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MATLAB Simulink Simulation of Refrigerator's Energy Consumption

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ABSTRACT

This research work studied simulation of energy consumption of a refrigerator with the aim of reducing the energy consumption. It was done by using a software known as MATLAB Simulink to simulate energy consumption of a domestic refrigerator which has three layers of wall, of which its middle wall was made of styro foam insulation and was substituted later with other insulations. The modelled refrigerator was fabricated and experiments on energy consumption of the fabricated refrigerator were conducted. The results of the simulation were validated with the experimental results. The results indicated that the modelled refrigerator whose middle wall was made of composite insulation and the fabricated refrigerator whose middle wall was made of composite insulation consumed the least amount of energy of 0.186 kWh/day and 0.195kWh/day, respectively. The validation of the simulation results with the experimental results indicated that there was a deviation of 4.61% of the simulation results from the experimental results.

Keywords: Energy Consumption, Experiment, Refrigerator, Simulation, Validation.

1. INTRODUCTION

It has been established by the US Department of Energy that domestic refrigerator is the second largest consumer of electricity in the average residence and has also estimated that domestic refrigerator is responsible for about 7.2% of the average residential energy consumption. Different countries worldwide have developed a list of programme to regulate its energy consumption, among which is the testing and labelling of energy consumption of a refrigerator. This has been proved to be a good tool to regulate the energy consumption of a refrigerator, but the testing can only be carried out on the finished products [1, 2]. It is, therefore, important to adopt an alternative approach with which the energy consumption can be known and reduced during the design phase of the refrigerator.

In the 16th century, the chemical refrigeration method, which was the first step toward artificial means of refrigeration, was discovered, in which sodium nitrate or potassium nitrate was added to water to reduce the temperature in order to create a sort of refrigeration bath for chilling wine. The first recorded method of artificial refrigeration was demonstrated by William Cullen in 1756 at the University of Glasgow, Scotland when he used a pump to create a partial vacuum over a container of diethylether which then boiled and absorbed heat from environment [3].

Before the advent of mechanical refrigeration, water was kept cooled by storing it in semi porous jugs so that the water could seep through and evaporate. The evaporation carried away the heat and cooled the water. This system was used by the Egyptians and by the Indians in the Southwest. Natural ice from lakes and rivers was often harvested during winter and stored in caves, straw lined pits, and later in sawdust-insulated buildings. The Romans carried pack trains of snow from the Alps to Rome for cooling the Emperor's drinks. Though, these methods of cooling made use of natural phenomena, they were used to maintain a lower temperature in the product and, therefore, can be called refrigeration [4].

In an attempt to evaluate the performance of a refrigerator, Admiraal and Bullard [5] made use of an alternative refrigerant to investigate the heat transfer in the refrigerator's condenser and evaporator. The conductance model was used to determine the heat transfer in the condenser and the evaporator, which was observed to depend on the characteristics of refrigerant. The result obtained from the models indicated that the variable conductance models were more accurate than the simple constant-conductance models. Variations in heat transfer resistance resulting from changes in refrigerant flow properties were accounted for by the variable conductance model. It was concluded that that the model could be used to predict the behavior of the refrigerator.

Bhatt [3] probed into an evaluation of energy indices of a refrigerator by statistical survey on a domestic refrigerator. It was observed that energy consumption varied between 3.23 and 4.19 kWh/y/l (kilowatt hour per year per liter) for a single door manual defrost unit and between 3.84 and 4.78 kWh/y/l for a double door auto defrost unit. The means for improvement in the performance of the refrigerator were the introduction of a better insulation and use of an alternative to chlorodifluoromethane (HCFC-22 or R-22).

Heat transfer, pressure drop, refrigerant distribution and the cyclic loss in a refrigerating system were evaluated by Sekhar et al. [6] with the aim of studying the energy efficiency improvement in a household refrigeration system. This was done by characterizing the cooling system and the plate of the evaporator of the refrigerator. By observing the different designs of a refrigerator, the heat transfer and air flow in the refrigerator was investigated by Laguerre [7]. He evaluated the various parameters, such as temperature and humidity of ambient air, which contributed to energy consumption of the refrigerating compartment.

A vapor compression refrigerator was designed and simulated by Yildiz [8]. The simulations were conducted for the condenser, evaporator, compressor, and capillary tube of the refrigerator. The heat transfer coefficient for each of the components was used as the main determinant for the design. The results of the simulation were compared with those of the convectional vapour compression refrigerator and were found to be in a good agreement. The heat load acting on a refrigerator, its pressure drop, the required length of the condenser and the evaporator were modeled by Girhe et al. [9], by using MATLAB Simulink. The results obtained during the simulation of the model were compared with the results obtained from other sources and the conclusion proved MATLAB as an effective tool for simulation of performance of a refrigerator.

Yusof et al. [10] performed an experiment on energy efficiency of a refrigerator by evaluating the performance characteristics of a minibar domestic refrigerator which utilized nanoparticles of aluminum oxide (Al_2O_3) as a refrigerant. The refrigerant was charged into the refrigerator at different charging pressures. The results from the evaluation showed that the refrigerator attained its optimum operating level at 42 psi. Highest percentage of energy consumption reduction was also noted at the optimum refrigerant charge. It was discovered that a better performance and reduction of power consumption was achieved by the addition of Al_2O_3 nanoparticles to the base fluid polyolester.

