Experimental and Fundamental Analysis of the Dynamical Behavior for the Thermal Distribution in a Cooling Chamber

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***Abstract*— A mathematical model is proposed to describe the dynamics of the heat extraction process in a domestic refrigerator. The concerned model is based on both the Newton's Law of Cooling and the Fourier Heat Equation; where the first one acts as the boundary condition to consider the physical properties of the insulation walls and their interaction with the environment and with the internal energy contained in the cooler chamber. The Fourier Equation has been implemented to describe the energetic behavior in the concerned chamber and it is grounded in the numerical consideration of the finite prismatic volumes concept, which take the respective thermodynamic properties of air or water as well as the thermal load distribution defines. The finite volume concept and the conductive equation consider the null mass exchange between volumes; therefore, heat conduction emulates the finite volumes interaction and convection simulates the cooling chamber boundaries. Codification was performed through Matlab and its experimental validation took places in the National Laboratory for Cooling Technology Research (LaNITeF). Certain finite volumes were located strategically into the cooling chamber to be compared with the sensor's measurements. The model provides useful data to improve the understanding of the temperature behavior in terms of the chamber geometry, cool air flow and thermal load ratio, leading to basics concepts for the future development of control strategies to implement several energetic consumption optimization algorithms.**

Keywords-Heat exchange;thermal diffusivity;finite volume.

I. INTRODUCTION

Nowadays, the implementation of new technologies in the refrigeration industry has increased significantly. The objective of these technological developments has different arguments, depending on the problem to solve, but in the global context, the most important issues are: the energy consumption of the vapor compression cooling systems, the heat extraction from of high magnitudes of thermal loads, the impact of the refrigerant gas leaks to the environment and the performance of the heat interchangers of the vapor compression thermodynamic cycle [1].

There are interesting contributions in the state of the art concerned with theoretical and/or experimental methodologies to extract the thermodynamic parameters of cooling devices or systems from several companies, moreover, from manufacturers of thermoelectric chillers (TEC) and thermoelectric generators (TEG).

The Lineykin et al. model could be useful to analyze the displacement requirements of the TEC and the loading effects of the TEG [2]. The cited review and analysis indicate that greenhouse emissions from conventional vapor compression refrigeration systems driven by diesel engines commonly used for the refrigeration of food transportation can reach 40% of the vehicle's engine emissions [3]

Thermoacoustic refrigeration is an alternative technology capable to provide cooling levels for several temperature magnitudes, without using any substance harmful to the nature environment. Therefore, thermoacoustic represents a technology niche to increase the cooling market for a bigger production of perishables products [4]. Currently, the most efficient thermoacoustic refrigerators are used in the industrial environments [5], which work by taking advantage of the interdependence between the enthalpy carried through by the Gedeon mechanism and the local temperature; as an example of this fact we have the recently developed four-stage progressive wave thermoacoustic engine [6].

The prime movers and refrigerators based on thermoacoustic have gained considerable importance toward practical applications because of: the absence of moving components, the reasonable efficiency, the use of environmentally friendly working fluids, etc. [7]. The results from the experimental studies were correlated in terms of: the Nusselt number, the Prandtl number and the Reynolds number to estimate their correlation in the heat transfer stage at the heat exchangers. Experimental data show that there are significant errors in the cited heat transfer correlation analysis algorithm. Dynamically, these results also show that there is a relationship between the oscillatory heat transfer coefficient at the heat exchangers and both the mean pressure and the frequency of oscillation [8].

The perishable products conservation has been indispensable in any place that requires a conservation process for food, as well as in: restaurants, large, medium and small commercial stores, that transport or shows different human consumption products which must remain at a minimum temperature level to be conserved in their best conditions, as well as for domestic purposes in daily life [9].

In the other hand, cooling technology is one of the most used and important services for the industry manufacturing process, more over it is critical for many specific sectors as well as the healthcare and feeding; essentially because of the infrastructure of their production and storage processes [10]. Therefore, cold needs are always present in some industries, where the material or product is obtained, cultivated or extracted, also where it is transferred to the plant, factory or warehouse, even though in its storage time, and in its production and conservation processes as well as when it is put on sale in optimal conditions for the final consumer [11] and [12].

