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SOKI – Super Optimized Carton Freezer

Energy optimization of batch freezing tunnel for meat

Title:
Energy optimization of batch freezing tunnel for meat

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Abstract

A large amount of meat is frozen in batches in blast freezing tunnels. These tunnels are designed according to old rules of thumb, and they are in most cases running a constant air flow. By optimizing the running conditions of the tunnel, extensive energy savings can be obtained. In this report, a research project founded by Danish ELFORSK regarding the energy saving potential of industrial blast freezing tunnels verifies these savings potentials. The project covers testing of an industrial tunnel combined with laboratory tests, models and Computational Fluid Dynamics (CFD) simulations.

The main purpose of the project is to reduce the energy consumption by 30 %. The optimization of the fan speed, the air flow distribution through the tunnel and a new air spacer are investigated.

The project demonstrates that a considerable saving in energy can be obtained by adjusting the air flow and the air distribution in the freezer. By reducing the air flow, the pressure drop in the freezer drops, which results in reduced energy consumption.

The total time, in which the products stay in the tunnel, is determined by the logistics of the tunnel, i.e. when the unloading of the tunnel fits into the employees' working schedule. Therefore, the energy optimization of the tunnel is about using the available time that the product stays in the tunnel in the most efficient way. The energy consumption of a test tunnel can be reduced by 86 % when reducing the air flow from 6.5 to 2.3 m^3/s, and it is still possible to maintain the required final temperature of the product.

Similar tests in the industrial tunnel showed that by reducing the flow from 6.5 to 5.0 m^3/s, the energy consumption was reduced by 61.9 %. The reason why the air flow was not reduced further was because the frequency drive was restricted and was running on lowest available frequency.

By introducing baffles to direct the flow to where it is needed, large energy savings can be achieved. By using baffles and reducing the flow to maintain the same freezing time as in the reference case, a saving in energy of 68 % can be expected. By reducing the air flow further down to 1.8 m^3/s and still maintain the required final product temperature, the savings are estimated to be 93 %.

A new type of plastic air spacers was tested and compared to the wooden type which is normally used today. The results in the test tunnel showed a reduction in the freezing time of 4.9 hours and a slight increase in energy usage for the same adjustments of the fan as in the reference case. By reducing the air flow to 2.8 m^3/s, a saving of 78.6 % was obtained. The freezing time was 30.7 hours, and therefore there is room for more savings by reducing the air flow further.

The conclusions are based on 25 different tests. 18 tests are performed in a test environment at Danish Technological Institute, and the last seven tests are performed in an industrial blast freezing tunnel at Claus Sørensen A/S; a big tunnel freezing company in Denmark with a number of tunnel freezing plants.

Preface

This report presents the conclusions of the project *Super Optimized Carton Freezer* (SOKI). The project goal was to reduce energy consumption in a tunnel freezer with up to 30 %. This is done by gathering experience from the end user, Claus Sørensen A/S, a manufacturer of tunnel freezers, Hørup Maskiner A/S, and a German manufacturer of evaporators, Güntner GmbH & Co. KG. Their experience combined with CFD modelling and tests carried out by Danish Technological Institute will show how a tunnel freezer is to be designed and controlled to obtain an energy efficient carton tunnel freezer.

The project scope is based on work from 2016-2018 and has been granted funding from the Danish research program PSO, ELFORSK. The report presents a brief introduction, different theoretical approaches, a description of the test setup, calculations and simulations, as well as measurements and results. As an appendix to this rapport, there is a paper in English presented at the Gustav Lauritzen conference in Valencia Spain in 2018 and a poster which was also presented at the same conference.

Nomenclature

Symbols	***Description***	***Unit***
τ	Time	[s]
dt	Time interval	[s]
h	Heat transfer coefficient	[W/m^{2}K]
t_s	Surface temperature	[°C]
t_a	Air temperature	[°C]
q_s	Convective heat transfer	[W/m^2]
L	Length	[m]
k	Thermal conductivity	[W/mK]
ρ	Specific weight	[kg/m^3]
c_p	Specific heat capacity	[kJ/kgK]
t_{start}	Initial temperature of water	[°C]
t_{final}	Final product temperature of phase	[°C]
ΔH_{vol}	Volumetric freezing enthalpy	[kJ/m^3]
δ	Thickness	[m]
b	Height of box	[m]
A	Area	[m^2]
f	Friction factor	[-]
L	Length	[m]
D_H	Hydraulic diameter	[m]
v	Velocity	[m/s]
k_r	Roughness	[m]
ν	Kinematic viscosity	[m^2/s]
$\dot{V}$	Volume flow	[m^3/s]
n	Rotational speed	[rpm]

Acronyms

CFD	Computational Fluid Dynamics
EES	Engineering Equation Solver
Bi	Biot number
Re	Reynolds number
HTC	Heat Transfer Coefficient
DTI	Danish Technological Institute
CS	Claus Sørensen

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1. Introduction

The freezing of food in blast freezing tunnels is of great importance. In Denmark, the amount of products frozen in tunnels is around 1,500,000 tons per year using approx. 220 GWh of electrical energy consumption in the tunnels per year. The goal of the project is to be able to save 30 % in electricity for the fans and in the refrigeration system, which would provide 66 GWh per year if all freezing tunnels in Denmark were optimized.

A blast freezing is widely used for freezing packed goods on pallets. The advantage of the blast freezing tunnels is that a large quantity of the products can be frozen with relatively low manpower. Fresh food is packed in boxes and placed on pallets by the producer and transported to be frozen by a specific freezing company which places the pallets in blast freezing tunnels that can contain up to 40 to 50 tons of product each. The freezer is typically 15 to 20 meters long, and the height is three to four pallets rows. The tunnel is then filled with the product which is batch frozen.

Evaporators and fans in the freezer control the air circulation and temperature. The fan draws cold air from the evaporator and blows it first through 10 pallets, see *Figure 1*. Then, the air changes direction in the reversing chamber and flows through further 10 pallets on its way back to the evaporator. The refrigerant in the coil is ammonia, and the refrigeration system is a conventional two-stage industrial ammonia plant. The air volume flow for this tunnel is 23,400 m^3/h (6.5 m^3/s).

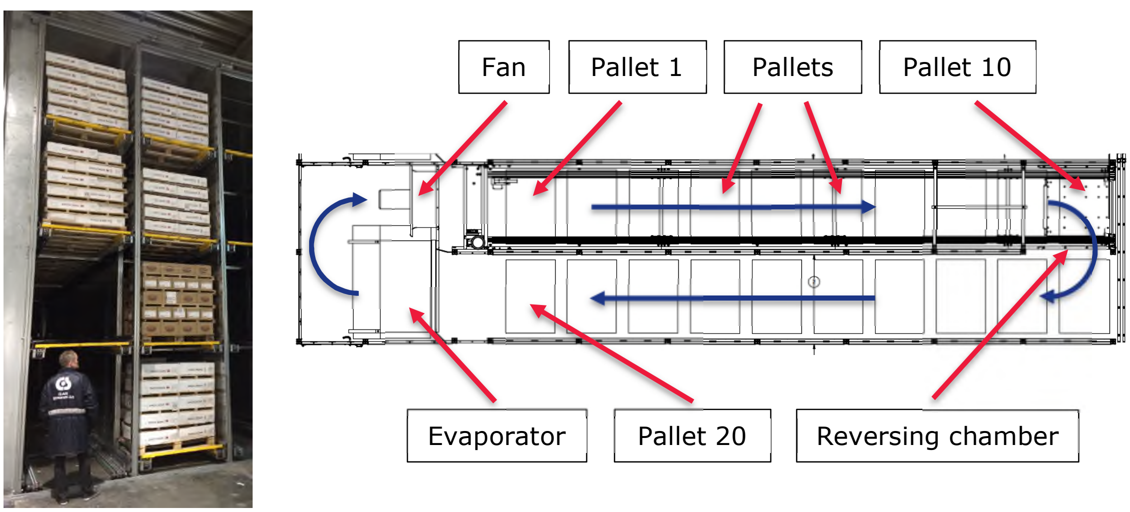


Figure 1: Freezer front view (left) and one row in the freezer seen from above (right).

The optimization of the freezing process, and thus the efficiency of the blast freezing process, is achieved by optimizing the contact between the air in the freezer and the boxes on the pallet. The boxes are separated by spacers, often made of wood, see Figure 2. The air spacers provide distance between the product package rows allowing the cold air to reach the top and the bottom of the product packages.

Figure 2: Left – wooden air spacer. Right – product pallet.

Although the construction of the existing blast freezers is far from optimal in terms of efficient freezing, the design has not changed much over time. The tunnel freezers are still designed according to old rules of thumb. In the tunnel freezer, the air velocity around the boxes is vital for energy efficient freezing. In a typical blast freezing tunnel, a large part of the air flows above and under the pallets instead of through the air spacer. This air shortcut results in poor utilization of the cold air and in a longer freezing time. To compensate for this, the airflow is increased, by using larger fans and the air temperature lowered to increase the heat transfer.

The energy consumption of the fans rises in the third power of the flow, and therefore the extraordinary energy consumption of bad design is significant. The lower air temperature in the evaporators results in lower suction temperatures for the refrigeration system, thus lowering the COP and increasing the power consumption. In addition, the power supplied to the fans goes directly to the refrigeration system and is thereby payed for twice. First directly and then through the refrigeration system.

A uneven air distribution through the tunnel results in an uneven freezing time of the pallets. The first pallet has good conditions and will be frozen significantly faster than the last one because of the higher air speed through the air spacers and the lower temperatures compared to those of the air in the last pallet. The box in the freezer, which takes the longest time to freeze, is the one that controls the freezing time. By distributing the air sensibly and by considering the differences in freezing time, the air flow can be brought down to a minimum throughout the logistic cycling time of the tunnel.

1.1. Problem definition

A substantial energy saving can be obtained by optimizing the airflow through the tunnel, which results in a higher efficiency of the freezer. The main goal is to develop a freezer where the direct energy consumption is reduced by 30 %. This is done by utilizing the air better through the freezer. This optimization is done by investigating:

1. The fan speed
2. The air distribution through the freezer
3. The packing of the pallets including new air spacers.

The optimization is first based on simulations and on model calculations of air flows as well as on the air distribution and the freezing time. These findings are first tested and validated in a laboratory test setup and then later validated in an industrial freezing tunnel at Claus Sørensen.

The air stream flowing above and under the first ten pallets travels throughout the freezer without obtaining a lot of energy from the product. When entering the reversing chamber, the air is mixed and then returns to the evaporator after traveling through ten more pallets. Also, here a large part of the air travels above and under the pallets. Before the evaporator, it mixes up with the air stream flowing through the air spacers between the products. This results in a lower average temperature of the air into the evaporator, which reduces its average efficiency. To compensate for the missing capacity, the suction temperature of the refrigeration system is reduced, which increases the total energy consumption of the tunnel.

2. Theory

The industrial blast freezer tunnel that has been examined in this project is a so-called batch freezer, i.e. the tunnel is filled up, the doors are closed, and then the freezing starts. The time that the batch stays in the tunnel is based on the logistics around the tunnel. Typically, it takes 22, 34 or 46 hours for each batch, using two hours to empty and fill the tunnel. Normally, the fans are driven at a constant speed throughout the freezing process.

Each tunnel at Claus Sørensen uses 20 kW on average for the fans. This effect transforms to heat in the freezer which is taken up by the air and must be removed by the refrigeration system through the evaporator. In this way, the power to the fans is payed twice. Both directly as energy to the fans and then through the refrigeration system as extra power to the compressors.

In this chapter, the various theoretical aspects used in the project, reaching from heat transfer to freezing time calculations, are explained.

2.1. Heat transfer

The freezing speed in the tunnel depends on two factors. How fast the air flows past the surface of the boxes and on the temperature of the air. The air velocity around the boxes determines the heat transfer coefficient (h) that controls the convective heat transfer from the surface. The temperature of the air (t_a) and the surface temperature of the product (t_s) control the heat removal from the product according to:

$$q_s = h\,(t_s - t_a) \tag{1}$$

The heat transfer coefficient for a wrapped product is also influenced by the eventual air gab between the product and the wrapping and the thickness of the wrapping.

The internal heat transfer in the product is controlled by the conduction through the product according to following equation:

$$q_s = -k\,\frac{dT}{dx} \tag{2}$$

The internal heat transfer for frozen products or the conduction heat transfer is dependent on the state of freezing, i.e. the down cooling, the freezing, and the sub-cooling. In the freezing phase, the condition is further complicated by the moving freezing front.

As the convective heat transfer (1) and the conduction heat transfer (2) are in series and equal, the surface temperature of the product adjusts accordingly.

2.2. Biot number

To visualize the effect of the convective heat transfer and the heat conduction in the freezing of products, a dimensionless quantity called the Biot number is defined:

$$Bi = \frac{h\,L}{k} \tag{3}$$

where *h* is the heat transfer coefficient [W/m^{2}K], *L* is the length from the surface to the middle of the product [m], and *k* is the thermal conductivity of the frozen product [W/mK].

The Biot number describes the effect of the convective heat transfer which is controlled by the air speed and the thermal conductivity through the product which is controlled by the product parameters. It is a number which indicates the relative importance of conduction and convection in the freezing process.

In general, problems involving small Biot numbers << 1 are problems where the convection is governing the heat transfer from the product. In this case, the change in the air speed and thereby in the heat transfer coefficient has a large effect on the freezing time.

Biot numbers >> 1 are on the other hand the ones where the convection governs the heat transfer. Here, a change in the air speed will have a small effect, and the only way to control the freezing time is by air temperature.

In blast freezers, which are the subject of this study, the heat transfer coefficients were measured to be around 40 [W/m^{2}K], and the thermal conductivity of water is 0.58 [W/mK], and of the ice it is 2.18 [W/mK]. The thickness of the product investigated is 150 mm, so the Biot number is around 10.3 for water and 2.75 for ice. This indicates that both the convective heat transfer and the air temperature are important. Optimizing the blast freezer is therefore far from obvious because the air speed and the air temperature are coupled. The optimization should aim at increasing the air flow around the product, which increases the air speed around the product and lowers the air temperature in the air spacers.

2.3. Heat transfer coefficient (HTC)

Determination of the heat transfer coefficients in the tunnels can be done by measuring temperature changes in an aluminum block according to the changes in the air temperature. The Biot number of the aluminum blocks is << 1, since aluminum has a high thermal conductivity, and the effect of conduction can be excluded. The heat transfer from the block can be expressed by following formulas:

$$\frac{dQ}{dt} = h\,A\,(T_{Alu} - T_a) \tag{4}$$

and

$$\frac{dQ}{dt} = \rho\,V\,cp\,\frac{dT}{dt}, \tag{5}$$

where *A* is the surface area affected by the air flow with temperature, T_a, ρ is the density of the aluminum block, V is the volume, and c_p is the specific heat capacity of aluminum.

By combining the equations (4) and (5) and integrate over the time interval (*dt*), the transient method for determining the heat transfer coefficient may be obtained, cf. (Becker, 2002) as:

$$h = \frac{\rho\, V\, cp}{A\, dt} ln\left(\frac{T_{Alu.1} - T_a}{T_{Alu.2} - T_a}\right). \tag{6}$$

This equation is used in the project to calculate the heat transfer coefficient from measurements on an aluminum block described in 4.2.

2.3.1. Empirical equation for the heat transfer coefficient (HTC)

For air-blast freezing, the HTC is related to the rate of air movement, and it depends on the nature of the air flow pattern, on the size and the shape of the object, and on the orientation of the object in the air flow. For forced convection over large product items with little interaction between items, the following approximations have been found, cf. (Valentas, Rotstein, & Singh, 1997):

$$h = 7.3\, v^{0.8}, \tag{7}$$

Where v is the average air velocity in the air spacer.

This equation is widely used to estimate the freezing time of products. The validity of this equation will be investigated in the project.

2.4. Freezing time

In industrial batch freezing tunnels, the freezing speed of a product is controlled by the air temperature and by the air speed. A lot of empirical equations are found to calculate the freezing time of products, e.g. (Granryd, 2003). The freezing of the product is divided in three phases, see Figure 3. The first phase is the down cooling period where the product is cooled down to the freezing point. The second phase is the freezing phase where the

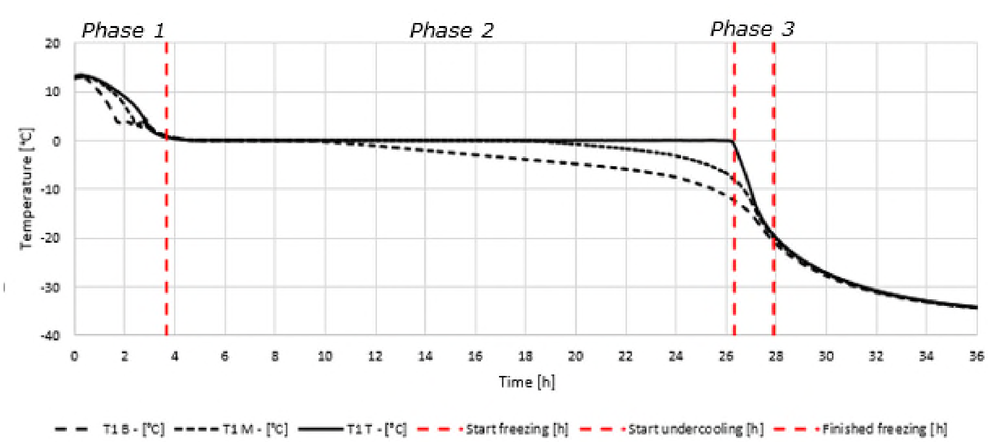


Figure 3: Temperatures inside a box measured at various heights from the bottom. The continuous line is the temperature at the bottom of the box. The dotted line is above the bottom and the centred line is at the middle of the box. The illustration is based on a box with water.

water in the product changes from liquid to solid ice. The third phase is where the frozen food is undercooled to the required final temperature.

The time for the different phases can be calculated from, e.g. (Granryd, 2003):

Phase 1:

$$\tau_{down\ cooling} = \rho \cdot c_p \cdot b \cdot ln\left(\frac{t_{start} - t_a}{t_{freezing} - t_a}\right) \cdot \left(\frac{1}{h} + \sum\left(\frac{\delta}{k}\right)_{Packing} + \frac{b}{2 \cdot k_{unfrozen\ product}}\right) \quad (8)$$

Phase 2:

$$\tau_{freezing} = \frac{\Delta H_{vol}}{t_{freezing} - t_a}\left(\frac{1}{h} + \sum\left(\frac{\delta}{k}\right)_{Packing} + \frac{b}{2 \cdot k_{frozen\ product}}\right) \cdot b \quad (9)$$

Phase 3:

$$\tau_{undercooling} = \rho \cdot c_p \cdot b \cdot ln\left(\frac{t_{start} - t_a}{t_{final} - t_a}\right) \cdot \left(\frac{1}{h} + \sum\left(\frac{\delta}{k}\right)_{Packing} + \frac{b}{2 \cdot k_{frozen\ product}}\right) \quad (10)$$

These equations indicate that the parameters, which can be adjusted to control the freezing time of a specified product, are the air temperature and the heat transfer coefficient through adjusting the air speed in the tunnel. By optimizing the distribution of the air in the tunnel, both the air speed and the temperature can be affected.

These equations also show the variety of products parameters necessary to estimate the freezing time. Estimating these parameters is difficult and is bound to a lot of uncertainty. This explains why it is difficult to accurately estimate the correct freezing time. One must bear in mind that these calculations always are a rough estimate of the actual freezing time.

These equations are used in the freezing time model described in 4.1

2.5. Energy usage of the fan

An important factor in reducing the energy consumption of the tunnel is to reduce the speed of the fan. The speed of the fan is directly related to the volume flow of air according to the affinity law for fans:

$$\frac{\dot{V}_2}{\dot{V}_1} = \frac{n_2}{n_1} \quad (11)$$

The pressure drop of air in the tunnel is related to the air velocity in second power. The air volume flow is the velocity times areal. Thereby, the volume flow is also related to the pressure drop in second power. Since the power in the air flow is the pressure drop times the volume flow, the power of the fan is related to the air flow in third power and thereby also to the fan speed according to:

$$\frac{P_2}{P_1} = \left(\frac{n_2}{n_1}\right)^3 \tag{12}$$

This shows, that by reducing the fan speed, the power to the fan is reduced in third power. Additionally, this power must be removed by the refrigeration system, so by reducing the speed of the fan, considerable energy can be saved.

2.6. Air velocity

To estimate the air velocity bypassing the pallet compared to the one going through the pallet, we can look at the pressure drop across the pallet. We assume that the pressure before the pallet in the whole cross section is the same. To calculate the pressure drop over the pallet in the tunnel, the following formula is used:

$$\Delta P = f \, \frac{L}{D_H} \, \frac{1}{2} \, \rho \, v^2 \tag{13}$$

Where f is the friction factor, L is the length, D_H is the hydraulic diameter, ρ is the density, and v is the velocity. By assuming the same pressure drop in the whole cross section, the average air speed around and through the pallet can be found.