A rotating heat exchangers was used as an alternative to evaporator of a refrigerator to provide an innovative solution to address the issue of energy consumption of the refrigerator [11]. The thermal resistance was reduced as a result of continuous disruption to the boundary layer which was caused by the rotation of the fins in the rotating heat exchangers. Examination of the modelling of a refrigerator was done by Ablanque et al. [12]. Modular approach was used to model each element of the system and simulations were conducted to predict the refrigerator behavior under the steady state conditions. The results of the simulation were compared with experimental values for the temperatures and the refrigerant charge distribution at different heat loads. The study revealed that the behavior of the refrigerator could be predicted by the model.

As it can be seen in the above-mentioned previous works, numerous means have been used by different researchers to develop and simulate models to improve on energy consumption of a refrigerator. It is evident that none of the previous researches made use of composite insulation to improve on energy consumption. Therefore, this work considered the use of MATLAB Simulink to develop and simulate a model for energy consumption of a domestic refrigerator. The reduction in the energy consumption was achieved by means of a composite insulation. Not only that, experimental results were used to validate the simulated results.

2. RESEARCH METHODOLOGY

This section presents the details of the methodology which was applied in the present research. A domestic refrigerator was fabricated. The fabricated refrigerator and a refrigerator manufactured by an LG company were modelled and simulated, and the simulation results were obtained. In addition, validation of the simulation results was carried out. The present section is divided into three sub-sections, viz. heat transfer in the refrigerator, modelling and simulation, and validation of the simulation results with experimental results.

2.1 Heat Transfer in the Walls of the Refrigerator

The layers of wall of the fabricated refrigerator are outside wall, inside wall, and middle wall. The outside wall is made of plastic. The inside wall is made of polystyrene and the middle wall is made of styro foam. In this work, the middle wall was a styro foam insulation and was substituted later with other walls made of different insulations. The details of these are presented in sections 2.3 and 2.4. The arrangement of the layers of the wall is shown in Fig. 2.1.

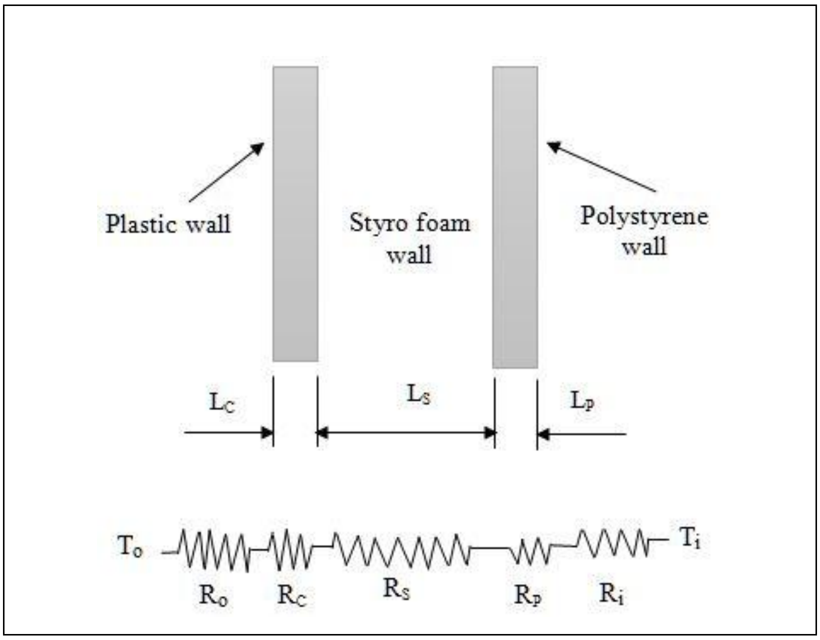

Fig. 2.1. Composite wall of the fabricated refrigerator

In the Fig. 2.1 above, R_C, R_S, and R_P are the thermal resistance of the outside wall, middle wall, and inside wall, respectively. R_o and R_i are the outside convective thermal resistance and the inside convective thermal resistance, respectively. T_o is the temperature of the fluid to which the outside wall was exposed to and T_i is the temperature of the fluid to which the inside wall was exposed to. L_C, L_S, and L_P are the thickness of the outside wall, middle wall, and inside wall, respectively.

Holman [13] has given the heat transfer equation to be:

$$Q = \frac{k.A.\Delta T}{L} = \frac{\Delta T}{R} = \frac{(T_o - T_i)}{R} \tag{2.1}$$

In Eq. (2.1) above,

$$R = \frac{L}{k.A} \tag{2.2}$$

in which k, A, ΔT, L, and R_{th} are the thermal conductivity $\left(\frac{W}{m.K}\right)$, area ($m^2$), temperature difference (K), thickness (m), and thermal resistance $\left(\frac{^oC}{W}\right)$, respectively, of the wall.

