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Study of Honeycomb Air Curtain for a Freezer Room to Enhance Protection against Warm Air Infiltration

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ABSTRACT

The objective of this research is to present the energy-saving effect of applying an air curtain to prevent the penetration of warm air through a freezer door. Retail business is highly competitive in many aspects, including the factors affecting the cost of the store. The most important cost for many businesses is the cost of supplying energy to refrigeration systems. Therefore, the operator must try to reduce the energy consumption of the freezer room. Normally, a freezer room consumes cooling energy when its door is opened for the loading and unloading of goods, leading to the infiltration of warm air from outside. For this reason, we conducted experiments in which air curtains were used. We compared two types of air curtain grille: Common and honeycomb. The experiment was designed to assess whether the honeycomb grille could provide a stronger air curtain and more effectively prevent the penetration of warm air. For the experiment, we used a freezer with a temperature of −25 ◦C. The freezer room door measured 200 × 100 m^2 and an air curtain was installed 5 cm above the outer freezer door. The velocity of the air curtain was 6.5 m/s. Simulations were carried out using solid workflow simulation software. The changes in temperature and air velocity were simulated in the room, considering three scenarios: Type 1: Leaving the freezer door open for 1 hour without the air curtain operating. This resulted in warm air inflow at the top of the door and cold air outflow at the bottom of the door. When a steady-state was reached, the room temperature was 6.05 ◦C. Type 2: Leaving the freezer door open for 1 hour, using an air curtain with a common grille to prevent the infiltration of warm air. The results showed that an air curtain could prevent the infiltration of warm air. The outside air tries to push through the air curtain, which can be seen from the curvature of the air curtain line in the model. When a steady-state was reached, the room temperature was −2.41 ◦C. Type 3: Leaving the freezer door open for 1 hour, using an air curtain with a honeycomb grille to prevent the infiltration of warm air. The honeycomb grille air curtain was slightly better at preventing the infiltration of warm air than the common grille. There was less curvature in the air curtain line, which means that the strength of the air curtain is greater. When a steady-state was reached, the room temperature was −2.64 ◦C. In conclusion, the results demonstrated that the honeycomb grille air curtain can prevent the infiltration of warm air 9.54% better than the common grille air curtain.

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1. Introduction

The modern retail industry is highly competitive, and retail stores are generally expensive to operate; particularly in terms of cooling power. Therefore, researchers have sought to find ways to save energy in this area; for example, through the development of environmentally friendly and energy-saving refrigerants, the development of glass doors to save energy for open freezer rooms, Finding the optimal thickness of Rockwool insulation to reduce the cooling load inside the building [1]. The use of loofah with good wetting ability of loofah as a cooling medium and high thermal conductivity of the heat transfer heat pipe [2], and the adoption of digital scroll compressors to enhance compressor performance. Figure 1 shows an energy bill breakdown for 30 convenience stores in Taiwan. It can be seen that most energy is used for the cooling and air conditioning systems. There are many reasons for this, including goods being brought into the cold storage, refrigerators being subject to high temperatures, customers entering the store, electrical equipment inside the store, and infiltration of warm air from the ambient environment.

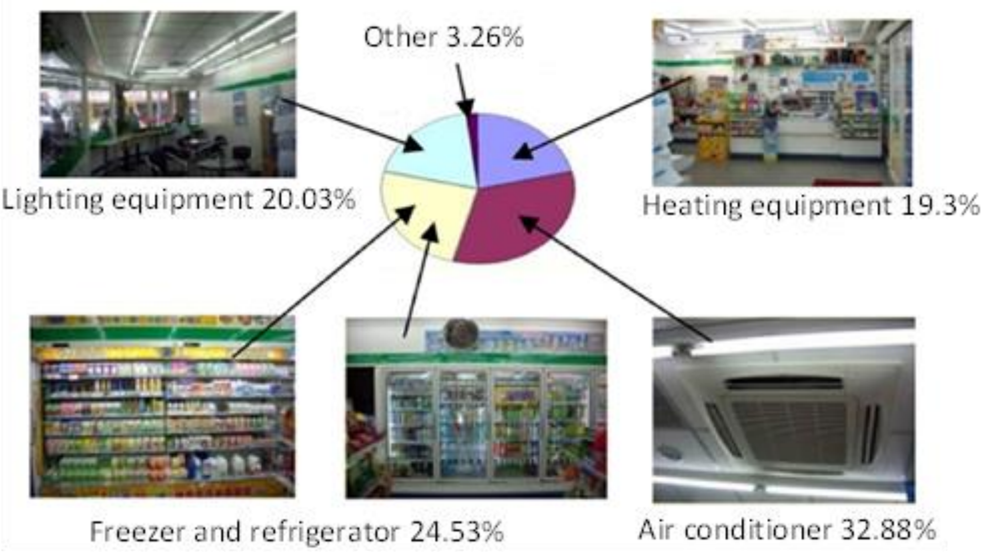

Fig. 1. Proportion of energy consumption in convenience stores in Taiwan [3]

There are three types of large retailers in Thailand: Department stores, discount stores, and supermarkets. The number of these large retailers exceeded 1000 in 2019, and continues to grow every year. The use of cooling energy in these stores increases with the size of the store, and the most energy-intensive stores typically require large refrigerators and freezers for food storage. One of the reasons for such high energy consumption is cooling losses due to the opening of freezer doors, which can lead to more heat entering from the outside. Therefore, more cooling energy is needed to recover the lost temperature. It has been experimentally determined that the penetration of warm air through the door accounts for approximately half of the total cooling load in the freezer room [4-9].

To prevent the high energy consumption problem arising from the infiltration of warm air, operators can install a strip curtain on the door. However, the loading and unloading goods can cause the curtain to be torn, and dirt can accumulate on the curtain or curtain rod. Therefore, strip curtains are rarely suitable for use as a protective curtain for freezer rooms.

Instead, air curtains should be used to prevent the infiltration of hot air. When an air curtain is installed, it can save up to 48% energy, compared to when no air curtain is used. Conventional grille air curtains can cause air to disperse laterally, leading to a loss of air velocity and possibly causing the air curtain to create a warm airflow. Conventional grilles are not very good at organizing the air blowing out of the air curtain. In this study, an experiment was conducted using a honeycomb grille, and collecting data to compare the effectiveness of protection against warm air infiltration by two grille types (i.e., common and honeycomb).

Much research has been conducted on the ability of air curtains to prevent temperature exchanges between the inside and outside environments in open showcase-type freezers. The infiltration of warm air is affected by the wind speed, wind angle, and height of the room [10], the prevention of which can prevent dust or germs from entering the room. Air curtains have many applications, such as in freezer rooms, shopping mall entrances, refrigerated cabinets, diagnostic rooms, and refrigerated trucks. Figure 3 shows an experiment involving the use of a guide bar installed in front of the shelf in an open showcase-type freezer. It is important to ensure that the air curtain does not spread out to the side and, in doing so, better air direction and velocity can be achieved; that is, the air curtain will be stronger. The use of an air-guide bar has resulted in a decrease in average cabinet temperature from 4.7 °C to −0.2 °C and a 34% reduction in cooling power [11], indicating that if an air guide band is applied to an air curtain, it should be able to increase the efficiency of the air curtain. Alternatively, the experiment presented in Figure 4 compares the installation of air curtains in refrigerated trucks, considering installation inside or outside of a refrigerated truck. The results showed that installing an air curtain outside the refrigerated truck can prevent the infiltration of warm air more effectively than when installing it inside. Outside the refrigerated truck, warm air is trying to enter; if an air curtain is installed outside [12], it can more effectively prevent the inflow of outside air. Many researchers have experimented with air curtains to understand them in more detail. In this study, when air curtains were installed on freezer trucks, energy savings of up to 48% could be achieved [13]. The speed of the air curtain suitable for a door height of 2 m during the first 30 seconds was 5 m/s [14], and the angle of the air curtain grille between 0° and 10° was chosen for the study. When the angle of the grille was facing out at the room at 10°, with a wind speed of 4 m/s, 17.6% more energy could be saved [15,16]. From Figure 2, at a height of 1200 mm with respect to the cabinet opening, a wind speed of 2.6 m/s prevented the air curtain from breaking [17]. Suitable locations for air curtain installation for a 1.36 m-high door for a freezer room at 3 m/s air curtain velocity and 0° angle have been examined. During the 30 s door opening period [18], the air curtain line did not bend into the freezer room. Changes in the open showcase-type freezer temperature emitted by the curtain did not affect the infiltration of warm air [19]. A previous study found that the cold loss caused by opening the freezer room door in industrial plants can be avoided through the use of an air curtain to prevent the infiltration of warm air [20].

