Optimization of Cooling Performance of Horizontal Commercial Refrigerator Prototype with Mathematical Modeling

Zafer Kahraman[1], Murat Hacı[1], Hakan Serhad Soyhan[2,3]
Öztiryakiler Madeni Eşya San. ve Tic. A.Ş, R&D Technology Center, 34500 Büyükçekmece, İstanbul, Turkey[1]
Sakarya University, Mechanical Engineering Department, Esentepe Campus, Sakarya, Turkey[2]
Sakarya University, YAM Research Center, Esentepe Campus, Sakarya, Turkey [3]
zkahraman@oztiryakiler.com.tr

Abstract: *In recent years, the problem of food safety and traceability has been one of the difficulties faced by restaurant and hotel businesses. Food spoilage can occur at any stage of the food chain; most of all food spoilage is due to improper storage conditions in refrigerators. Increasing attention to food quality and safety requires the development of sensitive and reliable analysis methods as well as innovative technologies for maintaining freshness and food quality. Freshness is a factor that has both health qualities and features that affect customer satisfaction and business profitability. Within the scope of this study, simulation studies were carried out to improve the cooling performance with mathematical modeling on a horizontal commercial refrigerator (operating temperature: -2/+8°C) prototype. Along with the original design, evaluations were made with mathematical modeling according to many different variables (temperature, airflow distribution, etc.) that affect the cooling performance, and R&D gains were achieved in developing the prototype according to the most suitable working conditions.*

Keywords: *COMMERCIAL REFRIGERATOR, ENERGY EFFICIENCY, MATHEMATICAL MODELING*

1. Introduction

Commercial cooler units are widely used in large enterprises (restaurants, hotels, shopping malls, dormitories, etc.) to keep food and beverages in suitable conditions for a long time. In particular, research and developments are continued on cooling products to ensure that the food chain is not interrupted and to provide adequate cooling properties according to many variable parameters (eg refrigerant [1-4], different condenser [5-7], evaporators [8-10] and compressors [11-13], etc.).

Our company's refrigerator products include commercial refrigerators and deep freezers (in different models and capacities). Within the scope of this study, activities aimed at improving the cooling performance were carried out with the original designs to be obtained by mathematical modeling and simulation studies on the horizontal-type refrigerator.

Since most of the studies in the literature are related to domestic refrigerator products, it has been determined that the studies on commercial products are limited. Various studies from literature research in this field in relation to refrigerant products are summarized below.

Mathematical applications for thermal analysis were carried out by Ledesma and Belman in order to keep the food in the fresh food compartment in the most suitable conditions by replacing the glass-sectioned shelves of the domestic refrigerator. The image of the displacement of the glass shelves for the thermal behavior examinations in the different compartments in the refrigerator is given in Fig. 1 [14].

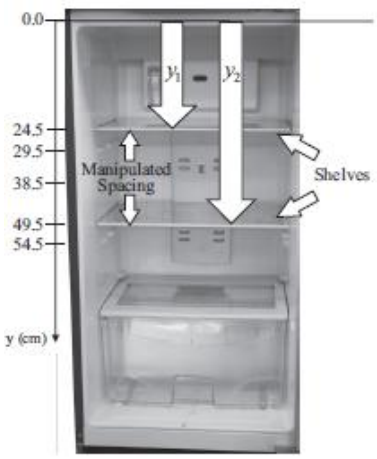

Fig. 1 *Position of shelves (y_1 and y_2) and manipulated spacing in a domestic refrigerator [14].*

Tests were carried out to evaluate the thermal difference of the domestic refrigerator according to the change of compartments. In the tests, the refrigerator was operated at a constant room temperature of 294 K ± 1.5 K and a relative humidity of 60 ± 5%. Evaluations were made to determine suitable shelf locations with 2D color temperature variance maps. A thermal map representing the temperature means in the fresh food compartment when the position of the glass shelves shown in Fig. 1 is changed (y_1 and y_2) is given in Fig. 2. High temperatures are shown in black. In contrast, the lowest temperatures (-3.3°C) are shown in dark blue [14].

