Research Article GU J Sci 36(3): 1259-1275 (2023) DOI:10.35378/gujs.1091383

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

Numerical Analysis of Air Flow in an Industrial Refrigeration System and Its Effect on Energy Consumption

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Highlights

- A new type airfoil integration effect on a horizontal industrial refrigerator performance.
- Decrease in cooling capacity of 3.82% has been achieved.
- 1726 tones/cabinet CO_2 reduction has been provided yearly.
- Average energy efficiency index value has been decreased by 10.37%.

Article Info

Received:21 Mar 2022
Accepted:28 June 2022

Keywords

Refrigeration
Energy efficiency
Display cabinet

Abstract

Refrigerated display cabinets as a type of cooling system is preferable commonly in food shops and grocery store to prevent foods from warm air. They do not have much more efficient compared to the cabinets with glass doors because of the interactions between air curtain. This paper presents experimental and numerical methods to seek energy performance of the horizontal refrigerated display cabinets in terms of design parameters. Two geometry with/without airfoil were designed and evaluated the effects of discharge velocity to create more efficient air curtain. 2D Computational Fluid Dynamics (CFD) model was performed to assess the effect of discharge flow on the cooling load performance of the horizontal display cabinet. The results showed that the airfoil design has increased the efficiency of the air curtain with achieving a more effective air curtain, resulted in mitigation of the ambient warm air infiltration into the cabinet. The return air temperature of the cabinet with airfoil decreased from 272.45 K to 270.62 K compared to the one without airfoil due to more effective air curtain. In this way, the cooling capacity of the refrigeration system has been decreased by 3.82% with airfoil usage. It is also concluded that the air temperature inside the cabinet and the cooling capacity have been decreased by 3.5°C and 2.82%, respectively when Case 7 for used the new type airfoil and Case 1 with the same air velocity are compared.

1. INTRODUCTION

There are two main types of industrial refrigerators, mainly known as types of display and storage. They can be classified horizontal and vertical in terms of orientation, open and closed in terms of infiltration, positive and negative pressure gauges in terms of inside pressure of the cabinet and etc. They can also be grouped considering service sections such as meat, appetizer and etc. Considering those kinds of applications, a horizontal type of industrial refrigerator has been considered to investigate. Therefore the present study focuses on to seek new design of an airfoil that will probably enhance efficiency in terms of cooling load and energy consumption

2009/125/EC of the European Parliament and council directive in accordance with a direct sales Function requirements as of March 1, 2021 with the paper on environmentally conscious design of refrigeration equipment, supermarket cabinets for home vertical and combined EEI<100 1 September 2023 onwards, and work from EEI<80 are required to be [1]. This paper aims to determine the requirements for environmentally sensitive design of refrigeration devices with direct sales function related to the supply or service [2].

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Another limiting factor is the Regulation on Fluorinated Greenhouse Gases (F-Gas Regulation). This regulation includes the basic principles of fluorinated greenhouse gases and the electronic recording, labeling, leakage control, reporting, placing on the market and use bans of products or equipment containing fluorinated greenhouse gases and fluorinated greenhouse gases [3].

Energy consumption, environmental safety and food quality issues have been taken into a framework with these regulations and studies. These limiting factors have led to the researchers to make energy efficient designs. One of the equipments consuming considerable energy is the cooling systems. The main purpose of the coolers is to reduce the temperature by cooling the hot ambient air in the cooling system and to provide cold storage by blowing on the products to be cooled. But in open-type systems, infiltration heat gains occur due to the effectiveness of the air curtain during air flow, and the suction air heats up, as a result of this, the cooling and defrost load increases. Because of this situation, the air cold cannot reach effectively onto the products to be cooled and can infiltrate towards the outside in certain areas. It appears the structure and effectiveness of air curtains are here more important to reduce heat gains. It is possible to use one or more air curtains, but the most commonly used are one-dimensional air curtains. In particular, it is used in horizontal type coolers. Computational Fluid Dynamics (CFD) models are performed to display heat gains, air velocities, and temperature distributions in air curtains. The fact that air curtains are so important attracts attention from the point of view of energy efficiency and cooling technique, and many studies are being carried out on it. Rossetti and his friends (2015) have numerically modeled and verified the airflow of an open-type horizontal display cooler. In the study, numerical modeling was created using CFD. With this modeling, the particle image velocity (PIV) was measured and the experimental data were compared. The evaporator is modeled using the equivalent resistance approach. In the results obtained, they proved that modeling the transition from turbulent flow to laminar flow within the evaporator volume is critical for an accurate trace definition in the evaporator. They noted that the correct installation of the inlet limit and the evaporator volume is of great importance [4].

According to Sun and et al. (2017) modeled the open-type vertical display coolers with/without air routing strips through CFD, and they compared the results. In addition to the single-layer air curtains, the effect the use of air guidance strips on the front faces of the cooler shelves on package temperature and cooling capacity was analyzed and thanks to this model, a more effective air curtain was achieved, and the penetration of ambient hot air into the cabin was mitigated substantially. In this way, the package temperatures were decreased from 4.7°C to -0.2°C, and the cooling capacity required to store the food was reduced by 34% [5]. Cui and Wang (2004) evaluated the air curtains of horizontal display coolers and used CFD method to make energy efficient design. They stated that the air curtain in refrigerants is one of the main elements affecting the cooling load and energy-efficient qualitative designs proposed. The air curtain is greatly influenced by the temperature and relative humidity of the ambient air. They showed that a lower air curtain and uniformity of speed can effectively shorten the main axis of the air curtain and reduce the cooling load [6].

Wu et al. (2004) developed a mathematical model to estimate the velocity vector and temperature distributions of the air curtain in a horizontal island-type display refrigerator. As a result of the model, it was determined that the convexly stacked goods in the refrigerated cabinet would improve the thermal insulation performance and also reduce the energy consumption of the cooling system would, in a concave manner of goods shrank so that the spray zone storage of the air curtain, air curtain between the increase of convective heat exchange with the ambient air to the mixture, and this increase also stated that it would increase the energy consumption of the cooling system, as well [7]. Gonçalves et al. (2012) modeled the tightness of horizontal and downward air curtains in cold rooms through CFD. A model has been developed for the three-dimensional simulation of turbulent non-isothermal air flow that occurs after the door of the cold room is opened. Horizontal air curtains downward as a result of the study, compared to 70% sealing efficiency, but the cost is high because of the confusion and vertical air curtain installation of the system [8].

