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Dynamic Simulation of Household Refrigerators: Numerical Model and Experimental Comparison

Nicolas Ablanque
Centre Tecnològic de Transferència de Calor (CTTC), Universitat Politècnica de Catalunya (UPC), nicolas@cttc.upc.edu

Carles Oliet
Centre Tecnològic de Transferència de Calor (CTTC), Universitat Politècnica de Catalunya (UPC), carles@cttc.upc.edu

Joaquim Rigola
Centre Tecnològic de Transferència de Calor (CTTC), Universitat Politècnica de Catalunya (UPC), quim@cttc.upc.edu

Oriol Lehmkuhl
Termo Fluids S.L., Barcelona, Spain, termofluids@termofluids.com

Assensi Oliva
Centre Tecnològic de Transferència de Calor (CTTC), Universitat Politècnica de Catalunya (UPC), oliva@cttc.upc.edu

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Simulation of Household Refrigerators with a Flexible Numerical Tool

Nicolás ABLANQUE[1]*, Carles OLIET[1], Joaquim RIGOLA[1], Oriol LEHMKUHL[1,2], Carlos-David PEREZ-SEGARRA[1]

[1]Universitat Politècnica de Catalunya – BarcelonaTech (UPC), Heat and Mass Transfer Technological Center (CTTC), Terrassa (Barcelona), Spain
(+34 937398192, +34 937398920, www.cttc.upc.edu)

[2]Termo Fluids, S.L.
Magi Colet, 8, 08204 Sabadell (Barcelona), Spain
(Tel. +34-93-783.61.13, www.termofluids.com)

* Corresponding Author

ABSTRACT

This work presents a flexible numerical platform to simulate a whole household refrigeration unit taking into account both the refrigeration cycle itself and the refrigerated compartments network. The methodology implemented to achieve the transient simulation of the whole system combines a transient-state approach for the refrigerated chambers network and a steady-state approach for the refrigerant loop. The latter includes the simulation of a capillary-tube/suction-line heat exchanger (to prevent liquid refrigerant from entering into the compressor), and the simulation of a receiver (to store excess refrigerant in its liquid state). In addition, the global system resolution includes two significant features, namely, a specific numerical method to predict the system dynamics when the compressor is switched off, and a control system to regulate the compartments inner temperatures by modifying a damper position (open/closed) and/or the compressor state (on/off).

In this work, the major numerical aspects of the platform are briefly described. Furthermore, an illustrative numerical simulation of a household refrigerator including most of the model features is shown in order to see the model potential.

1. INTRODUCTION

The wide use of appliances such as air conditioners and household refrigerators represent a significant energy consume in several countries. The improved efficiency of the aforementioned devices may lead into important energy savings. The computer simulation has been extensively used to optimize the design and to study the performance of refrigeration systems. This approach has shown to be less time consuming and less costly than the conventional method (i.e. the repeated process of developing a prototype, testing its performance and modifying its structure).

The simulation of any system can be carried out for steady-state or transient conditions. The former case is often used for performance prediction and unit design, while the latter is essential for control design (Qiao *et al.*, 2010). The requirements for an ideal simulation tool include stability, robustness, flexibility/adaptability, accuracy, rapidity and a generic approach. These desirable characteristics may come into conflict between each other so that the research should be oriented to achieve the best compromise (Ding, 2007).

The aim of this work is to implement a numerical platform able to simulate the transient behavior of household refrigerators considering all the relevant components/features but also reaching a compromise between the system simulation time and the level of detail. The most significant aspects of the simulation could be summarized as follows. The whole system is made up of two sub-systems (refrigerant cycle and refrigerated chambers network). The refrigerating cycle considers specific elements such as a capillary-tube/suction-line heat exchanger, a receiver placed downstream of the compressor, and an anti-condensation tube. The refrigerated chambers network includes several chambers, walls, and solid inner objects. The control system of the refrigerated chambers is taken into account. The air loop throughout the refrigerated cabinets has a damper with two possible positions (open/closed). The whole system is simulated whether the compressor is switched off or on. Some of the system components are simulated with relatively detailed numerical models (e.g. the capillary tube is solved with a detailed distributed model). In addition to this, the system solver, which is based on a sequential methodology, has been adapted to link the two sub-systems and to reduce the simulation time in order to achieve long-time period simulations.

