Analysis of the Dynamic Behavior of the Temperature Distribution Inside a Domestic Refrigerator

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***Abstract*— A mathematical model to describe the dynamics of heat extraction in a domestic refrigerator is exposed in this document. The concerned model is based on the Newton's Law for Cooling as a boundary condition (walls that isolate the volume of the box and keep the low energy level) for the Fourier Heat Equation, which is used to describe the energetic exchange among the mass nodes considered from the finite volumes concept. The model was codified through Matlab and used for simulation and validation with experimental results. The simulation results add information to validate that the temperature is not homogenous inside the appliance. The information provided helps to understand the evolution of temperature changes, assuming a homogeneous environment and different ratios of thermal capacity.**

Keywords- heat exchange; thermal diffusivity; finite volume.

I. INTRODUCTION

The implementation of new technologies for the refrigeration industry has increased significantly in recent years. The purpose of these new implementations was to address different issues, such as energy expenditure and the impact on the environment [1]. Cooling devices are mainly used for conservation of perishable foods, making them indispensable for the conservation of large volumes of food, for a commercial level, and in small quantities, for domestic consumption [2]. This article focuses on the exchange of energy inside a domestic refrigerator and the relation between energy consumption and thermal load contained in the refrigerator chamber [3], leading to better food conservation and reducing the negative environmental impact. The relevant understanding of the dynamics of energy can be achieved by formulating a mathematical model, using the law of cooling of Newton and the equation of heat of Fourier, and by solving both using the method of finite volumes.

The present work is structured as follows: Section II mentions the basic concepts to detail the proposed theories and the expected effects. Section III presents the mathematical model developed and the results obtained from the simulation. In addition, it provides an early interpretation of the process of energy exchange between mass along the internal volumes. Section IV explains the results generated by the simulations and their possible effect in the refrigeration cycle. Finally, Section V discusses the final conclusions of this first stage of the research developed.

II. BASIC CONCEPTS

To determine the mathematical model, certain conditions are assumed for the rest of this text, namely that the environment temperature is homogeneous, and the thermodynamic parameters of materials are constant. Previous considerations are proposed to generate a linear model. Newton's Law of Cooling models the transfer of heat between the environment and the internal volume, considering a thin layer of insulation [7]. Fourier's heat equation was used for the transfer of energy in the internal volume, ignoring the gas flow inside the cold chamber. The elements used as thermal loads were air and water. The Fourier heat equation, mainly used for conduction of heat energy between solid materials, can also be solved for gases, considering that the fluid will not have any movement, and only focusing our interest on the mass confined the volume protected by the insulator [10]. Newton's cooling law is used as the boundary condition that simulates the insulation from the environment, adding perturbation to the refrigeration cycle [8]. The outside temperature is considered uniform at the surface of each wall.

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Two states of thermal load, empty and full, are considered: 0% of thermal energy stored (empty), to determinate the temperature evolution and the energy decrease along time [9]. 100% of accumulated thermal energy (full), to show the difference between the absence of load in the refrigeration cycle [11].

A. *Characteristics of the model*

The transfer medium in the inside of the chamber, in 0% of thermal load and a time of 0 sec, is considered a homogeneous mixture (air), with a thermal conductivity of 0.024 w / m ºK. The movement of air is not considered. The internal energy is extracted, and it is expelled to the outside. The evaporator is maintained on to reduce the energy of the air in a first empty state.

The system dynamic is altered when the thermal load changes its state from empty to full. By modifying the thermodynamic properties, the extraction of heat of the thermal equilibria changes. It is considered that the properties of water in its liquid state can provide an approximation of the behavior of food in refrigeration.

For purposes of a first approximation, only two possible states of the thermal load are considered, considering that the space to extract the energy could be empty or totally full. As a future work, an adjustment may be made to consider different middle operation points.

