HYBRID CONTROL DEVELOPMENT FOR A HOUSEHOLD REFRIGERATION SYSTEM WITH TWO COMPARTMENTS

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Abstract. *In this work we develop a temperature control for a household refrigerator with two compartments: freezer and fresh-food. A real refrigerator was used in the experimental tests. A model for the freezer temperature dynamic due to changes in compressor speed was experimentally identified. A PI controller for compressor speed was designed. As the minimum compressor speed can exceed the speed corresponding to some desired equilibrium conditions, an on-off controller was designed to match the cooling capacity to the thermal load in these cases. A switching rule was empirically designed to change from PI to on-off controller and vice-versa. The fresh-food capacity is controlled by a damper which regulates the air flow from freezer to fresh-food. The damper control utilized was the one already embedded in the appliance and was treated as a disturbance to the compressor controller. Steady state tests and transient tests were carried out to evaluate the controller performance. The controller was able to reject disturbances with no overshoot and to keep the desired reference of freezer temperature. This is accomplished respecting the minimum compressor speed requirement.*

Keywords: *household refrigerator, PI Controller, on-off controller, experimental development*

1. INTRODUCTION

Energy efficiency is one of the main characteristics of household refrigeration systems. Since actuator devices such as variable capacity compressors, electronic dampers, variable speed fans, electric heaters and variable expansion valves have been developed and increasingly applied in refrigerators, control strategies are becoming an important feature in the reduction of energy consumption. Moreover control strategies may improve food preservation as temperature and humidity control play an important role in this task.

The simplest household refrigerators use on-off compressors controlled by electromechanical thermostats or logical (on-off) electronic thermostats. This configuration imposes a cyclic behavior to system and refrigeration capacity and to compensate for the reduction of the refrigeration capacity when the compressor is off, a capacity greater than thermal load must be imposed by the compressor during the period it is on. Despite on-off compressors are cheaper than variable capacity compressors they are less efficient. Refrigeration systems that apply variable capacity compressors may match refrigeration capacity to thermal load by operating continuously with higher evaporation temperature which increases system efficiency Possamai and Todescat (2004).

The problem of controlling the compressor capacity in refrigeration systems was deeply explored. An adaptive relay-based control for an on-off compressor was designed in Leva *et al.* (2010). In this case the problem was to minimize amplitude excursion for food preservation while maximizing the period to reduce compressor upset. In Aprea *et al.* (2004) fuzzy logic was applied for controlling compressor speed in order to use system knowledge in the design of the controller. Most of the works found in the literature refer to control variable capacity compressor with variable expansion device in purpose-built test facilities. A comparison between a configuration with variable capacity compressor with capillary tube and variable capacity compressor with variable expansion device was made in a real refrigeration system in Marcinichen and Melo (2006). The configuration with variable expansion device presented worse energy consumption when thermal load was lower than minimum compressor capacity leading the compressor to operate at on-off strategy. In Marcinichen *et al.* (2008) a dual-SISO strategy based on two PI controllers was used to control the refrigeration capacity by acting on the compressor speed and evaporator superheating through expansion valve position. Considering the same problem Hua *et al.* (2009) applied the dual-SISO PI controller with feedforward controllers to minimize the impact of control loops dependency. Ekren *et al.* (2010) compared three techniques, namely neural networks, fuzzy logic and PID. The best result in terms of energy consumption and temperature control was obtained with neural networks, but it is noteworthy that PID was designed by Ziegler-Nichols method which is not the best PID tuning. A multivariable controller based on H_∞ design was studied in Larsen and Holm (2003) and compared to dual-SISO controller. Both controllers had similar response. In Schurt *et al.* (2009) a model-driven multivariable LQG controller was designed and in Oliveira *et al.* (2011) a switched controller based on Lyapunov functions was designed and compared to dual-SISO PI controller. Beside simplicity, dual-SISO presented better energy consumption performance.

The aforementioned works did not consider neither analyze the effect of other controllable devices as damper, fans and heaters that are present in some real household refrigeration systems. Damper control was studied in Graviss and Collins (1996). In this study a comparison between manual damper, on-off damper and proportional damper was made. A comparison of a coupled and uncoupled actuation scheme of compressor and evaporator fan was also presented with fixed and variable temperature bandwidths for thermostat hysteresis. Results pointed that on-off damper with uncoupled actuation of compressor and evaporator fan and variable temperature bandwidths drives system to better energy savings. In Lee *et al.* (1994) a system with an evaporator fan to circulate cold air through freezer and a damper used to circulate air trough fresh-food was modified to operate with two fans, one to freezer and another to fresh-food. Fresh-food fan operates independently of compressor. The new configuration provided small temperature fluctuations and quicker response to thermal loads in fresh-food. Even though evaporator fan and damper control may improve energy efficiency, other factors such as temperatures stratification and oscillations may be compromised if control modifications are not accomplished with system modifications.

