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A low-cost HIL platform for testing professional refrigerators controllers ⋆

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Abstract: In this work, we present a Hardware In the Loop (HIL) platform for testing control strategies designed and implemented in a commercial electronic control unit for industrial refrigerators. The architecture structure consists of four elements: *(i)* a real-time processor, in which a detailed model of the refrigerator is implemented; *(ii)* the industrial control unit device under test; *(iii)* an Input/Output (I/O) hardware interface which allows data communication between the real-time processor (model) and the industrial device (control) and *(iv)* a power PC in order to display and save experimental results. Introducing the HIL methodology in the refrigerator industry could reduce electronic control unit testing costs and save time in the production stage because it is possible to verify the control strategy performances in real-time for several operating conditions and different refrigerator models avoiding expensive and time-consuming test bench procedures.

Keywords: Hardware In the Loop, Arduino, Refrigeration System

1. INTRODUCTION

In the green economy revolution, energy saving and time-consuming reduction in testing phase regarding electrical appliances have become primary goals for manufacturing industries. In order to reach these two objectives industrial and academia research are going to introduce innovation about materials and electrical devices employed in such appliances CECED (2003). In this context, refrigerators play a significant role, being always present and turned on at any business place or at public institutions or at home. In this paper, we deal with control units installed in professional refrigerator systems which have, usually, only one cell and are utilized at restaurants, bars, pubs, fast foods, etc. This kind of refrigerators is very important for the business where they are installed. Indeed, their performances and costs (power supply request and purchase cost) influence four relevant management aspects. First of all, they are always operative and, then, they are a fixed energetic cost. Even a small saving on power request, in the long period, could be a relevant cost reduction. Furthermore, they preserve foods and beverages which represent the raw materials of business for the user company. In order to guarantee conservation quality, it is necessary to have efficiently equipments with high performances and minimal defects (low maintenance costs). Another important parameter is, of course, the purchase price, which is a critical point in this particular period, and to reduce it the production costs have to be low. Finally, it is necessary to satisfy some hard constraints imposed by environmental and international standards ENERGY (2011). In order to satisfy the above-mentioned needs, manufacturing industries have to design a high quality product reducing production costs. One important cost is the testing of firmware implemented in electronic control units. This procedure is time-consuming and has to be repeated several times for different surrounding conditions and for each refrigerators model. In particular, each test has to verify that: *(i)* there are no software errors in the control strategy (debugging), *(ii)* all constraints are satisfied and several control parameters have to be tuned such that the performances are similar for all possible environmental conditions. Nowadays, testing is performed in a specific lab environment in which it as installed several devices that are able to modify surrounding conditions and acquisition hardware. In the testing space the refrigerator is placed with the control unit together with several acquisition instruments in which thermodynamic, energetic, acoustic and mechanical quantities are stored. In this paper we present a low cost HIL bench able to test a particular family of control units. For an HIL system we mean a system in witch the plant model

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is simulated over a real-time machine and the controller is the real ubit under test, as reported in Shokry and Hinchey (April 2009). The real-time machine used is the board Arduino mega. In others works,Matthew Coombes (September 2012) J. Mamala (2013) Chun Yina (2013) Marco Bonvini (2009) is used an Arduino board in the real-time loop. The main difference is that in this work we use the Arduino board as thge real time-machine to simulate the plant. Introducing the HIL methodology in refrigerator field could be useful because it is possible to verify and tune control strategies in real-time mode at design stage. In this paper we also present the mathematical model that we use to simulate the refrigerator dynamics. It is able to describe the dynamics of: *(i)* cooling systems, *(ii)* inner cell thermodynamics variables and *(iii)* the formation of ice on the evaporator in the normal use of the refrigerator. This last aspect is very important because the presence of ice influences significantly both the cooling system behavior and the inner cell thermodynamics variables. Furthermore, using this kind of model allows the testing of all the functionalities designed in the control module (such as the defrost algorithms, the command on the evaporator fan, etc,...). The paper is structured as follows. In Section 2 we present the refrigerator model. In Section 3, the hardware set-up is presented whose conceptual structure is showed in Figure 1. Basically, the system is made of four blocks. In the "Real Time Refrigerator Model" module, the model of the refrigerator is implemented using real time functions. The "VOPOS Controller" is a real electronic control unit used on a professional refrigerator produced by the Italian company Smartfreeze. It is connected to "Real Time Refrigerator Model" through an "I/O Interface". Experimental results are stored in "Windows Machine" module. In Section 3.5 experimental results are reported. Finally, in Section 4 we highlight the principal aspects of work and future activities.