Cortella (2002) performed CFD analyses for the estimation of the air flow model and food temperature in the cabinet in horizontal and vertical type display coolers. As a result of the models performed, it was seen that the packages that are close to the warmest package return air are the ones that are made. The lowest load temperature in the packages is reached at the end of the cooling period. They noted that during the subsequent 30–minute defrosting, the package temperatures increased by 2.5-3.5 °C due to the cessation of the cooling cycle and the heat load from the defrosting process [9].

Hadawey et al. (2012) designed the vertical type display cooler air curtain through CFD analysis. In the designed model, the effect of side flow on the performance of the display cooler was evaluated. As a result of the study, it was stated that tilting the air curtain by 5° to 10° outward provided the best protection against the environment. They also stated that the optimum air curtain mass flow rate should be about one third of the total air mass flow rate in the refrigerant [10].

According to Gaspar and et al. (2011) experimentally analyzed the thermal drift factor of the vertical type display cooler air curtain for different ambient weather conditions. The experiments were carried out under different conditions such as temperature, relative humidity, air direction, and speed. Experiments at 25°C 0.2 M/s air speed at the latent heat transfer rate of 35% and the relative humidity of 60% conditions, compared to the relative humidity of 60% in the environment with the latent heat transfer rate of the relative humidity of 35% conditions, the latent heat transfer rate as compared to 42% showed an increase. Ambient condition, 25°C and 60%, in an environment, the heat transfer is compared when the ambient air velocities are 0.2 m /s and 0.4 m /s, and the amount of infiltration in the air curtain also increased due to the increase in air velocity, and the total heat transfer rate was increased by 53%. As the velocity of the ambient air increases, it creates a decrease in the aerothermodynamic performance of the air curtain. This situation leads to unstable air distribution, and increase in energy consumption [11].

According to Field and et al. (2006) analyzed the drag of the air curtain down in a vertical type cooler. The velocity profiles of air curtains were studied using PGH. In the experiments, air curtain speeds were evaluated using different number and speed of evaporator fans. Reynolds, Richardson and Grashof numbers of the designed air curtains have been calculated and interpreted. As a result of the experiments conducted, they noted that the flow acceleration becomes more pronounced as the Richardson number of air curtains increases, the curtain thickness is independent of the Reynolds number, and thus the differences in curtain thickness are primarily due to negative lifting effects [12]. Cao and his friends (2010) presented an effective strategy for optimizing the design of air curtains in open-type vertical display coolers. They have implemented a new strategy to optimize the design of air curtains based on two fluid cooling loss (IASK) models and a support vector machine (DVM) algorithm. As a result of the application, the projected cooling loss was reduced by 19.6% and they found that the total energy consumption/total display area value of the optimum display case for 24 hours was reduced by 17.1% [13].

Moureh and Yataghene (2016) conducted numerical and experimental research on the jet properties and airflow models of an air curtain exposed to external lateral flow of an open-type vertical display cooler. The experimental results obtained with PGH showed that the highest effect was found to occur on the side of the air curtain corresponding to the beginning of the interaction between the air curtain and the lateral flow dec They noted that the breakage of the air curtain on the side cabin side, where the external lateral flow comes from, drags air through the medium in the cavity, and these intense convective changes induced by the external lateral flow for the display cooler will lead to an increase in energy consumption and food temperatures in the cooled compartment [14].

In this study, the air curtain with a new type of air foil in a horizontal type display refrigerator were analyzed with the CFD model. The obtained data are compared with the conventional air curtain structure. Based on the results of the analysis, it was aimed to determine the effect of the air curtain structure on display cabinet energy consumption with/without airfoil. The objectives of this study can be summarized as follows:

- to design and analyze new type air foil for air curtain structure
- to create an eco-friendly refrigerator
- to characterize the air curtain flow with air foil
- to determine the effect of the air curtain on the cooling load.

2. MODEL DESCRIPTION AND MESH STRUCTURE

Dimensions of the horizontal refrigerator type industrial cooler are of 965x1180 mm in a 2-dimensional plane as shown in Figure 1. Ansys Workbench Design Modeler program was used for geometry design. Analyzes were performed for two different geometries, with and without airfoil. After geometry design of the device as two dimensional was generated, the volume of the air flow was created by subtracting the geometry volume created from the volume of the room. Fan, evaporator, blowing and suction nozzles were modeled in the device. The heat transfer coefficient of the side panels for the device was calculated and entered into the model as 0.30 W/m^2K by using the thermal conductivity coefficient of 0.05 m polyurethane insulation material for the boundary conditions. In order to optimize the effectiveness of the air curtain, the air flow effects on the efficiency and energy performance of the air curtain were investigated by analyzing at different air velocities with and without airfoil.

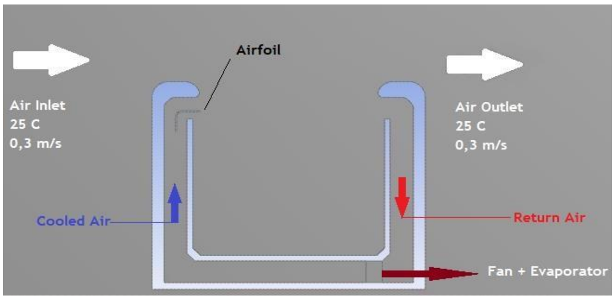

Figure 1. *Refrigerator Airflow Model*

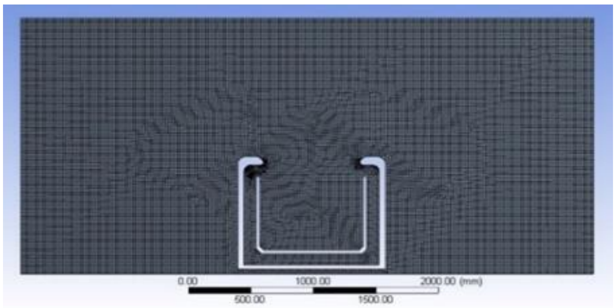

Figure 2. *Mesh Structure*

Ansys Mesh Module was used to generate mesh structure, and the generated one is shown in Figure 2. The mesh structure was with 25280 rectangular elements with maximum 20 mm spacing. Mesh quality is evaluated by looking at the skewness and orthogonal values. Since the maximum skewness value was 0.639 and the minimum orthogonal value was 0.744, the mesh quality was considered to be within acceptable values for accurate solutions.