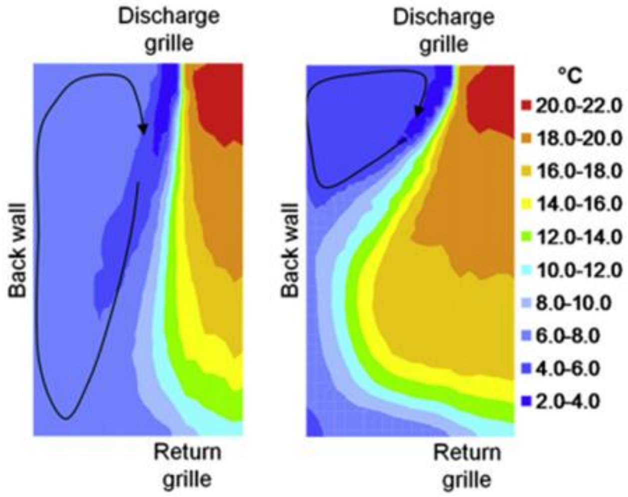

Fig. 2. Measured temperature profiles through central section of a cabinet with 1200 mm high curtain and 70 mm discharge air grille width. Left: A sealed curtain with 2.6 m/s discharge velocity. Right: A broken curtain with 1.7 m/s discharge velocity. Arrow denotes air circulation within the cold cavity [17]

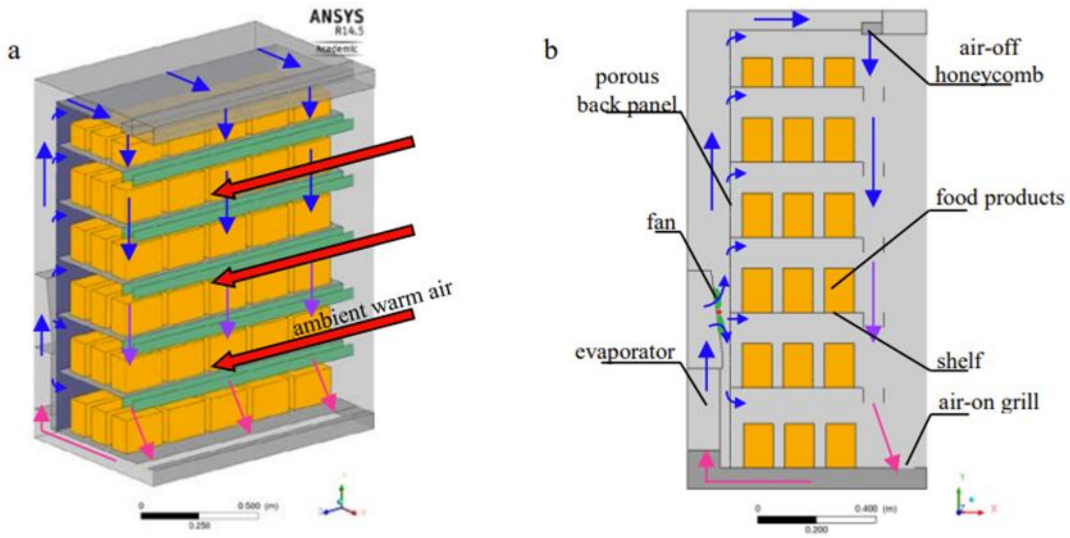

Fig. 3. Structure of a refrigerated cabinet: (a) 3D structure; and (b) 2D structure [11]

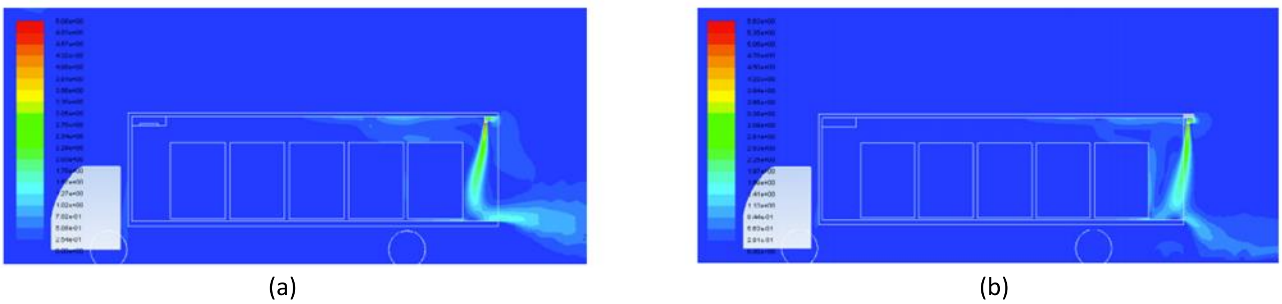

Fig. 4. Velocity contours with an air curtain placed (a) inside or (b) outside of a refrigerated truck, with discharge velocity of 4 m/s. Mid-product view [12]

Figure 4 shows the results using CFD to visualize the temperature and airflow direction more clearly. CFD has been widely used in various studies—for example, in the simulation of synthetic jet cooling [21]—in order to visualize heat transfer more clearly. Alternatively, complex and costly solid oxide fuel cell experiments require dynamic computational fluid simulations. CFD has been used in many studies, including in an overview of computational fluid dynamics modelling in solid oxide fuel cells [22]. It can make it easier to see the flow through natural gas pipelines which are difficult to access [23]. Fluid aerodynamics have been simulated to assess the performance of various NACA airfoils [24]. It has also been used to simulate fluid dynamics, in order to check the performance of a double-stage Savonius rotor [25]. CFD has also been to find the optimal location to install a boat hydrofoil [26] and to visualize the heat transfer inside pipes [27]. Therefore, researchers have used CFD methods in simulation research to make subsequent testing easier and more accurate. Air curtains were previously used in experiments with cold room door openings to compare the presence and absence of air curtains. including finding the right wind speed [28]. The horizontal and vertical mounting positions were also tested to compare the infiltration performance. which horizontal is more effective However, no experiments have been conducted to compare the grille of the honeycomb air curtain [29].

2. Methodology

The aim of this study was to simulate warm air infiltration events in a freezer room, using an air curtain mounted above the outer freezer door to prevent internal and external temperature exchanges. But a conventional grille still can't control the direction of the wind well. Warm air infiltration is still possible. The honeycomb grille is designed to reduce air dispersion. Therefore, the air grille used in the test was compared—namely, a conventional grille or a honeycomb grille—in order to see which is more effective at preventing the infiltration of warm air. The experimental air curtain was used in a Tesco lotus-type supermarket freezer. The freezer room temperature was in the range of −23 to −25 °C, and the outside room temperature was about 27 °C. The experiment was performed to simulate the infiltration of warm air, using CFD to establish the direction of wind flow and the temperature from the air curtain for ease of comparison. Three types of tests were performed: 1. A warm air infiltration test was performed by leaving the freezer room door open, but the air curtain would be turned off to determine the behaviour of the air flow without the air curtain. 2. A warm air penetration test was performed by leaving the cold room door open while using a conventional grille air curtain. 3. A warm air penetration test was performed by leaving the cold room door open while using a honeycomb grille air curtain. Once the tests were complete, all tests were compared and differentially analysed, in order to determine whether switching to a honeycomb grille could provide better protection against the infiltration of warm air.

