Modeling of the Freezing Process for Fish in Vertical Plate Freezers

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SINTEF

Introduction

Aims of the **SINTEF**-project *DANTEQ*[a]:

- **Reduce energy consumption** of a freezer-trawler and at the same time **preserve / enhance fish quality**.
- This needs an overall look on the big consumers on a freezer-trawler.

First step: Look at the freezing system on board.
Aims of this study:

- Find a model to estimate the temperature distribution in a fish block during freezing in vertical platefreezers.
- For a known temperature distribution the energy input to freeze the fish block can be precisely set.

[a] Development and assessment of novel technologies improving the fishing operation and on board processing with respect to environmental impact and fish quality

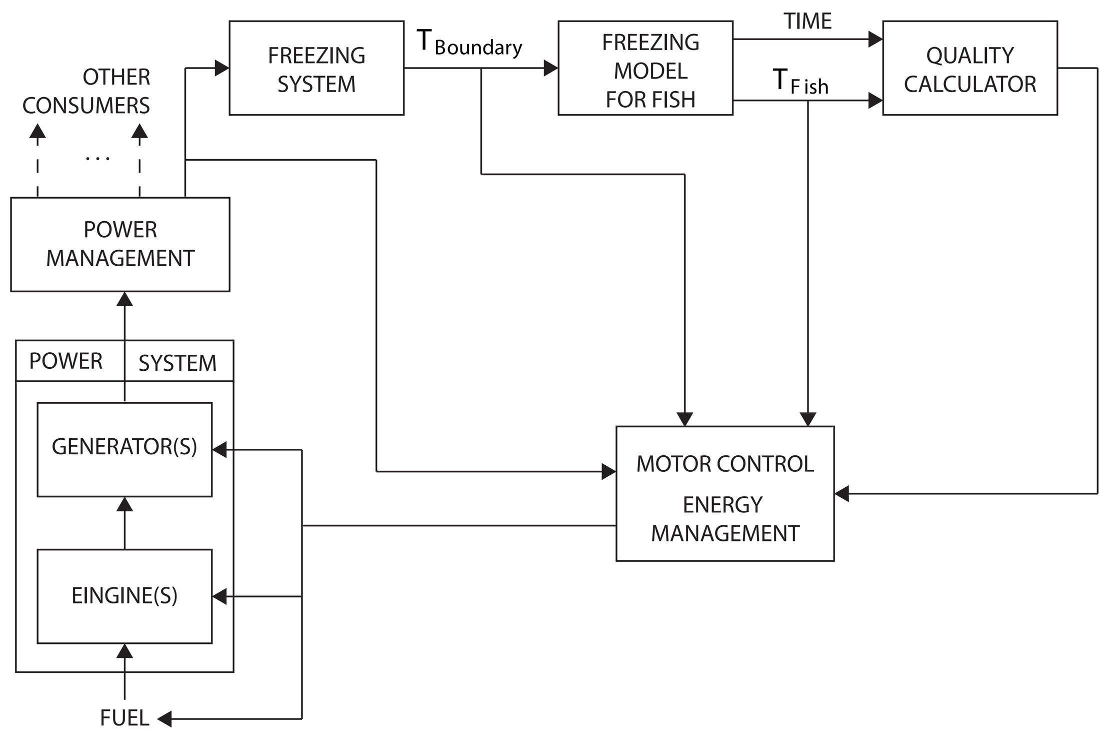

Figure 1: Simplified control scheme

The *freezing system* is an ammonia-circle-process and consists of [2]:

- compressor-unit
- condenser-unit
- separator (ammonia in liquid and vapor state)
- ammonia pump
- platefreezer

The *freezing model* for fish is a parameter-modified partial differential equation.

The *quality calculator* returns a number, that depends on the sizes of the ice-crystals, which grow depending on time and temperature of the freezing process.

