rise slightly faster than that using the numerical method. The reason for this is that in the analytical model the only resistance for heat to be pumped into the system is the concrete wall, while the heat resistance of the fish-seawater mixture is not taken into account. The similarity of the two temperature profiles can be seen as an indication that the model is accurate, and increases confidence in the numerical solution.

3.3 Development of TMA and NH_3

Applying the temperature development shown for the numerical solution in Figure 10 where a steady temperature load of 15°C is applied can now be used to calculate the development of the TMA, NH_3 and TVN in the catch over time.

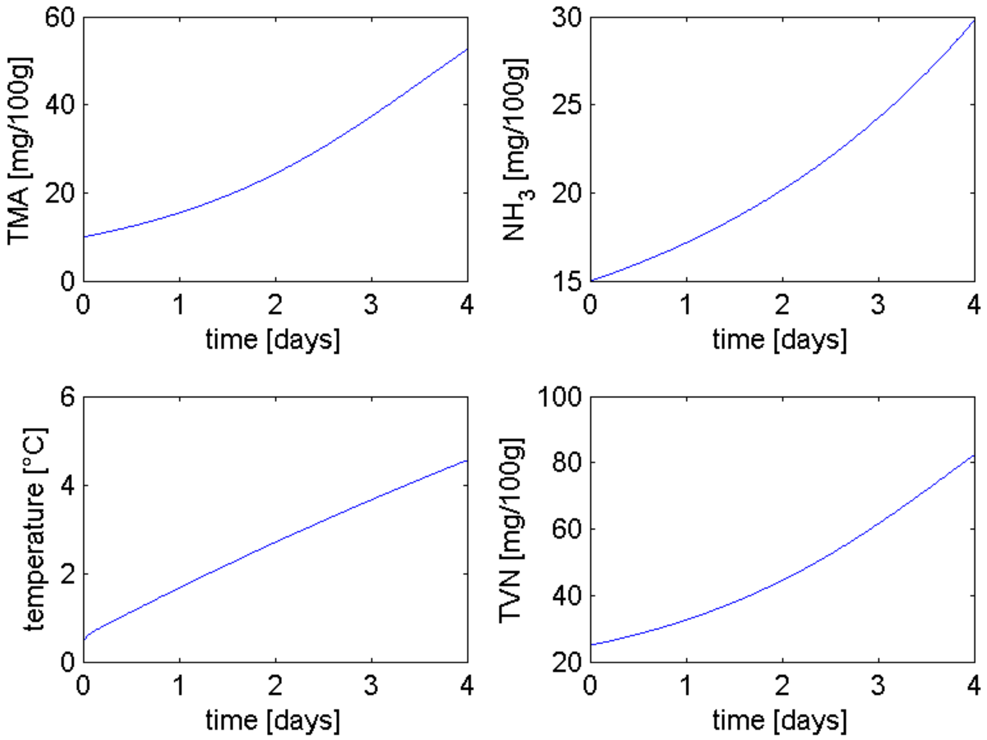

Figure 11: Formation of TMA, NH3 and the resulting TVN for the average temperature in the tank applying a 15°C steady temperature load.

Assuming an initial amount of TMA_0=10 mg/100g and $(NH_3)_0$=20 mg/100g the graphs displayed in Figure 11 are generated. The raw material is assumed to be blue whiting.

The temperature increases steadily during the four days which are examined, which results in a slow generation of TMA and NH_3 the first two days which then begins to increase rapidly and ends in a total volatile nitrogen (TVN) content of approximately 92 mg/100g.

The limits for production of high quality fish meal is usually around 100-120mg/100g (Gunnarsson, 1998). The final value of TVN for this given temperature history and initial values of TMA and NH_3 is slightly lower than this limit.

