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Improvement on Energy Consumption of Household Refrigerator

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Authors' contributions

This work was collaboratively carried out between both authors. Authors MTM and TOO participated in the tasks involved in making the publication of the work a reality. The work was supervised by author TOO. Both authors read and approved the final manuscript.

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ABSTRACT

In this work, a household refrigerator was fabricated and improvement on its energy consumption, by means of a composite insulation, was examined. The refrigerator was constructed with a cooler, which is made of 1.7 mm-thick plastic as its outer insulation. The outer, middle, and inner insulations of the cooler serve as the outer, middle, and inner walls, respectively, of the refrigerator. The inner insulation is 0.6mm-thick polystyrene and the middle insulation was originally 60mm-thick styro foam. After the initial experiment with the styro foam, it (the styro foam) was removed and replaced in succession with other insulations, namely rigid polyurethane foam, expanded polyurethane foam, fibre glass, and composite insulations, for which the experiments were successively repeated. The results indicated that the refrigerator with composite insulation consumed the least amount of energy of 0.195 kWh/day and it also had the lowest value of heat flux of 0.130 W/m^2. The results obtained from the experiments on instantaneous heat flux and instantaneous temperature further revealed that of all the insulations considered in the present work, the refrigerator with composite insulation has the highest capacity to retain heat in the refrigerating chamber of the refrigerator. The inference is that the use of composite insulation can reduce energy consumption of a household refrigerator.

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1. INTRODUCTION

In the observation of Harrington [1], refrigerator has become a basic item of many household and the production of domestic refrigerator is over 90 million units per year. Cooling in a refrigerator is achieved by the relationship between saturated vapor pressure and temperature, which creates two thermal conditions, namely a high temperature where the heat is rejected and a low temperature where the heat is absorbed [2,3]. A refrigerator is not only use to achieve low temperature, but also to maintain the low temperature for an extended time. The maintenance of temperature below that of its surrounding atmosphere, during which heat is transferred from a low-temperature region to a high-temperature region is known as refrigeration. The work for heat transfer is driven by a compressor of the refrigerator and that means that the refrigerator consumes energy [4,5].

The growth in the world population has caused the demand for energy to increase and some countries, including Nigeria, are facing shortage of electricity because the supply of electricity has failed to meet the demand of its consumers. In addition, the increase in electricity tariff has resulted in the preference of consumers towards appliances which consumes a small amount of energy. The need to overcome this challenge has motivated manufacturers to produce appliances, among which is a refrigerator, that consumes a small amount of energy.

Testing and labelling of energy consumption of appliances, such as a refrigerator, is used in some countries of the world to know the energy consumption of the appliances. With this approach, the energy consumption can only be tested for finished products. Hence, it has become necessary to devise a means of knowing the energy consumption of a refrigerator before it is manufactured.

Joh Gorrie, an American physician, in 1842, designed the first system for refrigerating water to produce ice and, at the same time, conceived the idea of using a refrigeration system to cool air for comfort in home and hospital. Alexander Twining began experiment on vapour compression refrigeration in 1848 and obtained patents between 1850 and 1853 [6].

In 1880, the first ammonia compressors which used natural refrigerants were produced. Ammonia, propane, and carbon dioxide were among the first and insulated cold stores put into use in the USA. Concerns about the safety of these substances, stemming mostly from their toxicity and high working pressures, led to the development of synthetic chemical alternatives. Chemical manufacturers developed competing synthetic refrigerants, known as safety refrigerants, most of which consisted of configurations of chlorofluorocarbons, popularly known as CFCs. After the Second World War, the development of small hermetic refrigeration compressors evolved and refrigerators began to take their place in home [7].

Since the domestic refrigerator has become an average household need, the desire to lower its energy consumption has become an important issue. The different factors which can be used to decrease energy consumption of household refrigerators have been a source of concern [8]. This has motivated different researchers to carry out different studies on how to reduce the energy consumption of domestic refrigerators.

Inan et al. [9] investigated heat and mass transfer in a refrigerator by evaluating the performance of its evaporator. The heat transfer and pressure drop in two different flow regions in the evaporator, that is, the two-phase mixture in the entry and the super-heated vapor region at the exit were modelled and simulated using the energy balance equation and mean temperature difference of the evaporator. It was observed that the energy consumption of the refrigerator could be reduced with the improvement in heat transfer coefficient and the performance characteristics of the various parameters.