Methods

Figure 2: Vertical platefreezer

The temperature distribution is described by a partial differential equation [1]:

$$\rho(T)\cdot c(T)\cdot\frac{\partial}{\partial t}T(t,x)=\lambda(T)\cdot\frac{\partial^2}{\partial x^2}T(t,x).$$

Further, the Dirichlet boundary conditions and the initial condition are set to:

$$\begin{aligned}T(t,0)&=235.15\text{ K},\\ T(t,L)&=235.15\text{ K},\\ T(0,x)&=283.15\text{ K}.\end{aligned}$$

Fish is considered as a thermodynamical alloy of basic components (water/ice, protein, fat, carbohydrates and ash).
The overall parameters are calculated by adding up the component's parameters multiplied by the mass fractions:

$$\begin{aligned}c(T)&=\sum_i c_i(T)\cdot x_i,\\ \rho(T)&=\sum_i \rho_i(T)\cdot x_i,\\ \lambda(T)&=\sum_i \lambda_i(T)\cdot x_i.\end{aligned}$$

Calculation of $c_i(T)$, $\rho_i(T)$ and $\lambda_i(T)$ according to [3]:

$$\begin{aligned}c_i(T)&=a_{c0,i}+a_{c1,i}\cdot(T-273.15)+a_{c2,i}\cdot(T-273.15)^2,\\ \rho_i(T)&=a_{\rho0,i}+a_{\rho1,i}\cdot(T-273.15)+a_{\rho2,i}\cdot(T-273.15)^2,\\ \lambda_i(T)&=a_{\lambda0,i}+a_{\lambda1,i}\cdot(T-273.15)+a_{\lambda2,i}\cdot(T-273.15)^2.\end{aligned}$$

Mass fractions are considered constant, except for water. Based on [4], an approximated function for the iced fraction of water is chosen to

$$x_{Ice}(T)=-1.342\cdot e^{\frac{2}{5}(T-273.15)}+0.9$$

for 233.15 K $\leq T\leq$ 272.15 K.

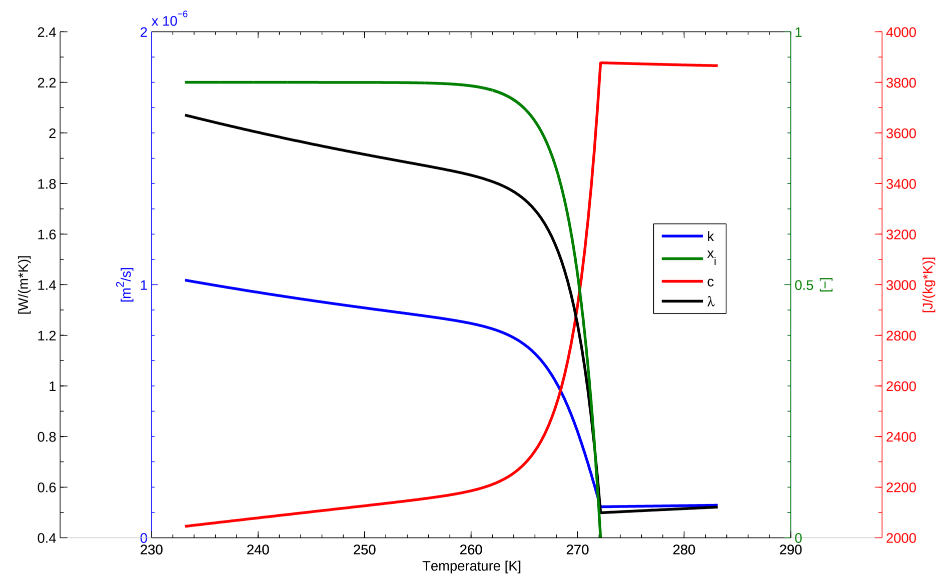

Figure 3: Essential parameters

The PDE is solved in MATLAB by

- discretizing in space (center difference approach)
- using a quasi-continuous stiff ODE-solver in time

$$\frac{\partial T}{\partial t}=\frac{k(T_n)\cdot(T_{n+1}-2T_n+T_{n-1})}{\Delta x^2}$$

with thermal diffusivity $k(T)=\lambda(T)\cdot(\rho(T)\cdot c(T))^{-1}$.
Thus, after reaching the freezing point (here 272.15 K) the properties of water change.