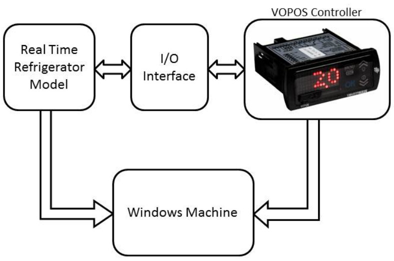

Fig. 1. Set-up of the HIL system

NOMENCLATURE

t	time $[s]$
U	internal energy $[J]$
$\dot{Q}$	thermal power $[W]$
T	temperature $[K]$
(UA)	thermal conductance $[W/K]$
m	mass $[kg]$
$\dot{m}$	mass flow $[kg/s]$
ω	specific humidity $[gv/kga]$
$\dot{L}$	electrical power $[W]$
h	heat transfer coefficient $[W/m^2K]$
ρ	density $[kg/m^3]$
A	area $[m^2]$
η	efficiency $[-]$
V	volume $[m^3]$
$\dot{V}$	volumetric flow $[m^3/s]$

SUBSCRIPTS

s	shell
e	external
i	internal
amb	environment
c	cabinet
food	food
a	air
inf	infiltration
v	vapor
fan	fan
out	out
aux	auxiliary
m	metallic
f	frost
cf	refrigerant fluid
j	row index
def	defrost
ev	evaporator
sat	saturation
att	effective area

2. REFRIGERATOR MATHEMATICAL MODEL

In this section we present the refrigerator model. The model considered in this work is explained in detail in R. Mastrullo (2013). In the following of the section we briefly describe the main components of the model. The considered refrigerator device is a vertical cabinet type which is typically used in restaurants and fast foods business. In particular the model describes:

- energy transfers between the refrigerator machine and the cabinet (size, refrigerant, compressor efficiency, compressor power request, evaporator size, isolation housing);
- the interaction with the user through the insertion/withdrawal of food or the opening/closing of doors;
- the environmental conditions of humidity;
- the formation of ice on the evaporator and the defrost process;
- the electricity consumption of the accessories.

Assumption 1. The refrigerator machine is assumed to work in "quasi-stationary" regime.

The assumption 1 allows to avoid the use of additional phenomenological equations to describe the behavior of the compressor, of the expansion device and of the condenser, as well as the calculation of the thermodynamic properties of the refrigerant. The model has been validated on several commercial refrigerator produced by DESMON, an Italian refrigerator manufacturer, partner of Smartfreeze.

Figure 2 reports a sketch of the refrigerator model here considered with the main components and signals of the refrigerator, particularly the control signals. The model

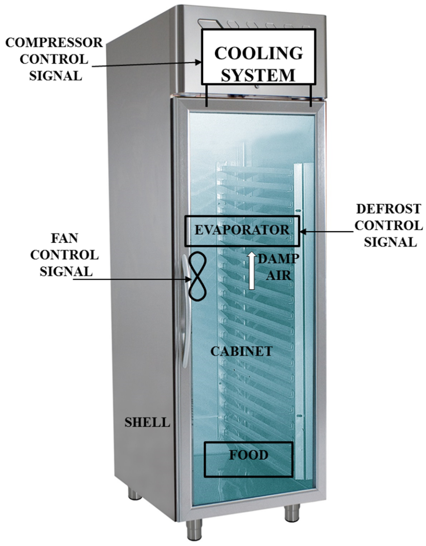

Fig. 2. Refrigerator scheme

describes the transient behavior of the refrigerator considering four main sub-models: the shell,the cabinet, the food, the evaporator. Each sub-models is described considering the following assumptions:

Assumption 2. All variables are zero-dimensional (that is they are function only of the time t) except for the evaporator, which was modeled considering also a variation with the row (the model is implemented with respect the row index j).