2.1. Theoretical Analysis and Solution

CFD uses numerical methods to predict velocity, temperature, pressure of fluid domain. Commercial FLUENT software solves the Navier-Stokes equations to determine fluid flow and energy equation to describe temperature distribution. The fluid equations are replaced by discrete approximations at grid points. For the two dimension CFD model, FLUENT solves for the five variables: in two dimension of x and y which are the x velocity and y velocity of fluid domain, relatively, plus the pressure, p, and temperature, T, of the fluid and/or solid materials. All of these variables are functions of x, y, and time.

Variables in the z direction in equations were neglected when computing the two dimension CFD modelling. Standard turbulence model (k-ε) as a type of turbulence model was used for turbulence interaction because it usually gives favorable solution between the numerical and experimental results. The flow at the evaporator outlet (evaporator coil air-off section) was regarded to have unchanging distribution.

The radiation heat transfer between industrial refrigerator which is designed in this study and the surrounding ambient air was considered, and surface to surface radiation model (S2S) was selected to take into account in this paper.

Continuity, momentum and energy equations are solved in 2D plane. The solution was defined as transient analysis and incompressible flow. Residual was defined as 10^{-3}. All results were converged.

In order to determine velocity field, Equation (1) which is for contiunity is used [15]

$$\frac{\partial \rho}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0\ . \tag{1}$$

In order to determine x and y momentums of fluid, Equations of (2) and (3) are used [15]

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+X \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+Y\ . \tag{3}$$

Equation (4) is used to determine temperature distribution between display cabinet and ambient air due to heat transfer [10]:

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=-\left(\frac{\partial}{\partial x}(q_x)+\frac{\partial}{\partial y}(q_y)\right)+q'' \tag{4}$$

Cooling load was calculated by Equation (5)

$$\dot{Q}_{\text{case}}=\dot{Q}_{\text{conduction}}+\dot{Q}_{\text{radiation}}+\dot{Q}_{\text{infiltration}}\ . \tag{5}$$

Considering the laws of thermodynamics which are commonly known as first and second, the display cabinet performances were calculated. The following equation can enable the cooling capacity ($\dot{Q}_e$) for the refrigeration system [16]

$$\dot{Q}_e=\dot{m}(h_1-h_4) \tag{6}$$

where $\dot{m}$ represents the mass flow rate of the refrigerant used, h_1 and h_4 represent the enthalpies of the refrigerant at the evaporator outlet and the evaporator inlet, respectively. The Equation (7) is also used to calculate the compressor power

$$\dot{W}_c=\dot{m}(h_2-h_1) \tag{7}$$

where h_2 and h_1 represent the enthalpies of the refrigerant leaving and entering the compressor, respectively. Through Equation (8), the coefficient of performance (COP) of the system can be determined

$$COP=\frac{\dot{Q}_e}{\dot{W}_c}\ . \tag{8}$$

When the electrical energy (kWh) consumed by the compressor used in the refrigeration system is evaluated, In the study reported [17], it was stated the average CO_2 equivalent density for electricity generation from coal as fuel approximately 0.96 kg CO_2/kWh. This value can be corrected as 2.08 kg CO_2/kWh when calculated with 40% transmission and distribution losses and 20% losses due to inefficient electrical appliances used [18].

CO_2 emission can be calculated by Equation (9) [18]

$$\Phi CO_2 = \Psi CO_2.\, \dot{W}_c. \quad (9)$$

The energy efficiency index (EEI) value can be computed by Equation (10). Energy efficiency classes are shown in Table 1. The annual energy value in the equation represents the annual energy consumption (kWh/year), and the SAE value is defined for the reference value of the annual energy consumption amount [19]

$$EEI = \frac{AE}{SAE}\ . \quad (10)$$

Table 1. *Energy efficiency classes [19]*

Energy efficiency class	*EEI*
A	*EEI <10*
B	*10≤ EEI <20*
C	*20≤ EEI <35*
D	*35≤ EEI <50*
E	*50≤ EEI <65*
F	*65≤ EEI <80*
G	*EEI ≥100*

In order to calculate the AE value in Equation (11), it is necessary to know the daily energy consumption [19]

$$AE = 365.\, E_{daily}. \quad (11)$$

SAE value can be calculated as European Parliamen and Council [1, 19].

The Y value should be taken as the sum of the total display areas in m^2 of all the compartments of the display cabinet in the same temperature class

$$SAE = 365.\ 1{,}1.\ (7{,}5 + 19{,}30.\ Y).\ 0{,}9. \quad (12)$$

3. RESULTS AND DISCUSSION

Firstly, Cases 1-4 given in Table 2 was analyzed. It was observed that most of air cooled infiltrated towards the ambient air region. This resulted in high cooling load because of insufficient air curtain. All results and calculations for those cases are given in Table 2. As the existing cabinet was tested at four different discharge velocities. During the testing, the compressor working duration was of about 16 hours, and the COP value of the system was determined as 2.52. As the discharge velocity was increased, the return air temperature of the cabinet decreased. The ambient temperature was heated instead of the products which was needed to be cooled. In other words, This conclusion led to higher cooling load. In order to reduce cooling load of the display cabinet, the geometry has been redesigned by integrating with an airfoil to mitigate mixing of the cooling air and the ambient air.

Table 2. *Temperatures along with variable discharge velocity in the cabinet with-without airfoil and calculated cooling load*s

Case No	Model	Discharge Velocity m/s	Flow Rate m^3/h	Discharge Air Grill Temperature K	Return Air Grill Temperature K	Air Temperature in cabin K	Cooling Load Watt and Change %	
1	without airfoil	1,26	453,6	270,32	277,6	275,22	1192	-
2	without airfoil	1,4	504	270,6	277,67	275,33	1286	+ 7,33
3	without airfoil	1,53	550,8	269,9	276,48	275,61	1308	+ 8,89
4	without airfoil	1,86	669,6	270	276,23	274,15	1506	+ 20,84

The new display cabinet design with the airfoil has been modelled through a commercial CFD code, and their results and calculations are given in Table 3 and Figures 3-6. As for evaluation of the results calculated (Table 3), it is noted that the positive and the negative signs in the table represent change in the cooling load. If the cooling load increases, the sign has been the positive. If not, it has been the negative. For the cooling load increase or decrease calculation, Case 1 has been considered the base. In the study presented, the testing and the analysis results have been evaluated considering the cooling load and the inside temperature of the cabinet. Calculations as given in Table 3 show that the display cabinet with the airfoil has been lower cooling load due to more effective air curtain.

