Comparison of airflow-uniformity in different ceiling-diffuser designs with various concentric circles in shrimp freezer using CFD

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Abstract. This study presents airflow patterns in the air chamber of a shrimp freezer by using computational fluid dynamics (CFD) simulations made with SC/Tetra V.13 software. The quality of the product depends on the duration of the freezing time and airflow-uniformity. The objective of this study is to improve the airflow pattern by simulating and analyzing the airflow distribution in the air chamber of a shrimp freezer with different designs of ceiling diffuser, with various concentric circles. The results from the simulations show that the ceiling diffuser with 5 concentric circles improves airflow-uniformity at the outlet by 13.57% in SD compared to the original model, resulting in a reduced freezing time.

1. Introduction

At present there are many methods used to preserve the quality of shrimp products; freezing is one of the best methods for preservation of seafood. A number of freezing techniques are used in the seafood industry including air-blast freezers, fluidized bed freezers, impingement freezers, and cryogenic freezers [1]. The commonly-used freezing technique is air blast freezing, which is the process that freezes the product until its core reaches the set temperature [2-3]. In this case, the core temperature of shrimps is generally expected to be –18 °C or below.

Air blast freezers are designed to supply low-temperature air over the food product with a uniform air velocity throughout the freezer. The quality of frozen foods depends on the freezing rate; a slow freezing rate can form large ice crystals that damage the food’s cellular structure and can cause the product to have a bad food texture. Additionally, the distribution of air flow, air flow rate or air velocity that has no uniformity at the outlet through to the freezing area can affect the temperature of frozen foods [4-8].

The airflow distribution in the air chamber can be solved based on the fluid flow equation. The technique of Computational Fluid Dynamics (CFD), which uses computers to simulate fluid flow in order to identify problems, is very powerful and effective in a wide range of industrial and non-industrial application areas. Based on academic research related to how to improve the air flow inside the air chamber of a freezer, many researchers have found that the air flow is a critical factor to the performance of cooling, and the temperature within the freezer. At present, there are patterns and different improvements such as developing a new air-supply into the fridge [9], design of airflow...
blockage and guide boards for a spiral quick-freezer [10], modifying the curvature of the corners of the room [11], and modify different ceiling geometries in a freezing tunnel [12].

The major objective of this paper is to compare airflow-uniformity in different designs of the ceiling diffuser with various concentric circles in a shrimp freezer using CFD. Six different designs of ceiling diffuser are investigated in this present study.

2. Method

2.1 The original air chamber model of a shrimp freezer

This study is based on the industrial freezing of shrimps in Thailand. The dimensions of the air chamber of the shrimp freezer are 995-mm wide, 1120-mm long and 500-mm high. The cool air flow inlet, which is at the top of the air chamber, has the radius of 250 mm. As shown in Figure 1, there are 25 slots for outlet at the bottom of the air chamber, columns 1 to 25. Each outlet slot has a 5-mm width, and an 830-mm length. The outlet is divided into 10 levels, rows a to j, simulation using the software SC/Tetra. Figure 2 shows 250 evenly-distributed surfaces in columns and rows.

![Figure 1. The original air chamber model of the shrimp freezer.](image)

In order to create the appropriate simulation results, Mesh Independent Analysis was used with 4 models with different mesh sizes near the outlet. The models show that a model of 11.2-million elements, which has a mesh size of 0.3125 mm, is an appropriate model in terms of minimizing computational time and improving the results from the calculation.
2.2 The boundary condition
The airflow distribution inside the air chamber is simulated using steady-state analysis by applying mass and momentum conservation equations. The properties of the air used in the calculation of the results are shown in Table 1, and the boundary conditions of the air inlet and outlet are shown in Table 2.

| Air properties |  |
|----------------|----------------|
| Temperature    | -15 °C |
| Density        | 1.3041 kg/m³ |
| Viscosity      | 1.6472 ×10⁻⁵ kg/m-s |

Table 2 Boundary conditions of the air inlet and outlet.

| Inlet air boundary condition |  |
|-----------------------------|----------------|
| Flow rate                   | 2.85885 m³/s |
| Outlet air boundary condition |  |
| Pressure                    | 0 Pa |

2.3 The different designs of ceiling diffuser with various concentric circles for the Shrimp Freezer
There are five designs of ceiling diffuser used in the analysis as shown in Figure 3. The ceiling diffuser has a radius of 250 mm, as does the original air chamber model. The gap between the circular plates of the ceiling diffuser with 3 circles is 140 mm, while the gap between the circular plates of the ceiling diffuser with 4 circles is 100 mm with 80 mm, 60 mm and 50 mm gaps for 5, 6 and 7 circles respectively.
3. Results and Discussion

The numerical simulations were carried out using the commercial CFD software, SC/Tetra. Fluid flow and absolute flow rate are simulated in this 3D steady state model. A fine hexahedral unstructured mesh is used in order to achieve accurate solutions. The model is solved when mass residuals are reduced to less than $10^{-5}$.

3.1 The total air flow rate at the outlet

The total air flow rate at the outlet as shown in Table 3 is the total air flow rate along column 1 to column 25 of each surface.

Table 3 The total air flow rate at the outlet of each surface.

| Surface | Original | 3 circles | 4 circles | 5 circles | 6 circles | 7 circles |
|---------|----------|-----------|-----------|-----------|-----------|-----------|
| a       | 0.26219  | 0.26265   | 0.26276   | 0.26448   | 0.26295   | 0.26297   |
| b       | 0.27386  | 0.27512   | 0.27563   | 0.27666   | 0.27544   | 0.27528   |
| c       | 0.28919  | 0.28964   | 0.28942   | 0.28921   | 0.28992   | 0.28963   |
| d       | 0.29938  | 0.29852   | 0.29828   | 0.29691   | 0.29851   | 0.29894   |
| e       | 0.30445  | 0.30294   | 0.30304   | 0.30139   | 0.30255   | 0.30306   |
| f       | 0.30452  | 0.30283   | 0.30299   | 0.30176   | 0.30348   | 0.30249   |
| g       | 0.29964  | 0.29867   | 0.29858   | 0.29779   | 0.29988   | 0.29868   |
| h       | 0.28944  | 0.28997   | 0.28935   | 0.28957   | 0.28999   | 0.28976   |
| i       | 0.27414  | 0.27574   | 0.27563   | 0.27657   | 0.27419   | 0.27491   |
| j       | 0.26204  | 0.26277   | 0.26318   | 0.26452   | 0.26195   | 0.26314   |
| SD      | 0.01666  | 0.01572   | 0.01559   | 0.01440   | 0.01606   | 0.01567   |

All designs of the ceiling diffuser with various numbers of circles give the total uniform air flow rate at the outlet higher than the original model. However, only 5 concentric circles model gives minimum standard deviation of the total air flow rate.
3.2 The airflow distribution in the air chamber

The airflow distribution in the air chambers in plane y-z at x=560 mm is shown in Figure 4.

![Figure 4. Distribution of the velocity contour in the air chamber with various concentric circles at the mid value of x](image)

All simulation results show vortexes in velocity contours in the air chamber. The cool air velocity of the inlet increases gradually after the installation of additional circles on the ceiling diffuser. It is clear that the ceiling diffuser with additional circles does not improve the airflow-uniformity.

4. Conclusions

The negative impact from vortexes could not be avoided in simulation models. However, the different designs of the ceiling diffuser with various numbers of circles gave positive results as shown in Table 1. The ceiling diffuser with 5 concentric circles optimized the airflow-uniformity at the outlet by 13.57% in SD compared to the original model. Correspondingly, the freezing time will be shortened.

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