ENERGY OPTIMIZATION OF BATCH FREEZING TUNNEL FOR MEAT

Jóhannes Kristófersson[(a)], Lars Reinholdt[(a)], Kenneth Kramer [(a)], Alexander Rosenvinge Lindholm Bork [(a)], Nis Peter Reinholdt [(a)]

[(a)] Danish Technological Institut, Aarhus, 8000, Denmark, JKRI@dti.dk

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 1. 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 m^3/h (6.5 m^3/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 2.

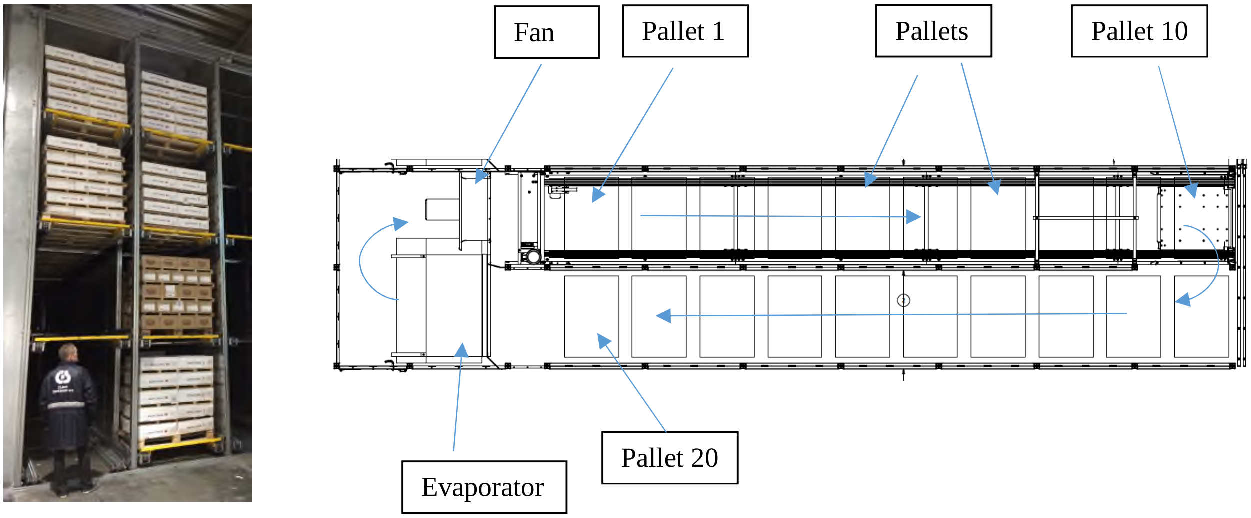

Figure 1: Left – a look inside the tunnel, where the air stream returns. Right - layout of the tunnel seen from above.

The air spacers used in the tunnel are of wooden type as shown to the left in Figure 2. The air spacers give distance between the product packages allowing cold air to reach the top and the bottom side of the product packages.

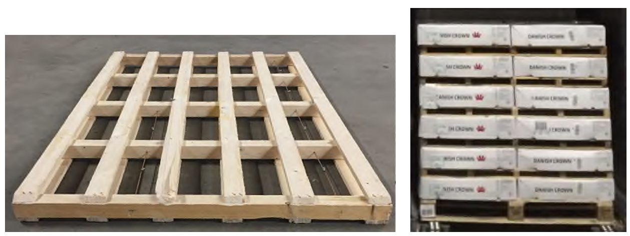

Figure 2: Left - wooden air spacer. Right - product pallet.

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 3. 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.

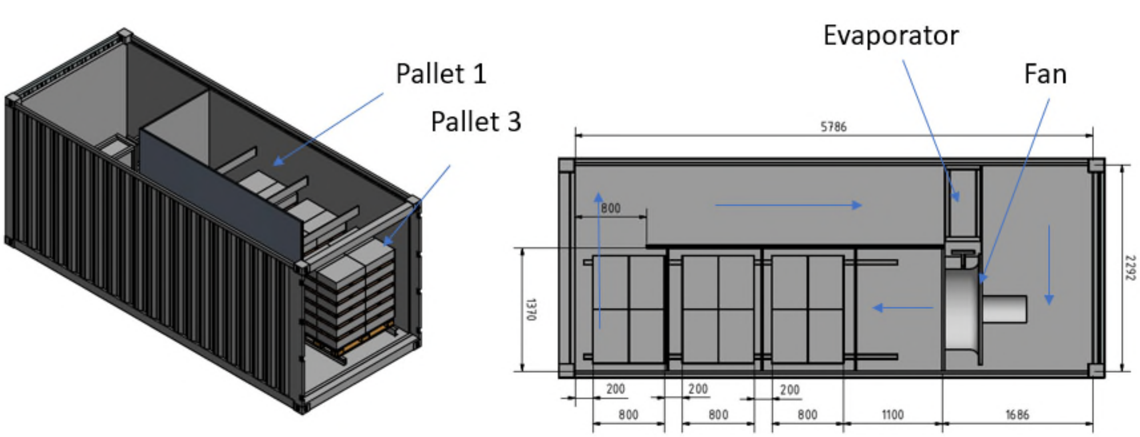

Figure 3: Test setup built into a container. Right - the layout seen from above.

