

Improvements of air flow distribution in a freezing tunnel using Airpak

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ABSTRACT

In a freezing tunnel, food products are cooled and frozen by cold circulating air. The products give off heat to the air, which is cooled down again in an air cooler. Refrigeration systems with freezing tunnels consume considerable amounts of energy and improvements in the tunnel design may reduce energy use. The necessary freezing time for products inside the tunnel depends strongly on air velocity and distribution. Uneven air velocity distribution results in non-homogeneous product freezing times and inefficient energy use for fans and refrigeration systems.

The analysis of the tunnel design has been performed by computational fluid dynamics (CFD) simulations with the software tool ANSYS Airpak. The analysis is based on an existing freezing plant where different ceiling geometries have been tested for the same model. This was done in order to identify problem areas, to improve the design, and to obtain better air distribution and optimized fan power consumption.

Results from the simulations show that fan power and air distribution can be strongly influenced by ceiling design and use of air guidance vanes, which may have a significant impact on the overall energy use for such a freezing tunnel. Several alternative ceiling designs resulted in one version with reduction in total energy consumption of approximately 12% compared to the baseline configuration. In addition, the minimum air fluxes over the products were increased from 2.6 to 4 kg/sm²; resulting in reduced necessary freezing time.

Keywords: Simulation; CFD; air distribution; energy consumption.

INTRODUCTION

In the food industry, blasting cold air is a common way for chilling and freezing [1]. During this operation, heat conduction occurs within the product while heat and water exchanges take place at the air-product interface [2]. The freezing time accounts for the time consumed on the change from an initial to a final temperature in the thermal centre of a product [3]. The freezing time for a product is affected by local air properties, air velocity and product characteristics [4]. Due to uneven air temperature and velocity across the freezing tunnel, the products will have a non-homogeneous freezing rate and this will contribute to different freezing times. Longer freezing times would be required in order to avoid too high temperature in the product sent to the storage and therefore lower quality.

The homogeneity of freezing and the freezing time are two economically important criteria of process efficiency. Both are affected by airflow distribution. Until now it has been a widespread technique to use design aids for dimensioning of air coolers, geometry and fans [5] based on experience about airflows. Nowadays, the computational fluid dynamics (CFD) have proved to be a tool for rationalising this design[6]; and theoretically solving the turbulence flow equations and the heat and mass transfers for each individual case simultaneously. With this method, it is possible to analyze different tunnel cross-sections and calculate the spatial distribution of the air characteristics (velocity, turbulence intensity, temperature). Based on this analysis, improvements in design of freezing tunnel geometries can be made to reduce energy use of the refrigeration system[7].

In this paper it is shown how CFD simulations are used to improve air distribution and fan work in freezing tunnels. Improved tunnel design was analyzed and compared to the base tunnel geometry with focus on velocity homogeneity improvements and energy consumption. This work identifies problematic regions with unnecessary pressure losses and areas with low air flow over the product surface and corrects them by simple geometrical

modifications on the layout of the tunnel. Furthermore, a simplified analysis of the energy use effect of introducing these modifications has been done.

MATERIALS & METHODS

Simulations with Airpak

This study is based on a real industrial facility for freezing of fish, located in Norway. The freezing tunnel is 7.35m wide, 6.70m high and 5.9m deep. Figure 1 shows the side view of the different designs which are presented in this paper. The fans are three axial blowers placed over the false ceiling with a 45 degrees tilt. They have 11kW nominal power input and the nominal efficiency 55-60%. Further details about the performance of these fans are described on its specification sheet.[8]

The air is blown by fans across the evaporator and over product shelves. The evaporator is a tube-fin heat exchanger which has been modelled as a 3-dimensional resistance to the air flow. The capacity of the evaporator is unknown and implemented in the simulation as a constant null. This is assumed to have a negligible effect on simulations since the buoyancy force is small compared with the forced airflow from the fans. Neglecting heat transfer effect in the velocity field also saves computational time.