The friction factor is calculated numerical from the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2 \, log\left(\frac{k_r}{3.7 D_H} + \frac{2.51}{Re\,\sqrt{f}}\right) \tag{14}$$

Where k_r is the roughness, and Re is the Reynolds number defined from:

$$Re = \frac{v \, D_H}{\nu}, \tag{15}$$

Where ν is the kinematic viscosity.

These equations are used in the freezing time model described in 4.1

2.7. Recap

This chapter illustrates the complexity of predicting and calculating the total freezing time. The freezing time depends on the size and on the type of meat in the boxes, and on how the product is packed in the boxes. This has a large influence on the product parameters used in the freezing time equations predicting the freezing time.

The freezing time also depends on the surface convection described by a surface heat transfer coefficient and on the conduction through the box, i.e. the air gabs, packaging material, and the actual packing of the pallet.

The heat transfer coefficients can be determined from an analytical approach when temperature and time for and aluminum box in the flow are known or by means of an empirical formula. The empirical formula has a large uncertainty in the value of the heat transfer coefficient.

The effect that the fan uses is dependent on the fan speed in third power. By reducing the fan speed, a considerable amount of energy can be saved.

The freezing time is divided into three different phases including cooling, freezing, and cooling down. Finally, calculations of velocities in the tunnel and Biot numbers are used.

3. Test setup

To simulate the industrial tunnel in a laboratory environment, a test tunnel was built in a container. The test tunnel was used to test different parameters to provide an insight into how effective the tested changes were. The product inside the boxes was water instead of meat to be able to run all the tests needed using the same test setup. The approach was to find a suitable candidate for improvements from simulations and calculations and to verify on water in the boxes in the test setup. Afterwards, the most promising candidates were tested in the industrial tunnel under real conditions with meat in the boxes.

In this chapter, the test setup is described.

3.1. Test freezing tunnel

By running CFD simulations in both the industrial tunnel and in the test tunnel, the test setup that best represented the industrial tunnel was found. The test tunnel contains tree pallets in a container as shown in Figure 4. CFD simulations showed that the first and the tenth pallet in the industrial tunnel were represented well by the first and the third pallet in the test tunnel. All dimensions perpendicular to the air flow and to the air return opening are true copies of the industrial tunnel, see Figure 4.

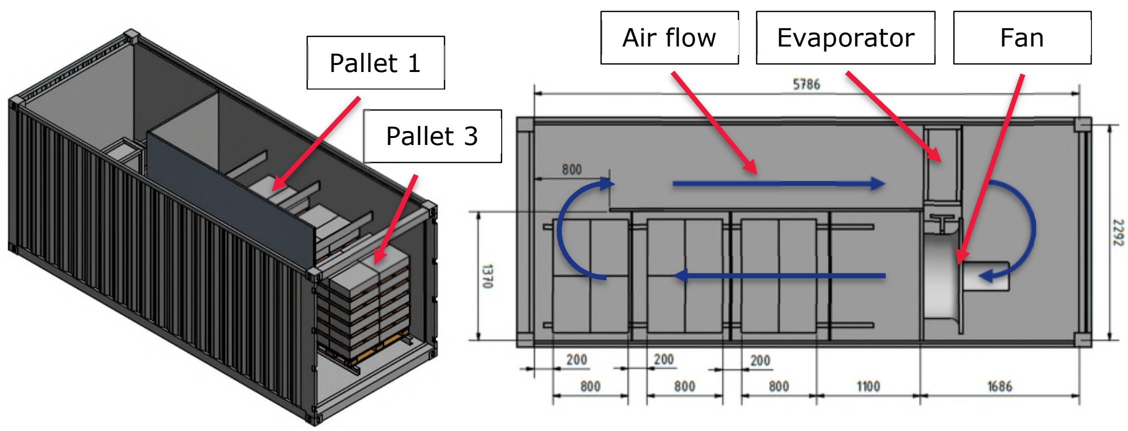


Figure 4: The test setup built into a container. An isometric view to the left and a cut through the view seen from above to the right.

A CFD simulation showed that the tenth pallet in the industrial tunnel, represented by the third pallet in the test tunnel, was the one that had the lowest air speed through the spacers and the lowest air temperatures around the product in the pallet. This indicates that the third pallet in the test tunnel and the tenth or the twentieth pallet in industrial tunnel are the ones taking the longest time to freeze. Thus, these pallets control the total freezing time of the tunnel.

As can be seen in Figure 4 to the right, the air flow follows the blue lines from the fan through the three pallets. Then, it enters the returning chamber on its way back to the evaporator. The air then flows through the evaporator and returns to the fan.

Figure 5: Selected images of the test setup at Danish Technological Institute. To the left a view into the open container. Middle upper is a side view of the container and the measuring equipment. Middle lower is the fan, and the one to the right is a view into the container looking at the third measuring pallet.

3.2. Product pallets in the tunnel

In the industrial tunnel, various product types are frozen in the tunnel at the same time, which leads to different pallet heights in each batch. This results in an enormous amount of pallet combinations inside the freezer. To reduce the amount of combinations to be simulated and tested in the test tunnel, a pallet with six product rows was chosen with a

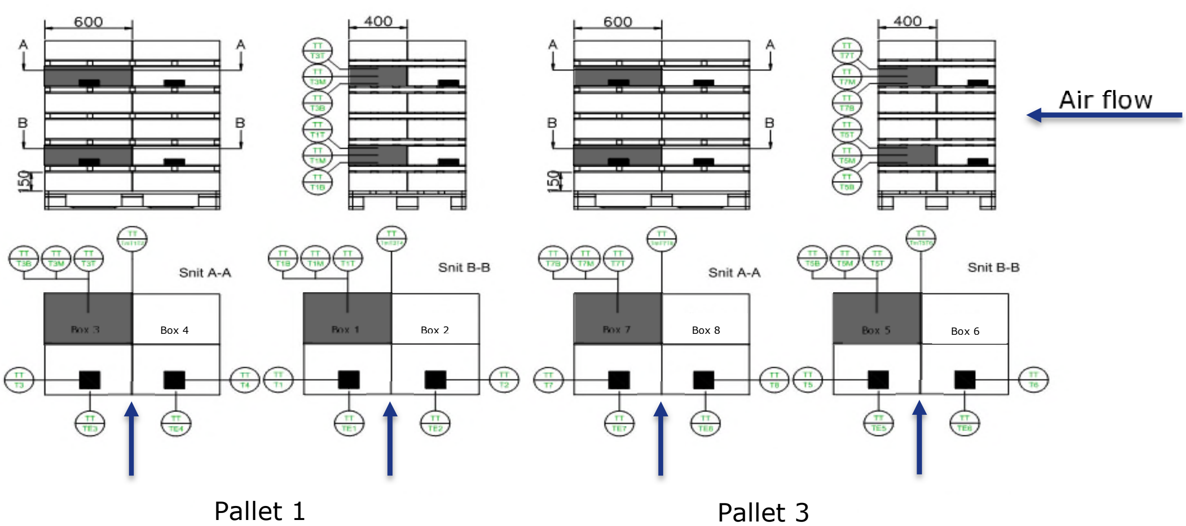


Figure 6: The shaded boxes represent the ones with temperature sensors at three levels. The black boxes show the placement of the HTC measuring device. Pallet 1 and 3 are measuring pallets while pallet 2 is a dummy.

product height of 150 mm as shown in Figure 6. This pallet represents the one with the highest product flow.

The test tunnel is used to find savings compared to a reference case, and it is presumed that the same trend is found in the industrial tunnel, even though the product combination is different, and water is used in the boxes instead of product.

The packages in the test tunnel were filled with water in bags, see **Fejl! Henvisningskilde ikke fundet.**. Temperature sensors were placed in two packages on pallet 1 and in two packages on pallet 3 in the test tunnel. In each package, the temperature sensors were fixed at three levels from the bottom of the box. The sensor closest to the bottom was 30 mm above the bottom, and the other two sensors were evenly distributed with a 30 mm distance in between. The horizontal placement was in the center of the box, see **Fejl! Henvisningskilde ikke fundet.** and **Fejl! Henvisningskilde ikke fundet.**. The two boxes with temperature sensors were placed in the worst locations of the pallet. These locations were found by means of CFD simulations and are shown in Figure 6 as the shaded boxes.

Figure 7: The construction of the measuring pallet. From the left: Water bags ready for water with thermocouples, in the middle in three different levels, finished water bag, and finally a frozen water bag.

The measurements of the surface heat transfer coefficient were done by placing an aluminum block with temperature sensors (the black boxes in Figure 6) in front of the product packages with thermocouples. In the middle of the air spacer, beneath the HTC measuring block, a temperature sensor was placed to measure the air temperature in the middle of the spacer.

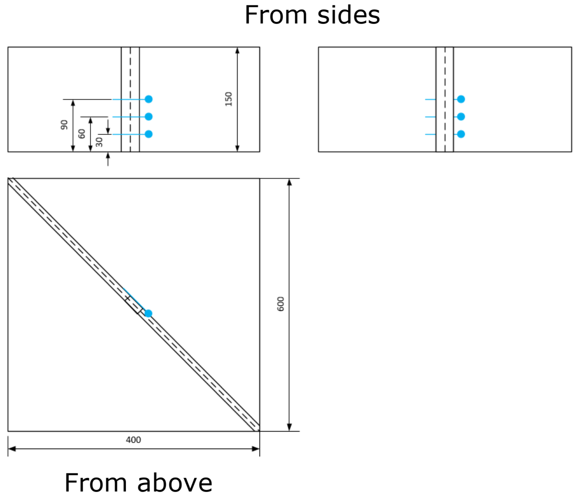


Figure 8: Graphic illustration of the exact location of each temperature measurement in the measurement boxes.

3.3. Additional measuring points

In addition to the temperature measurements in the boxes as described above, the temperature in the center of each pallet, where the four product packages meet, is measured. The air temperature in the tunnel is also measured both before and after the fan as well as before the evaporator, see Figure 9. The temperature after the last pallet right behind the air spacers in the middle of the pallet, close to the container door, is also measured (not shown in the figure). This sensor was used to try to control the fan speed according to the air temperature.

Flow is measured across the fan using a differential pressure transducer in combination with an air diffuser placed around the fan. The electrical energy to the fan is measured as well as the effect into the frequency drive for the fan. The refrigerant in the evaporator is

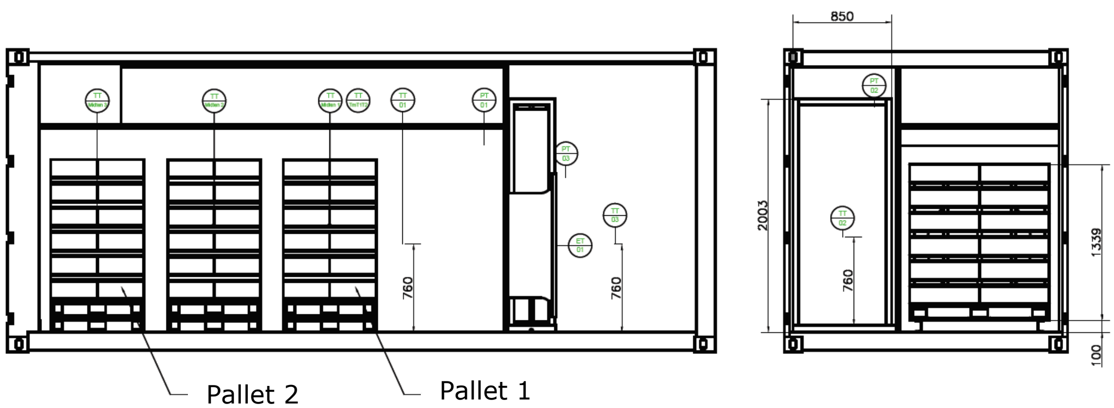


Figure 9: Illustration of the test setup and the measuring points outside the boxes.

CO_2 with an evaporation temperature of -39 °C. The temperature measuring points are shown in Figure 9.

The temperature measurements for a reference test are illustrated in Figure 10. The evaporator temperatures, the air temperatures and the water temperatures inside the boxes are represented. Figure 10 shows that the air temperatures rapidly fall to about -30 °C, after which they fall further through the freezing process. The freezing times for the boxes on pallet 1 are almost equal, while there are differences between the top box and the bottom box of pallet 3. Here, it takes the longest time to freeze the bottom measuring box, i.e. box number 5 in Figure 6. The freezing follows the three phases defined in section 2.4.

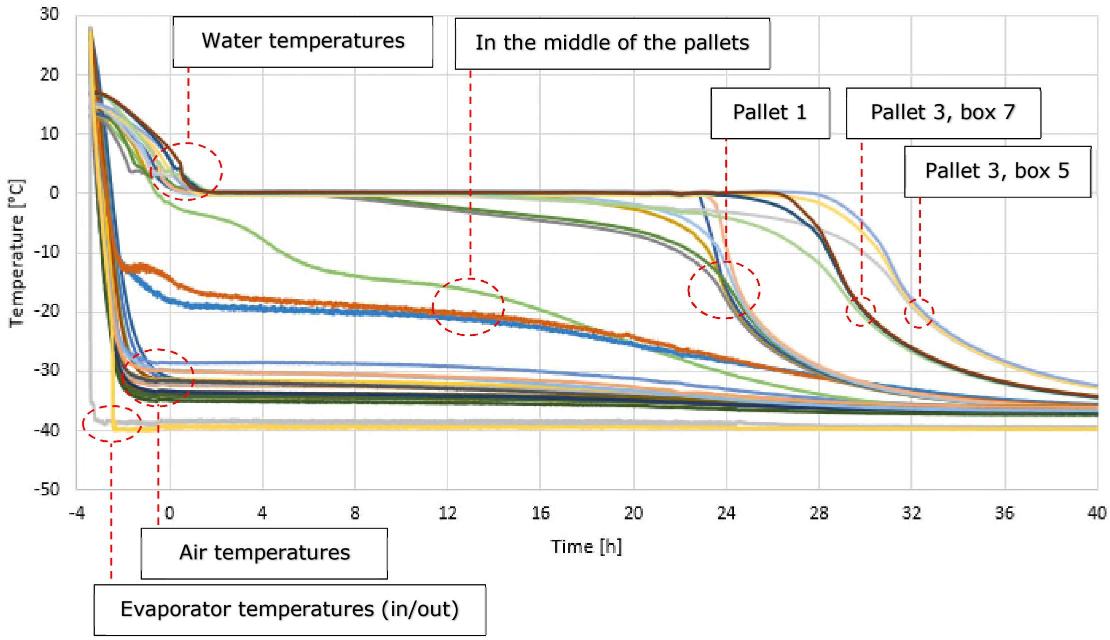


Figure 10: Illustration of all the temperature measuring points over a time period.

When looking at the water temperatures in the boxes at around 4 °C, a mixing of the water happens. This is due to the specific property of water that has the highest specific weight at 4 °C. When the temperature near the bottom of the box goes beneath 4 °C, the water at the bottom of the box becomes lighter than in the middle, and the water starts to mix because of natural convection. This is seen clearly in Figure 10. This will not occur in real situations with products in the boxes.

4. Calculations and simulations

Different calculations and simulations have been done to decide which test to be conducted. A model to estimate the freezing time, based on the equations described in chapter 2.4, has been prepared in EES, ref. (EES). Local heat transfer coefficients have been found by tests in the test tunnel and in the industrial tunnel. Different CFD simulations have been conducted to determine the measures to be tested in the test tunnel.

In this chapter, the various calculations and simulations conducted to find the configuration to be tested in the test tunnel are described.

4.1. The freezing time model

The purpose of the model in EES is to estimate the freezing times. The freezing times are calculated from different inputs such as airflow, geometry, definitions of product temperature at the start of the freezing, and when the freezing is considered finished. In addition to the freezing time, the air velocity is also calculated above, below, next to, and through the air spacers as explained in 2.5. The calculation is done with water in the boxes, which gives a much more precise product parameters. At an airflow of 6.5 m^3/s, and a product start temperature of 5°C, and an average temperature at the end of freezing of -20°C, a total freezing time of 32.6 hours is calculated, see Figure 11. This corresponds well with the measurements in the test tunnel for pallet 3.

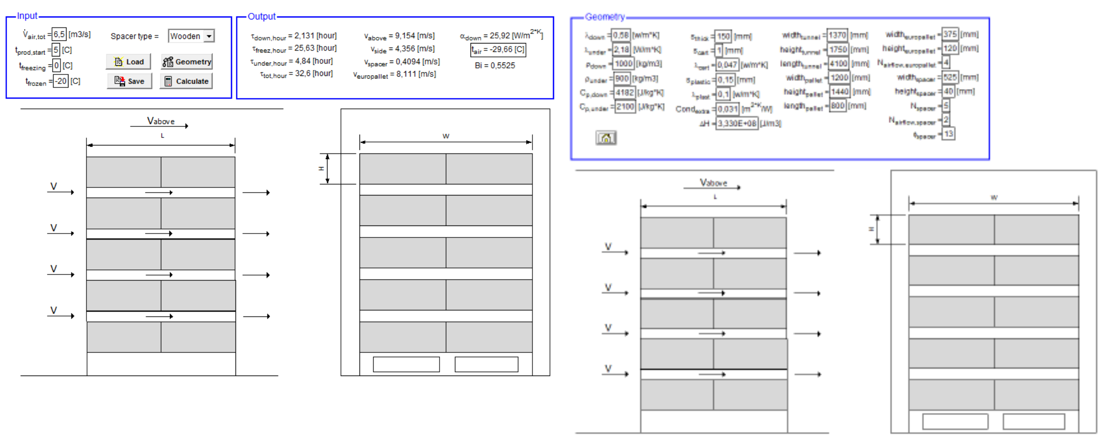


Figure 11: Illustration of the freezing time model. To the left, the main window, and to the right, the sub window with geometry settings.

The calculations are based on the equations (8)-(15). The heat transfer coefficient used in the equation is measured in the tunnel as explained in 4.2.

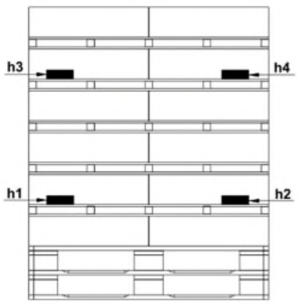
4.2. The surface heat transfer coefficient

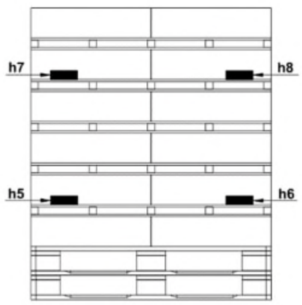
To be able to estimate how well the test tunnel represented the industrial tunnel at Claus Sørensen, the surface heat transfer coefficient was measured in both cases. To verify the CFD simulations of the test tunnel and of the industrial tunnel, a CFD calculation of the heat transfer coefficient was conducted.

This measurement of the surface heat transfer coefficient is also be used in the model described in 4.1.

4.2.1. In the test tunnel

The local heat transfer coefficients are measured in four different places in pallet 1 and 3 for the test tunnel. The eight different locations in the test tunnel are illustrated in Figure 12. The calculations are based on the equations (4) and (5). The measurements are performed at three different volume flows to be able to do an interpolation around the reference flow.





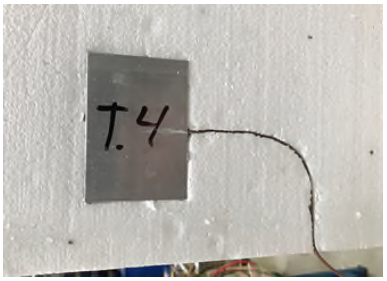


Figure 12: Illustration of the numbering for the different local heat transfer coefficients, *h*. To the left, a placement of the aluminium blocks looking along the air stream. To the right, a picture of the measuring device.

As expected, the measured heat transfer coefficients (HTC) indicated that pallet 1 is the one with the highest value, see Figure 13. The highest values in pallet 1 are in the upper part, *h3* and *h4*. The highest HTC values in pallet 3 are in the right side of the tunnel seen in the flow direction, *h6* and *h8*. This was also expected since there is a high air flow in the reversing chamber where the air flows to the second part of the tunnel.

The measurements also indicate that the HTC of the last pallet on the left (h7 and h5) experience the lowest HTC, and it does not change significantly at different flow rates. This

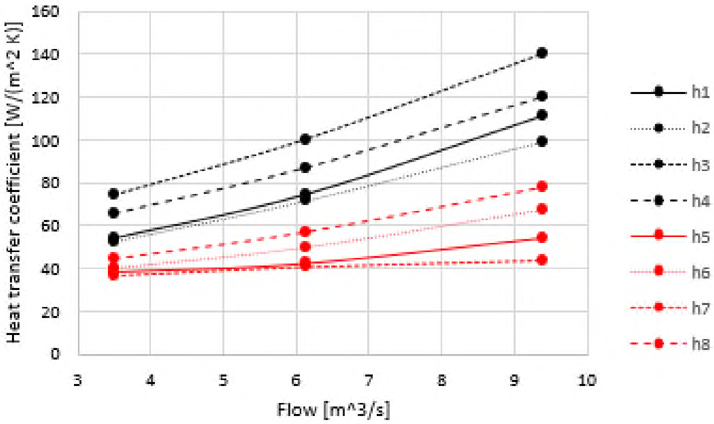


Figure 13: Illustration of the measured local heat transfer coefficient (HTC) based on three different flows: 3.5 m³/s, 6.1 m³/s, and 9.4 m³/s.

indicates a low air flow at that place in the tunnel, which is likely to control the freezing time for the tunnel.

