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Temperature Simulations in Cooling Appliances

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Abstract. The R&D laboratory of Gorenje d. d. develops complex cooling appliances. To develop optimal-performance appliances, regarding all functionalities, also engineers from other areas are participating in a developing process. To allow for an easier and faster development, we used mathematically-based simulation and optimization tools. A cooling appliance operates optimally when it is able to cool to the desired temperature at the lowest possible power consumption. For the purpose of our investigation we developed a simulator for simulating temperatures inside the appliance cabinets at different control parameters. By using simulations a considerable part of measurements was replaced, and as they are much time consuming due to the slow thermal processes, a lot of time was saved which in the end also minimized the development manufacture cost of the appliance.

Key words: Simulation, Cooling Appliance

1 INTRODUCTION

Tough market conditions require household appliances with a high added value. Besides the built-in functionalities, the appliances must operate with a minimal power and must have low power consumption. Among the household appliances, refrigerators and freezers are the largest electric power consumers. The leading Slovenian manufacturer of large household appliances is therefore taking an effort towards developing optimal-performance energy-efficient appliances. Optimal performance means that the appliance is able to cool to the desired temperature at the lowest possible power consumption. Such optimization usually requires a lot of long-term development measurements or a thorough theoretical analysis of the cooling system and the construction of a complex mathematical model for its simulation [1], [2], [3], [4], [5]. Such approach requires a lot of time and specific knowledge of often expensive tools (Gambit, Fluent, Matlab). Upon changes in the geometric features, the model construction process must be repeated almost from the beginning.

To determine the optimal performance of the refrigerator, we need to perform a set of development measurements for each new type of the appliance. Thermal processes in cooling systems are by nature very slow. One measurement for determining the power consumption under standard conditions takes several days. This paper presents a simulator that operates on a minimum set of different short measurements. These measurements are entered into Microsoft Excel in which a simulator is designed. Performing simulations based on the entered data requires minimal computer skills of the user. In case of changes inside the appliance (geometric dimensions, embedded components, modes of control, etc.), change-related short measurements are repeated and entered again. This means that it is very simple to adapt the simulator. When developing a completely new appliance, we can use a settled routine (automated measurements) and in a very short time we adapt the simulator for the use with the new appliance. Because of these advantages, Excel can simulate various complex systems [6], [7]. By comparing the measured values and simulated results accuracy of temperature simulation was proved. This was achieved without possessing any special knowledge of programming languages or using expensive software tools.

2 COOLING APPLIANCE DESCRIPTION

The appliance consists of three cabinets. The upper one has a refrigerator function and is called FF (Fresh Food). The central one is designed to produce ice and is called IM (Ice Maker). The bottom one that can operate in several different ways is called CD (Convertible Drawer). The lower two cabinets form FZ (Freezer). Temperature control is performed with a cooling system consisting of a variable-speed compressor driving the gas that expands in the evaporator and withdraws the heat from it. The evaporator cools the air blown into the cabinets with fans of the ventilation system. The central area (IM) and the lower space (CD) have a common cooling system (compressor, evaporator and fan) meaning that

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temperature control in these cabinets is interdependent. Therefore, both CD and IM cabinets have hatches at the input of the ventilation system regulating the cooled-air flow in each cabinet. Fig. 1 presents the cooling-appliance components.