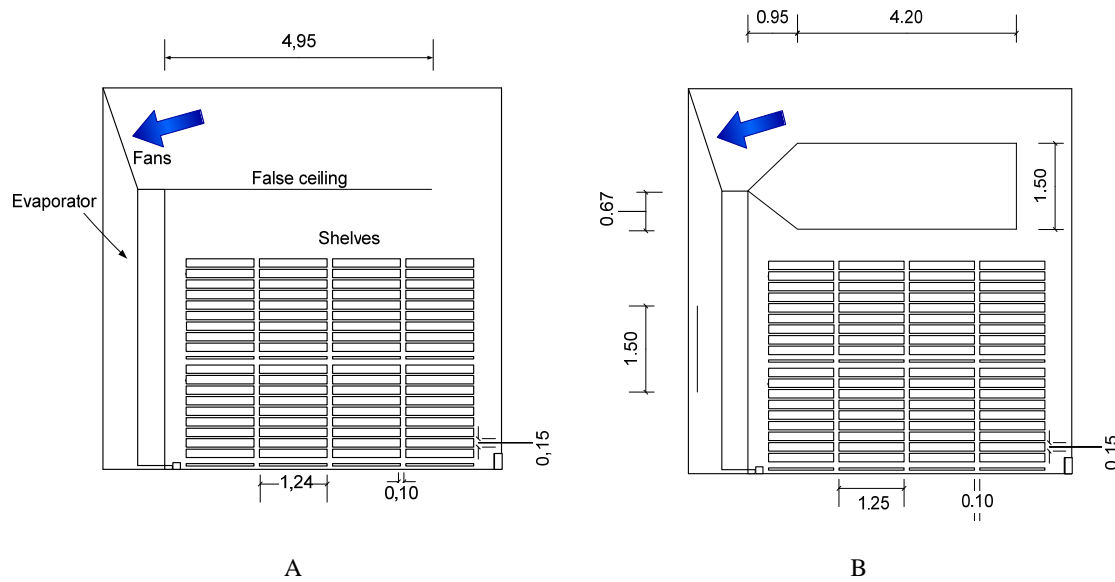


Figure 1. Air blast freezing tunnel with A: “Normal ceiling” and B: “Thick ceiling with vertical guiding plate” modelled in Airpak. This figure includes fans, evaporator and shelves with products.

CFD is used for modelling fluid flow and absolute velocity in this 3D steady state model. A fine hexahedral unstructured mesh is used in order to achieve accurate solutions. Furthermore, fluid motion is governed by mass, momentum (Navier-Stokes equations) and energy conservation equations [9]. The highly non linear differential equations are transformed into algebraic relations using finite-volume methods [10]. To account for the turbulence, the model is an *indoor zero equation*. The model is solved when mass residuals are reduced to less than 10^{-5} and velocity residuals to 10^{-4} .

Models

The start point for this paper was the “normal ceiling” design. Based on the simulation results for this geometry, regions with vortices and backflow were identified. Initial analysis determined that the evaporator geometry was far from ideal, but has been left unchanged in this work as the scope is to identify a low-cost solution for improving an existing plant.

Different modifications were implemented to correct problematic areas in the “normal design”. About 20 different configurations were tested. Among them, changes in length and thickness of ceiling, rounding of

corners and guiding blades were tested. The improved tunnel geometry was found by stepwise modification analysis, and the best solution is presented here. This improved design includes:

- Thicker ceiling to force more air over the product shelves.
- Guiding plate before the lower part of the evaporator to guide more air through the bottom of the evaporator and the lower shelves. The technical difficulties of installing this plate are not discussed in this paper.

The two cases to be further compared are:

- *Normal ceiling*, where the ceiling is 4.95m long, 5.9 deep and 0.05m thick. Figure 1A
- *Thick ceiling with vertical guiding plate*. The ceiling has a trapezoidal form with 1.5m width (see Figure 1B). It has a plate in the space between the wall and the evaporator to guide a higher air flow downwards before it goes into the evaporator. The idea was to prevent the air from going into the space between the ceiling and the shelves.

RESULTS & DISCUSSION

Airpack results

By solving the cases the velocity distributions of Figure 2 were obtained.

