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The design of a novel and portable energy performance-measuring device for household refrigerators

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Abstract: Refrigerators are one of the main devices used in our daily lives, and they play important roles in storing food and maintaining its freshness. Refrigerator manufacturing is improving day by day and it is important for the appliance to present a diverse array of functions to its users, since usage requirements vary from region to region. For this purpose, refrigerators must pass through various performance tests like an energy efficiency test while they are produced in factories. Factories have designated testing rooms for these performance tests. After the products' release, technical services and customers do not have such a luxury of pretesting the machines. In this study, a portable performance-testing device was designed specifically for household refrigerators. Experimental analyses were based on the TS EN 15 502 standards, which are compatible with the IEC 62552 standards. The test series consisted of temperature, current, voltage, and humidity measurements. The control results were indicated by an Arduino-based microprocessor. The tests could be controlled by the users in real time via an LCD panel on top of the indicated testing device. The monitor showed the relevant interface programs written in C# and a web interface. Moreover, the developed setup could determine the energy efficiency class of refrigerators, among their other qualities.

Key words: Refrigerator, electrical measurements, energy efficiency

1. Introduction

Global fossil energy sources are continuously diminishing as energy demands keeps rising exponentially. Hence, the unit price of those energy sources has been increasing rapidly. This situation limits many countries' resources, which in turn makes them seek new approaches to use energy more efficiently. In almost all of the member states of the European Union, legal regulations related to energy efficiency have become increasingly stringent and the most noticeable changes were the heightened availability and efficiency of low energy-consuming household appliances.

The concept of energy efficiency is used as a basis behind many common technologies such as buildings, vehicles, various instruments, power plants, and power generators, as well as various systems, including transportation, heating, lighting, industrial, transmission, and distribution. It is a well-known fact that having energy efficient appliances at home results in considerable savings in power, and therefore in money as well [1]. It is necessary to invest in such technologies in order to benefit from those savings. Governments in developed economies are claiming to make considerable investments in energy efficient technologies and encourage residential households to conserve energy [2]. In [3], it is argued that if all new Brazilian refrigerators had an energy

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efficiency level that suits the price for their given lifespan, the result would be an annual savings of 2.8 billion (US) dollars in electricity bills, 45 Terawatt-hours (TWh) of electricity demand, and 18 Mt of CO_2 emissions with a respective payback period of 7 years, which are all totals of less than half the average estimated lifetime consumptions of a refrigerator.

In 2010, it became a requirement for EU manufacturers of household refrigerators to produce refrigerators with a maximum energy consumption class of A+ for them to be allowed into the market. As the permitted maximum degrees of energy consumption for refrigerators are determined by the policies of the state, the minimum limits are determined by the competition between manufacturers. For example, an A+ fridge can be declared to need the most power, but an A+++ refrigerator should have a 50% lower consumption rate. Table 1 was created in 2001 as a summary of the declared refrigerator energy classes [4].

Table 1. Energy class for refrigerators.

Household Refrigerator – Differences in energy class					
Energy Class	B	A	A+	A++	A+++
A+++	–71%	–60%	–50%	–34%	0%
A++	–56%	–40%	–24%	0%	
A++	–41%	–20%	0%		
A	–27%	0%			
B	0%				

Almonacid-Merino and Torres stated that the changes in a refrigerator's cold and ambient temperature are the main cause of the exposed, stored products' low quality [5]. In Giannakourou and Taouki's research about the heat transfer between food and its convection cooling medium, the change in the method's heat transfer coefficient was deemed as another important factor. Given the prevalence of the use of refrigerators, the two stated refrigerator parameters are important factors within their base designs and possible improvements of their thermal performances [6]. Some researchers have proven that the consumption of energy in refrigerators is dominantly affected by real, operational circumstances, and the same equipment's daily energy consumption levels can differ [7,8]. Thus, measuring the electrical parameters precisely has become more important. Most researchers have designed various digital sampling electricity meters to measure parameters such as a machine's power, its power factor, and its frequency [9]. Some of the meters also measure the harmonic composition of the power signals [10].

