PRELIMINARY TESTS REGARDING THE OPERATING CONDITIONS AND MODELING OF THE ENERGY CONSUMPTION FOR A DOMESTIC REFRIGERATOR

Radu ROŞCA[1], Ciprian CHIRUŢĂ[1], Virgil VLAHIDIS[1]
Radu George CIORAP[2],

e-mail: rrosca@uaiasi.ro

Abstract

Energy saving and resources and environment preservation are key factors for the sustainable development of our society and hence domestic appliances are also targeted for energy efficiency improvements. Because refrigerators are the largest energy consuming appliances in households due to their widespread use and continuous operation there is a need for rigorous investigations regarding the energy consumption and efficiency of these devices. In the present paper the results of experimental tests are presented; in order to predict the energy consumption of the appliance in different operating conditions (ambient temperature, load and door openings) a simplified model was developed, based on the experimental data. A statistical analysis of the model was then performed in order to evaluate the goodness-of-fit between the model and the experimental data. The tests were performed in different days (starting at 7 a.m. each day) between may, 2015, and september, 2015. As the aim was to obtain results for two different ambient temperatures (25^0C and 30^0C) there was a selection of the results in order to achieve this goal; for the selected tests the actual mean environmental temperatures were: 25.08^0C and 30.04^0C respectively. The Multi linear regression method was used in order to develop the energy consumption model. The results confirmed that refrigerator load and ambient temperature have a significant effect on the energy consumption, when there was no door opening during the test period; when door openings were taken into account the significance of the above-mentioned factors was diminished.

Key words: energy consumption, multi linear regression, significance

It is well known that the refrigeration industry was brought to the public's attention because of the issues concerning the effect of the refrigerants on the depletion of the ozone layer. But because refrigerators are the largest energy consuming appliances in households due to their widespread use and continuous operation (Khan I.H. *et al*, 2013) there is a need for rigorous investigations regarding the energy consumption and efficiency of these devices. The results of the tests led to the conclusion that the energy use of these appliances is affected not only by their technical features, but also by the exploitation regime (Bhatt M.S., 2001); the ambient temperature and thermostat setting are among the most important parameters (Bhatt M.S., 2001; Geppert J., 2011). While the refrigerator load under static conditions has almost no impact on energy consumption (Geppert J., 2011), in dynamic conditions (door opening) the effects of number of door openings, ambient temperature and cabinet load over the energy consumption are significant (Khan I.H. *et al*, 2013).

MATERIAL AND METHOD

The appliance was a refrigerator-freezer, with two separate refrigeration systems. The fresh food compartment has a volume of 173 l; together with the vegetables compartment the volume of the refrigerator is 253 l. The evaporator is placed vertically, behind the back wall of the fresh food compartment.

The internal temperature in the fresh food compartment was measured using thermistor probes (47 kΩ at 20˚C). The probes were inserted in brass cylinders, wrapped in tin foil, in accordance with the requirements of the EN 15502:2005 standard and were placed into the fresh food compartment according to the requirements of the same standard. Two additional sensors were used in order to measure the temperature in the upper part of the fresh food compartment and on the back wall covering the evaporator; the actual arrangement of the temperature probes is shown in *figure 1*. The

[1] „Ion Ionescu de la Brad" University of Agricultural Sciences and Veterinary Medicine, Iaşi
[2] „Gr. T. Popa" University of Medicine and Pharmacy, Iaşi

temperatures were recorded every minute and saved in files on the computer HDD.

An energy meter (type Voltcraft Energy Logger 4000) was used in order to record the power consumption of the refrigerator; the data was finally saved as an Excel file.

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The following operating parameters were evaluated for the ambient temperature of 25^0C:

- power consumption;
- percent operating time, in 24 h;
- average duration of an operating cycle;
- average temperature inside the fresh food compartment: $\bar{t} = \left(t_1 + t_3 + t_4 + t_5\right)/4$.