The total thermal resistance is given by

$$R_{th} = R_o + R_C + R_S + R_P + R_i \tag{2.3}$$

in which $R_o = \frac{1}{h_o}$ is the outside convective thermal resistance, $R_c = \frac{L_c}{k_c.A_c}$ is the thermal resistance of the outside wall, $R_s = \frac{L_s}{k_s.A_s}$ is the thermal resistance of the middle wall, $R_p = \frac{L_p}{k_p.A_p}$ is the thermal resistance of the inside wall, and $R_i = \frac{1}{h_i}$ is the inside convective thermal resistance. The terms h_i and h_o are the convective heat transfer coefficient of the fluid to which the inside wall and outside wall, respectively, were exposed to. L_c is the thickness of the outside wall, k_c is the thermal conductivity of the outside wall, L_s is the thickness of the middle wall, k_s is the thermal conductivity of the middle wall, L_p is the thickness of the inside wall, and k_p is the thermal conductivity of the inside wall.

Combining Eq. (2.1) and (2.3) yields:

$$Q = \frac{(T_o - T_i)}{\frac{1}{h_o A_c} + \frac{L_c}{k_c.A_c} + \frac{L_s}{k_s.A_s} + \frac{L_p}{k_p.A_p} + \frac{1}{h_i A_p}} \tag{2.4}$$

2.2 Modelling and Simulation of the Refrigerators

MATLAB Simulink software [14] was used to model and simulate the fabricated refrigerator and the LG-manufactured refrigerator. The direct input method, otherwise known as masking method, was adopted in this work to input the parameters, given in Table 2.1, into the input interface of the software.

Table 2.1.: Parameters for modelling and simulation of the refrigerators

Symbol	Parameter	Value
L_O_shell	Outer plastic thickness	0.0017 m
K_O_Shell	Outer plastic thermal conductivity	0.46 W/m-K
L_Pol	Polystyrene thickness	0.0006m
K_Pol	Polystyrene thermal conductivity	0.029 W/m-K
L_Sty	Styro foam thickness	0.06 m
K_Sty	Styro foam thermal conductivity	0.033W/m-K
L_Steel	Steel thickness	0.0006m
K_Steel	Steel thermal conductivity	15.1 W/m-K
L_poly	Expanded polyurethane thickness	0.06m
K_Poly	Expanded polyurethane thermal conductivity	0.027 W/m-K
K_gas	Cavity gas thermal conductivity	0.011 W/m-K
L_Fg	Fibre glass thickness	0.06m
K_Fg	Fibre glass thermal conductivity	0.034 W/m-K
A(LG Ref)	Heat transfer area of LG refrigerator	2.367m^2
A(Ref Cooler)	Heat transfer area of fabricated refrigerator	0.255m^2
To	Ambient temperature	28 °C
Ti	Internal temperature of refrigerating chamber	3°C
K_Air	Air thermal conductivity	0.02439 W/m-K
L(LG)	Width of refrigerating compartment for LG refrigerator	0.5m
L(RC)	Width of refrigerating compartment for fabricated refrigerator	0.35m
g	Acceleration due to gravity	9.8m/s
NHD	No of hours in a day	24

2.3 Fabrication of the Refrigerator

A cooler, a condenser, a compressor, an evaporator, a fan, and a filter dryer were used to fabricate the refrigerator. The cooler has an outer wall and inner wall which are made of plastic and polystyrene, respectively. The middle wall of the cooler is made of styro foam, which was replaced later with other insulations for the purpose of performing different experiments presented in the subsequent section. The thicknesses of the walls are contained in Table 2.1 above.

To fabricate the domestic refrigerator, a shell-type evaporator was placed inside the plastic cooler. A hole was drilled through the side of the cooler to serve as a passage for the copper tube which carries the refrigerant from the compressor to the evaporator. The filter dryer was fitted to the discharge line of the condenser and the fan was installed in front of the condenser. The components of the refrigerator were mounted on a trolley. The three-dimensional drawing of the fabricated refrigerator is shown in Fig. 2.2.