Results

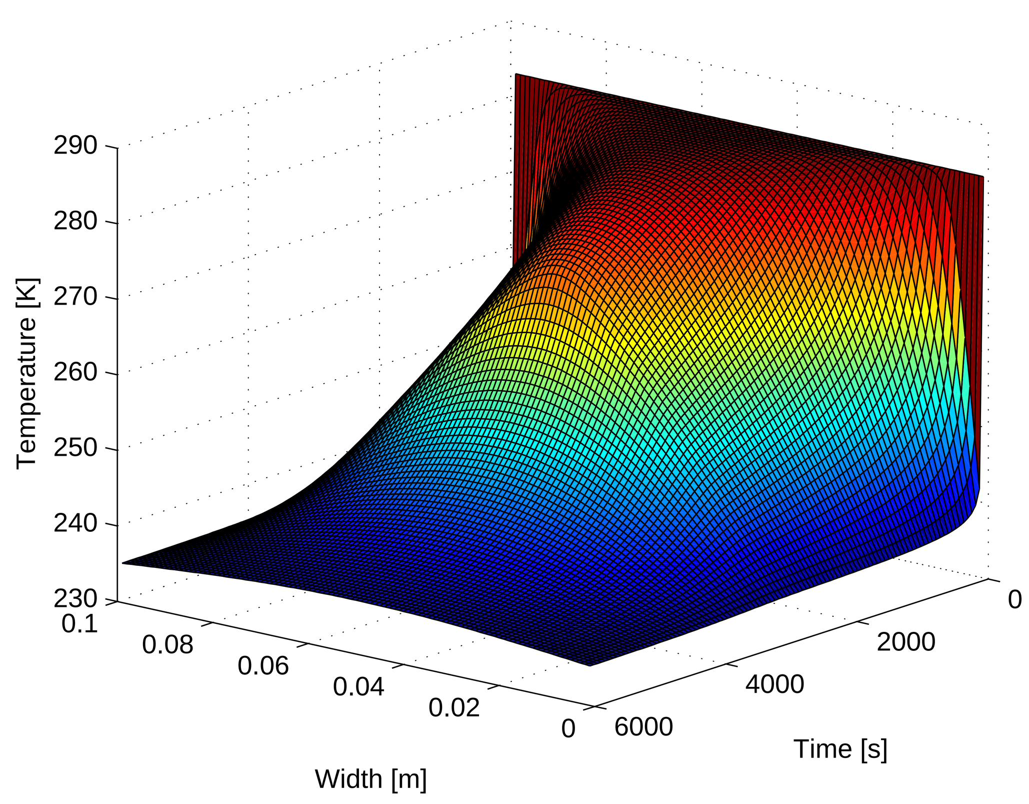

Figure 4: Temperature distribution (time and space)

- The temperature drops faster after reaching the freezing point due to changing parameters at this point.
- The simulated freezing happens faster than in a real plate freezer due to the simplifications that have been chosen.