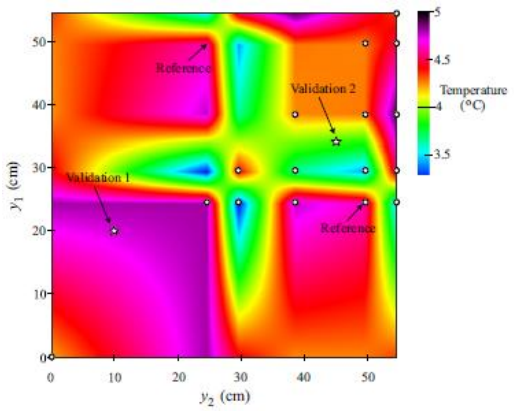

Fig. 2 *Temperature mean in the fresh food compartment of the domestic refrigerator. [14].*

Roccate and his work group evaluated probability density distributions for domestic refrigerator temperatures and storage times of refrigerated foods with long or short expiration dates for northern and southern European countries. They reported that storage time and temperature stand out as the two main factors affecting microbial growth and that there may be different approaches according to the purpose within the framework of food safety assessment. They emphasized the importance of shelf life studies and food safety risk assessments in domestic refrigerators [15].

Belman and Munoz analyzed a refrigerator compartment's flow and thermal behavior, where the cooling effect is based on diffusion-absorption technology using CDF. They compared the thermal behavior of a plate-evaporator design with a finned surface (reference refrigerator) and a plate-evaporator with a smooth surface (recommended design). The refrigerator's energy performance was analyzed according to the design of the plate evaporator [16].

A comparative analysis of the COP was made based on the design of the plate evaporator, and the cooling capacity of the refrigerator differed by about 0.5 W, while the COP difference was determined as 0.008. With this result, it was concluded that the plate evaporator design affected the thermal and energy performance of the refrigerator at a minimum level [16].

Belman and his work group evaluated various parameters that could increase the energy efficiency of a household refrigerator. It has been reported that the domestic refrigerator includes cabinet improvements (insulation, magnetic seals), refrigeration system improvements (adequate performance of components, use of harmless refrigerants), mechanism improvements (defrosting, temperature control), and minimal thermal stratification in compartments [17].

Chen and his work group were evaluated by comparing the modified ejector-enhanced dual temperature refrigeration cycle (MERC), and the basic ejector-enhanced dual temperature refrigeration cycle (BERC) with cycle performance by performing thermodynamic modeling with energetic and exergetic analysis methods. With the simulation data, they determined that the COP (coefficient of performance) and q_{ev} (volumetric refrigeration capacity ($kJ.m^{-3}$) values of MERC improved by 23.1% and 34.7% compared to BERC under general operating conditions of domestic refrigerator/freezer. The comparison of exergy destruction (E_{xd}) between the modified ejector-enhanced dual temperature refrigeration cycle (MERC) and basic ejector-enhanced dual temperature refrigeration cycle (BERC) is given in Fig. 3 [18].

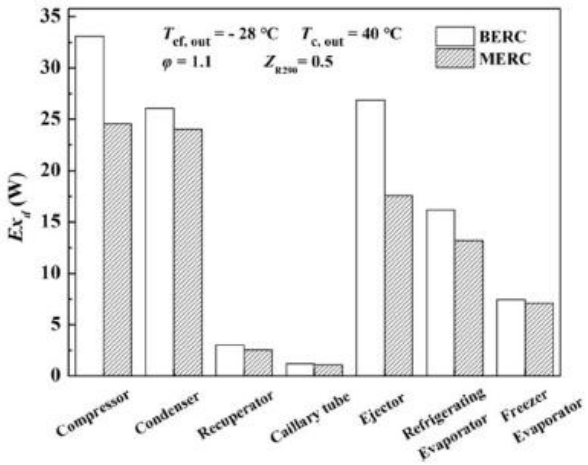

Fig. 3 *Comparison of exergy destruction values between MERC and BERC (Z: mass fraction of R290 in the mixture, φ: cooling capacity ratio) [18].*

Each component (see Fig. 3) of the modified ejector enhanced dual temperature refrigeration cycle (MERC) shows lower levels of exergy destruction compared to the basic ejector enhanced dual temperature refrigeration cycle (BERC). They conducted studies on energy modeling, exergy modeling, and ejector model validation within the scope of mathematical modeling [18].