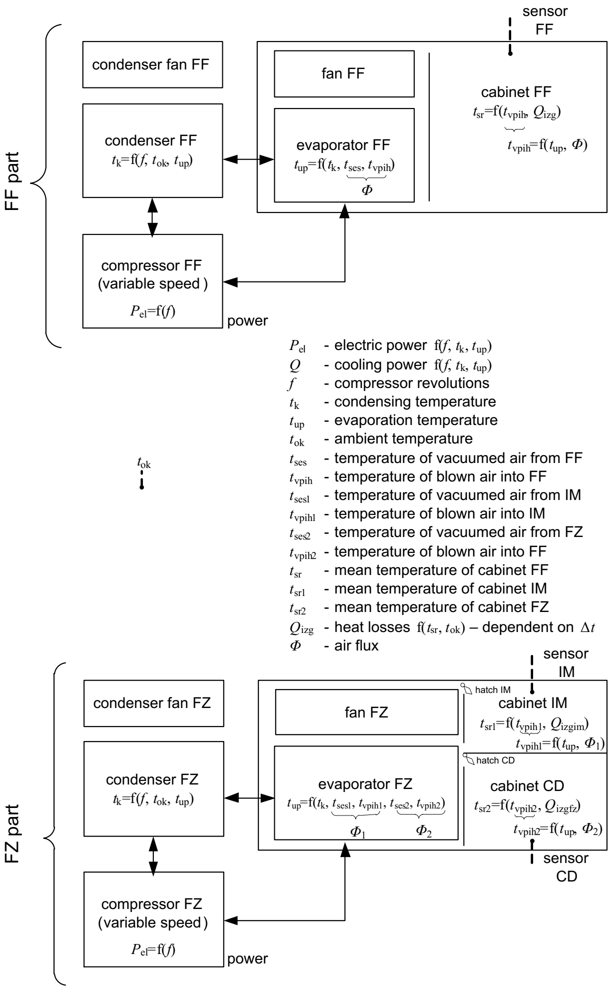


Figure 1. Block diagram of the cooling appliance

By changing the frequency input signal, the two compressors change the number of revolutions per minute (the compressor frequency), and consequently also the cooling capacity. The fan rotation speed can be switched to be either maximum, medium or minimum. The varying speed of fan rotations affects the quantity of the injected cooled air into each cabinet thus impacting the cooling conditions.

3 TEMPERATURE MEASUREMENTS AND ANALYSIS

We first measured temperatures acrose the entire cooling system (sensors; cabinet air-flow inlets and outlets; evaporator, etc.). Data acquisition was performed on a 30-second basis by a monitoring system (LabView) in the R&D laboratory. The same time step was also used in simulations. Therefore, one day is represented by 2880 steps.

By analyzing the measurement results it was noted that a satisfactory prediction of the sensor and cabinet temperatures can be done by taking into account only measurements of the temperature sensors as a function of the compressor. Measuring any other temperature does not significantly impact the prediction accuracy of the temperature sensor, because of the too many interdependencies between the different temperatures. Moreover, there is also some difference between measurements carried out under the same conditions, because of their further impacts (insulation material, sensor position, etc.) causing some additional undetermined noise. For the FZ part we measured only the temperatures at the IM and CD sensors and cabinets, and the compressor power. For the FF part we measured the temperature at the FF sensor and cabinet and the compressor power.

The FZ part operates in four modes giving four different responses; opened IM and CD hatches (denoted as 1-1); opened IM hatch and closed CD hatch (1-0); closed IM hatch and opened CD hatch (0-1); closed IM and CD hatches (0-0). The FF part has two operating modes only, i.e. the compressor powered on or off.

3.1 Measurement-data processing

Measurement-data processing was performed in MS Excel using several custom-created worksheets and macro programs. The data obtained for each measured compressor frequency and fan speed was put into a separate worksheet. Next, the time ranges were determined when the device was in one of the operating modes. To eliminate the impact of nondeterministic noise up to five ranges for each mode were determined, while the average value was calculated automatically. As noted in practice, three measurements are quite enough to eliminate the nondeterministic noise. The macro program automatically calculates the average value of the curves in a particular range (1-1, 1-0, 0-1 and 0-0) and determines coefficients (a, b, c, d) of the fourth order polynomial that approximate the measured curves.

$$T = at^4 + bt^3 + ct^2 + dt + e \tag{1}$$

Constant e is not given. It is recalculated during simulation (when changing the operation mode, compressor frequency or fan speed), so that the curve remains continuous (when needed the curve is moved up or down). For each mode there are also coefficients (a, b) given of the exponential function representing an approximation of the compressor power consumption.

