Simulation of the effect of control strategies on the performance of domestic refrigerator as a function of refrigerant charge – EVR2021 – 0039

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Abstract

The thermodynamic performance of domestic vapor compression refrigeration systems is still a research topic due to the cumulative effect on global energy consumption, representing about 8% of total energy consumption in Brazil in 2015. The use of variable speed compressors is a solution adopted to minimize energy consumption, which can be optimized through an appropriate compressor speed control system. In this work, three control systems are evaluated from the results of numerical simulation of the performance of a domestic refrigerator operating with R134a. For this purpose, two transient simulation models are employed that provide results of the system's performance as a function of the ambient temperature, the refrigerant charge and the thermal load. The models are fed with experimental data obtained from pull-down tests. The simulation results obtained allow comparing the studied control strategies.

Key words: Variable speed compressor, Refrigerant charge, Control strategies, Numerical transient simulations.

Introduction

Domestic vapor compression refrigeration systems are widely used, mainly guaranteeing food conservation and thermal comfort. It is estimated that there are approximately 1.5 billion units of household refrigerators in operation worldwide. The refrigeration sector is responsible for approximately 17% of the world's electricity consumption, 45% of which is attributed to residential demand (IIR, 2015). In Brazil, these systems are responsible for approximately 27% of residential electrical consumption (PROCEL & Eletrobrás, 2007), corresponding to about 8% of the country's total demand. These facts emphasize the importance of improvements in such systems.

To evaluate the behavior of domestic refrigerators, well-validated mathematical models are very important. This is because these tools allow the analysis of the performance of the system under different operating conditions and also the analysis of the influence of parameters such as geometric dimensions, refrigerant charge and control logic, among many others. This article presents numerical simulation results obtained with two transient mathematical models formulated with the lumped methodology presented in Gardenghi (2020). The fundamental objective of the study is the evaluation of control strategies of the system compressor based on its performance, depending on the ambient temperature, refrigerant charge and thermal load.

Methodology

The models consist in a set of ordinary algebraic differential equations obtained from the consideration of energy conservation and heat transfer rates equations (thermal model) and the conservation of mass and refrigerant charge distribution (capacitive model) in the system components. The equations are solved with the 4th order Runge-Kutta method in Python and with the CoolProp library (Bell *et al*., 2014) for calculating thermodynamic properties, see Gardenghi (2020).

The refrigerator studied is a vertical appliance with two compartments (fresh-foods of 207 L and freezer with 53 L) operating with 105 g of R134a, whose components are: a hermetic compressor with 163g of POE10 oil and a tube-wire condenser both cooled by natural convection; a capillary tube with heat exchanger with the suction line and a roll-bond type evaporator (box type in the freezer and plate type in the fresh-food compartment).

Experimental pull-down tests were performed to calculate the thermal conductance and capacitance of the system components, according to the standards NTB00048. The conductance of the compartments was obtained experimentally through a reverse heat loss measurement test (Melo et al., 2000).

The compressor efficiencies (volumetric, η_v and global, η_g) were obtained through experimental data from calorimetric tests provided by the manufacturer. These data are for the mass flow rate of the compressor, m_{com}, electric power consumption, W_{com}, and refrigeration capacity, Q_e, in steady state. Therefore, the efficiencies can be determined by relations as a function of the ratio between condensation P_{cond} and evaporation P_{evap} pressures (in Pa) or interpolated according to operational conditions, see Gardenghi (2020).

Control strategies

The first strategy is the on/off operation. The second strategy is appropriate to use with mechanical thermostat, because it does not need the acquisition of refrigerator internal air temperature. It consists on the evaluation of the time which compressor is activated.

The logic is based on a target time (t_{target}) and on a reference rotation. If the compressor reaches this time while on, the controller will evaluate the difference between the compressor rotation and the referenced one (N_{dif}). Being greater than an established value (R), the compressor rotation will be increased. If the difference is smaller, the rotation will be maintained, and, if the compressor reaches two times the target time while on, the compressor rotation will be increased. Finally, if the compressor turns off before the target time, its rotation will be decreased. In Figure 1 is shown a scheme of the logic.

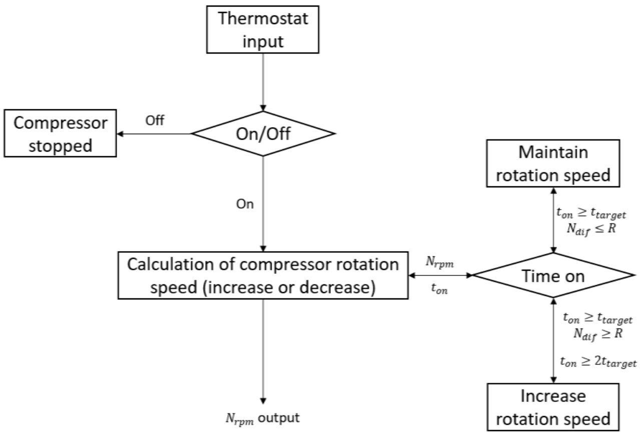


Figure 1: Scheme of the control logic based in compressor operation time.