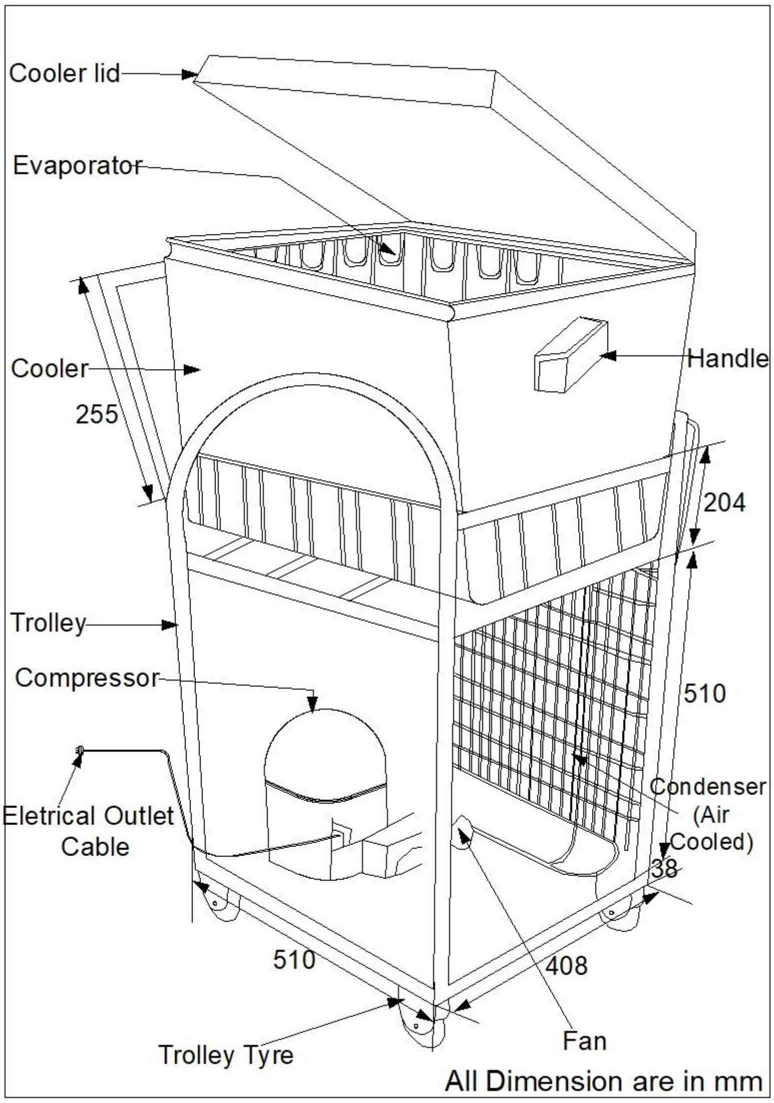

Fig. 2.2. Three-dimensional drawing of the fabricated refrigerator

2.4 Experiments conducted on the Refrigerator

2.4.1 Reverse heat loss measurement experiments

The experiment on reverse heat loss measurement was conducted to measure the heat flux in the refrigerator. A boiling ring was placed inside the cooler of the refrigerator which has its middle wall made of styro foam insulation.

The inner temperature and outer temperature of the cooler were measured with thermometers and the values of the temperature were recorded within an interval of thirty minutes. The styro foam insulation was substituted, in turn, with rigid polyurethane foam, expanded polyurethane foam, fibre glass, and composite insulations and the experiment was conducted for each of the styro foam insulation's substitutes.

2.4.2 Energy consumption measurement experiments

To conduct this experiment, a universal power meter was connected to the refrigerator to measure its energy consumption. The experiment began with the refrigerator which has styro foam insulation as its middle wall. The refrigerator with styro foam insulation was switch on for a period of one hour and the energy consumption, which was displayed on the power meter, was recorded. The time taken for the experiments was recorded by a digital stop watch. The styro foam was substituted, individually, with rigid polyurethane foam, expanded polyurethane foam, fibre glass, and composite insulations, after which the experiment was repeated with each of the replacements.

3 DISCUSSIONS OF THE RESULTS

The results of the simulations, experiments, and validation of the results of the simulation results are discussed in this section.

3.1 Simulation of Energy Consumption and Heat Flux

3.1.1 Simulation of energy consumption of the fabricated refrigerator and LG-manufactured refrigerator

The results of the simulation of energy consumption and heat flux of the fabricated refrigerator and those of the refrigerator manufactured by LG Company are presented in Table 3.1. The simulated results are depicted in Fig. 3.1. It can be seen in the Figure that the fabricated refrigerator and the LG- manufactured refrigerator consumed the maximum energy of 0.281kWh/day and 0.843kWh/day, respectively, when the middle wall of the refrigerator was expanded polyurethane foam insulation. A minimum energy of 0.186kWh/day and 0.147KW/day were consumed by the fabricated refrigerator and the LG- manufactured refrigerator, respectively, for the composite insulation.

Table 3.1. Simulation of energy consumption and heat flux of the fabricated refrigerator and LG-manufactured refrigerator

Middle wall of the refrigerator	Fabricated refrigerator		LG-manufactured refrigerator	
	Energy consumed (kWh/day)	Heat flux (kW/m^2)	Energy consumed (kWh/day)	Heat flux (kW/m^2)
Styro foam	0.265	0.308	0.596	0.283
Rigid polyurethane foam	0.265	0.243	0.294	0.232
Expanded polyurethane foam	0.281	0.652	0.843	0.496

Fiber glass	0.265	0.317	0.605	0.292
Composite (Rigid polyurethane and fibre glass)	0.186	0.131	0.147	0.130

The Figure further indicates that the same amount of energy of 0.265kWh/day was consumed by the fabricated refrigerator with the middle wall made of either styro foam or fibre glass insulations. An amount of energy of 0.596kWh/day and 0.605kWh/day was consumed by the LG-manufactured refrigerator for the styro foam and fibre glass insulations, respectively.

Therefore, it can be concluded that for the various insulations considered, the refrigerator with the composite insulation consumed the least amount of energy. The implication is that the utilization of the composite insulation as the middle wall of the refrigerator reduced the energy consumption of both the fabricated refrigerator and the LG-manufactured refrigerator.