2.1 Domain Geometry

As shown in Figure 5, the experiment was carried out in a back-store freezer with a rectangular shape of 3.3 m × 2.12 m × 2.8 m (L × W × H), with a wall thickness of 0.1 m on all sides of the freezer. The freezer door had dimensions of 2 m × 1 m. The air curtain in the experiment measured 1.05 m × 0.245 m × 0.209 m (L × W × H), with a weight of 14.8 kg. An Enclosure Class IP44 was mounted horizontally 0.05 m above the freezer door. The air outlet was 0.97 m × 0.06 m. The air velocity exiting the grille averaged about 6.5 m/s. An FCU was installed in the middle of the top of the wall behind the freezer, having a size of 1.28 m × 0.32 m × 0.32 m (L × W × H). Two 0.28 m diameter fans and a freezer were housed in the back stock, with dimensions of 35 m × 6 m × 6 m (L × W × H). The air velocity exiting the fan averaged about 3.5 m/s.

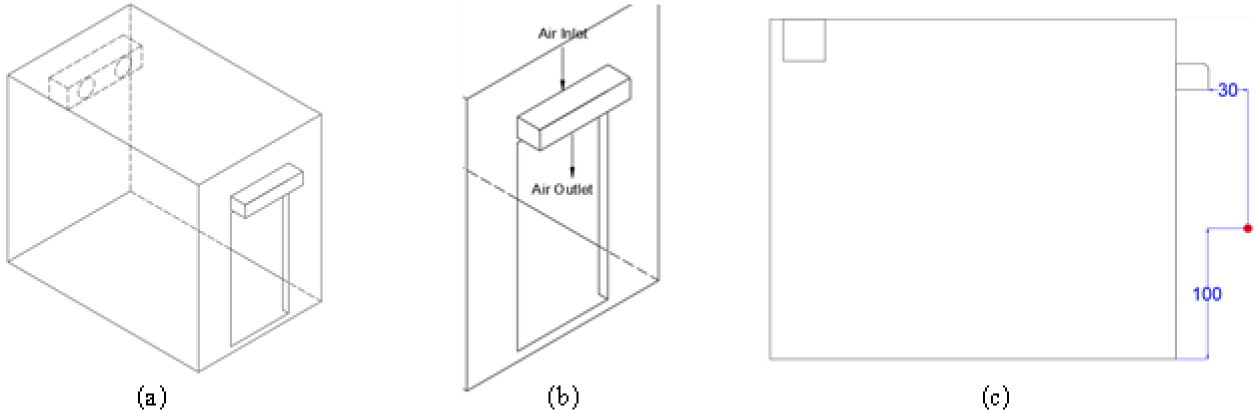

Fig. 5. (a) Dimensions of the freezer room; (b) location of air curtain; and (c) temperature measurement point outside freezer door

As can be seen in Figure 6, the typical honeycomb grille used in the test was a painted steel material 0.1 cm thick, comprising a total of 5 grids, each 85 cm long, with a distance of 1 cm between them, and a total of 4 sieve strips. All 5 grids were fixed perpendicularly. Each strip was installed 27 cm apart. The honeycomb grille featured an additional number of mounting strips. There were 33 pieces in total, each 3 cm apart. We anticipated that the addition of a grille mounting bar would reduce the turbulence of the wind coming out of the grille.

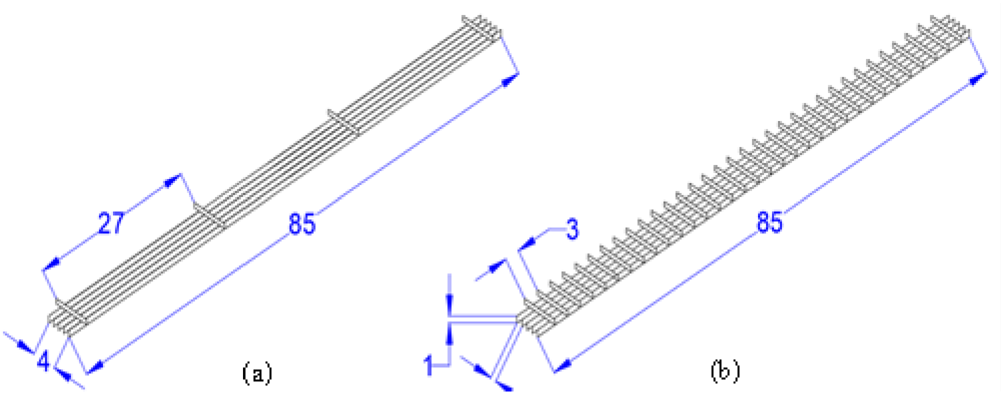

Fig. 6. (a) Dimensions of common grille (mm); and (b) dimensions of honeycomb grille (mm)

2.2 Requirements for CFD

The CFD event was simulated using the SOLIDWORKS flow simulation software, by creating a virtual freezer with an air curtain outside the room above the door to match the actual site. If the air curtain is installed inside the freezer, it can cause problems with the fan motor and set variables.

2.2.1 Numerical solution procedure

The SOLIDWORKS flow simulation program was used for CFD calculations and display. The model was created using ambient air-effect calculations with a temperature of 27 °C. The gravitational force was 9.81 m/s^2. It was defined in the negative Y-axis. Atmospheric pressure was defined as 1 Bar. We used the natural convection of a fluid, defined as air. The walls were insulated with polyurethane. We determined the size of the domain as 0 m from the floor, 2.5 m from the back wall, 3.5 m from the door, 2.5 m from the left and right walls, and 4 m from the top wall of the room.

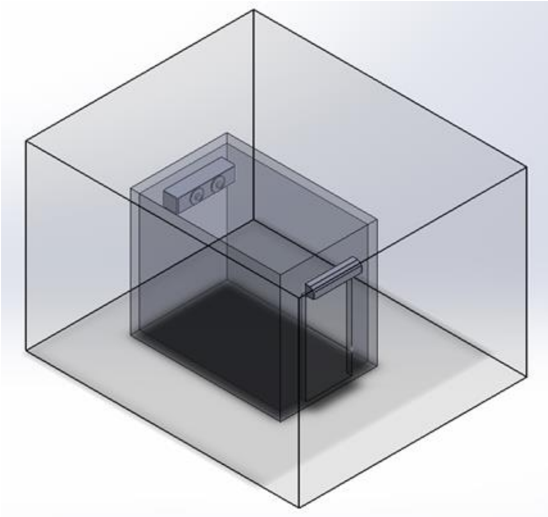

Fig. 7. Domain of flow simulation

2.2.2 Boundary, initial and test conditions

The FCU was installed behind the freezer with an air velocity of 3.5 m/s and an outlet temperature of −33 °C, and an air curtain was installed 5 cm above the entrance door to the freezer. The wind speed on the blowing side was 6.5 m/s. The air outlet temperature was −25 °C, and the temperature measurement point outside the freezer room was 100 cm above the floor and 30 cm away from the air curtain. The air curtain was initially closed, in order to simulate heat transfer without an air curtain. The air curtain was then set up to allow air to flow in at the top and flow out of the grille at the bottom. The wind that flows before the grille was tilted at an angle of 35°, in order to increase the visibility of the wind turbulence.