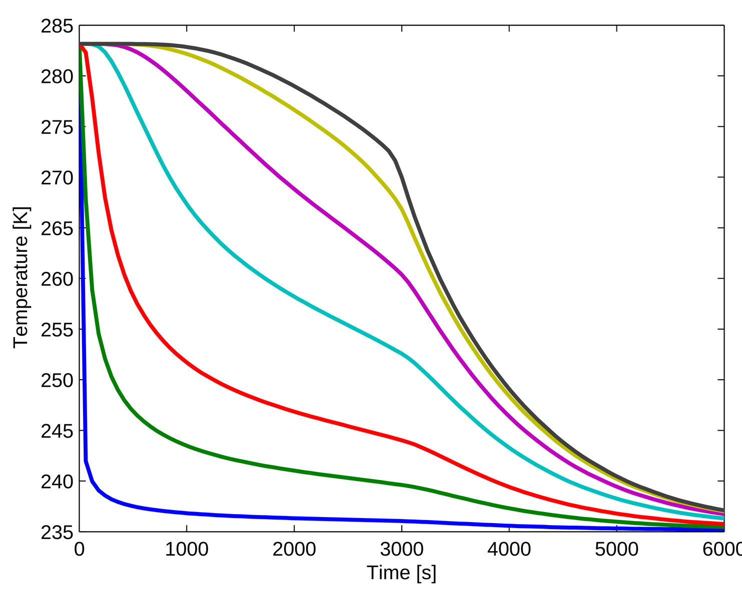

Figure 5: Temperature vs. time at different places

- The core temperature in the middle of the fish block has to reach at least 255.15 K ($-18\,^\circ$C) as fast as possible.
- Fast freezing will cause small ice crystals and therefore lead to a good quality measure.

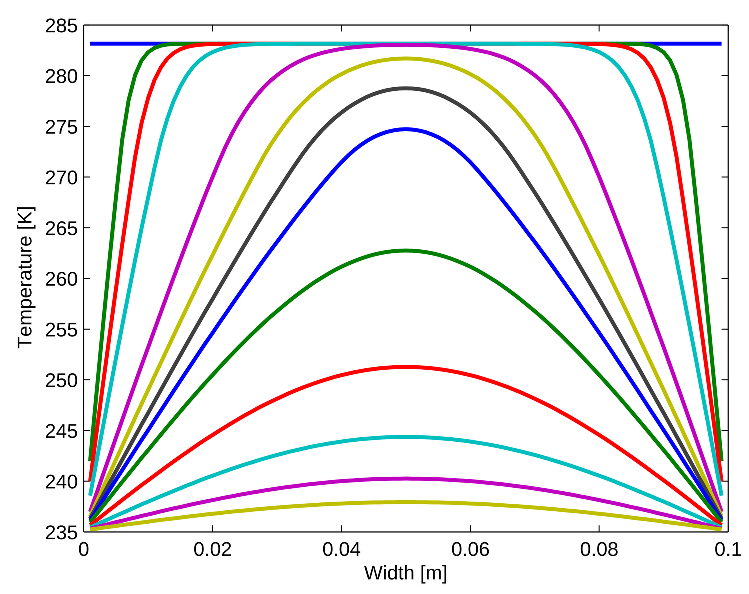

Figure 6: Temperature distribution at several times

Discussion

The above presented results were achieved by several simplifications:

- The boundary conditions are set to constant values.
- The initial condition is equally distributed.
- Latent heat of fusion is not explicitly modeled.
- Consideration of only one spatial dimension.
- The platefreezer is perfectly isolated.
- The areas of uninsulated surfaces are small compared to the area of the freezing plates.
- The values of the simulation parameters are approximations of the real values.
- The fish in between the freezing plates is considered as a homogenous mass without any entrapped air.

Future work:

- Describe the boundary conditions, which are the output of the *freezing system*, as functions of time.
- Consideration of many platefreezers in parallel, what will cause higher load for the freezing system and thus lead to a faster warming of the ammonia.
- Take the latent heat of fusion into account.
- Add a model for nucleation and growth of ice crystals in order to calculate the quality measure.
- Validation of the simulation results by measurements.

References

[1] L. Clavier, E. Arquis, J. Caltagirone, and D. Gobin. A fixed grid method for the numerical solution of phase change problems. *International Journal for Numerical Methods in Engineering*, 37:4247–4261, 1994.

[2] J. Graham. Planning and engineering data, 3. fish freezing. Technical Report 771, FAO Fisheries Circular, 1984.

[3] V. Harðarson. *Matvarens termofysiske egenskaper og deres betydning ved dimensjonering av frysetunneler.* PhD thesis, Universitetet i Trondheim – Norges Tekniske Høgskole, March 1996.

[4] W. Johnston, F. Nicholson, A. Roger, and G. Stroud. Freezing and refrigerated storage in fisheries. Technical Report 340, FAO Fisheries, 1994.