Based on these aspects, in this paper a controller for a variable capacity compressor applied to a real household refrigeration system was developed and analyzed. The system comprises a damper to control fresh-food temperature, an evaporator fan to circulate air through compartments and a heater for defrost operation. The approach was maintain original damper control in order to keep fresh-food conditions in terms of temperature stratification and oscillations. Thus damper was considered as a disturbance for compressor control. Evaporator fan was kept on while compressor was kept on. Defrost heater was actuated externally. The strategy was control freezer temperature by modulation of compressor capacity. The authors consider these issues a contribution of this paper as other works found in literature focusing compressor control did not consider other controllable devices in a joint control strategy.

This paper is organized as follows. This section presented a brief overview of control opportunities in household refrigeration systems and presented the specific objective and contribution of this paper. Section 2 describes the experimental apparatus. Section 3 presents control development. Section 4 is dedicated to the presentation of the obtained results. Finally, in section 5 main conclusions are presented and some future works are proposed.

2. EXPERIMENTAL SETUP

The tests were performed with a 422 L bottom-mount household refrigerator with a 302 L fresh-food and a 120 L freezer. The system comprises a conventional refrigeration cycle with a variable capacity compressor with operation range from 1200 rpm to 4500 rpm, a static condenser, a fixed restriction expansion device named capillary tube and a no-frost evaporator with a distributed heater to perform defrost operation. A heat exchanger is built between capillary tube and suction line. The evaporator is whole placed inside freezer compartment. The evaporator fan is used with an electronic damper to cool fresh-food. In order to sense and control compartment temperatures two NTC sensors are used. One NTC is placed in evaporator air outlet and is used to measure freezer temperature (T_{fz}). The other NTC is placed at the top of fresh-food air flow duct and is used to measure fresh-food temperature (T_{ff}). A schematic overview of this system is presented in Fig. 1.

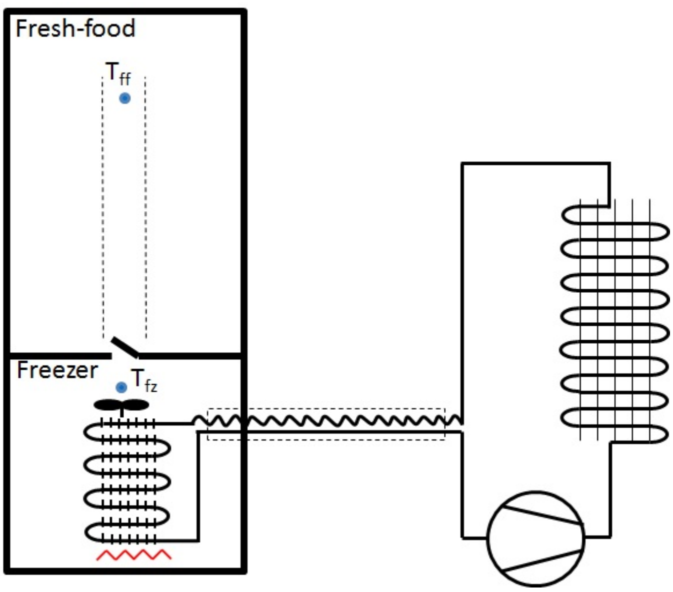


Figure 1: **Schematic diagram of the system**

In order to allow for controlling the system externally without using the original electronic board, thermocouples were installed in the same positions of original NTC sensors. Moreover the inverter used to drive compressor is able to be controlled by serial communication. Thermocouples were installed in each drawer and shelf of freezer and fresh-food with the objective to estimate system capacity and temperatures stratification. Every thermocouple used is T type with $0.2\,^{\circ}\mathrm{C}$ uncertainty. A wattmeter with $\pm 0.1\%$ was used to measure system power. The refrigerator was placed inside an environment chamber with controlled air temperature and humidity. The climate chamber is able to control the air temperature ranging from 15 to 50 °C ($\pm 0.2\,^{\circ}\mathrm{C}$ uncertainty band) and the relative humidity ranging from 40 to 95% ($\pm 5\%$ uncertainty band).

