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Examination of Thermal Dispersion and Airflow within a Refrigerator

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ABSTRACT

A blast freezer, characterized by its capability to diminish the core temperature of cooked food from 100 °C to -18 °C within 270 minutes, constitutes a critical component in this preservation process. This study endeavors to model a blast freezer system employing Computational Fluid Dynamics (CFD) methodologies, subsequently validating the CFD analysis through empirical investigations. The pressure-based k-ε turbulence model is employed to solve the Navier-Stokes and energy equations. The ensuing analyses encompass airflow assessments and temperature evaluations for unloaded and fully loaded blast freezers. Results gleaned from experiments and analyses indicate a temperature escalation within the cabin as it approaches the enclosure walls. Maximum velocities of 31.1 m/s and 26.9 m/s are recorded for unloaded and fully loaded freezers. The average disparity between the CFD and experimental models is computed as -0.7 °C, signifying a close alignment between the simulated and actual outcomes.

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ÖZ

Pişmiş gıdanın çekirdek sıcaklığını 270 dakika içinde 100 °C'den -18 °C'ye düşürme kapasitesiyle karakterize edilen bir şok dondurucu, muhafaza sürecinin kritik bir bileşenini oluşturur. Bu çalışma, hesaplamalı akışkanlar dinamiği metodolojilerini kullanarak bir şok dondurucu sistemini modellemeyi ve ardından deneysel araştırmalarla CFD analizlerini doğrulamayı amaçlamaktadır. Çalışmadaki nümerik analizlerde k-ε türbülans modeli kullanılmıştır. Hem boş hem de tam yükle dolu olan şok dondurucular için deneysel ve CFD hesaplamaları yapılarak elde edilen sonuçlar birbiriyle karşılaştırılmıştır. Deneylerden ve analizlerden elde edilen sonuçlar, kabin duvarlarına yaklaştıkça kabin içindeki sıcaklığın arttığını göstermektedir. Boş ve tam dolu dondurucular için maksimum hızlar sırasıyla 31,1 m/s ve 26,9 m/s olarak elde edilmiştir. CFD ve deneysel modeller arasındaki ortalama farklılık -0,7 °C olarak hesaplanmıştır. Bu durum da, simüle edilen ve gerçek sonuçlar arasında yakın bir uyum olduğunu gösterir.

1. INTRODUCTION

The most common methods of food preservation are drying, salt brining, canning and cooling. However, losses in nutritional values are quite high in both drying, brine, or canning processes. For these reasons, the cooling method is the most effective method in terms of applicability to many foods, preservation of nutritional/quality values, and ease of application. The most efficient cooling system within today's technological possibilities is deep-freezing technology [1]. Blast Freezer, which are used for rapid cooling of cooked food without losing their nutritional value and preventing bacterial growth, have gained importance in the food industry in many countries in recent years [2].

Although its use is compulsory in many countries, especially in the European Region, due to health-related regulations, the number of global manufacturers in this field is insufficient. The development of designs for homogeneous temperature distribution in the cabinet is a subject that has been studied intensively. It is seen that the temperatures are higher in the upper parts of the freezer as a result of the downward movement of the cold air and the rise of the warm air [3]. The inhomogeneous temperature distribution in the freezer decreases the performance of the freezer and increases energy consumption. Fans are used to provide homogeneous temperature and airflow in the freezer [4]. In addition, the distribution of velocity vectors at the front and rear of each fan and temperature changes in the blowing directions are important issues [5]. Analyzing the fans correctly within the scope of numerical methods and obtaining the CFD results is a very important work base.