Heat transfer and air flow in a refrigerator was investigated by Laguerre [10]. Different designs of the refrigerator were observed and evaluation of the various parameters (such as temperature, humidity of ambient air) which contributed to the energy consumption of the refrigerator was carried out.

The energy consumption of a refrigerator was modelled by showing the sensitivity of the refrigerator’s energy consumption to various usage condition with the realistic range by means of empirical studies [11]. The investigation revealed that ambient temperature has the greatest impact on the refrigerator's energy consumption. An experiment was also performed and the information gathered from the experiment was used as a base for development and validation of a simplified model that allows the prediction of the energy consumption of the refrigerator.

Rasti [12] experimentally conducted an investigation by substituting R134a refrigerant with a mixture of R290 and R600a with a mass ratio of 56:44 in an evaporator of a refrigerator without any modification in refrigeration cycle. The refrigerator's power consumption during the operation and the temperatures in different sections of the refrigerator were measured. Results showed that in comparison to the base refrigerator working with R134a, there was 5.3% reduction in the energy consumption per day.

Boussin approximation was used by Zhang and Lian [13] to model heat transfer phenomena in a refrigerator by investigating the heat transfer from the inner compartment, the evaporator, and outside thermal insulation foam in the system. The discrete ordinate method was used to show the impact of radiation heat transfers between the evaporator and outer warm surfaces. The accuracy of the numerical method was verified through grid sensitivity analysis and comparison with available numerical and experimental data.

Through an evaluation of the performance characteristics of a minibar domestic refrigerator which utilized nanoparticles of aluminum oxide (Al_2O_3) as a refrigerant, an experiment on energy efficiency of a refrigerator was conducted by Yusof et al. [2]. The refrigerant was charged into the refrigerator at different charging pressure. Highest percentage of energy consumption reduction was observed at the optimum refrigerant charge. It was concluded that better performance and reduction of power consumption could be achieved by the addition of Al_2O_3 nanoparticles to the base fluid polyolester.

Raveendran and Sekhar [14] examined the performance of a refrigerator with water-cooled condenser. The water used for general purposes in a residential building was considered as the cooling water for the condenser. The circulation quantity of water per day was varied and the variation of coefficient of performance was studied. The results obtained from the theoretical and experimental studies showed that the energy consumption of the system with water-cooled brazed plate heat exchanger was higher than that of air-cooled brazed plate heat exchanger.

The various studies above is an indication that various researchers have adopted different methods, such as increase in evaporator size with counterblow arrangement, substitution of refrigerants with other ones, high-efficiency compressor substitution, increase in condenser size with counterblow arrangement, and increase in surface area and number of fins of evaporators. Despite this, an investigation on composite material vis-a-vis energy consumption of a refrigerator has not yet been reported. In this work, a household refrigerator was fabricated and improvement in its energy consumption by means of a combined rigid polyurethane and fibre glass insulation was examined.

2. THEORETICAL BACKGROUND OF HEAT TRANSFER IN THE REFRIGERATOR

Fig. 2.1 shows the composite wall of the refrigerator. It has three layers of different materials tightly fitted to one another. The layers are an inner insulation, a middle insulation, and an outer insulation. The inner insulation is made of polystyrene. The middle insulation was originally a styro foam material, which was later on substituted, separately, with expanded polyurethane foam, rigid polyurethane foam, fibre glass, and composite insulation. The outer insulation is made of plastic material.

The equation for the transfer of heat [15] through the walls of the refrigerator is:

$$q = \frac{(T_o - T_i)}{R_{th}} = \frac{k.A.\Delta T}{X} \qquad (2.1)$$

where T_o and T_i are the temperature of the fluid to which the outer insulation and inner insulation, respectively, are exposed to; R_{th}, k, and A are the total thermal resistance, thermal conductivity, and heat transfer area, respectively, of the insulation; X is the thickness of the insulation.