3. CONTROL DEVELOPMENT

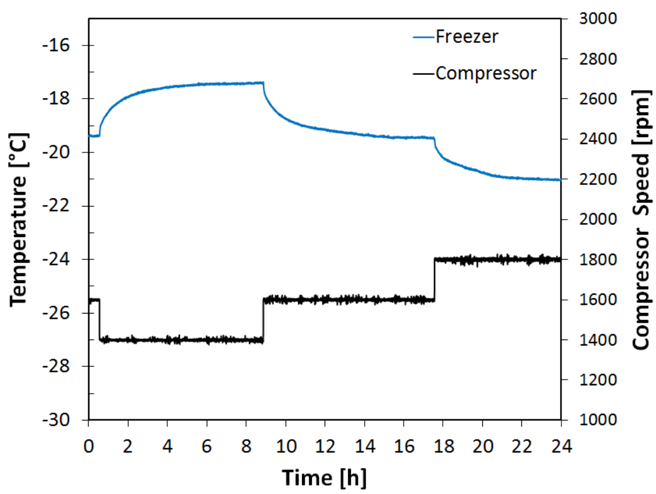
Preliminary tests show that compressor has to be turned off in order to match system capacity to thermal load when ambient temperature is under $25\,^{\circ}\mathrm{C}$ even if compressor speed is at minimum speed. The compressor is oversized for steady state operation because it has to produce enough capacity for pulldown and disturbance rejection. Therefore the control strategy for compressor speed should attempt to continuous speed operation from 1200 rpm to 4500 rpm and to on-off operation when thermal load is low enough. For this reason in this work it was developed a hybrid control comprising a PI controller for continuous speed operation, a hysteresis based controller for on-off operation and a switching logic to define the operation mode.

3.1 PI Controller

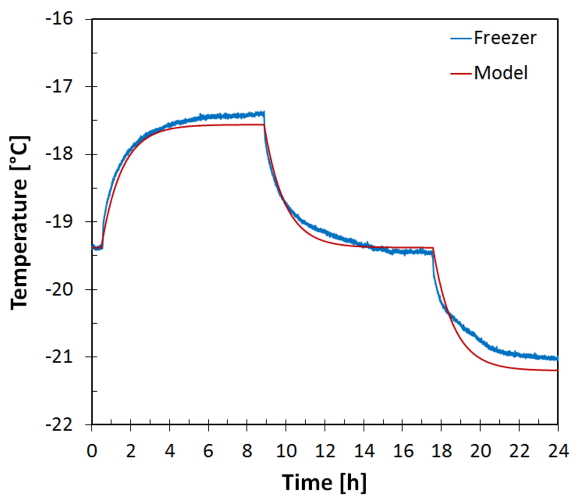
PI controllers are known by their simplicity, robustness, capacity to track constant reference and reject constant disturbance. These characteristics are the reason for the choice of this structure in this work. Equation (1) presents the transfer function in Laplace domain for PI controller where K_c is the proportional gain and T_i is integral time constant.

$$C(s) = K_c(1 + \frac{1}{T_i s}) \tag{1}$$

In order to design PI controllers, which means calculate parameters K_c and T_i, a black box model considering freezer temperature variation as output and compressor speed variation as input was experimentally identified. The identification was based on step response method to capture the behavior of the system near the operation point. As the system is nonlinear, there is a small mismatch between the system response and the model response as shown in the Fig. 2(b). For each step a first order model was obtained and the average model of this set of models is used to design a PI controller that is robust enough to face the mentioned small mismatch. Figure 2(a) presents graphically freezer temperature and compressor speed during identification test. To carry out the test, the damper was kept at 25% opened, chamber temperature was controlled at $32\,^{\circ}\mathrm{C}$ and chamber humidity at 50%. The compressor point of operation chosen was 1600 rpm, which drive temperature freezer to around $-19.5\,^{\circ}\mathrm{C}$. Around this operation point, the compressor speed was disturbed in steps of ± 200 rpm.



