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Report

„Optimal control of a freezing tunnel process using transient modelling“

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Chapter 1

Introduction

Norway is one of the world's largest exporters of fish and seafood. Fish is mainly transported froozen, so freezing the fish is a important and also a very energy consuming part of the fishing industry. Normally the fish is froozen by a flow of cold air blown over the product. In most freezing plants only very simple means of control and monitoring for the fans and compressors used in a freezing tunnel are installed.

With continously increasing international competition and a growing focus on enviromentally friendly production, the need for improvement on traditional methods and processes is great. According to [1] a very promissing approach is to control the fan and the refrigeration compressor through the course of a freezing process. This approach is demonstrated by a transient model using the free object-oriented, equation based language Modelica used together with the Dymola 3.1 software, for more informations see [2] and [3]. In addition the Modelica library TIL, develloped by TLK [4] in Braunschweig, Germany, has been used, providing detailed and realistic models of all needed components to model the freezing process. In this work, a model of the fish, that can be frozen in a realistic way according to the ASHRAE handbook of refrigeration, was created. This fish was included in a newly created model of a freezing plant. This transient model of the refrigeration system was used to optimize the design and operating parameters of a CO_2 refrigeration system.

Chapter 2

Fundamentals

The Refrigerant

CO_2 is a naturally available refrigerant. In low concentrations it is nontoxic and it has no ozon depletion potential. CO_2 is an inert gas and as a result of its low price there is no need for reclaiming or a special waste management.
The need of high pressures in a CO_2 cycle is a disadvantage, but its high volumetric cooling capacity and its high heat transfer coefficient allow very compact CO_2 cooling cycles.

The Fishmodel

In this work the first step to transient modelling was the creation of a fish model. This fish model should be able to be froozen in a very realistic way, what means that, based on the ASHRAE handbook of refrigeration, curves for the during the freezing process changing thermal conductivity and heat capacity were created, the used Modelica-codes for both can be seen in illustration 2.1.

```
a)
 for T>271.15 then
   lambda=0.5;
 elseif T<271.15 and T>258 then
   lambda= -0.0085*(T-273.15)^2 - 0.23*(T-273.15) + 0.06;
 else
   lambda=1.8;
 end if;

b)
 if T<271.15 and T>258 then
    c=(164.5*E^(0.3307*(T-273.15)))*1000+4000;
 else
    c=5000;
 end if;
```

Figure 2.1: Used Modelica codes for a) thermal conductivity, b) specific heat capacity.

Both, the heat capacity and the thermal conductivity of a fish, are changing considerably throughout the freezing process. The changes of the heat capacity occur because of the phase change of liquid water to ice and the corresponding latent heat and are shown in illustration 2.2.

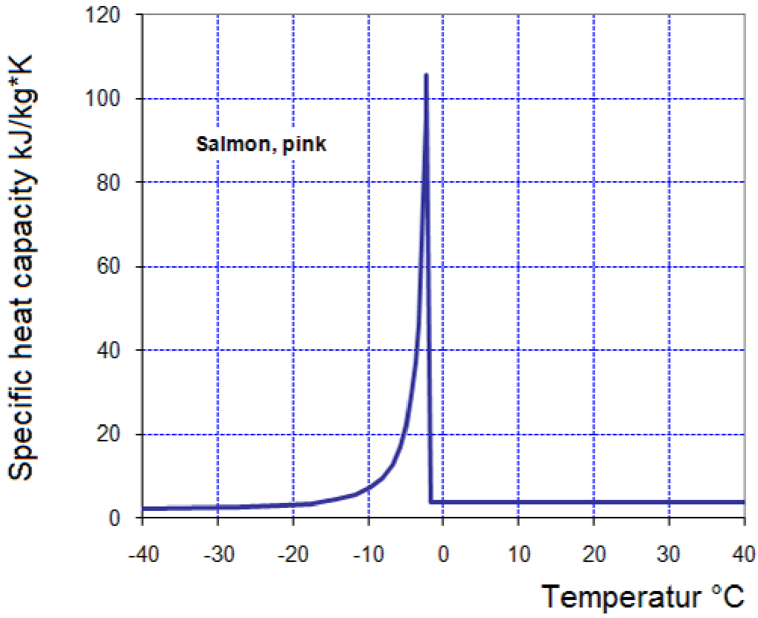

Figure 2.2: Specific heat capacity of Salmon over the temperature,[6].