The numerical platform presented herein is a flexible numerical tool. It has a component-based structure to establish a clear distinction between the whole system solver and the particular resolution scheme of each component. For instance, the platform allows to easily adapt/modify the system layout without any major change on the global structure (e.g. introduce a new element on the refrigerant cycle, simulate a different chamber layout, modify the system temperature control etc.).

This work is divided in five Sections. The second Section is devoted to explain the main details of the numerical platform including the system solver, the strategies considered, and a brief review of the components numerical models. In the third Section, a full pseudo-transient simulation of a complete household refrigerator is numerically done. The simulation contains all the features mentioned in order to illustrate the platform capabilities. Finally, in the fourth Section some conclusions are given.

2. NUMERICAL MODEL

In this Section, the global resolution procedure used to solve thermal systems is described. Subsequently, the most important aspects that have been modified/added to achieve the complete simulation of a household refrigerator are listed and briefly explained. Finally, a brief review of the numerical models used to simulate each component of the system is provided.

2.1 System Resolution: Modular Approach

The numerical procedure presented herein to simulate household refrigerators is based on a modular strategy where the whole system is defined by several discrete components and their links. The system solver is decoupled from the particular resolution algorithm of each component (the specific resolution of each component is carried out independently during the system iterations). In this work the system solver consists of a sequential procedure where the solution is attained iteratively by transferring appropriate information between the components.

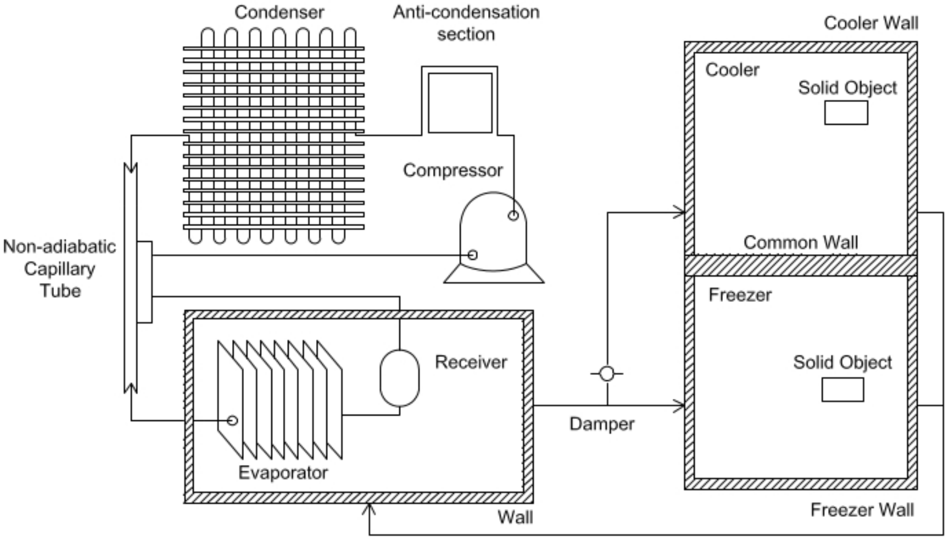

Figure 1: Simplified scheme of the refrigeration system.

The modular approach makes it possible to focus whether on the system solver or on any particular component without the need of major modifications to the global infrastructure. In other words, a different solver could be introduced at the system level, and similarly, the model of any component could be easily replaced (e.g. a heat exchanger model may vary from a simple ε-NTU approach to a distributed model considering two-phase flows or to any other model with a higher level of complexity). The modular approach also allows adding, subtracting and substituting components in order to represent a different system configuration. The object-oriented numerical tool called NEST used for this purpose has already been applied to energy balances in buildings (Damle *et al*., 2011a) and hermetic reciprocating compressors (Damle *et al*., 2011b).