(a) Model identification



(b) Model x Experimental data

Figure 2: **System identification**

Based on the previous experiment, a first order model was obtained with the structure presented in Laplace domain in Eq. (2).

$$G(s) = \frac{y(s)}{u(s)} = \frac{K_p}{\tau s + 1} \tag{2}$$

where y is the output, u is the input, K_p is the static gain and τ is time constant. The parameter values were estimated graphically as $K_p = -0.0091\,°\text{C/rpm}$ and τ = 3810 s. The freezer temperature model is compared with the experimental data in Fig. 2(b).

The PI controller of the compressor was designed by the well known root locus method. The specifications considered in the design were constant reference tracking with no error, closed loop system three times faster than open loop system and no overshoot. These specification led to parameters $K_c = -945\,°\text{C/rpm}$ and $T_i = 1423$ s.

A reference filter was designed to smooth system response when a reference change is applied. Equation (3) presents the transfer function of the filter. The parameter p_f was calculated leading to 0.000703.

$$F(s) = \frac{p_f}{s + p_f} \tag{3}$$

An anti-windup structure was designed to smooth control action in saturation regions by discharging integral action from PI. Figure 3 presents control loop with mentioned structures.

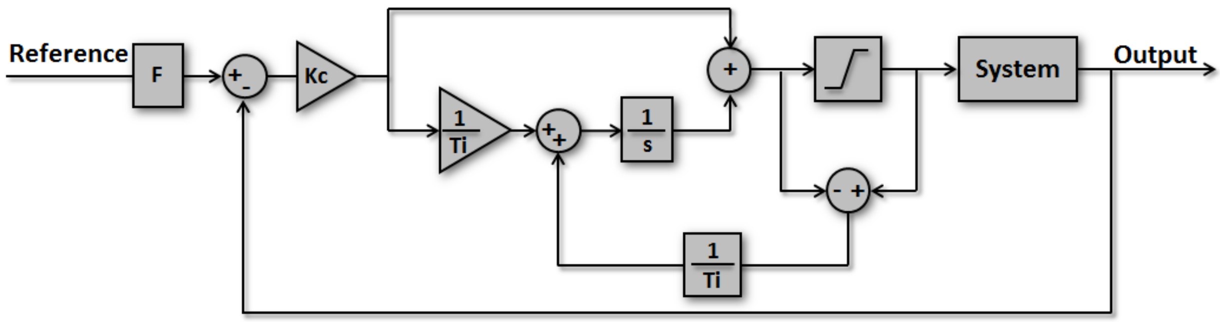


Figure 3: **Control structure**

As the objective is to implement the aforementioned controller in a digital device, a discretization was done using *Tustin* method with 10 s of sample time. The discrete PI controller is presented in Eq. (4) and sampled reference filter is presented in Eq. (5). Parameters α, β and γ from sampled controller were calculated respectively -948.32, 0.0035 and 941.68. Parameters ω and λ from sampled reference filter were calculated respectively 0.993 and 0.003503.

$$u(k) = u(k-1) + e(k)[\alpha + \beta e_{aw}] + e(k-1)[\gamma + \beta e_{aw}] \tag{4}$$

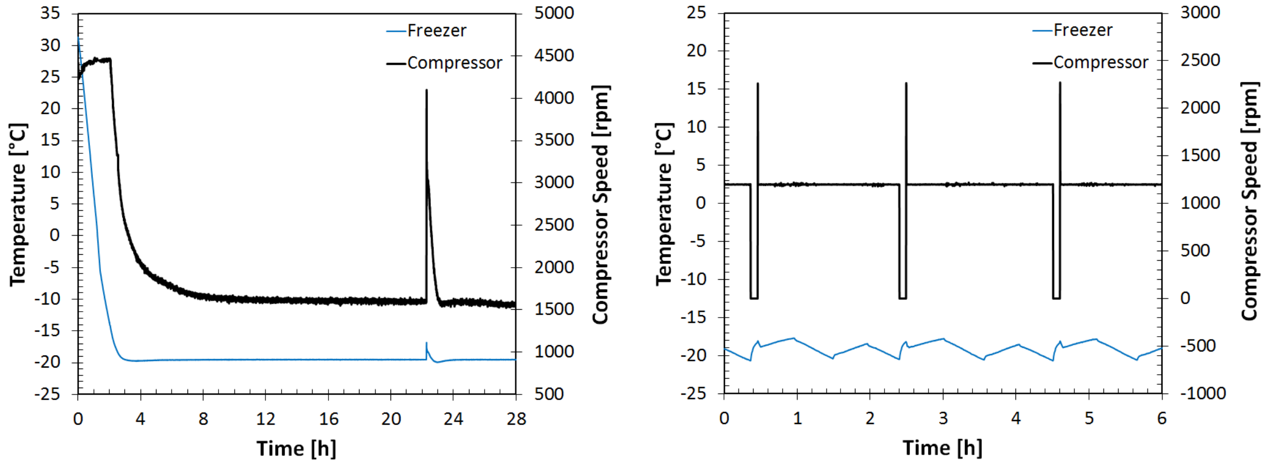
$$r_{eff}(k) = \omega r_{eff}(k-1) + 2\lambda r_{ef}(k) \tag{5}$$