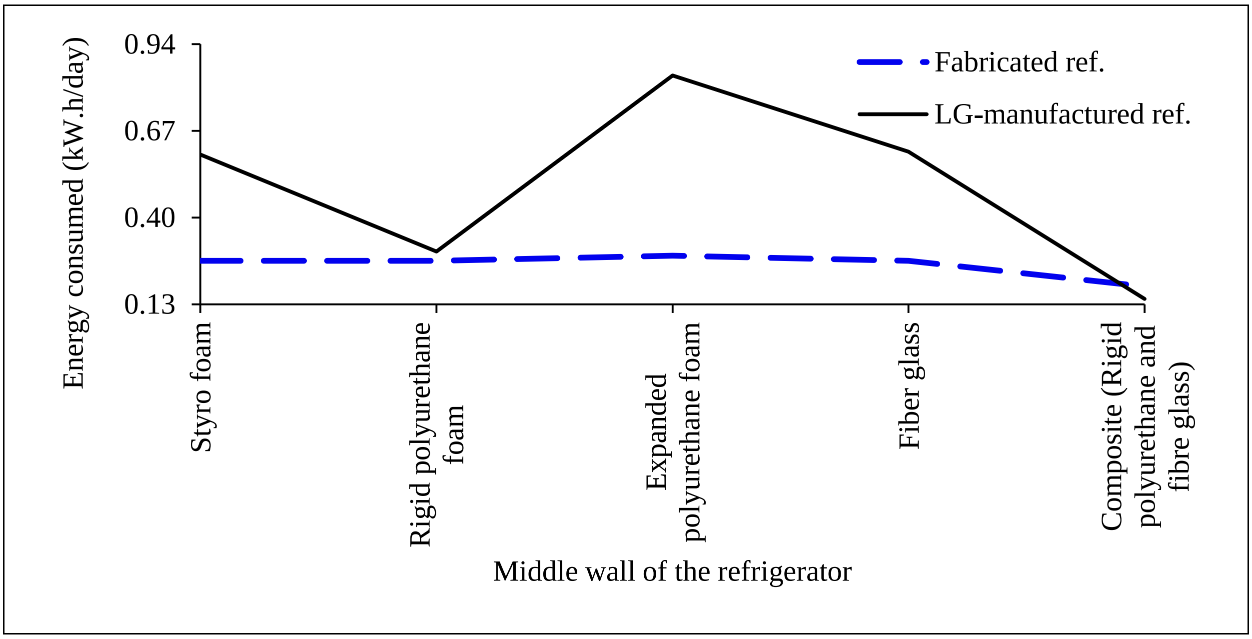

Fig. 3.1. Simulated energy consumption of the fabricated and LG-manufactured refrigerators

3.1.2 Simulation of heat flux of fabricated refrigerator and LG-manufactured refrigerator

The heat flux in the LG-manufactured refrigerator and the fabricated refrigerator is shown in Fig. 3.2. The heat flux in the fabricated refrigerator and the LG- fabricated refrigerator has a maximum value of 0.652kW/m^2 and 0.496kW/m^2, respectively, when the middle wall of the refrigerator was expanded polyurethane foam insulation.

A minimum value of 0.131kW/m^2 and 0.130kW/m^2 were obtained in the fabricated refrigerator and the LG-manufactured refrigerator, respectively, when the middle wall was replaced with a combined polyurethane foam and fibre glass insulation.

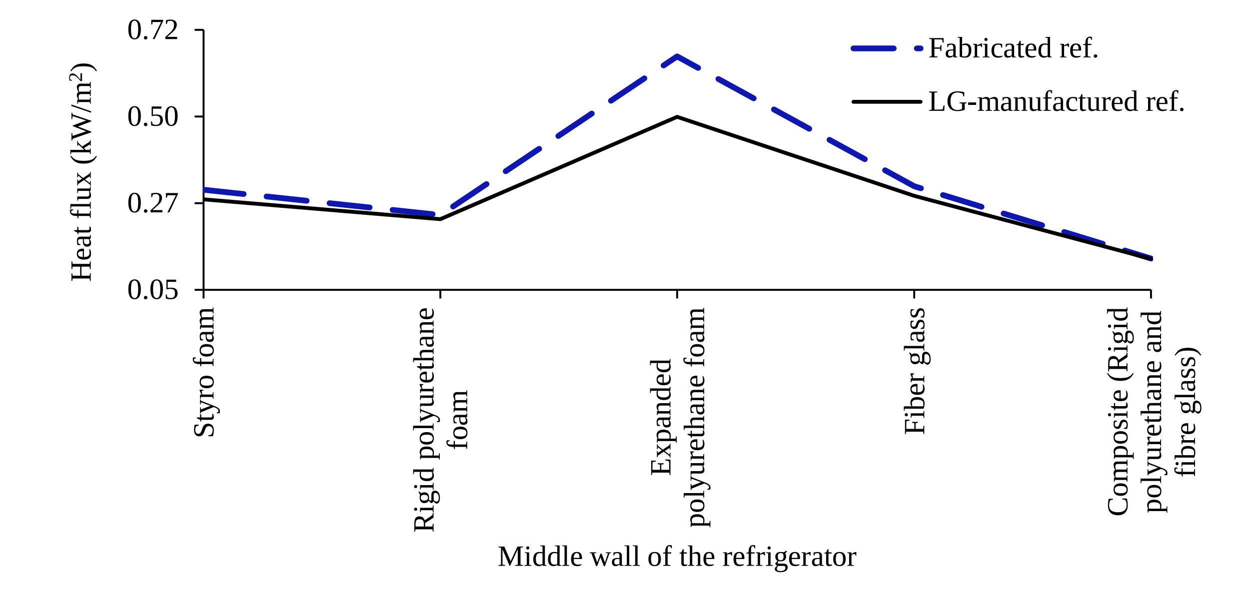

Fig. 3.2. Simulated heat flux of the fabricated and LG-manufactured refrigerators

The fact that the heat flux in the refrigerator for the case of the composite insulation (that is, combined rigid expanded polyurethane and fibre glass insulations) was lower than the case of expanded polyurethane or fibre glass insulation is an indication that least amount of energy was consumed by the compressor of the refrigerator with composite insulation. This inference is in agreement with the observation of Melo et al. [15]. This implies that of all the insulations considered, the heat loss by the refrigerator with composite insulation was the lowest, whereas the heat loss by the refrigerator with polyurethane foam insulation or fibre glass insulation was the highest. This is a confirmation of reduction in energy consumption of the refrigerator by the use of the composite insulation since the refrigerator with the composite insulation has the highest capability to retain heat.