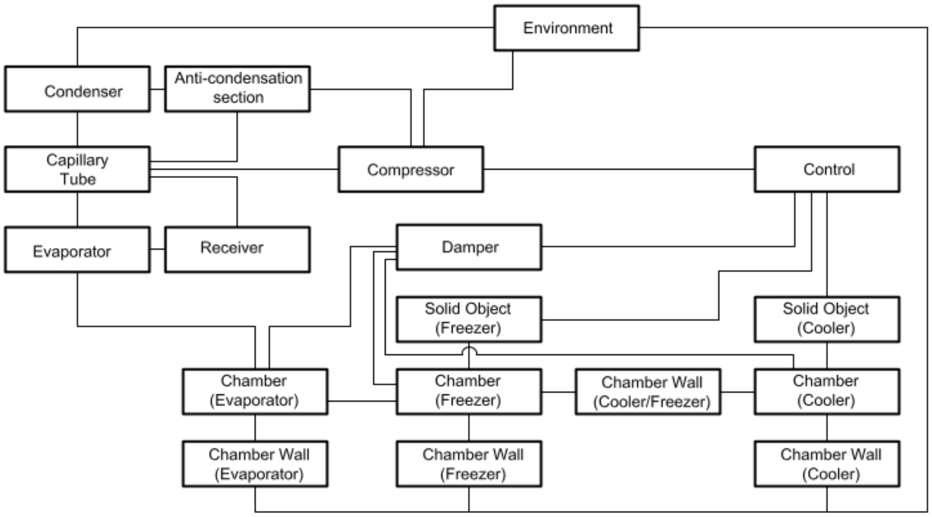

Figure 2: block diagram of the refrigeration system.

In this particular work the modular approach is applied to household refrigerators. The scheme of a complete refrigerator (cycle and refrigerated chambers network) and the corresponding block diagram used for its modular resolution are presented in Figures 1 and 2 respectively. It is observed that each component of the cycle is represented by a discrete element in the block diagram.

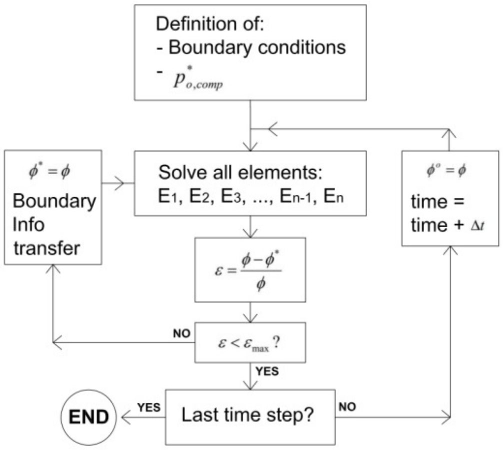

Figure 3: System global transient resolution algorithm.

The basic transient solution scheme for a defined system is depicted in Figure 3. At the starting point, the whole system boundary conditions are defined (i.e. components external conditions) together with an initial guessed/known value map for each component. From then on, the iterative procedure of solving all the components independently and sharing the information between them begins. The resolution of a particular time step finishes when a converged solution - defined by system level residual equations - is attained. Further calculations with the same procedure are carried out for the next time steps.

2.2 Household Refrigerator Simulation

The scope of the present work was to achieve a transient simulation of a complete household refrigerator including both the refrigerating cycle itself and the refrigerated chambers network (see Figure 1). The efforts were focused on different aspects: i) simulating all the relevant components which the system is made up, ii) taking into account all the system operational possibilities (e.g. compressor on/off, damper open/closed), iii) include the refrigerator temperature control, and iv) achieve a stable and low time-consuming simulation. The most significant aspects of the modified model are commented in the following paragraphs.

2.2.1 System Components. The most relevant components of the household refrigerator were taken into account for the present simulation. On one hand, the refrigeration cycle, which is usually simplified to the four main elements (compressor, condenser, expansion device and evaporator) has been simulated considering the following components: a commercial compressor, an anti-condensation tube (i.e. tube located all the way along the edge of the freezer door and used to prevent ice generation), a typical wire-and-tube condenser, a capillary-tube/suction-line heat exchanger, a fin-and-tube evaporator, and a receiver (to store liquid refrigerant). On the other hand, the refrigerated compartments network includes three separated chambers (the freezer, the cooler and the chamber where the evaporator is located), four insulation layers (one for each chamber and a common wall shared by the cooler and freezer), an air circuit with a damper that can enable or block the air flow through the cooler, and two solid objects, one inside the cooler and one inside the freezer, which represent small brass cylinders used to measure the temperature to be regulated in these rooms (they could alternatively represent a piece of food).

