

Research Article

Development of Deflector Structure and Effects on Performance: Refrigerated Display Cabinet Application

Havva Demirpolat¹, Fatma Nur Erdoğan², Melis Öder^{2*}, Süleyman Erten²

¹Havva Demirpolat, Orcid ID: 0000-0002-2981-9867, hdemirpolat@selcuk.edu.tr

²Fatma Nur Erdoğan, Orcid ID: 0000-0002-8887-6597, fatmanurerdogmus@nurdil.com.tr

²Melis Öder, Orcid ID: 0000-0002-1894-1445, melisoder@nurdil.com.tr

²Süleyman Erten, Orcid ID: 0000-0002-7811-6148, suleymanerten@nurdil.com.tr

*Correspondence: melisoder@nurdil.com.tr; Tel.: +90 5347931805

(First received September 22, 2022 and in final form December 12, 2022)

Reference: Demirpolat H., Erdoğan F. N., Öder M., Erten S Development of Deflector Structure and Effects on Performance: Refrigerated Display Cabinet Application. The European Journal of Research and Development,2(4), 155-168.

Abstract

Air flow is of great importance in terms of energy efficiency and homogeneity of the cooled package temperatures in open type refrigerated display cabinets (RDCs). Deflectors are critical components for air curtains which are provides air directioning to air channel and grill. A new deflector structure was investigated to increase the performance of the air curtain in this study. Current design deflector structure (Design 1) and new design deflector structure (Design 2) were compared for temperatures of air off-air on and energy consumption parameters. Airflow in the new design deflector structure was tested under Class-3 conditions (25 °C temperature and %60 relative humidity) with ISO 23953-2 2015 standard. According to the results obtained the data compared with the current design deflector structure. The thermal performance has been increased by reducing the temperature of the air off by 1.2 °C on average, the air on temperature by an average of 2.05 °C and the average package temperature by %17.8 with the new deflector design. Cooling performance was increased using new deflector structure with effective airflow between the air off and air on. In addition, thanks to Design 2, the annual energy consumption of RDC has been reduced by 10.17% and accordingly the CO₂ emissions released to the environment have been reduced at the same rate.

Keywords: Refrigeration, Open type refrigerated display cabinet, Deflector, Air curtain, Energy Efficiency

1. Introduction

In the commercial refrigeration industry, the energy performance of open type refrigerated display cabinet (RDC) is important. The cooling process mainly consist of cold air flow in the cabinet. The commercial refrigeration process has a significant energy consumption potential. Therefore the energy efficient cooling process and convenient equipment must be designed to maintain products temperature acceptable. Air curtains are considered as a barrier between the cooled cabinet inside and the exterior ambient. But heat gain by infiltration is approximately %70 of the cooling load of RDC in the literature [1].

In order to keep the products in the RDC within the desired temperature range, it is aimed to direct the cold air at the evaporator outlet through the discharge air grille (DAG) to the RDC with high thermal performance of the air curtain. This air guiding part is called a deflector in RDC. The cooled air off from the air duct is directed towards the honeycomb by contacting the deflector. In this way, the air is dragged towards the DAG. Design elements such as designed deflector size, position, angle, etc. are extremely important. Deflector structures used in the literature and their areas of use were investigated. Chen (2009) has worked on improving the air curtain in RDC. In the study, he calculated and compared the H/b (height/width) ratio in three different ways: 10, 15 and 20. When the h/b ratio is 20, the air curtain does not work properly and the temperatures of the packages in the middle and lower parts cannot be kept at the desired levels. However, air curtains with small height/width ratios have been observed to show good insulation performance. The air off angle of the air curtains has been tested as 5° and 10°. When the air off angle is 10°, it is seen that thermal insulation is provided. It has been suggested that the deflector angle should be in the range of 15°-20° to provide better thermal protection [2].

Wu et al. (2020) uniform distribution of gas-liquid flow in variable aperture deflector in parallel flow heat exchanger was investigated. Six deflector structures were studied in the experiment. Deflector structures; Three aperture symmetrical deflector structure (A1 and B1), two aperture symmetrical deflector structure (A2 and B2), and uniform aperture deflector structure (A0 and B0) were compared. In the results of the experiments, it was stated that in the heat exchanger with three deflectors with the same open area, the best gas-liquid homogeneous distribution performance was B1 and the worst one was B0. When the A1 variable aperture deflector heat exchanger is compared with the A0 and A2 structured deflectors, the gas phase irregularity value ranges from 30.8% to 37.2%, 8.7% to 23.4%, and the liquid phase irregularity value to 4%. They observed that it increased from .4 to 21% and from 7.7% to 12.6%. According to these test

results, they reported that the A1 deflector with three aperture symmetrical deflector structure had the best effect [3].