A CFD simulation showed that the tenth pallet in the industrial tunnel (see Figure 1) represented by the third pallet in the test tunnel (see Figure 3) 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 4. 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 3. 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 4.

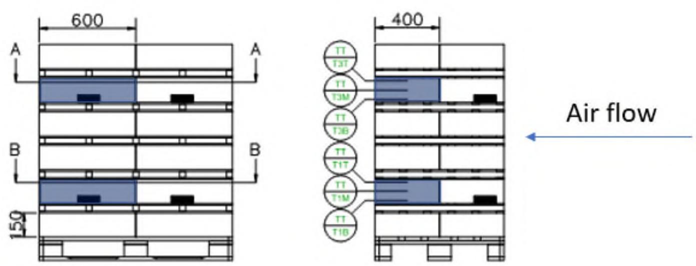

Figure 4: Shaded boxes represent the ones with temperature sensors at the levels

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 5.

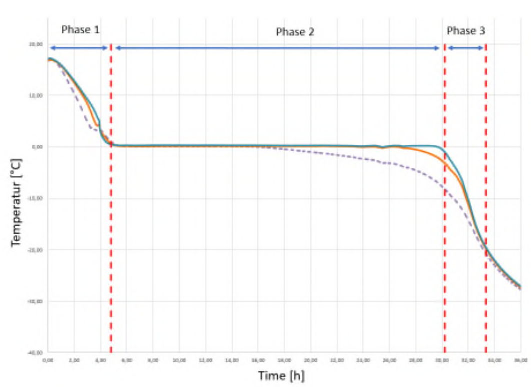

Figure 5: Temperatures inside box measured at various heights from the bottom of the boxes.

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 5 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:

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

Phase 2:

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

Phase 3:

$$\tau_{undercooling} = \rho \cdot c_p \cdot b \cdot ln\left(\frac{t_{start} - t_{air}}{t_{final} - t_{air}}\right) \cdot \left(\frac{1}{\alpha} + \sum\left(\frac{\delta}{\lambda}\right)_{Packing} + \frac{b}{2 \cdot \lambda_{ice}}\right) [sek] \qquad (3)$$

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 6 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.

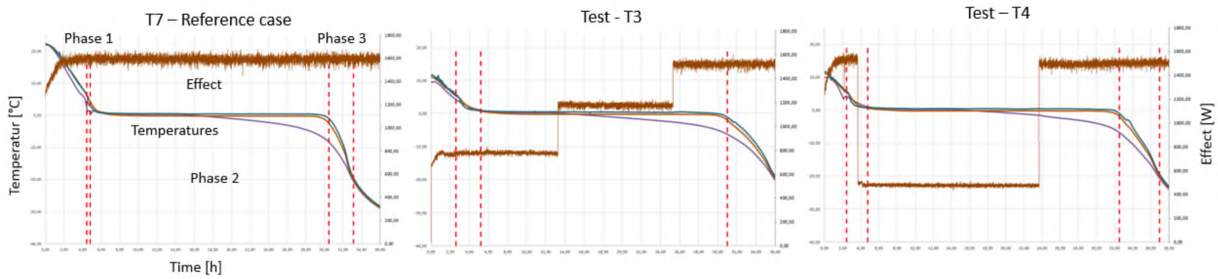

Figure 6: Freezing temperatures in the worst box on the pallet and the effect usage on the secondary axes. The one to the left is the reference case. The other two show the tested running strategies.

The energy savings and the increased freezing time can be seen in Table 1.

	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%
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 1: 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.

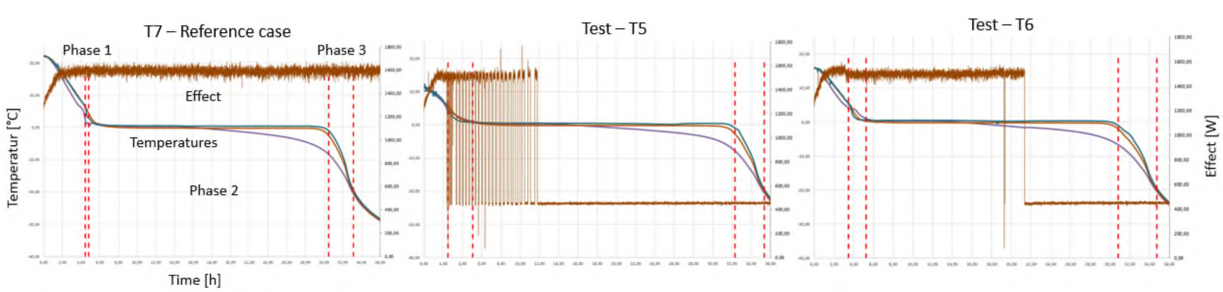

Figure 7: Freezing temperatures (left axes) in the worst box on the pallet and the effect usage (right axes). The one to the left is the reference case. In the other two graphs, the air set point is -30°C and -32°C, respectively.