CFD analyzes were made using different parameters for freezer cabinet design by Pakdil [6]. In addition, the experimental setup was set up and the results were compared. In this study, the position of the coldest packages was determined and the parameters affecting the temperature in the freezer cabinet were examined. Dempsey and Bansal (2012) determined with their CFD analysis that the blowing direction in double fan blast freezers has a great effect on the cooling efficiency of the food in the freezer cabinet [2]. They also saw that the distance of the evaporator from the fans is a very important factor in Blast Freezer designs. They concluded that the distance between the fan and the evaporator is a parameter that prevents frost in unnecessary places. Alonso and Andersen (2011) investigated the exit of the flow from the evaporator and its circulation in the cabinet in horizontal type freezers. In this study, they also investigated the effect of the distance between the walls and the evaporator on the velocity of the flow. As a result, they determined that the flow at the wall edge has a high velocity [7]. Shih et al. (2011) conducted numerical analyzes on the heat transfer of the air passing over the evaporator in a conventional freezer [8]. It aimed to make improvements in energy consumption by increasing heat transfer performance. They used turbulent kinetic energy equations in their analysis. As a result, they saw that the heat transfer rate decreased along the path of the air. Chourasia et al. (2007) investigated the heat transfer and moisture loss in the freezer in order to preserve the potatoes chosen as food without spoiling in their study [9]. The study was carried out both experimentally and numerically. Assuming that the airflow inside the cooler remains constant, the airflow is stated as a steady-state. Numerical analyzes were performed using a 2D model. In the results of the numerical analyzes, the average temperature value was achieved with a difference of 0.5 °C compared to the experimental study results. In addition, the moisture loss obtained with the numerical solution is 0.61% higher than that obtained with the experimental results. Amara et al. (2008) investigated the hydrodynamic boundary layer thickness formed during natural convection in a domestic freezer and the flow movements of vertical walls depending on the boundary conditions [10]. For this, they made both experimental and numerical analyzes. They used the PIV (Particle Image Velocity) technique for the experiments. While doing the numerical solution, they created the simulation of the cabinet with Fluent software. They used the global heat transfer coefficient for the walls in the analyzes where the outside temperature was considered constant. They also have laminar airflow dissolved because it dissolves natural convection. In the model he built by ignoring the evaporator, they defined a constant temperature on the back wall where the evaporator is located and provided cooling inside the cabinet from this wall. They defined these temperatures as -10 °C and 0 °C, respectively, based on the experimental data of the compressor running and stopping times. As a result, the results of the 3D simulation and experimental study were close to each other. Ding et al. (2004) explored the correlation between the temperature dispersion within the freezer and the spatial dimensions, specifically the gap separating the shelves from both the evaporator and the door. p[11]. They made both experimental and numerical analyzes for these two different cases. The first of the models he established is the model in which natural convection is dominant, and the second is the model in which forced convection is dominated by the fan and air duct. Numerical analyzes were performed with Star-CCM+ software. As a result of the analyzes and experiments they have done, it has been seen that the shorter distances ensure that the temperatures in the cabinet are more regular.

Mirade et al. (2002) aimed to ensure that the airflow reaches all parts of the cabinet in a homogeneous state and to optimize the design in terms of energy efficiency [12]. In this study, a turbulence model was created with the finite volume method and CFD analyzes were performed. Lacerda et al. (2005) investigated the temperature distribution of a freezer against forced convection using CFD and experimental models [13]. The importance of this study is the comparison of the internal flow in the unloaded and full-loaded of the freezer. In the experimental study carried out by Poyraz (2011), the freezer compartment of a two-door freezer was examined [14]. The evaporator temperature and the airflow rate passed through the evaporator and blown into the cabin were selected as the parameters affecting the energy consumption. By determining the effect of these parameters on the freezer operating rate, energy consumption inference can be made. As a result of the experimental studies, it was determined how the evaporation temperature and the airflow rate affect the freezer energy consumption. Rodezno et al. (2013) examined the effect of a blast freezer in the food mass center in their study [1]. Experimental analyzes were carried out in this study. The refrigerant in the first experiment was helium and the refrigerant in the second experiment was air. As a result of these experiments, in the analyzes made on fish, the loss of weight of the meals was measured in a lower amount when air shocked and based on the results, it was determined that shock freezing with air was much more efficient.