This article analyzes the energy exchange mechanism between the thermal load and tend the volume cooled by the evaporator. This analysis scope is extended to the behavior of the temperature distribution in the cooling chamber of a domestic refrigerator, by modifying both the density of the elements (finite volumes) according to their position into the cooling volume and the ratio between its energy consumption and the total thermal load (considering 3 percentages of full load or volume) [13]; with the purpose to focus on the cooling power to get a better conservation performance of the food characteristics for and then to improve the energetic performance of the concerned cooling systems [14].

Several deeper researches work on different areas of refrigeration technologies (i. e., condenser, energy exchange) shows that the environmental conditions change strongly affects these systems performances. In the matter of fact all cooling systems designs needs to take in account this to improve its energetic performance and to reduce its effect in the natural environment health. The improvements can also be developed to decrease the negative environmental impact of refrigerant leaks by prediction and monitoring their flow by using a mathematical model. These mathematical models have been developed by taking considering the different relationships between the thermodynamically variables of interest [15].

One of the most relevant foundation for the dynamic analysis of energy in the state of the art, was achieved and documented on [16], where there is a formulated mathematical model which use also both the Newton law for cooling and the heat transfer Fourier equation; by solving both equations using the finite volume method, without mass flow, considering just the thermodynamic characteristics of the water in different percentages of thermal load [17].

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 simulations, in addition to have 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 presents the conclusions of this first stage of the developed research.

II. BASIC CONCEPTS

The most important assumptions considered in the mathematical model proposed here, are listed as follows:

-The environment temperature and pressure are homogenous and time invariant.

-The thermodynamic characteristics of the involved materials are also time invariant and spatially isotropic.

-There is no mass flow through the finite volume nodes into the refrigerator chamber.

-Energy interchange into the chamber is carried out by conduction between inside nodes and by convection at the boundary conditions.

As it was defined, with these assumptions the dynamic model can be synthetized as a linear relationship for the considered variables through both the Newton law for cooling and the Fourier heat transfer equation.

In the testing procedure to emulate different levels of thermal load some water containers were used and locate at the refrigerator and freezer chambers.

It is important to clarify that the Fourier heat transfer equation was implemented to solve the temperature conduction between the internal nodes conceived as finite volumes into the chamber, so that the mass flow has been considered null [18]. In addition, The Newton law for cooling solves the heat convection between the internal finite volume nodes and the boundary nodes at the isolation walls. Table I provides a useful list of terms used in this work and the mathematical symbols related.

TABLE I. NOMENCLATURE

Symbol	Description	Units SI
α	Thermal diffusivity	K/ρC
K	Thermal conductivity	W/m °C
ρ	Density	Kg/m^3
C_v	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
CFC	Compressor Cooling Capacity	W
CFE	Refrigerator capacity of the evaporator	W
Ta	Room Temperature	°C
R134a	Refrigerant	Gr.
Te	Evaporator temperature	°C
$V_{subnodo}$	internal temperature constant	m^3
Ti	Constant of volumes	°C
τ_0	internal temperature constant	-
τ_0	Constant of volumes	-
τ_2	Evaporator constant	-
%CT	percentage of thermal load	% o lt.

Experimentally, two states of thermal load ratio, empty (0%) and full (100%), were tested to determine the temperature evolution and the energy behavior along the testing time [19]. The main purpose of both tests was to quantify the effect of the thermal momentum into the refrigeration cycle performance [20].

A. Characteristics of the model

The transfer medium into the confined volume of the refrigerator chamber for the empty scenario was considered as a homogeneous air mix with a thermal conductivity of 0.024 w / m ºK, where the initial condition is the environment temperature as 25 °C.

The system dynamics is altered when the thermal load ratio changes its magnitude from empty to full, then the thermodynamic properties were modified (by adding water to the transfer media). In this scenario the heat extraction behavior takes more time from its initial to its final equilibrium. It must take in account that the water as transfer media is considered due to its magnitude into the food composition.