Table 3. *Temperatures along with variable discharge velocity in the cabinet with-without airfoil and calculated cooling load*s

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4	without airfoil	1,86	669,6	270	276,23	274,15	1506	+ 20,84
5	with airfoil	1,11	399,6	269,96	277,92	272,45	1148	-3,82
6	with airfoil	1,22	439,2	269,97	277,27	271,85	1157	-3,00
7	with airfoil	1,26	453,6	269,98	277,06	271,72	1159	-2,82
8	with airfoil	1,4	504	269,94	276,45	271,36	1184	-0,65
9	with airfoil	1,53	550,8	269,96	275,92	271,09	1185	-0,59
10	with airfoil	1,61	579,6	269,97	275,64	270,96	1186	+ 0,11
11	with airfoil	1,7	612	269,97	275,39	270,84	1197	+ 0,45

12	with airfoil	1,78	640,8	269,99	275,17	270,74	1198	+ 0,52
13	with airfoil	1,86	669,6	269,97	274,95	270,62	1204	+ 0,97
14	with airfoil	1,93	694,8	269,98	274,8	270,55	1209	+ 1,40
15	with airfoil	2,14	770,4	270,31	274,68	270,62	1215	+ 1,91

When Case 1 and Case 7 which have been tested at the same air velocity are evaluated each other to examine the airfoil effect, one can say that the returned air temperature decreased, decrease in the inside temperature of the cabinet was about 3.5°C. The main reason for this temperature decrease is that the air circulated was not infiltrated to the outside of the cabinet much more through the air foil designed and integrated. With decrease in the inside temperature of the cabinet and the returned air temperature, the infiltration rate was decreased. As a result of this, the cooling load of the display cabinet was decreased in 2.82%. For Case 4 and Case 13 that have been tested at the same velocity, it is observed that the inside temperature of the cabinet was decreased and decrease in the cooling load was 20.1%. This conclusion resulted in less energy consumption.

When the maximum air velocity case which is represented as Case 15 is evaluated, it is concluded that the minimum inside temperature of the cabinet and the returned air temperature were achieved. However, due to increase in the air velocity, the infiltration rate increased.

When it is examined in Table 3, one can say that increase in the cooling load for Case 10-15 was compared to Case 6-9 although the air foil was used for Case 10-15. This is because the infiltration rate increased when the air velocity was increased.

The cooling load increased with increasing the air velocity for Case 1-4 tested. The maximum increase was for Case 4 with the maximum air velocity of 1.86 m/s. The cooling load for Case 4 has been more 20.84% compared to that for Case 1.

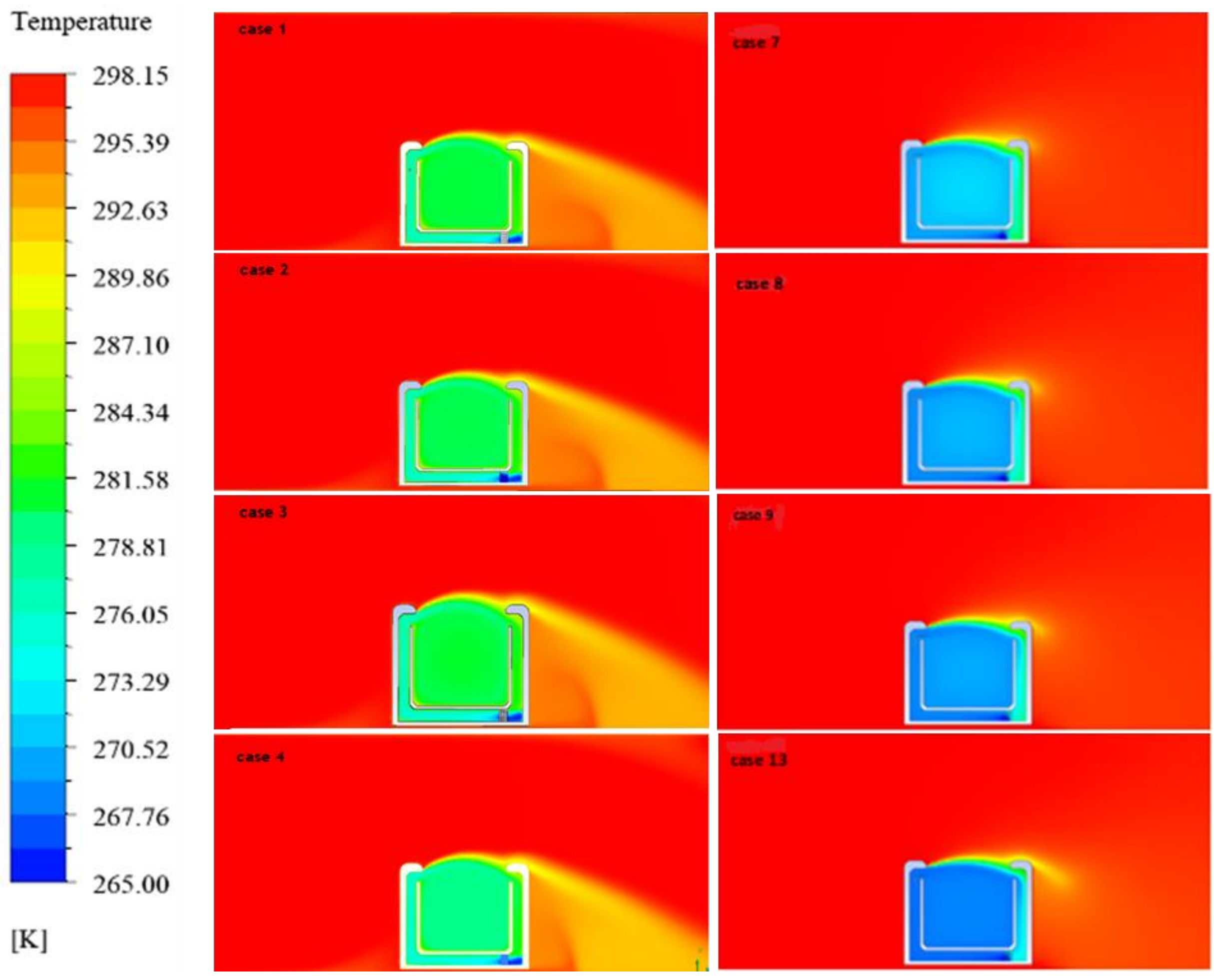

Figure 3. *Temperature contours for Case 1-4, Case 7-9, and Case 13*

As seen in Figure 3, The infiltration rate increased for Case 4 modelled compared to that for Case 1. When it is evaluated, it is seen from the figures that some of the cooled air cooled the products and the rest ones cooled the outside of the display cabinet. The infiltration rate was decreased with the airfoil integrated, resulting in decrease in the inside temperature of the cabinet was achieved.