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 2, 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	
		[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.	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 2: 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 8, one can see that the total freezing time increases as the air flow reduces.

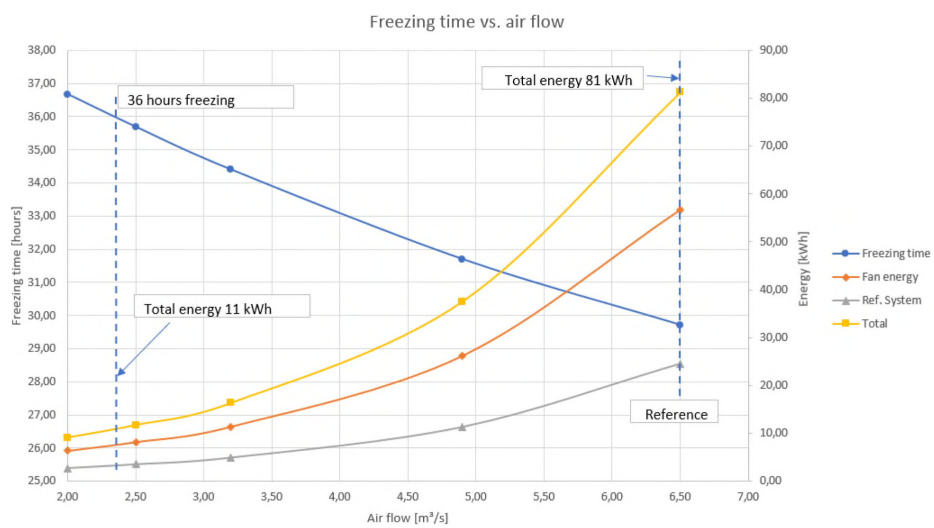

Figure 8: Total freezing time and energy usage of fan for various air flows.

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 9. 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.

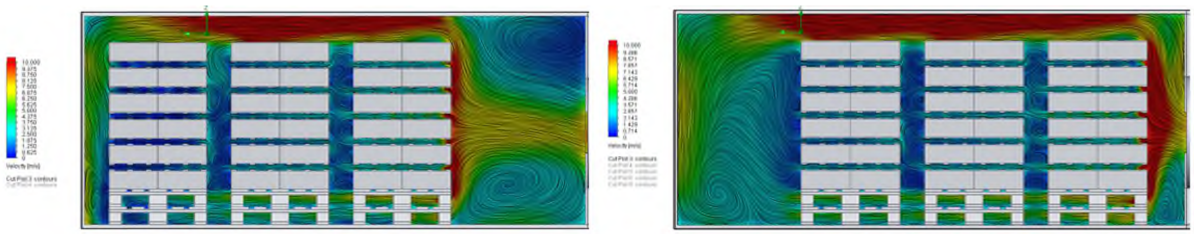

Figure 9: Air flow 6.5m³/s contour lines. To the left the reference case and to the right pallets closer to the fan making space after pallet 3.

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 3. 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 3: 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.

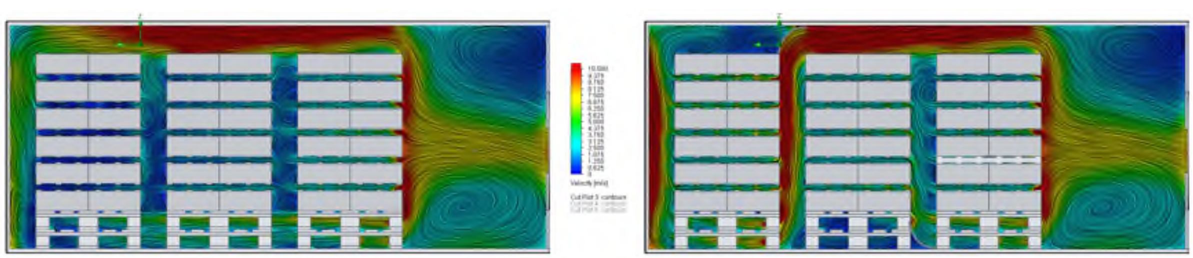

Figure 10: Air flow 6.5m³/s contour lines. To the left the reference case and to the right configuration with baffles in the top and bottom of the setup.

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 10.

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 4.

	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 4: 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 m³/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 m³/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)		

REFERENCES

Dempsey, Patrick and Bansal, Pradeep, 2010,"Air blast freezers and their significance to food freezing" 13 th. Brazilian Congress of Thermal Sciences and Engineering

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.