B. Theoretical Proposal

The mathematical fundamentals of the dynamic model to analyze the relationship between the heat extracted from the cooling chambers volume and its temperature distribution, comes from the convection Newton Law [21],

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

From the Newton law the amount of heat energy is included in the space discretized Fourier equation where it can see that some characteristics can change in the time domain according to the estimated amount of energy that the heat extractor absorbs, therefore the most significant coefficients are the thermal conductivity, the temperature gradient and the volume; but in this proposal to obtain a linear approximation, the properties are considered time invariant throughout the simulation [22].

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

C. Volume Analysis

The objective of this proposal is to describe the thermal distribution into the refrigerator chamber; therefore, all real spatial dimensions and thermal conduction properties of the refrigerator components materials were considered. Then, from time and space discretized the Fourier heat transfer equation, the formulation for the next time state of the temperature was synthetized for each i, j, k internal node, in terms the thermal properties of the materials, which occupy the confined volume causing a orthonormal heat transfer flow with its neighbors through the three spatial directions as were.

$$T^n_{i,j,k} = \alpha \cdot \Delta t\left(\frac{T^{n-1}_{i+1,j,k} - 2T^{n-1}_{i,j,k} + T^{n-1}_{i-1,j,k}}{\Delta x^2} + \frac{T^{n-1}_{i,j+1,k} - 2T^{n-1}_{i,j,k} + T^{n-1}_{i,j-1,k}}{\Delta y^2} + \frac{T^{n-1}_{i,j,k+1} - 2T^{n-1}_{i,j,k} + T^{n-1}_{i,j,k-1}}{\Delta z^2} + \frac{1}{k}\dot{Q}^n_{i,j,k}\right) + T^{n-1}_{i,j,k} \quad (3)$$

$$T^n_{i,j,k} = \tau_1\left(T^{n-1}_{i+1,j,k} - 2T^{n-1}_{i,j,k} + T^{n-1}_{i-1,j,k} + T^{n-1}_{i,j+1,k} - 2T^{n-1}_{i,j,k} + T^{n-1}_{i,j-1,k} + T^{n-1}_{i,j,k+1} - 2T^{n-1}_{i,j,k} + T^{n-1}_{i,j,k-1}\right) + \tau_2\left(\dot{Q}^n_{i,j,k}\right) + T^{n-1}_{i,j,k} \quad (4)$$

$$\tau_0 = \frac{\left(\frac{K}{\rho C_V}\right)(\Delta t)}{\left(\Delta_{x,y,z}\right)^2} \quad (5)$$

$$\tau_2 = \left(\frac{\alpha * \frac{\Delta t}{V_{subnodo}}}{\frac{k}{\rho C_V}} \right) = \frac{°C}{W} \quad (6)$$

$$\tau_1 = \frac{\tau_0 * V_{nodo}}{V_{Subnodo}} \quad (7)$$

Spatially, some finite volume nodes location was defined in the same places that some sensors were located which were used to validate the numerical prediction. The heat source is the evaporator device, so that its heat input is negative, because it extracts the energy from the confined volume of the refrigerator chamber. The interaction of energy between the evaporator and the outside variables is not explained in this document. Fig. 1 shows the finite volume nodes distribution for the temperature model inside the refrigerator chamber.

III. MATHEMATICAL MODEL AND SIMULATION RESULTS

In this section, the final formulation of the mathematical approach developed in the present work is detailed; adding the data of the real thermal and energetic conditions which are considered in the synthetized model (4). Furthermore, the Matlab codification of (4) is compiled and executed to generate the numerical results shown on Fig. 3.

The data acquisition process is applied to a commercial fridge with a linear compressor and the following features

- 132 watts, 60 Hz, 0% of thermal load ratio.
- 313 watts, 150 Hz, 100% of thermal load ratio.

To clarify the proposal, a computational node was defined for each finite volume; as it is shown in both Fig. 2 and Fig. 4.

The width of the insulating wall (polyurethane) for the refrigerator chamber is 0.05 m, and the energy entering this chamber was quantified as 1.64 W by equation (3); this energy magnitude which is added to the heat extracted by the evaporator, depends of the environment temperature and it is consistent with other authors reports [16] and [17].

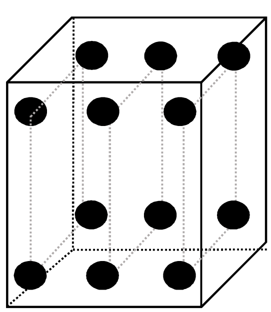

Figure 1. Spatial distribution of the finite volume nodes of the time discrete model for the temperature into the refrigerator chamber.