Figure 2B shows a large recirculation of air above the ceiling, which blocks out major part of the volume of air. This is the reason for high velocities in the top part of the tunnel. Due to the turbulent movement of the air before the fan, it is observed that there are vortices in the fan and after it; but due to this, high velocities in the air which is going to the evaporator are found. In the lower part of Figure 2A, lower velocities in the furthestmost lower and all top shelves are related to local lower freezing rates and therefore to lack of homogeneity in the freezing process. The fact of having too low height of product shelves affects creating a way for the air to shortcut back towards the fan. However in this narrow way the air goes preferably in the upper part and therefore next to the highest shelves the velocity is very low.

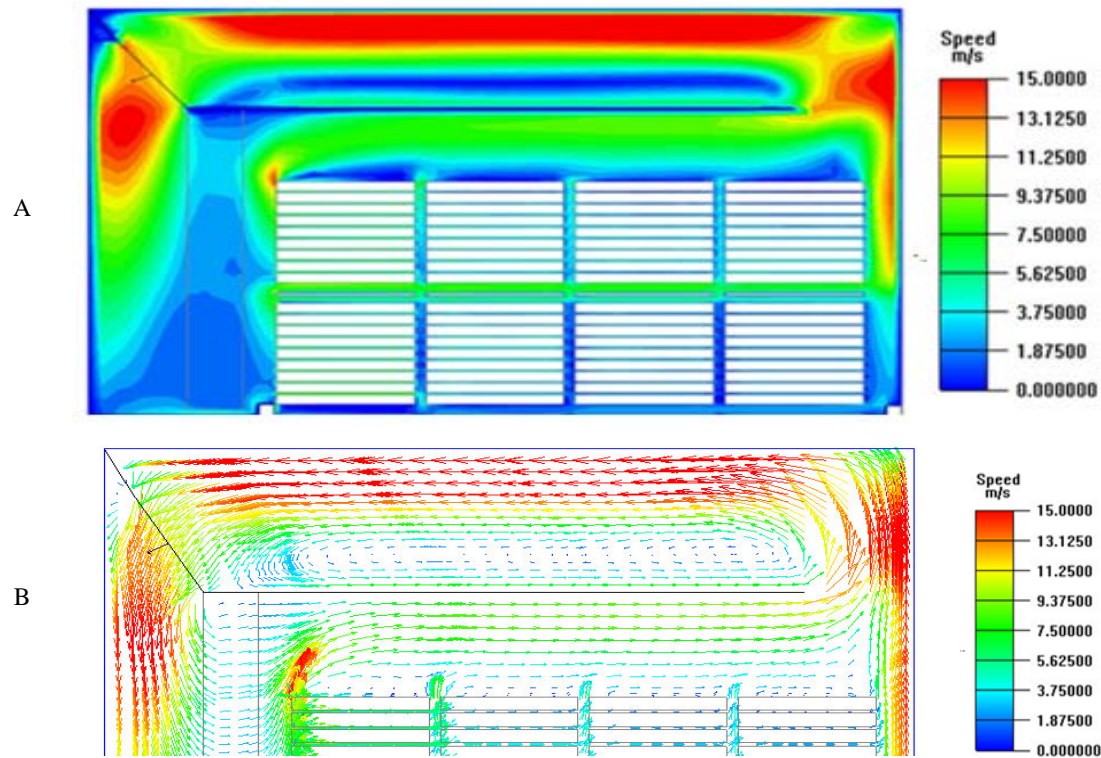


Figure 2 A: Distribution of the contours of velocity for “Normal ceiling” , B: Velocity vectors in the upper part of the tunnel for “Normal ceiling” (Note: not to scale)

Figure 3B shows how a plate placed facing the lower part of the evaporator improves the airflow into the lower shelves. The thick ceiling also reduces the way for the air and the low velocities on the top shelves are now in much higher values. This configuration improves the air flow distribution of the previous since it guides the air towards the lower shelves and gives a higher velocity through the shelves. The velocity of the air at the entrance of the shelves reaches values of around 10.3 m/s in the upper shelves and 2.8 m/s in the lower. In addition, the distribution of the air velocities is more even; showing almost the same speed in the lower and upper shelves since in this case the flow is not blocked by any vortex. Along with that, the air is quite uniformly distributed through the columns, Figure 3A. One problematic area can be seen right below the ceiling Figure 3B. Here, the open area with small resistance gives a major short-circuiting return flow. This gives problems on the lower shelves furthest from the evaporator.