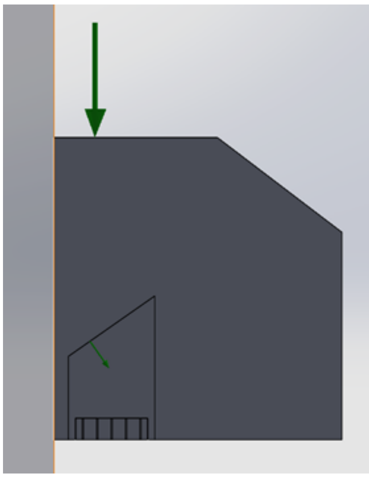

Fig. 8. Direction of air flow through the air curtain

The FCU was set up to allow air to flow in at the back and out of the fan at the front

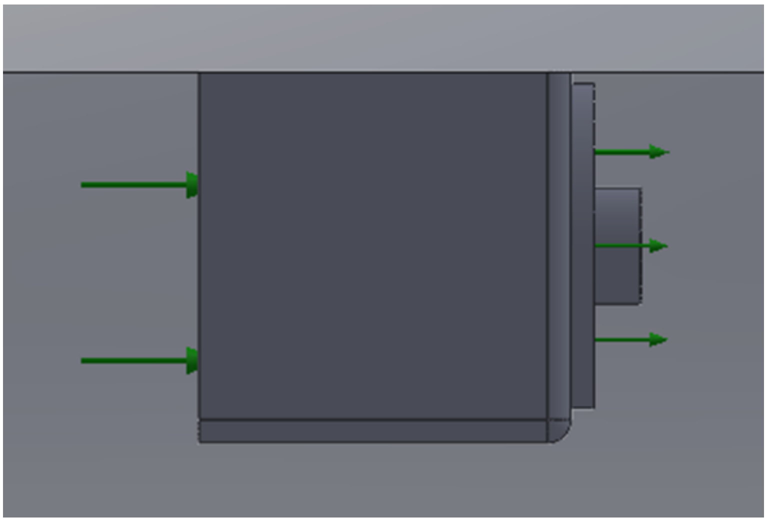

Fig. 9. Direction of air flow through the FCU

Next, we determined the flow rate of the air curtain and FCU. The form of the fan was a curve and the pressure difference was 0. The volume flow rate was calculated as follows:

$$Q = AV \quad (1)$$

Placing the Q value of a fan in an air curtain and the FCU utilized in a simulation must firstly determine the cross-sectional area and wind speed of the fan. The air curtain is defined as A = 0.0718 m2 and V =6.5 m/s, calculated as Q=0.4667 m/s3, shown on Table 1; while the FCU is defined as A = 0.1074 m2 and V =3.5 m/s, calculated as Q=0.3759 m/s3, shown on Table 2.

Table 1
The flow rate of the air curtain

A (m^2)	V (m/s)	Q (m^3/s)
0.0718	3.5	0.2513
0.0718	4	0.2872
0.0718	4.5	0.3231
0.0718	5	0.359
0.0718	5.5	0.3949
0.0718	6	0.4308
0.0718	6.5	0.4667
0.0718	7	0.5026
0.0718	7.5	0.5385
0.0718	8	0.5744
0.0718	8.5	0.6103
0.0718	9	0.6462
0.0718	9.5	0.6821
0.0718	10	0.718
0.0718	10.5	0.7539

Table 2
The flow rate of the FCU

A (m^2)	V (m/s)	Q (m^3/s)
0.1074	0	0
0.1074	0.5	0.0537
0.1074	1	0.1074
0.1074	1.5	0.1611
0.1074	2	0.2148
0.1074	2.5	0.2685
0.1074	3	0.3222
0.1074	3.5	0.3759
0.1074	4	0.4296
0.1074	4.5	0.4833
0.1074	5	0.537
0.1074	5.5	0.5907
0.1074	6	0.6444
0.1074	6.5	0.6981
0.1074	7	0.7518

2.2.3 Mesh independence

Meshing is the division of a workpiece into smaller geometric parts for use with existing formulas. Therefore, creating a mesh is very important. If we divide the workpiece poorly, the program may distort the shape that needs to be analysed, which can cause the analysis results to be wrong. The more refined the mesh, the more accurate the simulation [30, 31]; however, the suitability must be taken into account: if the mesh is set to have a high resolution, the resulting file will have a large file size.

2.2.3.1 Global mesh setting

As seen in Figure 10, we created a mesh that was used to calculate all common areas. In this task, the mesh was set to level 5. The characteristic number of cells across the channel was set to 5, the maximum channel refinement was set to level 3, and advanced refinement was set to level 1.

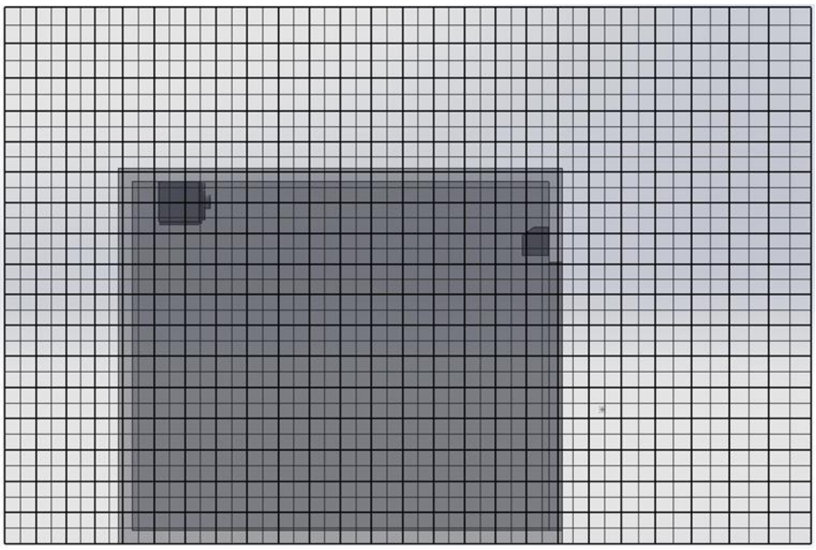

Fig. 10. Global mesh for freezer room

2.2.3.2 Local mesh

As can be seen in Figure 11 and 12, the mesh was more precisely defined in the moving region for higher computational accuracy. Local meshes were applied to the airflow in and out areas of the FCU and air curtain. The wind grille area, in particular, must have a high mesh resolution, for which we set equidistant refinement to level 7.