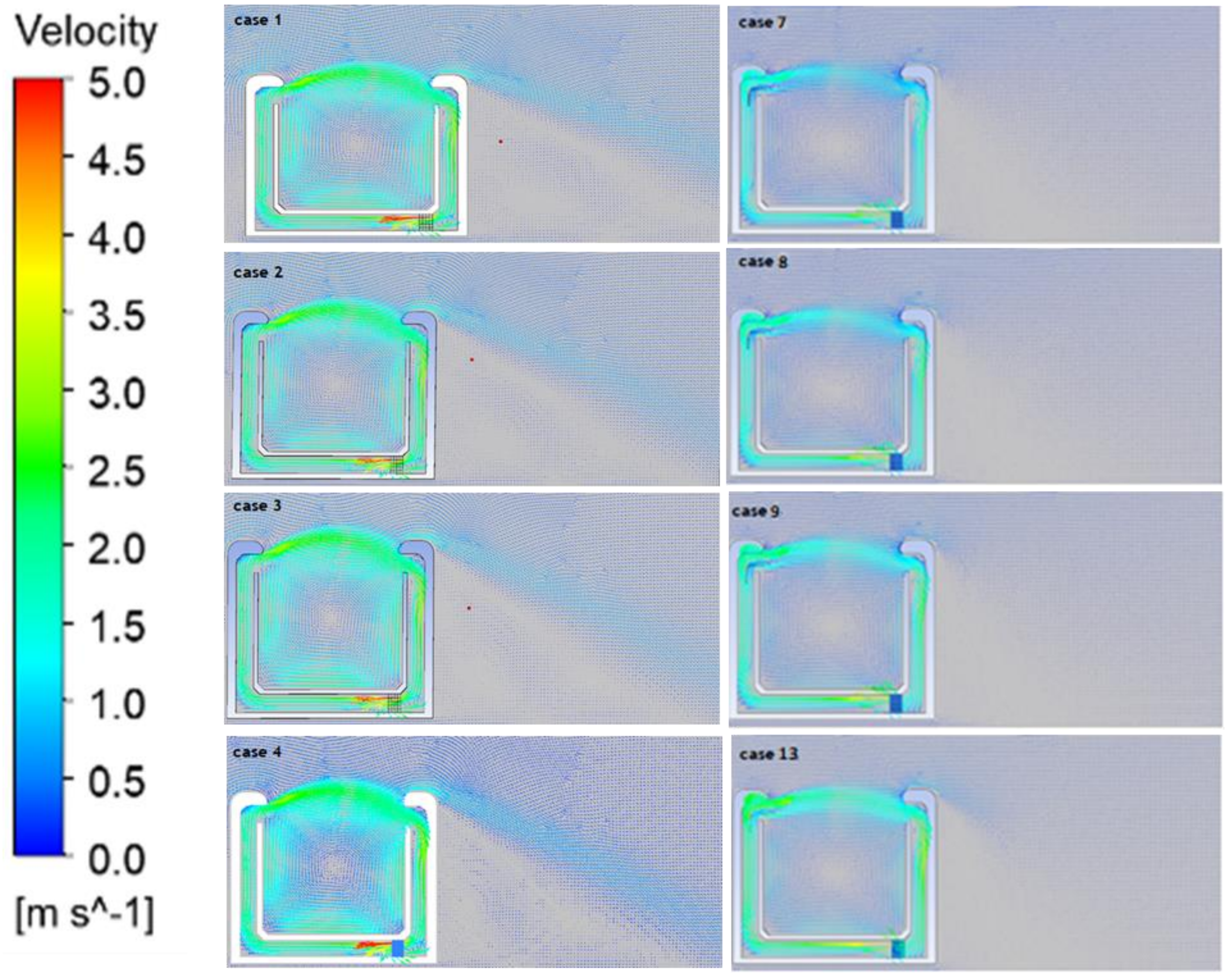

Figure 4. *Velocity vectors for Case 1-4, Case 7-9, and Case 13*

Increase in the infiltration rate can be seen from Figure 4. With integration of the airfoil like a barrier, for the air that wants to infiltrate, the infiltration rate was decreased. This airfoil mitigated the air velocity as well. In this way, more amount of the air cooled can stay inside the cabinet, resulting in decrease in the inside temperature of the cabinet was achieved. For Case 5-6, Case 10-12, Case 14-15, temperature contours are shown in Figure 5.