$$P = at^b \tag{2}$$

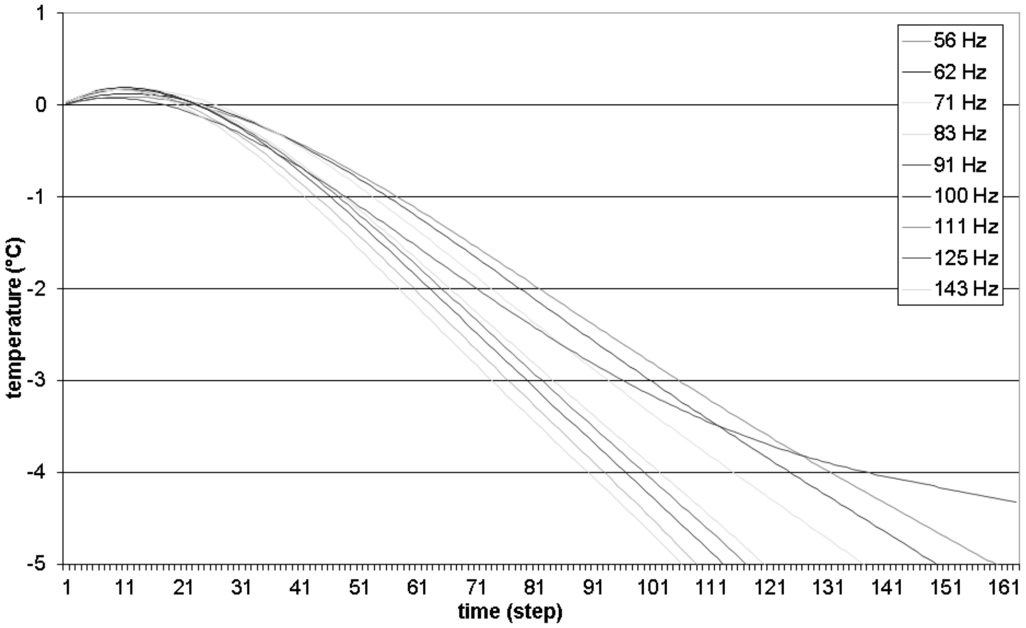
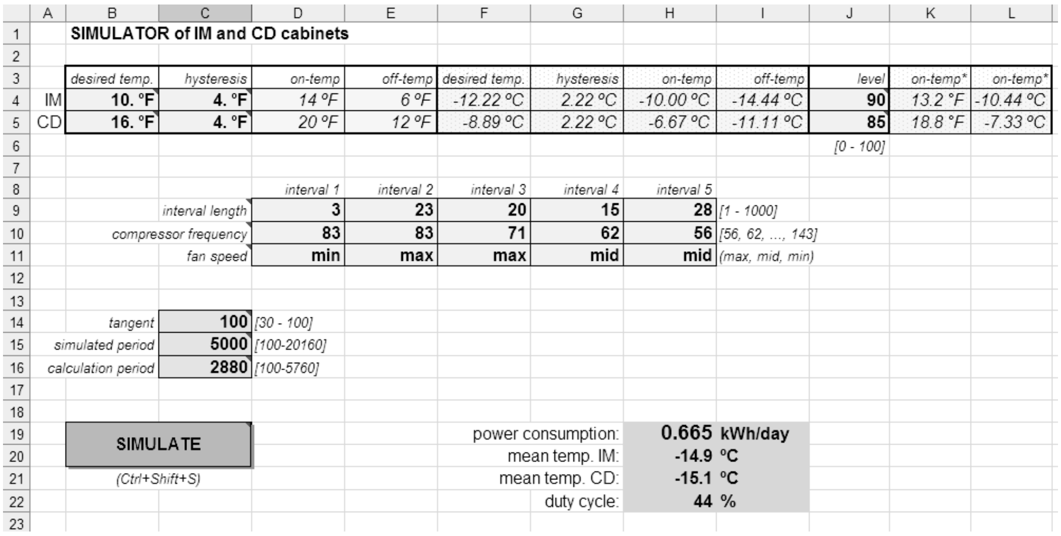


Figure 2. Temperature responses at different frequencies



	A	B	C	D	E	F	G	H	I	J	K	L
1		**SIMULATOR of IM and CD cabinets**										
2												
3		*desired temp.*	*hysteresis*	*on-temp*	*off-temp*	*desired temp.*	*hysteresis*	*on-temp*	*off-temp*	*level*	*on-temp**	*on-temp**
4	IM	**10. °F**	**4. °F**	*14 °F*	*6 °F*	*-12.22 °C*	*2.22 °C*	*-10.00 °C*	*-14.44 °C*	**90**	*13.2 °F*	*-10.44 °C*
5	CD	**16. °F**	**4. °F**	*20 °F*	*12 °F*	*-8.89 °C*	*2.22 °C*	*-6.67 °C*	*-11.11 °C*	**85**	*18.8 °F*	*-7.33 °C*
6										*[0 - 100]*		
7												
8				*interval 1*	*interval 2*	*interval 3*	*interval 4*	*interval 5*				
9			*interval length*	**3**	**23**	**20**	**15**	**28**	*[1 - 1000]*			
10			*compressor frequency*	**83**	**83**	**71**	**62**	**56**	*[56, 62, …, 143]*			
11			*fan speed*	**min**	**max**	**max**	**mid**	**mid**	*(max, mid, min)*			
12												
13												
14		*tangent*	**100**	*[30 - 100]*								
15		*simulated period*	**5000**	*[100-20160]*								
16		*calculation period*	**2880**	*[100-5760]*								
17												
18												
19		SIMULATE					power consumption:	**0.665**	**kWh/day**			
20							mean temp. IM:	**-14.9**	**°C**			
21		*(Ctrl+Shift+S)*					mean temp. CD:	**-15.1**	**°C**			
22							duty cycle:	**44**	**%**			
23												

