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Dynamic simulation of batch freezing tunnels for fish using Modelica

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Abstract

Fish products are frozen to preserve quality and extend shelf-life. However, freezing processes in the industry are typically very energy demanding and seldom optimized with regard to energy usage. During freezing, the operating conditions for the refrigeration cycle, as well as the driving temperature difference over the product changes significantly from start to finish. A complete transient model including a refrigeration plant, an air blast freezing tunnel and food products has been built, based on the Modelica programming language. The product model is discretized into uniform layers, described with equations for temperature dependent properties such as thermal conductivity and heat capacity. Normally, fan power represents about 25 – 30% of the total refrigeration requirement, but at the end of the freezing process, heat from the fans can represent up to 95-99% of the refrigeration load. The results from this model indicates that a 33% reduction in total power consumption, with a penalty of 14% longer freezing time is possible with better operation of the fan. In general, this model can be a useful tool for visualization of energy saving measures. It combines a product model with a refrigeration system, demonstrating the effect of process modification on both single components and overall process performance.

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Keywords: dynamic simulation; freezing tunnels; fan control; energy saving

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1. Introduction

Fish products are frozen to preserve quality and extend shelf-life. However, freezing processes in the industry are typically very energy demanding and seldom optimized with regard to energy usage. 15% of

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the world's electricity is used for refrigeration [1]. With increasing world population and increasing electricity prices, a focus on increased energy efficiency is necessary.

In this paper, the freezing of packed pelagic fish is considered. The freezing process for this kind of product is usually 12-20 h. It is difficult to make changes to the process without affecting the quality or the work schedule on a freezing plant. Performance improvements (e.g. reduced energy usage) of an existing plant can be predicted by simulating a refrigeration system in a computer model. There are many ways to model these systems and the selected method should be stable, rapid and accurate [2]. Fig. 1 shows a blast air tunnel with main components.

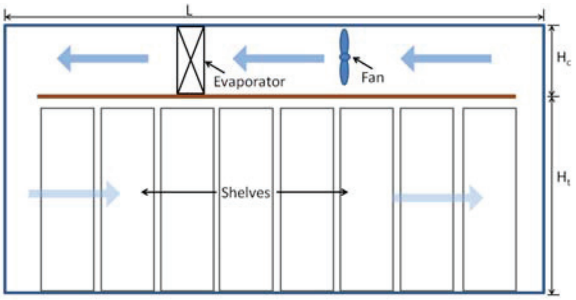

Fig. 1. Side view of a blast air freezing tunnel

During freezing, the operating conditions for the refrigeration cycle, as well as the driving temperature difference over the product changes significantly from start to finish. Due to product stacking and placement inside the boxes, the temperature and freezing rate in the fish will progress differently. Transient modelling can take these effects into account.

In most industrial batch freezing tunnels, the air fans run at full power through the whole freezing process. This is not very energy effective, as the refrigeration system needs to remove the energy added by the fan, in addition to remove heat from the product. Normally, fan power represents about 25 – 30% of the average refrigeration requirement, but at the end of the freezing process, heat from the fans can represent up to 95-99% of the refrigeration load [3]. Therefore, improving fan control can have large impact on increased energy efficiency of the total system.

The goal of this work has been to build a complete transient model including a refrigeration plant, an air blast freezing tunnel and food products, and show which impact different control strategies may have on freezing time and energy use.

2. Materials and Methods

Modelica has been used together with the simulation environment Dymola[4] as the platform for the model. Modelica is an open object oriented equation based programming language for modelling of complex physical systems including mechanical, electrical, thermophysical subcomponents etc. [5]. The object oriented structure allows reuse of developed components, such as compressors, heat exchangers, valves, etc. The objects are translated and executed with a simulation engine (compiler).

In this work, an air blast freezing tunnel and a two-stage ammonia refrigeration system are used as basis for model design. Modelica allows easy coupling of complex systems and cycles. All components in the system, except the product model, have been modelled with components from the TIL library [6].