3.2 Laboratory Experiments

3.2.1 Energy consumption of the fabricated refrigerator

The results of the experiments conducted on the energy consumed by the fabricated refrigerator are shown in Table 3.2 and it is graphically displayed in Fig. 3.3.

Table 3.2. Experimental energy consumption of the fabricated refrigerator

Middle wall of the refrigerator	Energy consumed (kW h)	Energy consumed (kWh/day)
Styro foam	0.011	0.268
Rigid polyurethane foam	0.011	0.271
Expanded polyurethane foam	0.012	0.288

Fiber glass	0.011	0.269
Composite (Rigid polyurethane and fibre glass)	0.008	0.195

From Fig. 3.3 below, it is seen the lowest amount of energy, which is 0.195kWh/day, was consumed by the fabricated refrigerator with composite insulation as its middle wall. Moreover, the fabricated refrigerator with the expanded polyurethane foam insulation consumed the highest amount of energy of 0.288kWh/day. Thus, the energy consumption of the refrigerator was reduced by means of composite insulation.

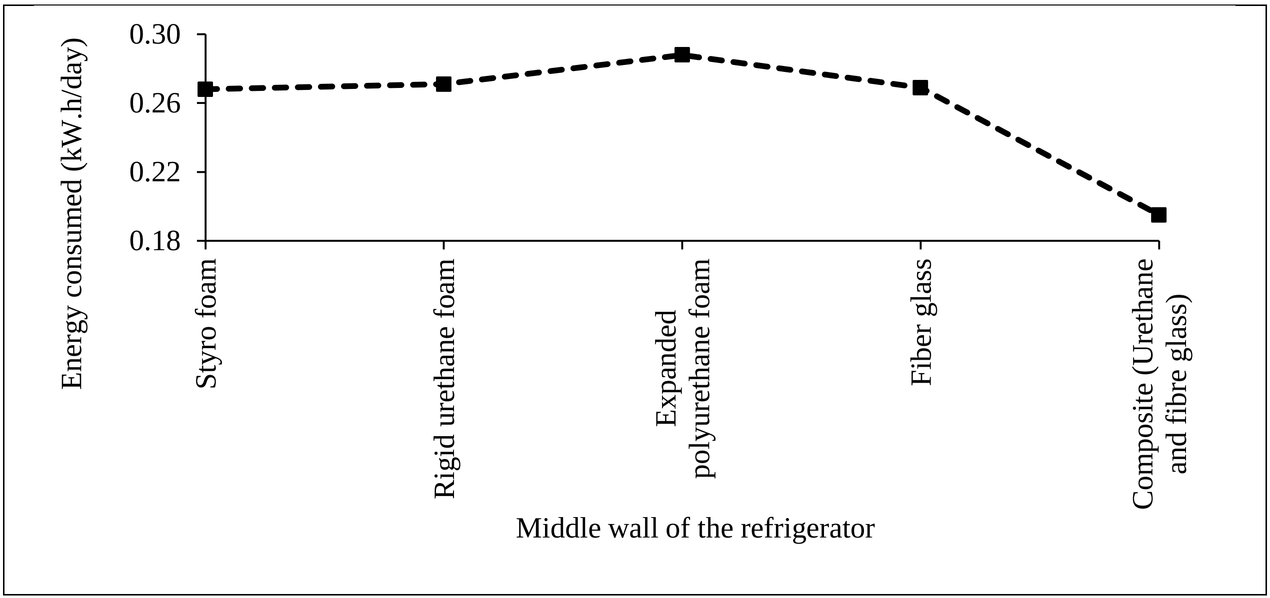

Fig. 3.3. Experimental energy consumption of the fabricated refrigerator

3.2.2 Reverse heat loss in the fabricated refrigerator

Table 3.3 and Fig. 3.4 demonstrate the results of the experiments performed on the heat flux in the fabricated refrigerator. It is evident in Fig. 3.4 that the heat flux in the refrigerator with expanded polyurethane foam as its middle wall was the highest of all insulations considered. In particular, the fabricated refrigerator whose middle wall was composite insulation had the least heat flux of 0.130kW/m^2, whereas the heat flux in the fabricated

Table 3.3. Experimental heat flux in the fabricated refrigerator

Middle wall of the refrigerator	Heat flux (kW/m^2)
Rigid polyurethane foam	0.244
Expanded polyurethane foam	0.651
Styro foam	0.309
fiberglass	0.318
Composite (Rigid polyurethane and fibre glass)	0.130

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refrigerator with expanded polyurethane foam insulation was 0.651kW/m^2. The interpretation is that the performance, in terms of retaining heat inside the cooler, of the refrigerator which has composite insulation as its middle wall was the best out of all the insulations considered.