In this study, a novel and portable performance-measuring device was developed for refrigerators by using an Arduino microcontroller circuit. Thanks to their C# and web interfaces, the corresponding test operations could be monitored with a remote. The monitoring system read each refrigerator's humidity, temperature, and flowing current and voltage. Over the course of 12 h, their outputs were investigated in both full and empty status. Then their concluded energy classes and the overall success or failure determinations were reported to the study's web interface for the products' users. The developed measuring system also measured the machines' energy efficiency classes. The prior processes inspired a new, untested portable device idea, which was proposed in a symposium shortly thereafter [11,12]. After it was tested in a designated room (the Ankara Energy Efficiency of Household Appliances, Technologies Research Center), which followed the related standards, some adjustments and improvements were implemented to the device model, mainly to its software.

The device enabled a country's refrigerator tests to be conducted with a portable module. In that proposition, refrigerators no longer needed to go to a specific testing room to evaluate their performance capacities. Refrigerator factories and technical service points could then alternatively use the new device.

2. The general structure of the performance-testing device

Two tests were applied to each sample refrigerator at unloaded and loaded conditions for 25 °C in the average external ambient temperature. In these TS EN 15502 tests, the power, humidity, and temperature values of the sample refrigerators were discovered. The block diagram of the system is given in Figure 1.

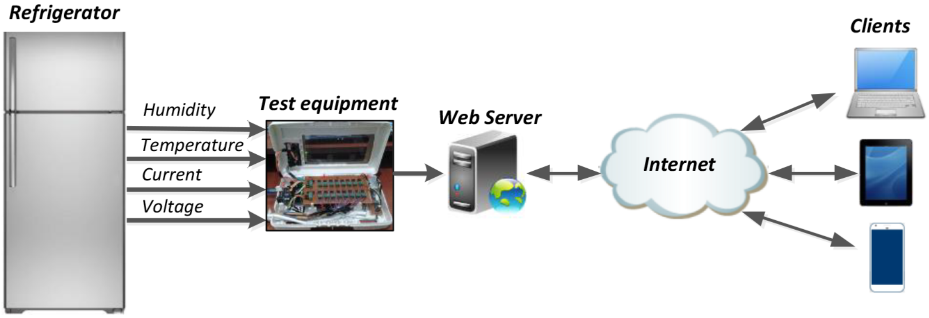


Figure 1. The block diagram of the system.

The tests were for each conducted at least 12 h while the refrigerators were loaded and empty. During them, the LCD screen on top of the testing device displayed the results through the C# interface program it was connected to, and the data were measured and viewed by the user's input to an internet database. Type K thermocouples were used for temperature measurements. The information coming from thermocouples was sent to the Arduino module through its card. An ACS712 sensor measured the current statistics, and a DHT11 sensor was used to measure the humidity levels. A voltage divider card was designed for the Arduino processor card to read and measure the voltage information. The Arduino processor card was fashioned to mount on the testing device. Figure 2 shows the internal structure of the test device. In Table 2, descriptions of the test equipment are given. The data that came from the refrigerators were taken for each second as a snapshot on the C# interface in both numerical and graphical forms.

Figure 2. Internal structure of the test device.

Before starting tests, the researchers selected the fullness and energy class levels of their subjects in the program interface. In viewing the final results, the testers reported to the users whether or not the machines statistically corresponded to their listed classes of performance from both the web interface and the C# interface programs.

Table 2. Descriptions of the test equipment.

No.	Explanations
1	16 × 2 LCD monitor
2	Arduino Uno R3 microprocessor card
3	Voltage divider card
4	Temperature measurement card
5	K type thermocouple cable
6	220/9 volt AC transformer

3. Hardware infrastructures

3.1. Temperature measurements

In this test, each refrigerator's cooling system, freezer, and compressor inlet temperatures were measured with the K-type thermocouples. The temperature values were measured in millivolt (mV) analogue, in which OPAMP gain values transpired on the testing device and were sent to the Arduino board. With the definitively elevated mV values from the Arduino cards, the thermocouple temperatures were determined. Figure 3 shows the thermocouple measurement circuit. That card evaluated 16 °C. The thermocouples' data were measured with the Multiplexer 4017.