From the theory of heat transfer and with reference to the equation

$$R_{th} = R_o + R_1 + R_2 + R_3 + R_i \qquad (2.2)$$

where,

R_i and R_o are the convective thermal resistance of the fluid to which the inner insulation and outer insulation, respectively, are exposed to; R_1, R_2, and R_3 are the thermal resistance of the outer insulation, middle insulation, and inner insulation, respectively.

In the equation 2.2 above,

$$R_o = \frac{1}{h_o} \tag{2.3}$$

$$R_1 = \frac{X_1}{k_1.A_1} \tag{2.4}$$

$$R_2 = \frac{X_2}{k_2.A_2} \tag{2.5}$$

$$R_3 = \frac{X_3}{k_3A_3} \tag{2.6}$$

In the equations (2.3) to (2.6), h_i and h_o are the inner convective heat transfer coefficient and outer convective heat transfer coefficient, respectively; X_1, X_2, and X_3, are the thickness of the outer insulation, middle insulation, and inner insulation, respectively; A_1, A_2, and A_3, are the area of the outer insulation, middle insulation, and inner insulation, respectively; k_1, k_2, and k_3, are the thermal conductivity of the outer insulation, middle insulation, and inner insulation, respectively.

By substituting equations (2.2) to (2.6) into equation (2.1), the equation for the transfer of heat through the walls of the refrigerator becomes

$$q = \frac{(T_o - T_i)}{\frac{1}{h_oA_1} + \left(\frac{X}{kA}\right)_1 + \left(\frac{X}{kA}\right)_2 + \left(\frac{X}{kA}\right)_3 + \frac{1}{h_iA_3}} \tag{2.7}$$

3. METHODOLOGY FOR THE EXPERIMENTS

3.1 Construction of the Refrigerator

The refrigerator was constructed with a cooler, a condenser, a compressor, an evaporator, a fan, and a filter dryer. The cooler is made of 1.7 mm-thick plastic as its outer insulation, which serves as the outer wall of the refrigerator. The inner insulation of the refrigerator is 0.6 mm-thick polystyrene. Initially, the middle insulation of the refrigerator was 60 mm-thick styro foam. The styro foam was removed later and replaced with other insulations, which were expanded polyurethane foam, rigid polyurethane foam, fibre glass, and composite insulator (which is a combination of rigid polyurethane and fibre glass).

The construction of the refrigerator involved folding an evaporator into the required shape and then positioned it inside the 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 compressor was fastened to the plate provided for it. A portable fan was placed in front of the compressor to cool it. A filter dryer was attached to the discharge line of the condenser to prevent circulation of moisture along the refrigerant.

The specifications of the materials used for the fabrication of the refrigerator are shown in Table 3.1. The picture of the refrigerator and its plastic cooler are shown in Fig. 3.1 and Fig. 3.2 respectively. The isometric drawing of the refrigerator is presented in Appendix I.

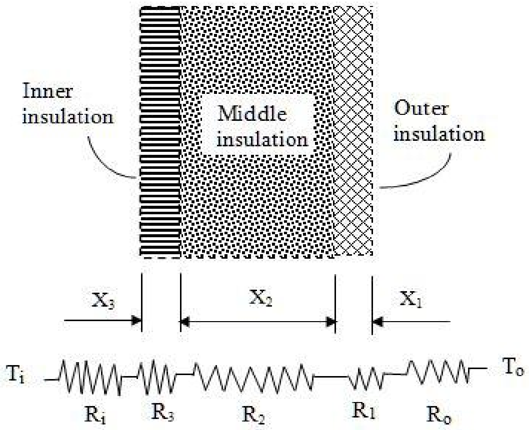

Fig. 2.1. Layers of insulation of the refrigerator's walls

Table 3.1 Specifications of the materials used for the fabrication of the refrigerator