Within the scope of this study, fan, outer construction, and insulation group designs were made for a blast freezer to increase the air circulation inside the cabinet. Then, cooling analyzes were carried out with the CFD technique. Blast freezer systems are produced with a very different technical infrastructure compared to conventional freezers. In this context, the most basic difference compared to existing freezers is that the temperature of the food mass center can be reduced from 100 ^{o}C to -18 ^{o}C in 270 minutes. The main feature that distinguishes this study from the previous literature is that it examines the turbulent flow formed by the effect of fans in the numerical analysis of the study and shows how efficient this flow is in terms of design. The results of data logger measurements and climate chamber tests, which were used as experimental methods, were used to verify the numerical results of the model. The data logger records all the desired or undesired changes of the device in one minute intervals. In these studies, with the help of data loggers, temperature measurements of the packages in the freezer were recorded in one minute intervals during the experiment. Following the numerical analysis, peak velocity magnitudes of 31.1 m/s and 26.9 m/s were identified for the empty and fully-loaded freezers, respectively. Regarding freezer temperature, the mean deviation between the Computational Fluid Dynamics (CFD) and experimental models was calculated at -0.7 °C. This shows that the data obtained from the CFD analysis are compatible with the experimental results.

In the material and methods section of the paper, information about the working principle of the blast freezer is given and the details of the experiment conducted for this study are mentioned. In the numerical method section, numerical analyses were performed for the designed blast freezer. Firstly the geometries to be used in the analyses were drawn and then the mesh process was performed. Detailed information was given about the quality of the created mesh structure and the boundary conditions used in the analyses were mentioned. In the Results section, the data obtained from CFD analyses and experiments were examined comparatively. These examinations were made separately for 60, 120, 180 and 240 minutes. In the Conclusions section, the important data obtained from this study are interpreted briefly.

2. MATERIALS AND METHOD

2.1. Working Principle of Blast Freezer

The cooling process in a freezer is provided by the thermodynamic refrigeration cycle. The basic principle in the blast freezer is to increase the convection heat transfer coefficient with the fan power and thus to provide rapid heat transfer [15]. A classical thermodynamic refrigeration cycle has four main elements. These are evaporator, compressor, condenser, and capillary tube [16]. The air supply system in blast freezer cabinets consists of fans. The fan in the freezer used in this study sucks the air inside the cabinet from inside and sends it to the area where the evaporator is located. The air-cooled in the area where the evaporator is located is given back into the cabinet from the sides and thus the packages are cooled [17]. One of the advantages of blast freezers is that the frost-icing phenomenon seen in conventional freezers does not occur.

The passing of the air over the evaporator by the force of the fan ensures that the frosting event does not appear. In this way, bad appearance and volume shrinkage due to snow and icing in the cabin are prevented [18].

2.2. Preparation of the Experiments

Energy consumption in freezers should be measured under certain standards. These standards have contents such as ambient temperature, cabinet position, and placement of packages. Freezers are tested in climate chambers in order to keep the temperature of the environment tested at the desired. After the freezer is taken into the experiment room, packages of different sizes representing the food are placed according to the cooling capacity. According to the standard of the European Union numbered EN 16825:2015, the distance between the sidewalls of the blast freezer and the walls of the experiment room is set to a minimum of 150 cm. The sensors measuring humidity and temperature were placed at a distance of 50 cm from the walls of the experiment room, and radial fans have been used on the side walls to distribute the temperature and humidity homogeneously. In addition, with the use of the data logger, the temperatures of each package have been measured in an unlimited range. Data loggers are devices that can record information according to pre-set time intervals. Data logger device keeps all desired or undesired changes in its memory every one minute. In these studies, the core temperature of the 14 packages has been measured once every minute. The measuring range of the device is between -30 and +190 °C. There are 14 shelves in the blast freezer used in the experiment, and a 1 kg package is placed on each shelf. The experimental arrangement is depicted in Figure 1 and 2, illustrating the configured setup for the study.

Figure 1. The blast freezer

Figure 2. Placing the packages into the blast freezer

3. NUMERICAL METHODS

The results obtained from the experiments for blast freezers have been compared with the CFD analyzes. Figure 3 shows the CAD model of the interior of the cabinet. The model has been prepared with the SolidWorks program. Since it would be difficult to create a numerical solution network for the CAD model, the model has been simplified, and the analysis model is shown in Figure 4. After it has been combined with the fans that were also modeled. The interior dimensions of this cabinet are 67.5×68.1×107.8 cm. The thickness of the side, rear and upper walls is 6 cm and the thickness of the lower wall is 14 cm. The insulation material is polyurethane in 0.5 mm stainless steel. In the analysis model, 3 axial fans with 40 cm diameter and 5 blades have been used. Then, package models representing the food have been created in accordance with the package layout plan.