Finally the control structure was validated in a reference tracking and disturbance rejection test as presented in Fig. 4(a).

3.2 ON-OFF Controller

On-off controller was designed experimentally. A set of tests were carried out with the objective to find a hysteresis region and compressor speed that better deals with the trade-offs between energy consumption, temperature fluctuations and compressor on-off switching frequency.

Tests were defined considering compressor efficiency which decreases in lower speeds against system efficiency which increases in lower compressor speeds and consequently higher compressor run time. Therefore a set of experiments were carried out varying minimum compressor speed applied and freezer temperature bandwidth. These tests were carried out at $25\,°\text{C}$ for ambient temperature. Analyzing temperature fluctuations, energy consumption and compressor on-off switching frequency, the temperature bandwidth comprised in the interval $(-21\,°\text{C}, -17\,°\text{C})$ with 1200 rpm compressor speed was chosen for hysteresis control. Figure 4(b) presents the result obtained with the designed hysteresis control. It may be observed the low frequency in on-off compressor switching and small freezer temperature fluctuations.



(a) PI Controller

(b) On/Off Controller

Figure 4: **Controllers' validation**

As the goal is to maintain freezer medium temperature at $-18\,^{\circ}\mathrm{C}$ the hybrid logic defines PI operation until freezer temperature reaches $-21\,^{\circ}\mathrm{C}$. At this point the system starts to be driven by on-off controller and return to PI only when freezer temperature is over $-16\,^{\circ}\mathrm{C}$.

4. RESULTS

A set of tests were specified to evaluate the performance of developed controller. The performance was measured by system energy consumption, compartments reference temperature tracking and load disturbance rejection. In practice system energy consumption and temperature maintenance were evaluated in steady state tests, reference temperature tracking was evaluated in pull-down test and load disturbance rejection was evaluate in defrosting tests and freezer door opening tests.

4.1 Steady state experiments

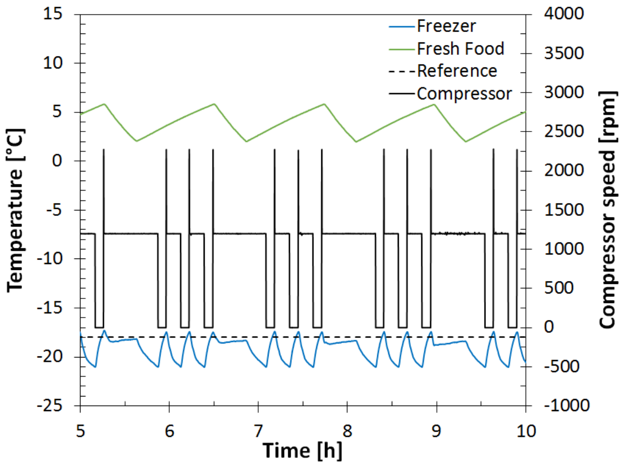
Steady state tests were carried out in three different ambient temperatures ($18\,^{\circ}\mathrm{C}$, $25\,^{\circ}\mathrm{C}$ e $32\,^{\circ}\mathrm{C}$) and 50% of relative humidity. Doors were kept closed and no charge was added into compartments. Freezer and fresh-food temperatures kept around references.

Figure 5 presents results obtained at $18\,^{\circ}\mathrm{C}$, $25\,^{\circ}\mathrm{C}$ and $32\,^{\circ}\mathrm{C}$. Comparing the results it is observed that compressor run-time increases as ambient temperature increases till 100% turned on at $32\,^{\circ}\mathrm{C}$ in which PI controller is always actuating. At ambient temperatures of $18\,^{\circ}\mathrm{C}$ and $25\,^{\circ}\mathrm{C}$ compressor is kept on always damper is opened (which is verified by fresh-food temperature decreasing) and it is turned off only when damper is closed (which is verified by fresh-food temperature increasing). At $32\,^{\circ}\mathrm{C}$ it is verified freezer temperature oscillations caused by damper cyclic behavior that is considered as a disturbance to freezer PI controller. In the presented strategy damper was not considered in the system model. However PI controller always drive freezer temperature to the reference ($-18\,^{\circ}\mathrm{C}$) which happens in the moment that damper is opened. At this condition, the system dynamic is similar to the point in which PI was designed.