2. Methodology

The temperature and airflow distribution in the horizontal commercial refrigerator compartments have been studied in the literature. Numerical methods have been used to predict the temperature distribution inside the refrigerator. By 3D simulations, temperature uniformity and airflow in a natural convection refrigerator can be improved. In this work, a numerical simulation is used to model the performance of a convection refrigerator. The compartments are investigated to improve operating conditions. Through simulations, we proposed a new design for the shelves in the air outlets achieving a better thermal profile. A thermal camera to observe the temperature distribution of the horizontal commercial refrigerator as an alternative method to analyze the cooling system; we compared the thermal behavior of the new design with conventional thermocouples.

The temperature distribution in the compartments is investigated numerically and experimentally, and, in most cases, results with numerical simulations are compared. The method to reach temperature uniformity inside the horizontal commercial refrigerator and temperature distribution influenced by the geometric configuration, the accessory position in the compartment, and the refrigerating space are investigated.

3. Experimental procedure

The results of various simulation analyses (velocity distribution, distribution of streamlines, time-dependent thermal analysis) on the horizontal commercial refrigerator prototype are shown in Fig. 4-7.

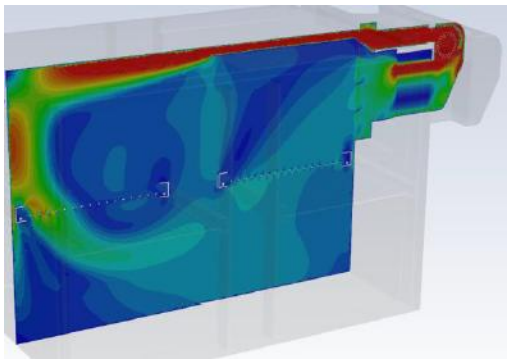

Fig. 4 *Flow analysis (velocity distribution) of a horizontal commercial refrigerator prototype.*

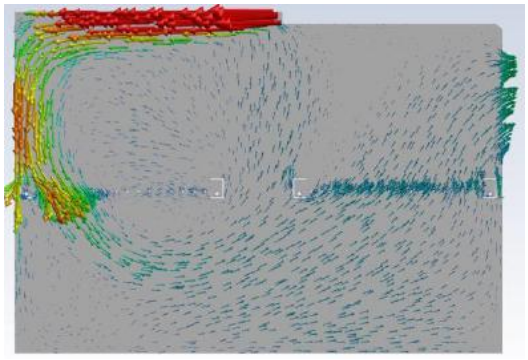

Fig. 5 *Flow analysis (distribution of velocity vectors in the cross-section) of a horizontal commercial refrigerator prototype.*

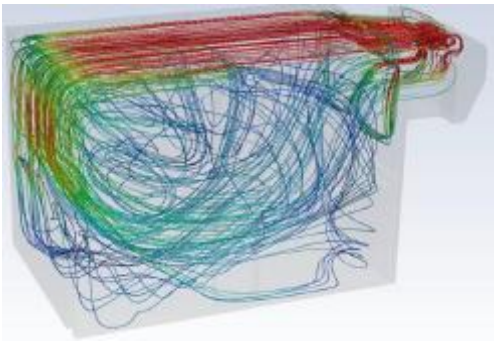

Fig. 6 *Flow analysis (distribution of streamlines) of a horizontal commercial refrigerator prototype.*

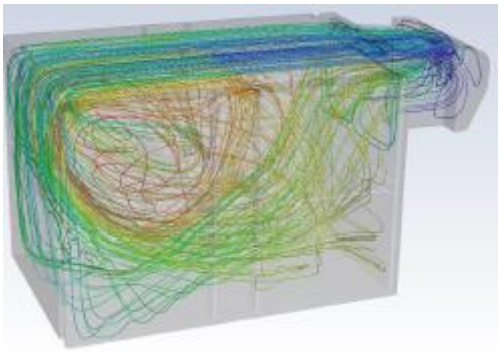

Fig. 7 Time-dependent thermal analysis (time: 9.6 sec.) of a horizontal commercial refrigerator prototype.

As seen in Figs. 4-6, flow analysis shows a good velocity distribution in the horizontal commercial refrigerator prototype. Fig. 7 shows that surfaces are colder than compartments near the trays. This is improved by adding censors in several places.

4. Conclusions

Mathematical modeling and simulation studies were carried out to optimize the cooling performance of the horizontal commercial refrigerator prototype.

According to the positioning of the cooler group elements (compressor, evaporator, fan, etc.) on the existing product, evaluations were made regarding the distribution of the cooling air in the cabinet of the horizontal commercial refrigerator prototype (according to the blowing and suction conditions of the air).