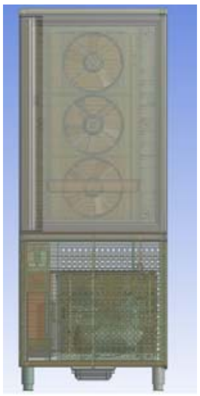

Fig. 3. CAD drawing model of blast freezer

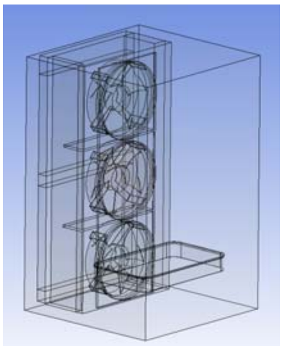

Figure 4. CAD simplified model of blast freezer

3.1. CFD Application for Unloaded Blast Freezer

In conjunction with the cabin featuring airflow volume, the air supply system has been meticulously modeled. Notably, the fan has been intricately incorporated into the air supply system model, whereas the fin elements on the evaporator have been excluded from the modeling process. This is because these elements are very small in size. In this study, with the rotation of the fan, the airflow velocity in the cabinet and the cooler performance of the cabinet have been investigated. Ansys Fluent V16 [19] commercial software has been used to create the mesh file and to perform the numerical solution. The mesh structure of the evaporator region has been formed from hexahedral grids and is shown in Figure 5.

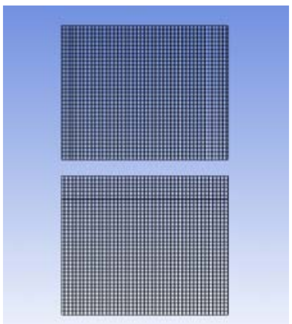

Figure 5. The mesh zone of the evaporator (rear view)

Due to the complex geometry of the fan and the high velocities around it, it is aimed to create cells with a lower skewness value in this region. Since the fan blades are very thin, superficial celling is done instead of volumetric celling. A volume has been created to only contain the fan, and this volume has been determined as the “moving reference frame”. With this method, the rotation of the fan is simulated. All of the grid cells created in all the fans are of a tetrahedral type and the mesh zone is shown in Figure 6. In addition, the size of the fan surface and the surrounding elements is given as 0.8mm, which will be lower than the other regions.

Figure 6. The mesh zone of the [19]

The main criterion in determining the quality of the solution mesh of the model is the skewness value. The high skewness value creates the risk of making wrong solutions. On the other hand, in Fluent software, this value should not be greater than 0.95 for a solution to be made. As seen in Table 1, in this study, there were no cells with skewness in the range of 0.9-1.0, which is the maximum critical range. The highest skewness is 0.863 and is located in the fan region. In this case, it can be said that the solution network is of good quality.

Table 1. Distribution of the number of elements according to the skewness value

Skewness range	Number of elements	Percent
0 ------ 0.1	1314205	31.12
0.1 ------ 0.2	374623	8.87
0.2 ------ 0.3	675552	16
0.3 ------ 0.4	1054824	24.98
0.4 ------ 0.5	424808	10.06
0.5 ------ 0.6	248883	5.89
0.6 ------ 0.7	109773	2.6
0.7 ------ 0.8	19514	0.46
0.8 ------ 0.9	44	0
0.9 ------ 1	0	0

After the mesh file created for this study is finished, a thorough assessment of orthogonal alignment has been carried out to confirm its accuracy. The precision and fluidity of the geometric relationships between the mesh network's parts are referred to as the orthogonal quality. An increased orthogonal quality indicates better element alignment and a more seamless connection [20]. This, in turn, establishes a foundation for more exact and dependable analytical outcomes. Within the domain of finite element analysis, orthogonal quality is important since a poor mesh network can lead to erroneous conclusions and forecasts. To clarify, a mesh network with low orthogonal quality could ignore or distort important information like load distribution or stress concentration. Closeness to 1 in the maximum values denotes an excellent orthogonal quality, suggesting that the pieces connect at around 90-degree angles [21]. This closeness to unity is a desired quality for accuracy in findings, highlighting the significance of well-connected element surfaces. Table 2 provides the orthogonal quality range values of the generated grids.