In the testing scenario the internal temperature of the cooling chamber volume as well as the thermal load energy start at the ambient temperature, so the despondency process is also considered for this prediction; to look for the variation magnitude in the thermal inertial moment of the entire load inside. Then, the entering energy leaks from the ambient were quantified in the same point of the initial thermal equilibrium as

$$\dot{Q} = \frac{\Delta T}{RT} = \frac{Ta - Ti}{RT} \quad (8)$$

$$CFC = (1.05)(CFE) \quad (9)$$

The value of energy that comes from the environment is considered homogeneously for each existing volume, in any of its three directions at the boundary conditions, as it is illustrated in Fig. 2. In the node net shown (Fig. 2) the nodes next to the red wall, represent the ones which utilize the convection mechanism of energy transfer with the environment while the in the remaining nodes interaction is describe by conduction just.

A. *Operation of the model*

The behavior of the temperature must be radial from the center at the energy outlet location of the evaporator node. Each node will have an energy extraction limit that matches with the phase change energy of each material in the confined volume as it is shown in Fig. 3. Fig. 4 helps to detail the energy transfer mechanism between nodes.

The first simulation was developed proposing an empty stage for the cooling chamber, without: shelves with water inside, any object or internal products. Here the logic predicts that there is a smaller amount of energy to be transported by the refrigeration systems which in consequence takes less time to get an internal thermal equilibrium at the refrigerant boiling point (see Fig. 5).

The empirical behavior is consistent with the theoretical radial propagation, hence the location of the evaporator to show the lowest values of temperature as shown in Fig. 2, depositing the element of higher density to the bottom of this. The empirical behavior is consistent with the theoretical radial propagation, hence the location of the evaporator to show the lowest values of temperature as shown in Fig. 3, depositing the element of higher density in the lower part of it. By combining both proposed equations, depending on where the type of material is located, it should be remembered that the proposed model is not considered as non-linear, all the characteristics developed throughout the phenomenon must be constant for a first approach with the operation of the refrigeration cycle and a greater understanding of which properties may have the greatest impact.

Fig. 4 shows the same behavior as Figure 2, but with a transverse view on the z-axis, divided into 9 different instants. Subfigures 1, 2 and 3, which are the first layers, show a considerable decrease in internal energy. Layers 4, 5, 6 show a higher energy, but a decrease in the lower part of the chamber, due to the density of the air increases when the temperature decreases (energy is extracted from the air by the evaporator).

The red zone in Figure 4 indicates that after working at 100%, with a total time of 12 hours (simulated), the system does not reach the stable state. However, with 0% thermal load, the system stabilizes or reaches the same, because there is a minimum energy exchange that is very difficult to notice experimentally.

The numerical solution of the finite volume nodes for the temperature determines the coldest and hottest zones in the refrigerator chamber, depending on the current thermal load ratio and its distance from the evaporator location, without considering the flow rate of the evaporator existing energy in it.

IV. Analysis of results

The Fourier's equation (proposed model) solved in finite differences, holds a dynamic behavior like a first order system for all its nodes, based on the concept of finite volume and the sub-node strategy. The dynamic behavior obtained with the experimental characterization represents a behavior consistent to the empirical results.

The stabilization time of the model is in good agreement with the experimental results, since the model proposed in finite differences, in each iteration, is fed by temperature data at the output of the evaporator (sensor available in the refrigerator). However, the theoretical values of the constants require adjustments; to reduce the deviations in a steady state.

Based on the results obtained from the tests, 4 critical zones were chosen to analyze the dynamic response due to the thermal load, as well as the dynamic response due to the speed of the compressor (Fig. 7). 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

The presented article develops a useful mathematical model and the results of a Matlab codification in forms of graphs.