Li et al. (2022) designed four different deflectors to prevent the air flow in the air conditioning unit in a high speed train. The deflector designs made are triangular, right triangle, semi-elliptical and concave. They stated that for the designed triangular, right triangular, semi-elliptical and concave deflectors, the resistance increased by 3.2%, 3.4%, 1.1%, and 5.3%, respectively, compared to the case without the deflector [4].

Gao et al. (2019) stated that by attaching a deflector to the duct fittings, it will reduce the resistance and energy consumption. By examining the position of the deflector at different flow rates, the effect of the energy on the dissipation area was analyzed. In the experiments carried out, a decrease in the resistance of the five different types of deflectors ranging from 5.2% to 38.4% was observed. They emphasized that the placement of the deflector significantly affects the energy consumption [5]. Hadaway et al. (2012) examined the velocity of the air curtain, the width of the air curtain, the angle of discharge of the air, the honeycomb structure for the formation of the air curtain in industrial display type refrigerators with the 3-dimensional u Computational Fluid Dynamics (CFD) method. As a result of the analyzes, the width of the h hunting curtain was changed from 110 mm to 90 mm. The air curtain discharge angle has been reduced from 12 to 8o. As a result of these improvements, the air curtain improved [6]. Shi et al. (2011) experimentally examined the performance of microchannel evaporators with different manifold structures. For the study, 8 evaporator samples with 7 different I/O manifold designs and 5 different rotation manifold designs were made. The results of changes in the cooling capacity and air temperature distribution of the evaporator due to the deflector designs in the I/O manifold and the flow hole arrangements in the return manifold were analyzed. The addition of a deflector to the I/O manifold increases evaporator cost and pressure drop, as well as significantly improved air temperature distribution [7]. Redo et al. (2020) added a deflector with a vertical header and divided the vertical collector tubes into two equal chambers. They reported that the double-chamber cap produced a higher Reynolds count for the liquid, pushed the liquid into a higher channel, and reduced the relative standard deviation at the lower inlet mass flow by approximately %30 to %80 [8].

Wang et al. (2021) focused on optimizing air curtains in RDC. Two dimensionless parameters describing the profile of the air curtain are proposed based on CFD and experimental results. The effect of air flow, the length and location of the holes in the cabinet rear panel, on the structure of the air curtain was investigated. In this study, it was stated that the speed limit of the air curtain should be between 0.8 and 0.9 m/s. They

suggested that the fan should not be enlarged when the integrity of the air curtain and the temperatures of the products in the cabinet are homogeneous [9].

Li et al. (2022) examined the performance of double air curtains in an RDC. In the study, the effects of single and double air curtains on system performance were compared. It is stated that ambient air has decisive effects for both air curtains, and that double air curtains can provide energy savings of up to %29, %30.6 and %41.6 for Condition 2, Condition 3 and Situation 6 respectively compared to a single air curtain [10]. Yuan et al. (2022) investigated the effects of fin use in RDC. The RDC with and without fins was tested and compared under Class-3 conditions (25°C and %60 RH). They found that the maximum temperature difference of the packages in the test chamber was reduced by 0.6°C and the total energy consumption by %21.7 compared to the refrigerant used in the fin coolant [11].

Design elements such as the size, position and angle of the designed deflector are important as can be seen from literature studies. The fact that the flow of air off is not effective at the intersection point of the deflector and the honeycomb adversely affects the cooling performance. Accordingly, the desired air jet effect cannot be created in the air curtains. In this case, a new deflector structure is needed to ensure that the air creates a jet effect. In addition, the homogeneity of the temperature values of the foods close to the air curtain in the front part and the food in the back and the thermal balance (homogeneously between "M1" -1, +5 °C temperature limits) should be ensured at all points in the RDC.

In this study, there improvements were aimed;

- Providing homogeneous temperature distribution in refrigerated cabinet,
- Increasing thermal efficiency,
- The package temperatures kept more precisely within the standard range while thermal balance is providing in the temperatures and relative humidity,
- Reduction of air temperature and relative humidity in cabinet with less energy consumption

in the RDC.