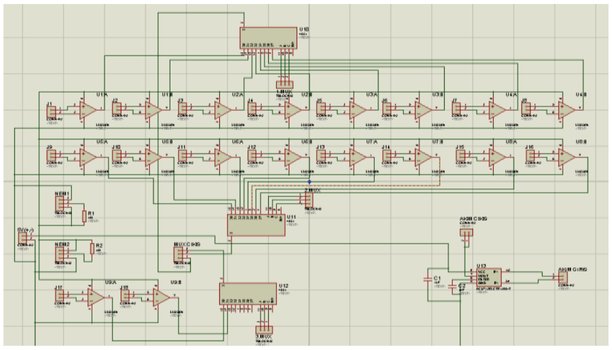


Figure 3. The thermocouple measurement circuit.

3.1.1. Current and humidity measurements

An ACS712 current sensor and a DHT11 humidity sensor are shown in Figure 4. The elements on those cards were fed through an Arduino card using a supply voltage of 5 V DC.

3.2. Voltage measurements

The circuit diagram of the voltage measurement circuit is shown in Figure 5. It measured each refrigerator's voltage. The transformer in this circuit converts the voltage from 220 to 9 V.

3.3. Software infrastructures

To start the program, the serial port was connected and the start button was pressed. Then the humidity, temperature, current, and voltage data were consecutively streamed at one-second intervals. The read data could be monitored both from a graphical interface and the LCD display on the device. The user could monitor the results remotely with a web interface.

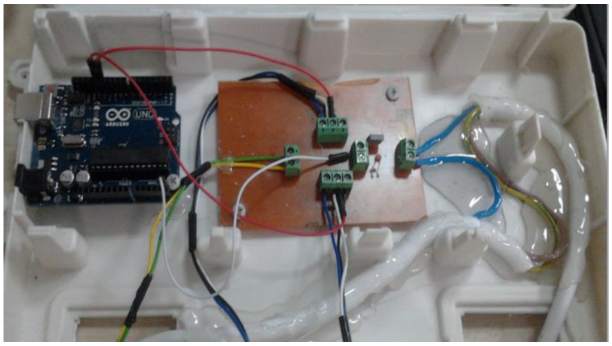


Figure 4. ACS712 current sensor and DHT11 humidity sensor.

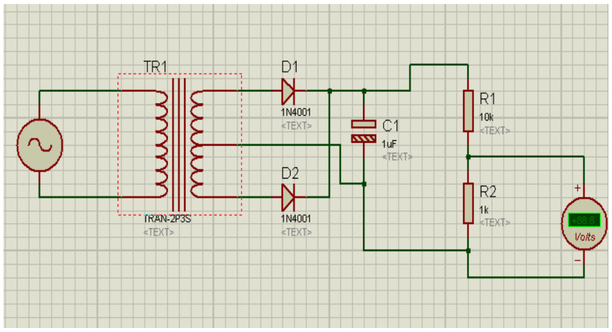


Figure 5. The circuit diagram of the voltage measurement circuit.

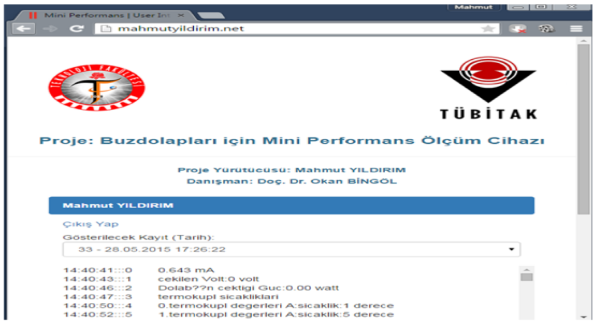
Data that were transferred through the serial port could be read and followed simultaneously by viewing the computer interface in Figure 6 and the LCD screen on the testing instrument in Figure 7. At the same time, if an Internet connection is available, all the read data can be displayed via the web interface in Figure 8. Figure 9 shows the graphical interface of the test system and explanations of the graphical interface are given in Table 3.

```
8:38:24:::12796     cekilen Akim:306.475 mA
8:38:26:::12797     cekilen Volt:219 volt
8:38:28:::12798     Dolab??n cektigi Guc:671.21 watt
8:38:29:::12799     termokupl sicakliklari
8:38:32:::12800     0.termokupl  degerleri A:sicaklik:1 derece
8:38:34:::12801     1.termokupl  degerleri A:sicaklik:4 derece
8:38:36:::12802     2.termokupl  degerleri A:sicaklik:1 derece
8:38:38:::12803     3.termokupl  degerleri A:sicaklik:1 derece
8:38:40:::12804     4.termokupl  degerleri A:sicaklik:1 derece
8:38:42:::12805     5.termokupl  degerleri A:sicaklik:23 derece
8:38:44:::12806     6.termokupl  degerleri A:sicaklik:14 derece
```