For the ambient temperature of 30^0C only the power consumption was recorded.

In order to perform the necessary tests the following parameters had to be established:

- thermostat temperature setting;
- number of door openings per cycle and their duration;
- refrigerator load.

The thermostat temperature setting affects the interior temperature of the refrigerator. For the tested appliance the thermostat had no numerical temperature scale; as a result a median position was chosen, between the minimum and maximum marks, as shown in fig. 2.

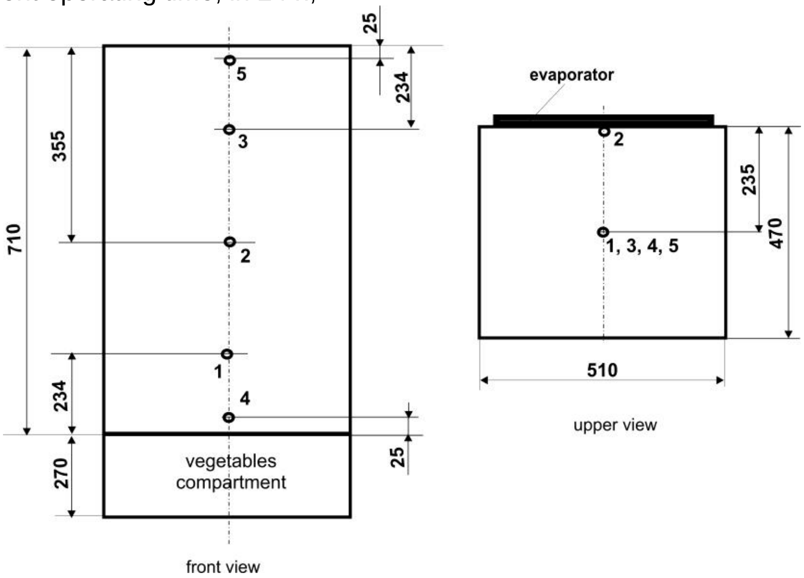


Figure 1 **Placement of the temperature probes**
1, 3, 4 – temperature probes according to EN 15505:2005;
2, 5-additional temperature probes.

Figure 2 **Thermostat setting during tests**

As far as the number of door openings is concerned, the data presented in the international references, based on polls and surveys, varies largely, as shown in Table 1. The total daily door opening time also varies largely, being ranged between 1.5 and 19.3 minutes; the average duration of a door opening was ranged between 7.3 to 15 seconds (Geppert J., 2011).

Taking into account the above mentioned facts it was decided that the refrigerator door should be opened 24 times during a test cycle, in two sessions (one in the morning and one in the afternoon, in order to simulate the daily behavior of the family members having breakfast from 9 a.m. and dinner from 6 p.m.); the duration of each door opening was 15 sec. and the door was opened at an angle of 90^0. During each test the energy consumption of the appliance and the interior temperatures were monitored and recorded for 24 hours; the testing program is presented in fig. 3.

The results of worldwide surveys of the consumer habits regarding the refrigerator filling level are very different: a study performed in four European countries (Germany, Great Britain, France and Spain - Geppert J., 2011) and based on the answers given by the participants showed that on average only 10.4% of the consumers kept their refrigerator filled with foodstuff, while 31% of the people inquired indicated that they keep the refrigerator approximately half filled.

Another detailed analysis of the consumers' habits, based on the occupied volume of the refrigerator, indicated that, on average, only 23...28% of the available volume is used (Geppert J., 2011).

Table 1

Published results regarding the number of door openings

Reference	No. of samples	No. of door openings per day: % total samples
Derens E. *et. al.*, 2001	119	<10: 19% 10-20: 43% >20: 38%
Saidur R. *et al.*, 2008	104	<10: 17% 10-20: 39% 21-30: 28% 31-40: 11% >40: 5%
Evans J., 1998	60	<30: 60%

There are no similar statistics available for Romania, but taking into account the lower income of the inhabitants compared to the developed countries it was decided to consider the following cases:

- 0% load - refrigerator completely empty;
- 3.5% load - refrigerator filled with 12 test packages of 0.5 liters each;
- 10% load - refrigerator filled with 12 bottles of 0.5 liters each + 2 bottles of 5 liters each.