2. Materials and Methods

2.1. Theoretical Analysis

In the mechanical vapor compression refrigeration cycle, the cooling capacity is calculated with the following equation [12].

$$\dot{Q}_e = \dot{m}_a (h_{inlet} - h_{outlet}) \quad (1)$$

The sealing ability of an air curtain depends on the size of the momentum and transverse forces. The dimensionless ratio is known as the modulus of momentum and transverse force orientation. The orientation module of the air curtain is calculated with the help of the equation given below [6].

$$D_m = \frac{\rho_o b_o U_o^2}{gH^2(p_c - p_w)} \quad (2)$$

When the air density at a given atmospheric pressure is directly proportional to the absolute temperature, the orientation module of the h, the orientation module of the hunting curtain is found with the help of the following equation.

$$D_m = \frac{b_o U_o^2}{gH^2 \left[\left(\frac{T_o}{T_c} - \frac{T_o}{T_w} \right) \right]} \quad (3)$$

The velocity of the air curtain is found by the equation given below.

$$U_o^2 = \frac{D_m g H^2 \left[\left(\frac{T_o}{T_c} - \frac{T_o}{T_w} \right) \right]}{b_o} \quad (4)$$

For the best sealing value according to H/b_o , its value should be between 0.14 – 0.18. If D_m the value of H/b_o is between 16 and 64, it is calculated as follows [13]:

$$D_m = 0,257 (H/b_o)^{-0,1336} \quad (5)$$

The initial velocity of the air curtain is found with the help of the following equation.

$$U_o^2 = \frac{0,257 (H/b_o)^{-0,1336} gH^2 \left[\left(\frac{T_o}{T_c} - \frac{T_o}{T_w} \right) \right]}{b_o} \quad (6)$$

If the H/b_o value is less than 16 and the orientation module is 0.18, the air curtain velocity is found with the help of the equation given below.

$$U_o^2 = \frac{0,18gH^2 \left[\left(\frac{T_o}{T_c} - \frac{T_o}{T_w} \right) \right]}{b_o} \quad (7)$$

The cooling capacities of the two systems using identical evaporators were calculated with the help of Equation 1. Since the H/b_o ratio of the DAG in the conventional and new system is between 0.14 and 0.18, the routing module (D_m) was calculated using equation 5. Using Equation 4 with the calculated D_m value, the air off rate U_o was found. Equations 2 and 3 can be used when the H/b_o ratio is not between 0.14 and 0.18.

The energy efficiency index (EEI) value can be calculated with Equation 8. The AE value in the equation represents the annual energy consumption (kWh/year), the SAE value represents the reference value of the annual energy consumption amount [14].

$$EEI = \frac{AE}{SAE} \quad (8)$$

CO₂ emission can be calculated by Equation 9 [15].

$$\phi_{CO_2} = \Psi_{CO_2} \times \dot{W}_C \quad (9)$$

Within the scope of this study, analysis of Design 1 (Figure 1) and test activities were carried out according to ISO 23953-2:2015 standard Class 3 conditions (25 °C, 60% RH) conditions. As a result of the analyzes and test activities, it was observed that the air velocity value was lower than desired. For this reason, Design 2 was designed (Figure 2).

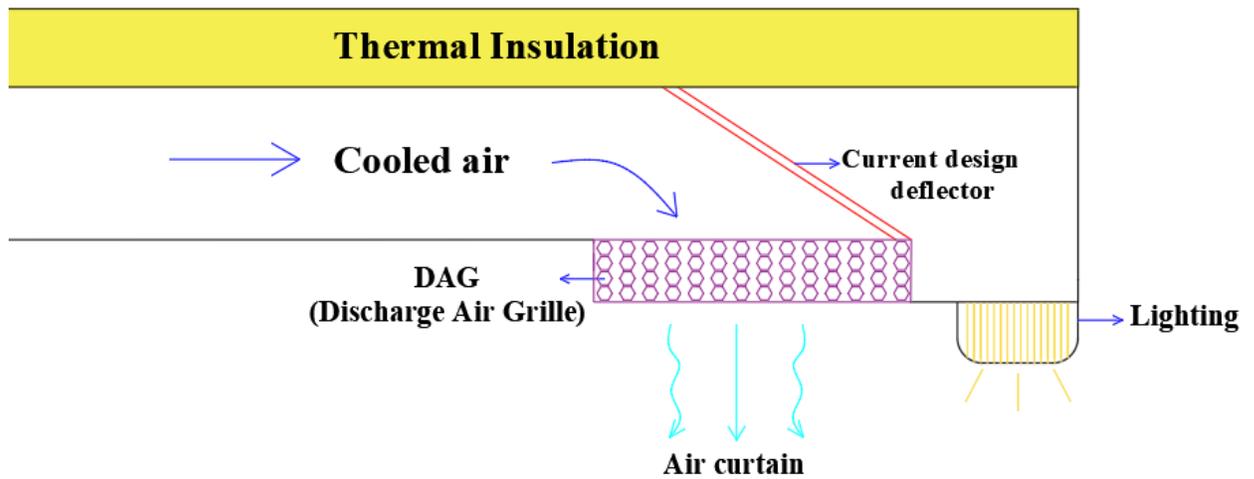


Figure 1. Design 1

Due to the narrow angle and inclination of the Design 1, the air off cannot be effectively dragged into the honeycomb. Therefore, the velocity of the air off is low and the infiltration rate in the air curtain is high. The newly designed deflector has high thermal performance thanks to its curved structure. Thanks to this structure, the air flow area is narrowed and the honeycomb section is reduced compared to the existing system. Thus, the air off was dragged more easily and the desired air jet effect was achieved on the air curtain by gaining momentum.