2.2.2 Control System. The transient simulation of the household refrigerator is equipped with a control system used to regulate the temperature inside both the freezer and the cooler. The control system used in this work is initially fed with four reference values, namely, the maximum and minimum temperatures allowed inside both the cooler and the freezer. During the transient numerical resolution an independent subroutine, in charge of the system control, is called once every time step. It works as follows: according to the input parameters (current freezer and cooler temperatures) and the predetermined reference values, the control system could modify two different operational characteristics, namely, the compressor state (on/off) and the damper position (open/closed). The control system could be easily changed or modified (e.g. include more inputs, act on other elements, etc…).

2.2.3 Cycle with compressor switched off. In household refrigerators the compressor could be operating at different speeds and/or simply be switched on/off depending on the thermal load needs. The components arrangement used to represent the refrigerating cycle when the compressor is switched on is not adequate to predict the cycle behavior when the compressor is switched off because of the different phenomenology. Therefore, an alternative cycle lay-out has been proposed to predict the cycle behavior at the off state in order to fully simulate the transient characteristics of a household refrigerator.

The implemented cycle configuration for the off condition is made up of only three components, namely, a high pressure side component (with a macro volume equivalent to the condenser and the anti-condensation tube inner volumes combined), a low pressure side component (with a macro volume equivalent to the evaporator, the receiver and the compressor inner volumes together), and an adiabatic capillary tube connecting both volumes (with the same diameter and total length of the non-adiabatic capillary tube used in the cycle when the compressor is switched on). The unique link between both components is the capillary tube as the compressor inner valves remain closed when the compressor is switched off. The resolution procedure is carried out sequentially every time step: the fluid state is recalculated inside both volumes from the capillary tube previously predicted mass flow rate. The heat exchange with the surroundings and the mass transfer between both macro volumes is also considered.

2.2.4 Pseudo-transient approach. The pure transient simulation of the whole household refrigerator and its components is rather complex, time consuming, and with serious convergence challenges. In this work a pseudo-transient approach is proposed in order to reach rapid and stable simulations. The whole system shown in Figure 1 is divided into two sub-systems, namely, the refrigerant loop and the refrigerated cabinets loop. The resolution procedure is carried out sequentially and combines two different approaches as the former loop is solved in a stationary way while the latter is solved in a transitory way. This methodology is feasible due to the relatively larger time scale of the chambers network compared to the refrigeration cycle. Each sub-system is solved every time step and shares information with the other sub-system. On one hand, the temperature of the chamber where the evaporator is located acts as the boundary condition for the refrigerant loop, and on the other, the heat absorbed by the evaporator acts as the boundary condition for the chambers network.

In the steady state simulation of the refrigerant loop the mass flow rate is common to all the components so that the resulting set of equations is indeterminate. In order to overcome this limitation, and to achieve full closure, the refrigerant mass inside the system must be known. Therefore the resolution methodology is carried out by means of two iterative loops. The refrigeration cycle is iteratively solved for a guessed compressor outlet pressure, which in turn is iteratively re-adjusted until convergence is attained (i.e. the calculated refrigerant mass is equal to the system refrigerant mass).

The scope of this work, besides achieving a full pseudo-transient picture of the whole system, is to simulate long time periods of operation. In order to attain the latter goal the steady state simulation of the refrigerating loop was not solved every global system time step but instead it has been previously characterized. The steady state refrigerating cycle response to any boundary condition is calculated prior to the full simulation, therefore, at every system time step, the heat transferred from the evaporator chamber air to the evaporator itself is readily obtained.

2.3 Mathematical Model of Elements

The studied household refrigerator includes two linked sub-systems (vapor compression refrigerant cycle and refrigerated cabinet network) with several components (see Section 2.2.1). In this Section a brief description of the models used to simulate the components is presented.