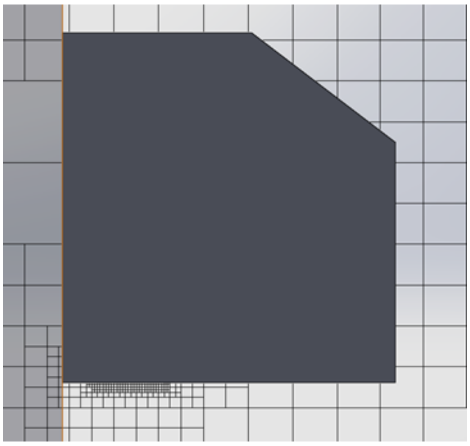

Fig. 11. Mesh for grille area

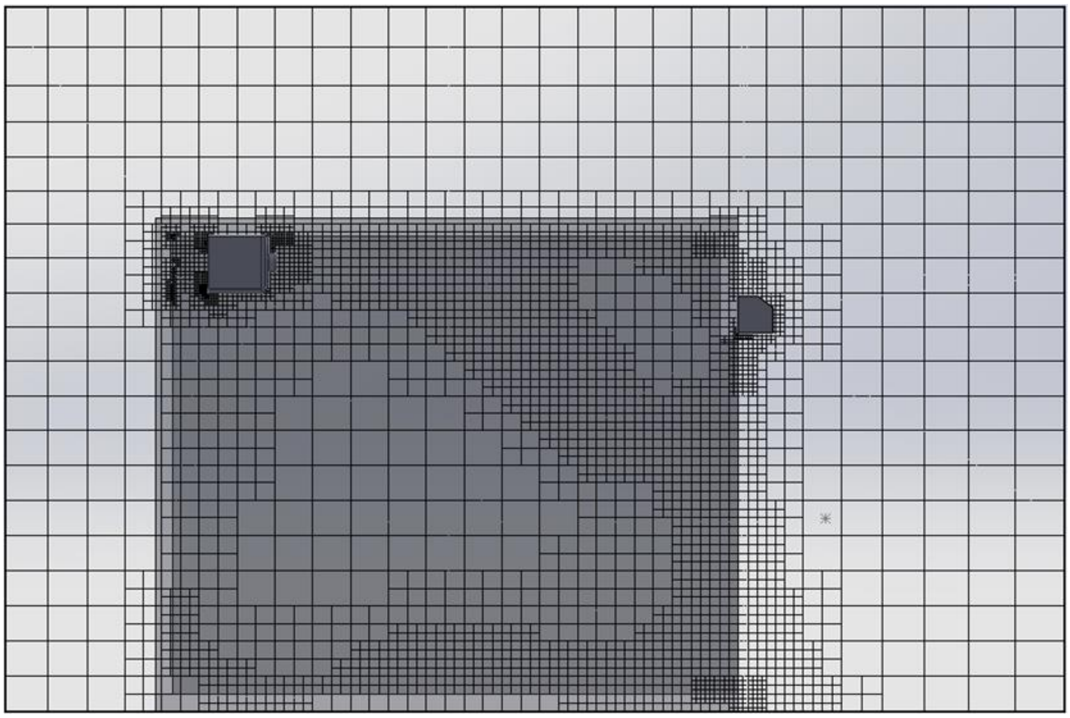

Fig. 12. Mesh for freezer room with air curtain

3. Results

Table 3 shows the simulation results of the average temperature inside the cold storage. After one hour, the average temperature inside without an air curtain is at 6.25°C; the average temperature inside with a common grille air curtain is at -1.420°C; and the average temperature inside with a honeycomb grille air curtain is at -2.26°C respectively.

Table 3
Simulation results for the average temperature inside the door

Time (s)	Avg. Temperature Inside Door (◦C)		
	Without Air Curtain	Air Curtain with Common Grille	Air Curtain with Honeycomb Grille
1	-22.02	-22.49	-22.49
10	-5.03	-14.77	-14.73
20	-0.13	-12.13	-11.85
50	6.73	-10.02	-10.39
100	3.45	-9.82	-7.45
300	6.28	-1.48	-1.41
600	6.07	-0.25	-0.08
1200	6.24	-2.62	-2.3
1800	6.26	-2.45	-2.59
2400	6.27	-2.95	-3.08
3000	6.23	-0.64	-2.61
3600	6.25	-1.42	-2.26

The simulation results of the temperature outside the cold storage are shown in Table 4. After one hour, the temperature outside without an air curtain is at 27.4°C; the temperature outside with a common grille air curtain is at 28°C; and the temperature outside with a honeycomb grille air curtain is at 28°C respectively.

Table 4
Simulation results of temperature points outside door

Time (s)	Temperature Point Outside Door (◦C)		
	Without Air Curtain	Air Curtain with Common Grille	Air Curtain with Honeycomb Grille
1	20.33	25.2	25.19
10	26.83	19.85	19.43
20	26.82	26.8	25.22
50	27.68	27.97	28.05
100	26.91	28	28
300	27.5	28	28
600	27.47	28	28
1200	27.45	28	28
1800	27.46	28	28
2400	27.46	28	28
3000	27.46	28	28
3600	27.46	28	28

Table 5 shows the simulation results of the average wind speed inside the cold storage. After one hour, the average wind speed inside without an air curtain at is 0.44°C; the average wind speed inside with a common grille air curtain is at 0.76°C; and the average wind speed inside with a honeycomb grille air curtain is at 0.79°C respectively.

Table 5
Simulation results of average air velocity inside door

Time (s)	Avg. Air Velocity Inside Door (m/s)		
	Without Air Curtain	Air Curtain with Common Grille	Air Curtain with Honeycomb Grille
1	0.31	0.28	0.28
10	0.54	0.48	0.48
20	0.36	0.43	0.44
50	0.41	0.49	0.45
100	0.42	0.55	0.57
300	0.44	0.8	0.79
600	0.44	0.81	0.81
1200	0.44	0.78	0.79
1800	0.44	0.78	0.79
2400	0.44	0.78	0.77
3000	0.44	0.78	0.78
3600	0.44	0.76	0.79

3.1 Infiltration behaviour without air curtain

Figure 13 and 14 show graphs for the freezer room having a temperature of −25 °C with the door left open and no air curtain, for 1 hour (as for all experiments). The temperature in the freezer quickly rose from −22 °C to 8 °C and then stabilized at 6 °C. The average temperature inside the freezer was 6.05 °C and the average freezing room temperature was 27.47 °C. The air velocity in the initial freezer was turbulent for the first 300 s, and stabilized at about 0.4 m/s.