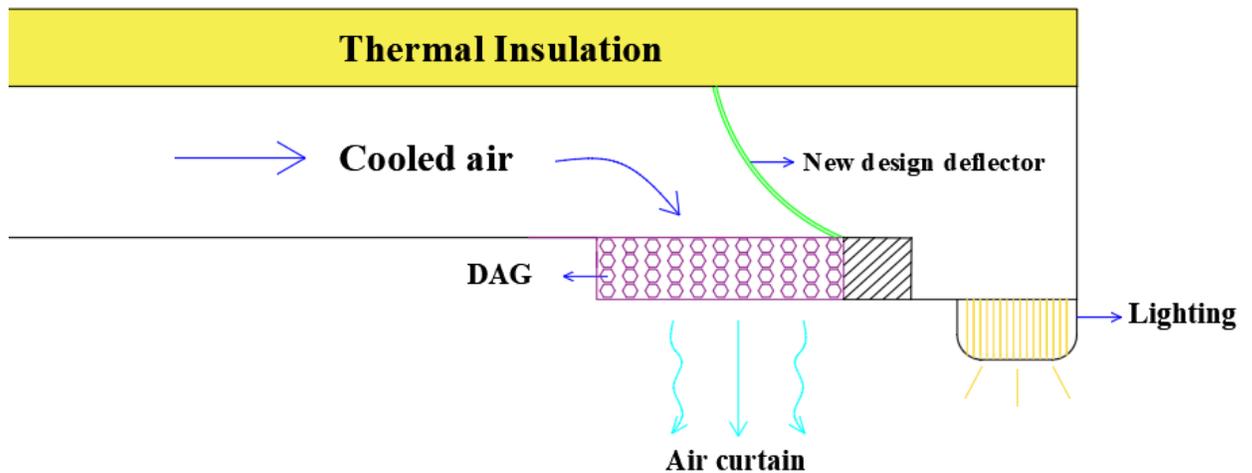


Figure 2. Design 2

Parameters, such as air on temperature, air off velocity and temperature, cooling air temperature and relative humidity values affects the air curtain thermal efficiency between the RDC and the ambient air for the Design 1 and the Design 2. Further, it is also important to maintain the products in the desired temperature class in accordance with

the ISO 23953-2:2015 standard. Thermal analyses were performed with temperature, humidity and air velocity measurements for the Design 2. The refrigerated display cabinet was tested under Class-3 conditions in accordance with ISO 23953-2:2015 standard and the results obtained were analyzed by measuring the air on – air off temperature and velocity, test package temperatures. The test packages were placed in the RDC in accordance with the standard and the temperature values in 8 test packages in front of the rack were recorded. Side section technical drawing and test package layout of the RDC is given in Figure 3.