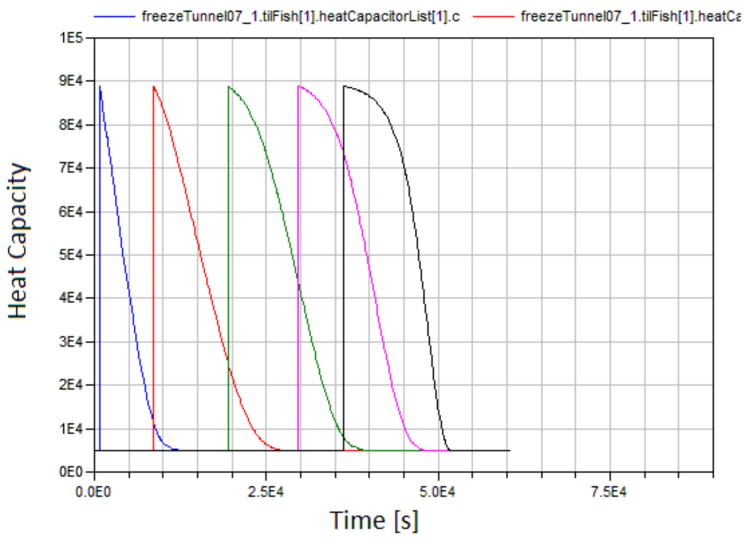

Figure 2.3: Specific heat capacities of five fishlayers during the freezing process.

The phase change is indicated by a huge increase of the heat capacity at the freezing point, which is rapidly decreasing with increasing ice fraction. This phase change occurs time shifted for all fish layers and is shown for an example of a five layer fish in illustration 2.3.

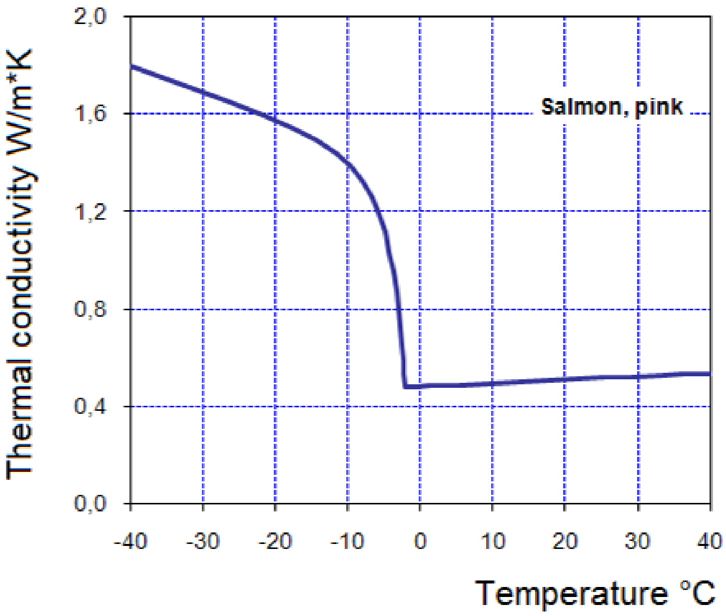

Figure 2.4: Thermal conductivity of Salmon over the temperature,[6].

The change of the thermal conductivity occurs because of the better heat transfer ability of ice compared to the one of water, so with a increasing ice-fraction in a fish layer, the thermal conductivity of this layer is increasing as shown in illustration 2.4.

In this work it is assumed that the freezing process starts at -2°C and is finnished at -12°C [5]. This wide temperature span occurs because of the rising salt concentration in the not yet froozen parts of the fish, which lowers the freezing temperature of the water solution. Depending on the temperature, the thermal conductivity and the capacity of the fish are calculated by selfmade equations based on the above mentioned curves.