2.1. The product model

A finite volume model of the product has been built. It was assumed that the fish were vacuum packed in boxes. The boxes were discretized with equal thickness of each layer (t_{hight}, t_{length} and t_{with}). This means that each layer was represented as a box with equal shape, but different size (see Fig. 2). However, the outermost layer has half the thickness of the other layers, to better represent effects near the surface.

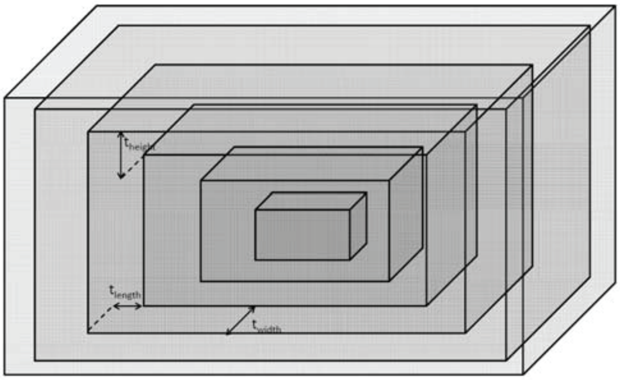

Fig. 2. Discretization of the fish model

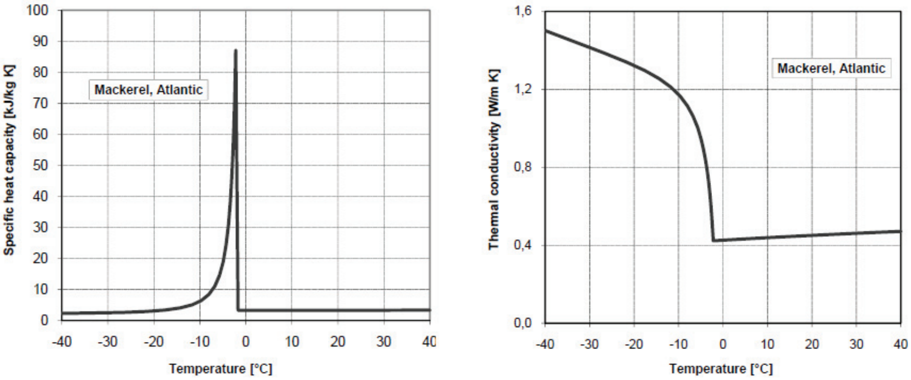

Fig. 3. Thermal properties of Mackerel

Each layer was modelled with a temperature dependent heat capacity and thermal conductivity found in ASHRAE [7]. In all results presented in this paper, composition data for mackerel were used. The specific heat capacity and thermal conductivity is shown in Fig. 3.

Fig. 4 shows an example of the temperatures in the different layers of the fish box (10 layers) during freezing. The non-linear physical properties contribute strongly to uneven freezing of a product box.

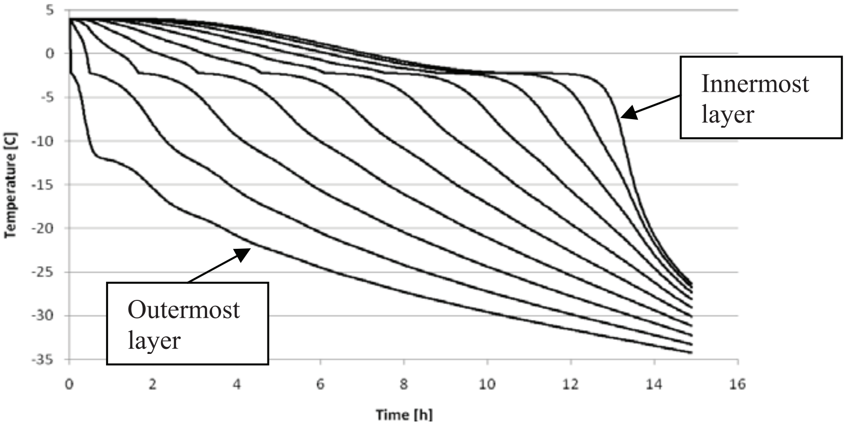

Fig. 4. Example of temperatures of the fish layers during freezing (simulation result from model)

2.2. The tunnel model

The tunnel model was separated into three parts: The main tunnel (where the fish is frozen), the fan and the evaporator (see Fig. 1).