2.3.1 Compressor. The compressor model is based on the work by Ndiaye and Bernier (2010) where a simplified model is reported. It consists of three main parts, namely, shell inner volume, compression chamber, and discharge line. Both a mass and an energy balance equations are applied to the fluid inside the shell, while an energy balance over the compressor solid part is also considered. The model is fed with some empirical heat transfer coefficients and assumes the following hypotheses: oil effects are neglected, the suction pressure is equal to the pressure inside the shell, the suction and discharge mufflers influence is not taken into account, the mixture inside the shell is considered thermally homogeneous. In addition to the model equations, the compressor is characterized by the electromechanical, the volumetric and the isentropic efficiencies. The last two are also expressed by means of the compression pressure ratio (the corresponding mathematical relations are obtained from experimental tests or detailed numerical simulations previously carried out).

2.3.2 Non-adiabatic tubes. The thermal and fluid-dynamic behavior of flows inside tubes is predicted with a distributed two-phase fluid flow model based on the work by García-Valladares *et al.* (2004). The fluid domain is represented by means of consecutive control volumes where the governing equations (continuity, momentum and energy) are applied and solved. The flow is evaluated on the basis of a step-by-step numerical implicit scheme where the wall temperature map acts as the boundary condition. The formulation requires the use of empirical correlations to evaluate the void fraction (ε), the shear stress ($\overline{\tau}$) and the convective heat transfer coefficient used to evaluate the heat transferred between the tube and the fluid ($\dot{Q}_{wall}$).

2.3.3 Heat Exchangers. For fin-and-tube evaporators different levels of simulation could be considered. First, the detailed model called CHESS (Pérez-Segarra *et al.*, 2008, and Oliet *et al.*, 2010) where the domain is divided into a set of control volumes as fin-and-tube blocks. That model allows steady and unsteady analysis, flexible geometry and circuitry, and working at dry or wet/frosting conditions. The inner refrigerant flow is solved with the two-phase flow model where non-uniform heat transfer coefficients can be considered in radial and axial directions. Second, a ε-NTU based (steady, multi-zone) fin-and-tube heat exchanger model is also available (quickCHESS), considering dry and wet airside conditions, and evaporation/condensation for the refrigerant (Oliet *et al.* 2007). A similar approach is used for the wire-and-tube condenser.

2.3.4 Non-adiabatic capillary tube. The algorithm to simulate the capillary tube is detailed in Ablanque *et al.* (2010). It is based on the two-phase flow algorithm presented in Section 2.3.2. The resolution procedure consists in determining the capillary tube critical condition. The mass flow rate inside a capillary tube increases as the evaporating temperature decreases (lower discharge pressure) but only up to a critical value from which the mass flow rate remains constant. This critical limit occurs when the entropy generation equation is not accomplished anymore. This limit can be alternatively calculated when *dp/dz* approaches to infinity at the capillary tube discharge end. Then, once the critical condition is met, by comparing the current discharge pressure with the critical pressure (outlet pressure at critical conditions) it is possible to deduce if the capillary tube is operating at critical or non-critical conditions. An additional control volume is considered at the capillary tube outlet end where an energy balance is applied to calculate the capillary tube discharge enthalpy (heat transfer and transient terms are neglected).

2.3.5 Receiver. The numerical algorithm used to simulate this component is based on a full energy balance, where the following hypotheses have been assumed: i) the refrigerant inside the receiver is divided into perfectly defined liquid and vapor zones, ii) the internal energy is equal to the enthalpy in the liquid zone, iii) the kinetic and potential effects are neglected, iv) when mixed flow enters into the receiver it separates instantaneously. The model is comprehensively described in Sadurní (2010).

2.3.6 Refrigerated chambers. The refrigerated chambers are configured as a collection of other components, namely, air volumes, solid objects, and walls, which are linked between them. For instance, the component for an air volume consists of a single control volume including mass, moisture and energy balances. The component for walls consists of a multiple material layer, with one dimensional heat conduction, moisture transport, and heat convection at surfaces together with thermal radiation and solar gains. The solid objects exchange heat with the surroundings and could accumulate or release heat accordingly (food or temperature sensors with a non-negligible mass that could be inside the chambers are simulated with this type of component).