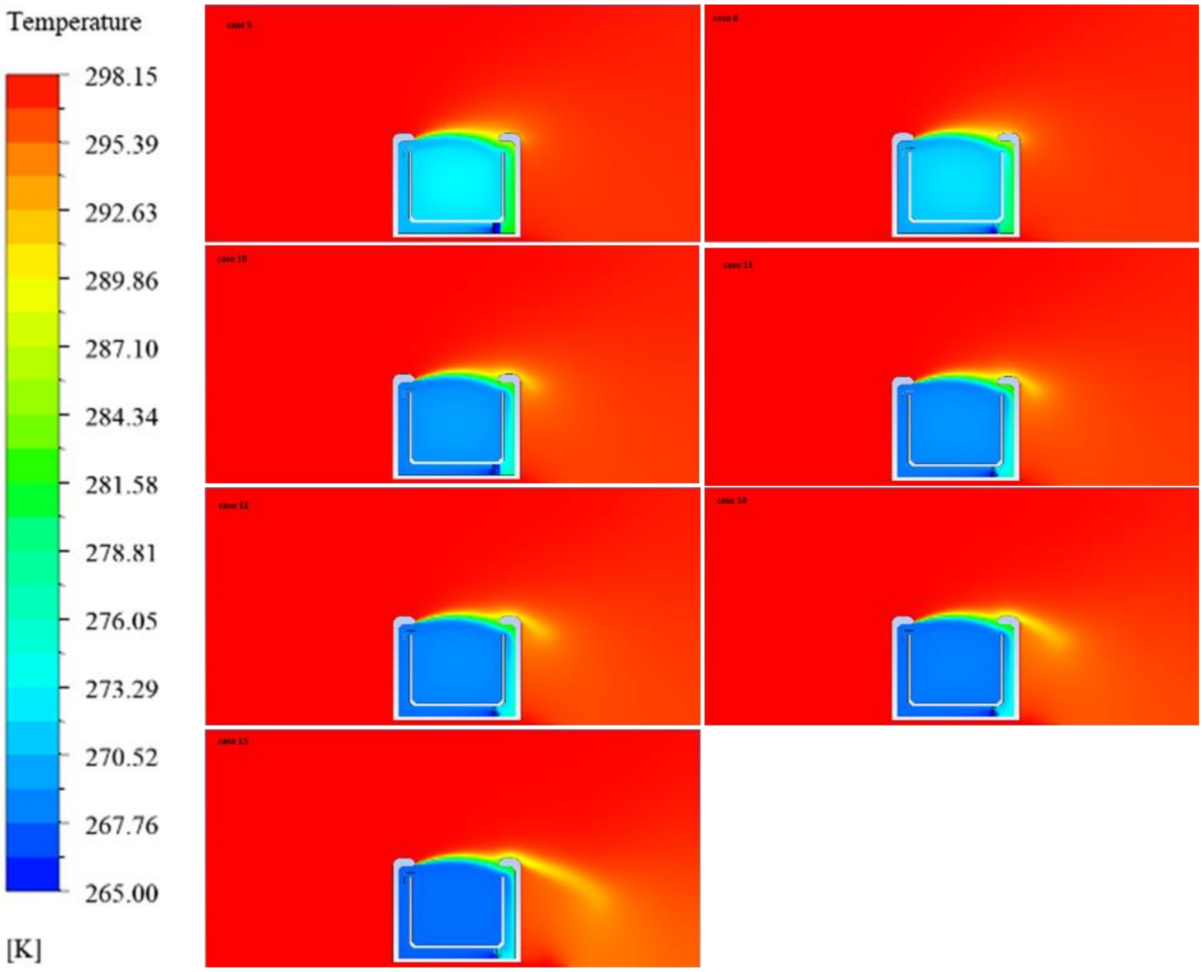

Figure 5. *Temperature contours for Case 5-6, Case 10-12, and Case 14-15*

For Case 5-6, Case 10-12, Case 14-15, velocity vectors are shown in Figure 6.

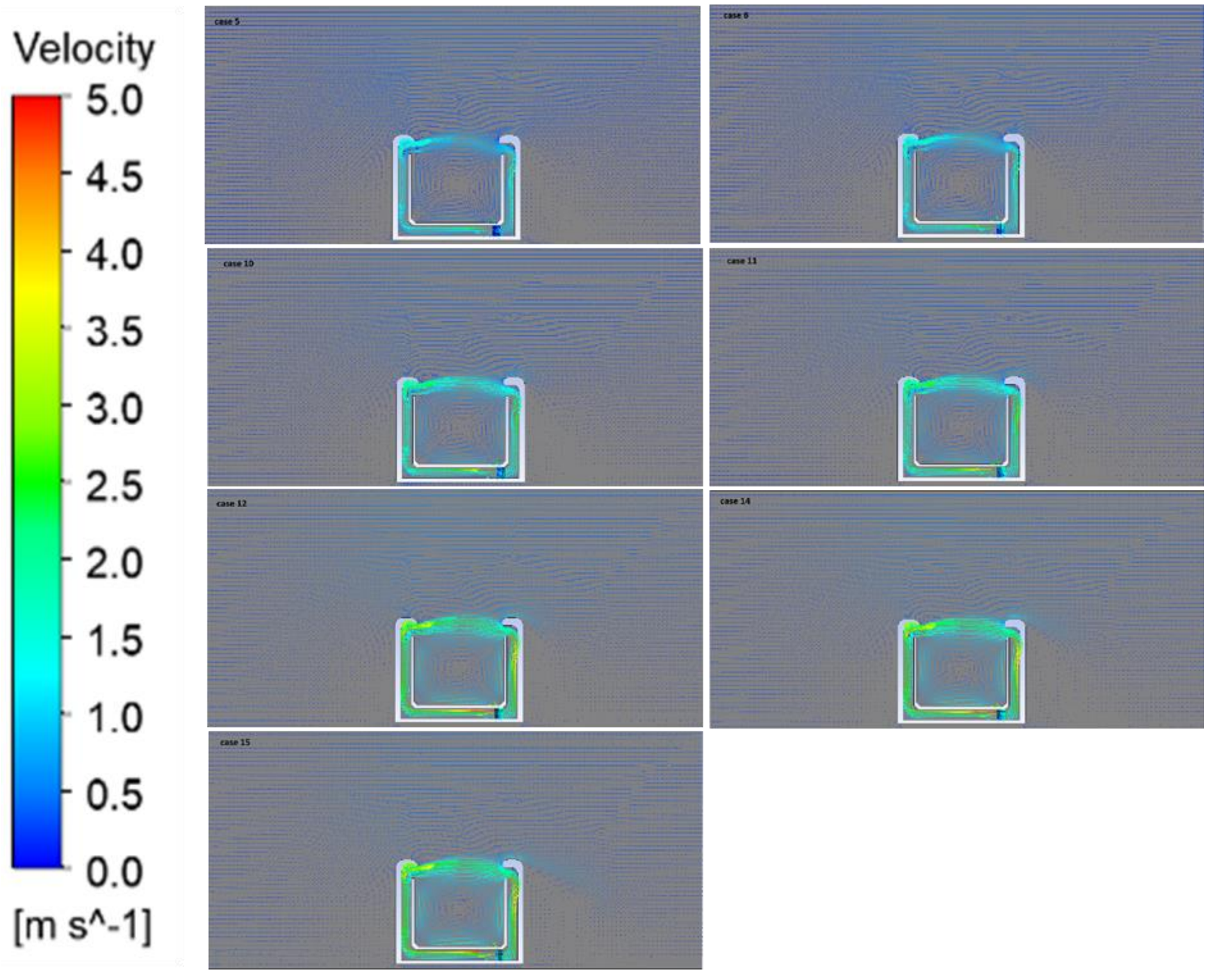

Figure 6. *Velocity vectors for Case 5-6, Case 10-12, and Case 14-15*

When Case 15 having the minimum the inside temperature of the cabinet and Case 5 that has the minimum cooling load are compared, although the airfoil was used for both, the discharge air velocity for Case 15 was more 48.1%, and this situation led to an increase of 5.5% in the cooling load. However, the inside temperature of the cabinet was achieved 1.83°C less for Case 15 compared to that for Case 7. It is consequently suggested that the lower inside temperature, the better cooling products.