The main tunnel was modelled as a channel with the face area equal to the total face area of the tunnel (W x H_t) minus the total face area of the boxes. The air distribution in the channel was assumed to be ideal (equal velocity over the whole cross-section). Lengthwise, the tunnel was divided into the same number of segments as the defined number of fish rows, to get the effect of air temperature rise through the tunnel.

The convective heat transfer coefficient (h) between the air and the product was given by the following formula [8]:

$$h = 7{,}3 \times u_a^{0{,}8} \tag{1}$$

where u_a is the air velocity. The pressure drop was calculated with the following formula:

$$\Delta p = k \times \frac{1}{2\rho} u_a^{2} \tag{2}$$

where k is a constant that has to be assumed, or calibrated with measurements from a real tunnel. ρ is the density of air.

The evaporator was modelled as a tube and fin heat exchanger. The evaporator had to be dimensioned according to size of the tunnel and together with the rest of the refrigeration plant. The Haaf [9] correlations were used for air side heat transfer and pressure drop.

The fans were modelled as one single fan, with constant hydraulic and drive efficiency. The hydraulic efficiency was used to calculate the shaft power, which is entirely transferred to the air flow. The drive efficiency was used to calculate the power consumption of the fan. Since it was assumed that the fan motor was placed inside the tunnel, the drive efficiency was sat equal to 1 and the hydraulic efficiency equal to the product of the real hydraulic and drive efficiency.

The fan was connected to a controller, which could control the mass flow, the volumetric flow or the pressure difference through the fan. The controller “measured” the air temperature difference through the freezing chamber and used this as a control parameter.

2.3. The refrigeration plant

The refrigeration plant was connected with the freezing tunnel through the evaporator. The process layout of the refrigeration system is illustrated in Fig 5.

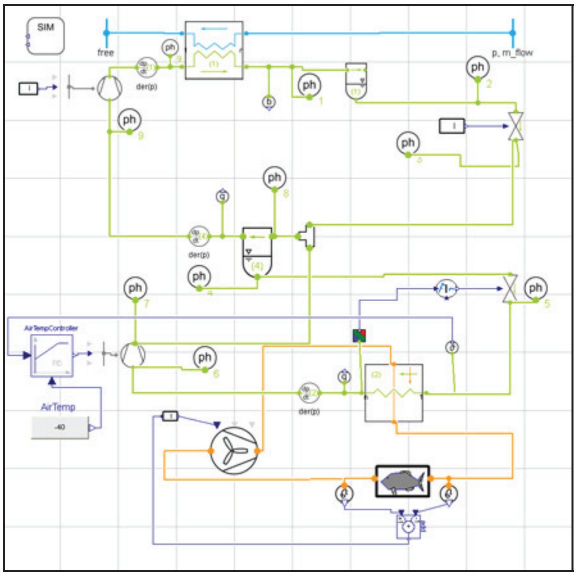

Fig. 5. Refrigeration system layout

The basic refrigeration system was designed as a classical two-stage system with an open intercooler and ammonia as working fluid. It could be desirable to have a closed intercooler system, however this component is not available in the TIL library. It might be possible to emulate a closed receiver with a combination of components, but this would complicate the system severely.

The two-stage systems require several control strategies. The high pressure receiver made sure that the condenser outlet was saturated, and would therefore automatically control the high pressure together with the high pressure compressor. The high pressure valve was used as a floating valve for the intercooler. The low pressure valve was designed as a thermostatic valve. This is not typical in ammonia plants (due to the high heat of evaporation), but worked fine in the simulations, and the results should similar to a system with a receiver and a self circulating system.