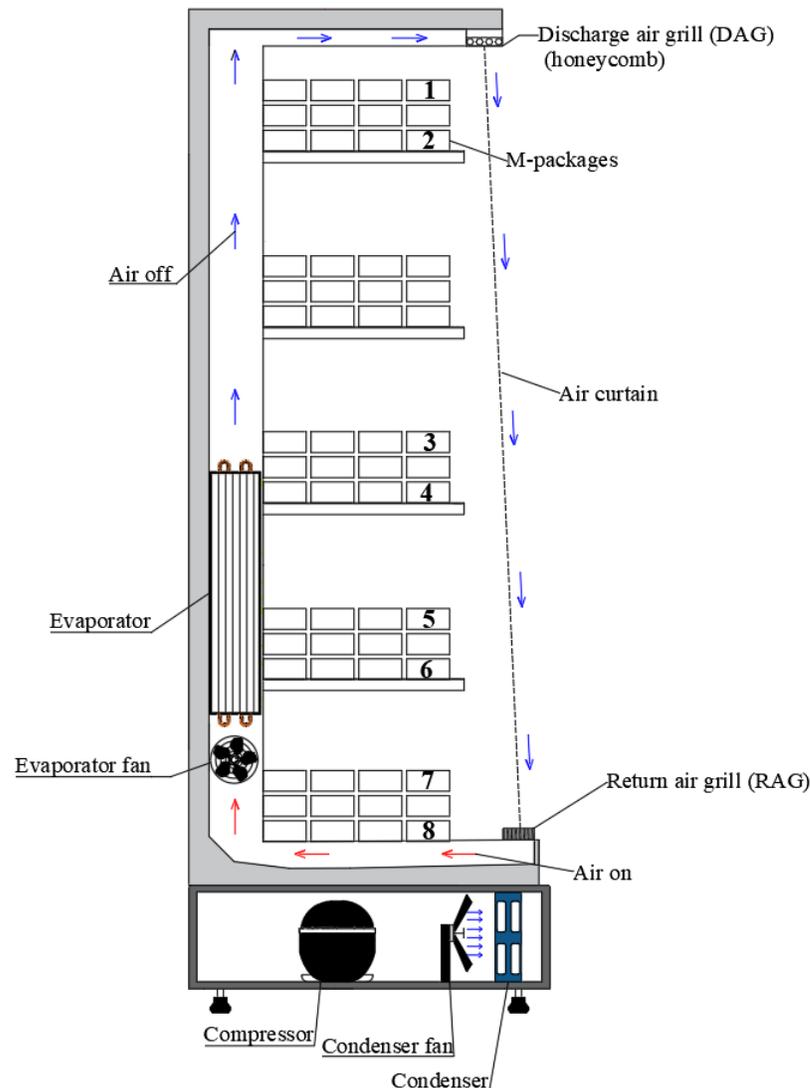


Figure 3. Side section technical drawing of the RDC and test package placement

The Design 1 and Design 2 were analyzed with the help of the equations given in the theoretical analysis section. Experiments were carried out according to the ISO 23953-

2:2015 standard. As a result of the analysis carried out, the H/b_0 recovery rate of the newly designed deflector structure compared to the traditional deflector structure was % 25, the deflection module (D_m) recovery rate was % 2.3 and the initial velocity of the air curtain (U_0) recovery rate was % 10.1.

3. Results

In this study, two different deflector design; the Design 1 of the RDC and the Design 2 were analyzed. Deflectors were tested under Class-3 conditions in accordance with ISO 23953-2:2015 standard. Parameters, such temperature, velocity and relative humidity values were analyzed as a result of the tests.

Figure 4 provides a comparative air on – air off temperature graph of the existing and Design 2. The air off temperatures on the left and right sides of the Design 1 are shown as 1.2 °C and 1.5 °C respectively, and the air on temperatures on the left and right sides are shown as 11.5 °C and 12.1 °C. The temperature graph of the air on – air off of the Design 2 is given. The air off temperatures on the left and right sides of the Design 2 are shown as 0.1 °C and 0.2 °C respectively, and the suction temperatures on the left and right sides are 9.5 °C and 10 °C.

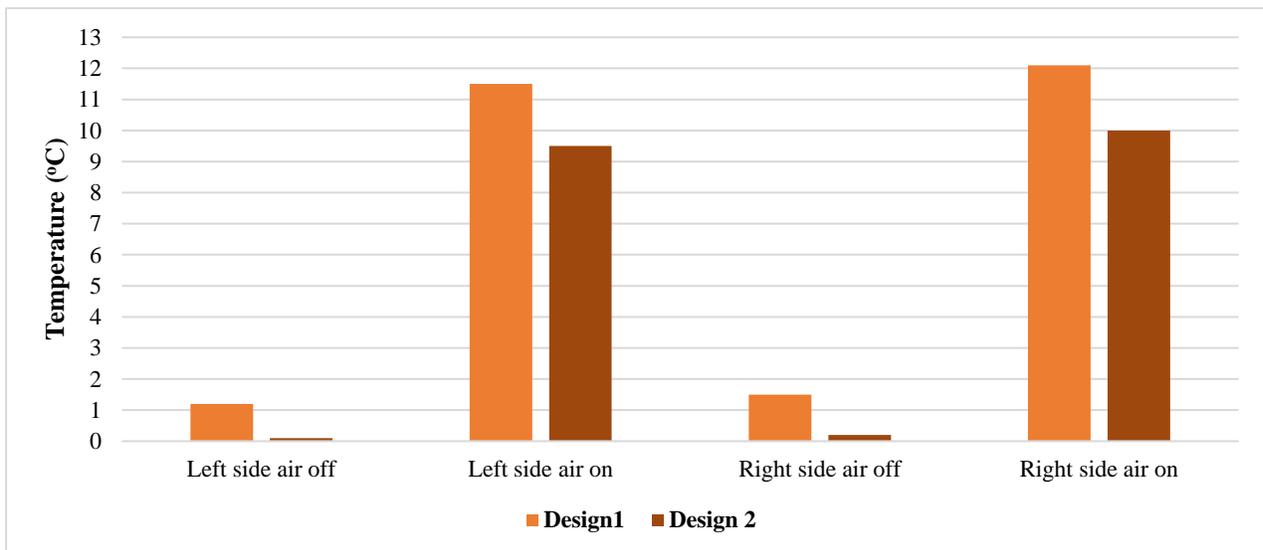


Figure 4. Comparison air on and air off temperature graph of existing and Design 2

Thanks to the Design 2, an average reduction of 1.2 °C in air off temperature and an average reduction of 2.05 °C in air on temperature has been achieved. Effective cooling process has possible by creating air jet effect to the products. At the same time, the difference between the air off temperature on the right and left sides is reduced, ensuring that the products placed in the RDC is cooled more homogeneously.