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, as well as 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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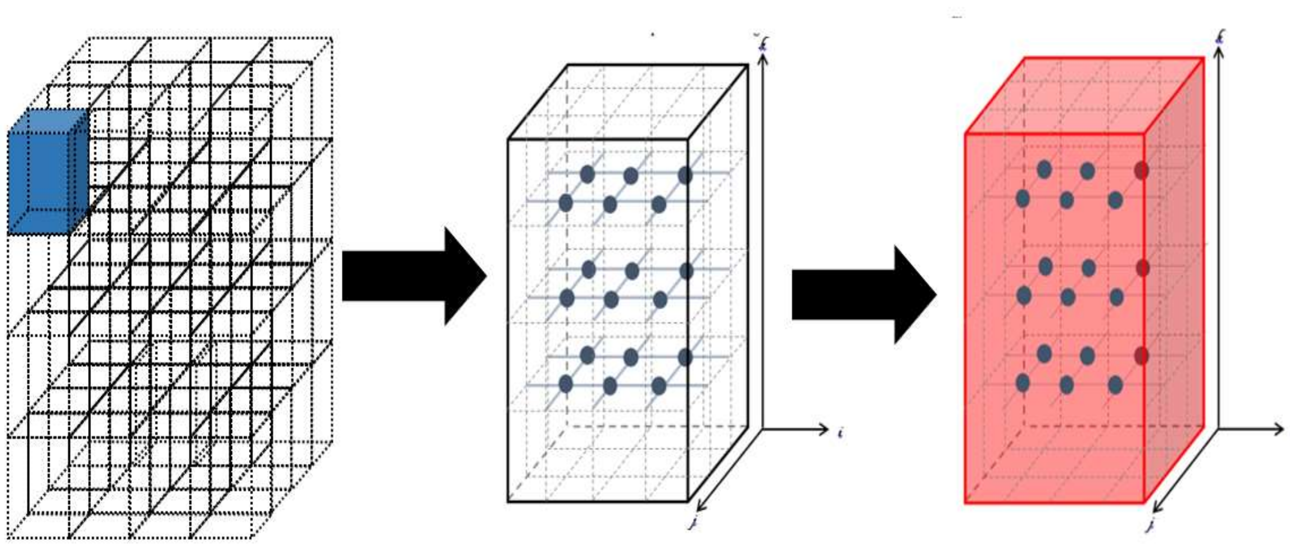