Assumption 3. The shell and the food are considered constant mass control volumes, whereas the cabinet and the evaporator are interested by mass variation due to infiltration (in the case of the cabinet) and vapor condensation (in the case of the evaporator).

2.1 Shell control volume

The shell control volume is modeled considering the energy balance:

$$\frac{dU_s}{dt} = \dot{Q}_{s,e} - \dot{Q}_{s,i} \tag{1}$$

where $\frac{dU_s}{dt}$ is the variation of internal energy of shell control volume, $\dot{Q}_{s,e}$ is the thermal power transferred from environment to the shell and $\dot{Q}_{s,i}$ is the thermal power exchanged between the shell and the cabinet. Considering the temperature difference between environment T_{amb} and internal shell T_s, it is possible to define the thermal power $\dot{Q}_{s,e}$ as

$$\dot{Q}_{s,e} = (UA)_{s,e} \cdot (T_{\text{amb}} - T_s) \tag{2}$$

where $(UA)_{s,e}$ is the overall heat transfer coefficient. Its value has been computed through experimental test and considering a natural convection coefficient of $6W/m^2 \cdot K$. Instead, the heat power exchanged between the shell and the cabinet $\dot{Q}_{s,i}$ is defined as

$$\dot{Q}_{s,i} = (UA)_{s,i} \cdot (T_s - T_c) \tag{3}$$

where T_c is the inner cabinet temperature and $(UA)_{s,i}$ is the overall heat transfer coefficient whose value has been computed through experimental tests, too.

2.2 Food control volume

The food control volume is modeled by the energy balance equation

$$\frac{dU_{\text{food}}}{dt} = \dot{Q}_{\text{food}} \tag{4}$$

where $\dot{Q}_{\text{food}}$ is the energy exchanged from the cabinet to the food, and is evaluated as

$$\dot{Q}_{\text{food}} = (UA)_{\text{food}} \cdot (T_c - T_{\text{food}}) \tag{5}$$

where the heat transfer coefficient $(UA)_{\text{food}}$ is estimated from correlation curves.

2.3 Cabinet control volume

The internal energy balance equation on the cabinet control volume is

$$\begin{aligned}\frac{dU_c}{dt} &= \dot{Q}_{s,i} + \dot{Q}_{\text{food}} + \dot{L}_{\text{aux}} \\ &\quad + \dot{m}_{a,\text{inf}} \cdot h_{\text{amb}} + \dot{m}_{a,\text{fan}} \cdot (h_{\text{out}} - h_c)\end{aligned} \tag{6}$$

and the mass balance equations on the air and vapor mass are:

$$\frac{dm_a}{dt} = \dot{m}_{a,\text{inf}} \tag{7a}$$

$$\frac{dm_v}{dt} = \dot{m}_{a,\text{fan}} \cdot (\omega_{\text{out}} - \omega_c) + \dot{m}_{v,\text{inf}}; \tag{7b}$$

the infiltration flowrate is evaluated as

$$\dot{m}_{\text{inf}} = \rho_{a,\text{amb}} \cdot (1 + \omega_{\text{amb}}) \cdot A_{\text{inf}} w_{\text{inf}} \tag{8}$$

where $\dot{m}_{a,\text{fan}}$ is the mass flowrate elaborated by fan, ω_{out} and h_{out} are the specific humidity and enthalpy at the evaporator outlet, ω_c and h_c are the specific humidity and enthalpy in the cabinet control volume, $\dot{L}_{\text{aux}}$ is the power required by the auxiliary power units, calibrated on the basis of the experimental data.