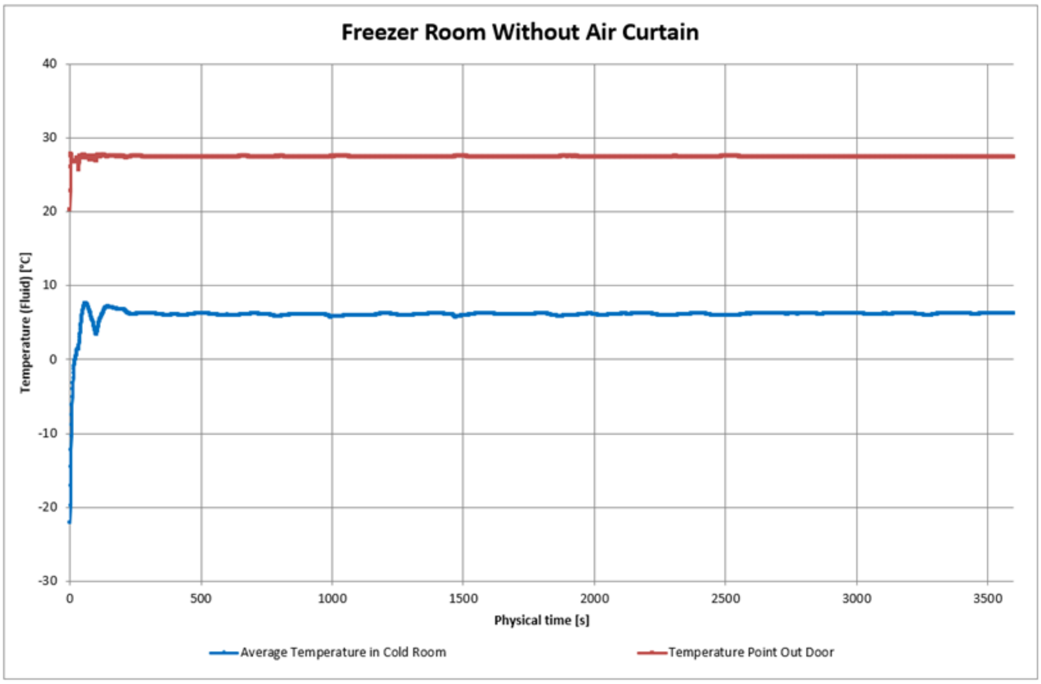

Fig. 13. Temperature of freezer room without air curtain

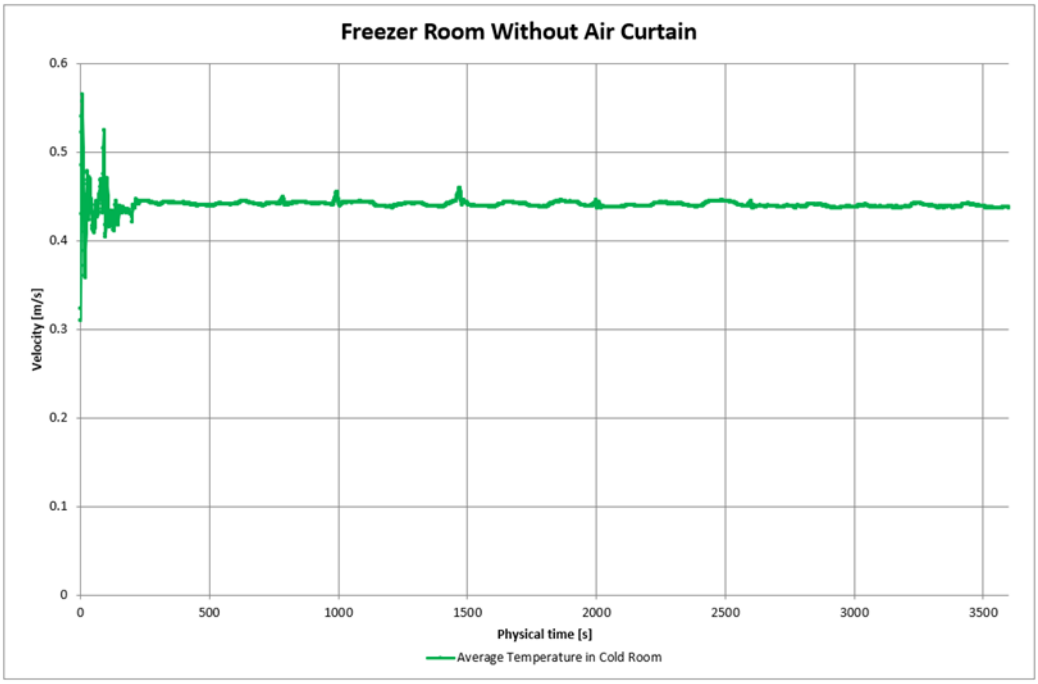

Fig. 14. Air velocity for freezer room without air curtain

3.2 Infiltration behaviour with common air curtain grille

Figure 15 and 16 show the results for the −25 °C freezer room with door left open and air curtain having a common grille. Over the entire 1 hour experiment, the freezer temperature rose sharply from −20 °C to −10 °C and began to stabilize at around 0 °C, with a mean temperature inside the freezer of −2.41 °C and a mean freezing room temperature of 27.97 °C. The air velocity in the initial freezer was turbulent for the first 700 s, and stabilized at about 0.8 m/s.

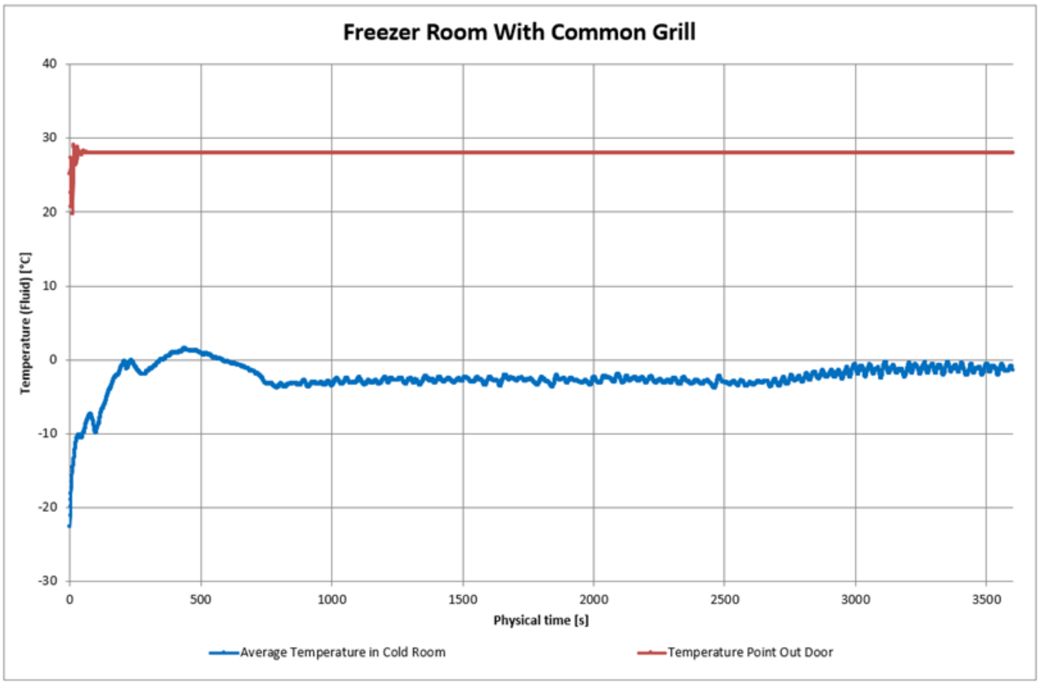

Fig. 15. Temperature of freezer room with common air curtain grille

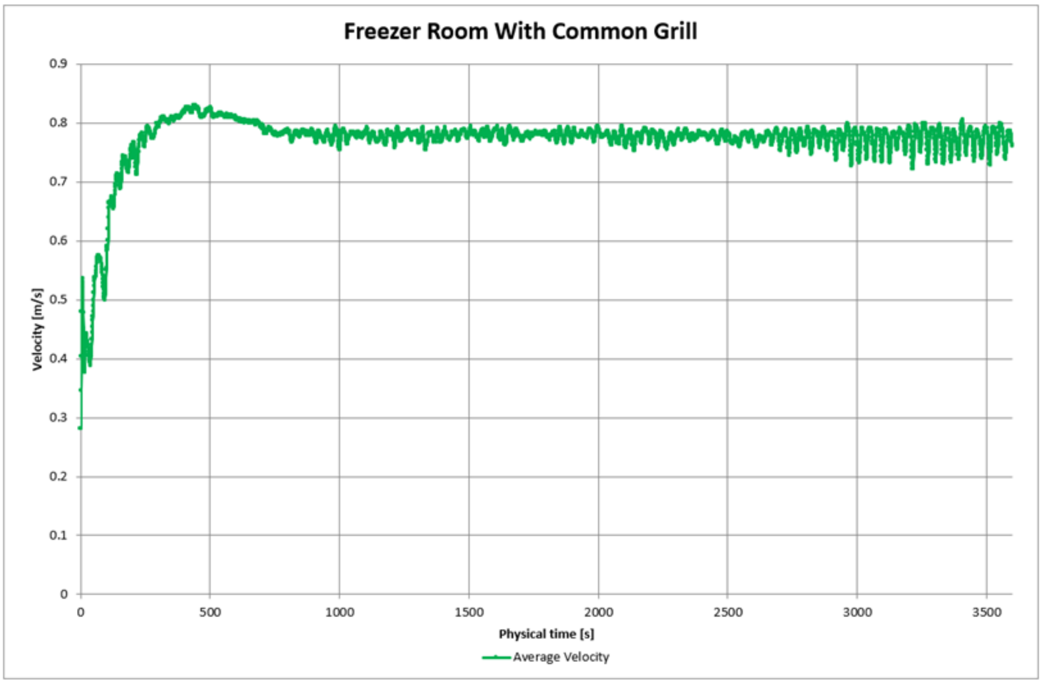

Fig. 16. Air velocity for freezer room with common air curtain grille

3.3 Infiltration behaviour with honeycomb air curtain grille

Figure 17 and 18 show the results for the −25 °C freezer with the door left open and with air curtain having a honeycomb grille. Over the entire 1 hour experiment, the freezer temperature rose sharply from −20 °C to 0 °C and began to stabilize at −2 °C, with a mean temperature inside the freezer of −2.64 °C and a mean freezing room temperature of 27.97 °C. The air velocity was initially turbulent for the first 700 s, and also stabilized at about 0.8 m/s.