The different material characteristics used in the model are presented in TABLE I:

TABLE I. VALUES USED IN THE MATHEMATICAL MODEL

Symbol	Characteristics	
	Name	*Unity*
α	Thermal diffusivity	K/ρC
K	Thermal conductivity	W/m °C
ρ	Density	Kg/m^3
C	Specific Heat	J/Kg °C
$\Delta_{x,y,z}$	Delta	m
Δ_t	Time Differential	s
V_{nodo}	Node volume	m^3
$\dot{Q}$	Generated Heat	W

B. *Theoretical Proposal*

For this investigation, the model was focused on the internal volume of refrigeration (evaporator output), considering that its motion has a static behavior and is described by the following dynamics, as observed in equation (1).

$$\dot{Q}_{conducción} = -kA\frac{dT}{dx} \quad (1)$$

According to the elapsed time, and the amount of energy that the heat source can emit, the characteristics vary, which are the thermal conductivity, the temperature gradient and the volume. In order to obtain a linear approximation, constant properties are considered throughout the duration of the simulation.

C. *Volume Analysis*

Considering that the objective is to describe the thermal distribution in space of the chamber, three space dimensions are considered, obtaining the mathematical model indicated in equation (2).

The volume of each material is considered. The assumption that there are no spaces of different materials is applied. All possible volumes in the total space are in prismatic form, causing the transfer of heat between the formed nodes similar to a solid. The only path of heat transference is in the direction of the three space dimension.

$$T_{i,j,k}^{n+1} = \alpha \cdot \Delta t\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{k}\dot{Q}_{i,j,k}^{n}\right) + T_{i,j,k}^{n-1} \quad (2)$$

Solving the dynamic model helped to generate the distribution of temperature as a function of time and space.

The heat source is the evaporator, but the sign of its effect in the system is negative, because of the idea of extracting energy from the interior, instead of inserting energy from the exterior. The interaction of energy between the evaporator and the outside is not explained in this document.

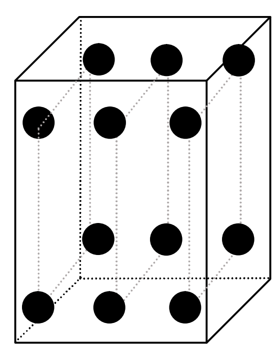

Figure 1. Distribution of nodes in the space of the cold chamber.

In Figure 1, the temperature nodes inside the chamber are shown.

III. MATHEMATICAL MODEL AND SIMULATION RESULTS

The process of data acquisition requires a commercial refrigerator with linear compressor, with the following characteristics: 132 watts 60 Hz and 313 watts 150 Hz, representing 0% and 100% thermal load, respectively.

In addition, the width of the insulating wall (polyurethane) has a value of 0.05 m. The energy entering the cold chamber was 1.64 W, this energy being added to the heat generated (extraction of energy from the evaporator). The minimum value of the evaporator in an empty state, and it is selected assuming that no thermal load with greater conductivity than water leads to minimum work from the evaporator. The interaction of energy between temperature nodes causes an increase or decrease in energy of every surrounding node.

A. Operation of the model

The temperature behavior should be radial with the center in the evaporator output. Every node will have a limit of energy extraction coinciding with the phase change energy of every material.

The simulation was generated proposing the space of the refrigerator as empty, without shelves any object or product inside.

As explained in Section II, only rectangular heat fluctuation is considered. It is for this reason that no other geometric flow is considered.

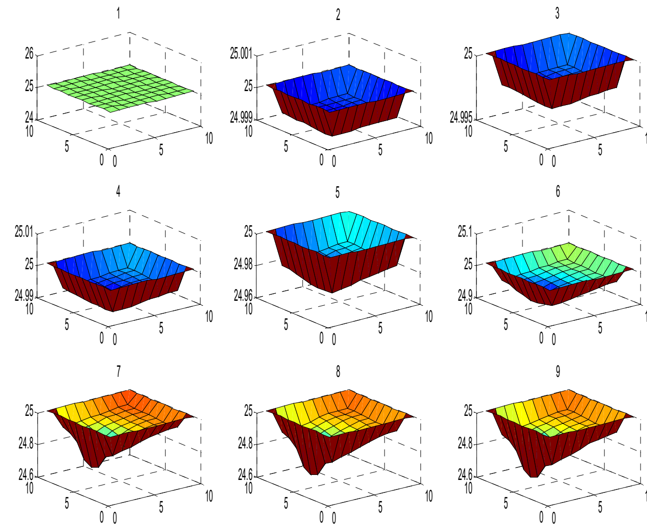

Figure 3. Behavior of the temperatures according to the height of the refrigerator.