2.4 Evaporator control volume

To describe the frost formation and the heat transfer resistance variation, the evaporator is better described assuming the frost thickness constant at each row. For this reason the equations related to the mass and energy balances are referred to each row, according to the subscript j. The energy balance equation on the metallic mass of the evaporator is

$$\frac{dU_{m,j}}{dt} = \dot{Q}_{f,j} - \dot{Q}_{cf,j} + \eta_{\text{def}} \cdot \dot{L}_{\text{def,j}} \tag{9}$$

where $\dot{Q}_{f,j}$ is the heat power exchanged between frost and metallic mass at each row, $\dot{Q}_{cf,j}$ is the heat power exchanged with the refrigerant fluid, $\dot{L}_{\text{def,j}}$ is the electric power for defrosting (uniformly distributed in each row), η_{def} is the defrosting efficiency, calibrated on the basis of the experimental data. Data on the compressor were employed in the model in order to find a polynomial fit of refrigerant cooling capacity $\dot{Q}_{cf}$ as a function of the evaporation temperature TEV according to ARI procedure ANSI/AHRI (2004). The heat power exchanged between frost and metal, $\dot{Q}_{f,j}$, was evaluated as

$$\dot{Q}_{f,j} = (UA)_{f,j} \cdot (T_f(j) - T_m(j)). \tag{10}$$

The calculation of $(UA)_{f,j}$ is based on the thermal resistance of the ice based on the actual value of the frost formed on the evaporator, as described below. The control volume of the frost is described by the following mass and energy balances:

$$\frac{dm_{f,j}}{dt} = \dot{m}_{c,j} \tag{11}$$

$$\frac{dU_{f,j}}{dt} = \dot{Q}_{\mathrm{ev,j}} - \dot{Q}_{f,j} + \dot{m}_{c,j} \cdot h_{v,j} \tag{12}$$

where $\dot{m}_{c,j}h_{v,j}$ is the energy flow associated to vapor flowrate that condenses in each row to form the frost, evaluated as

$$\dot{m}_{c,j} = h_{m,j} \cdot [\omega_{\mathrm{ev,j}} - \omega_{\mathrm{sat,j}}] \cdot A_{\mathrm{att,j}}. \tag{13}$$

With the mass transfer coefficient $h_{m,j}$ evaluated as reported in literature Kays and London (1998), ω_{ev} is the specific humidity in the row j at the air temperature, whereas ω_{sat} is the saturation humidity at the contact temperature in the row j, that is, the frost temperature $T_{f,j}$. The effective area interested to the mass transfer is $A_{\mathrm{att,j}}$, evaluated as the sum of the fan and the tube exchange area, that varies with the row due to the variation of frost thickness $s_{f,j}$, with frost thickness $s_{f,j}$ evaluated as reported in Hermes et al (2009) C. J. L. Hermes (2009). The heat power exchanged between air and frost at row j, $\dot{Q}_{\mathrm{ev,j}}$ was evaluated as

$$\dot{Q}_{\mathrm{ev,j}} = (UA)_{\mathrm{ev,j}} \cdot (T_{a,j} - T_{f,j}) \tag{14}$$

where $(UA)_{\mathrm{ev,j}}$ is based on calibration data.
The balances performed for the control volume of the air flow were developed in quasi-steady-state, considering that at each time instant the values are adjusted on the basis of the other dynamics in the evaporator; the balances for dry air, vapor and enthalpy are:

$$\dot{m}_{a,\mathrm{ev,j}} = \dot{m}_{a,\mathrm{ev,j+1}} = \dot{m}_{a,\mathrm{ev}} \tag{15a}$$