S/N	Item	Description	Material	Quantity
1.	Angle iron	1.5 x 1.5 inches	Mild steel	One full length and half
2.	Flat bar	1.5 x 1.5 inches	Mild steel	Half length
3.	Castor	75 mm diameter	Aluminum and rubber	Four
4.	Round pipe	1.5 inches diameter	Galvanized pipe	$^{1}/_{6}$ of full length
5.	Refrigerating cooler	45 liters (Esikmo brand)	Plastic with insulation	1
6.	Compressor	Hermetically sealed	Mild steel	1
7.	Condenser	Air-cooled	Copper	1
8.	Evaporator	Shell type	Aluminum	1
9.	Fan	1000 rpm	Aluminum blade with electric coil	1
10.	Thermostat	Whirlpool bimetal defrost	Copper	1
11.	Dryer	HVAC-XF_154	Copper	1
12.	Wire	Single core 1.5mm^2	Copper	1
13.	Insulation materials	4 x 8 sheet (6 yards)	Expanded polyurethane foam, rigid polyurethane foam, styro foam, and fibre glass	6

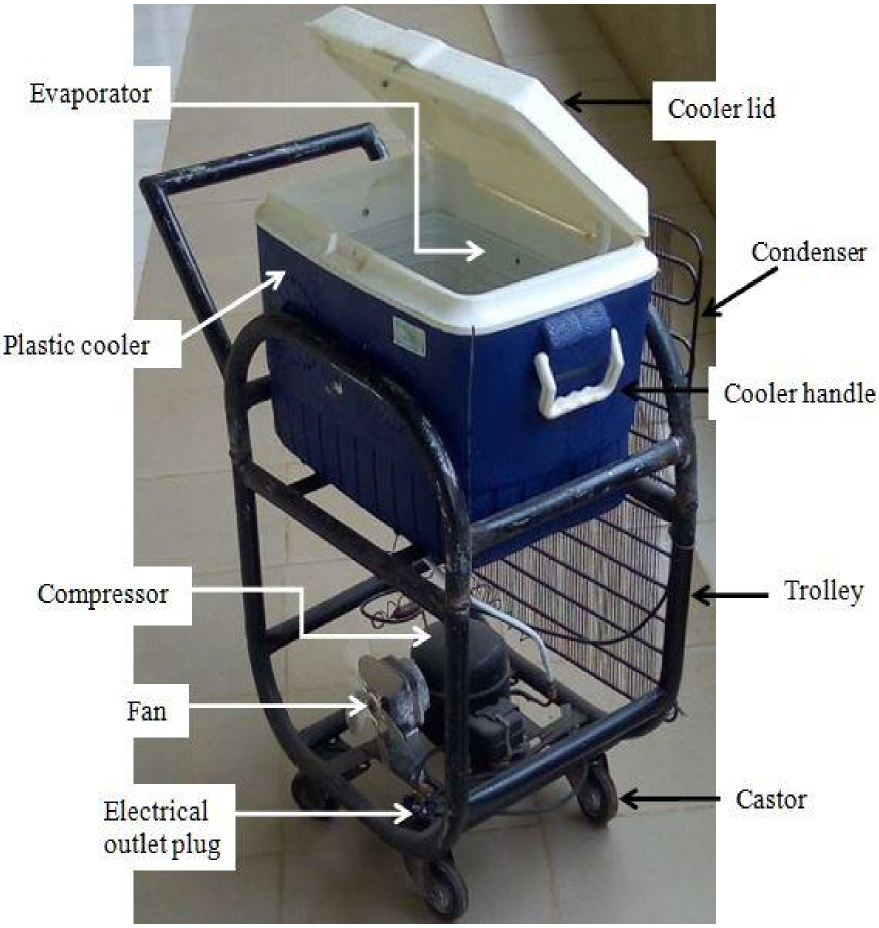

Fig. 3.1. Picture of the refrigerator

Fig. 3.2. Plastic cooler of the refrigerator

3.2 Procedure of the Experiments

The two different experiments which were conducted are presented in this section. They were energy consumption measurement experiment and reverse heat loss measurement experiment.

3.2.1 Experiments on energy consumption

In order to perform the experiments on energy consumption, the refrigerator was connected to a universal power meter, as shown Fig. 3.3.

The universal power meter, shown in Fig. 3.4, was connected to the refrigerator to measure its energy consumption. The meter has an LCD screen where the values of the energy measurement are displayed.

The refrigerator which has styro foam as inner insulation of its cooler was switched on for a period of one hour and the energy consumption was recorded. Also, the time taken for the experiment was recorded by a digital stop watch. Thereafter, the styro foam was removed and replaced in succession with other insulations, namely rigid polyurethane foam, expanded polyurethane foam, fibre glass, and composite insulations, for which the experiments were successively repeated.