4.2.2. The industrial tunnel at Claus Sørensen

As in the test setup, the HTC is also measured in the industrial tunnel at Claus Sørensen. The calculations are likewise based on the equations (4) and (5). The purpose of performing the calculations at Claus Sørensen is to get an indication of how well the test setup matches the real tunnel. The HTC measurements at Claus Sørensen are taken in pallets 1, 10 and 20. The measurements in pallet 1 correspond to pallet 1 in the test setup, and pallet 10 corresponds to pallet 3. The measurements were taken at the same location on the pallet as in the test tunnel.

Table 1: The measured HTC (W/m²K) at Claus Sørensen.

6 m³/s	*Pallet 1*	*Pallet 10*	*Pallet 20*
h1, h5, h9	81.0	35.1	58.0
h2, h6, h10	82.2	39.9	53.8
h3, h7, h11	78.7	35.3	70.7
h4, h8, h12	70.5	33.7	55.4
Average	78.1	36.0	55.7

As can be seen in Table 1, the packages on pallet 10 have the lowest HTC, which indicates that it is those packages that take the longest time to freeze, and thereby they control the freezing time in the tunnel. This also applies to the test setup. It is hereby pallet 10 that dictates the freezing time.

In Table 2 and in Table 3, the differences between the test setup and the measurements at Claus Sørensen are shown. The average difference in HTC in pallet 1 is 6 %, while the difference is 24 % for the pallet in the reversing chamber, i.e. the HTC is slightly higher in the test setup. Since the test setup is a simplified version of the industrial tunnel, these deviations are within the limits of accepting the test setup to be a representative version of the industrial tunnel for pallet 1 and pallet 10.

Table 2: The differences for pallet 1 between the surface heat transfer coefficient (W/m²K) measured at Claus Sørensen, CS, and the test setup at Danish Technological Institute, DTI.

6 m³/s	*DTI*	*CS*	*Deviation*
h1	74.5	81.03	-9%
h2	71.6	82.17	-15%
h3	100.3	78.69	22%
h4	87.0	70.5	19%
Average	83.3	78.10	6%

Table 3: The differences for pallet 10 (3) between the heat transfer coefficient measured (W/m^2K) at Claus Sørensen, CS, and the test setup at Danish Technological Institute, DTI.

6 m^3/s	*DTI*	*CS*	*Deviation*
h5	42.5	35.08	17%
h6	49.7	39.95	20%
h7	40.6	35.34	13%
h8	57.0	33.75	41%
Average	47.5	36.03	24%

To compare these results to the empirical equation presented in 2.3.1, the average velocity in the air spacer is calculated. The free space in and around the pallet is 1.32 m^2 which gives an air velocity of 4.55 m/s for the volume flow of 6 m^3/s. The results are presented in Table 4.

Table 4: The HTC in the air spacer according to the empirical equation $h = 7,2 \cdot v^{0,8}$ calculated by using the average air velocity through the free area.

6 m^3/s	*DTI*	$h = 7{,}2 \cdot v^{0,8}$
Average	47.5	24.2

Looking at the calculated HTC in Table 4, one can conclude that the calculated HTC is somewhat lower than the measured. By using the empirical equation, the calculated freezing time will be longer than the actual one. This can also be used as an safety on the HTC calculations for tunnel blast freezers since all other parameters in cooperated in the calculations are bound with a lot of uncertainty.

4.2.3. Calculated HTC using CFD for the test tunnel

In addition to the measurements of the HTC, these are also simulated in SolidWorks, ref. (SolidWorks). The heat transfer coefficient determined by CFD is difficult to estimate, since it requires a fine mesh in the boundary layer and hence a large calculation time. Two approaches are tried. First, where the empirical equation (7) is used and then by using equation (1).

Based on the empirical equation (7) and on a simulation of the flow in the test tunnel, it is possible to estimate the HTC. It can be seen from Figure 14, that the HTC for pallet 1 is between 15 and 45 W/m^2K while the heat transfer coefficients for pallet 3 are between 1 and 25 W/m²K. Figure 14 also shows, that it is the left side of pallet 3 which has the lowest heat transfer coefficient and thus the longest freezing time.

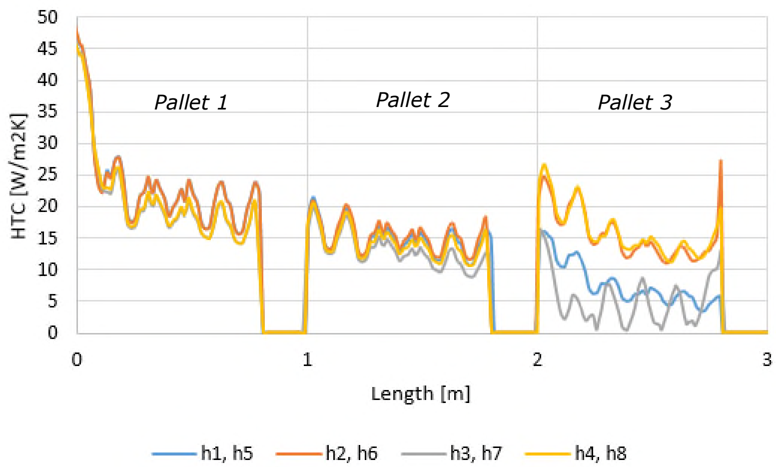


Figure 14: Heat transfer coefficients through the three pallets, in four different places. The calculations are based on empirical equation (7) with the flow simulation at 6.5 m³/s.

The size of the heat transfer coefficients calculated by using equation (7) is considerably lower than the measured heat transfer coefficients in the test tunnel according to Figure 13. This further indicates that the empirical equation is not well suited for calculating the HTC in tunnel freezers.

Another way to simulate the HTC in CFD is by using equation (1). The results are illustrated in Figure 15. These are closer to the measured heat transfer coefficients since the measurements were made at the beginning of the air space channel.

The graph in Figure 15 also indicates the difference in the local HTC from the entrance to the exit of the air spacer. This will favor the products closer to the entrance (they will

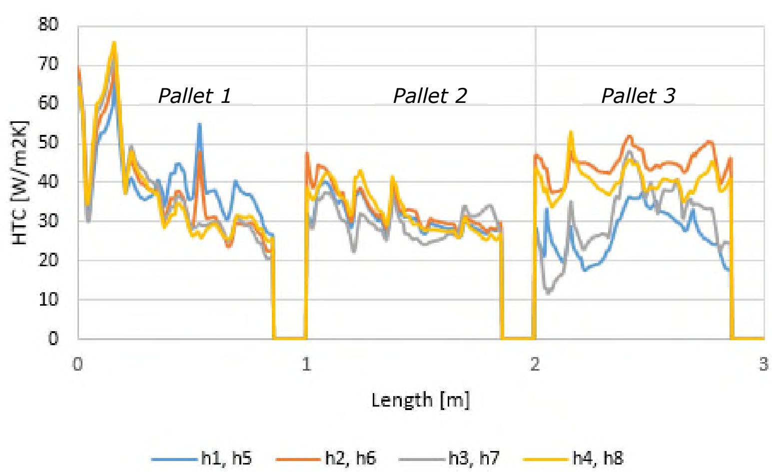


Figure 15: Heat transfer coefficients through the three pallets at the same place as measured in the test container. The heat transfer coefficients are based on equation (1) with air temperature, surface temperature, and heat transfer from a simulation at 6.5 m³/s.

freeze quicker). By reversing the flow, this effect could be reversed, and the total freezing time could be reduced.

Figure 16 and Figure 17 illustrate slices of velocities (seen from above) and temperatures throughout the tunnel at the two levels where the HTC measuring device is placed in the test tunnel. Since the driving force of freezing is a combined effect of velocity and temperature, these graphs indicate the freezing conditions of the boxes. Pallet number 1 in the air flow direction has the best conditions, the highest air speed, and the lowest air temperature, which corresponds well with the measurements of the HTC.

When looking at pallet 3, the velocity is very low in the left side of the pallet, seen in the flow direction. This also corresponds well with the measurements of the HTC in the test container and indicates that the last boxes on the left side of the pallet 3 are the ones controlling the freezing time and therefore the ones with the largest optimization potential.

The temperature distribution also shows the highest temperature for the last boxes in the air flow direction for pallet 3. Since the temperature is the other driving force of the heat transfer, this condition also increases the freezing time.

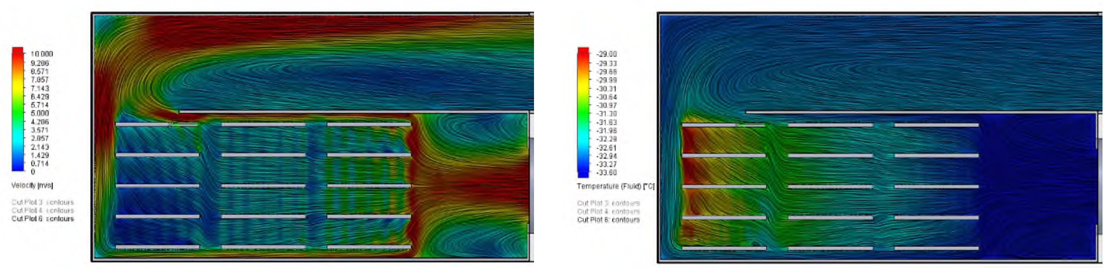


Figure 16: Illustration of the velocity (to the left) and of the temperature (to the right) development of the lower measurement layer at *h1*, *h2*, *h5,* and *h6,* respectively. Seen from above.

When looking at the upper plane in Figure 17, the same trend appears as for the lower plan in Figure 16.

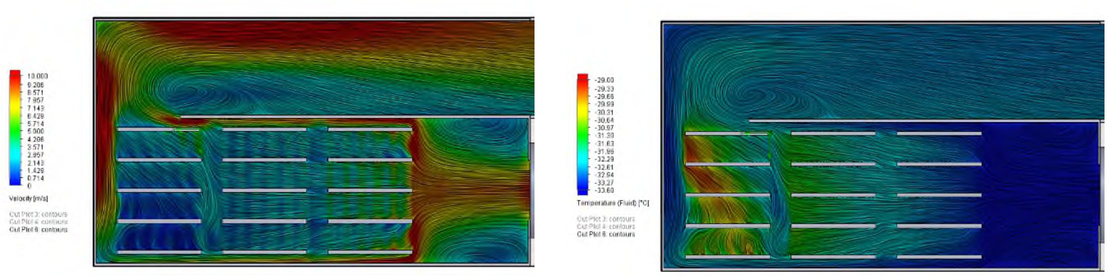


Figure 17: Illustration of the velocity (to the left) and the temperature (to the right) development of the upper measurement layer at *h3*, *h4*, *h7,* and *h8,* respectively. Seen from above.

4.3. CFD – Test tunnel

The purpose of the CFD simulations was to simulate the temperature and the flow distribution of various design modifications. These modifications are simulated in the CFD model, and afterwards the most promising solutions are tested and verified in the test container. The CFD simulations give us the air velocity and the temperature distribution but not directly the freezing times. Since the temperature and the air velocity are the driving forces behind the freezing time, the freezing time estimations can indirectly be drawn from the simulation. The colder the temperatures and the greater the velocity, the faster the freezing times will be.

By looking at the CFD simulations for the industrial tunnel and for the test tunnel, it becomes evident that most of the flow is directed in channels above and under the products as shown in Figure 18. This is also consistent with the EES model.

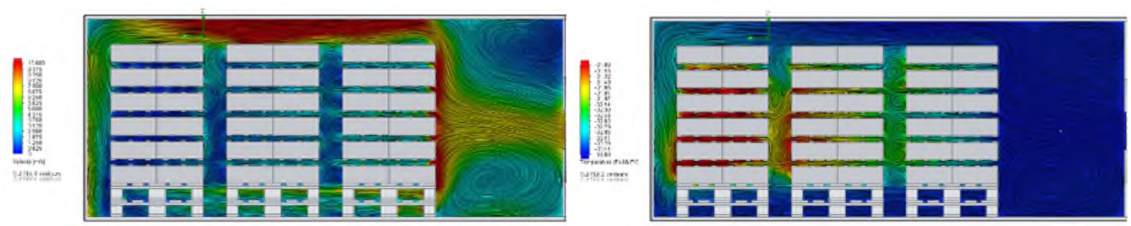


Figure 18: Air flow 6.5 m^3/s contour lines. To the left, the flow distribution, and to the right, the temperature distribution.

4.3.1. Change in the location of the pallets

Measurements and simulations show that the last pallet, i.e. pallet 3 in the test tunnel and pallet 10 in the industrial tunnel, is the one with worst conditions and the one that takes the longest time to freeze. To reduce the freezing time, the conditions for the last pallet must be improved. The first attempt to do so was to move the pallets closer to the fan to make space behind the last pallet for the air to flow before it changes direction and returns to the second half of the tunnel. By running CFD simulations with the pallets in different distances from the fan, a position where the first pallet was 300 mm from the fan was selected compared to 1100 mm as in the original setup.

4.3.2. Air distribution

By looking at the simulation of the test container, Figure 18, it is clear that a large part of the air flows with high speed above and under the pallets. The temperature profile shows the same trend. To try to utilize the air flow better, an attempt to distribute the air better using baffles was investigated. Several CFD simulations were performed with various kinds of baffle configurations. Sixteen different types and sizes of baffles were simulated. All simulations indicate that conducting the air better, would result in significantly lower temperatures and in a higher air velocity in the air spacers between the boxes. Some of the simulated configurations can be seen in Figure 19.

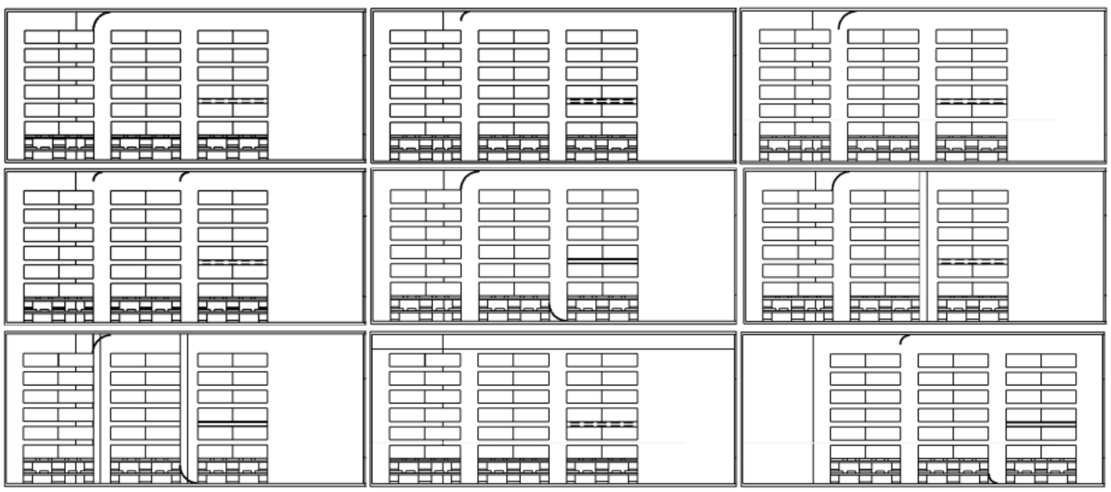


Figure 19: A variety of different configurations with baffles.

Based on the different simulations, the best was chosen to be tested in the test container. The solution chosen (see Figure 20 and Figure 21) was the one where the air from above the pallets is directed downwards before the third pallet, and where the air flowing beneath the pallet is directed upwards before pallet two. The flow and temperature distributions from the simulation are shown in Figure 20 and in Figure 21. When compared to Figure 18, the air velocity and the temperature improvements are evident.

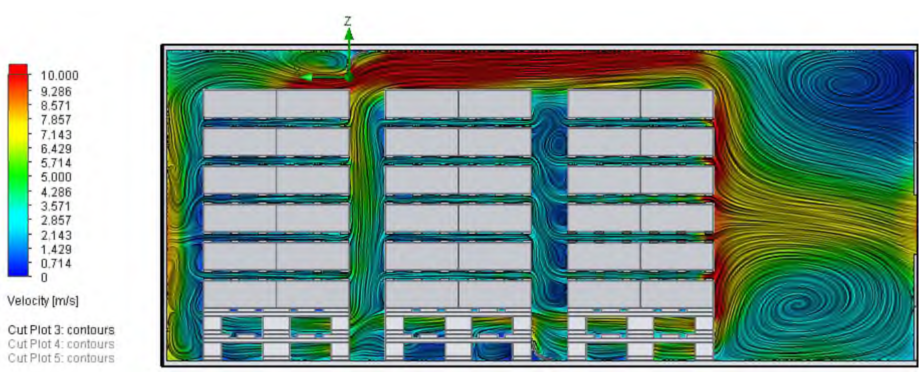


Figure 20: Flow distribution with an air flow of 6.5 m^3/s and two baffles.

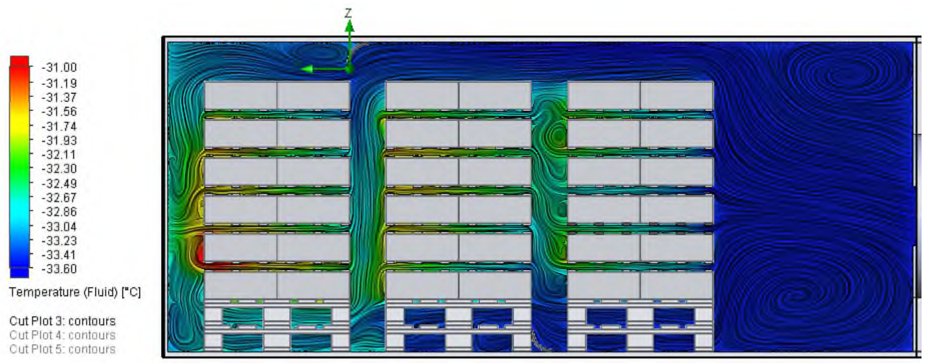


Figure 21: Temperature distribution with an air flow of 6.5 m³/s and two baffles.

By plotting the temperature profiles through the test tunnel for the reference case and for the one with baffles (see Figure 23), the air temperature in the last pallet will be about 1.5 °C colder than in the reference test, which will improve the freezing time considerably.

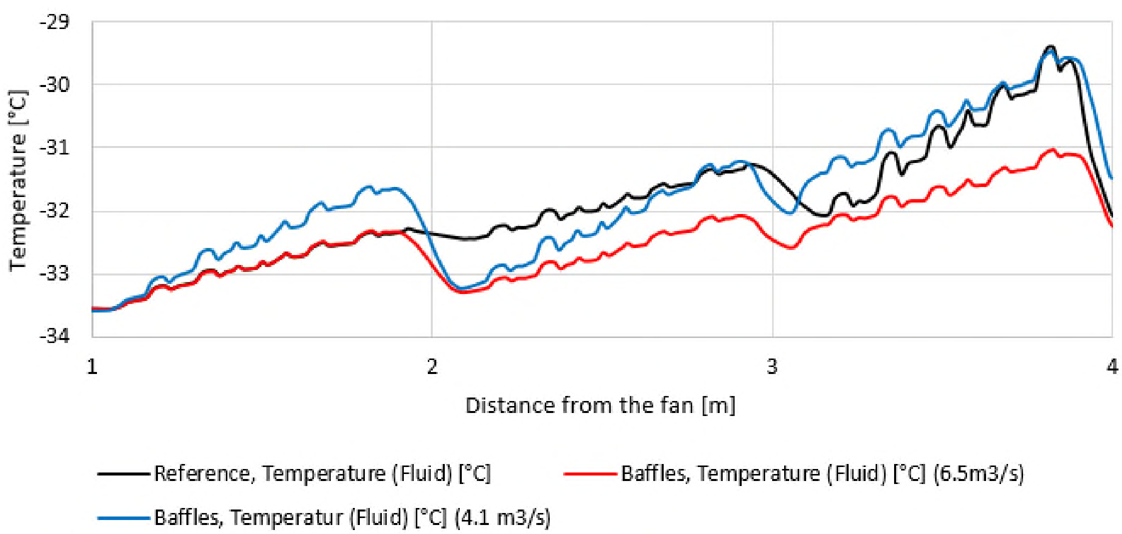


Figure 23: Temperature improvements of 1.5 °C at the last box. This is at the expense of a pressure increase of approximately 150 Pa.

Since the goal is to reduce energy consumption for the same freezing time, it would be possible to reduce the air speed in the tunnel to reach the same air temperature in the last pallet as for the reference case. A so-called Goal Optimization was performed in the CFD software focusing on changing the flow until the air temperature of the last pallet was 29.5 °C. This showed that it could be accomplished by lowering the air flow to 4.1 m³/s, which is shown in Figure 23 as the blue line. By doing this, the expected energy savings would be considerable. This energy savings will be measured in the test tunnel and is described in chapter 5.2.4.2.

4.4. CFD – Industrial tunnel

A simulation of one row in the industrial tunnel at Claus Sørensen was conducted to analyze the effects found in the simulation of the test tunnel.