$$\dot{m}_{a,\mathrm{ev,j}} = \dot{m}_{v,\mathrm{ev,j+1}} + \dot{m}_{c,j} \tag{15b}$$

$$\begin{aligned}\dot{m}_{a,\mathrm{ev}}h_{\mathrm{ev,j+1}} &= \dot{m}_{a,\mathrm{ev}}h_{\mathrm{ev,j}} - \dot{Q}_{\mathrm{ev,j}} \\ &\quad - \dot{m}_{c,j}h_{v,j} + (1-\eta_{\mathrm{def}})\dot{L}_{\mathrm{def}}\end{aligned} \tag{15c}$$

The air flowrate $\dot{m}_{a,\mathrm{ev}}$ was evaluated by the fan flowrate $\dot{m}_{a,\mathrm{fan}}$ calculated as

$$\dot{m}_{a,\mathrm{fan,j}} = \dot{V}_{a,\mathrm{fan}}/V_a \tag{16}$$

where $\dot{V}_{a,\mathrm{fan}}$ is the flowrate imposed by the fan and evaluated on the basis of the pressure drop in the evaporator, knowing the fan characteristic curves. The pressure drop in the evaporator was evaluated by means of the Kays London correlation (1998) Kays and London (1998) with the friction factor from Wang et al (2000) Chi-Chuan Wang (2000). Some of the parameters of the model are not known from catalogue datasheets and required a calibration procedure in order to match the results of the simulation with the experimental data. In particular, the calibration was applied to the following variables:

- evaporator thermal inertia, $m_tc_t + m_{fin}c_{fin}$;
- cabinet thermal inertia, m_cc_c;
- cabinet thermal conductivity, k_c;
- defrosting efficiency, η_{def};
- by-pass section flow resistance, R_{flow}.

The evaporator thermal inertia was chosen in order to fit the experimental trend of temperatures of the evaporator metal and of evaporation during the cabinet temperature pull-down after door opening. Since the data on evaporator density and specific heat are available from the literature, the calibration was intended to be performed on the masses, which can differ from their estimations from technical data sheets for tolerance influence on fins and for the addition of other parts during the setup of the experimental test facility. The same consideration is valid for the cabinet thermo-physical properties and thermal inertia. Defrosting efficiency was set to 30%, according to Bansal et al Bansal PK (2010), in order to match the experimental data of cabinet temperature during the defrosting period. To account for some dynamics inside the evaporator surface during defrosting there is the possibility that, if the amount of water fused overcomes a critical value, the frost thickness is set to zero, to simulate the frost separation from evaporator surface. Otherwise, the temperature of the frost is linked to its internal energy and is zero during the melting process. Finally, the flow thermal resistance in the by-pass section was set to 8000 Pas/m^3, in order to have a by-pass factor of 0.1 when no frost is present, according to experiments.

3. INNOVATIVE HIL TEST BENCH

The scheme of the proposed HIL system is shown in figure 3. In the following subsections we explain the blocks of the system.

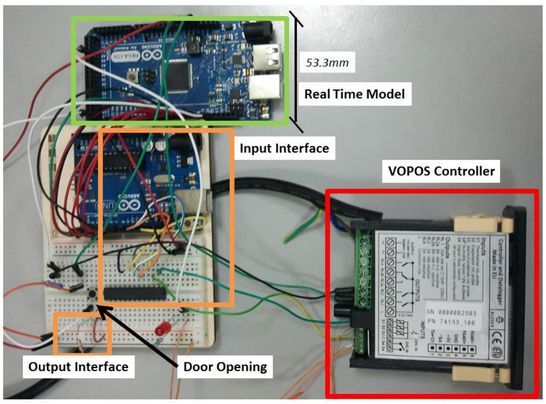

Fig. 3. HIL system set-up

3.1 Real time model of the refrigerator and real time Hardware

Here we explain the necessary procedure in order to implement the real time model of the refrigerator for the HIL simulation starting from the model described in section 2. The first step is to encode the Simulink model into a C code such that it is possible to run its dynamics in real-time simulation environments or for real-time applications. This task is performed by Real Time support library of Simulink for Arduino lib (2014).