Figure 6. Computer interface of the system while the system is running.

Figure 10 shows the rear part of the connection locations of the refrigerator compressor where the thermocouples were attached to the surface of the aluminum heat pipe with preventive bands. The temperature was measured at 6 points. These points were the compressor output (T1), condenser output (T2), attenuation valve output (T3), evaporator input (T4), evaporator output (T5), and the compressor input (T6). The pressure measurement points included the output of the compressor (P1), the output of the condenser (P2), the evaporator input (P3), and the compressor input (P4). To measure the humidity of the refrigerator and freezer sections, humidity sensors were placed in the appropriate positions.

Figure 7. LCD screen display of the system while the system is running.



Proje: Buzdolapları için Mini Performans Ölçüm Cihazı

Proje Yürütücüsü: Mahmut YILDIRIM
Danışman: Doç. Dr. Okan BİNGÖL

Mahmut YILDIRIM

Çıkış Yap

Gösterilecek Kayıt (Tarih): 33 - 28.05.2015 17:26:22

```
14:40:41:::0     0.643 mA
14:40:43:::1     cekilen Volt:0 volt
14:40:46:::2     Dolab??n cektigi Guc:0.00 watt
14:40:47:::3     termokupl sicakliklari
14:40:50:::4     0.termokupl degerleri A:sicaklik:1 derece
14:40:52:::5     1.termokupl degerleri A:sicaklik:5 derece
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Figure 8. The web interface of the system (in Turkish).

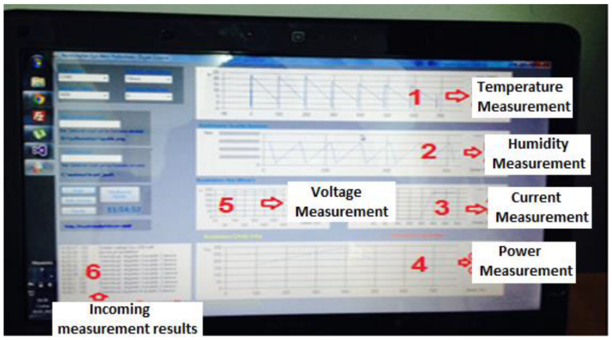

Figure 9. Graphical interface of the test system.

Figure 10. The rear part of the connection locations of refrigerator compressor.

Table 3. Explanations of the graphical interface of the test system.

No.	Explanations
1	Temperature graphics
2	Humidity graphic
3	Current graphic
4	Power graphic
5	Voltage graphic
6	Instantaneous data coming from serial port

In the first stage of the experiment, a refrigerator was in the no-load state, and its temperature, humidity, and power values were read and recorded for 12 h. Then after completely filling the refrigerator with water bottles, the temperature, humidity, and power values were read and recorded for 12 h.

The refrigerator test condition with no-load and load is shown in Figures 11a and 11b. The average temperature, humidity, and power measurements with load and no-load were recorded for 12 h in Tables 4–6, respectively. The loaded and unloaded refrigerators' temperatures were recorded at various points while they were in a room that was around 25 °C, and one statistical set is indicated in Table 4. It is important to note that the values in Table 4 both indicate the temperature values measured by the novel portable device and in the test cell, which were measured according to the standard IEC 62552. Values from T1 to T6 do not exist for the standard test cell measurements as these values (compressor output (T1), condenser output (T2), attenuation valve output (T3), evaporator input (T4), evaporator output (T5), and the compressor input (T6)) are not required by the established standard, IEC 62552. Therefore these measurements can be assumed as novelties introduced in this paper. From the uncertainties point of view, it is obvious that since the portable device operates in an ordinary kitchen, it is impossible to keep ambient temperature at a constant level, namely at 25 °C within a narrow interval. In addition, the portable device measures cooling temperatures without the decimal point. Therefore, while it is possible to present the temperature changes on a plot as illustrated in Figure 12 for the test cell, it is only possible to give average temperature measurement results within 12 h for the portable device. It is interesting to note that