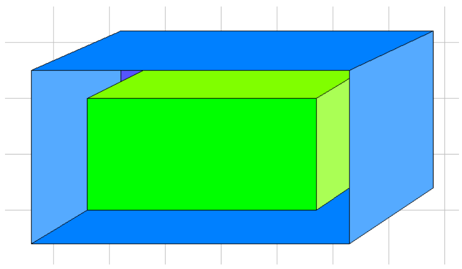

Figure 2.5: Model of a two layer fishbox. Each fishlayer is enbedded in the next bigger layer.

The fish itself consist of severall layers to get a higher accuracy and a higher resolution of the freezing process in the fish. The basic idea behind this fish layers is shown in illustration 2.5. These layers are created as an array of TIL components. A fish-layer consist of two major components, heat capacities and thermal conductors. These components of a fish are arranged in an array. The components of this array are connected through „for-loops“, as can be seen in illustration 2.6.

```
for i in 2:N loop
  connect(heatCapacitorList[1].port, fishPort);
  connect(thermalConductorList[i-1].port_b, heatCapacitorList[i-1].port);
  connect(heatCapacitorList[i].port, thermalConductorList[i-1].port_a);
end for;
```

Figure 2.6: Modelica code to connect an array of heat capacities and thermal conductors using a „for-loop“.

This is a fast way to create a dynamic model of a component consisting of numerous and, most important, possibly changing numbers of models, as these numbers are parameters free to be changed by the user if neccesary. These parameters can be accessed by dialog boxes as shown in illustration 2.7.

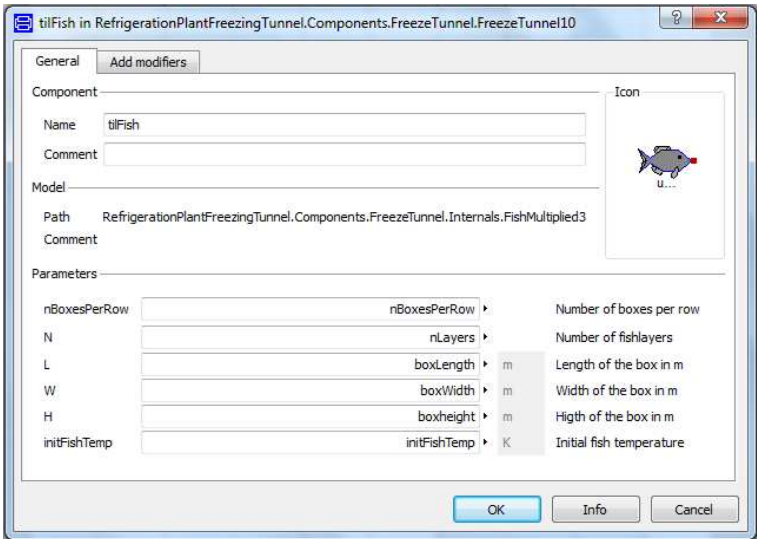

Figure 2.7: This Modelica dialog box enables the user to define the dimensions of a fish box and the number of layers of each fish.

Through using arrays, number and size of the layers are free variables which can be defined before simulating. On this way it is easy to follow the freezing process and to design comparable criteria for the end of the freezing/cooling process. The fish layers can be seen as boxes with a defined wall thickness. These fishboxes can be imagined as beeing put into the next bigger fishbox and so on, until the outer layer is reached. All layers have the same thickness, but because of their different volume a different mass. The fish starts to freeze beginning with the outer layer, because this is the only layer with contact to the cold air blown over the fish. The heat from the surface of the fish-layer is transportet by convection to the air. Inside the fish, heat is only transported by heat conduction. The amount of heat, that is transported, is depending on the effective temperature difference between two fishlayers, or between the top fish layer surface and the surrounding air. In addition the transported heat is also depending on the during the freezing process changing heat capacity and the thermal conductivity. As mentioned, the last two variables are temperature-dependent and are calculated during the simulation.