Once compiled the model must be loaded on a real time machine. As we stated in the introduction the main idea of this work is to realize a low cost and replicable HIL platform able to test refrigerator controllers. For this reason we have selected the board Arduino MEGA nic (2014) as real time hardware. Arduino MEGA is a real time microcontroller based on the cpu ATmega2560. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16MHz crystal oscillator, a flash Memory of 256kB, a USB connection, a power jack, an ICSP header, and a reset button.

3.2 VOPOS Controller

The VOPOS vop (2014) is an electronic microprocessor controller for the control of the refrigeration temperature and humidity suitable for professional refrigerator applications. It is, furthermore, equipped with a data logger which is useful for HACCP data recording. The VOPOS can be configured in order to manage the defrost application that could be performed in different ways: *i)* stopping the compressor, *ii)* switching an electric heater or *iii)* reversing the refrigerator cycle. In the controller also a diagnostic strategy is designed, achieved through continuous monitoring of current absorptions on the relays connected to the refrigerator components. In case of abnormal absorption, the controller activates alerts regarding possible component failures which can prevent emergency situations. The controller has 4 relays, respectively of $20A$-$8A$-$5A$-$5A$ and $220V$, 3 inputs for NTC temperature probes, 1 humidity sensor input, alternately used as a digital signal and an internal buzzer for the beeps and alarms. Each of the relays is configurable, through special parameters, to handle any of the 14 actions performed by the controller (cooling, defrost, ventilation, etc..).

3.3 Input Interface

The input interface blocks consist of a set of Hardware and Software modules which convert the digital signals representing temperatures from the real time target into signals that can be read by the VOPOS Controller. Which is designed to read a temperature variation as a resistance variations provided by the NTC probe. The NTC probes considered in this work have the characteristic relation shown in the figure 4.

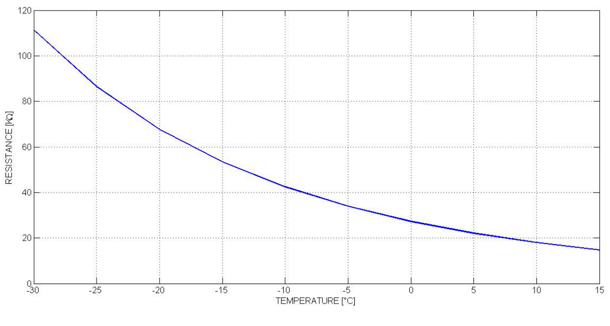

Fig. 4. NTC probe input-output relationship

We have used a digital potentiometer (AD 5206 pot (2014)) to convert a digital signals into a resistive signals. The AD5206 contains a fixed resistor with a wiper contact that taps the fixed resistor value at a point determined by a digital code loaded with SPI Arduino library spi (2014) into the SPI-compatible serial-input register. The resistance varies linearly with respect to the digital code transferred into the VR latch. In particular the digital potentiometer used has 256 position digitally controlled from a serial input to represent resistive values from 0kΩ to 100kΩ. Since we use 8 bit to encode the temperature values for each temperature signals from the real time hardware (Arduino MEGA) we have to convert the parallel value into a serial digital signals to control the digital potentiometer. To do this an Arduino UNO is used as shown in the system block set-up 3.

3.4 Output Interface

Since the VOPOS controller commands a set of relays, the output conditioning block converts ON/OFF state of the relays into digital signals. The output block is made with the circuit shown in the figure 5.