Air velocities were measured from the left, middle and right center points in the system DAG using the existing and Design 2. These measurement points are given in Figure 5.

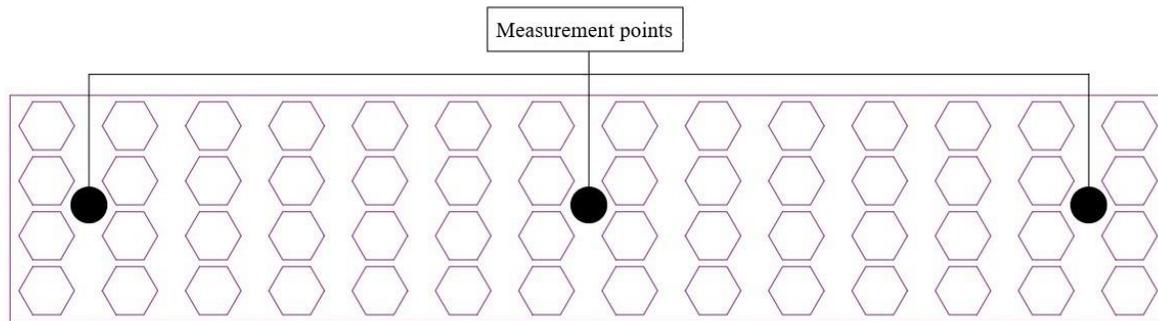


Figure 5. Air velocity measurement points

The air off velocity graph of the Design 1 is given in Figure 6. The average air off velocity values measured from the left, middle and right sides are 0.44 m/s, 0.43 m/s and 0.44 m/s respectively.

Thanks to the design, the velocity of the air off has increased. The average air off velocity values measured from the left, middle and right sides were measured as 0.47 m/s, 0.5 m/s and 0.47 m/s respectively.

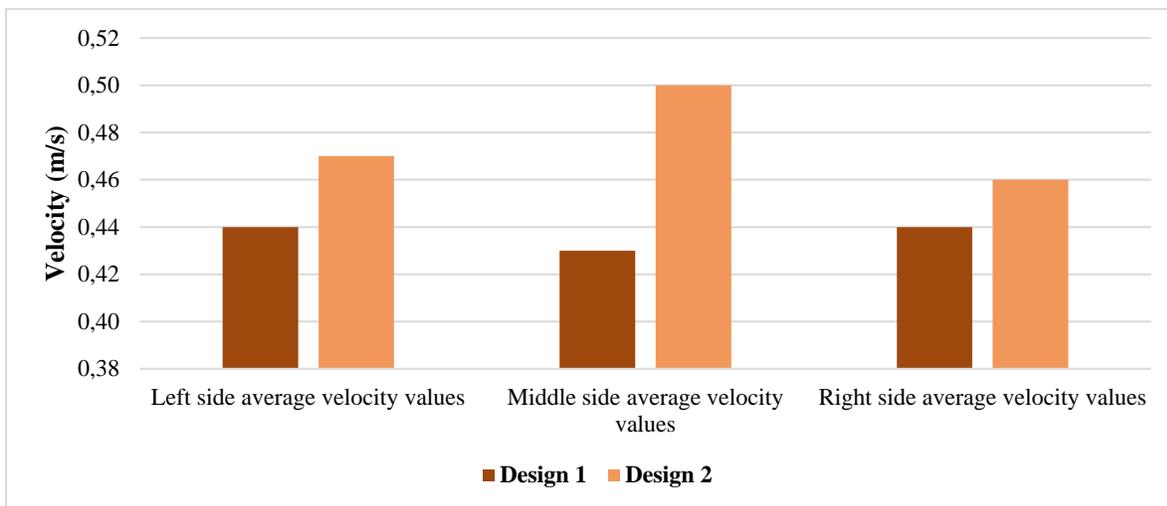


Figure 6. Air off velocity values in existing and newly designed deflector systems

As the air velocity increased, the air curtain improved and the infiltration rate decreased. Thanks to the Design 2, improvements in air curtain, air off temperature and velocity, as well as a decrease of %51.2 in the cabinet temperature and %12.8 in relative humidity value compared to the Design 1, were observed.