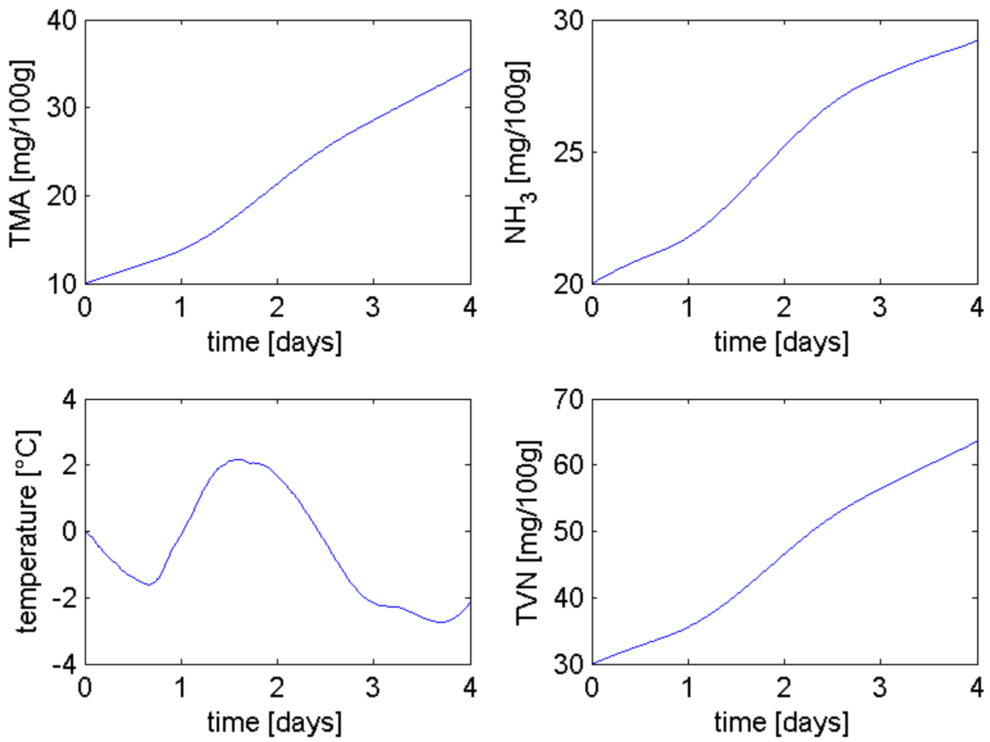

Figure 12: Formation of TMA, NH3 and the resulting TVN for the temperature at the top of the tank closest to the wall where the same temperature load as in Figure 5 is applied.

The model which has been developed in this project is very robust in the sense that it can be applied to any point in a CFD model which can also be forced with any temperature time series. This is done by coupling Fluent, a general purpose CFD program, with MATLAB, a high performance language for technical computing.

Figure 12 shows the versatility of the methodology which has been developed in this project. The point at the top of the tank closest to the concrete wall is selected which is the most sensitive to external temperature load. The same transient temperature history as in Figure 5 is then applied to the system for the first four days and the resulting spoilage indicators found using the quality forecasting model.

The influence of temperature on the spoilage indicators can clearly be seen on Figure 12 where a rise from -1°C to 2°C on the second day greatly increases the formation of TMA and NH_3. The speed at which the TMA and NH_3 are generated then decreases again when the temperature gets lower. Since the ambient temperature is low during that time period the overall formation of TVN is limited and well within the limits of high quality meal, where the final value at day 4 is approximately 63mg/100g.

4 Conclusions and future work

The main conclusion is that it is possible to model heat transfer in storage tanks for pelagic species using computational fluid dynamics. Both steady and transient temperature load can be applied and the usage of flake ice can be taken into account by modelling a certain portion of the system in a solid phase. The numerical method gives similar results as the lumped heat capacity method, but is probably more accurate since it takes into account heat transfer inside the medium, rather than assuming it as a body with uniform temperature distribution.

During the time period, which the effects of a transient temperature load were examined, the temperature fluctuated around 0°C. The result of this was a limited effect on the average temperature on the fish-seawater mixture. However, the response of the system was evident, especially close to the concrete walls and the top layer of the mixture.

The quality forecast model was also successfully coupled into the thermodynamic model by integrating Fluent with the technical computing language MATLAB. This way it is possible to directly forecast the quality of the catch from ambient temperature only. This could prove immensely useful in the management and processing of pelagic species.

In future work the model could be improved in several ways. The assumption that the mixture of fish and seawater can be examined as a homogenous fluid is the most likely to introduce some inaccuracies. A more detailed solution to that problem would be very useful for further studies utilizing computational fluid dynamics in the seafood industry.

The model could be improved in several other ways. For example some methods could be developed to take the surface area of the flake ice into account. That would likely give a more realistic image of the effects of ice application and to which extent it stabilizes the temperature of the contents of the tanks. Another way, in which the model could be improved, would be to introduce air-convection outside the walls of the tanks. This could be a good improvement on the model, and introduce the effects of wind speed on temperature response.

Experimental results on the formation of TMA and NH_3 in pelagic species given some transient temperature load could prove to be very useful in future research. This could improve the quality forecasting model and hence further increase its reliability.

Acknowledgements

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