Figure 3. Simulation parameters setting

A by-product of data processing is a comparison of temperatures in various operating modes in correlation with the compressor frequency and/or fan speed. On one of the worksheets the frequencies and speeds can be set to be included in a comparison used in finding the frequency/speed settings when the device does not respond as expected. Based on such comparison the cause for non-correlations can be easily found (e.g. the system is not appropriate for high frequencies, the fan is not blowing enough air, measurement error, etc.). An example of temperatures at various frequencies and maximum fan speed in the IM cabinet with open IM and CD hatches is presented in Fig. 2.

4 TEMPERATURE SIMULATIONS

The simulator is designed in Microsoft Excel. It consists of four worksheets and macro programs (about 600 lines of Visual Basic code) for simulating the cooling-appliance operation.

The desired temperature of the IM and CD cabinets and the value of the IM and CD hysteresis were put into the simulator interface (Fig. 3). Additionally, the

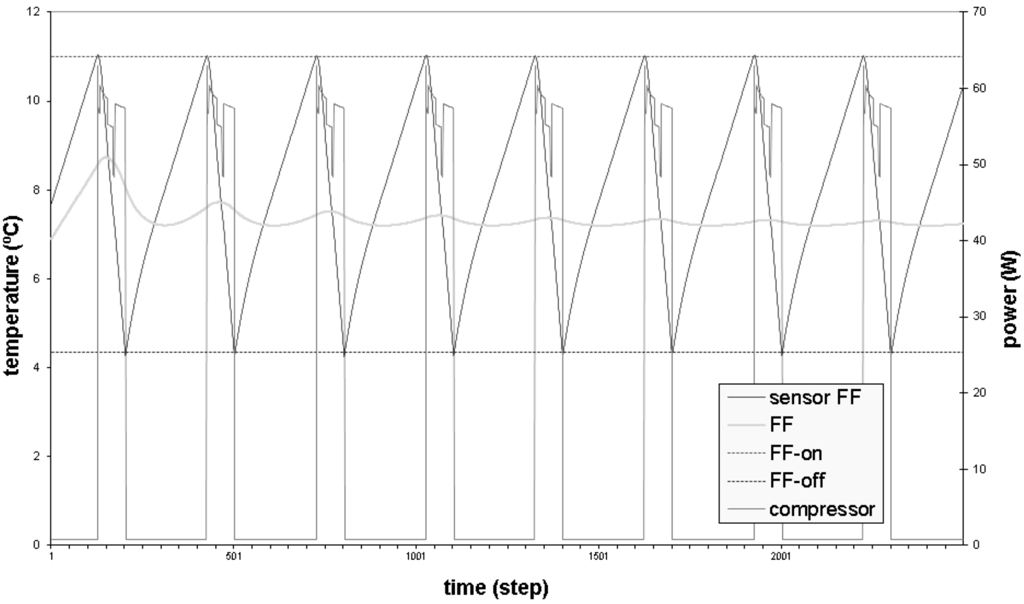


Figure 4. Result of simulation - graphical representation

level of temperature was set for each cabinet when the hatch opens, although the on-temperature is not achieved yet, but due to opened hatch of the other cabinet (and the running compressor) it was quite reasonable to cool that cabinet, too. The temperatures are presented in the Fahrenheit and Celsius degrees. The compressor cycle is divided into five intervals. For each interval its length and operating mode were set. The first interval started at each compressor start-up, the second interval began after the first had been completed, etc. When the compressor was on for longer than was the duration of five intervals, the settings of the last interval were used. In each interval the compressor frequency and the fan speed were set. The discrete frequency range was determined by the development team, while the fan speed could be maximum, medium or minimum. Further, the simulated period and the period of the total simulated time were set, too. We considered them in our calculations of power consumption enabling us to ensure that the transitional state ceased and the appliance operated in the steady state mode.