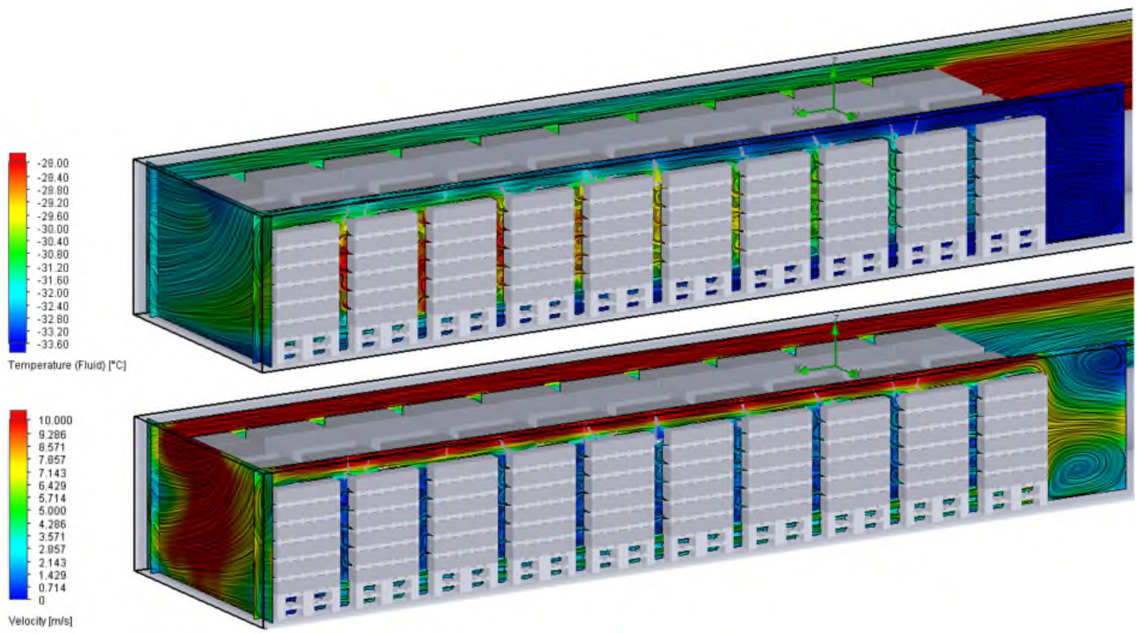


Figure 24: Illustration of velocity (lower) and temperature (upper) in an industrial tunnel at 6.5 m^3/s.

Figure 24 shows the simulated velocity and temperature profiles for one row through the industrial tunnel. These simulations show the same results as for the test tunnel i.e. that most of the air travels above and under the pallets.

In Figure 26, the temperature drop through the freezer is depictured. The continues line, where the distance is 200 mm between the pallets, is the reference case. The temperature drop through the first 10 pallets is around 3 °C. Then, the temperature is mixed in the return chamber and returns to the remaining 10 pallets.

Figure 25 illustrates the differences between the test setup and the tunnel at Claus Sørensen, depictured from parametric length in relation to temperature, velocity and pressure. Since the test tunnel has no pallets in the return channel, the parametric length that can be compared is from 0 to 0.5.

The temperature profile illustrates that there is a difference of 1.5 °C in the first part of the tunnel. This is understandable since there is considerably more product in the industrial tunnel the air has to travel through before entering the 10'th pallet.

The velocity profile up to the parametric length of 0.5 illustrates that the velocity in the air spacer is lowest in pallet 3 in the test tunnel and pallet 10 in the industrial tunnel. The difference in velocity between the two setups from start to finish is approximately the same. Finally, the pressure difference illustrates that there are differences between the two configurations caused by more pallets in the industrial tunnel, which means that more energy will be used at Claus Sørensen.

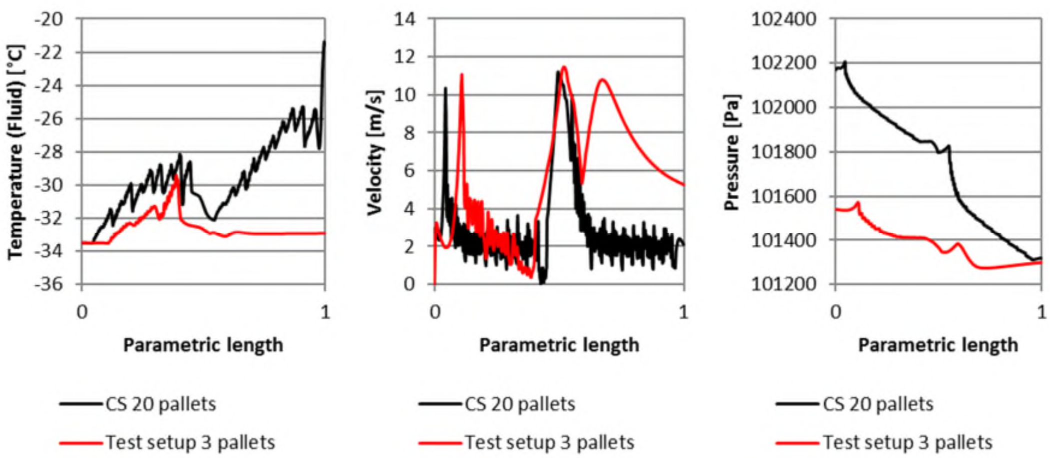


Figure 25: The difference between the test setup and the tunnel at Claus Sørensen described with parametric length in relation to temperature, velocity and pressure.

A comparison of the measurements shows the same trends for the test tunnel as for the industrial tunnel. This indicates that the test tunnel can be used to find and measure various actions that later is verified in the industrial tunnel.

4.4.1. Change in the location of the pallets

To improve the air flow around pallet 10 in the industrial tunnel, the idea was to move the pallet stack closer to the fan. This was impossible to accomplish in the real tunnel because of construction restrictions. The only way to make the extra space behind pallet 10 was to reduce the distance between the pallets in the stack.

To investigate if reducing the space between the pallets in the stack would give us the same benefits as moving the hole stack closer to the fan, a simulation was conducted. The temperature profiles through the freezer are depicted in Figure 26. From the temperature profiles, it seems that reducing the distance between the pallets will increase the pressure drop and thereby reduce the flow resulting in higher air temperatures and presumably a lower HTC for the last pallet in each row, i.e. pallet 10 and pallet 20. Therefore, this does

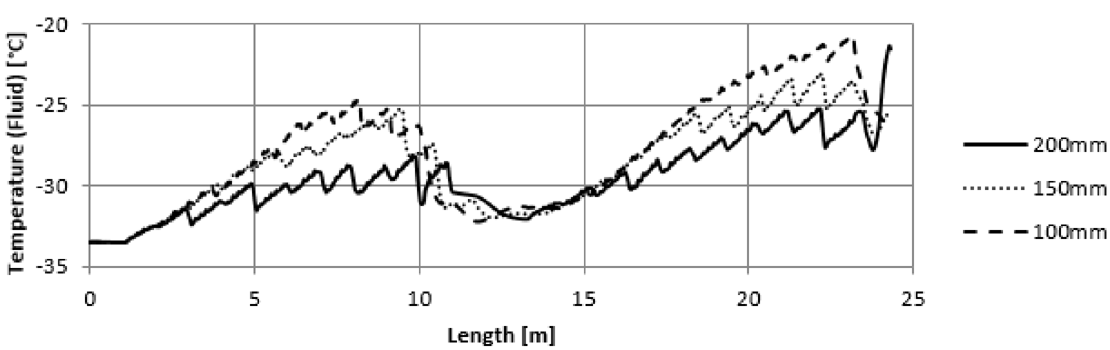


Figure 26: Temperature distribution with three different distances between the pallet. The one with 200 mm is the original.

not seem to have the same noticeable effect for the last pallet as moving the pallets closer to the fan as shown in 4.3.1.

4.4.2. Air distribution by baffles

To simulate the use of baffles, which was found beneficial in 4.3.2, a simulation was performed where baffles were installed at the same locations as in the test tunnel (see Figure 27), i.e. in the first part of the tunnel (for pallets 1 to 10). The result is shown in Figure 27 and in Figure 28.

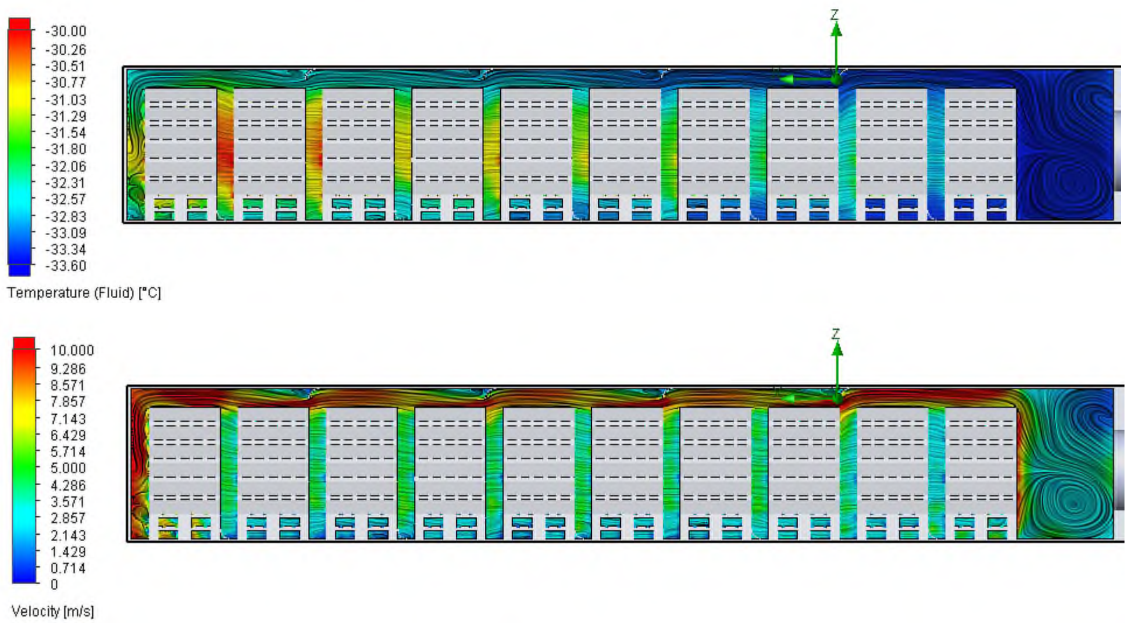


Figure 27: Illustration of temperature and velocity in an industrial tunnel at 6.5 m³/s with baffles.

The baffles result in a lower temperature for the last pallet and in a higher velocity in the air spacers. Baffles will therefore result in shorter freezing times for the worst pallets since the velocity is higher, and the temperature is lower.

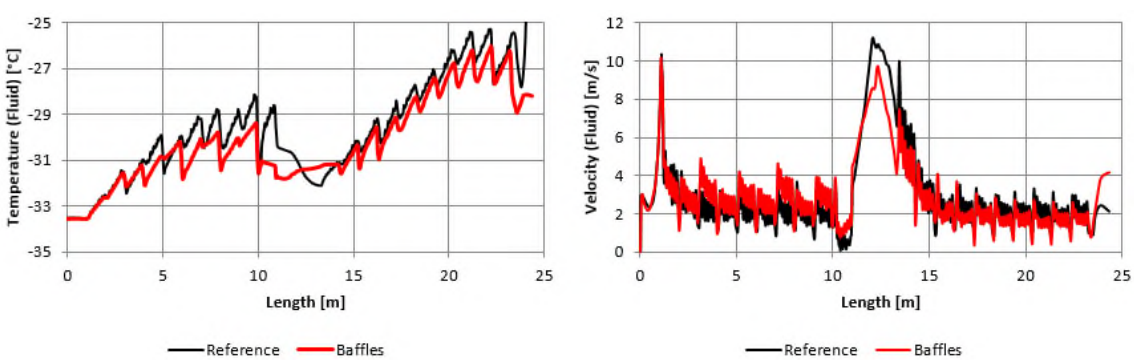


Figure 28: The difference in temperature and velocity in the tunnel at Claus Sørensen with and without baffles.

4.5. Recap

Several preliminary tests and simulations have been performed, and a model of the freezing process has been constructed to find the solutions that are most promising to be tested in the test container and then later in the industrial tunnel at Claus Sørensen.

A freezing time model was built in EES to estimate the freezing times and the air velocities. Measurements on HTC were used in the model.

HTC is measured in the industrial tunnel at Claus Sørensen and also in the test setup. A CFD simulation to simulate the HTC is also made. By comparing the HTC from the CFD simulations with measurements in both the test tunnel and the industrial tunnel, a difference is found. There is however an uncertainty in the HTC calculation using the CFD simulations based on limitations in the CFD software. The difference between the HTC measured in the test setup and in the industrial tunnel at Claus Sørensen is on the other hand small, especially at the first pallet. This is because it is located at the same place in the two scenarios (just after the fan). The second measuring pallet is placed, as the third pallet in the test setup and the tenth pallet at Claus Sørensen and deviate more in the HTC calculations, but the measurements are within reasonable limit.

CFD simulations have been performed to estimate the effect of design changes in the tunnel. The two most significant impacts are to move the pallets closer to the fan and to use baffles. CFD simulations on these changes have been performed for both the test setup and the industrial tunnel.

Based on the performed simulations, it can be concluded that the test layout built in the container allows for realistic comparison with the freezing tunnel at Claus Sørensen. However, it should be kept in mind that the last pallet has an average difference in the heat transfer coefficient of 24 % and a difference in the air temperature of 1.5 °C according to the simulation. This is of course because of the eight pallets between the first and the tenth in the industrial tunnel compared to one in the test setup.

It can be concluded that the test setup can be used to test trends, and then the best results can be implemented and tested in the industrial tunnel at Claus Sørensen.

5. Measurements and results

In industrial batch freezing tunnels, the time the products stay in the freezer, i.e. the cycle time, is dependent on site logistics of the tunnel. This means that the products stay in the freezer until the next unloading takes place, normally with full fan speed the whole time. For the product size investigated in the project, the cycle time in the freezer is 36 hours.

The optimization of the energy usage is then done by utilizing the 36 hours in the best way. Two approaches were investigated. The first approach was to reduce the air flow and to increase the freezing time to match with the 36 hours. The second approach was directed at distributing the air through the tunnel in the best possible way. A part of the air distribution test was to test another type of air spacers. Instead of the most used wooden air spacer, a new plastic type from Neptun was tested. The complete test matrix is summarized in Table 5.

Table 5: Test matrix.

Introduction	T1	Documentation of; air flow, heat transfer coefficient and pressure drop.
Reference	T2	Reference test to be able to compare time, temperature and energy consumption in subsequent test.
Adjusting the air flow	T3	Three-step air flow control starting with low flow – Time dependent.
	T4	Three-step air flow control; high-low-high flow – Time dependent. (Based on conclusion from test 3)
	T5	Air flow controlled by temperature -30°C on air from pallet 3.
	T6	Air flow controlled by temperature -32°C on air from pallet 3.
Verification of reference test	T7a T7b T7c T7d T7e	A new reference test established.
Constant air flow	T8a	Low air flow.
	T8b	Middle air flow.
Air distribution	T9	Pallet 300 mm from the fan (Based on CFD).
	T10	Only two pallets.
	T11a	Baffles (6.5 m^3/s) (Based on CFD).
	T11b	Baffles (4.1 m^3/s) (Based on CFD).
	T12	Baffles and pallets 300 mm from the fan.
Neptun air spacer	T13	High air flow.
	T14	Middle air flow.
	T15	Low air flow.
	T16	Maximum flow.
	T17	Flow back and forth.
	T18	Flow back and forth 2.
Test at Claus Sørensen	T19	Reference test 1 (6.5 m^3/s).
	T20	Reference test 2 (6.5 m^3/s).
	T21	Reference test 3 (6.5 m^3/s).
	T22	Low air flow (38 Hz).
	T23	Neptun air spacer.
	T24	Middle air flow (43 Hz).
	T25	Nine pallets instead of ten.
	T26	Flow back and forth.

As a starting point, a reference case was established where the air flow and the placement of the pallets in the test tunnel were comparable to those of the industrial tunnel. The measurements were done for 36 hours to lay the foundation for the reference case. Five reference measurements (T7) were made, and the average values of these were used as a reference for the following evaluation.

To evaluate the time in the test setup for each phase (see chapter 2.4) during freezing, the boxes with temperature sensors were monitored. To have a common reference between measurements for when the cooling starts, the average temperature of all sensors in the box was followed, and the cooling phase was considered started when it reached 5 °C (start of phase 1). To estimate when the freezing phase started, the temperature sensor at the bottom of the box was used, and the freezing phase was considered started when it reached +1 °C (start of phase 2). To predict when the freezing phase ends, and the undercooling phase starts, the top sensor placed in the middle of the box was used, and the freezing phase was considered over when it reached -1 °C (start of phase 3). The undercooling phase was considered finished when the average temperature in the box reached -20 °C.

The total freezing time of the test tunnel is the time that it took the worst box to finish all phases. When comparing the energy usage, the tunnel was considered to run for 36 hours, even though the freezing temperature of -20 °C was reached earlier. The extra effect used in the refrigeration system to remove the heat from the fan was also considered. As a COP for the refrigeration system, a value of 2.3 was found to represent the system found at the industrial site.

For the test at the industrial tunnel at Claus Sørensen, the temperature of the products when entering the tunnel was in most cases quite close to the freezing point so the down cooling phase was missing. The freezing phase started when the temperature of the lower temperature sensor was 1°C. The product in the boxes at Claus Sørensen was chicken, and the temperature requirement for successful freezing is that the center temperature of the product has reached -12°C. This is a requirement from the customer. In the freezing time estimation for the Claus Sørensen tests, the freezing is therefore considered finished when the temperature of the sensor in the middle of the box, i.e. the top sensor, reaches -12°C.

The results from test 1, *T1,* are documented in chapter 4, and the rest of the results are documented in this chapter.

5.1. Overall results

All the conducted tests are presented in Table 6 where the freezing times and the energy consumption are given for box 1, 5 and 7. The box numbering is illustrated in Figure 6.