Figure 2. Decomposition in finite volumes

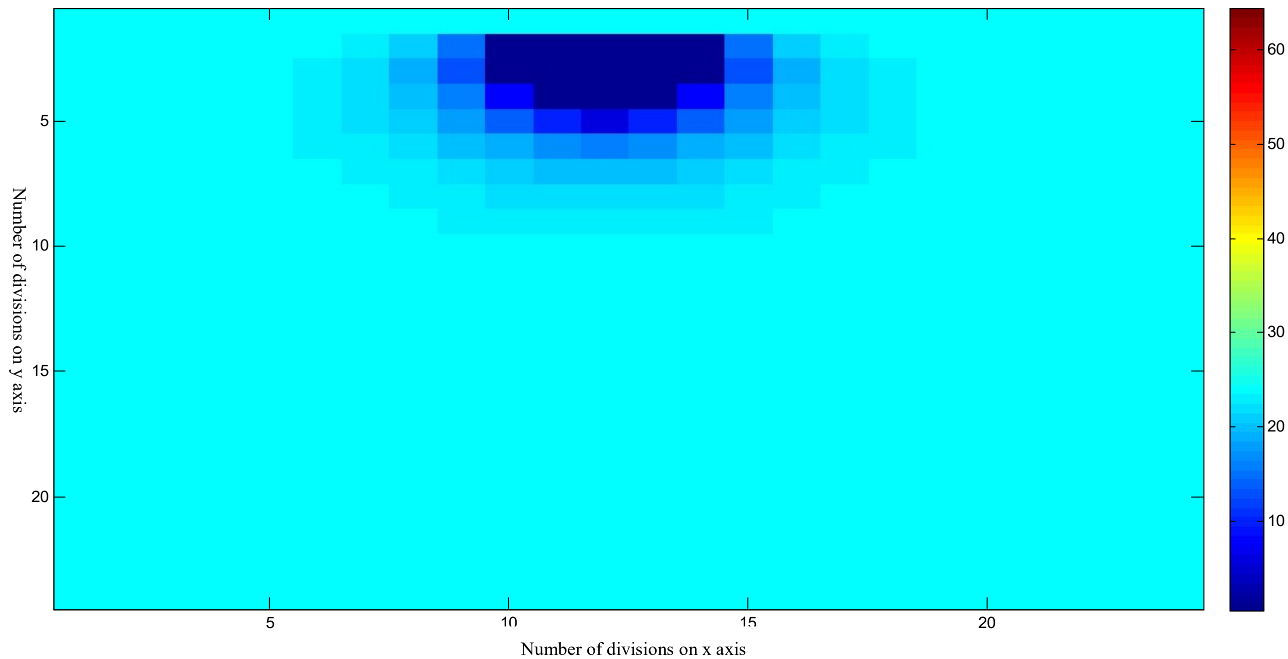

Figure 3. Prediction of the temperature distribution into the domestic refrigerator chamber