CO_2 emissions given in Table 4 have been calculated using the Equation (10). According to the results analyzed, the minimum CO_2 emission has been calculated for Case 5. This value has been calculated as 15.16 kg/day. When it is compared to Case 4 in which the maximum CO_2 release took place, it can be said that 4.73 kg/day CO_2 has been saved. When the negative impact of the emissions released is considered, With design of the airfoil, release of 1726 tones/cabinet CO_2 can be avoided in a year.

Table 4. *The daily CO_2 emission amount for the cabinet with-without airfoil*

Case	Cooling Load (W)	Daily energy consumption of the compressor (kWh)	Daily CO_2 emission amount of the refrigerated display cabinet (kg)
1	1192	7,568	15,742
2	1286	8,165	16,983
3	1308	8,305	17,274
4	1506	9,562	19,889
5	1148	7,289	15,161
6	1157	7,346	15,280
7	1159	7,359	15,306
8	1184	7,517	15,636

9	1185	7,524	15,650
10	1186	7,530	15,663
11	1197	7,600	15,808
12	1198	7,606	15,821
13	1204	7,644	15,900
14	1209	7,676	15,966
15	1215	7,714	16,046

With integration of the airfoil, the minimum CO_2 emission value has been calculated for Case 5. For Case 1-4, one can say that there has been a linear increment from Case 1 to Case 4. In other analyzes (Case 6-15), there has been a slight increase compared to that for Case 5.

Total Display Area (TDA) of the cabinet has been calculated as 1.05 m^2. EEI values for Case 1-15 have also been calculated considering the TDA value calculated and the energy consumption of the cabinet. Table 5 shows the EEI values calculated. As seen from the table, it can be said that energy consumption is directly related to EEI value. With increase in energy consumption, the EEI value increases. As reported in the literature review, the EEI value must be lower than 100 from 2021, and 80 from 2023. According to the values calculated, one can say that the value for Case 4 has been 109.14, and the cabinet representing with Case 4 can not be sold. However, till 2023, the other cabinets designed could be sold. All cabinets representing with all cases have been G class energy label.

Table 5. *EEI values variations*

Case	Energy consumption	EEI
1	7,568	86,38
2	8,165	93,19
3	8,305	94,73
4	9,562	109,14
5	7,289	83,19
6	7,346	83,84
7	7,359	83,99
8	7,517	85,8
9	7,524	85,88
10	7,530	85,94
11	7,600	86,74
12	7,606	86,81
13	7,644	87,25
14	7,676	87,61
15	7,714	88,04

While the average EEI value of case 1-4 was 95.86, the average EEI value of case 5-15 was decreased to 85.92.

4. COMPARISON WITH PREVIOUS STUDIES

The results obtained within the scope of this study were compared with the studies in the literature, and the findings are given in Table 6.

Table 6. *Comparison with previous studies*

References	Key Words	Type of Industrial Cabinet	Main Results
[5]	They modeled through a CFD and compared the results for the cases with and without the air guiding strips in the open vertical type display cabinet	Open vertical type display cabinet	The effect of the use of air directional strips on the front of the cooler shelves on the package temperature and cooling capacity was analyzed, and due to the newly designed model, the package temperatures decreased from 4.7 °C to -0.2 °C and an increase of 34% in cooling capacity was achieved.
[6]	They evaluated the air curtains of horizontal display coolers and used CFD method to make energy efficient design	Open horizontal type display cabinet	They showed that a lower air curtain and uniformity of speed can effectively shorten the main axis of the air curtain and reduce the cooling load.
[20]	An open type cabinet was modeled through a computational fluid dynamics, and tests were performed according to ISO 23953 standards. The tests carried out were evaluated, and as a result of the evaluation, the relevant parameters were determined for the optimization of the ideal air curtain, and its effect on the instant cooling capacity was observed.	Open type cabinet with multi-shelf	As a result of the computational fluid dynamics analyzes and tests carried out, it has been observed that the air curtain provides energy savings of approximately 14% by improving the air curtain.
[21]	In this study, CFD analyzes were made for single-jet, two-jet and three-jet systems in the air curtain of industrial cabinets. For 22, 25, 28 and 31°C values of the ambient temperature, the results of temperature changes obtained at 15 different points in the cooling cabinet were evaluated when single, two and three jet systems were active.	Open type vertical cabinet	The optimum values for the single-jet system in the air curtain, the temperature value of the air supplied from the jet is 1.5 ºC, the optimum values for the two-jet system, the temperature values of the air supplied from the jets are 25ºC and 0ºC at the outer and middle vents, respectively, and the optimum values for the three-jet system are the outer, middle and were found to be 25.3 and 3ºC, respectively, in the interior vents. It has been observed that single-jet and two-jet systems are weak systems at high ambient temperatures and speeds, whereas three-jet systems provide the desired storage temperatures for the products even at high temperatures and speeds.
This Study	In the study, 15 cases in which the airfoil has been used and not used were analyzed through CFD. The first 4 cases in which the airfoil was not used were tested at different air	Open type horizontal display cabinet	The cabinet air temperatures and the cabinet cooling loads were evaluated. Compared to the Case 7, which uses the airfoil, and the Case 1, which has the same air velocity value, it was concluded that the inside temperature of the cabinet decreased by 3.5°C, and the cooling load decreased by

	velocities. Then, an airfoil was integrated to the cabinet, and CFD studies continued at different air velocities. The obtained results were evaluated.		2.82%. When Case 15 and Case 7 are compared, in which both airfoils are used but air velocities are different, it is seen that the cooling load for Case 15 is 5.5% higher than Case 7, but the inside temperature value is 1.83°C lower.

When the studies on open display type industrial refrigerators are examined, it is seen that the new type of airfoil structure applied within the scope of this study contributes to the air flow structure in the air curtain both in terms of cooling load and refrigerated cabinet temperature.

5. CONCLUSION

In this study, an air curtain structure using 15 different case in horizontal type display refrigerator were analyzed with the CFD model. The conclusions of this study can be summarized as follows:

- new type air foil for air curtain structure provides 3.82% cooling capacity reduction.
- an eco-friendly and applicable air curtain structure was achieved. With design of the airfoil, release of 1726 tones/cabinet CO2 reduced yearly.
- average EEI value in cases 5-15 is reduced by 10.37 % compared to the average EEI value in cases 1-4.
- It has been demonstrated that air foil provides benefits both in terms of reducing the cooling load (infiltration heat load) and refrigerated cabinet temperatures.

The results obtained in terms of air curtain structure, air flow and cooling technique will benefit researchers.