2.3.7 Air circuitry. The air flow that circulates through the three refrigerated chambers is also taken into account for calculating heat balances inside chambers. In addition, two possible circuit schemes are considered depending on whether the damper is open or closed (when the damper is closed no air is flowing from the evaporator chamber to the cooler). In this work the mass flow rates were not calculated but defined according to a preliminary design study.

3. VIRTUAL REFRIGERATOR: ILLUSTRATIVE CASE

In the current Section, an illustrative pseudo-transient numerical simulation of a full household refrigerator, consisting of refrigeration cycle and refrigerated chambers, is carried out. The system lay-out is depicted in Figure 1, while the simulation is based on the modular approach presented in Section 2.1 including all the features mentioned in Section 2.2. It should be remembered that in order to speed up the numerical model response, the refrigeration cycle is not solved every time step of the whole system when the compressor is switched on. Instead, the cycle has to be previously characterized (i.e. perform and store a set of simulations at different boundary conditions) so that the cycle response within the whole system transient simulation is instantaneous.

The main characteristics of the refrigerated compartments network are described in this paragraph. The freezer volume is 0.133 m^3, the cooler volume is 0.209 m^3 and the evaporator chamber volume is 0.04 m^3. The insulation used in walls has the following properties: thermal conductivity 0.029 W/m K, density 40 kg/m^3 and specific heat 1674 J/kg K. The solid objects located inside both the cooler and the freezer represent typical elements for temperature measurements. Their temperatures are calculated in each iteration step and used by the refrigerator control system. These objects are made of brass and have a volume of 2.7 cm^3.

The control system regulates the temperature of both the cooler and the freezer (the temperature of the brass objects not the air temperature). The minimum and maximum temperatures allowed in the cooler are 3 and 5 ºC, respectively, while the minimum and maximum temperatures allowed in the freezer are -20 and -18 ºC, respectively. The control system can modify the compressor operating state (on/off) as well as the damper operating position (open/closed) according to the following parameters: current compressor operating state (on/off), current damper position (open/closed), current rooms temperature values (temperature of brass objects), and the maximum and minimum allowed temperatures for both the cooler and the freezer.

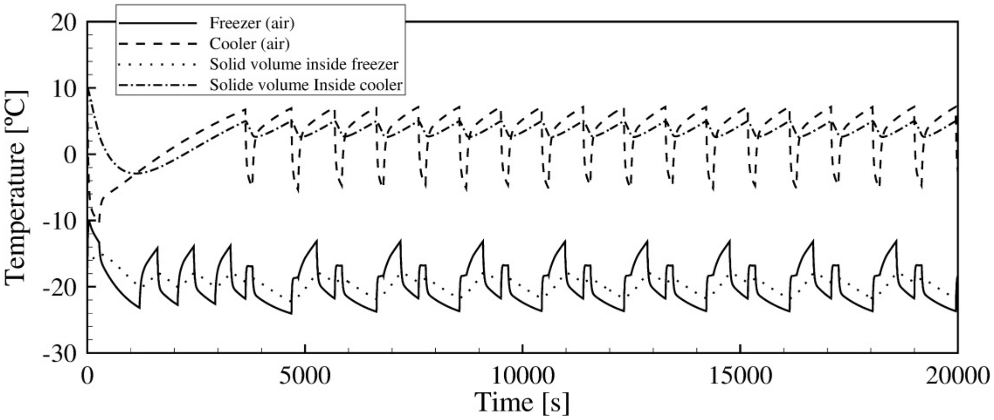

Figure 4: Freezer and cooler relevant temperatures evolution.

Figure 4 shows the pseudo-transient behavior of the most relevant temperatures in the studied household refrigerator. The aim of this particular Figure is to underline that a quite long period of time has been simulated (up to 20000 s) with a relatively short CPU time (3000 s). It could be observed how the system variables vary at the beginning of the simulation to finally reach a cyclical behavior which is repeated over the time. On one hand, the reason for the first unstable period is that the simulation starts from a set of initial/guessed values (air, brass object, and wall temperatures of all the chambers) which gradually converge into a thermally balanced solution. On the other hand, a perfectly cyclical behavior is achieved because the system external conditions are kept constant during all the simulation (e.g. environment temperature). The system control is well implemented as the temperature of the brass objects inside both the freezer and the cooler are always within the defined temperature range. A typical on/off cycle is extracted from Figure 4 and studied in the following paragraphs.