Table 6: The overall results from the various tests

			Box 1	Box 5				Box 7				Energy				
	Test	Freez-ing Total	Freez-ing	Freez-ing	To phase 2	To phase 3	To phase 4	Freez-ing	To phase 2	To phase 3	To phase 4	Temp. start	Fan 36 hours	Ref. System	Total	Savings
		[h]	*[h]*	*[h]*	*[h]*	*[h]*	*[h]*	*[h]*	*[h]*	*[h]*	*[h]*	*[°C]*	*[kWh]*	*[kWh]*	*[kWh]*	*[%]*
Reference	*T2*	32.4	25.5	32.6	1.2	27.5	3.8	29.8	1.2	25.4	3.1	15	57.2	24.9	82.1	-0.9%
Adjusting the air flow	*T3*	33.5	25.4	33.5	2.5	25.8	5.2	30.5	2.5	23.9	4.1	11	42.8	18.6	61.4	24.5%
	T4	34.5	26.2	34.5	2.3	27.8	4.4	32.4	1.6	27.0	3.9	10	33.6	14.6	48.2	40.7%
	T5	32.8	22.8	32.9	2.6	27.2	3.0	31.4	2.5	25.3	3.6	10	22.7	9.9	32.6	60.0%
	T6	31.1	23.1	31.3	1.8	25.6	3.9	30.6	1.9	25.8	3.0	16	34.7	15.1	49.8	38.8%
Verification of reference test	*T7a*	29.6	21.1	29.6	0.6	25.9	3.1	28.6	0.8	25.9	1.9	10	57.7	25.1	82.8	-1.8%
	T7b	31.7	19.5	28.8	1.7	25.3	1.9	30.1	2.8	26.3	2.8	22	56.2	24.4	80.6	0.9%
	T7c	30.3	19.1	29.1	1.7	24.4	3.0	30	1.0	26.8	2.2	24	57.1	24.8	81.9	-0.7%
	T7d	28.6	15.3	27.6	1.8	23.1	2.7	28	1.3	24.7	1.9	24	57.6	25.0	82.6	-1.6%
	T7e	28.6	14.8	28.7	0.4	25.7	2.6	27.3	1.1	23.2	3.0	22	54.9	23.9	78.8	3.2%
	T7 average	**29.8**	**18.0**	**28.8**	**1.2**	**24.9**	**2.7**	**28.8**	**1.4**	**25.4**	**2.4**		**56.7**	**24.7**	**81.4**	**0.0%**
Constant air flow	*T8a*	34.4	NA	33.9	1.3	31.3	1.7	34.3	1.2	29.7	3.0	23	11.4	5.0	16.4	79.9%
	T8b	31.7	NA	30.5	0.9	26.1	3.5	30.6	1.0	27.5	2.0	20	26.2	11.4	37.6	53.8%
Air distribu-tion	*T9*	26.8	NA	26.8	0.8	24.0	2.0	25.2	1.0	22.1	2.1	20	57.8	25.1	82.9	-1.9%
	T10	24.4	NA	24.4	0.6	21.9	1.9	22.2	0.9	18.3	3.0	22	57.5	25.0	82.50	-1.4%
	T11	26.6	NA	26.6	0.5	24.0	2.1	23.6	0.9	23.6	2.0	23	56.6	24.6	81.21	0.2%
	T11b	30.8	NA	30.8	2.3	26.6	2.0	27.7	1.3	23.9	2.5	19	18.3	8.0	26.26	67.7%
	T12	30.1	NA	30	1.2	27.4	1.4	27.7	1.3	24.6	1.9	20	53.1	23.09	76.19	6.3%
Neptun air spacer	*T13*	27.5	NA	27.5	1.0	23.4	3.1	25.9	0.9	23.1	1.9	18	57.9	25.17	83.07	0.0%
	T14	28.6	NA	28.5	1.0	23.5	4.1	28.5	1.6	23.3	3.6	20	26.6	11.57	38.17	54.1%
	T15	30.7	NA	30.7	1.1	25.1	4.6	30.3	1.4	27.0	2.0	19.9	12.4	5.39	17.79	78.6%
	T16	25.1	NA	25.1	1.0	20.4	3.8	23.5	1.3	20.4	1.8	24	286	124.35	410.35	-394.0%
	T17	25.6	NA	25.5	1.2	18.8	5.5	25.6	0.9	23.4	1.3	20	51.4	22.35	73.75	11.2%
	T18	26.1	NA	25.4	1.1	19.1	5.2	26.1	1.9	22.6	1.6	20	47.2	20.52	67.72	18.5%
Test at Claus Sørensen	*T19*	32.3	26.1	32.3	2.1	15.2	15.1	31.6	1.5	5.7	24.3	2.4	734.8	367.4	1102.2	0.0%
	T20	34.6	32.3	34.6	0.0	20.8	13.9	28.2	0.0	11.7	16.5	-7.4	755.8	377.9	1133.7	-2.9%
	T21	30.7	25.7	30.7	0.0	13.9	16.8	26.9	0.0	12.9	14.0	-15.2	767.4	383.7	1151.1	-4.4%
	T22	38.3	38.3	35.7	0.0	20.9	14.8	32.4	0.0	5.6	26.8	5.9	286.8	143.4	430.2	61.0%
	T23	34.4	29.9	34.4	0.0	3.4	31.0	29.6	0.0	3.1	26.5	-7.6	735.4	367.7	1103.1	-0.1%
	T24	38.0	30.8	38	0.0	23.4	14.6	36.5	0.0	0.0	36.5	-11.8	435	217.5	652.5	40.8%
	T25	37.0	29.6	31.8	0.0	16.3	15.5	37	0.0	15.6	21.4	-5.9	753	376.5	1129.5	-2.5%
	T26	26,4	23,9	20,2	0,7	15,9	3,5	26,4	0,7	16,8	9	2,1	676	338	1014	10,2%

5.2. The various tests in the test tunnel

All the tests in Table 6 can be divided into six categories, i.e. the reference tests, adjusting the air flow during freezing, constant air flow during freezing, air distribution, Neptun air spacers, and test at Claus Sørensen. In this section, these tests are described, the results are discussed, and the conclusion for each category is formed.

5.2.1. The reference tests

The purpose of the reference tests is to get a documented basis to compare the results of the subsequent tests. The air flow of 6.5 m^3/s (23,400 m^3/h) was used. The conditions for the refrigeration system is the same for all measurements.

The average temperature for each of the four measuring boxes is illustrated in Figure 29 along with the average temperature for all the boxes and the air temperature, *TT01,* which is the temperature after the fan and before pallet 1. The total freezing time is 32.4 hours. The total energy consumption for the fan and for the refrigeration system for a freezing time of 36 hours was 82.1 kWh. The total measured freezing time corresponds with the model described in section 4.1. Here, a freezing time of 32.6 hours is calculated based on the same test prerequisites.

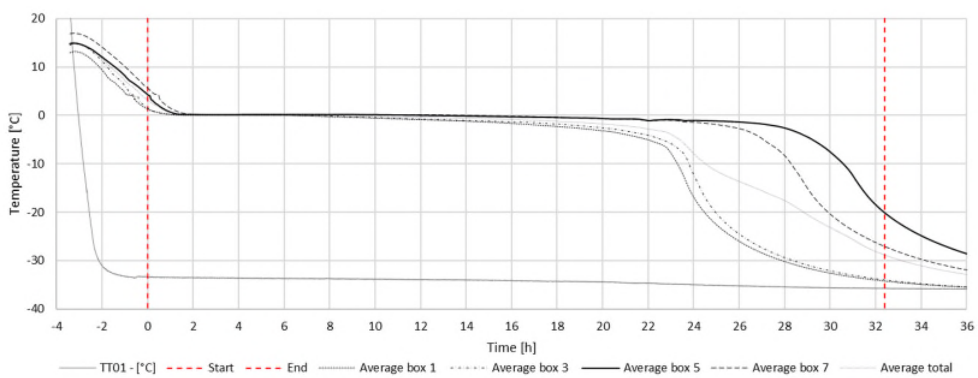


Figure 29: Illustrations of the freezing time for the four measuring boxes and the air temperature before pallet 1 (TT01).

During the first few tests, it was noticed that the test setup had changed. The air spacers had settled, and the boxes had sunk slightly into the wooden air spacers, see Figure 30. It was decided to perform a new reference test. Five more reference tests were conducted, *T7a – T7e,* and the average of these tests was used as a reference.

Figure 30: Illustration of the test change. To the left, a change in box structure. To the right, a change in air spacers.

Based on these five different reference tests compared to the original reference test, it is evident that there has been a change in the test setup. The total freezing time is more than two hours shorter. The new reference freezing time is thus 29.8 hours.

5.2.2. Adjusting the air flow

The first attempt to reduce the energy for the test tunnel and to utilize the tunnel cycle time better was done by adjusting the fan speed. This changed the volume flow of air in the freezer, and the freezing time of the product is affected according to the equations in section 2.4. By controlling the air flow, the air velocity passing the product and the air temperature are both affected. By reducing the air flow in some part of the freezing period, the freezing time will be longer, and the optimization is about prolonging the time from 29.8 hours in the reference case to 36 hours by reducing the air flow.

Two tests were conducted. The first test, *T3,* started with a low speed on the fan, i.e. a low air flow for 12 hours as shown in Figure 31, and then it was adjusted to end on the reference flow. In the second test, *T4,* the air flow started with the reference flow during the down cooling phase followed by a lower flow through most of the freezing phase. Finally, the air flow was increased to the reference flow again.

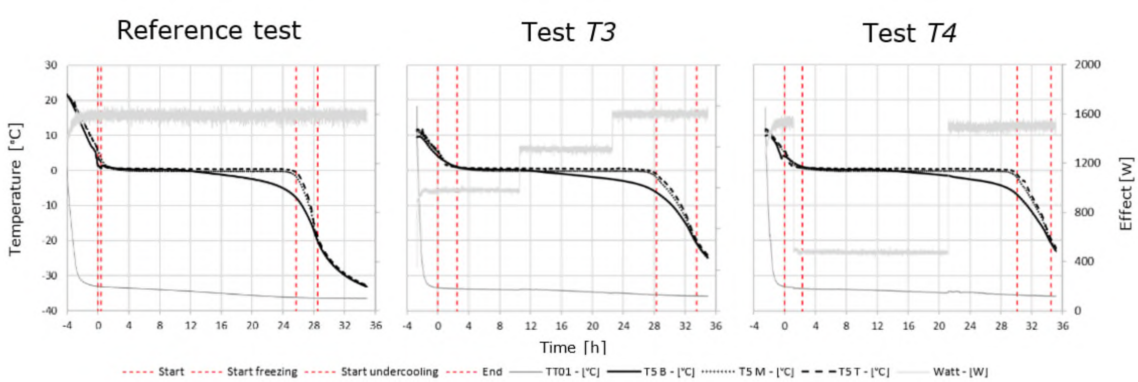


Figure 31: The freezing temperatures on the primary axis in the worst box of the pallet and the effect usage on the secondary axes. The one to the left is the reference case, and the others show the tested running strategies. When changing air flows the effect jumps as is seen in the graps.

The energy savings and the increased freezing time can be seen in Table 7.

Table 7: Freezing time and energy savings when controlling the air flow.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T7a - T7e**	6.5	29.8	0.0	0.0%	56.7	24.7	81.4	0.0	0.0%
Fan control. Variable flow	**T3**	4.2/5.0/6.5	33.5	-3.7	-12.6%	42.8	18.6	61.4	19.9	24.5%
	T4	6.5/4.0/6.5	34.5	-4.7	-15.9%	33.6	14.6	48.2	33.1	40.7%

For the first test, *T3,* there was an increase in the freezing time of 3.7 hours and a total energy saving of 24.5 % compared to the reference case. For the second test, *T4,* the increase in freezing time was 4.7 hours, and the energy savings were 40.7 %. The energy savings are considerable, and the cycle freezing time is still within the 36 hour limit.

In a search for a parameter to control the fan by, two tests, *T5* and *T6,* were conducted. In both tests, the fan was controlled according to the temperature measured after the last pallet in the test container. In test *T5,* the temperature set point was -30 °C, and in test *T6* the set point was -32 °C. The PLC controller used did not have a normal PI control loop to control the temperature. Therefore, a control loop was programmed, and it shifted between two speeds of the fan. If the temperature set point was not met, the fan was running on reference speed. When the temperature was lower than the set point, the fan changed to lower speed.

In test *T5,* the fan shifted frequently between low and high speed for the first 12 hours. Thereafter, the fan was running constantly on low speed since the air temperature did not get above -30 °C. For test *T6,* the fan was running on high speed for just over 22 hours and thereafter dropped to a low speed, see Figure 32.

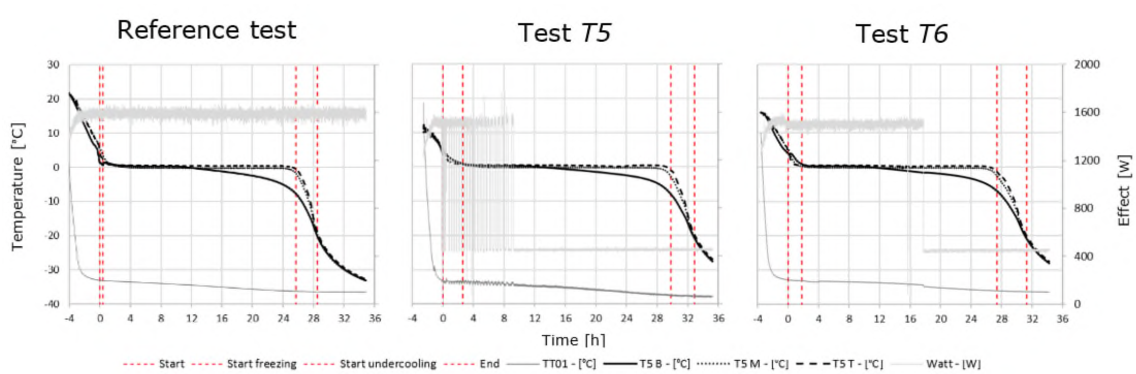


Figure 32: The freezing temperatures in the worst box of the pallet and the effect usage on the secondary axes. The one to the left is the reference case. In the other two graphs, the air set point is -30 °C and - 32 °C, respectively.

For an actual industrial tunnel, the air temperature will depend on the load from the pallets which again depends on how far the freezing progress is progressed, and how the tunnel is loaded with pallets. To find a set point for the air temperature to control the fans by would therefore depend on the actual freezer and its product loading which would be difficult to utilize in a real situation.

When looking at the freezing time and the energy savings for the two control strategies as seen in Table 8, an increase in the freezing time for both cases is noticed, as expected, but both within the available 36 hours. The energy savings for T5 and T6 are 60 % and 38.8 %, respectively. This indicates a large potential in energy savings when lowering the fan speed.

Table 8: Freezing time and energy savings when controlling the air flow by the temperature of the air from the last pallet.

		Air flow	Freezing time			Energy usage				
	Test no.		Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T7a - T7e**	6.5	29.8	0.0	0.0%	56.7	24.7	81.4	0.0	0.0%
Fan control. Variable flow	**T5**	6.5/4.2	32.8	-3.0	-10.2%	22.7	9.9	32.6	48.8	60.0%
	T6	6.5/3.95	31.1	-1.3	-4.5%	34.7	15.1	49.8	31.6	38.8%

5.2.3. Constant flow

From the tests in 5.2.2, it is evident that the lowest energy consumption for a certain available tunnel cycle time is where the fan is running on the lowest available speed throughout the total cycle time. To investigate how the freezing time and the energy consumption would change according to a constant air flow, two tests were conducted. In test

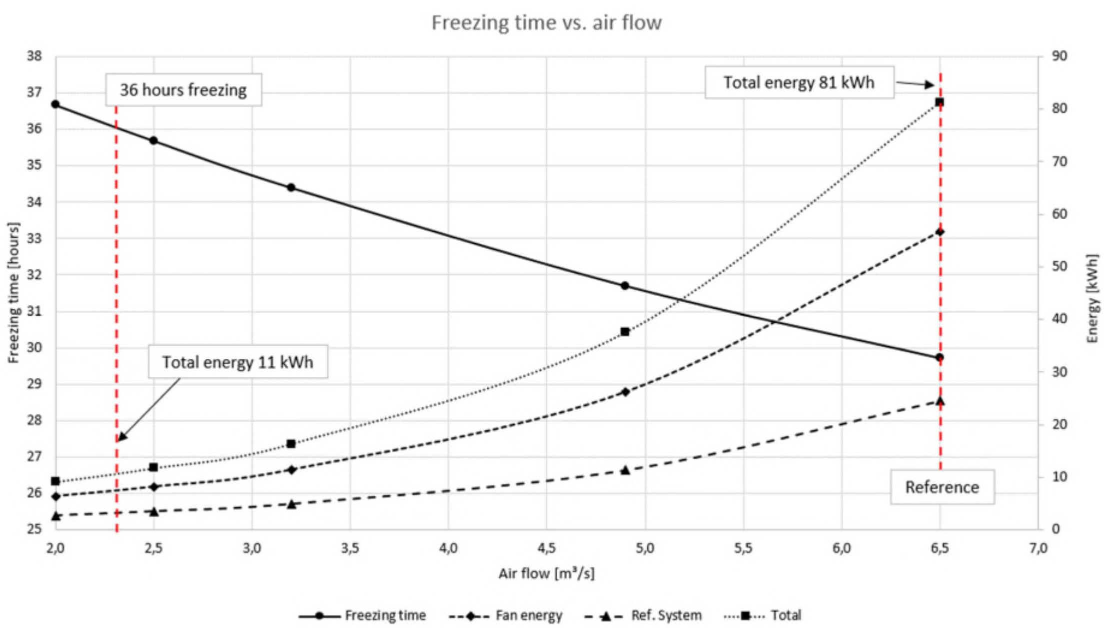


Figure 33: Total freezing time and energy usage of the fan for various air flows.

T8a, the air flow was adjusted to 3.2 m^3/s throughout the whole tunnel cycle time. In test *T8b,* the flow was adjusted to 4.9 m^3/s. The reference case was running on 6.5 m^3/s.

By plotting the freezing time and the energy consumption into a graph, as shown in Figure 33, and by fitting a curve through the points, one can see how the total freezing time increases as the air flow reduces. By extending the curve down to a freezing time of 36 hours, the total energy usage can be estimated.

The figure shows three curves that indicate the energy usage of the setup. The curve with triangles show the energy used by the refrigeration system with a COP of 2.3. The curve with diamonds shows the direct energy usage of the fan. The curve with boxes is the total energy usage for both the refrigeration system and the fan. The total energy usage for the reference case in the test tunnel was 81 kWh, and the freezing time was just under 30 hours. By fitting a curve through the measured points and finding the point on the curve where the total freezing time reaches 36 hours, one finds that the total energy needed is 11 kWh for an air flow of 2.3 m^3/s. This is a considerable energy saving corresponding to about 86 %. By looking at the graph, it becomes evident that the largest energy savings are achieved for the first reduction in speed, and then the energy savings decline. A reduction from full flow to for example half flow gives an energy saving of 80 %. When running on half flow, the total freezing time is just above 34 hours which is saving a freezing time of two hours. Getting from half flow down to the total freezing time limit of 36 hours adds another 6 % to the total energy savings. This indicates that the largest energy savings can be harvested in the first part of the flow reduction.

Another benefit when reducing energy usage in the tunnel is that it opens the opportunity to change from normal axial fans with frequency drive to the new EC fan type which is high efficient and has an integrated speed control which gives a lower total purchase price.

By comparing the tests *T3* - *T6* to the one described in 5.2.2, i.e. *T8*, where the air flow was controlled, it can be concluded that the largest energy savings can be obtained by finding the lowest air flow acceptable for the tunnel instead of trying to control the flow under the freezing process.

5.2.4. Air distribution

Another approach to save energy was to distribute the air flow through the tunnel in a more energy efficient way. By looking at CFD simulations for the industrial tunnel and for the test tunnel, it becomes evident that most of the flow is directed in channels above and under the products, see section 4.3. In addition, the CFD simulations and test measurements indicate that the last pallet, i.e. pallet 3 in the test tunnel, takes the longest time to freeze. To reduce the freezing time, the conditions for the last pallet must be improved. The first attempt to do so was to change the location of the pallets by moving them closer to the fan. This was done to increase the space behind the last pallet and to move it out of the return chamber to have a more unified flow through the whole pallet. Next attempt was to use the baffle to direct the flow in the tunnel.

5.2.4.1. Change in the location of the pallets

Two tests were performed. One with the pallets moved closer to the fan and another with two pallets in the tunnel instead of three.

The conclusion in section 4.3.1 was to move the pallets 800 mm closer to the fan, which, according to the CFD simulation, would result in less pressure drop and a smaller temperature difference. The first pallet is then 300 mm from the fan. The result was an improvement in freezing time of three hours while the energy consumption remained nearly the same, see *T9* in Table 9. This shows that it is more important to move the last pallet out of the return chamber, and that the distance from the fan to the first pallet is less important.

Table 9: Freezing time and energy savings when moving the pallets in the tunnel.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T7a - T7e**	6.5	29.8	0.0	0.0%	56.7	24.7	81.4	0.0	0.0%
Air	**T9**	6.5	26.8	3.0	9.9%	57.8	25.1	82.9	-1.6	-1.9%
	T10	6.5	24.4	5.4	18.0%	57.5	25.0	82.5	-1.1	-1.4%

An idea of a new design for the tunnel was to rotate the pallets 90° on the pallet conveyer and to move the pallet conveyer closer to the center line of the tunnel with a distance between the pallets of 200 mm, see Figure 34. This would give space on both sides for the same width of tunnel for the air entrance into the pallets and exit from the pallets. In this setup, the evaporators would be placed above the pallets, and the air would flow through two pallets. This would decrease the freezing time because of a colder air temperature and a higher air velocity.

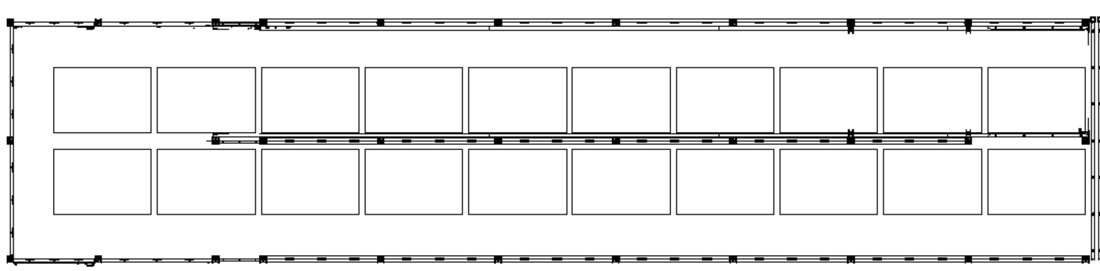


Figure 34: New design of the tunnel.

To test how much reduction in freezing time could be accomplished, test *T10* was conducted. The result was an improvement in freezing time of 5.4 hours, see Table 9, and the energy usage stayed nearly the same.

5.2.4.2. Air distribution with baffles

To distribute the air better in the test tunnel, baffles were tried. The configuration that gave the best air and temperature distribution according to CFD simulations was the one with a baffle placed in the top channel before pallet 3 and another baffle placed in the bottom channel before pallet 2, as described in section 4.3.2. This configuration was tested in the test tunnel with two air volume flows. One test where the air flow was the same as for the reference case and another test with a lower air flow. Here, an attempt was made to hit the same total freezing time as for the reference case. The results are shown in Table 10.

Table 10: Freezing time and energy savings using baffles.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	T7a - T7e	6.5	29.8	0.0	0.0%	56.7	24.7	81.4	0.0	0.0%
Air	T11	6.5	26.6	3.2	10.6%	56.6	24.6	81.2	0.1	0.2%
	T11b	4.1	30.8	-1.0	-3.5%	18.3	8.0	26.3	55.1	67.7%

For test *T11*, where the air flow was the same as for the reference case, the energy usage was the same. However, the total freezing time was 3.2 hours shorter. Subsequently, in test *T11b* the flow was reduced to 4.1 m^3/s which resulted in a 67 % saving in energy and nearly the same total freezing time as for the reference case. By fitting a quadratic function through the measured points and interpolating it to 36 hours, the estimated savings were 93 %, see Figure 35. This shows that by using baffles, a large saving in energy can be obtained, but it also increases the complexity of the tunnel design and generates challenges with implementation in older tunnels.