Table 2. Distribution of the number of elements according to the orthogonal quality value

Orthogonal quality range	Number of elements	Percent
0 ------ 0.1	0	0
0.1 ------ 0.2	0	0
0.2 ------ 0.3	0	0
0.3 ------ 0.4	0	0
0.4 ------ 0.5	0	0
0.5 ------ 0.6	109777	2.6
0.6 ------ 0.7	870623	20.62
0.7 ------ 0.8	1111712	26.33
0.8 ------ 0.9	1221912	28.94
0.9 ------ 1	908201	21.51

The mesh file created for the blast freezer model exhibits an appropriate orthogonal quality range of its grids when Table 2 is examined.

In the CFD analysis, air was selected as the working fluid for the blast freezer. The reason is harmless to the environment and safer than other refrigerants. At the same time, the cost of air is much cheaper than other working fluids. The physical properties of air are provided in Table 3.

Table 3. Properties of the air

Properties	Value
Density	1.177 (kg/m3)
Specific heat capacity	1004 (J/kg.K)
Thermal conductivity	0.02625 (W/m.K)
Dynamic viscosity	1.845E-05 (kg/m.s)

4.2 million grids have been used to create the entire mesh structure of the blast freezer. The mesh structure is shown in Figure 7. The computer used in the analysis is eight-core, its processor is Intel Core i7 and its speed is 3.70 GHz.

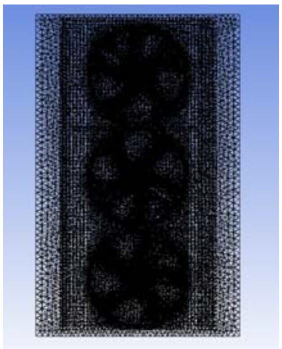

Figure 7. Mesh structure of unloaded blast freezer

Real experimental conditions are given as boundary conditions in the solution method of the models. The following Navier-Stokes equations are used in this technique. In the next steps, Energy equations have been used for temperature analysis. k-ε realizable is used as turbulence model. In this model, "k" denotes the kinetic energy of the turbulence, and "ε" denotes the propagation of the turbulence. In order to obtain more precise results in CFD analysis, the second-order upwind spatial method is generally preferred. In this study, the first-order upwind spatial method has been preferred to save solution time. At the beginning of this study, two methods have been tried separately and it has been seen that there was no difference between the results. For this reason, there has been no problem in using the first-order upwind spatial method to spend less time on solutions. The equations of the turbulence model are as follows.

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \tag{2}$$

$$C_1=max\left[0.43,\frac{\eta}{\eta+5}\right] \tag{3}$$

$$\eta=S\frac{k}{\varepsilon} \tag{4}$$

$$S=\sqrt{2S_{ij}S_{ij}} \tag{5}$$

1500 rpm, which was measured in the experimental results, has been accepted as the number of revolutions of the fan. In addition, the sidewalls, the walls of the place where the blast freezer is located, and the upper and lower sides are applied as boundary conditions. For this, the side, rear, and upper walls have been applied as a boundary condition with a 6 cm insulation and a 14 cm insulation for the lower wall. The outdoor temperature has been taken as +35 °C as in the experimental analysis. Since the analysis aims to measure the cooling status at the end of the 60, 120, 180, and 240 minutes periods of the blast freezer, it has been run depending on time. The transient scheme has been used in Fluent.

3.2. CFD Application for Full-loaded Blast Freezer

Package models representing foods have been created in accordance with the package layout plan and the properties of the materials have been applied to the CFD program as a boundary condition. The dimensions of the packages are shown in Figure 8 and their placement in Figure 9.