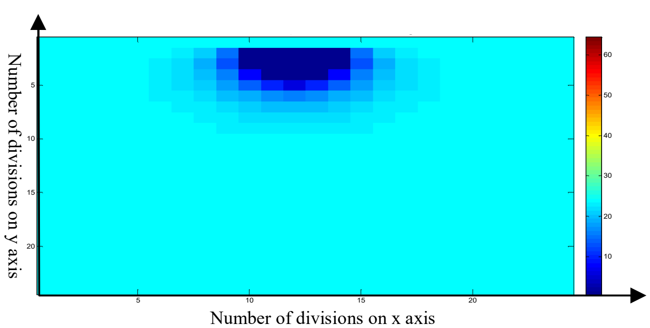

Figure 2. Behavior of the temperature distribution in the domestic refrigerator vacuum

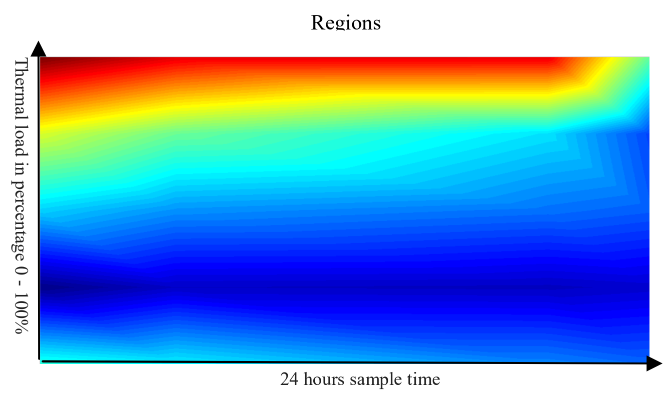

Figure 4. Distribution of the energy inside the cold chamber with different thermal loads.

The empiricial behavior is coherent with the theoretical radial propagation, hence, the evaporator location to show the lowest values in temperature as seen in Figure 2. Figure 3 shows the same behavior as Figure 2, but with a transversal view on the z axis, divided into 9 different instants. The subfigures 1, 2 3 are the first layers and show a considerable decrease in the internal energy, in layers 4, 5, 6 they show a higher energy, but a decrease in the lower part of the chamber, because the density of the air increases when temperature decreases.

The solution of finite volumes determines the zones of the refrigeration cycle depending on the thermal load and the percentage of use of the compressor, empty or full as mentioned previously, generating two zones. In Figure 4, the red zone indicates that after working at 100 percent and with a total time of 12 hours (simulated), the system does not reach steady state. However, with thermal load in 0%, the system stabilizises.

The results will be further analized in Section IV.

IV. ANALYSIS OF RESULTS

Based on the concept of finite volume, the Fourier's equation (proposed model) solved in finite differences considering the sub-node strategy, maintains a dynamic behavior similar to a first order system for all its nodes. The dynamic obtained with the experimental characterization represents a behavior consistent with the empirical results. Since the model proposed in finite differences, in each iteration, is fed by temperature data at the output of the evaporator inside the cold chamber (sensor available in the refrigerator), the stabilization time of the model is consistent with the experimental results. However, the theoretical values of the constants require adjustments; to reduce the deviations in a permanent regime. Based on the results obtained from the tests, 4 critical zones were chosen to

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analyze the dynamic response due to the thermal load, as well as the dynamic response due to the speed of the compressor. In each zone, the corresponding dynamic poles are calculated from each time constant. Considering the poles obtained for the 4 regions of the load-velocity space, the errors with respect to the theoretical values must be considerably reduced.

V. CONCLUSIONS

Based on the results, a strong dependence has been observed between the coefficients of the model (thermodynamic properties) and the control variables that are regulated in the refrigerator device. The speed of the compressor and the distribution and magnitude of the thermal load inside the refrigerator are variables that contribute to modify the temperature evolution of the system. The non-linearity of the phenomenon must be considered when modifying the value of the poles in the model and is supported by the improvement of the results.

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