The Freezing Cycle Model

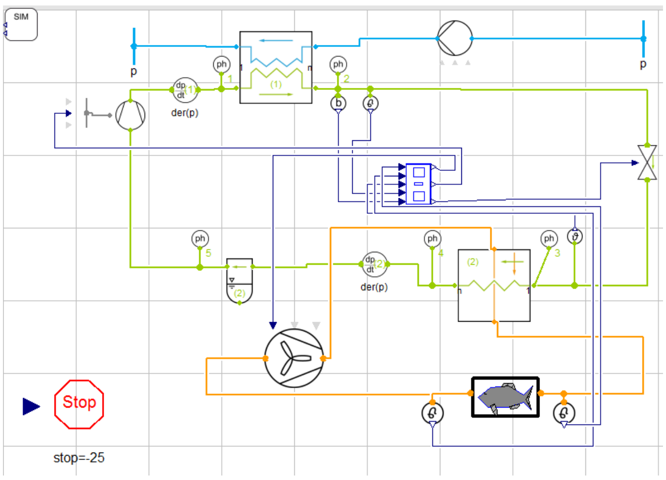

Figure 2.8: model of the freezing tunnel with a CO2 freezing circle.

In this work a model for a transient freezing tunnel was created. The freezing tunnel is designed to cool down and freeze an amount of about 20t of fish in a batch [5]. In less than 24 hours [5] the freezing process has to be completed to leave enough time for discharging and refilling the tunnel with new product.

The freezing of the fish is seen to be complete when the central layer reaches a temperature of - 25°C. Though freezing should be completed at -12°C, a temperature of -25°C assures that a good quality is maintained during storage.

The freezing cycle model basically consist of a water cooled freezing cycle. The basis for this assumption is a freezing plant with acces to seawater [5] and therefore quite constant cooling water temperature and a reliable availability of cooling water. The freezing cycle itself is realized by a single stage CO_2 cooling cycle.

The CO_2 Cycle

The CO_2 cycle basically consist of a compressor, a valve, a receiver and the two heat exchangers, the condenser and the evaporator. The compressor compresses the CO_2 to a high pressure of about 68 bar. The CO_2 is heaten up during this process to about 156°C and is afterwards cooled down in the condenser to a temperature of about 20°C. The CO_2 condenses and is then beeing subcooled. In the following valve the CO_2 is beeing relaxed to about 10 bar. At this pressure the CO_2 evaporates at a temperature of about -42°C. This enables a very cold airstream to cool down the product fast. The heat transfer between air and CO_2 is realized in the evaporator. Most, to all of the CO_2 is evaporating in the evaporator, but nevertheless, to make sure only gaseous CO_2 reaches the compressor and to prevent a real compressor to get damaged, a receiver is placed after the evaporator, that separates liquid from gaseous CO_2.

The Freezing Tunnel

The cooling cycle is used to cool down air to a temperature cold enough, so that it will freeze the product when blown over it in the freezing tunnel. This heat exchange is done in the evaporator. In this model one fan provides the necessary massflow of cooling air, and there is only the need to control this one fan to save energy. Perfect air distribution is assumed, and the pressure drop can be calculated by the Haaf equation in the evaporator and with the following formula in the tunnel: $dp = \zeta * 0,5 * \rho * v^2$. In this formula ζ stands for the friction coefficient between air and the blades of the fan, ρ stands for the density of the cooling air and v stands for the speed of the cooling air. The value of ζ can be adjusted to get a reasonable pressure drop. In a real freezing tunnel several fans would keep the air velocity at a constant level over the whole length of the freezing tunnel and would provide the necessary turbulence for a good heat exchange between air and product.

In the freezing tunnel, the massflow used in the fan, is adjusted in such a way to provide air at a average velocity of 1.91 $\frac{m}{s}$ at the freezing tunnel inlet. The fishboxes reduce the free volume for the flowing air significantly, so the air velocity increases in the tunnel to about 5.74 $\frac{m}{s}$. In the freezing tunnel the fishboxes are arranged in rows, and there are several rows in a freezing tunnel. Both, number of rows and number of boxes per rows are parameters and can be changed to fit a special freezing tunnel geometry. The dimensions of the fishbox itself, its width, length, hight and number of fishlayers per box, are also parameters which can be changed for different products if needed as shown in illustration 2.7.