In this strategy, the target time was 60 min, the reference rotation, the average speed on the last cycle (while compressor was activated), and the reference value for the difference between compressor rotation and the referenced one was 100 rpm. Compressor rotation was limited to be between 1600 and 4500 rpm, to ensure the compressor security.

The third strategy is based on the classic proportional control. This logic needs the acquirement of the compartment internal air temperature, so, it is appropriate to use with electronic thermostat. Figure 2 shows how the logic works.

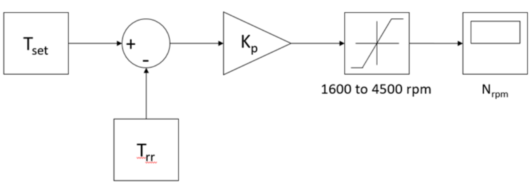
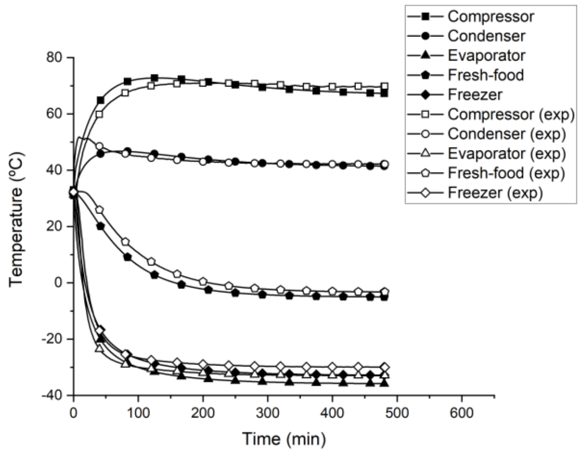


Figure 2: Proportional based control logic.

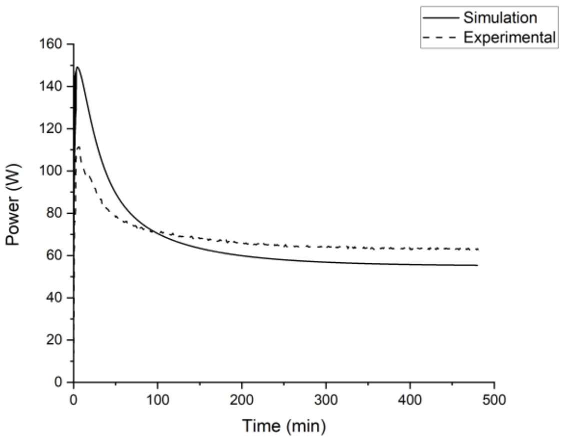
The parameters evaluated on this control are a target temperature, T_{set}, a proportionality constant, K_p, and the temperature inside the fresh-food compartment. The controller analyses the difference between T_{ff} and T_{set}, this way an "error" can be obtained. Then, the error is multiplied by K_p, resulting on a new rotation value, which is corrected by the limiter to be in the range of 1600 to 4500 rpm. On the simulations K_p was established as 1500 and T_{set}, the inferior temperature of thermostat.

Results

Numerical results for pull-down tests with the thermal model are compared with experimental data to make a simple validation of the models. The tested and simulated conditions were T_{amb} = 32°C, refrigerant charge of 105g and rotations of 1600, 3600 and 4500 rpm. The components temperatures and compressor electric power are shown in Figures 3(a) and (b) for the 3600 rpm.



(a)



(b)

Figure 3: Pull-down results under 3600 rpm: (a) temperatures; (b) compressor electric power.

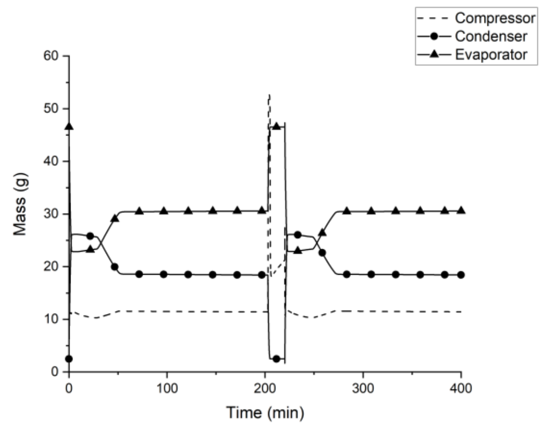
The simulation results are coherent with the experimental data. Considering the results for all the rotations (not showed) it is noted that the temperatures on compressor shell and the electric compressor power increase with rotation. Also, elevated rotations promote the increase of the condensation pressure and the decrease of the evaporation one, provoking the augmentation of condenser temperature and the reduction of evaporator temperature. The temperatures on fresh-food compartment and freezer were decreased.