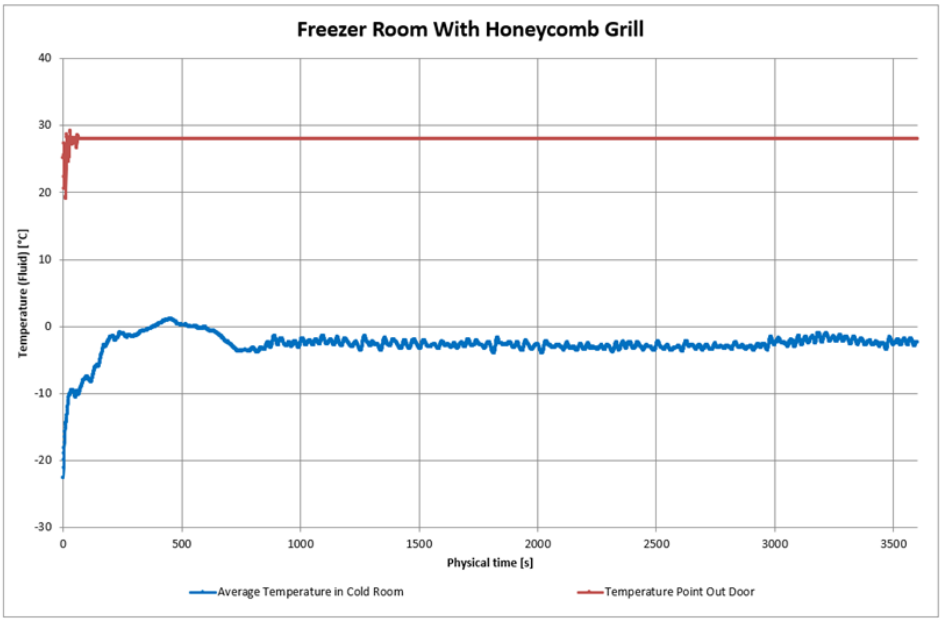

Fig. 17. Temperature for freezer room with honeycomb air curtain grille

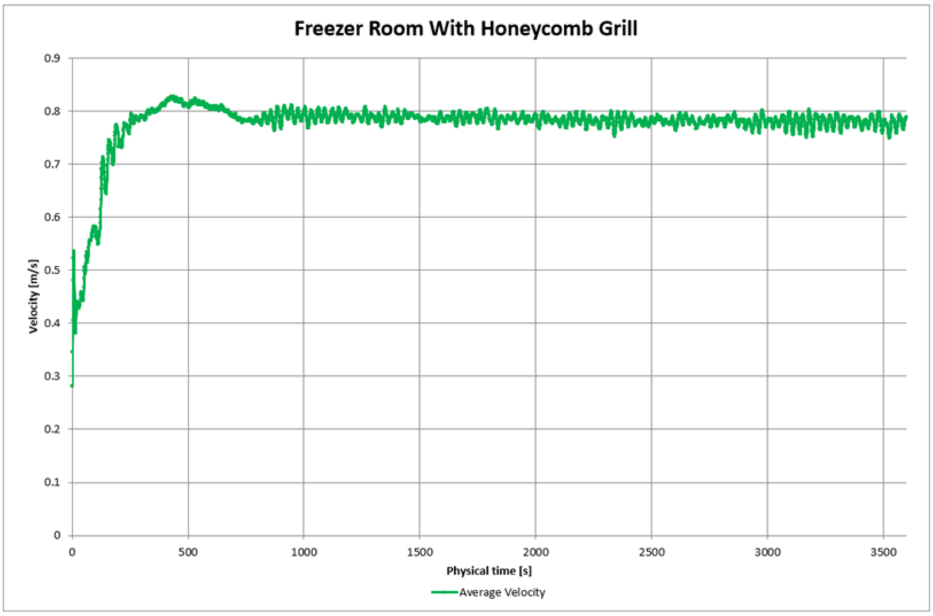

Fig. 18. Temperature for freezer room with honeycomb air curtain grille

3.4 CFD temperature simulation

Figure 19(a) shows the results for the experiment performed with the freezer door open and the air curtain inactive. At 100 s, the cold room temperature flowed downward and warm air entered upward. Experiments at 5 m, 10 m, and steady-state present the same pattern of temperature loss. However, inside the refrigeration chamber, a certain temperature was maintained, as the FCU was still operating. The average temperature inside the freezer was 6.05 °C. Figure 19(b) shows the experiment in which the freezer door was left open and the infiltration of warm air was prevented by use of an air curtain having a conventional grille. At 100 s of the experiment, it can be seen that the air curtain had just begun to function and was weak, as observed by the bending of the temperature line around the door. At 5 m, the air curtain was strengthened, but warm air was still trying to enter the freezer room. This can be seen from the temperature lines, which curve inward into the freezer. At 10 m and steady-state, the air curtain was strengthened, as the inward temperature curve in the freezer was reduced. The average temperature inside the freezer was −2.410 °C. Figure 19(c) shows the experiment carried out by leaving the freezer door open and preventing the infiltration of warm air by using an air curtain having a honeycomb grille. The experimental results were similar to those of the conventional grille, as they were the same air curtain, only with different grille characteristics. However, at steady-state, the honeycomb grille air curtain had lower curvature in the door temperature line, compared to the conventional grille, and the average room temperature was −2.64 °C.