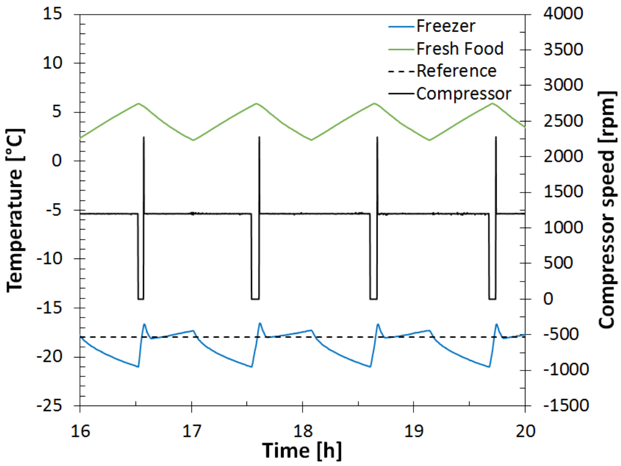
Table 1 presents results for steady state tests.

Table 1: **Steady State**

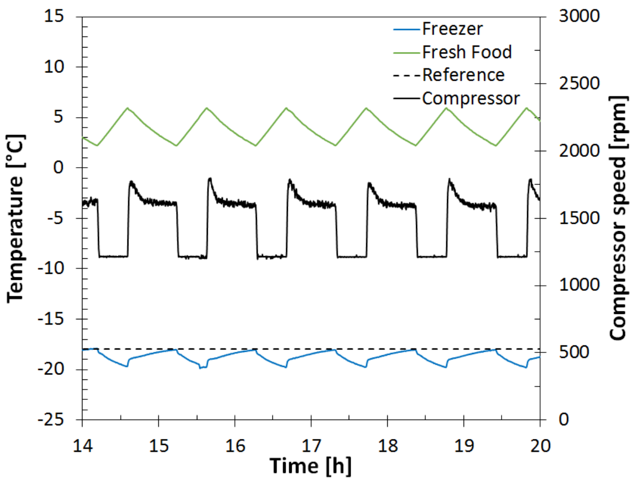
Ambient [°C]	**Fresh Food** [°C]	**Freezer** [°C]	**Consumption** [kWh/m]
18	2.5	−19.6	22.0
25	2.3	−19.1	28.2
32	1.7	−19.0	36.9



(a) 18°C



(b) 25°C



(c) 32°C

Figure 5: **Steady state**

4.2 Pull-down experiment

Figure 6 presents pull-down test at 32°C of ambient temperature. Reference filter smoothed compressor speed acceleration that took about 2 minutes to go from 0 rpm to 4500 rpm. Freezer temperature took about 2.5 hours to reach 99% of reference.