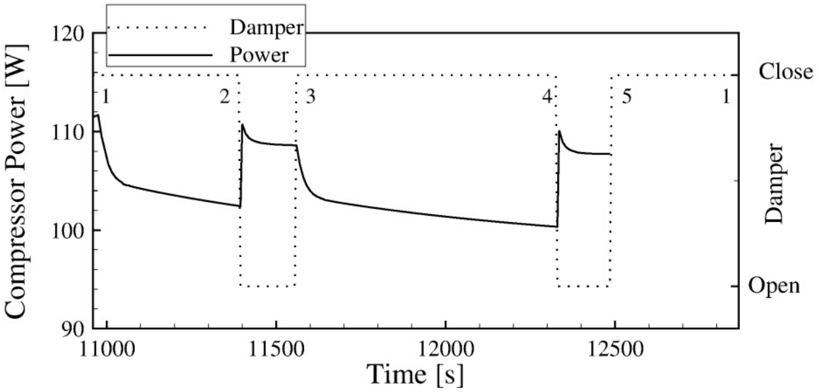

Figure 5: Compressor power evolution during an on/off cycle of the refrigerator.

Figure 5 shows the compressor power consumption evolution during a complete on/off cycle. The power consumption is only reported during the first portion of the on/off cycle because the compressor is switched on (within numbers 1 to 5 according to the Figure), and on the contrary, the power consumption is not reported for the second portion because the compressor is switched off (within number 5 and number 1 of the next cycle). For this illustrative case the damper is opened by the control system two times within an on/off cycle. It is interesting to see how the compression consumption rises when the damper is opened by the control system. It occurs that at this specific point the “cold” air from the freezer mixes with the “hot” air from the cooler, and therefore, the air temperature in contact with the evaporator increases and forces the refrigerating cycle to consume more energy. It can be deduced that when the temperature of the brass object inside the cooler is too high as shown in Figure 8 (this is the reference temperature for the cooler), the damper is opened by the control system (see numbers 2 and 4), then the room temperature drops rapidly to an acceptable lower value, and the damper is closed again by the control system (see numbers 3 and 5).

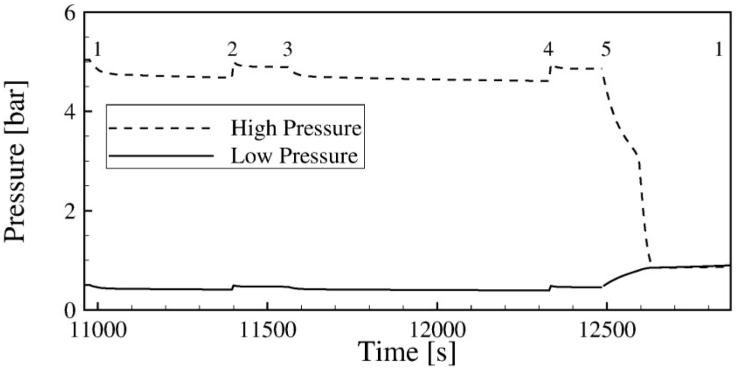

Figure 6: System pressures evolution during an on/off cycle of the refrigerator.

Figure 6 shows the evolution of both the high and low pressures of the refrigerating cycle. It is observed that during the “on” phase (from number 1 to number 5), the system pressures vary little, except for the particular moments when the damper position changes. As it has been seen before, a change on the damper position generates a sudden change on the system load demand, and therefore, the refrigerant cycle pressures are directly affected. In this Figure the consequences of the “off” phase over the refrigerating cycle are clearly observed (see the last section from number 5 to the next number 1). When the compressor is switched off, the system high pressure begins to drop and the system low pressure begins to rise, and after some time, the whole system pressure equalizes. In this particular case, the refrigerating cycle equalized pressure is about 3 bar.