Each test package (bottle) was filled with calcium chloride solution (concentration: 9.4%; freezing point: -5.2^{0}C; specific heat at 0^{0}C: 3625 J/kg·K, very close to the specific heat of lean beef – 3650 kJ/kg·K, according to ASHRAE 2006).

In order to predict the energy consumption of the appliance in different operating conditions (ambient temperature, load and door openings) a simplified model was developed based on the experimental data. A statistical analysis of the model was then performed in order to evaluate the goodness-of-fit between the model and the experimental data.

The Multi linear regression method was used in order to develop the energy consumption model. The method assumes that the dependent variable y (energy consumption) is given by the equation:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n,$$

where x_1, x_2..., x_n are the independent variables and b_0, b_2..., b_n are the coefficients of the linear regression equation. For the present case the two independent variables were considered (environmental temperature and refrigerator load). Using the multi linear regression method the values of the coefficients were calculated based on the experimental results and the ANOVA significance test was performed for each coefficient aiming to establish whether the respective coefficient is significant ($p<0.05$) or not. Table 2 summarizes the data for the Multi linear regression analysis.

Table 2

Summary of the testing program

Factor A: ambient temperature	Factor B: refrigerator load	Response C: test regime
A_1: 298 K A_2: 303 K	B_1: 0% B_2: 3.5% B_3: 10%	1. static, no door opening 2. dynamic, 24 door openings/24 h

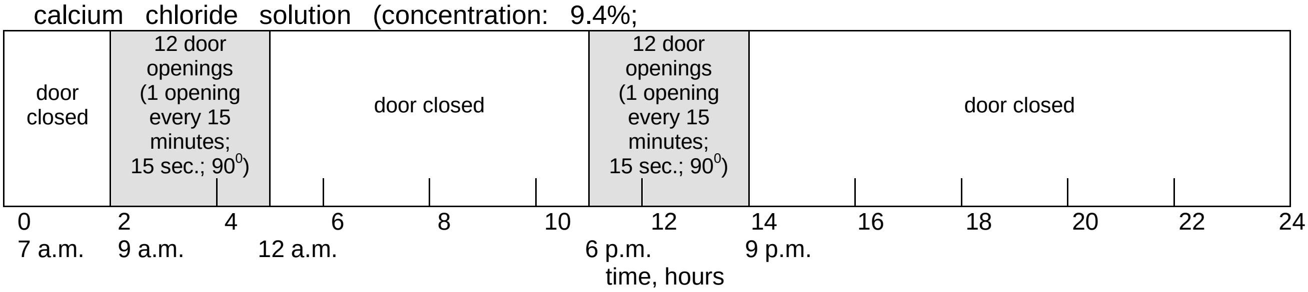


Figure 3 **Test program with refrigerator door opening**

RESULTS AND DISCUSSION

The system's compressor was turned on when the temperature (sensor 2, *figure 1*) reached 5.6…6^{0}C and was turned off when the temperature reached -18.4…-18.6^{0}C (*figure 4*).

Table 3 summarizes the results of the tests for the ambient temperature of 25^{0}C; the results concerning the energy consumption at 30^{0}C are presented in *Table 4*.

Active energy consumption

As expected the active energy consumption has increased when the refrigerator load was increased; in the meantime opening the refrigerator door also led to the increase of the energy consumption. The analysis of significance showed that the differences recorded between the operating regimes (without or with door opening) were significant ($p<0.05$) or distinctly significant ($p<0.01$).