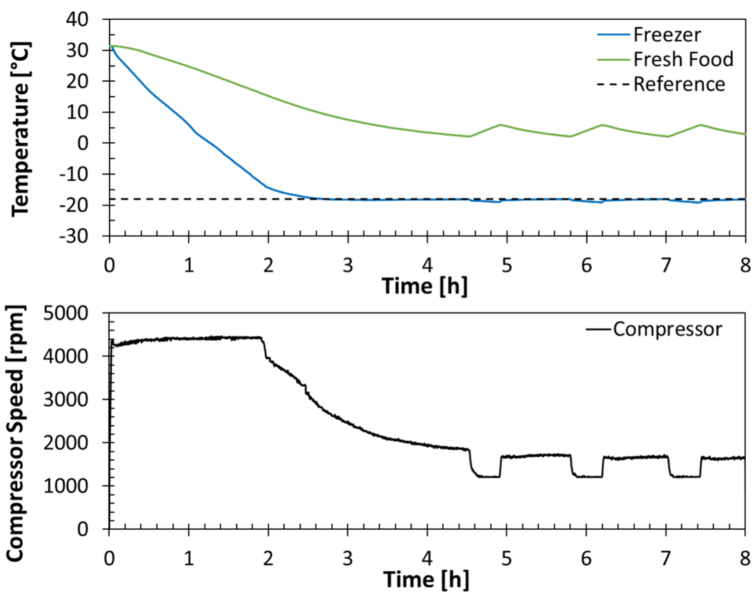
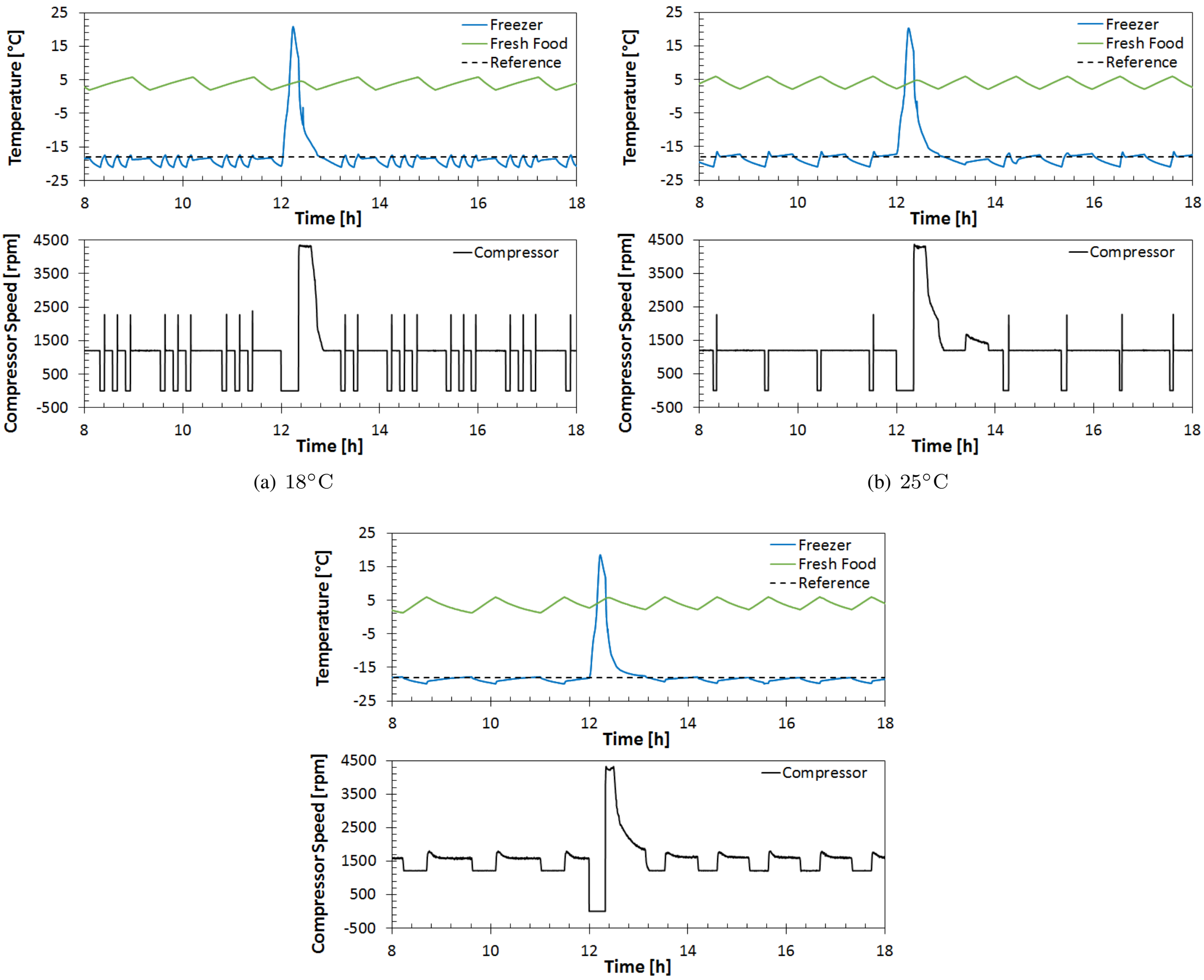