Symbol and Abbreviations

Symbol

C_p	Specific heat capacity (kJ/kgK)
h	Enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/h)
p	Pressure (N/m^2)
q''	Heat generated per unit volume
q_x	Heat flux in x direction (W/m^2)
q_y	Heat flux y direction (W/m^2)
q_z	Heat flux in z direction (W/m^2)
$\dot{Q}_{conduction}$	Heat transfer by conduction (W)
$\dot{Q}_e$	Cooling capacity (W)
$\dot{Q}_{infiltration}$	Heat transfer by infiltration (W)
$\dot{Q}_{radiation}$	Heat transfer by radiation (W)
t	Time (s)
T	Temperature (K)
u	x component respectively of the velocity (m/s)
v	y component respectively of the velocity (m/s)
w	z component respectively of the velocity (m/s)
$\dot{W}_c$	Compressor power (W)
X	x direction body force per unit volume
Y	y direction body force per unit volume
Z	z direction body force per unit volume
ΦCO_2	Amount of CO_2 (kg CO_2/h)

ΨCO_2	Average amount of CO_2 emissions

Greek symbols

μ	Dynamic viscosity (kg/m.s)
ρ	Density (kg/m^3)

Abbreviations

AE	Annual energy consumption (kWh/year)
C	Coefficient
CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
COP	Coefficient of performance
EEI	Energy efficiency index
E_{daily}	Daily energy consumption (kWh)
SAE	Represents the reference value of the annual energy (kWh/year)
P	Coefficient
M	Coefficient
N	Coefficient
Y	Total display area (m^2)

ACKNOWLEDGEMENTS

We thank Nurdil Refrigeration Inc. for its contributions to this work. We also thank Gazi University for allowing to use Ansys Fluent program in modeling studies.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] Commission Regulation (EU) 2019/2024 of 1 October 2019 laying down ecodesign requirements for refrigerating appliances with a direct sales function pursuant to Directive 2009/125/EC of the European Parliament and of the Council. (2019, 1 October). Office Journal of the Europian Union (L 315).

[2] Doğrudan Satış İşlevli Soğutma Cihazlarının Çevreye Duyarlı Tasarım Gerekliliklerine Dair Tebliğ (2019/2024/Ab) (Sgm: 2021/9) (2021, 25 Mart). Resmi Gazete (Sayı 31434).

[3] Florlu Sera Gazlarına İlişkin Yönetmelik (2018, 4 Ocak), Resmi Gazete (Sayı 30291).

[4] Rossetti, A., Minetto, S., and Marinetti, S., "Numerical modelling and validation of the air flow maldistribution in the cooling duct of a horizontal display cabinet", Applied Thermal Engineering, 87: 24-33, (2015).

[5] Sun, J., Tsamos, K.M., and Tassou, S.A., "CFD comparisons of open-type refrigerated display cabinets with/without air guiding strips", Energy Procedia, 123: 54-61, (2017).

[6] Cui, J., and Wang, S., "Application of CFD in evaluation and energy-efficient design of air curtains for horizontal refrigerated display cases", International Journal of Thermal Sciences, 43(10): 993-1002, (2004).

[7] Wu, Y., Xie, G., Chen, Z., Niu, L., and Sun, D., "An investigation on flowing patterns of the airflow and its characteristics of heat and mass transfer in an island open display cabinet with goods", Applied Thermal Engineering, 24(13): 1945-1957, (2004).

[8] Gonçalves, J.C., Costa, J.J., Figueiredo, A.R., and Lopes, A.M.G., "CFD modelling of aerodynamic sealing by vertical and horizontal air curtains", Energy and Buildings, 52: 153-160, (2012).

[9] Cortella, G., "CFD -aided retail cabinets design", Computers and Electronics in Agriculture, 34(1-3): 43-66, (2002).

[10] Hadawey, A.F., Jaber, T.J., Ghaffar, W.A., and Hasan, A.H.A.M, "Air Curtain Design Optimization of Refrigerated Vertical Display Cabinet using CFD", International Journal of Scientific Engineering and Technology, 1(4): 76-88, (2012).

[11] Gaspar, P.D., Gonçalves, L.C.C., and Pitarma, R.A., "Experimental analysis of the thermal entrainment factor of air curtains in vertical open display cabinets for different ambient air conditions", Applied Thermal Engineering, 31(5): 961-969, (2011).

[12] Field, B.S., and Loth, E., "Entrainment of refrigerated air curtains down a wall", Experimental Thermal and Fluid Science, 30(3): 175-184, (2006).

[13] Cao, Z., Gu, B., Han, H., and Mills, G., "Application of an effective strategy for optimizing the design of air curtains for open vertical refrigerated display cases", International Journal of Thermal Sciences, 49(6): 976-983, (2010).

[14] Moureh, J., and Yataghene, M., "Numerical and experimental investigations on jet characteristics and airflow patterns related to an air curtain subjected to external lateral flow", International Journal of Refrigeration, 67: 355-372, (2016).

[15] Çengel, Y.A., and Cimbala, J.M., Fluid Mechanics Fundamentals and Applications, Second Edition, Palme, Ankara, 468, (2015).

[16] Yamankaradeniz, R., Horuz, İ., Coşkun, S., Kaynaklı Ö., and Yamankaradeniz N., Soğutma Tekniği ve Isı Pompası Uygulamaları 4th Edition, Dora, Bursa, 30-32, (2017).

[17] Sovacool, B.K., "Valuing the greenhouse gas emissions from nuclear power: A critical survey", Energy Policy, 36(8): 2950-2963, (2008).

[18] Tripathi, R., Tiwari, G.N., and Dwivedi, V.K., "Overall energy, exergy and carbon credit analysis of N partially covered photovoltaic thermal (PVT) concentrating collector connected in series", Solar Energy, 136: 260-267, (2016).

[19] 2019/2018 of 11 March 2019 supplementing regulation (EU) 2017/1369 of the european parliament and of the council with regard to energy labelling of refrigerating appliances with a direct sales function, Official Journal of the European Union, (2019).

[20] Balkan, Ç., and Kaynaklı, Ö., "Bir açık tip çok raflı soğutuculu teşhir dolabında tasarım parametrelerinin HAD üzerinde incelenmesi", IV. Uluslararası Katılımlı Anadolu Enerji Sempozyumu, Edirne, 1582-1591, (2018).

[21] Çalışkan, S., Altunok, T., Başkaya, Ş., and Güngüneş, H.M., "Hava perdeli bir ticari soğutma kabininin sayısal analizi" Gazi University Journal of Engineering and Architecture, 26(2): 415-425, (2011).