temperature values for the cooler (Load 2) and vegetable compartment (Load 1) are very similar for both portable device and test cell measurements. Table 5 shows the humidity levels of the same refrigerator for no-load and load in addition the standard values described within IEC 62552. Section 8.3. Humidity. It is stated in section 8.3 that: Unless otherwise specified, relative humidity shall not exceed 75%. Table 6 finally shows the power consumption of the device under test (DUT) for 12 h for the portable device and 24 h, as dictated by the standard. The standard only accepts measurements with standard test loads and open air thermocouple, which are shown in Figure 13. Table 6 shows the uncertainties for the case of energy consumption for i) portable device, ii) test cell and iii) data provided by the manufacturer. Although they seem to be different for each case the energy efficiency index (EEI) falls in the same category for all cases.

Figure 11. Refrigerator test condition a) no-load, b) with load.

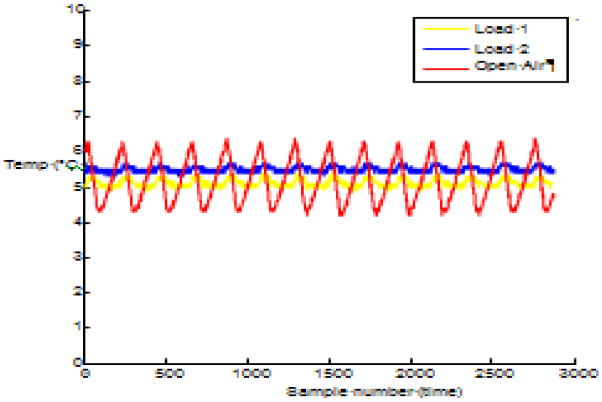

Figure 12. Temperature measurements obtained from the standard test loads and open air thermocouple in the refrigerator.

Table 4. The refrigerator temperature measurements.

Sensors	No-load temperature (°C)	Temperature with load (°C)	Measurements at test cell, Standard IEC 62552 (°C)
T1	41.1	61.2	Not available
T2	38.0	45.7	Not available
T3	–18.1	–4.3	Not available
T4	–17.4	–4.1	Not available
T5	14.3	24.3	Not available
T6	14.7	24.7	Not available
Freezer	–18.5	–6.2	–18
Cooler	2.1	4.2	Please observe Figure 12
Vegetable compartment	1.2	3.9	Please observe Figure 12
Media (ambient) temperature	$24 \pm 1\,K$	$24 \pm 1\,K$	$25.0 \pm 0.5\,K$

Figure 13. Standard test loads and open air thermocouple.

Table 5. The refrigerator humidity measurements.

	No load humidity (RH%)	Humidity with load (RH%)	Measurements at test cell, Standard IEC 62552 (RH%)
Humidity cooling rate	55% RH	61% RH	50% RH
Humidity freezing rate	43% RH	49% RH	50% RH

Table 6. Power measurements of the refrigerator.

	Portable Devices		Measurements at test cell (kWh) (Only with standard test loads) Based on standard 24 h	Manufacturer's data provided
	No load (kWh), based on 12 h	With load (kWh), based on 12 h		
Total energy	0.33	0.37	0.6491	0.76 kWh/24 h
Total energy consumption per year	240.9	270.1	236.922	280 kWh/year

4. Calculating an EEI

First, the variables that compose a refrigerator's EEI must be identified and calculated. The AEC defines the collective consumption while the DUT is at a steady rate. It is of course found by multiplying by 365 as one year has 365 days and each day has 24 h. The AEC is calculated according to Eq. (1):

$$AE_c = E_{24h} \times 365 \tag{1}$$

E_{24h} : DUT's energy consumption in 24 h (kilowatt hour, kWh)

The tricky bit is calculating the SAEC (the standard energy consumption of a similar refrigerator per year) because it depends on many factors, including the appliance's size, purposes for cooling, and the climate it is intended to operate in. The SAEC is calculated according to Eq. (2):

$$SAE_c = V_{eq} \times M + N + CH \tag{2}$$

V_{eq}: The equivalent volume of the refrigerator

M, N: Coefficients determined from the category of the refrigerator and the climate conditions it has been designed for, respectively. These values can be taken from the standard, IEC 62552.

CH: 50 kWh/year is a correction factor for refrigerators with a cellar compartment larger than 15 L.

As mentioned before, the developed equipment also measures the EEI classes of refrigerators. An EEI is calculated with Eq. (3), which basically converts the DUT's energy consumption level to its standard consumption level for 1 year in a percentage form. The resulting statistic is a sample of its needs if it were to be a marketed device.