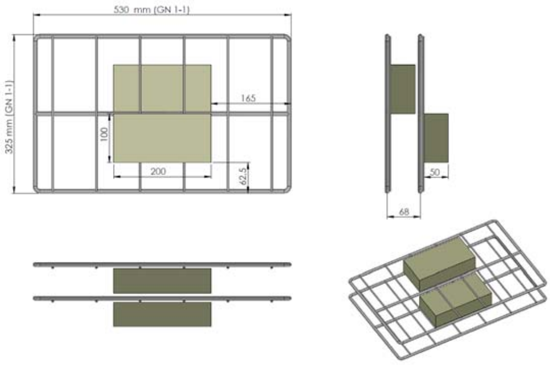

Figure 8. CAD drawing of packages tested

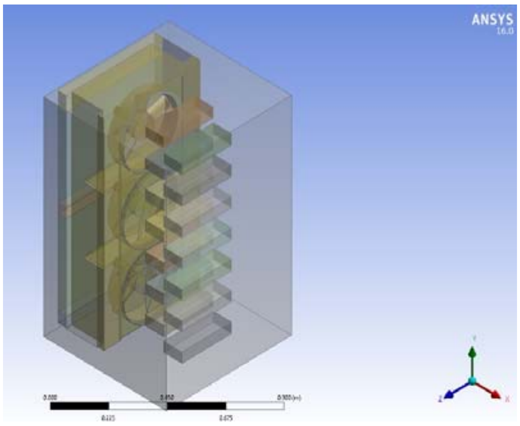

Figure 9. Simplified solid model of blast freezer with full loaded package

The mesh structure and boundary conditions for the model are presumed to be consistent with those utilized in the analysis of the unloaded freezer. The mesh structure used in the analysis is shown in Figure 10.

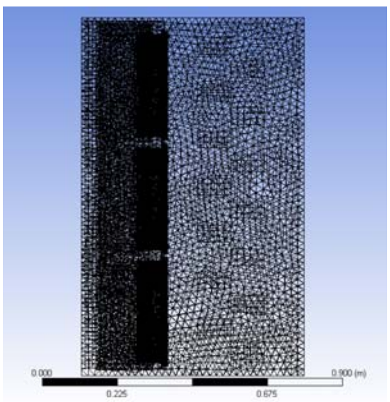

Figure 10. Mesh structure of full loaded blast freezer

4. RESULTS

4.1. CFD Application for Unloaded Blast Freezer

The rotation of the fan has been investigated in the analysis. Depending on the rotation direction of the motor, the fan rotates counterclockwise when viewed from the opposite side of the cabinet. As seen in Figure 11, the flow has been more intense around the fans. Especially in the middle fan, it is more concentrated than the other fans. This is because the middle fan is open from both sides (top and bottom). In the analyzes made, it has been observed that the region with the highest air flow rate has been the region of the middle fan. In this region, the velocity reaches 31 m/s.

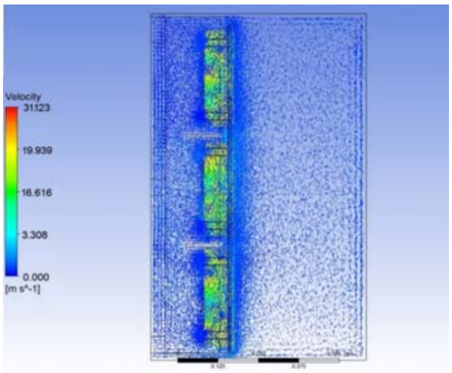

Figure 11. Velocity distribution in the unloaded blast freezer

4.2. CFD Application for Full-loaded Blast Freezer

In the analyzes made, it has been observed that the region with the highest air flow rate has been the fan region. In this region, the velocity reaches 26 m/s. The effect of counterclockwise rotation of the fan is observed in Figure 12.

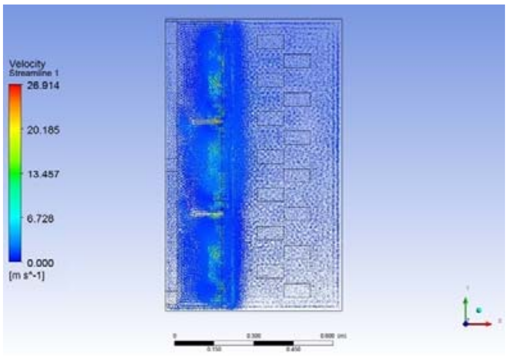

Figure 12. Velocity distribution in the full loaded blast freezer

Tables 4 and 5 show the maximum velocity distribution in the X, Y, and Z directions at the outlet and inlet points of the middle fan. The velocity value at the outlet of the fan has been calculated in the experimental analysis.