Various flow analyses (velocity distribution, distribution of streamlines, time-dependent thermal analysis) on the horizontal commercial refrigerator prototype have provided data on improving the effective and efficient operating performance.

A mathematical method is considered to analyze the thermal behavior of the compartments in a horizontal commercial refrigerator. This work mainly focused on studying the thermal effect in the horizontal commercial refrigerator compartment when the shelves' location is changed. Finally, we proposed using thermal maps to find the most appropriate shelf location for a compartment as the specific application in this kind of fridge. The main conclusions of this paper are summarized as follows:

• The temperature analysis provides an easy way to evaluate the thermal change rate.

• To analyze the thermal distribution of the horizontal commercial refrigerator compartments, an algorithm is developed.

• The temperature variance map shows the temperature average in the compartments of the horizontal commercial refrigerator as a function of the shelves' location. This map is an excellent tool for finding suitable shelf locations to attain the proper temperature.

Acknowledgment

This study was prepared from the project numbered 9210010 within the scope of TÜBİTAK-TEYDEB 1509 International Industry R&D Projects Support Program. We would like to thank TÜBİTAK-TEYDEB Machine-Manufacturing Technologies Group (MAKİTEG) for their contribution to the project.

5. References

1. J.M. Belman-Flores, Y. Heredia-Aricapa, D. Pardo-Cely, D.A. Rodríguez-Valderrama, M. De Alba-Rosano, J.C. Silva-Romero, International Journal of Refrigeration, **142**, 148–155, (2022)
2. D. M Madyira, T. O Babarinde, P. M Mashinini, Fuel Communications, **10**, 100034, (2022)
3. C. Aprea, F. Ceglia, R. Llopis, A. Maiorino, E. Marrasso, F. Petruzziello, M. Sasso, Energy Conversion and Management: **X 15**, 100262, (2022)
4. O.S Moronkola, O.S Ohunakin, D.S Adelekan, A.J Oti, O.I Oseahon, F.M Nekabari, Materials Today: Proceedings, **65**, 2119–2123, (2022)
5. P. Saji Raveendran, S. Joseph Sekhar, Energy and Buildings, **134**, 1–10, (2017)
6. T. Tito Godinho de Rezende, F. Neves Teixeira, J. Antonio da Silva, L. Gustavo Monteiro Guimaraes, M. dos Santos Guzella, Flow Measurement and Instrumentation, **72**, 101695, (2020)
7. Z. Zhang, D. Huang, R. Zhao, Y. Leng, Applied Thermal Engineering, **114**, 785–792, (2017)
8. A S. Pegallapati, M. Ramgopal, International Journal of Heat and Mass Transfer, **175**, 121317, (2021)
9. J. Boeng, A. A. Marcon, C. J.L. Hermes, International Journal of Heat and Mass Transfer, **147**, 118913, (2020)
10. Z. Li, D. Zhao, G. Ding, T. Ren, S. Miao, X. Han, International Journal of Refrigeration, **89**, 51–60, (2018)
11. D. Wang, J. Sun, Q. He, J. Si, T. Shi, F. Li, J. Yang, K. Xie, W. Li, F. Ge, Engineering Failure Analysis, **141**, 106585, (2022)
12. F. T. Knabben, Adriano F. Ronzoni, C. J.L. Hermes, International Journal of Refrigeration, **130**, 347–355, (2021)
13. Z. Zhu, K. Liang, Z. Li, H. Jiang, Z. Meng, Applied Thermal Engineering, **198**, 117467, (2021)
14. S. Ledesma, J.M. Belman-Flores, International Journal of Refrigeration, **74**, 362–370, (2017)
15. A. Roccato, M. Uyttendaele, J-M. Membre, Food Research International, **96**, 171–181, (2017)
16. J.M. Belman-Flores, A. Gallegos-Munoz, Applied Thermal Engineering, **106**, 743–752, (2016)
17. J.M. Belman-Flores, J.M. Barroso-Maldonado, A.P. Rodriguez-Munoz, G. Camacho-Vazquez, Renewable and Sustainable Energy Reviews, **51**, 955–968, (2015)
18. Q. Chen, M. Yu, G. Yan, J. Yu, Energy, **244**, 122565, (2022)