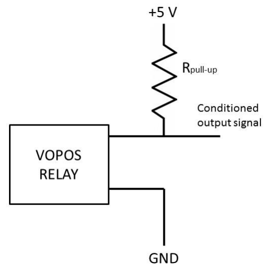

Fig. 5. Output conditioning circuit

The circuit conditioning block is equivalent to the following if-else statement code:

```
if Relay status == ON
   output signal = 0
else
   output signal > 0
end
```

The output signal is connected to Arduino MEGA and is encoded with one logical bit, that if the relay status is ON the digital signal read is 0 and 1 if the relay status is OFF.

3.5 Validation phase

As described in the section 3.2 the VOPOS controller has 3 input for NTC probes, 1 digital sensor for the door opening and 4 relays for the output commands. In this work we test two of the most important functionalities of the controller device.
Scenario 1:
In this first scenario we test the control of cabinet temperature. Moreover, we have the possibility to simulate the event of door opening using a switch.
The control law, implemented on the VOPOS controller, is a simple hysteresis-based relay that turns OFF the compressor if the temperature of the cabinet is less than $T_{\rm set} - \Delta T_{\rm set}$ and turns it ON if the temperature is greater than $T_{\rm set} + \Delta T_{\rm set}$. Figure 6 shows the results obtained.

In the figure 6 the cabinet temperature is plotted with the set-point fixed to -20^oC , $\Delta T_{\rm set} = 1^oC$ and a sample

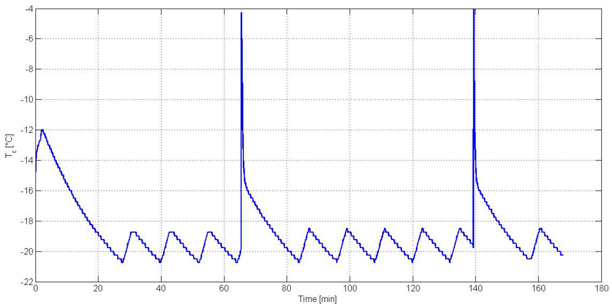

Fig. 6. Cabinet temperature with a hysteresis control algorithm

time fixed to 5*sec*. The peaks are due to the door openings which are random events that occurs when the button in the HIL system is pressed.

Scenario 2:

As second scenario we consider the manual functionality of the Vopos controller. In particular we focus our attention on the manual defrost action. The duration of the defrost action has been setted, on the VOPOS, with a fixed time of 15 min. In figure 7 the result obtained are shown considering the model of the frost as described in section 2.4 and duration of the experiment of about 3.5 hour.

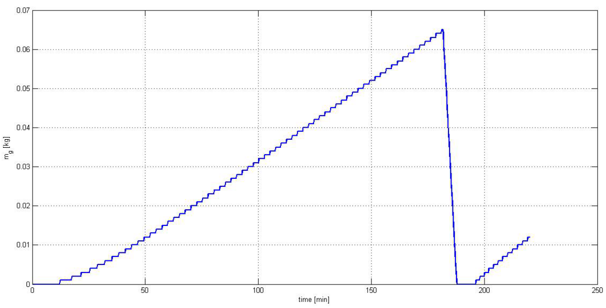

Fig. 7. Mass of ice with defrost control action

In figure 7 the mass of ice is shown. The defrost control action has been commanded after 180 min. As shown in the figure we have a complete defrost of the ice on the evaporator in about 8 min. Of course if we test the Vopos controller in a scenario of more hours we can have the situation that the time fixed for the defrost action (in this scenario is fixed to 15 min) can not be enough to completely defrost the ice on the evaporator. A typical value of the duration for the defrost action in professional use is 30 min.

4. CONCLUSIONS

In this work, we proposed a low cost HIL system bench for testing control strategies based on a detailed mathematical model of commercial refrigerators. As first results we have used the HIL system to test the simple cabinet temperature control algorithm of a commercial controller. Future steps will be focused on testing all the current functionalities of the controller as the evaporator fan control and the defrost system, and more sophisticated control algorithms. We remark that the HIL platform can be straightforwardly used with controllers of any maker for the given class of refrigerators, since electrical connections were standardized.

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