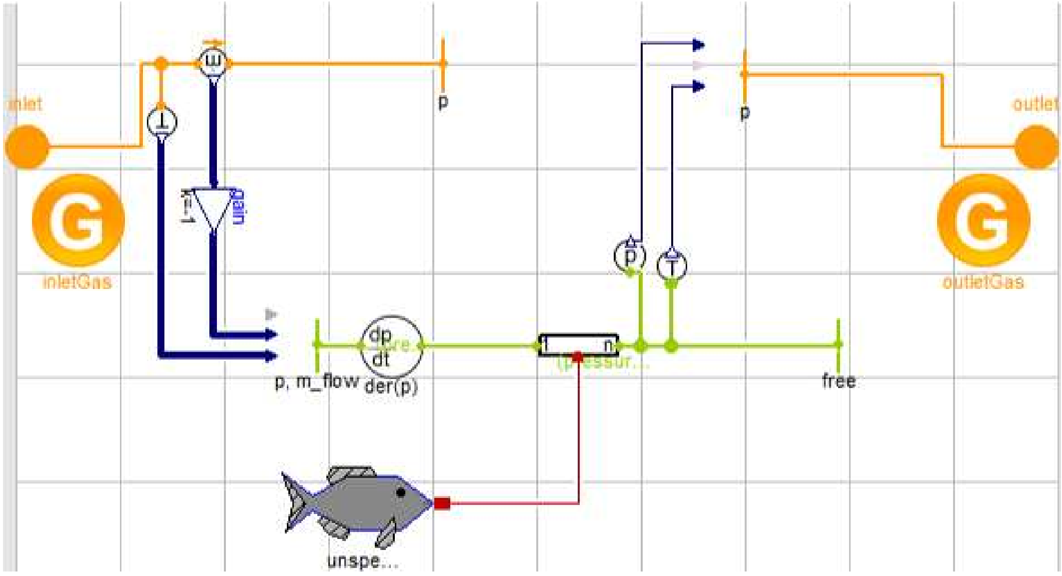

Figure 2.9: The fishes in the freezing tunnel, designed as an array of fishboxes connected to a pipe with the flowing cooling air inside.

The freezing tunnel itself is an array, in which the number of fishboxes, depending on the number of fishes per row and number of rows, is connected to a pipe model as shown in illustration 2.9.

Chapter 3

Control of the Freezing Tunnel

There are two components of a freezing cycle that consume the most energy, the fans and the compressors. In order to reduce the energy consume of the freezing plant it is necessary to find parameters to control these components.

Control of the Fan

It is assumed that in most actual freezing plants the fan would work at a constant rotatory speed. At the beginning of the freezing process,due to the higher temperature difference between air and product, there is a lot of heat emitted by the product, but as shown in illustration 4.2 the transferred amount of heat is decreasing seriously during the freezing process and there is no more need for such a high massflow of cooling air as at the beginning of the freezing process. All the energy used by the fan is transferred to the air in the freezing tunnel and dissipated to heat. This heat has to be removed by the cooling cycle, which results in a higher cooling load.

By controlling the fan, that means altering its rotatoty speed, it is possible to reduce directly the energy used by the fans but also to reduce the heat dissipated by the blades to the cooling air. As a result of this, the cooling system needs to handle less heat and can also reduce its capacity.

The fan speed is therefor controlled by two temperature sensors, measuring the freezing tunnel inlet air temperature and outlet air temperature. The cold air from the inlet is heaten up during the freezing process. To provide an uniform freezing of the whole freezing tunnel content, it is necessary that this temperature difference between inlet- and outlet air temperatures is not to high, else it wouldn't be possible to guarantee complete freezing of the whole batch of product within a reasonable time. The air temperature difference is directly relating to the air massflow in the tunnel and with that, directly relating to the rotatory speed of the fan.

But with the decreasing amount of heat beeing emitted by the product, the needed massflow of cooling air is decreasing aswell. In this model the measured temperature difference is used to control this massflow. The reference temperature difference is two degree [5]. If the measured temperature difference is bigger, the rotatory speed of the fan can be increased, the massflow of cooling air is increasing and with this the amount of heat transported by the cooling air can be increased.
If the measured temperature difference is smaller than two degree, the rotatory speed of the fan can be reduced, which reduces the transported massflow of cooling air, but also reduces the consumed energy of the fan and the necessary capacity of the cooling system.