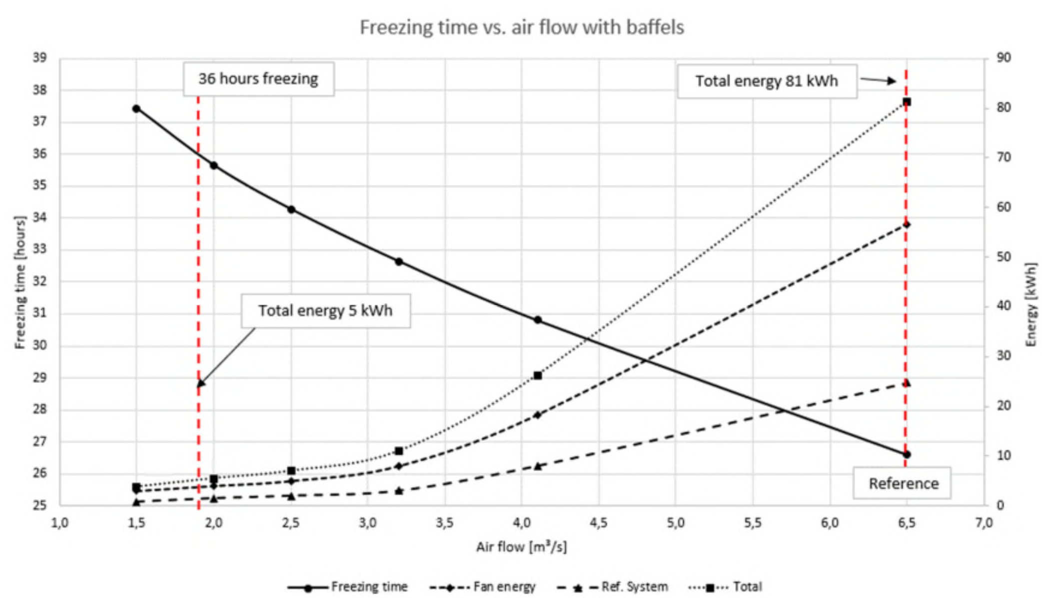


Figure 35: Total freezing time and energy usage of the fan for various air flows for a tunnel with baffles.

Figure 35 shows that for the tunnel with baffles, the largest part of the energy savings can be achieved by reducing the air flow to the half of what the traditional design rule of thumb states.

Moving the pallets closer to the fan in Test *T9* improved the freezing time by three hours, and using baffles in test *T11* improved the freezing time by 3.2 hours. The logical subsequent test was a combination of these two tests. Test *T12* was conducted with the pallets located 300 mm from the fan and with two baffles. The result was very unexpected as this combination resulted in a slower freezing time than the reference test and small reduction in energy usage, see Table 11.

Table 11: Freezing time and energy savings – combination of the tests T9 and T11.

		Air flow	Freezing time			Energy usage				
	Test no.		Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T7a - T7e**	6.5	29.8	0.0	0.0%	56.7	24.7	81.4	0.0	0.0%
Air	**T12**	6.5	30.1	-0.3	-1.1%	53.1	23.1	76.2	5.2	6.3%

This indicates that the combined effect of both actions is not beneficial.

5.2.5. Neptun air spacer

To save more energy, a new type of air spacer was tested in the tunnel. The air spacers can be seen in Figure 36. These air spacers are produced by a company called Neptun FreezTec. They are made of plastic and should ease the air passage through the pallet compared to the typical wooden air spacers.

Figure 36: Neptun air spacer.

Six different tests have been performed with these air spacers. The first four tests, *T13* to *T16,* were performed with different constant flow to estimate the improvement of the air spacers and at the same time to be able to conclude on freezing times and energy usage. In the last two tests, *T17* and *T18,* the air flow is reversed to try to even out the air temperature distribution in the tunnel and decrease the freezing time of pallet 3.

The first test, *T13*, is with the same speed of the fan as for the reference case. It gives slightly lower flow as for the reference test case with wooden air spacers. This indicates that the Neptun air spacers have a slightly larger pressure drop compared to the wooden air spacers. Here, the original reference test, *T2,* for the wooden spacers is used since there was no deviation in the test setup noticed during these tests. The reason is a strengthened test setup. Slightly more energy is used while the flow is slightly lower for the same configuration. On the other hand, there is an improvement of 4.9 hours in the freezing time corresponding to 16.5 %, see Table 12.

Table 12: Freezing time and energy savings by replacing the air spacers.

	Test no.	Air flow [m³/s]	Freezing time Total [h]	Freezing time Improvements [h]	Freezing time Improvements [%]	Energy usage Fan [kWh]	Energy usage Ref sys [kWh]	Energy usage Total [kWh]	Energy usage Improvements [kWh]	Energy usage Improvements [%]
Reference	**T2**	6.5	32.4	0.0	0.0%	57.2	24.9	82.1	0.0	0.0%
Neptun	**T13**	6.3	27.5	4.9	16.5%	57.9	25.2	83.1	-1.0	-1.2%

To be able to utilize the benefits of the Neptun air spacers, the reduction in air flow is important.

By plotting the freezing time and the energy usage into a graph for the different flows, the result is as shown in Figure 37 and in Table 13. The figure shows that the air flow can be reduced considerably without the total freezing time exceeding 36 hours. This means that great energy savings can be achieved by using the air spacer. At an air flow of 2.8 m^3/s, an energy saving of 78.6 % occurs, and the freezing time is only 30.7 hours. By comparing the results with the ones with the wooden air spacers in Figure 33, one would estimate a freezing time of approximately 35 hours for the same air flow. This shows that higher energy savings may be expected when using the Neptun air spacers compared to the wooden air spacers.

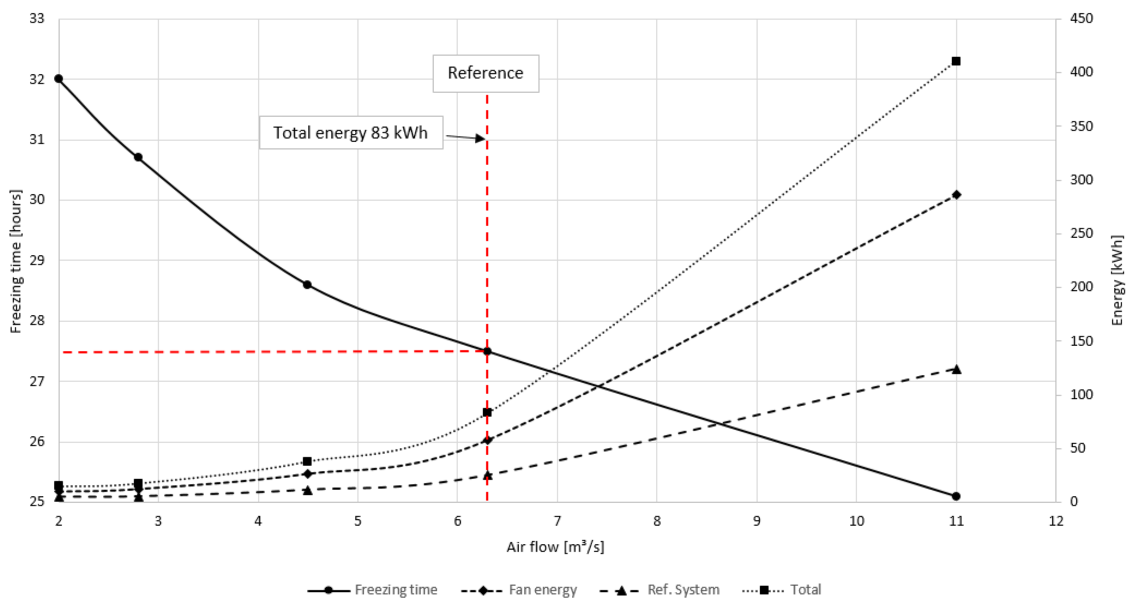


Figure 37: Total freezing time and energy usage of fan for various air flows.

Test *T16* was used to investigate if it would be possible to increase the air flow and decrease the freezing time so much that the logistical cycle time of the freezer, for this product, could be changed from 36 hours to 24 hours. Test *T16* was conducted with an air flow of

11 m³/s. Here, the energy consumption gets very high, and the total freezing time is still above 24 hours.

Table 13: Freezing time and energy savings for different continuous flows.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T13**	6.3	27.5	0.0	0.0%	57.9	25.2	83.1	0.0	0.0%
	T14	4.5	28.6	-1.1	-4.0%	26.6	11.6	38.2	44.9	54.1%
Neptun	**T15**	2.8	30.7	-3.2	-11.6%	12.4	5.4	17.8	65.3	78.6%
	T16	11	25.1	2.4	9%	286.0	124.3	410.3	-327.3	-394%

The challenge with increasing the air flow is that the power consumption increases in third power of the air flow. This extra power must be cooled away by the air, which thereby increases the load on the evaporator and on the refrigeration system leading to lower benefit of the air velocity increase. In the test tunnel, the test showed that it is not possible to decrease the logistical cycle to 24 hours.

An idea came up: Would it be beneficial to reverse the air flow? In reverse, the fan will run with lower efficiency, but the temperature conditions for the last pallet will be improved. This would have the same effect for the wooden air spacers, even though it was conducted with the Neptun air spacers since this was the test setup running when the idea came up. To test this idea, two tests were conducted, *T17* and *T18*. The purpose was to test whether it will give a noticeable effect if the airflow is reversed, so that pallet 3 is exposed to the coldest air for some part of the freezing time. In test *T17,* the airflow is reversed halfway through the freezing. In *T18,* the flow is reversed in a one hour cycle, see Figure 38.

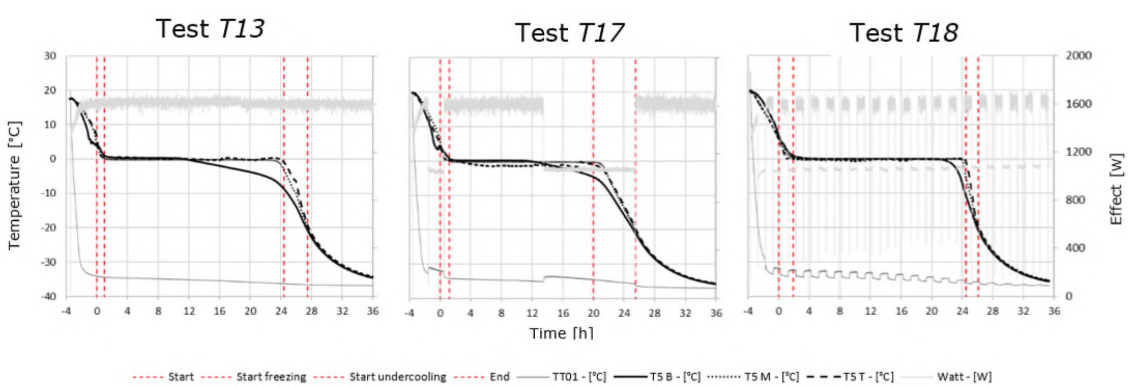


Figure 38: The freezing temperatures in the worst box of the pallet and the effect usage on the secondary axes. The drop-in effect is when the airflow is reversed.

The results were an improvement of 7 % and 5 %, respectively, in freezing time and an energy saving of 11 % and 18 %, respectively, see Table 14.

Table 14: Freezing time and energy savings when reversing the air.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T13**	6.3	27.5	0.0	0.0%	57.9	25.2	83.1	0.0	0.0%
Neptun	**T17**	6.2	25.6	1.9	7%	51.4	22.3	73.7	9.3	11%
	T18	6	26.1	1.4	5%	47.2	20.5	67.7	15.4	18%

It is quite easy to reverse the air flow in the tunnel if a frequency drive is used for the fan. This will give a reduction in the energy consumption and decrease the freezing time as shown. The energy savings could be increased further by reducing the air flow to match the freezing time to the one in the reference case. This was though not performed in the project due to lack of time resources.

5.2.6. Test in the industrial tunnel at Claus Sørensen

To test the trends witnessed in the test setup in a real situation, different tests have been performed in the industrial tunnel freezer at Claus Sørensen. The tests were performed in the tunnel described in chapter 1.

Eight tests have been conducted. Three reference tests with an air flow of 6.5 m^3/s, test *T19*, *T20* and *T21*, one test with an air flow of 5 m^3/s, test *T22*, and one test with an air flow of 5.6 m^3/s, test *T24*. One test was done with only nine pallets instead of 10 to make space behind the last pallet in the row, test *T25,* and one test was done with the new Neptun air spacer, test *T23*. A test where the air flow in the tunnel was reversed was tested in test 26. The test setup at Claus Sørensen is illustrated in Figure 39.

Figure 39: Illustration of the test setup at Claus Sørensen. From the left: Placement of the temperature sensors, pallet assembly, finished pallet, and placement in the tunnel.

A significant difference in the test setup in the industrial tunnel compared to the test tunnel, is the air spacer. Instead of the normally used wooden air spacers, this product pallet uses an older type of plastic air spacers from Neptun. The product in the boxes is chicken. The size of the packages is also different. Here, there are two packages between each spacer. This does not matter since the purpose of the test is to test the trends found in the test setup and not to compare the test setup with the industrial tunnel. The first three tests work as a reference that the subsequent tests will be compared up against.

It is difficult to make the tests at Claus Sørensen completely repeatable since the loading of the tunnel newer is the same from time to time. Therefore, there is basically a new test setup for each test. This illustrates the complexity in the real-life situation. In addition, it is not possible to get the same starting conditions for the packages in each test, i.e. the meat temperatures have been from 2 °C to - 0,5 °C at the start of freezing. This indicates that the down cooling phase is not present in some cases. The temperature sensors are pressed into the boxes at a certain height, which can give a variation in the actual placement between tests. The location of the temperature sensor can also be inside a piece of chicken or in the air space in between. The difference between the reference tests illustrates the difficulties. In the reference test, there is a difference in the freezing time from 27.9 hours for the first test to 31.3 hours for the next test to 24.7 hours for the last one, see Table 15. The location of the temperature sensor is important, which could indicate that the upper temperature sensor is located further within the meat than the upper temperature measurement in test *T19.* However, the measurement of energy consumption is consistent, see Table 15.

The placement of the measuring boxes on the pallet was the same as in the test tunnel described in 3.2, and the measuring pallets were pallet number 10 by the door and pallet number 20 before the evaporator.

Table 15: Freezing time and energy savings.

		Air flow	Freezing time	Energy consumption		
	Test no.		**Total**	**Fan**	**Ref sys**	**Total**
		[m³/s]	**[h]**	**[kWh]**	**[kWh]**	**[kWh]**
CS	**T19**	6.5	27.9	734.8	367.4	1102.2
	T20	6.5	31.3	755.8	377.9	1133.7
	T21	6.5	24.7	767.4	383.7	1151.1
	Average	6.5	28	752.7	376.3	1129.0

As can be seen from the freezing curves for the reference case, tests *T20* and *T21* start in the beginning of the freezing phase without the down cooling phase present, but *T19* has a short down cooling phase before entering the freezing phase.

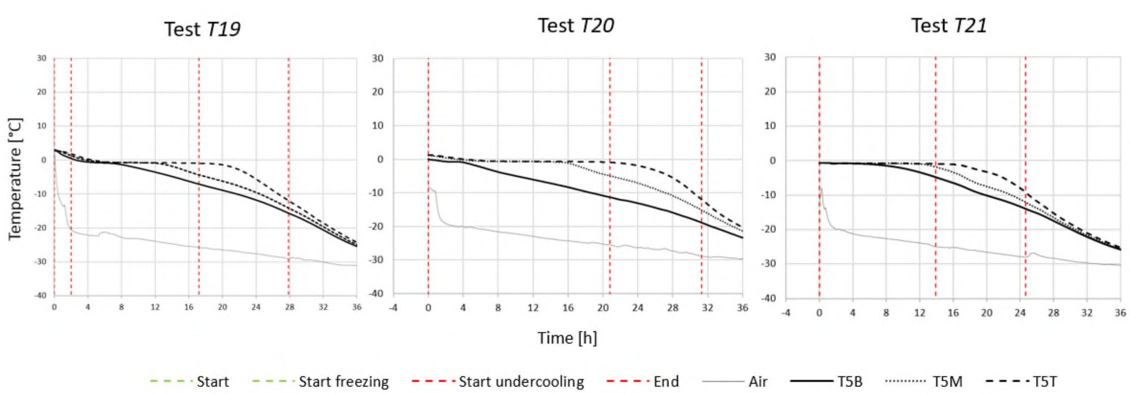


Figure 40: Illustration of the freezing process for the critical box in the three reference tests.

In the tests *T22* and *T24,* the air flow was reduced. The plan was to reduce the frequency of the fan down to 27 Hz corresponding to 3.5 m^3/s air flow. This was on the other hand not possible in the frequency drive where the lowest frequency was 38 Hz corresponding to 5 m^3/s. Instead, it was decided to run the test at 43 Hz corresponding to 5.6 m^3/s. A plot of the freezing time and the energy usage is shown in Figure 41.

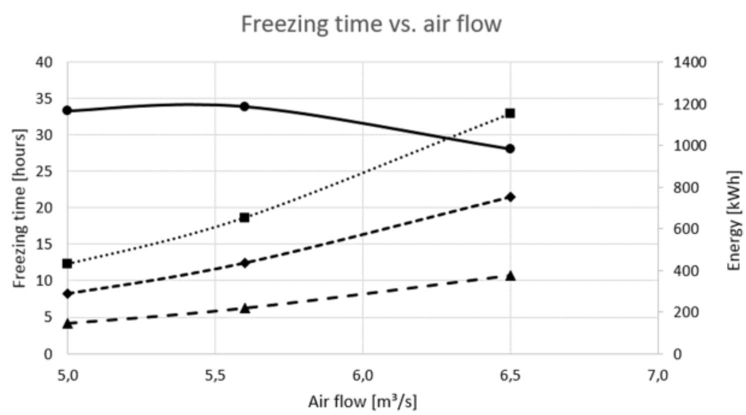


Figure 41: Total freezing time and energy usage of the fan for various air flows.

The idea was to have tree points to be able to make a curve as for the test setup. From that curve we would be able to estimate the minimum air flow and the energy usage for a freezing time of 36 hours. But because of the uncertainty in the test setup and since two of the points in tests *T22* and *T24* lie to close to each other, it is impossible to make such curve. The figure and test results in Table 16 show that by reducing the flow to 5.0 m^3/s, an energy saving of 61.9 % can be achieved, and the freezing time is still within the 36 hour frame. This is also consistent with the findings in the test tunnel, see Figure 33.

Table 16: Freezing time and energy savings at different flows.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	T19-T21	6.5	28.0	0.0	0.0%	752.7	376.3	1129.0	0.0	0.0%
CS	T22	5.0	33.3	-5.3	-19%	286.8	143.4	430.2	698.9	61.9%
	T24	5.6	33.9	-5.9	-21%	435.0	217.5	652.5	476.5	42.2%

In test *T25,* the pallet stack should be moved closer to the fan to make space behind for the last pallet before the air reversing chamber. However, in the industrial tunnel at Claus Sørensen, it is not possible to move the pallets closer to the fan due to the construction of the conveyer. It was therefore decided to try to test this by removing pallet 10. Therefore, a test with only nine pallets instead of ten pallets was conducted. Table 17 summarizes the results. It seems to have no effect to drop the last pallet, and there was an increase in freezing time of 3 %.

Table 17: Freezing time and energy savings with only nine pallets.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T19-T21**	6.5	28.0	0.0	0.0%	752.7	376.3	1129.0	0.0	0.0%
CS	**T25**	6.5	28.7	-0.7	-3%	753.0	376.5	1129.5	-0.5	0.0%

However, it is difficult to conclude from these results since the rest of the tunnel tests had 10 pallets. This has possibly changed the flow for the row that was tested compared to the other rows in the tunnel.

Another attempt to lower the energy consumption was to test a new air spacer from Neptun, see Figure 36. The results of the test are summarized in Table 18.

Table 18: Freezing time and energy savings by replacing the air spacers.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T19-T21**	6.5	28.0	0.0	0.0%	752.7	376.3	1129.0	0.0	0.0%
CS	**T23**	6.5	30.0	-2.0	-7%	735.4	367.7	1103.1	25.9	2.3%

The difference in the freezing time between the older type of the Neptun air spacers (see Figure 39) and the new type, is an increase in the freezing time of 7 %. In addition, a small reduction in energy consumption of 2.3 % is measured. Because of uncertainty in the test setup as described previously it is hard to conclude but it seems that the new air spacers have similar thermodynamic benefits as the older type. The test in the test tunnel showed though a considerable savings compared to the wooden air spacers.

The last attempt to lower the energy consumption was to reverse the air flow every two hours. The result of this test is summarized in Table 20.

