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Research Paper

Analysis of the flow and temperature distribution inside the compartment of a small refrigerator

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HIGHLIGHTS

- CFD is employed to model and simulate the thermal behavior of a small refrigerator.
- An analysis of flow and temperature are carried out inside of the compartment of refrigerator.
- A proposal for an alternative design for the plate-evaporator free of extended surfaces.
- The influence of the wired shelf position over the thermal behavior was analyzed.

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ABSTRACT

This work presents the analysis of the flow and thermal behavior of the compartment in a refrigerator, in which its cooling effect is based on diffusion-absorption technology. CFD was used to model and simulate the refrigerator. The main objective was to compare the thermal behavior of a plate-evaporator design with a finned surface (reference refrigerator) and a plate-evaporator with a smooth surface (proposed design). Moreover, the study was completed with the discussion about the velocity distribution and the pathlines of the temperature and velocity. This was also observed under the influence of the wired shelf location inside the compartment. Additionally, the performance of the refrigerator was evaluated. This study aims to expand our knowledge about the temperature and flow fields of this refrigerator model. Finally, the development of this work highlights the importance of the numerical simulation in the search for improvements in the design of this refrigerator model, which might help manufacturers of diffusion-absorption refrigerators.

1. Introduction

Refrigeration systems are extremely important in daily life, especially in terms of preserving food, health, and comfort. The basic function of a domestic refrigerator is to preserve the quality of perishable products, and this quality depends on a good refrigerator performance, which is highly linked to temperature distribution and the air flow inside the compartments.

For refrigerators based on vapor compression, several studies have been conducted, particularly focusing on the temperature and air flow distribution of the compartments. In the literature we may find works related to the study of the air speed using the Particle Image Velocimeter technique (PIV) [1,2], along with 3D numeric simulations using CFD software [3]. For instance, Laguerre et al. [4] conducted a numeric study of air flow and heat transfer in a natural convection domestic refrigerator. Gupta et al. [5] introduce the development of a model for a frost-free refrigerator where they predict and experimentally compare temperature profiles, obtaining a certain discrepancy in their results. In order to improve the temperature uniformity and the air flow in a natural convection refrigerator, Ding et al. [6] observed that the temperature distribution depends on the internal geometry of the refrigerator, specifically in the spaces between the refrigerator shelves and the liner bottom wall. Yang et al. [7] present a numerical simulation of a forced convection refrigerator concluding that the freezer and the fresh food compartment are found in phase (synchronized) with one another. Through simulation the authors proposed a new internal design. Torabi et al. [8] worked particularly on the freezer of a natural convection refrigerator; by means of experimentation and the use of CFD they analyzed the design of 17 models to optimize the field of temperatures in the freezer. Bayer et al. [9] simulate the fluid flow with a reduced order modeling method and temperature distribution in a refrigerator compartment.

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Nomenclature

c	specific heat [J/kg K]
g	gravity [m/s^2]
k	thermal conductivity [W/m K]
P	pressure [bar]
T	temperature [K]
u	velocity [m/s]

Greek symbols

β	thermal expansion coefficient [1/K]
ρ	density [kg/m^3]
μ	dynamic viscosity [kg/m s]

Subscripts

b	bottom
d	door
l	left
p	plate
r	right
u	top
x, y, z	space coordinates
∞	reference condition

Afonso and Matos [10] simulated the internal air temperature with Fluent. Björk et al. [11] used a thermographic camera to observe the temperature distribution of a household refrigerator, as an alternative method to analyze the refrigeration system compared with conventional thermocouples. Belman-Flores et al. [12] analyzed the thermal stratification in the compartments of a bottom mount forced convection refrigerator through CFD, and the results were experimentally validated. Kumlutas et al. [13] developed an ANN model to find temperature distribution inside the refrigerator in order to predict the design parameters.