Control of the CO_2 Compressor

To save energy, the compressor is controlled by two means.
First, the refrigerant inlet temperature in the evaporator. This temperature is set to -50°C. This temperature provides a very cold inlet temperature of the air in the freezing tunnel and that leeds to a fast freezing of the product. If the evaporator inlet temperature falls below -50°C, the rotatory speed of the compressor will be reduced.
Second, the temperature difference between the refrigeration inlet temperature of the evaporator and the air inlet temperature of the freezing tunnel. If this temperature difference falls below 3°C, the rotatory speed of he compressor will also be reduced. A low temperature difference between refrigerant inlet temperatur, which ideally equals the freezing tunnel cooling air inlet temperature, is a sign of a reduced freezing load, so that the rotatory speed of the compressor can be reduced to save energy.
Both conditions could be used to control the rotatory speed of the compressor on its own, but they are combined in a logical interface and only the condition with the lowest demand of compressor rotatory speed is used to control the compressor.

Chapter 4

Results

The Temperature Curves

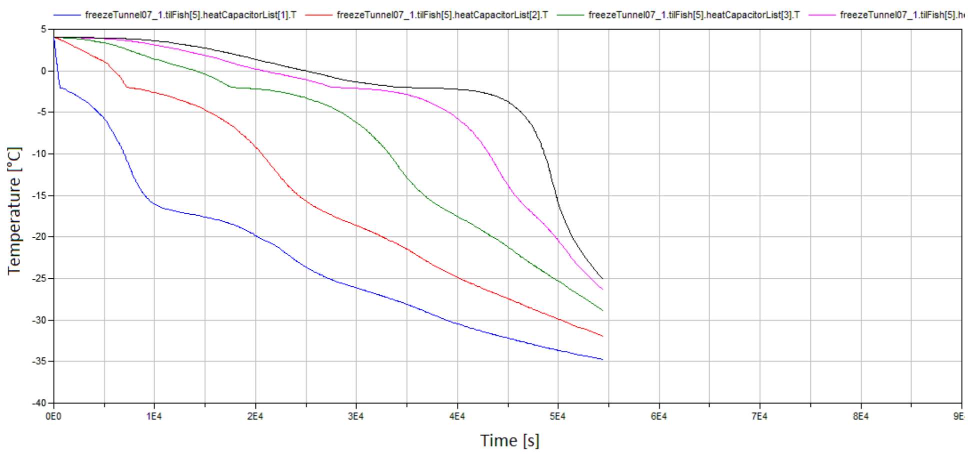

Figure 4.1: Temperature curves of a five layer fish model.

First the cold air is cooling down the fishlayers, but at a temperature of minus two degree celsius the freezing starts. As the water starts to freeze, the heat capacity immediately increases to its maximum level, before it gradually decreases as more and more water is frozen out. This results in a temperature plateau where the main part of the freezing takes place. This process can be observed time shifted for all fishlayers, as they start freezing each one after another. Due to poor heat conductivity it takes a while until the last fishlayer in the center of the fish starts freezing, but because of its small mass, the further cooling after freezing is quite rapid and only limited by the poor heat conduction. In this model the heat is thought to be transported directly from the fish surface to the air, without an additional isolating layer of a plastic box or air, isolating the fish from the direct airflow. This may influence statements concerning the freezing time of the product, and with this the needed energy for freezing.