Table 19: Freezing time and energy savings by reversing the air flow.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Improvements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	**T19-T21**	6.5	28.0	0.0	0.0%	752.7	376.3	1129.0	0.0	0.0%
CS	**T26**	6.5	26.4	1.6	6%	676.0	338.0	1014.0	115.0	10.2%

The reduction in freezing time compared to the reference case is 6% and the energy savings 10.2%.

5.3. Recap

Throughout the testing, 25 different tests have been performed. The first 18 tests are conducted in a test setup at Danish Technological Institute while the last seven tests are performed at Claus Sørensen in order to verify some of the results from the test setup. For various reasons, some of the observations could not be implemented in the industrial tunnel at Claus Sørensen.

The boxes in the test setup contain water instead of meat which freezes and thaws repeatedly. This caused problems in the test setup, as the boxes sank into the air spacer, and the air spacers settled. The test setup was therefore subjected to several additional reference tests to obtain valid data to compare the subsequent tests with. In order to freeze three pallets of water, from 5 °C to -20 °C, at a flow of 6.5 m^3/s, the freezing took 29.8 hours with an energy consumption of 81.4 kWh.

This result is based on an average of five reference tests. The initial reference test where the boxes had not yet settled resulted in a freezing time of 32.4 hours which showed to only deviate 0.2 hours from the freezing time calculated with the freezing time model constructed.

The first attempt to save energy was to change the air flow throughout the tunnel cycle time. These tests showed that within an acceptable increase in freezing time, it is possible to save up to 60 % in energy consumption.

From the test on controlling the air flow it became evident that the largest energy savings could be obtained by simply reducing the air flow to a minimum throughout the tunnel cycle time. A test was conducted in the test tunnel to be able to establish the minimum energy usage at the lowest air flow. The total energy saving for a 36 hour freezing time is estimated to be 86 % which corresponds to a flow of 2.3 m^3/s. The same tests were performed in the industrial tunnel where the maximum reduction in air flow that could be accomplished was 5.0 m^3/s. This resulted in a 61.9 % reduction in energy consumption and a freezing time of 33.3 hours. A further reduction of the air flow would save even more energy.

Based on the CFD simulations it has been shown that it is the pallet in the reversing chamber that takes the longest time to freeze. To give this pallet better conditions, the pallet stack was moved closer to the fan in the test tunnel leaving a free space for the air to return to the second half of the tunnel. This gave a noticeable effect on the freezing time which was reduced by three hours (5.4 %) with a slight increase in energy usage of 1.4 %.

To try to verify this, the tests in the industrial tunnel at Claus Sørensen were conducted. This decrease in freezing time could not be verified. The reason is probably that it was not possible to move the pallet stack closer to the fan. Instead, a test with nine pallets instead of ten was conducted for one of the rows in the tunnel.

A test with two pallets was conducted in the test tunnel, and it showed a decrease in freezing time of 5.4 hours with nearly the same energy usage.

CFD simulations indicated that the use of baffles would be beneficial. By implementing them in the test tunnel, it was found that the freezing time was improved by 3.2 hours. By reducing the air flow simultaneously down to 4.1 m^3/s, the freezing time was one hour longer than in the reference case, and a saving of 68 % was achieved. If the freezing time is extended to 36 hours it will result in an energy improvement of 93 %. A combination of moving the pallets closer to the fan and using baffles had a negative effect.

Changing the air spacers from the wooden type to the plastic type resulted in a shorter freezing time of 4.9 hours compared to the reference test, and the used energy was nearly the same. At a flow of 2.8 m^3/s, an energy saving of 78.6 % occurs, and the freezing time is only 30.7 hours. By reducing the air flow further, more energy savings are expected. These air spacers were also tested at Claus Sørensen and resulted in a 6 % increase in the freezing time compared to the older type of Neptun plastic air spacers.

By reversing the air flow back and forth to distribute the cold air better throughout the freezer two test where conducted. One where the air flow was reversed halfway through the tunnel freezing cycle time and another where the air reversing occurred on one hour basis. The reduction in freezing time was measured to be 1.9 hours or 7% and energy reduction 11%. For the one hour cycle the air flow was slightly lower and the freezing time improvements 1.4 hours or 5% and the energy reduction 18%.

The same test where conducted in the industrial tunnel verifying the test tunnel test, where an reduction in freezing time of 1.6 hours was obtained corresponding to 6% improvements and an energy savings of 115 kWh corresponding to 10.2% savings.

6. Conclusion

The main objective of the project was to save 30 % energy per freezing in commercial freezing tunnels. This goal will result in an annual saving of 66 GWh if all tunnels are optimized.

Adjusting the air flow in a certain step showed considerable savings but also revealed that the largest savings could be achieved by finding the lowest air flow and still maintain the freezing time within the tunnel cycle time.

A large saving was found by reducing the air flow through the freezer to extend the freezing time throughout the cycle time of the freezer. The savings by doing this in the test tunnel were 86 %.

When verifying this in the industrial tunnel freezer, the lowest air flow available was 5.0 m^3/s. This resulted in an energy reduction of 61.9 % and a freezing time of 33.3 hours. A further reduction of the air flow would save even more energy. The easiest and cheapest method of increasing the efficiency of the industrial tunnel freezers is by adapting the freezing time to the tunnel cycle time.

By increasing the space behind the last pallet in the test tunnel a decrease in freezing time of 3 hours was measured with nearly the same effect to the fan.

The increase of the space for the last pallet was tried out in the industrial tunnel by removing one pallet in the row where measurements where done. This showed no improvements in freezing time or energy. It is questionable if conclusions can be drawn from the industrial tunnel test because of influence of the other rows in the freezer.

By using baffles in the test tunnel to direct the air flow in the freezer and at the same time reduce the air flow, a saving of 93 % was estimated.

Using baffles in the industrial tunnel was not possible because of constructional obstacles and was therefore not verified.

The test in the test tunnel with the new plastic air spacers revealed a faster freezing time compared to the wooden air spacers. An energy savings of 78.6% was measured for a freezing time of 30,7 hours. A measurement where the freezing time of 36 hours where utilized where not performed but the savings would probably be above the 86% measured for the wooden air spacers.

The test in the industrial tunnel where conducted with an older type of plastic air spacers from Neptun so the verification of improvements compared to wooden air spacers could not be done. A comparison between the older and newer type of plastic air spacers showed no improvement.

The project has thus fulfilled the target, as it is possible to save energy in the test setup and at Claus Sørensen. The tests indicate that it is possible to save much more energy than initially anticipated.

By reversing the air flow back and forth midway through the freezing a reduction in freezing time in the test tunnel was measured to be 1.9 hours or 7% and energy reduction 11%.

When reversing with one hour interval the air flow was slightly lower and the freezing time improvements 1.4 hours or 5% and the energy reduction 18%.

The same test in the industrial tunnel verified the test tunnel test with an reduction in freezing time of 1.6 hours, corresponding to 6% improvements and an energy savings of 115 kWh corresponding to 10.2% savings.

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8. Appendix

8.1. Paper

ENERGY OPTIMIZATION OF BATCH FREEZING TUNNEL FOR MEAT

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ABSTRACT

A large amount of meat is frozen in batches in blast freezing tunnels. These tunnels are designed according to old rules of thumb, and they are in most cases running a constant air flow. By optimizing the running conditions of the tunnel, extensive energy savings can be obtained. A Danish ELFORSK research project regarding the energy saving potential of industrial blast freezing tunnels verify these savings. The project covers testing of an industrial tunnel combined with laboratory tests, models, and CFD calculations.

This paper presents the results of the project. The focus is on the possibilities to either optimize the efficiency of the tunnel or to reduce the freezing times. Optimization is achieved through modelling and testing. The optimization of the fans, the air flow through the tunnel, and the control strategy are investigated.

Keywords: Blast freezing tunnels, Energy efficiency, Control strategy, CFD, Air flow optimization

1. INTRODUCTION

The freezing of food in blast freezing tunnels is of great importance. In Denmark, the amount of products frozen in tunnels is around 1,500,000 tons per year using approx. 220 GWh of electrical energy in the tunnels per year. The goal of the project is to be able to save 30% in electricity for the fans and in the refrigeration system, which would provide 66 GWh per year if all freezing tunnels in Denmark were optimized. This is a realistic goal according to Dempsey, Patrick el al. [1].

The freezing process is rather complex, which leads to an extensive use of rules of thumb when designing the tunnels. These generalised rules of thumb and the complicity of the process lead to non-optimized designs, which use more energy than needed. In this paper, the results of the optimization of the operation of the fans and the distribution of the air through the tunnel are investigated and verified by laboratory tests, which are to be followed by tests in an industrial full scale carton freezing tunnel. The conditions inside the packages are not addressed in this paper.

2. TEST SETUP

To simulate the industrial tunnel in a laboratory environment, a test tunnel was built in a container. In this container, various tests are conducted, which later will be verified in the industrial tunnel.

2.1 The industrial freezing tunnel

The selected industrial freezing tunnel consists of a room with four product rows, which contain 20 pallets of meat in vertical position in each row as shown in *Figure 42*. Each tunnel contains around 30 tons of products frozen in batches and has four rows. The site, where the tunnel is running, has 11 similar tunnels. The air flows from the fan through 10 pallets, after which the air stream returns and flows back through 10 more pallets on its way to the evaporator. From the evaporator, the air flows to the fan again for another round inside the tunnel. One fan is installed for each row of products. In the evaporator, the air is cooled down. The refrigerant in the coil is ammonia, and the refrigeration system is a conventional two-stage industrial ammonia plant. The air volume flow is 23,400 m³/h (6.5 m³/s), and the total cycle time of the freezer for the investigated products is 36 hours with full fan speed the whole time.

Each pallet consists of layers of products separated by air spacers and placed on top of a euro pallet as shown to the right in *Figure 43*.

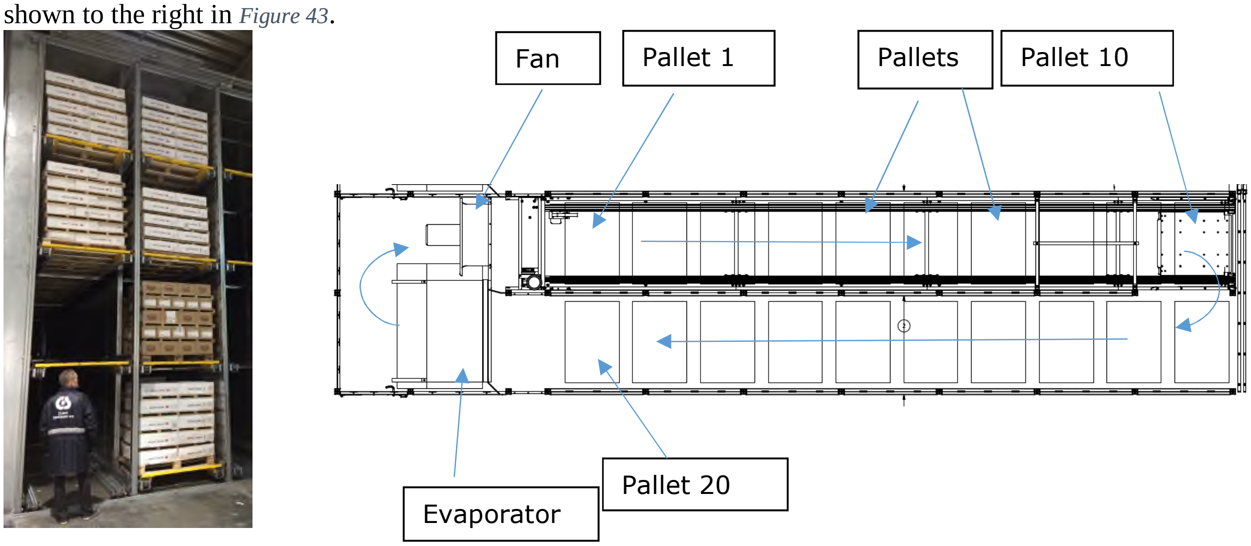

Figure 42: Left – a look inside the tunnel, where the air stream returns. Right - layout of the tunnel seen from above.

The air spacers used in the tunnel are of wooden type as shown to the left in *Figure 43*. The air spacers give distance between the product packages allowing cold air to reach the top and the bottom side of the product packages.

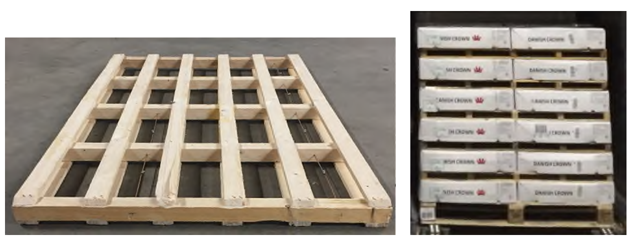

Figure 43: Left - wooden air spacer. Right - product pallet.

2.2 Test freezing tunnel

To be able to simulate this tunnel under laboratory conditions, a test tunnel was designed and built in a container. By running CFD simulations on both the industrial tunnel and the test tunnel, the test setup that best represented the industrial tunnel was found. The test tunnel contains tree pallets in a container as shown in *Figure 44*. CFD simulations showed that the first, the second, and the tenth pallet in the industrial tunnel were represented well by the three pallets in the test tunnel. All other dimensions perpendicular to the air flow and the air return opening, are true copies of the industrial tunnel.

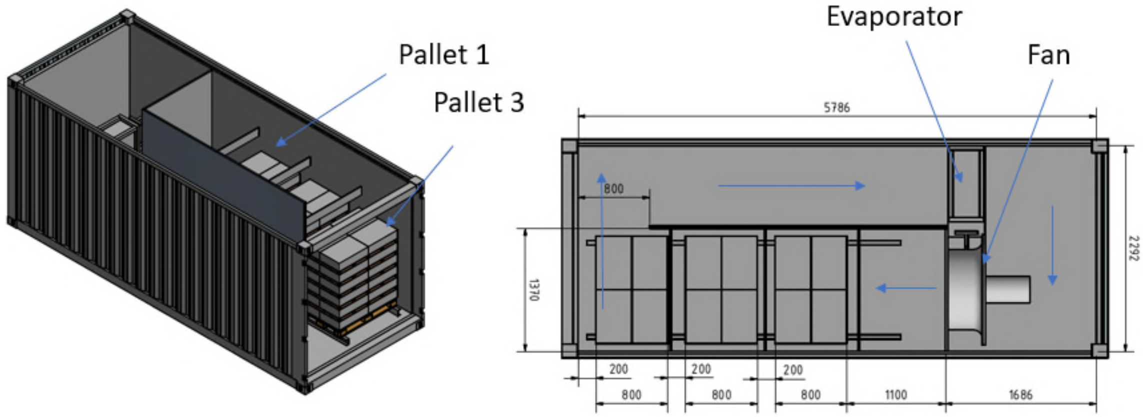

Figure 44: Test setup built into a container. Right - the layout seen from above.

A CFD simulation showed that the tenth pallet in the industrial tunnel (see *Figure 42*) represented by the third pallet in the test tunnel (see *Figure 44*) were the one that had the lowest air speed through the spacers and the lowest air temperatures around the product. This indicates that the third pallet in the test tunnel and the tenth pallet in the industrial tunnel are the ones taking the longest time to freeze. Thus, these pallets control the total freezing time of the tunnel.

2.3 Product pallets in the tunnel

In the industrial tunnel, various product types are frozen at the same time, which leads to different pallet heights and different product packages on each pallet. This results in an enormous amount of pallet combinations inside the freezer. To reduce the amount of combinations to be simulated in the test tunnel, a pallet with six product rows was selected with a product height of 150 mm as shown in *Figure 45*. This pallet represents the one with the highest product flow. The test tunnel is used to find savings compared to a basis case, and it is presumed that the same trend is found in the industrial tunnel, even though the product combination is different.

The packages in the test tunnel were filled with water. Temperature sensors were placed in two packages on pallet one and three in the test tunnel, see *Figure 44*. In each package, the temperature sensors were fixed at three levels from the bottom of the box. The sensor closest to the bottom was 30mm above the bottom and the other two sensors were evenly distributed with a 30mm distance in between. The horizontal placement was in the centre of the box. The two boxes with temperature sensors were placed in the worst locations on the pallet. These locations were found by means of CFD simulations and are shown in *Figure 45*.

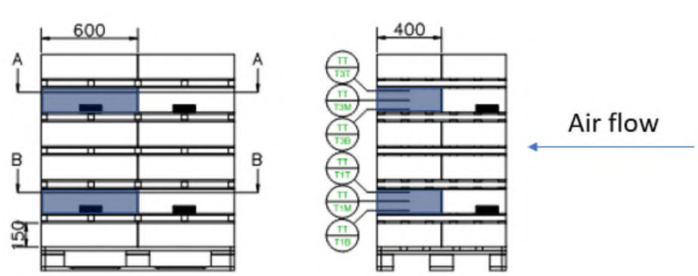

Figure 45: Shaded boxes represent the ones with temperature sensors at the levels

3. FREEZING TIME

In industrial batch freezing tunnels, the freezing time is controlled by air temperature and air speed. An empirical equation is often used to calculate the freezing time of products and can be found in various books on the subject, e.g. Granryd (2). The freezing of the product is divided in three phases as seen in *Figure 46*.

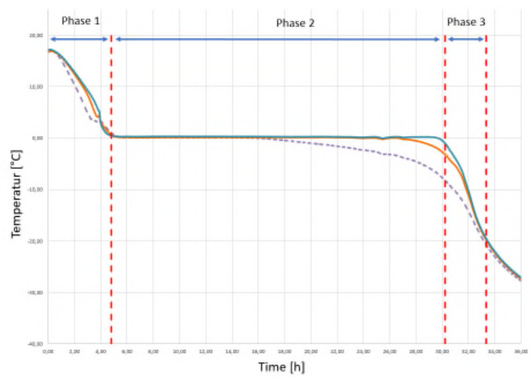

Figure 46: Temperatures inside box measured at various heights from the bottom of the boxes.

The first phase is the down cooling period where the product is cooled down to the freezing point. The second phase is the freezing phase where the water changes from liquid to solid ice. The third phase is where the frozen food is under cooled to the required final temperature.

Figure 46 shows the temperature inside a box from the test tunnel. The temperature is shown at various heights from the bottom of the box. The dotted line is the one closest to the bottom. As seen from the figure, the temperature in phase 1 of cooling is equalised around 4°C. The reason for this is the phenomena of water to have highest specific weight at 4°C which will stir up the water in the box at that temperature. This will not occur in the package containing product since the water is contained in the meat. The freezing phase 2 covers the plateau where the temperature is constant. Then phase 3 the under-cooling takes over with drop in temperature down to the final temperature.

As mentioned earlier, the freezing time can be calculated by empirical equations, e.g. Granryd (2), which states the following:

Phase 1:

$$\tau_{down\ cooling} = \rho \cdot c_p \cdot b \cdot ln\left(\frac{t_{start} - t_{air}}{t_{freezing} - t_{air}}\right) \cdot \left(\frac{1}{\alpha} + \sum\left(\frac{\delta}{\lambda}\right)_{Packing} + \frac{b}{2 \cdot \lambda_{water}}\right) [sek] \quad (16)$$

Phase 2:

$$\tau_{freezing} = \frac{\Delta H_{vol}}{t_{freezing} - t_{air}} \left(\frac{1}{\alpha} + \sum\left(\frac{\delta}{\lambda}\right)_{Packing} + \frac{b}{2 \cdot \lambda_{ice}}\right) \cdot b\ [sek] \quad (17)$$

Phase 3:

$$\tau_{undercooling} = \rho \cdot c_p \cdot b \cdot ln\left(\frac{t_{start} - t_{air}}{t_{final} - t_{air}}\right) \cdot \left(\frac{1}{\alpha} + \sum\left(\frac{\delta}{\lambda}\right)_{Packing} + \frac{b}{2 \cdot \lambda_{ice}}\right) [sek] \quad (18)$$

These equations indicate that the parameters, which can be adjusted to control the freezing time of the specified product, are the air temperature and the heat transfer coefficient through adjusting the air speed in the tunnel.

4. MEASUREMENTS AND RESULTS

In industrial batch freezing tunnels, the time, where the products stay in the freezer, is more dependent on site logistics rather than optimum energy usage. This means that the products stay in the freezer until the next unloading takes place, normally with full fan speed the whole time. The freezing cycle time is typically 24 or 36 hours depending on the product size. For the product size investigated in the project, the total freezing time in the freezer is 36 hours.

To optimize the energy usage to approaches was investigated. The first approach to lower the energy usage, was to utilize the total freezing time in the tunnel and controlling the air flow. The second optimization was directed at distributing the air flow through the tunnel in the best possible way.

As a starting point, a reference case was established, where the air flow and the placement of the pallets in the test tunnel were comparable to the those of the industrial tunnel. The measurements where done for 36 hours to lay the foundation for the reference case. Five reference measurements were made, and the average values of these were used as a reference for the following evaluation.