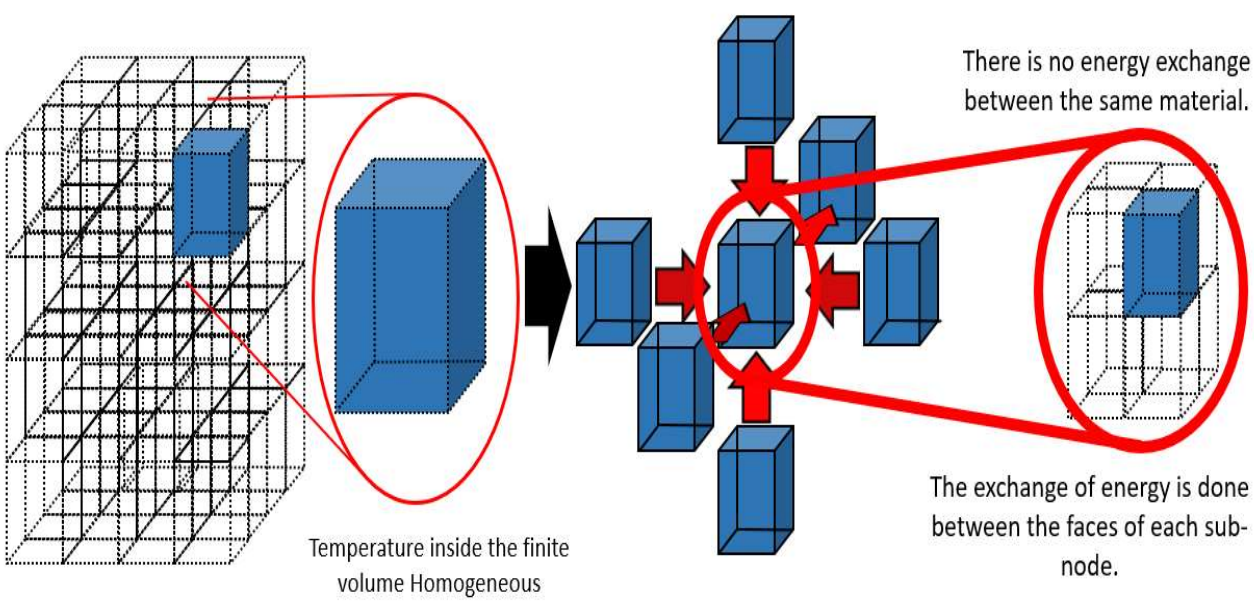

Figure 4. Heat exchange of cold chamber volume by finite volume

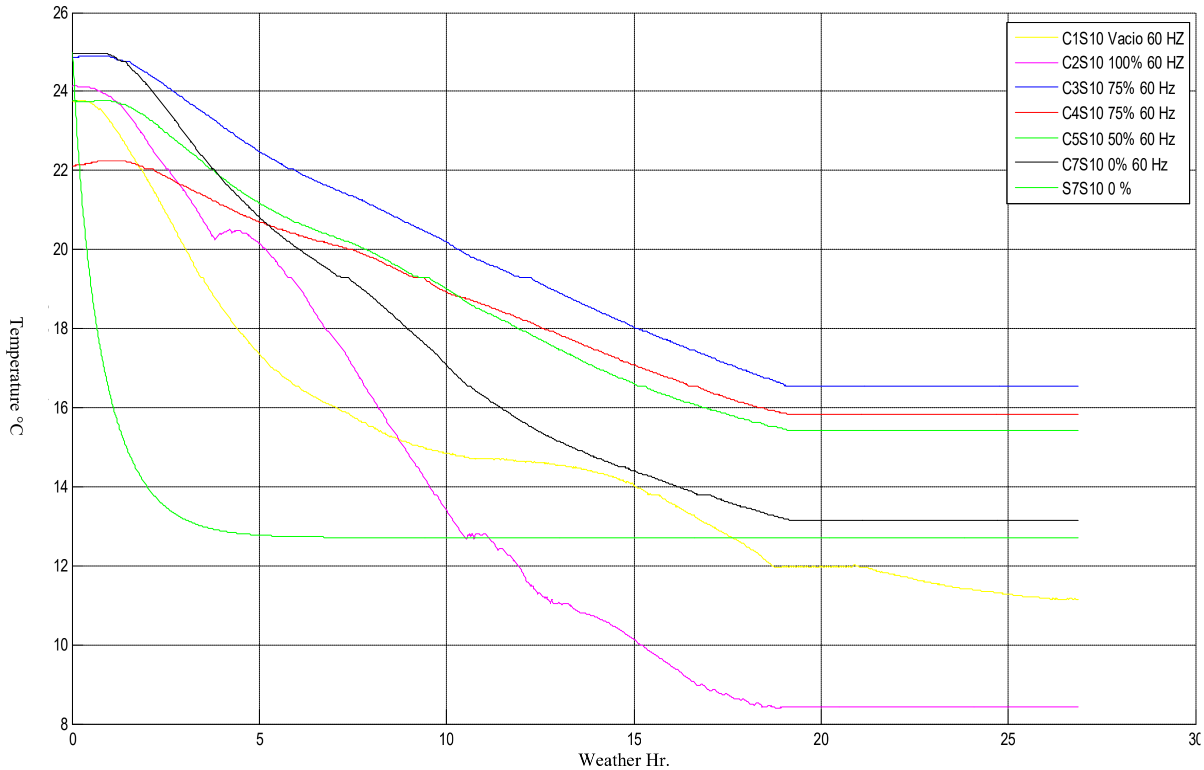

Figure 5. Experimental results of instrumented chiller chamber

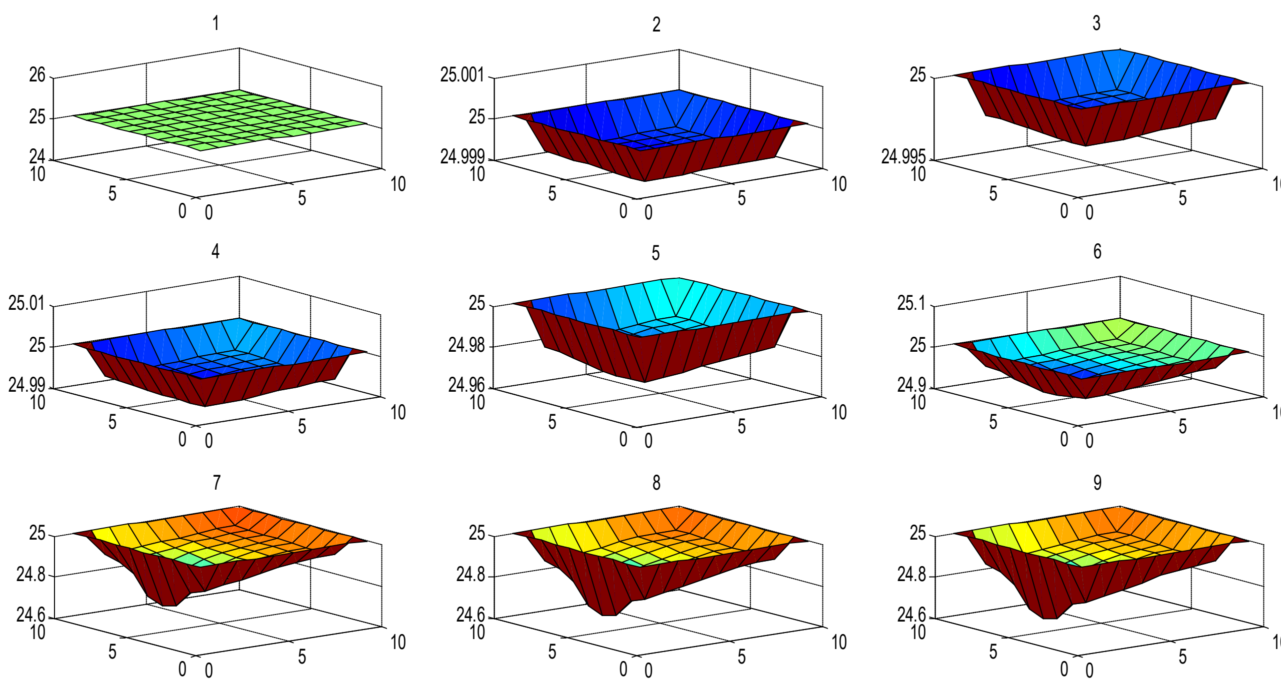