The low pressure compressor was controlled to reach a defined minimum evaporation temperature. This means that it ran at maximum speed until the temperature was reached, and then reduced the speed to keep the evaporation temperature constant. The high pressure compressor was used to set the middle pressure to the geometric mean of the high and low pressure.

2.4. Model applications

As opposed to steady state models, dynamic models can be used to evaluate and improve the control system for transient processes. The main purpose of this model was to show how relatively simple changes to existing systems can reduce the energy consumption of the process. Some examples of such modifications will be discussed in the following paragraphs.

3. Results and Discussion

To show usage for this model, simulations of the assembled system with automatic control of fan speed have been compared to the baseline operation with constant fan power. As previously discussed, air fans are directly and indirectly responsible for a major part of the total energy consumption.

Fig. 6 shows the accumulated system (fans + compressors) power consumption for the two cases; constant fan power, and one where the fans were controlled to give a total air temperature rise through the tunnel of 2 K. The fan speed can be reduced down to 25% of maximum speed. The results showed a 33% reduction in total power consumption, with a penalty of 14% longer freezing time. The freezing time was defined as the time it takes for the innermost layer of the last row of fish to reach −25°C.

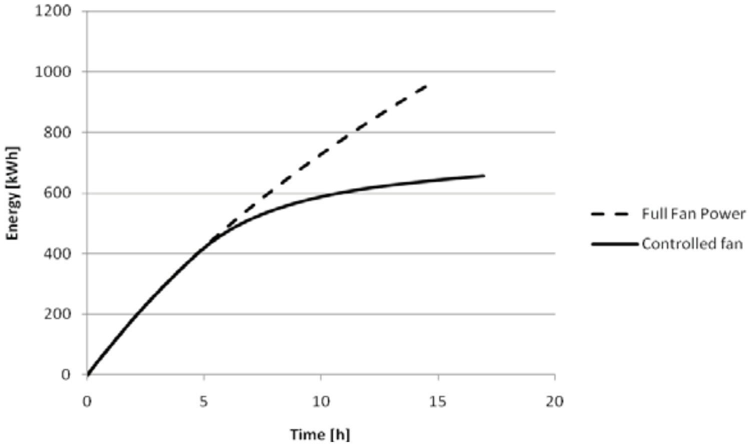

Fig. 6. Effect of fan speed control

Fig. 7 shows the difference in fan power and temperature rise through the tunnel. As known from the "similarity laws" [10] the change in power is proportional to the change in volumetric flow rate to the power of 3. This results in a reduction in fan power of about 98% when the volumetric flow is reduced to 25%.