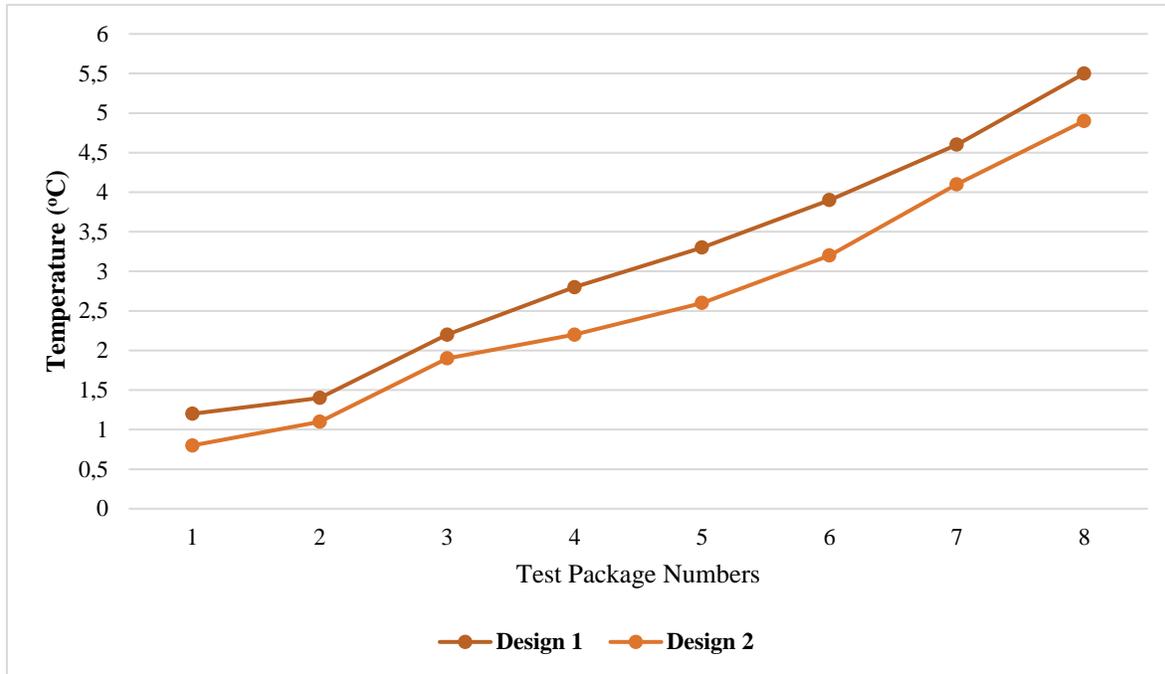


Figure 7. Air off temperature values in existing and Design 2

The temperature graph of the test package of the existing and Design 2 is seen in Figure 7. Thanks to the Design 2, average package temperatures are reduced by %17.8. With the formation of the air jet effect in the air curtain, the packages 7 and 8 given in Figure 3 with the highest package temperatures were kept within the temperature range required by the standard.

Zhijuan et al. (2013) examined the relationship between cooled package temperature and environment. They noted that when the velocity of the air curtain increased by 0.15 m/s, there was a decrease in the temperature of the packages by 0.2 °C ~ 1.1 °C [16]. Wu et al. (2016) reported that the effect and performance of the bending point positions of the deflector on the velocity distribution at the honeycomb output was at an average feed air velocity of 0.78 m/s, while the average product temperature could be reduced by 0.2 K without increasing the thermal drag factor [17].

Table 1. Table of parameters comparing Design 1 and Design 2

Parameters	Design 1	Design 2
Energy Consumption (kWh/annum)	10767,5	9672,5
EI	48,4	43,4
CO₂ Emission (kgCO₂/annum)	22396,4	20118,8

Thanks to the new deflector design made in Design 2, the annual energy consumption of the RDC calculated according to the ISO 23953-2:2015 standard has been reduced by 10.17% as seen in Table 1. While the EEI value calculated using equation 8 based on annual energy consumption was 48.4 in Design 1, it was reduced to 43.4 with Design 2. In addition, 2277,6 kg CO₂ emissions have been reduced by using Design 2, of per year for just one RDC.