Figure 6: **PullDown**

4.3 Disturbance rejection experiments

Figure 7 presents results obtained at defrosting tests in which control aims to reach reference temperatures after defrost heater is turned off and compressor is turned on. During defrost period compressor and evaporator fan are kept off. Damper is kept closed. Defrost heater is turned on until defrost sensor reaches 20 °C. After that, heater is turned off and compressor and evaporator fan are turned on. PI controller is activated. For ambient temperature at 18 °C PI rejects disturbance caused by defrost operation in about 25 minutes. On-off controller is reactivated after damper is closed in instant freezer reaches hysteresis lower temperature. For ambient temperature at 25 °C PI rejects the same disturbance in about 32.5 minutes. It can be observed that PI controller is kept actuating for one more damper cycle until reaches hysteresis lower temperature and then it is switched to on-off controller. Finally for ambient temperature at 32 °C PI rejects defrost disturbance in about 50 minutes and remains active for the whole test period.



(a) 18°C (b) 25°C

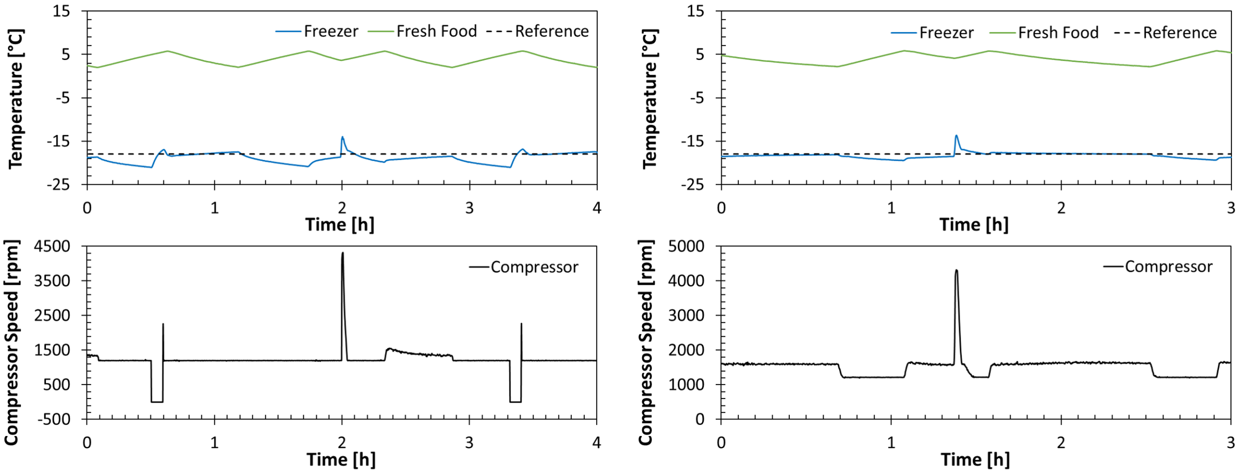
(c) 32°C

Figure 7: **Defrost disturbance**

Figures 8(a) and 8(b) present freezer door opening tests carried out at 25 °C and 32 °C respectively. At steady state operation, freezer door was opened for 30 seconds. In both tests damper was closed in order to speed up disturbance rejection in the freezer. At 25 °C disturbance is reject in about 5.5 minutes, considering time to reach 99% of reference. Using the same methodology, disturbance is reject in about 9 minutes in test at 32 °C.

5. CONCLUSIONS

This paper presented a hybrid control for compressor speed applied to a real household refrigeration system. The hybrid control comprises a PI plus a hysteresis and a logic to switch between them. The simplicity of the controller and an intuitive design are interesting features of the proposed control strategy. Moreover, the controller exhibited good performance and robustness in real tests with the refrigeration system. The performance was measured by system energy consumption, compartments reference temperature tracking and load disturbance rejection. Energy consumption and temperature maintenance were evaluated in steady state tests, reference temperature tracking was evaluated in pull-down test and load disturbance rejection was evaluate in defrosting tests and freezer door opening tests. All these positive aspects of the proposed control strategy are the contributions of the paper.



(a) 25°C (b) 32°C

Figure 8: **Door opening disturbance**

The authors would like to suggest some proposals for future researches in control of household refrigeration systems. The first one is to consider a feedforward control to minimize damper disturbance on compressor speed control loop. The second one is to compare the proposed technique with a multivariable control considering damper and compressor speed as input variables for both fresh-food and freezer temperatures. The third one is to study evaporator fan influence on fresh-food and freezer temperatures and on system efficiency. The last point is that it seems important to investigate defrost control strategies as a way to minimize defrost impact on compartment temperatures and energy consumption.

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