The sensible heat introduced by the outside air entering the fresh food compartment when the door was opened caused the increase of the energy consumption; the increase in energy consumption was ranged between 11.1% (at 10% load) and 16.8% (at no load); the results clearly show that the thermal inertia of the load has reduced the effect of door opening on energy consumption: without door opening, the energy consumption increased by 9.9% from 0% load to 3.5% load and by 14% from 0% load to 10% load; with door opening the energy consumption increased only by 2.3 and 8%, respectively.

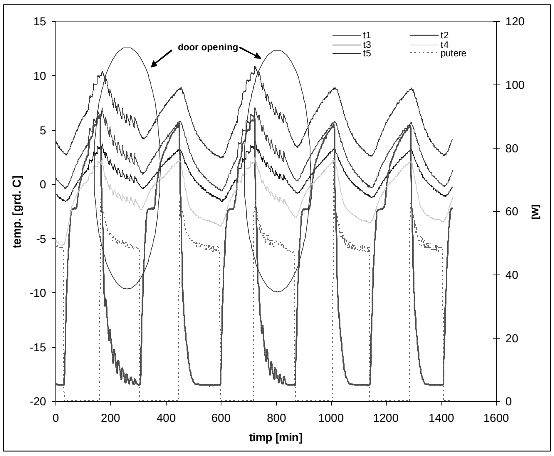


Figure 4 **Energy consumption and temperature levels** (10% load; with door opening; 25^{0}C)

The energy consumption increased (by 3.8 to 14%) when the refrigerator load was increased because of the additional sensible heat which had to be removed from the product load.

Increasing the environmental temperature from 25^{0}C to 30^{0}C has led to the increase of the energy consumption (*Table 4*) by 16.7…19.4%, depending on the refrigerator load and operating regime (without or with door opening).

Table 5 summarizes the significance level of the differences in energy consumption when the refrigerator load was increased. The results show that there were no significant differences between variants when the load was increased from 0 to 3.5% (with one exception, at 30^{0}C and door opening). When load was further increased to 10% the energy consumption increased significantly for the static operating regime ($p<0.05$).

The same analysis was performed in order to evaluate the effect of increasing the environmental temperature; the results presented in Table 6 show that the increased environment temperature significantly affected the energy consumption only when the appliance was operating in the static conditions (no door opening).

Operating time and cycle duration

Opening the door during the tests led to the increase of the operating time of the appliance: when the door was opened the operating time represented 44.6…55% of the total time of 1440 min, compared to 38…44% when there was no door opening.

Table 3

Experimental results for the ambient temperature of 25^{0}C

Parameter		No door opening			With door opening		
		Refrigerator load [%]			Refrigerator load [%]		
		0	3.5	10	0	3.5	10
Active energy [kW·h]		0.474	0.492	0.541	0.554	0.567	0.603
Operating time (in 24h)	[min]	548	556	635	643	699	792
	[%]	38.05	38.6	44.1	44.65	48.5	44.0
Average cycle duration [min]		68.5	69.5	113.1	80.37	137.0	158.4
Average temperature [^{0}C]		2.648	2.141	1.752	2.654	2.607	1.802

Table 4

Data for Multi linear regression analysis

Factor A (environ. temp.) [K]	Factor B (load) [%]	Response C (energy consumption) [kW·h]							
		Without door opening				With door opening			
		1	2	3	Mean	1	2	3	Mean
298	0	0.468	0.482	0.470	0.474	0.545	0.565	0.552	0.554
298	3.5	0.489	0.495	0.493	0.492	0.551	0.573	0.578	0.567
298	10.0	0.536	0.548	0.540	0.541	0.605	0.578	0.625	0.603
303	0	0.546	0.552	0.560	0.553	0.548	0.583	0.567	0.566
303	3.5	0.572	0.591	0.583	0.582	0.668	0.672	0.697	0.679
303	10.0	0.615	0.642	0.647	0.635	0.715	0.682	0.765	0.720