To evaluate the time for each phase under freezing, the boxes with the temperature sensors were monitored. To have a common reference between measurements for when the cooling starts, the average temperature of all sensors in the box was followed, and the cooling phase was considered started when it reached 5°C. To estimate when the freezing phase started, the temperature sensor at the bottom of the box was used, and the freezing phase was considered started when it reached 1°C. To predict when the freezing phase ends and the undercooling phase starts, the top sensor was used, and the freezing phase was considered over when it reached -1°C. The undercooling phase was considered finished when the average temperature in the box reached -20°C. The total freezing time of the tunnel is the time it took the worst box to freeze. When comparing the energy usage, the fan was considered to run for 36 hours, even though the freezing temperature of -20°C was reached earlier, plus the extra effect used in the refrigeration system to remove the heat from the fan. As a COP for the refrigeration system, a value of 2.3 was found to represent a system found at the industrial site.

3.1 Adjusting the air flow

By adjusting the fan speed, the volume flow of air in the freezer is controlled, and the freezing time of the product is affected according to the equations in section **3. FREEZING TIME**. By controlling the air flow, the air speed passing the product and the air temperature are both affected.

The first attempt to optimize the energy of the fans was to adjust the flow throughout the freezing period. Two test were conducted. First test (T3) started with a low flow for 12 hours as shown in *Figure 47* and then adjusted as shown in the figure. In the second test (T4), the air flow started with a high flow during the down cooling phase followed by a lower flow through most of the freezing phase. Finally, the air flow was increased again.

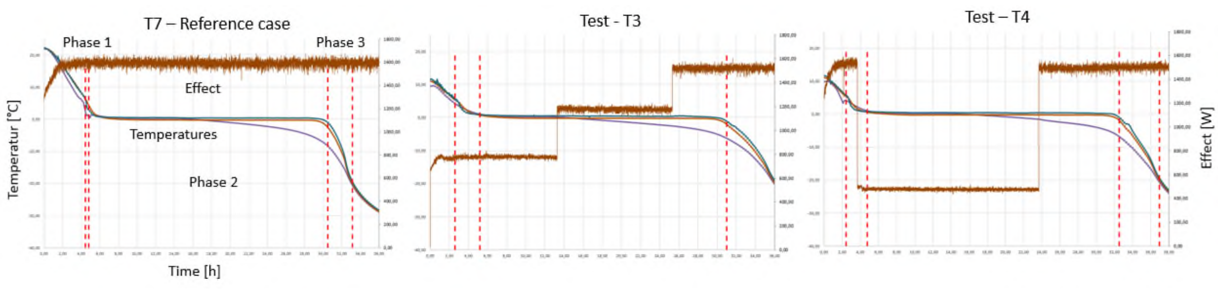

Figure 47: Freezing temperatures in the worst box on the pallet and the effect usage on the secondary axes. The one to the left is the reference case. The other two show the tested running strategies.

The energy savings and the increased freezing time can be seen in *Table 20*.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Impovements		Fan	Ref sys	Total	Improvements	
		$[m^3/s]$	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	T7a - T7e	6,5	29,8	0,0	0,0%	56,7	24,7	81,4	0,0	0,0%
Fan control.	T3	4,2/5,0/6,5	33,5	-3,7	-12,6%	42,8	18,6	61,4	19,9	24,5%
Variable flow	T4	6,5/4,0/6,5	34,5	-4,7	-15,9%	33,6	14,6	48,2	33,1	40,7%

Table 20: Freezing time and energy savings when controlling the air flow.

For the first test (T3), there was an increase in the freezing time of 3.7 hours and a 24.5% saving in total energy compared to the reference case. For the second test (T4), the increase in freezing time was 4.7 hours and the energy savings were 40.7%. The energy savings are considerable and the cycle freezing time still within the 36 hours limit.

In the search for a parameter to control the fans, two tests (T5 and T6) were conducted. In both tests, the fan was controlled according to the temperature measured after the last pallet in the test container. In test T5, the temperature set point was at -30°C and in test T6, the set point was set at -32°C.

In test T5, the fan was controlled between low and high speed for the first 12 hours, and thereafter constantly on low speed since the air temperature did not get above -30°C. For test T6, the fan was running on high speed for just over 22 hour and thereafter dropped to a low speed. This indicates how difficult it is to control the fans by using the air temperature as a control value.

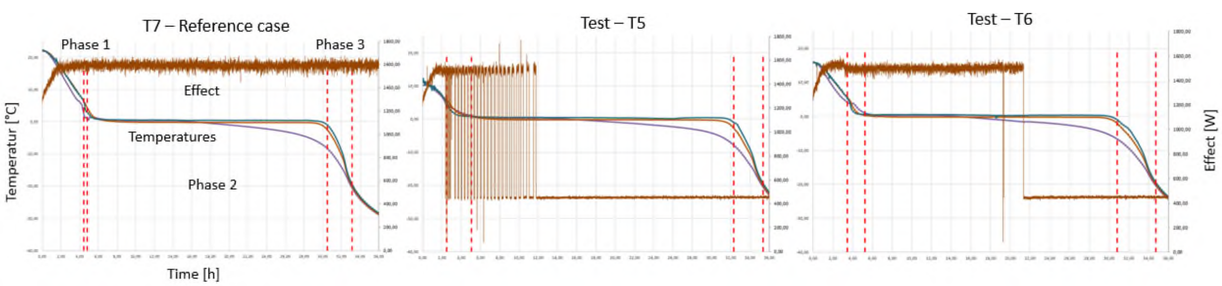

Figure 48: Freezing temperatures (left axes) in the worst box on the pallet and the effect usage (right axes). The one to the left is the reference case. In the other two graphs, the air set point is -30°C and -32°C, respectively.

For an actual industrial tunnel, the air temperature would depend on the load from the pallets which again depends on the time of freezing and how the tunnel is loaded with pallets. The set point would therefore be dependent on the actual freezer and its product loading.

When looking at the freezing time and the energy savings for the two control strategies as seen in *Table 21*, an increase in the freezing time for both cases is noticed, but both within the available 36 hours. The energy savings for T5 and T6 are 60% and 38,8%, respectively. This indicates the large potential in energy savings when using the fan speed. However, the need for a control variable to control the fans is essential.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Impovements		Fan	Ref sys	Total	Improvements	
		$[m^3/s]$	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	T7a - T7e	6,5	29,8	0,0	0,0%	56,7	24,7	81,4	0,0	0,0%
Fan control.	T5	6,5/4,2	32,8	-3,0	-10,2%	22,7	9,9	32,6	48,8	60,0%
Variable flow	T6	6,5/3,95	31,1	-1,3	-4,5%	34,7	15,1	49,8	31,6	38,8%

Table 21: Freezing time and energy savings when controlling the air flow by the temperature of the air from the last pallet.

To investigate how the freezing time and the energy usage would change when using a constant air flow instead of trying to control the air flow under the freezing process, two tests (T8) was conducted. In test

T8a, the air flow was adjusted to 3.2 m³/s throughout the whole freezing process, and in test T8b the flow was adjusted to 4.9 m³/s. The reference case was running on 6.5 m³/s. By plotting the freezing time and the energy usage into a graph as shown in *Figure 49*, one can see that the total freezing time increases as the air flow reduces.

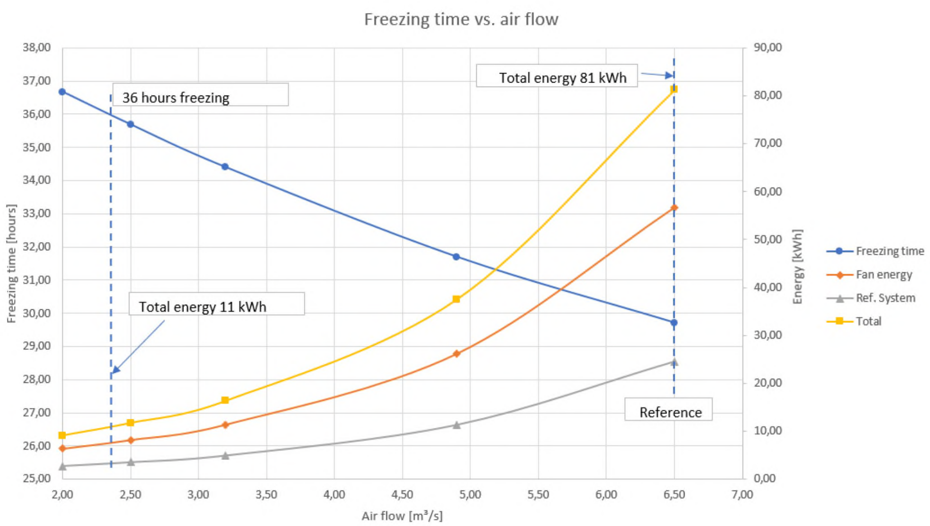

Figure 49: Total freezing time and energy usage of fan for various air flows.

The figure also shows three curves, that indicate the energy usage of the setup. One of the curves shows the energy used by the refrigeration system with a COP of 2.3, and another curve shows the direct energy usage of the fan. The third curve is the total energy usage for both the refrigeration system and the fan. The total energy usage for the reference case in the test tunnel was 81 kWh, and the freezing time was just under 30 hours. By fitting a curve through the measured points and finding the point on the curve where the total freezing time reach 36 hours, one finds that the needed total energy would be 11 kWh for an air flow of 2.3 m³/s. This is a considerable saving in energy, corresponding to about an 86%. By looking at the graph, it becomes evident that the largest energy savings are achieved in connection with a reduction from full flow to for example half flow or an 80% saving in energy. When running on half flow, the total freezing time is just above 34 hours which gives a safety in the freezing time of two hours. Getting from half flow down to the total freezing time limit of 36 hours adds 6% to the total energy savings. This indicates that the largest energy savings can be harvested in the first part of the flow reduction.

Another benefit of reducing the air flow in the tunnel is being able to use fans with a lower power consumption.
This opens the opportunity to change from normal axial fans with frequency drive to the new EC fans type which is less expensive and has an integrated speed control.

By comparing test T3 to T6 with T8, it can be concluded that the largest energy savings can be obtained by finding the lowest air flow acceptable for the tunnel instead of trying to control the flow under the freezing process.

3.2 Air distribution in the tunnel

The second attempt to save energy was to distribute the air flow through the tunnel in a more energy efficient way. By looking at CFD simulations for the industrial tunnel and the test tunnel, it becomes evident that most of the flow is directed in channels above and under the products as shown to the left in *Figure 50*. The air flow through the spacers on the pallet is determined by the pressure drop through the spacer and the pressure drop around the product pallet.

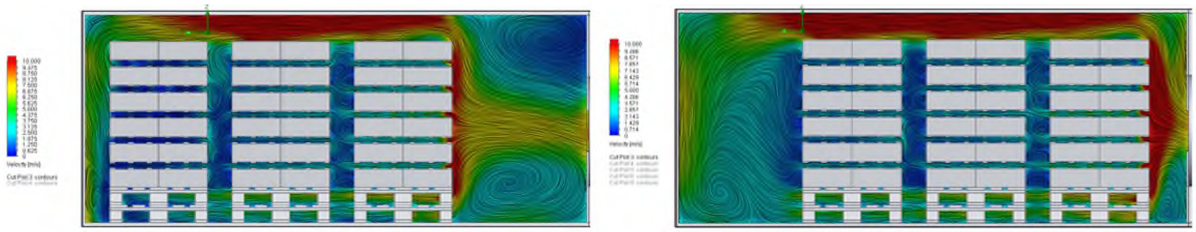

Figure 50: Air flow 6.5m³/s contour lines. To the left the reference case and to the right pallets closer to the fan making space after pallet 3.

From CFD simulations and test measurements, it is seen that the last pallet, i.e. pallet 3 in the test tunnel and pallet 10 in the industrial tunnel, takes the longest to freeze. To reduce the freezing time, the conditions for the last pallet must be improved. The first attempt to do so was to move the pallets closer to the fan to make space behind the last pallet for air to flow before it changes direction and returns to the second half of the tunnel. By running CFD simulations with the pallets in different distances from the fan, a position where the first pallet was 300 mm from the fan was selected. This distance did not contribute considerably to the pressure drop and gave flow improvements to the last pallet. This configuration was tested in the test tunnel, and the results can be seen in *Table 22*. The energy usage was close to the reference case, but the improvement in freezing time was three hours. This could also be used to save energy by lowering the flow until the total freezing time of 36 hours was utilized.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Impovements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	T7a - T7e	6,5	29,8	0,0	0,0%	56,7	24,7	81,4	0,0	0,0%
Air	T9	6,5	26,8	3,0	9,9%	57,8	25,1	82,9	-1,6	-1,9%

Table 22: Freezing time and energy savings when moving the pallets closer to the fan compared to the reference case.

Another attempt to distribute the air better in the test tunnel was to use baffles. Thus, a number of CFD simulations was performed with various kinds of baffles configurations.

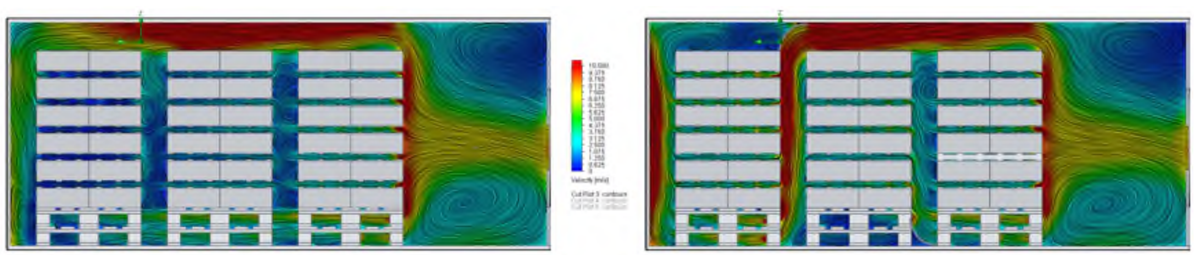

Figure 51: Air flow 6.5m³/s contour lines. To the left the reference case and to the right configuration with baffles in the top and bottom of the setup.

The configuration that gave the best air and temperature distribution was the one with a baffle placed in the top channel and another in the bottom channel as shown in *Figure 51*.

This configuration was tested in the test tunnel with two air flows. One test where the air flow was the same as for the reference case, and another test with a lower air flow. Here, an attempt was made to hit the same total freezing time as for the reference case. The results are viewed in *Table 23*.

	Test no.	Air flow	Freezing time			Energy usage				
			Total	Impovements		Fan	Ref sys	Total	Improvements	
		[m³/s]	[h]	[h]	[%]	[kWh]	[kWh]	[kWh]	[kWh]	[%]
Reference	T7a - T7e	6,5	29,8	0,0	0,0%	56,7	24,7	81,4	0,0	0,0%
	T11	6,5	26,6	3,2	10,6%	56,6	24,6	81,2	0,1	0,2%
	T11b	4,1	30,8	-1,0	-3,5%	18,3	8,0	26,3	55,1	67,7%

Table 23: Freezing time and energy savings when using baffles compared to the reference case.

For test T11, where the air flow was the same as for the reference case, the energy usage was the same. However, the total freezing time was 3.2 hours shorter. Subsequently, in test T11b, the flow was reduced to 4.1 m^3/s, which resulted in a 67.7% saving in energy and nearly the same total freezing time as the reference case. By fitting a quadratic function through the measured points and interpolating it to 36 hours, the estimated savings were 93%. This shows that by using baffles, a large saving in energy can be found, but it also increases the complexity of the tunnel and generate challenges in older tunnels.

4. CONCLUSIONS

As shown in this paper, a considerable saving in energy can be obtained by adjusting the air flow in the freezer. By reducing the air flow, the pressure drop in the freezer drops which results in reduced energy consumption. By reducing the energy consumption, the opportunity to use the new fan concept, the so-called EC fans, appears. These fans are less expensive and more energy efficient than traditional solutions, and they are easier to speed control.

The total time, which the products stays in the tunnel, is determined by the logistics of the tunnel, i.e. when the unloading of the tunnel fits into the employees working schedule. Therefore, the energy optimization of the tunnel is about using the available time in the most efficient way. As has been shown in this paper, the energy consumption of a test tunnel can be reduced by 86% when reducing the air flow from 6.5 to 2.3 m^3/s.

By introducing baffles to direct the flow to where it is needed, large energy savings can be achieved. By using baffles and reducing the flow to maintain the same freezing time as in the reference case, a saving in energy of 68% can be expected. By further reducing the air flow and utilizing the total freezing time, a saving of 93% can be expected. Further tests on the industrial tunnel is to be conducted to verify the findings of the test tunnel. Tests with other types of spacers will also be conducted in the test tunnel.

NOMENCLATURE

τ	Time (sec)	ΔH_{vol}	Volumetric freezing enthalpy (kJ/ m³)
ρ	Specific weight (kg/m³)	α	Heat transfer coeff. (W/m²·K)
c_p	Specific heat capacity (kJ/kg·K)	δ	Thickness (m)
t_{start}	Initial temp. of water (°C)	λ	Thermal conductivity (W/m·K)
t_{air}	Air temp. (°C)	b	Height of box (m)
$t_{prod,final}$	Final product temp. of phase (°C)		

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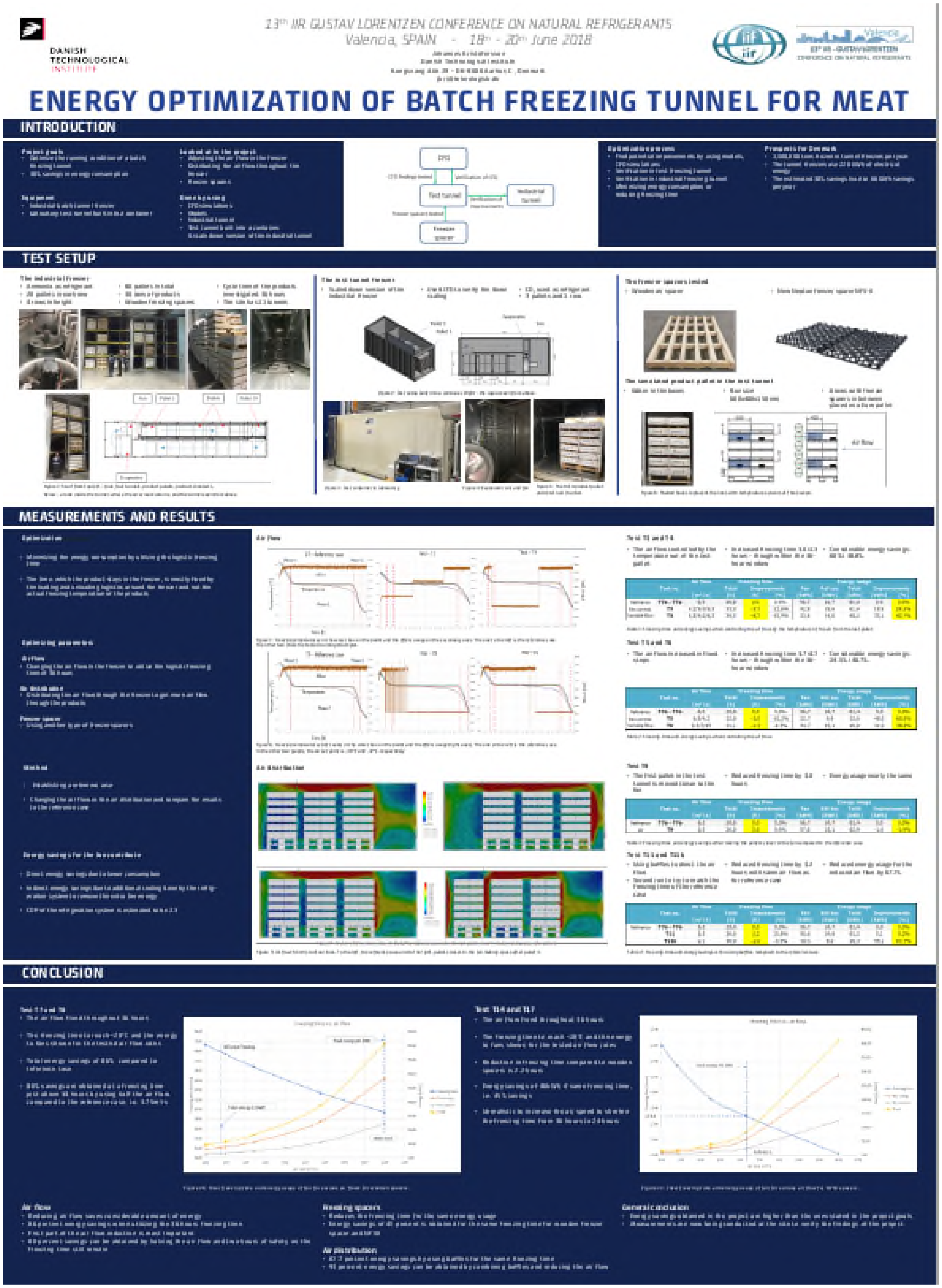
Granryd, Eric, 2003. Refrigerating Engineering Part II. Department of Energy Technology, Division of Applied Thermodynamics and Refrigeration, Royal Institute of Technology, Stockholm, page 13:1-13:19.

8.2. Poster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13th IIR GUSTAV LORENTZEN CONFERENCE ON NATURAL REFRIGERANTS
Valencia, SPAIN - 18th - 20th June 2018
ENERGY OPTIMIZATION OF BATCH FREEZING TUNNEL FOR MEAT
INTRODUCTION
TEST SETUP
MEASUREMENTS AND RESULTS
CONCLUSION