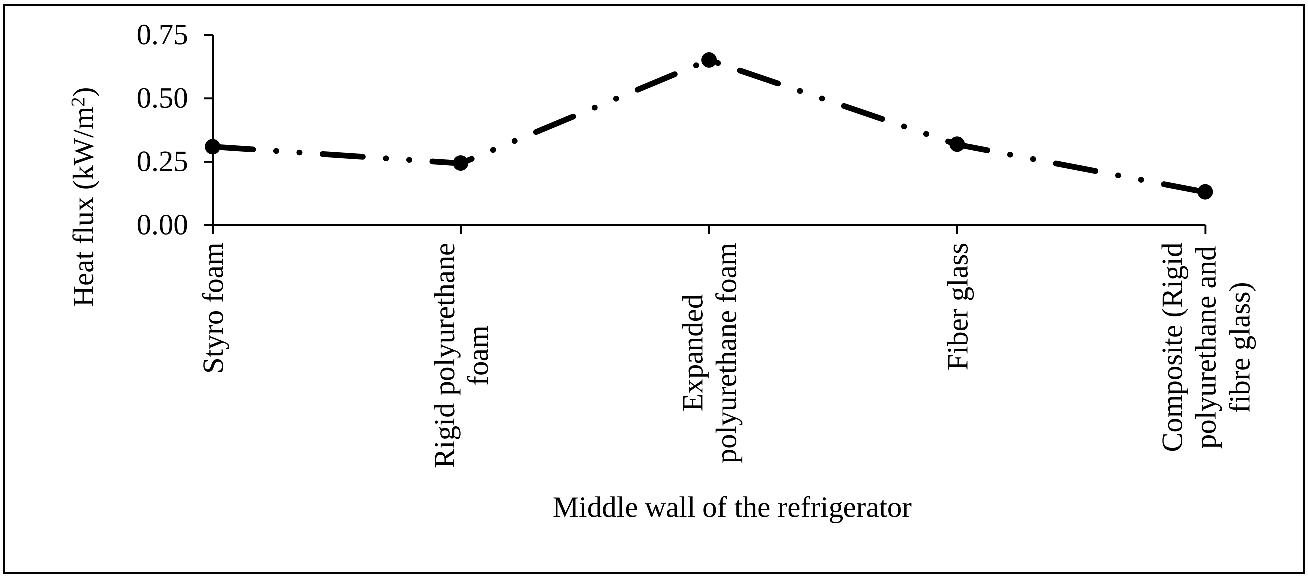

Fig. 3.4. Experimental heat flux in the fabricated refrigerator

3.3 Validation of the Simulation Results

The results obtained from the simulation were validated with those obtained from the experiments and they are presented in this section.

3.3.1 Validation of the energy consumption of the refrigerator

The results of the simulations and experiments on energy consumed and heat flux are shown in Table 3.4.

Table 3.4. Simulated and experimental results of energy consumption and heat flux of the fabricated refrigerator

	Simulation		Experiment	
Middle wall of the refrigerator	Energy consumed/day (kWh/day)	Heat flux (kW/m^2)	Energy consumed/day (kWh/day)	Heat flux (kW/m^2)
Styro foam	0.265	0.308	0.268	0.309
Rigid polyurethane foam	0.265	0.243	0.271	0.244
Expanded polyurethane foam	0.281	0.652	0.288	0.651
Fiber glass	0.265	0.317	0.269	0.318
Composite (Rigid polyurethane and fibre glass)	0.186	0.131	0.195	0.13

 Online ISSN: 2456-883X

The simulation results of the energy consumption of the modelled refrigerator were validated with the experimental results obtained from the energy consumption of the fabricated refrigerator. The results are graphically presented in Fig. 3.5 and indicated that there was a deviation of 4.61% of the experimental results from the simulation results.