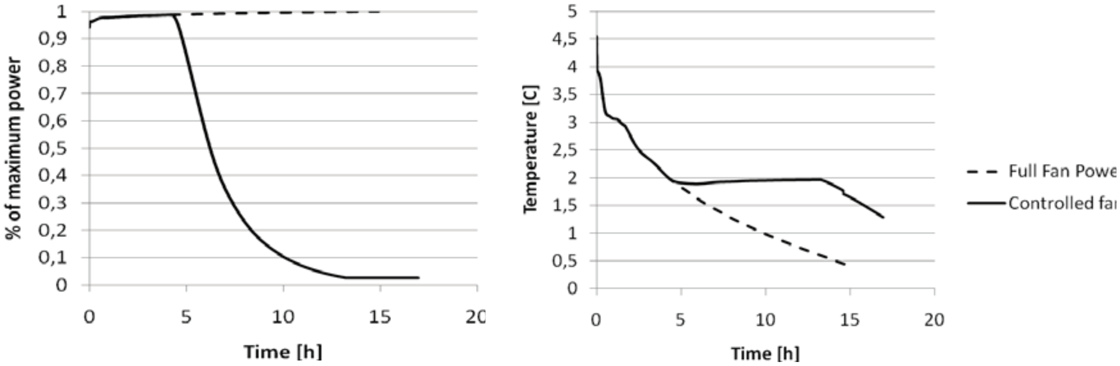

Fig. 7. Fan power input and temperature difference through the tunnel

A second measure for reducing the fan power consumption is to minimize the pressure drop through the tunnel (while maintaining a good air distribution). This model is not suited to calculate the pressure drop in the tunnel, but is well suited for demonstrating the effect on the total power consumption. Alonso et al. [11] showed that it is possible to reduce the pressure drop by up to 13% by altering the ceiling design. Fig. 8 shows how this will influence the total power consumption of the process. The 13% reduction in pressure drop results in a 10% reduction in the total power consumption.

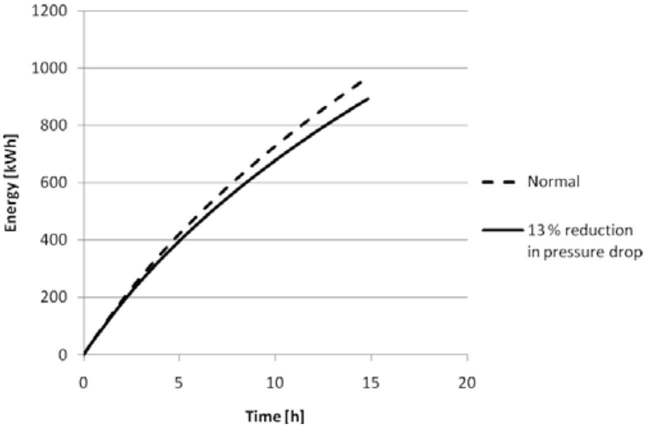

Fig. 8. Effect of reduced pressure drop through the tunnel

4. Conclusions and further work

It is clear that there is a large potential for energy savings in the fish freezing industry. The model presented in this paper could be a useful tool for visualization of energy saving measures. It combines a product model with a refrigeration system, demonstrating the effect of process modification on both single components and overall process performance.

In further work with this model, the results will be compared to measurements from an existing plant. Some parameters such as pressure drop through the tunnel, capacity of the evaporator and heat transfer resistance due to packaging can be used as tuning parameters.

When the model and parameters are found to be similar to a real situation, they can be used for process optimization.

Acknowledgements

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References

[1] Coulomb, D., Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment. *Trends Food Sci Tech*, 2008. 19(8): p. 413-417.

[2] Ding, G.-l., Recent developments in simulation techniques for vapour-compression refrigeration systems. *Int. J. Refrig*, 2007. 30(7): p. 1119-1133.

[3] Magnussen, O.M. and T.S. Nordtvedt, Enøk i kuldeanlegget, in *SINTEF Rapport TR A6287*. 2006, SINTEF Energiforskning: Trondheim.

[4] Dassault Systems. Multi-Engineering Modeling and Simualtion - Dymola. 03-01-2011]; Available from: http://www.3ds.com/products/catia/portfolio/dymola.

[5] Modelica Association. Modelica and the Modelica Association - Modelica Portal. 2010-02-02]; Available from: http://www.modelica.org/.

[6] Richter, C., Proposal of New Object-Oriented Equation-Based Model Libraries for thermodynamic Systems. 2008, Technische Universitat Braunschweig.

[7] ASHRAE, *Handbook - Refrigeration*, ed. M.S. Owen. 2006: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc..

[8] Valentas, K.J., E. Rotstein, and R.P. Sing, Handbook of food engineering practice. 1997: CRC Press.

[9] Haaf, S., Wärmeübergang in Luftkühlern, in *Handbuch der Kältetechnik*, R. Plank, Editor. 1988, Springer Verlag: Berlin. p. 435-491.

[10] White, F.M., *Fluid Mechanics*. 4th ed. 1999: McGraw-Hill.

[11] Alonso, M.J., T. Andresen, and F. Frydenlund, Improvements of air flow distribution in a freezing tunnel using Airpack, in *SINTEF Report TR F6962*. 2010, SINTEF Energy Research: Trondheim.

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