Table 4. Maximum velocity components at the outlet of the middle fan

Velocity in the X direction	Velocity in the Y direction	Velocity in the Z direction
24.5 m/s	8.8 m/s	4.3 m/s

Table 5. Maximum velocity components at the inlet of the middle fan

Velocity in the X direction	Velocity in the Y direction	Velocity in the Z direction
6.6 m/s	2.1 m/s	1.8 m/s

Another issue examined in the study is the temperatures of the packages in the blast freezer. The temperature distribution of the packages observed in the experimental study is shown in Table 6. The initial temperatures are the values measured for the packages at the moment the blast freezer starts operating. The final temperatures are the values measured from the packages when the blast freezer stops. In addition, the temperature is recorded every 60 minutes. Temp1 denotes the temperature of the package positioned on the uppermost shelf of the freezer, whereas Temp14 signifies the temperature of the package located on the lowest shelf.

Table 6. The temperatures of the packages taken from every 60 minutes in the experimental results

Package number	Initial temp. (°C)	60 min. (°C)	120 min. (°C)	180 min. (°C)	240 min. (°C)
1	71.1	0.2	-27.6	-35.8	-36
2	69.2	0.3	-27.4	-35.4	-36
3	69.8	0.2	-27.6	-35.8	-36.9
4	71	0.3	-27.4	-36	-36.8
5	69.9	0.2	-27.4	-36.1	-37.1
6	75	0.4	-27.6	-36.7	-37.4
7	75.5	0.2	-27.8	-36.8	-37.7
8	74.2	0.3	-27.4	-36.4	-35.9
9	76.1	0.4	-27.6	-35.9	-36.7
10	75.3	0.3	-27.3	-35.8	-36.9
11	77.8	0.4	-27.4	-35.8	-36.9
12	76.6	0.3	-27.4	-36.1	-36.4
13	78	0.4	-27.4	-36.2	-36
14	78.2	0.4	-27.4	-35	-35.4

When the experimental results are examined it has been observed that the package on the bottom shelf is the hottest and the package on the middle shelf is the coldest. Similar results have been also found in CFD analysis. In the packages located on the middle shelves, more cooling has been observed with the effect of both the middle fan and the lower and upper fans. The CFD results of the same situation are shown in Table 7. A comparison of experimental and CFD results is shown in Table 8.

Table 7. The temperatures of the packages taken from every 60 minutes in the CFD results

Package number	Initial temp. (°C)	60 min. (°C)	120 min. (°C)	180 min. (°C)	240 min. (°C)
1	71.1	0.0	-28.6	-37	-37.1
2	69.2	-0.1	-28.4	-36.5	-37.3
3	69.8	0.0	-28.6	-36.8	-37.6
4	71	0.1	-28.2	-36.8	-37.7
5	69.9	0.0	-27.9	-37	-37.8
6	75	0.0	-28.1	-36.2	-37.8
7	75.5	-0.2	-28.9	-37.1	-37.9
8	74.2	-0.1	-28.2	-36.9	-36.7
9	76.1	0.1	-28.5	-36.7	-37.7
10	75.3	0.1	-28.4	-36.9	-37.3
11	77.8	-0.1	-27.9	-36.2	-37.7
12	76.6	0.1	-28.1	-36.9	-37.5
13	78	0.3	-28.2	-36.9	-36.9
14	78.2	0.2	-28	-36.2	-36.4

Table 8. Comparison of experimental and CFD results

Package number	60 min. ΔT (°C)	120 min. ΔT (°C)	180 min. ΔT (°C)	Final temp. ΔT (°C)
1	0.2	1	1.2	1.1
2	0.4	1	1.1	1.3
3	0.2	1	1	0.7
4	0.2	0.8	0.8	0.9
5	0.2	0.5	1.5	0.8
6	0.4	0.3	0.5	0.1
7	0.4	1.1	0.3	0.5
8	0.4	0.8	0.5	1.1
9	0.3	1.1	0.8	1
10	0.2	1.1	1.1	0.4
11	0.5	0.5	0.4	0.8
12	0.2	0.7	0.8	1.1
13	0.1	0.8	0.7	0.9
14	0.2	0.6	1.2	1