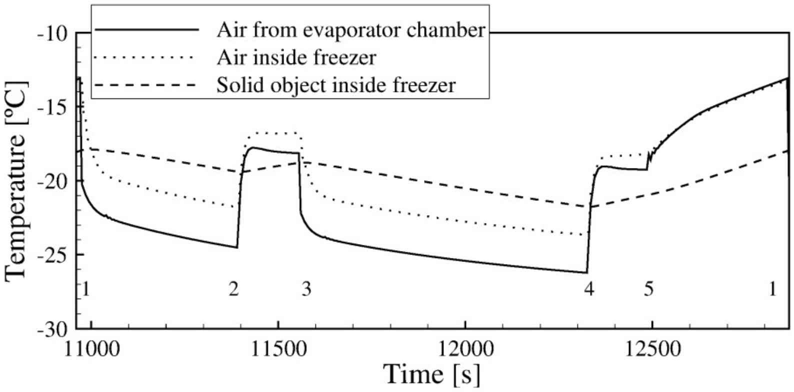

Figure 7: Freezer relevant temperatures evolution during an on/off cycle of the refrigerator.

Figure 7 shows both the freezer air and the brass object temperatures. The evolution of the air temperature inside the freezer during an on/off cycle is as follows. First, the compressor is switched on and the damper is closed so that the freezer air temperature decreases (from number 1 to number 2), second, when the damper is opened by the control system due to an increase of the cooler temperature (see Figure 8), the air temperature rises as the “hot” air coming from the cooler mixes with the current air (from number 2 to number 3), third, again the damper is closed by the control system so again the air temperature drops (section from number 3 to number 4), fourth, the damper is opened again (from number 4 to number 5), and fifth, the compressor is switched off (because both chambers temperatures have attained acceptable values) and the air temperature begins to rise due to the freezer external heat gains. The evolution of the solid brass object temperature follows a similar behavior to the air. However, this object is not affected by sudden heat exchanges like the air (i.e. when the damper is open and the freezer air mixes with air coming from the cooler).

Figure 8 presents a similar picture than Figure 7 but for the temperatures inside the cooler. In this case similar conclusions can be drawn as regards the air and the object temperatures evolution. However, it can be seen that both the air and the object temperatures are always increasing when the damper is closed whether the compressor is switched on or off due to the external heat gains of the cooler. These temperatures diminish only when the damper is opened by the control system so that "cold" air coming from the evaporator chamber arrives.

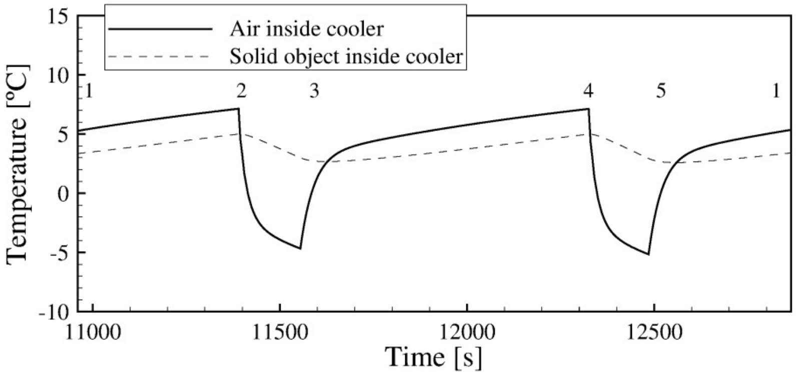

Figure 8: Cooler relevant temperatures evolution during an on/off cycle of the refrigerator.

4. CONCLUSIONS

In the present work a numerical simulation of a household refrigerator system in transient conditions has been carried out. The main goal was to implement a flexible numerical platform to study household refrigerators including its most relevant components/aspects and reaching a compromise between the system transient execution time and its simulation detail level. The illustrative case analyzed herein was based on typical household refrigerator geometries and components but the work was mainly focused on numerical aspects rather than validations. The upcoming step is oriented to validate the model and to study relevant aspects of the system (e.g. to analyze the influence of particular parameters over the whole system, to study control strategies in long time period simulations, etc.).

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