Table 5

Significance levels (load)

Operating regime	Environ. temp. [^{0}C]	Load increase [%]	Significance level (p)
No door opening	25	0 → 3.5	p>0.05
		3.5 → 10.0	***p<0.01***
	30	0 → 3.5	p>0.05
		3.5 → 10.0	***p<0.05***
Door opening	25	0 → 3.5	p>0.05
		3.5 → 10.0	p>0.05
	30	0 → 3.5	***p<0.05***
		3.5 → 10.0	p>0.05

The refrigerator load has affected the operating regime of the appliance; thus, when there was no door opening, the cycle duration increased from 68.5 min (no load) to 69.5 min (3.5% load); the overall operating time (in 24 h) increased from 548 min to 556 min. When load was increased to 10% the cycle duration was 113 min and the overall operating time was 635 min. Statistically there was no significant difference between the cycle durations with no load and 3.5% load ($p>0.05$).

At 0% load there was no significant difference between the cycle durations with and without door opening ($p>0.05$); a totally different situation was recorded when the refrigerator was loaded as the cycle duration increased and the difference compared to the "no load" case was very significant ($p<0.001$ at 3.5% load) or significant ($p<0.05$ at 10% load).

Table 6

Significance levels (environ. temp.)

Operating regime	Load [%]	Environ. temp. increase	Significance level (p)
No door opening	0	$25^0C \rightarrow 30^0C$	**p<0.01**
	3.5		**p<0.01**
	10		**p<0.05**
Door opening	0		p>0.05
	3.5		**p<0.05**
	10		p>0.05

Fig. 5 presents the comparative power consumptions and cycle durations without and with door opening, for the three refrigerator loads taken into account (0%; 3.5%; 10%).

At 0% load (*figure 5a*) different durations were recorded only for the cycles during which the refrigerator door was opened; for the rest of the cycles the differences between the two cases were small and this explains why there was no statistical difference between the two cases.

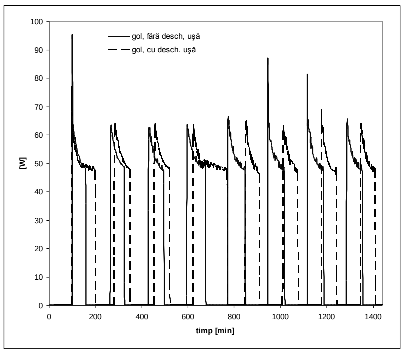
At 3.5% load (*figure 5b*) longer operating cycles were recorded when the refrigerator door was opened; the longest durations were recorded exactly for the two cycles during which the door was opened, leading to statistically very significant differences.

Statistically significant differences in cycle durations between "no door opening" and "door opening" operating conditions were also recorded at 10% load (*figure 5c*), but these were lower than the ones for the 3.5% load. The differences were probably reduced due to the thermal inertia of the load.

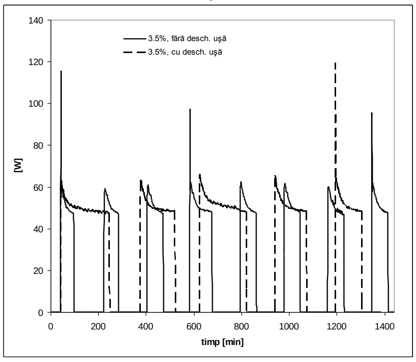
Average internal temperature

The recorded temperature charts (similar to the one presented in figure 4) show that, due to the higher density of cold air, the lowest temperatures were recorded in the lower part of the refrigerator, in the vicinity of the vegetables compartment (temperature measuring point 4, *figure 1*) and the highest temperatures were recorded in the upper part of the fresh food compartment (point 5, *figure 1*).