Upon scrutinizing the average temperatures of the packages, it is evident that congruent outcomes are observed in the CFD results. The examination of individual packages reveals an average discrepancy of approximately 0.7 °C between the experimental and CFD results. This implies a close alignment between the CFD and experimental outcomes, thereby instilling confidence in the reliability of the CFD methodology. Consequently, the potential to predict blast freezer results without resorting to experimental procedures is feasible, achieved by manipulating boundary and initial conditions within the CFD analysis. Figures 13, 14, 15, and 16 visually present the package results derived from both experimental and CFD analyses at the conclusion of each 60-minute interval, distinctly showcasing the proximity of results obtained from both methodologies.

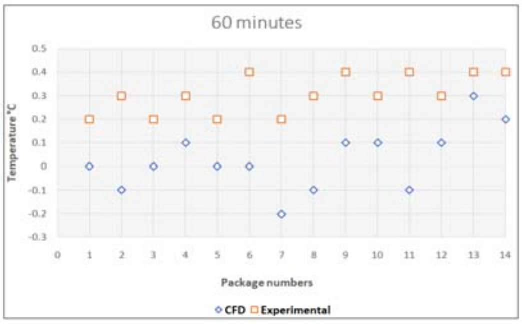

Figure 13. Comparison of experimental and CFD results (after 60 minutes)

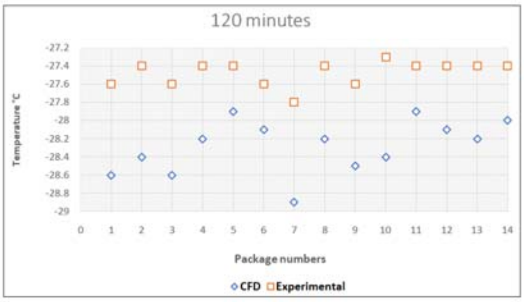

Figure 14. Comparison of experimental and CFD results (after 120 minutes)

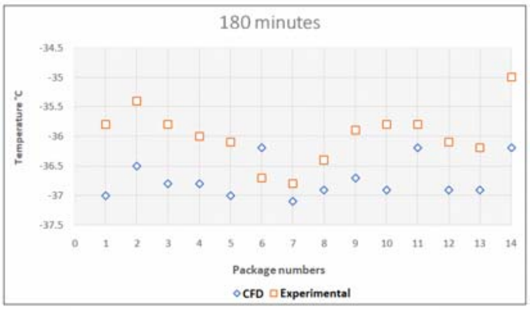

Figure 15. Comparison of experimental and CFD results (after 180 minutes)

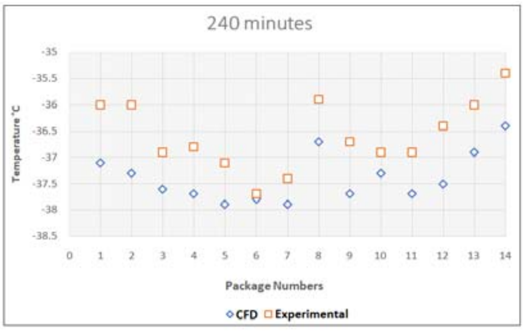

Figure 16. Comparison of experimental and CFD results (after 240 minutes)

5. CONCLUSIONS

This investigation involved a comparative analysis between numerical simulations and experimental findings for a blast freezer. A comprehensive CAD model of the blast freezer was developed, and its simplified version was subjected to Computational Fluid Dynamics (CFD) analysis. Airflow patterns were examined in the unloaded blast freezer, revealing the highest airflow velocity at the fan outlets. Subsequently, the blast freezer was loaded with one package on each of the 14 shelves, and a new mesh was generated. The mass, momentum, and energy equations were then solved to address the heat transfer problem. The resulting maximum temperatures of the packages were compared with experimental data. Notably, the temperatures obtained through CFD analyses were, on average, 0.6 °C lower than those observed experimentally. Given the negligible nature of this difference, the validity of the CFD analyses was affirmed. Future extensions of this research could involve employing different turbulence models for further analyses.

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