$$EEI = \frac{AE_c}{SAE_c} \times 100 \tag{3}$$

AE_c : The DUT's annual energy consumption (kWh/year)

SAE_c : The standard energy consumption of an example refrigerator per year (kWh/year)

A refrigerator's EEI is calculated by using power measurements. The EEI value for the sample refrigerator in a study was found to be 28, which confirmed the manufacturer's claimed energy efficiency index of A++. Table 7 gives the corresponding EEI classes for the EEI intervals. The A+++ EEI is the most efficient, while class G is the least efficient product.

Table 7. EEI classes.

Energy efficiency class	EEI
A+++	EEI $<$ 22
A++	22 $\leq$ EEI $<$ 33
A+	33 $\leq$ EEI $<$ 44
A	44 $\leq$ EEI $<$ 55
B	55 $\leq$ EEI $<$ 75
C	75 $\leq$ EEI $<$ 95
D	95 $\leq$ EEI $<$ 110
E	110 $\leq$ EEI $<$ 125
F	125 $\leq$ EEI $<$ 150
G	EEI $\geq$ 150

4.1. Verifying the designed device's found facts

To verify the results of the designed measurement device in this given study, it was retested in a test cell (room) compatible with the standards. The test cell was inside the test and measurement laboratory, and it was named the Ankara Energy Efficiency in Household Appliances Technologies Research Center; it was financially supported by the United Nations Development Program. Measurements were recorded according to the standards indicated by the following directory: IEC 62552 > Household refrigerating appliances > Characteristics and test methods > Part 3: Energy consumption

All energy efficiency measurements were taken at the aforementioned research center. Figure 14 shows the test cell. The test cell provided a unique environment with controlled temperature, air flow, and humidity levels. In addition to following the IEC 62552 standards, the test cell was designed and built to be light- and soundproof in order to make the noise and vibration tests better than the standards' requirements. The test results confirmed the manufacturer's claimed energy efficiency index (A++) as given in Table 6.

The cell was only connected to the measurement laboratory through a cable canal, as illustrated in Figure 15. In order to not perturb the standards' parameters (such as temperature, humidity, and air flow) during measurements, the said setup was in place, and the test and measurement equipment was in the laboratory instead of the cell. Moreover, three refrigerators were tested both by the designed device and by the test cell. It is understood that their results were compatible, although they will not be included in this report for the sake of brevity.

Figure 14. The test cell.

Figure 15. Measurement laboratory next to the test cell separated by a cable canal only.

5. Conclusion

In this study, a portable performance-testing device was designed. Then household refrigerators were investigated experimentally. The experimental study room's temperature was a constant 25 °C, since the refrigerators' temperatures were sought when they were empty and full. Humidities, temperatures, and degrees of power were measured for each subject and condition state. On examination, the obtained results of the loaded refrigerators showed that the power and humidity values were high, and it was seen that in that situation the temperature in the internal circuits also increased.

Now, soon-to-be marketed refrigerators can be evaluated with a portable module. As a result, refrigerators do not need to go to a test room for a performance test. Refrigerator factories and technical service points can use the developed device as an alternative to test rooms.

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