The results presented in Table 3 show that, due to the sensible heat of the infiltrated air, the average internal temperature has slightly increased when the refrigerator door was opened while the appliance was in operation. In the meantime the presence of load slightly diminished the average interior temperature (from 2.648^0C at no load to $1,752^0C$ at 10%, without door opening). This behavior was probably caused by the fact that the temperature field became more uniform due to the load being stacked on the shelves (one at the bottom of the fresh food compartment and the others above points 1 and 3, *figure 1*); the thermal inertia of the load also contributed to the reduction of the average temperature. The amplitude of the average temperature variations decreased with load and was lower in the static tests than in the dynamic ones.



a)



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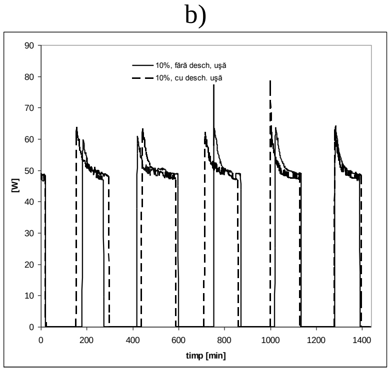

c)

Figure 5 **Cycle durations**

The energy consumption model

The Multi linear regression method was used in order to develop the energy consumption model; Table 4 summarizes the data used for the Multi linear regression method. Starting from the quadratic model an iterative process was used, in which each coefficient was tested for significance; the insignificant terms (p-value>0.05) were removed.

For the static tests (no door opening) the final regression equation is:

$$C = -4.743+0.017489\cdot A+0.00754\cdot B \text{ [kW}\cdot\text{h]}.$$

The Pearson coefficient of the regression $r^2=0.994$ shows that 99.4% of the results (energy consumption) are due to the two influencing factors (environment temperature and load).

For the dynamic tests (with door opening) the p-values of the coefficients for factors A and B were higher than 0.05, while the value of the Person coefficient was $r^2=0.683$, which means that these factors alone can not explain the values of the active energy consumption. As the main difference compared to the previous cases was the infiltration of warm air from the environment into the refrigerator compartment when the door was opened, the heat load due to the infiltration of outside air was evaluated using the ASHRAE method:

$$P = q \cdot D_t \cdot D_f \cdot (1 - E) \quad [\text{kW}/24\text{h}],$$

where q is the sensible and latent refrigeration load for fully established flow, D_t is the doorway open-time factor, D_f is the doorway flow factor and E is the effectiveness of doorway protective device. The heat load introduced by the warm air (factor D) was 0.018 kW/24 h at 25^0C and 0.027 kW/24 h at 30^0C (50% increase, compared with only 21.7% increase of the heat load transferred through the walls). The final regression equation for this case is:

$$C = 0.3702+0.00963\cdot B+8.9506\cdot D \text{ [kW}\cdot\text{h]}.$$

The Pearson coefficient of the regression is $r^2=0.81$.

This result confirms that in the dynamic operating regime the effect of increased environment temperature (factor A) on energy consumption of the appliance is less important compared to the effect of warm air entering the fresh food compartment when the door is open (factor D).

CONCLUSIONS

Tests were performed using a domestic refrigerator-freezer unit in order to asses the effect of operating regime, environmental air temperature and refrigerator load over the some operating parameters (active energy consumption, operating time and cycle duration, average internal temperature). An energy consumption model was created using the Multi linear regression method.

The results showed that the thermal inertia of the load has reduced the effect of door opening on energy consumption; the environmental temperature had a significant effect over the energy consumption only in static test conditions.

In the static tests the factors affecting the energy consumption were the environmental temperature and refrigerator load; in the dynamic tests the energy consumption model is based on the load and sensible and latent heat of infiltration air. In order to obtain more reliable results the relative humidity of the inside air should be monitored because the condensing water which freezes on the back wall of the appliance increases the thermal load of the refrigeration system due to the latent heat.

Further tests, using warm test packages, should be performed in order to obtain more realistic results concerning the effect of refrigerator load on energy consumption.

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