The Freezing Process

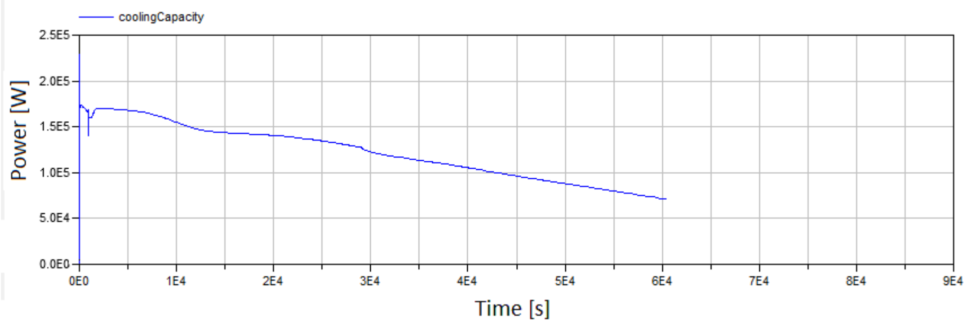

Figure 4.2: plot of the transferred heat in the evaporator during the cooling process .

As shown in illustration 4.2, the heat transferred from the fish to the air in the freezing tunnel is significantly higher in the early stages of the freezing process and is constantly decreasing during the process. This enables the energy saving potential of a freezing tunnel control, because the amount of transferred heat is correlating with the neccesary airflow to transport this heat away from the fish, and this airflow is directly depending on the rotatory speed of the fan. According to [1], reducing the rotatory speed of the fan is the main source to save energy, but with the during the freezing process decreasing amount of heat that has to be removed, the reduction of the rotatory speed of the compressor also saves a considerably amount of energy.

Effects of Control

The results of the simulations shall be used to demonstrate the effects of the control.
In the first scenario, with constant maximum fan rotatory speed and constant maximum rotatory speed of the compressor, an energy consumption of 12.97GJ was calculated to cool down 20 tons of fish to a minimal temperature of -25°Celsius of the central volume element of the product. The freezing tunnel needed 15.8 hours, so freezing was achieved fast enough.
In the second scenario, the same amount of fish can be froozen with an calculated energy consumption of 8.32GJ, with controlled fan and compressor. The freezing process was not as fast as the uncontrolled reference with 16.8 hours needed, but still fast enough. The plots of the energy consumptions of these two CO_2 cycles are compared in illustration 4.3.
With only one hour more freezing time, it is possible to save about one third of the energy by using a propper control, compared to a system running with maximal rotatory speeds for its fans and compressor.

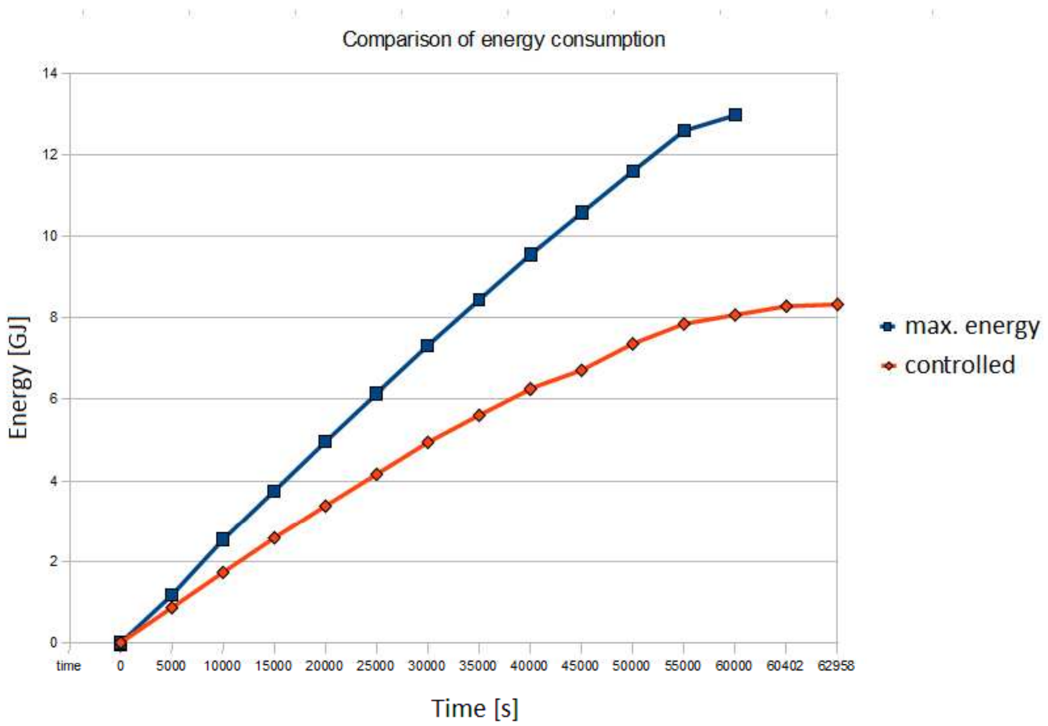

Figure 4.3: Comparison of the energy consumption of two different controlled CO_2 freezing tunnels.