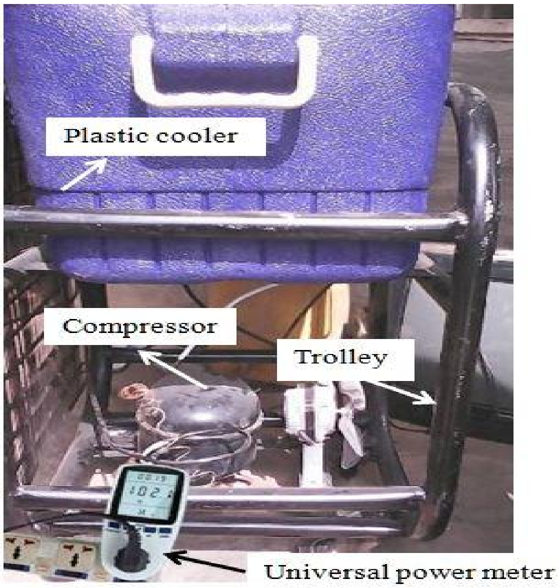

Fig. 3.3. Energy consumption measurement experiment

Fig. 3.4. Universal power meter

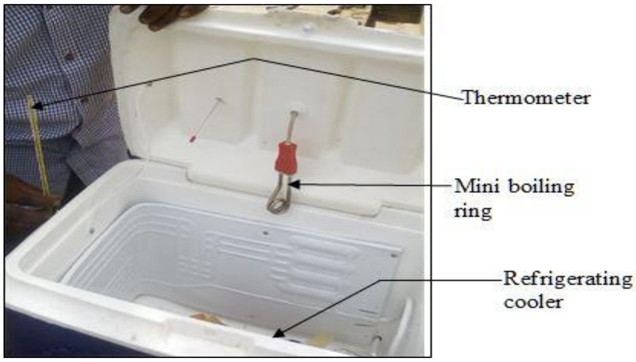

Fig. 3.5. Reverse heat loss measurement experiment

Fig. 3.6. Boiling ring

3.2.2 Experiments on reverse heat loss

Reverse heat loss in the refrigerator means that the refrigerator did not lose heat, but gained heat through a source of heat inside the refrigerator. The reverse heat loss measurement experiment was conducted to measure the heat flux in the refrigerator. Two thermometers were inserted into the cooler of the refrigerator with styro foam insulation to measure its inside and outside temperature. In addition, a boiling ring, which served as a heat source inside the cooler of the refrigerator, was placed inside the cooler, as shown in Fig. 3.5.The boiling ring is shown in Fig. 3.6 and the schematic diagram of the reverse heat loss measurement experiment is displayed in Appendix II.

The inner temperature (T_i) and outer temperature (T_c) of the cooler of the refrigerator were measured and recorded within an interval of thirty minutes. As in the case of energy consumption measurement experiment mentioned above, the styro foam insulation of the cooler was removed and replaced with different insulations (rigid polyurethane foam, expanded polyurethane foam, fibre glass, and composite insulations) and the experiment was repeated for each of the different insulations.

4. RESULTS AND DISCUSSION

In this section, the results of the experiments on energy consumption and heat flux of the refrigerator are discussed.

4.1 Energy Consumption for Different Insulations

The experimental results obtained for the energy consumption of the refrigerator are depicted in Table 4.1 and Fig. 4.1.

It is observed in Fig. 4.1 that the refrigerator with the expanded polyurethane foam consumed the highest amount of energy of 0.288 kWh/day. Not only that, the lowest amount of energy of 0.195kWh/day was consumed by the refrigerator with the combined rigid polyurethane and fibre glass insulations (that is, composite insulation). The energy consumed by the refrigerator with styro foam, rigid polyurethane foam and fiber glass insulations has an approximately the same value of 0.269 kWh/day. This means that the energy consumption of the refrigerator can be reduced by means of composite insulation.

In effect, a 2-star refrigerator, which is the refrigerator with composite insulation, has been able to be used in this work as a 3-star refrigerator to improve on energy consumption of the household refrigerator.