Several simulations of the refrigerator operating with the three control strategies were carried out for T_{amb} = 32 °C and 105 g of R134a using the capacitive model. Some average performance parameters are presented in Table 1. The results show that the time-based control performs better in the simulated conditions. The on/off control is that which produces the higher energy consumption and inefficiencies of the refrigeration system.

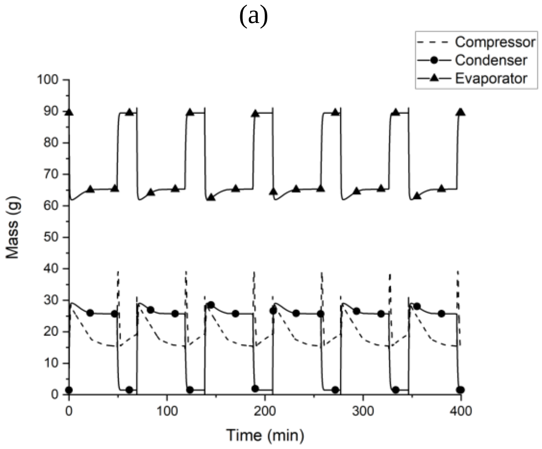
Table 1: Average simulated performance parameters with the three control strategies

	On/Off	Time-based	Proportional
COP	0.85	1.21	1.31
$Q_{e,avg}$ (W)	44.70	43.71	43.77
W_{avg} (W)	52.90	36.05	33.30
Consumption (kWh/month)	38.09	25.96	23.97
t_{on} (min)	24.29	47.61	57.39
t_{off} (min)	23.44	20.17	20.33

It is also interesting to evaluate the behavior of the refrigeration system with variable speed control strategies and different refrigerant charges. In Figure 4 are shown some simulation results for the proportional logic control with 70 and 130 g using the capacitive model.



(a)

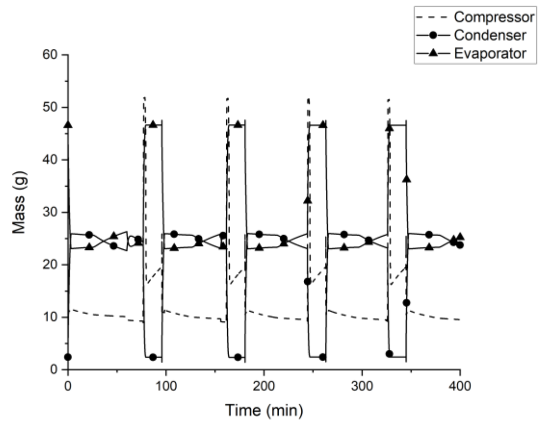


(b)

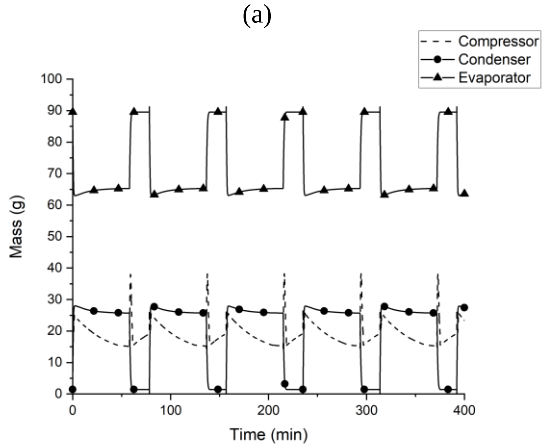
Figure 4: Mass of refrigerant in heat exchangers and compressor for proportional control simulations: (a) 70g and (b) 130g of R134a.

The reduction of the cooling capacity causes considerably longer cycles for the 70g case. The compressor electric power and the rotation follow this same expected behavior, not shown due to space limitations. Concerning the refrigerant mass distribution, with more refrigerant amount, the simulations show that the mass content in all components, as well as the mass difference between the heat exchangers, increase, see Figure 4. This fact leads to the augmentation of cycle pressure differences, causing higher compressor electric power.