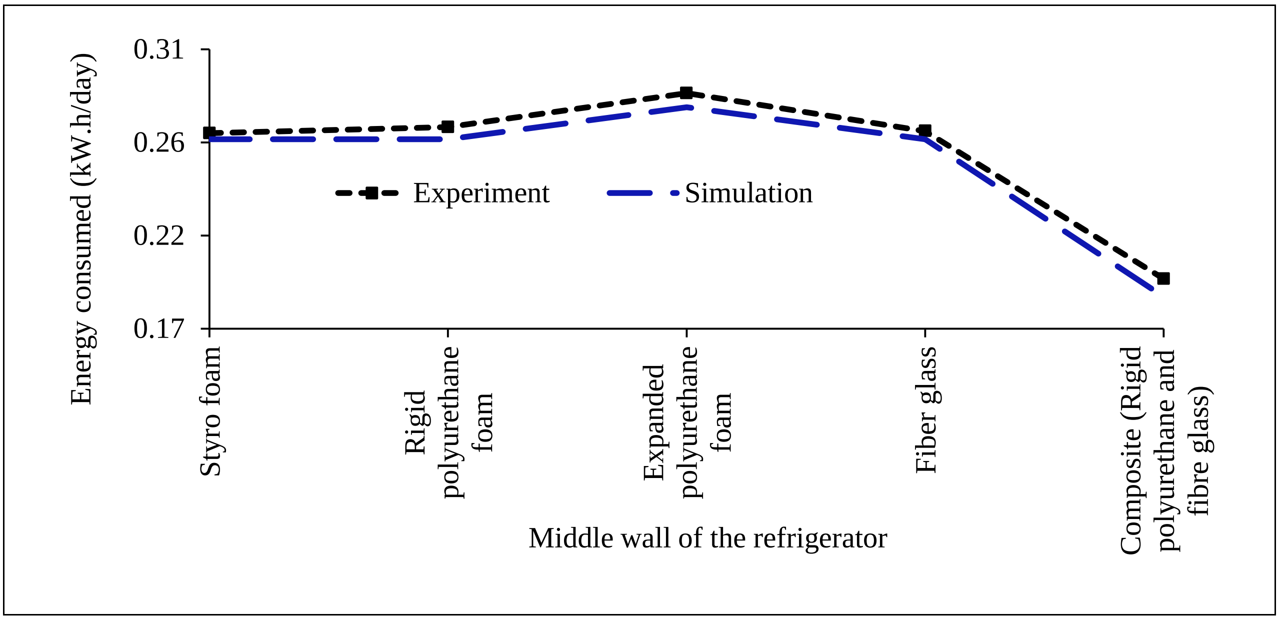

Fig. 3.5. Validation of energy consumption of the modelled refrigerator with the fabricated refrigerator

3.3.2 Validation of the heat flux in the refrigerator

The simulation results of the heat flux in the modelled refrigerator were validated with the experimental results obtained from the heat flux in the fabricated refrigerator and are depicted in Fig. 3.6. From the Figure, it can be inferred that the simulation and experimental results are in harmony with a discrepancy of 0.77%.

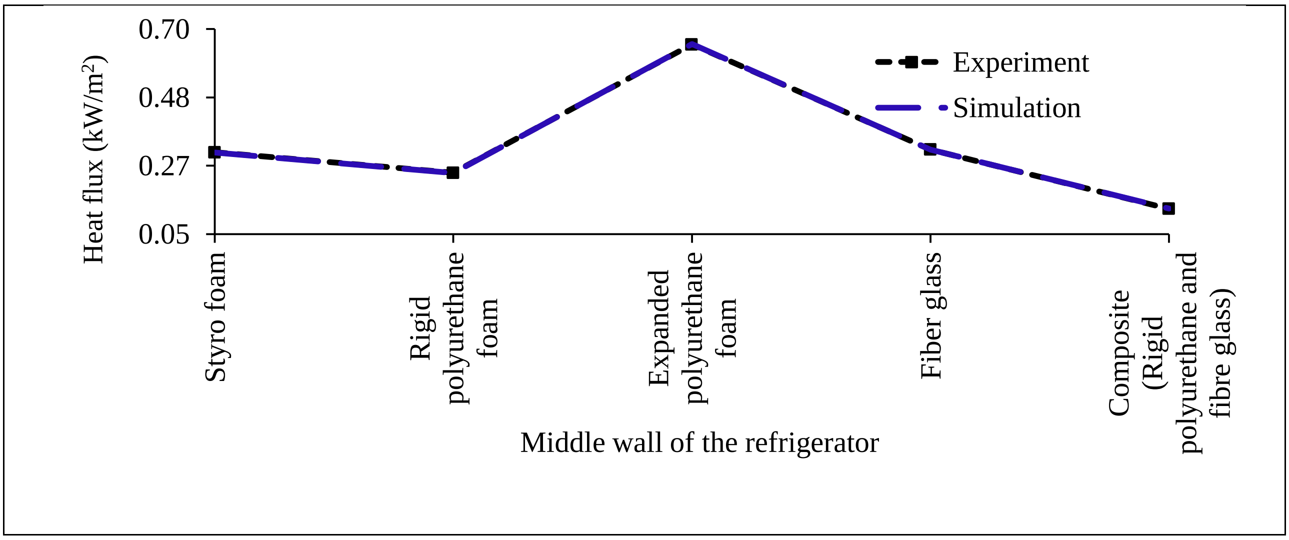

Fig. 3.6. Validation of energy consumption of the modelled refrigerator with the fabricated refrigerator

4 CONCLUSIONS

The following conclusions were drawn from the work:

i. The use of MATLAB Simulink software to simulate energy consumption of a domestic refrigerator was considered in this research.

ii. The refrigerator was fabricated and experiments on energy consumption and heat flux were carried out on it. The experimental results were used to validate the simulation results.

iii. Simulation and experimental results of the energy consumption of the refrigerator showed that the refrigerator with composite insulation consumed the least amount of energy.

iv. Also, the simulation and experimental results of the heat flux in the refrigerator indicated that the refrigerator with composite insulation had the lowest amount of heat flux.

v. Validation of the simulation results of energy consumption and heat flux with their respective experimental results of energy consumption and heat flux revealed that the simulation results were in good agreement with the experimental results.

LIST OF NOMENCLATURES

A	Area (m^2)	ΔT	Temperature difference (°C)
g	Acceleration due to gravity (m/s)	Subscripts	
h	Convective heat transfer coefficient ($W/(m^2$-K)	c	Outside wall
k	Thermal conductivity (W/m-K)	i	Inside
L	Thickness (m)	o	Outside
Q	Heat transfer (W)	p	Inside wall
R	Thermal resistance (^{o}C/W)	s	Middle wall
T	Temperature (°C)	th	Total

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