Figure 6. Behavior of the temperatures according to the height of the refrigerator

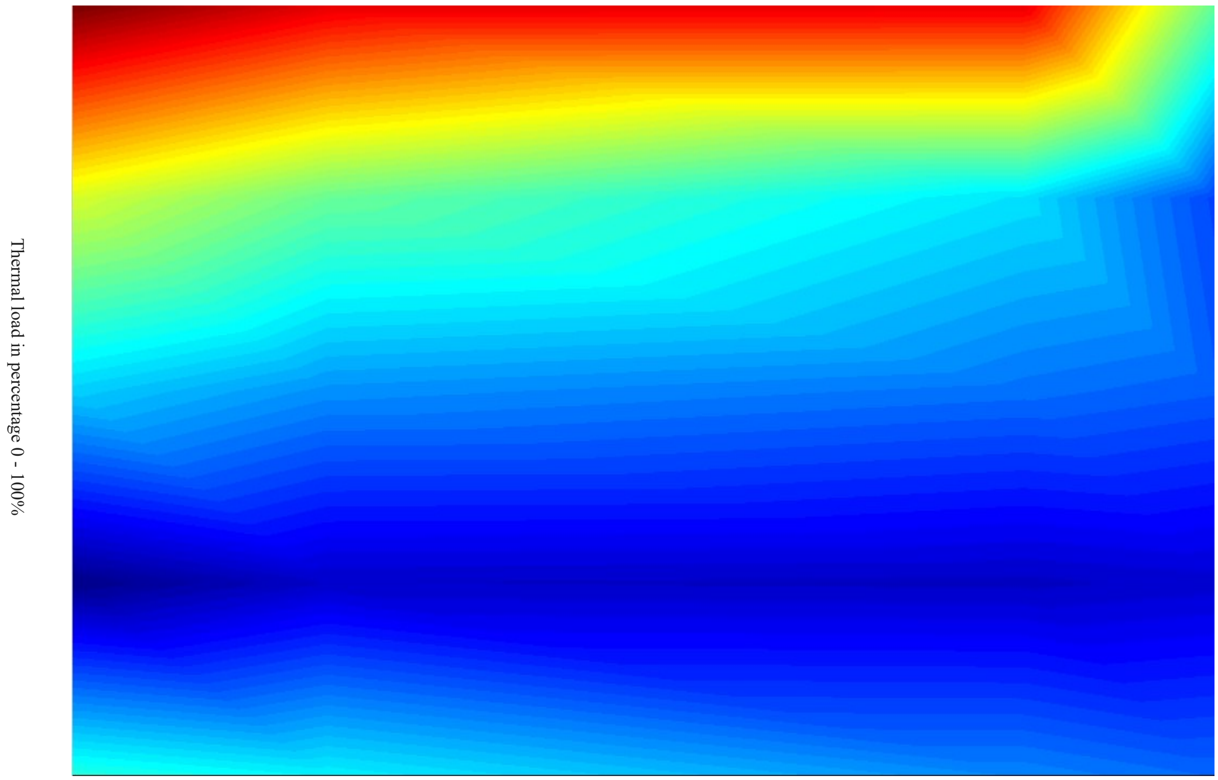

Figure 7. Distribution of the energy inside the cold chamber with different thermal loads.

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