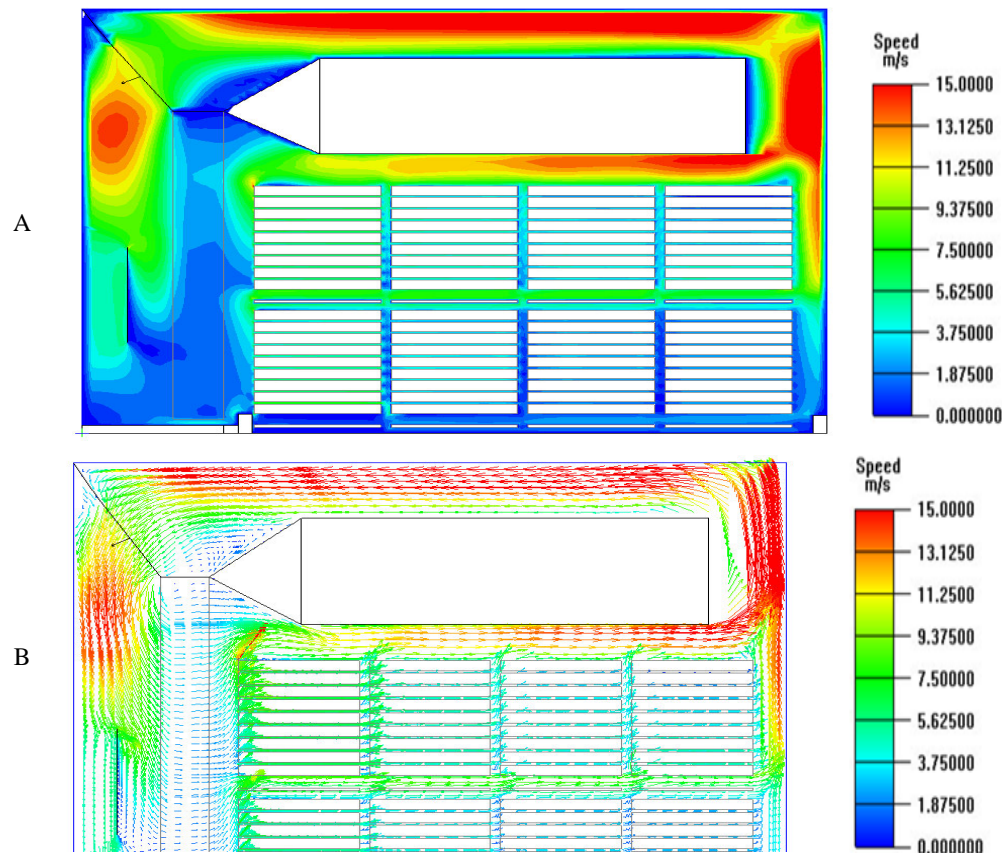


Figure 3 A: Distribution of the contours of velocity for “Thick ceiling with vertical guiding plate”, B: Velocity vectors in the upper part of the tunnel for “Thick ceiling with vertical guiding plate” (NOTE: not to scale)

Pressure drop and velocities

In order to compare the efficiency and the working point of the fan, further data has been analyzed. Table 1 shows some overall results from the simulations. The air flow rate over the fans has been obtained from Airpak as the volume through the volume of one fan. The fact of having a higher volume in the improved model is related to the reduction of backflow.

The two next columns show the maximum and minimum air flux over product surfaces, representing the span in freezing conditions. These values are obtained as the higher and lower values of the velocity among two product rows. Airpak gives the velocities for every node of the mesh between the product boxes. The assumption followed for these values is related to the fact that exactly the same mesh is assumed in this part of the tunnel. The velocity at surface of the product is zero[7]. Therefore, these values are comparable. The minimum air flux over the product is seen as a limiting factor for total freezing time. It is important to increase the minimum velocities since these are related to local lower freezing times. Different freezing rates can be related to lower quality in the total final product.