4.2 Heat Flux for Different Insulations

The results of the experiments conducted on the heat flux in the refrigerator are shown in Table 4.2.

In the Table 4.2, T_i and T_c are the inner and outer temperature, respectively, of the cooler of the refrigerator. The boiling ring, which was the heat source, was placed inside the cooler. Consequently, the inner temperatures of the cooler were higher than those of its inner temperature.

Table 4.1. Energy consumption of the refrigerator

S/N	Insulation material	Energy consumed (kW h)	Energy consumed (kWh/day)
1.	Styro foam	0.0112	0.268
2.	Rigid polyurethane foam	0.0113	0.271
3.	Expanded polyurethane foam	0.0120	0.288
4.	Fiber glass	0.0112	0.269
5.	Composite (Rigid polyurethane and fibre glass)	0.0081	0.195

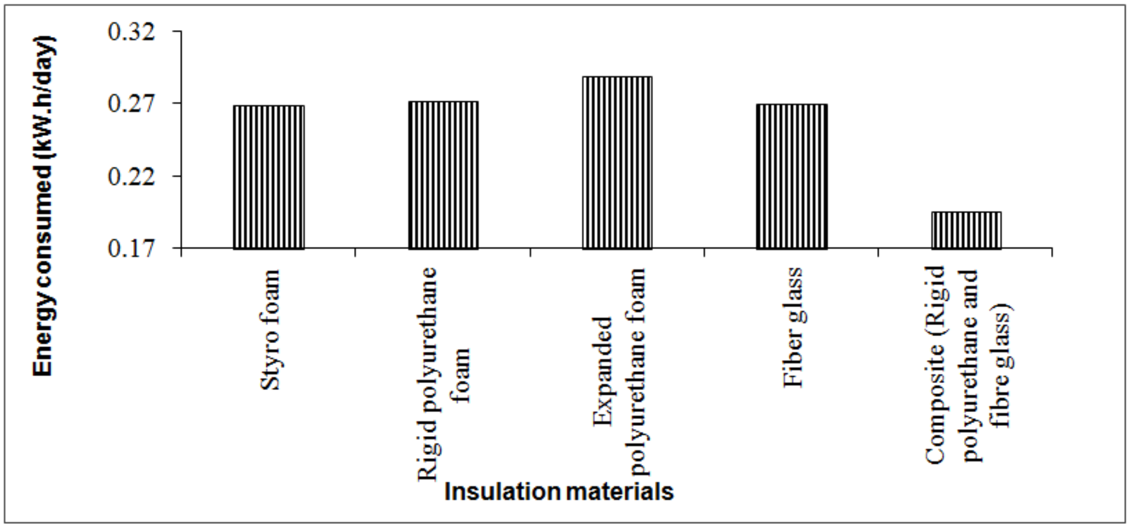

Fig. 4.1. Energy consumption of the refrigerator

Table 4.2. Heat flux in the refrigerator

S/N	Insulation material	Ambient temp	T(0.5h)		T(1hr)		T(1.5h)		T(2.0h)		T(2.5h)		T(3.0h)		Mean of T_i	Mean of T_c	Heat flux (kW/m^2)
		°C															
		(Ta)	T_I	T_C	T_I	T_C	T_I	T_C	T_I	T_C	T_I	T_C	T_I	T_C			
1.	Styro foam	28	72	15	101	22	135	30	152	35	160	40	179	40	133.17	30.33	0.309
2.	Rigid polyurethane foam	28	75	6	101	12	138	26	155	30	165	37	182	37	136.00	24.67	0.244
3.	Expanded polyurethane foam	28	70	48	99	57	130	65	150	68	162	70	180	70	131.83	63.00	0.651
4.	Fiber glass	28	73	12	102	25	135	31	154	37	160	42	180	42	134.00	31.50	0.318
5.	Composite (Rigid polyurethane and fibre glass)	28	71	4	100	8	137	10	155	15	161	20	180	20	134.00	12.83	0.130

It is revealed in Fig. 4.2 that the refrigerator with composite insulation has the least heat flux, which is 0.130 kW/m^2. Of all the insulations considered, the heat flux in the refrigerator with expanded polyurethane insulation is the highest with a value of 0.651 kW/m^2 and it is five times higher than that in the refrigerator with composite insulation. This indicates that the performance of the refrigerator with composite insulation is better than that which was insulated with expanded polyurethane foam. It also implies that of all the insulations considered, the performance of the refrigerator with composite insulation was the best from the point of view of retention of heat in the refrigerator.