Consequently, when the average air off velocity in the middle increased by 0.07 m/s, the temperature of the packages on the 3rd shelf decrease by 0.2 °C ~ 0.6 °C. Thus new design deflector Design 2 supports the improvement of air curtain performance and provides steady state thermal conditions cabinet inside. Discussion and Conclusion

In this study, two different deflector designs; first one currently used Design 1 and newly designed Design 2 and their performance are investigated. The results obtained can be outlined as follows:

- The temperature of the air off from the refrigerant cabinet decreased by an average of 1.2 °C and the air on temperature decreased by an average of 2.05 °C. Thus, lower temperature air is sent to the products in the RDC and the cooling performance is increased.
- At the same time, the difference between the air off temperature on the right and left sides is reduced, ensuring that the products placed in the RDC are cooled more homogeneously.
- With the Design 2, the relative humidity value is reduced by %12.8 and the cabinet temperature value is reduced by %51.2.
- Thanks to the Design 2, the average air off velocity values have increased by %10.1. Thanks to the Design 2, the air off was more easily dragged and accelerated, contributing to the formation of the air jet effect in the air curtain, thus creating a more effective air curtain.
- With Design 2, the annual energy consumption of the RDC has been reduced by 1095 kWh.
- The CO₂ emissions decreases by 10.17% per year with the Design 2.

4. Acknowledge

We would like to thank Nurdil Refrigeration Inc. for their contributions.

References

- [1] Laguerre, O., Operation (2015), Design and performance of retail display cabinets. Evans, J,A, Foster, A,M, editors. Sustainable Retail Refrigeration, UK: Wiley Blackwell, 17-31.
- [2] Chen, Y,G, (2009). Parametric evaluation of refrigerated air curtains for thermal insulation. International Journal of Thermal Sciences, 48(10), 1988-1996.
- [3] Wu, X, Gao, Z, Meng, H, Wang, Y, Cheng, C. (2020). Experimental study on the uniform distribution of gas-liquid two-phase flow in a variable-aperture deflector in a parallel flow heat exchanger. International Journal of Heat and Mass Transfer, 150, 119353.
- [4] Li, X., Wu, F., Tao, Y., Yang, M., Xu, R., Vainchtein, D. (2022). Numerical investigation of flow deflectors for the improvement of condensing air flux through the air-conditioning unit on high-velocity trains. Building and Environment, 215, 108949.
- [5] Gao, R., Li, H., Li, A., Liu, K., Yu, S., Deng, B. (2019). Applicability study of a deflector in ventilation and air conditioning duct tees based on an analysis of energy dissipation. Journal of Wind Engineering and Industrial Aerodynamics, 184, 256-264.
- [6] Hadawey, A, F, Jaber, TJ, Ghaffar, WA, Hasan, AHAM. (2012). Air curtain design optimization of refrigerated vertical display cabinet using CFD. International Journal of Scientific Engineering and Technology,1(4), 76-88.
- [7] Shi, J, Qu, X, Qi, Z, Chen, J. (2011). Investigating performance of microchannel evaporators with different manifold structures. International Journal of Refrigeration, 34(1), 292-302.
- [8] Redo, MA, Jeong, J, Yamaguchi, S, Saito, K, Kim H. (2020). Characterization and improvement of flow distribution in a vertical dual-compartment header of a microchannel heat exchanger. International Journal of Refrigeration, 116, 36-48.
- [9] Wang, Y., Qian, S., Xu, J., Li, L., Dou, X., Li, X., Yan, G., Yu, J., (2021). Numerical study on the air curtain characteristics of a dual-temperature open display cabinet. International Journal of Refrigeration, 126, 23-34.
- [10] Li, X., Zhang, Z., Liu, H., Hu, X., Liu, S., Xu, Z., Wang, Q. (2022). Performance of an open refrigerated display cabinet with two air curtains. Applied Thermal Engineering, 212, 118549.
- [11] Yuan, P, Zeng, QH, Wu, YX, Lu, YL, Hu, CL, Sun, H, C, Tao, W, Q. (2022). Experimental study of using aerofoils in a refrigerated display cabinet. International Journal of Thermofluids, 14, 100140.
- [12] Cengel, AY, Boles, AM. (2008). Thermodynamics an engineering approach. İstanbul, TURKEY: Literatur Publishing.
- [13] Hayes, FC. (1969). Heat transfer characteristics of air curtain. ASHRAE Transactions, 153-167.
- [14] Commission Delegated Regulation (EU) 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. Office Journal of the European Union. Available from:
http://data.europa.eu/eli/reg_del/2019/2018/oj

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

[16] Zhijuan, C, Xuehong, W, Yanli, L, Qiuyang, M, Wenhui, Z. (2013). Numerical simulation on the food package temperature in refrigerated display cabinet influenced by indoor environment. *Advances in Mechanical Engineering*, 5, 1-7.

[17] Wu, X.,H., Chang, Z.,J., Ma, Q.,Y., Lu, Y.,L., Yin, X.,M., (2016). Optimization and investigation of the effect of velocity distribution of air curtains on the performance of food refrigerated display cabinets. *Heat and Mass Transfer*, 52, 1633-1647.