Table 1 Volume flow through the fan and pressure drop for the different ceiling configurations.

Ceiling design	Volume flow [m ³ /s]	Max. air flux over product column [kg/sm ²]	Min. air flux over product column [kg/sm ²]	Pressure increase over fans [Pa]
Normal ceiling	18.25	10.3	2.6	386.5
Thick ceiling with vertical guiding plate	19.15	10.3	4.0	336.2

Energy consumption analysis

The difference between the normal ceiling design and the thick ceiling design is greater than the values in Table 1 indicate, when considering the total energy use for the freezing tunnel. Energy consumption of the refrigeration system and freezing times are better indicators of performance than total volume flow.

A simple calculation based on simple assumption has been performed in order to represent how this change would affect the energy use of these tunnels.

In blast air tunnel freezers, the fan power is commonly around 30-55% of the compressor power [11], [12]. Common COP's for refrigeration systems for tunnel freezers are 2-3. For the following calculations, based on these assumptions, a fan power ratio of 40% and COP of 2.5 are assumed.

The simulation results show a 13.0% difference (in favour of the improved design) in air side pressure drop. This corresponds to 13.1% decrease in fan power due to the reduction of the pressure losses. At the same time, the minimum air velocity over the worst case between two heights of products has increased from 2.3 to 2.8 m/s due to better air distribution. For this product, it is assumed to result in an increased heat transfer coefficient of 13.1% using Valentas et al [13] to compare the different alternatives.

This again reduces the necessary freezing time by approximately 5% according [14].

Simultaneously, less fan power also means that less heat must be removed from the tunnel, which for this example was calculated in a reduction of compressor work by 2.1%. Considering assumed reduction in freezing time, the overall reduction in tunnel energy consumption is 12.0%.

All in all, due to the energy savings and to the even distribution of air flow in the tunnel, the thick ceiling configuration provides a better solution. Due to the better air flow distribution, the estimation of freezing ratio can be done in a more accurate way. The products placed at the same distance from the evaporator will have approximately the same freezing rate. This assuming a further accumulation of the product will be related to a better quality of the total frozen product. The fact of having an even freezing rate is seen as the most important parameter when talking about high quality frozen product. Furthermore, with the second configuration a higher air flow velocity will also improve the economical parameters since it is related to a shorter freezing time.

CONCLUSION

CFD simulations show that improvements to a freezing tunnel can be made, by implementing simple geometrical modifications to the tunnel geometry. CFD simulation was a powerful tool to analyze improvements without the need of extensive physical testing. For this paper approximately 20 different modifications were tested in order to present the best solution and the results were easily comparable. Using this method, negative effects of flow vortices and backflows can be reduced to a minimum. Simulation results were also used together with simple assumptions to calculate energy use and freezing. An existing industrial freezing tunnel design has been simulated and compared to an improved version of the same tunnel. The results show a small reduction in pressure drop and improvement in minimum air velocity over the products:

- The Normal ceiling is the traditional solution and gives acceptable profiles which can be improved with geometrical changes. A small amount of the moving air is involved in a vortex over the ceiling but the air flux over the shelves is between 10 and 2.6 kg/sm² through the shelves. Air across products on the upper shelves has higher velocity than closer to the floor. Only at the lower part of the evaporator vortices can be found.
- The thick ceiling with vertical guiding plate shows better air velocity homogeneity. In addition the air achieves air fluxes of 10.3 kg/sm² in the shelves and the minimum air flux over the product surface is 4 kg/sm². Introducing the guiding plate increases the speed in the lower shelves, giving an acceptable speed in the lower

shelves. Less air is involved in vortices, and the backflow of air through the evaporator has been removed. The technical problems in the placing of this plate may be the most critical drawback.

All in all, the improvements in design yield a more homogeneous flow which will be related to an improvement in the quality. A reduction in energy use and a reduction of the freezing time which may be economically beneficial.

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