The simulation takes about 10 seconds when simulating 48 hours of a operating time (i.e. 5760 steps) on a 2GHz computer. The results of the simulation show the daily power consumption in kilowatt-hours, mean temperature in the IM and CD cabinets, and the compressor duty cycle. To calculate the power consumption, the maximal interval within the period for the calculations is used containing the whole cycles (an interval starts with the beginning of one cycle and ends just before the last non-complete cycle gets started). In such way the calculation of power consumption, in kilowatt-hours per day (Eqn. 3), is more accurate for taking into account only whole cycles; this is being an equivalent to the calculation procedure of the measuring system in the laboratory, as defined by the measuring standard [8].

$$consumption = \frac{consumption_{\mathrm{interval}} \times 2880}{length_{\mathrm{interval}} \times 12000} \qquad (3)$$

The mean IM and CD temperatures are the average temperature in each cabinet throughout the calculation period. The duty cycle is a fraction of the time the compressor is on.

The most important results of our simulation are the level of the power consumption and the cabinet temperatures. As our solutions are supposed to be feasible and usable in real appliances, the simulator also shows variations of the simulated temperatures over the simulation time (Fig. 4). They are shown for the steady state only (operating point). By changing the control parameters, we can simulate the appliance at its different operating points. So we get an insight into a variations in the sensor temperature, cabinet mean temperature, and compressor power consumption. Based on these data, we are able to calculate the power consumption for the case of normal usage, which according to standard [8] implies that the appliance is loaded and its door is closed.

Using the simulator with different control-parameters settings the most appropriate control parameters can be found. They are entered into the appliance that is than measured, to confirm its behavior. The search time for an optimal setting is much shorter than when searched

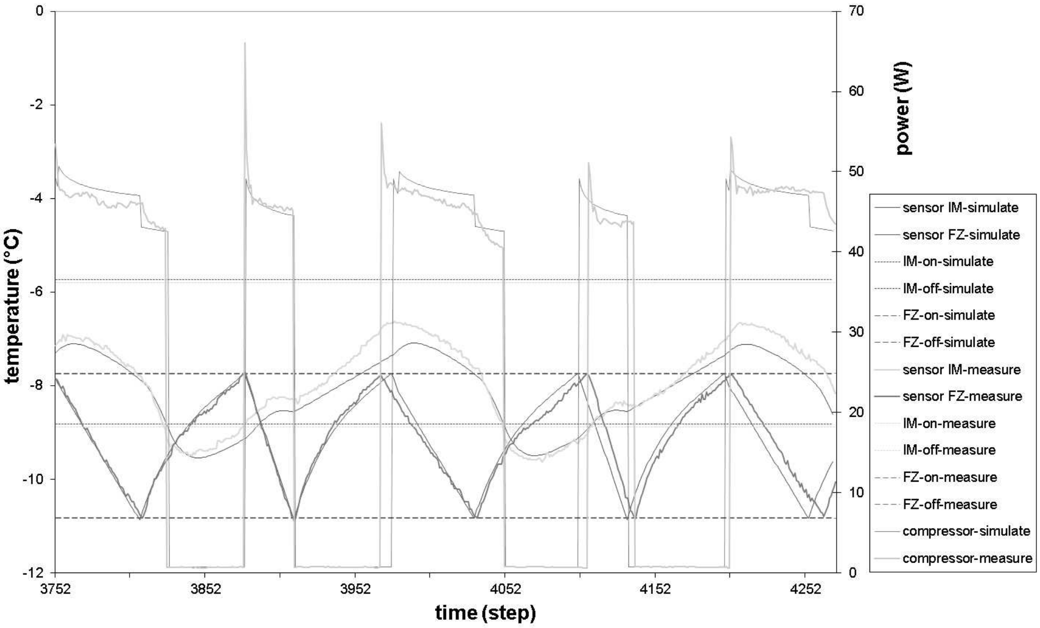


Figure 5. Comparison of measured and simulated curves

with measurements only.