In a second step, it was analysed what component saves more energy, the controlled compressor or the controlled fan. With a calculated energy consumption of 8.75GJ, in 16.3hours, a system with a controlled fan, but with a compressor with maximum rotatory speed, saves nearly as much energy as a fully controlled system. A system with a fan with maximum rotatory speed but with controlled compressor consumed 12.967GJ in 15.8h.This clearly indicates, that controlling the fan has the major impact on the freezing system energy consumption. The energy savings mainly result from the direct reduction of the energy consumption by the fan itself because of the reduced rotatory speed, but also by the reduced heat dissipation by the fan blades.

Chapter 5

Further work

In addition to the single step CO_2 cooling cycle model, a two step ammonia cooling cycle model was created, as shown in illustration 5.1 . At the time of this report the design of the ammonia cycle is not fully optimized yet, but first simulations indicate that a two step ammonia cooling cycle consumes less energy than the presented CO_2 cooling cycle in this work. This approach, combined with the control mechanisms presented in this work, results in even more energy efficient freezing plants.

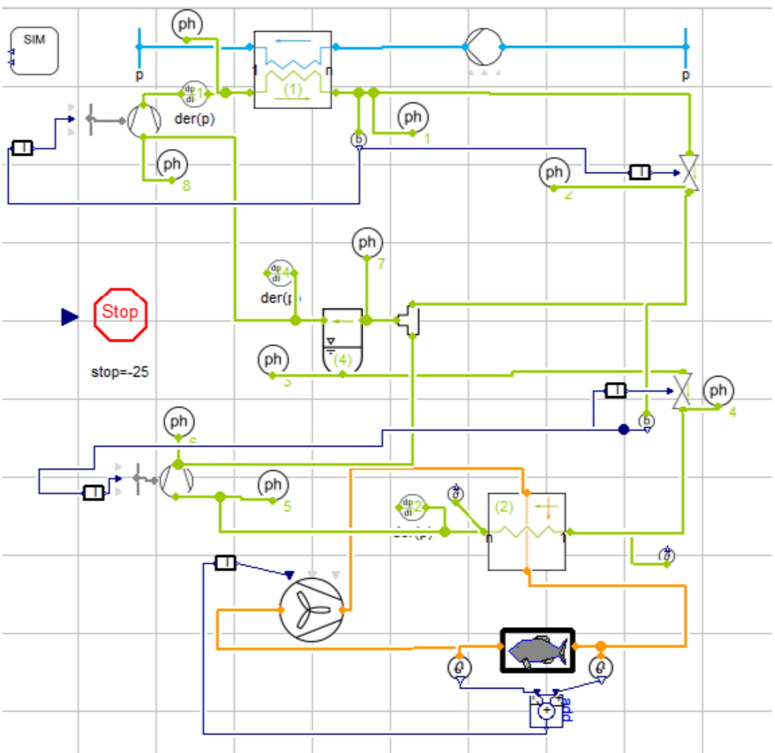

Figure 5.1: Model of the two step ammonia cooling system.

Sources:

[1]“Parametric study of economical energy usage in freezing tunnels“M.A. Harrison and P.J. Bishop,
[2]„Introduction to Physical Modeling with Modelica“ Michael M. Tiller, Kluwer Academic Publishers 2001
[3] Dymola User Manual Volume 1, Dassault Systems
[4] TLK-Thermo GmbH “http://www.tlk-thermo.com/‘“
[5] In agreement with my supervisor Trond Andresen, Sintef Energy Research, Trondheim
[6] ASHRAE handbook of refrigeration