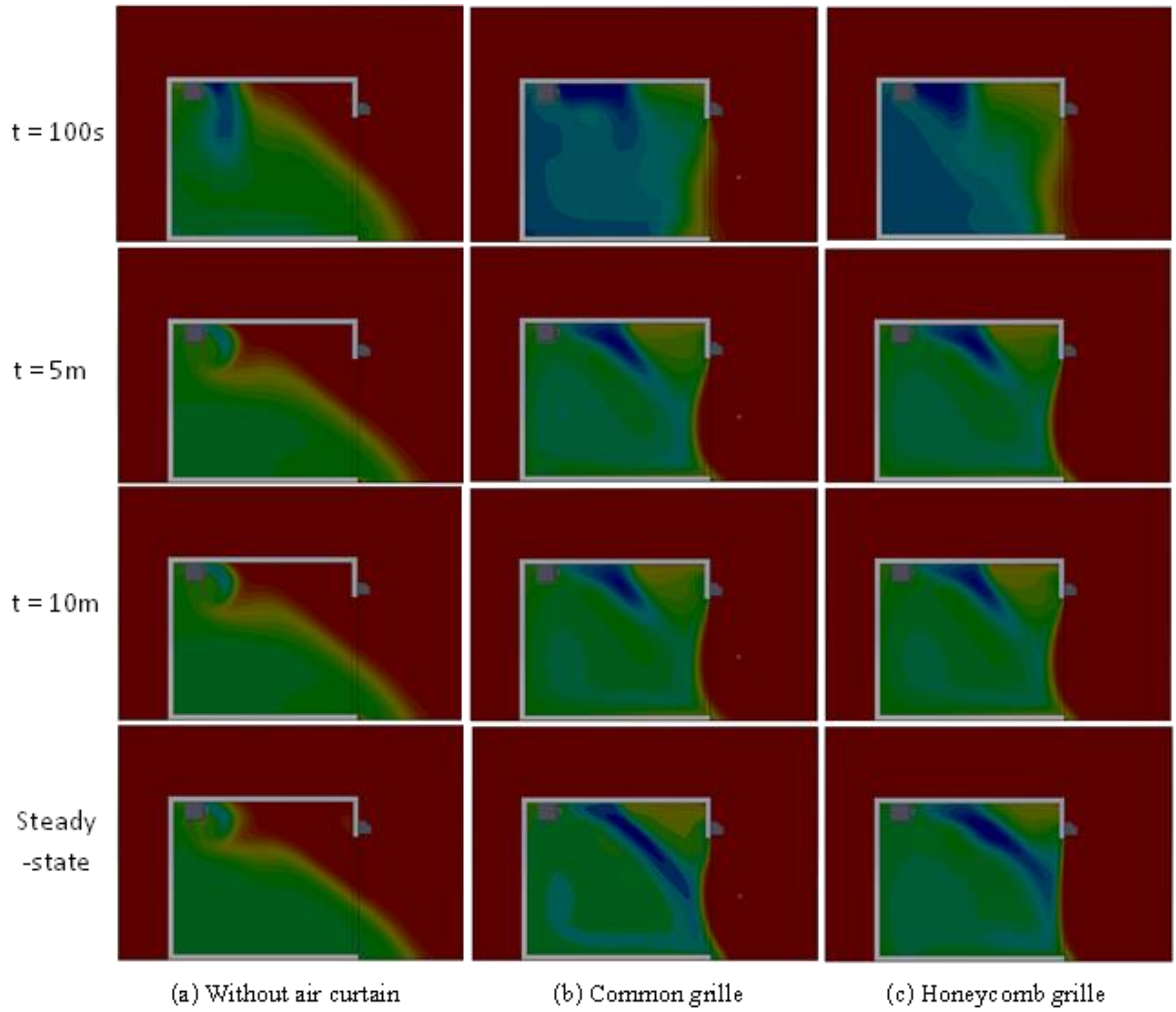

Fig. 19. (a) Temperature in freezer room without air curtain; (b) Temperature in freezer room with common air curtain grille; and (c) Temperature in freezer room with honeycomb air curtain grille

3.5 CFD velocity simulation

Figure 20(a) shows the results for testing the freezer chamber by leaving the door open and the air curtain closed. The wind above the door was flowing into the freezer room while, below, it is possible to see the wind blowing out. Figure 20(b) shows that the use of a conventional grille prevented the inflow of air, but the nature of the airflow emitted by the air curtain is very curved, due to the influx of warm air from outside. Figure 20(c) shows that the honeycomb grille was able to prevent air exchange more effectively as conventional grilles; however, the curvature of the air curtain was lower, as the honeycomb grille reduced the dispersion of the released air. Therefore, the air curtain was stronger.

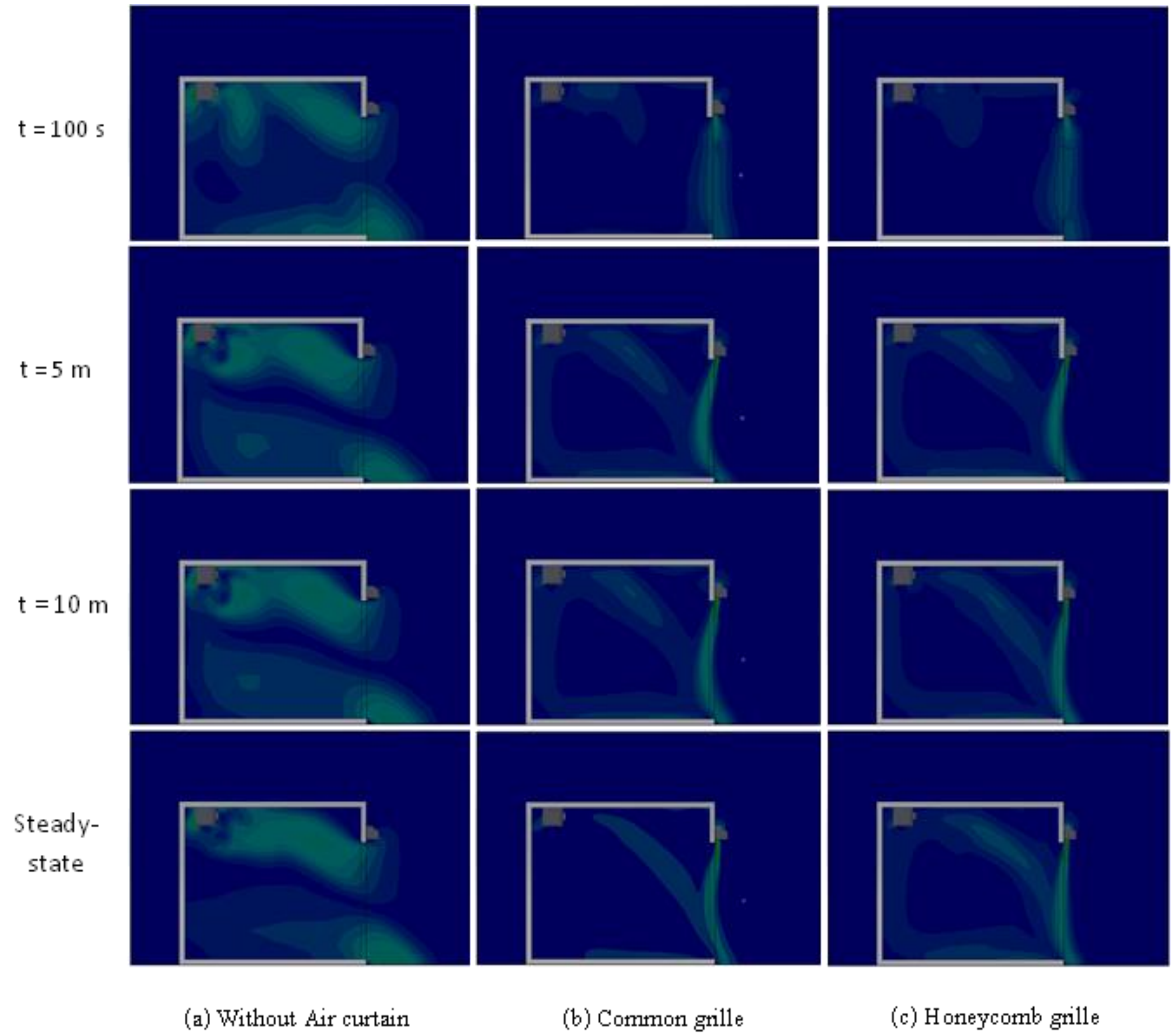

Fig. 20. (a) Velocity in freezer room without air curtain; (b) Velocity in freezer room with common air curtain grille; and (c) Velocity in freezer room with honeycomb air curtain grille

4. Conclusions

We carried out an experiment considering a freezer room at a temperature of −25 °C with the freezer door open. The FCU was still operating normally, and the air curtain was initially closed. The results showed that it took about 300 s for the temperature inside the freezer to stabilize at about 6.05 °C. We then conducted the same experiment, using an air curtain having a common grille. When steady-state conditions were reached, the temperature inside the freezer was −2.41 °C. We then experimented using an air curtain having a honeycomb grille. When steady-state conditions were reached in this scenario, the temperature inside the freezer was −2.64 °C. In conclusion, comparing the results of these experiments, it was found that the air curtain with the honeycomb grille could prevent airflow through the door more effectively than the air curtain having a common grille, better maintaining the cold temperature inside the freezer with an energy saving of 9.54%.

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