In Figure 5 are presented some results for the simulations under the time-based control with 70 and 130g. The controller with this strategy set the compressor rotation in greater values, related to the minimum of 1600 rpm, with 70g. This is realized to avoid excessively long functioning periods (according to the target time), which occur due to reduced instantaneous cooling capacity values. So, the compressor electric power is increased and the duration of on/off cycles is reduced, compared to the proportional case.



(a)

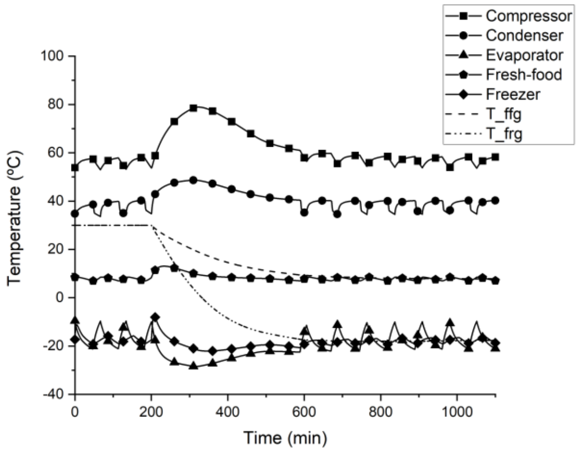


(b)

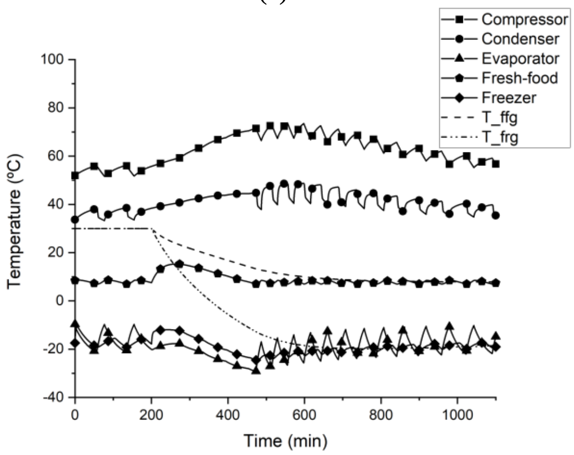
Figure 5: Mass of refrigerant in heat exchangers and compressor for time-based control simulations: (a) 70g and (b) 130g of R134a.

The following simulations are performed with the capacitive model to study the system behavior with variable speed strategies, T_{amb} = 32°C, 105g of R134a and the presence of goods inside the cabinet. In Figure 6 it is shown how the temperatures increase at minute 200, when the goods are inserted into the compartments (6kg in the fresh-food compartment and 3kg in the freezer).

The graphs displayed in Figure 6 show how the proportional control, with electronic thermostat and reading the temperature on fresh-food compartment, is faster than the time-based control to detect the situation inside the cabinet, and this fact directly reflects on the system behavior. When the food is put inside the compartments, the temperature inside them raises, so, the electronic thermostat turns on the compressor. As the calculated speed for proportional control is based on the error between the preset inferior limit temperature and the one on the fresh-food compartment, the speed (and the electric power) increases until the limit of 4500 rpm. This way the cooling capacity is maximized and the temperature in the compartments decreases quickly.



(a)



(b)

Figure 6: Temperatures of components and compartments indoor air with goods inside compartments: (a) proportional, (b) time-based.

With the time-based control, when the temperature on fresh-food compartment reaches the thermostat superior limit, the system is turned on and maintains 1600 rpm up to the target time, so, a new rotation is calculated and this process is repeated until the thermostat inferior limit is established and the system turns off. Then, in the next cycles, the rotation is decreased and becomes 1600 rpm again.

The Table 2 presents some performance parameters of the system operation for the whole operation time simulated. The gain on COP and consumption is evident with variable speed applications. It can be noted the fact that the proportional control provided faster reading of the fresh-food compartment situation caused higher COP and less energy consumption. The same is observed for the other simulated values of the refrigerant charge.

Table 2: Average simulated performance parameters with the three control strategies with thermal load.

	On/Off	Time-based	Proportional
COP	0.96	1.19	1.25
$Q_{e,avg}$ (W)	58.46	57.44	57.84
W_{avg} (W)	60.77	48.16	46.28
Consumption (kWh/month)	43.76	34.67	33.32
t_c (min)	232.79	318.67	388.57

Conclusions

The application of variable speed compressor associated to speed control strategies promotes great gains in several conditions simulated. Energy consumption reductions up to 31 % were obtained.

The proportional logic proved to be more efficient than the time-based one, as, in more severe operation, the controller with this strategy is able to read the situation inside the compartment faster and take the best decision.

Agradecimentos

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