The simulator for the FF part simulates the temperature in one cabinet only. We need to set less input data and the output is slightly different, too.

4.1 *Simulator validation*

Simulator validation was carried out in the Gorenje R&D laboratory. It was based on a comparison of measurement and simulation results. The differences between the measured and simulated curves were negligible and acceptable as far as the number of impacts is concerned. The differences were even smaller than expected according to the number of factors that affect the appliance operation. Our comparison of the measured and simulated data made with the same control parameters was carried out with a comparison chart (Fig. 5).

The differences seen are due to the noise impact. Similar differences are noticed when comparing two measurements obtained at the same settings. It is clear that the operating stability of the appliance is impacted by many factors and not all can be identified. This means that a solution for controlling an appliance must be sufficiently robust to ensure its reliable and optimal operation.

5 RESULTS

A satisfactory prediction of the temperature sensor and the cabinet temperature can be done by taking into account only measurements of the temperature sensor as a function of the compressor. It is important that all the possible operating modes are considered. Temperature responses should be measured for all frequencies. During data processing we can notice if some combination is not appropriate and should therefore be omitted (too high power consumption, inability of reaching the desired temperature). The number of initial measurements increases with the number of independent parameters. In our case, we applied ten compressor frequencies and three fan speeds. Our analysis also involved minimization of the number of the needed initial measurements as well as their automatization. Correct measurements are of key importance for an accurate and robust simulation.

As observed, the optimal results of one prototype do not apply to another. Changes in the appliance characteristics and its thermal responses change the optimal settings, too. Nevertheless, if some components bring improvement to the appliance, they are further optimized. Those with no positive impact on the appliance performance are omitted thus leading to cost reduction. This is some kind of evolutionary selection of the reliable and robust components.

Fig. 6 shows a comparison between results of different simulation settings. The compressor duty cycle is correlated with the power consumption. It should be noted that the measured consumption varies by about ± 1 % due to disturbances. Disorders affecting the energy consumption are the noise of the ambient temperature, accuracy of the measurement system, power-supply voltage oscillations, etc.

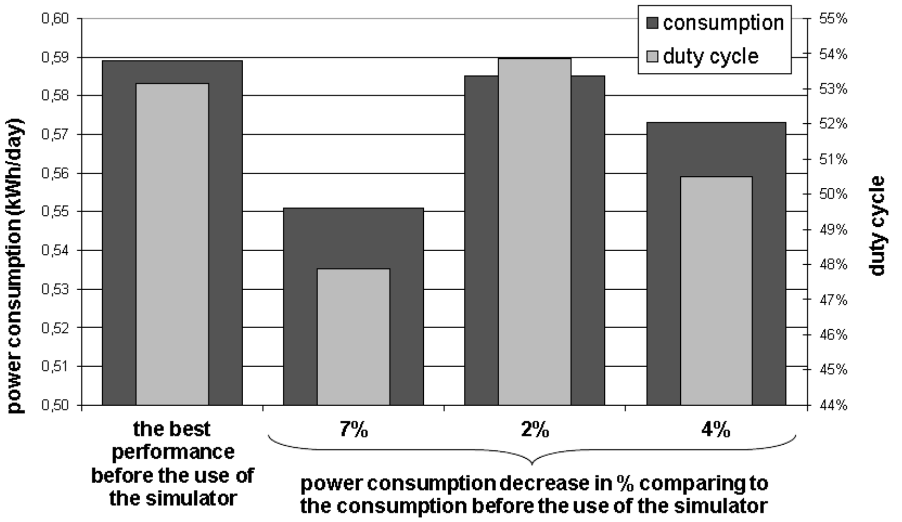


Figure 6. Comparison of results for different settings

Due to the low complexity of the FF part, the simulator is used to determine the number of different options (variable-frequency compressor, variable-speed fan) needed for controlling the FF part. Consequently, this would lead to a simpler control algorithm, and a simpler as well as less expensive control electronics of the investigated appliance.

6 CONCLUSION

The development process of a complex cooling appliance is measured in months. By using a simulator a large part of the development measurements can be omitted thus reducing the development costs. An approximate cost of such measurements is 50 Euro per day. By using the developed simulator the appliance behavior can be simulated just in a few seconds thus importantly reducing the development time and costs. Using te above described simulations, our goals regarding power efficiency and appliance reliability were achieved.

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