4.3 Instantaneous Heat Flux for Different Insulations

The instantaneous heat flux in the refrigerator is shown in Table 4.3.

At 0.5hr interval of time, as represented graphically in Fig. 4.3, the instantaneous heat flux in the refrigerator with expanded polyurethane foam has the highest value of 1.371 kW/m^2, but the refrigerator with composite insulation has the lowest value of 0.111 kW/m^2. At 1.0hr interval, the refrigerators with composite insulation and expanded polyurethane foam insulation have the lowest instantaneous heat flux (0.08 kW/m^2) and highest instantaneous heat flux (0.584 kW/m^2), respectively. At interval of time of 1.5hr, 2.0hr, 2.5hr, and 3.0hr, the refrigerator with composite insulation has the lowest instantaneous heat flux and the refrigerator with expanded polyurethane foam insulation has the highest instantaneous heat flux.

4.4 Instantaneous Temperature for Different Insulations

The instantaneous temperature for reverse heat loss in the refrigerator is shown in Table 4.2 and it is depicted in Fig. 4.4.

As it can be seen in Fig. 4.4, the temperature difference between 0.5 hour and 1.0 hour intervals of time is 29°C, 26°C, 29°C, 29°C, and 29°C for the refrigerator with styro foam, rigid polyurethane foam, expanded polyurethane foam, fiber glass, and composite insulations, respectively. This is an indication that between these two intervals of time, the refrigerator with rigid polyurethane foam insulation had lowest temperature difference and, therefore, retained the highest temperature.

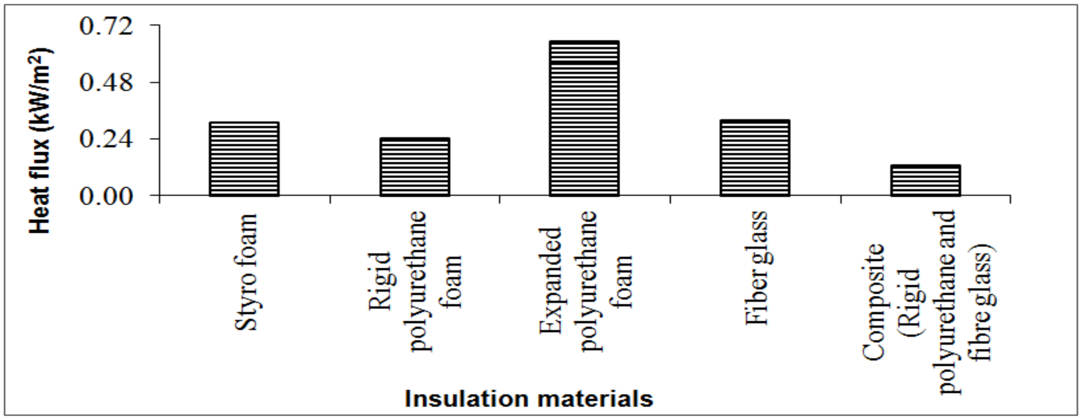

Fig. 4.2. Heat flux in the refrigerator

Table 4.3. Instantaneous heat flux

S/N	Interval of time, t (hr)	0.5h	1h	1.5h	2h	2.5h	3h
	Insulation material			Heat flux (kW/m^2)			
1.	Styro foam	0.405	0.219	0.223	0.231	0.250	0.224
2.	Rigid polyurethane foam	0.150	0.119	0.189	0.194	0.225	0.204
3.	Expanded polyurethane foam	1.371	0.584	0.502	0.455	0.433	0.390
4.	Fiber glass	0.316	0.246	0.230	0.241	0.263	0.234
5.	Composite (Rigid polyurethane and fibre glass)	0.111	0.080	0.073	0.097	0.124	0.121