Furthermore, some technologies have emerged in response to the search for alternative refrigeration systems, among them those thermally activated (solar energy, geothermal, residual heat, etc.) that reflect a reduction in greenhouse gases and zero contribution to global warming depending on the type of working fluids. In this field, the diffusion-absorption refrigeration systems are widely used in domestic applications such as hotel rooms as they are quiet and safe. Although these systems can operate continuously for many hours, their application is limited exclusively to refrigerators of small cooling capacity [14]. The research of the diffusion-absorption technology is focused on evaluating different mixtures [15–17], the application of nanorefrigerants [18], the analysis of configurations [19,20], and the increased energy performance [21–26], among other situations.

Based on the above, there are no works related to thermal behavior of the compartment of refrigerators with diffusion-absorption technology, nor analysis of the design of components such as the plate-evaporator. In the literature there are only investigations with refrigerators based on vapor compression. Thus, this article presents an extension of the numerical model in CFD in order to analyze the thermal behavior in the compartment of a small refrigerator, which is based on diffusion-absorption technology. The main contributions of this paper into this field are:

- An analysis of flow and temperature fields where stagnation points are identified, and of minimum and maximum temperatures inside the refrigerator compartment.
- A proposal for an alternative design for the plate-evaporator free of extended surfaces, which was also modeled to compare both designs: reference refrigerator (finned plate-evaporator), and the new model (plate without fins).
- Based on the results obtained in this work, researchers or developers may wish to find possible improvements in the design that lead to adequate thermal behavior, and in turn, represent a decrease in the manufacture costs.

2. Diffusion-absorption refrigeration system

The commercial refrigerator used in this study was of small capacity (0.03 m^3) as seen in Fig. 1a. The external dimensions of the experimental refrigerator were 0.4 m × 0.35 m × 0.50 m (width × depth × height) and the wall thickness was approximately 0.037 m insulated using cyclopentane. It consisted primarily of the equipment shown in Fig. 1b and used three working fluids to produce the cooling effect: ammonia, water and hydrogen, which are used as a refrigerant, absorbent and auxiliary gas, respectively. A thermostat through which the user could manipulate the thermal condition of the compartment was located in the back and bottom of the unit. That is, ON and OFF cycles of the electrical resistance (65 W) placed at the bottom of the bubble pump which were controlled with the thermostat. Initially, the refrigerator was evaluated for the 3 positions of the thermostat (low, medium, high); thus, the thermal behavior of the working fluid in the inlet and the outlet of each of the components was determined [23]. Simultaneously, the thermal behavior of the compartment was also evaluated, which is the main point in this work.

To perform the cooling effect and maintain the compartment temperature lower than the surroundings, inside the refrigerator there was an aluminum plate with rectangular fins, which was directly in contact with the evaporator tube, and by this means, the heat transfer was achieved in the food compartment (see Fig. 2). The plate consisted of 19 fins and was 0.3 m × 0.3 m.

The refrigerator was instrumented with 16 type K (±0.3 K) thermocouples placed in different areas that belong to the minibar inside, such as: walls, finned plate, shelves and wired shelf. The refrigerator operated at constant room temperature of 294 K ± 1 K and with a relative humidity of 70 ± 5%. The points of interest for the experimental analysis of this study are indicated in Fig. 2 with circles T_u, T_r, T_p, T_l, T_b, T_d, which represent an average of the temperature measurements on the inside walls (2 thermocouples in each wall) of the refrigerator. The signals generated by the sensors were stored through NI-9213 data acquisition cards from National Instruments. Subsequently, the system was connected via a USB port to a computer that allows to monitoring the equipment's experimental conditions in real-time through the Signal Express software programmed in the LabView environment. Temperature measurements were taken at intervals of 10 s. The results for each test throughout the whole period (approximately 6 h later once the thermal stability was reached) were exported and processed using Excel. The position that has been taken into account in the development of this work, represents the lower thermostat condition (this condition corresponds to the highest temperature in the refrigerator compartment). In this position, the ON lapses had a duration of 18 min, and the OFF lapses had a length of 11 min. The average temperature of the walls (Fig. 2) for this position is taken into account for the boundary conditions in the development of the numerical analysis of this work. This average temperature corresponds to the last hour of thermal stability.