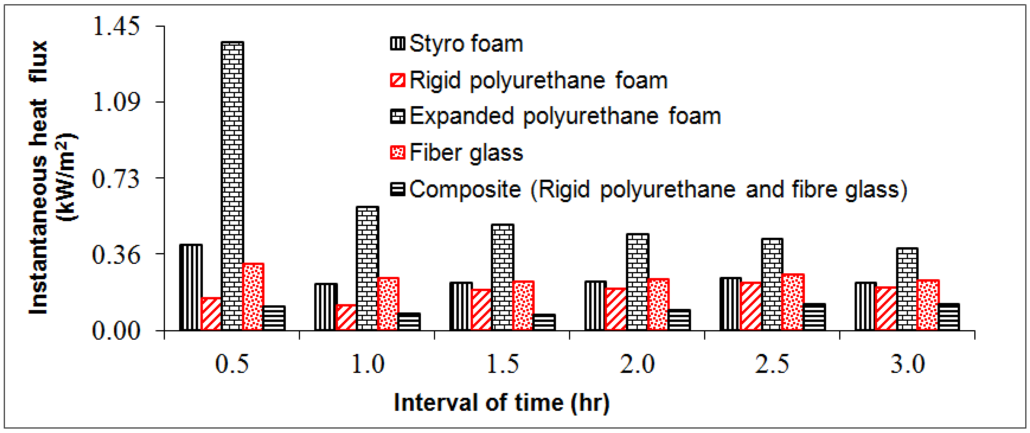

Fig. 4.3. Instantaneous heat flux in the refrigerator

Table 4.4. Instantaneous temperature

S/N	Time, t (hr)	0.5h	1h	1.5h	2h	2.5h	3h
	Insulation material			**Temperature (°C)**			
1.	Styro foam	72	101	135	152	160	179
2.	Rigid polyurethane foam	75	101	138	155	165	182
3.	Expanded polyurethane foam	70	99	130	150	162	180
4.	Fiber glass	73	102	135	154	160	180
5.	Composite (Rigid polyurethane and fibre glass)	71	100	137	155	161	180

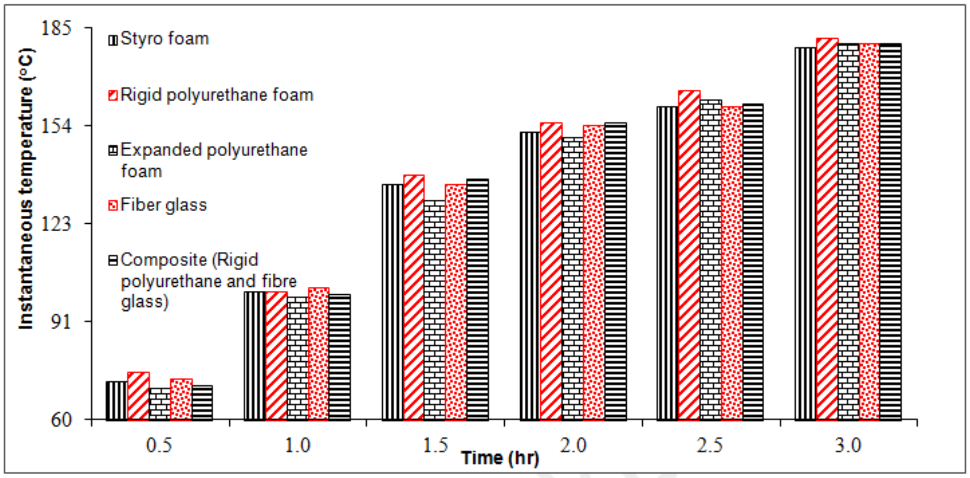

Fig. 4.4. Instantaneous temperature in the refrigerator

Between 1.0 hour and 1.5 hour intervals of time, the refrigerator with expanded polyurethane foam insulation had lowest temperature difference of 31°C and, hence, retained the highest temperature. In between 1.5 hour and 2.0 hour intervals of time, the refrigerator with rigid polyurethane foam insulation had lowest temperature difference of 17°C; this made it to retain the highest temperature between those intervals. For the case of the period between 2.0 hour and 2.5 hour intervals of time, and between 2.5 hour and 3.0 hour intervals of time, the refrigerators with composite insulation and styro foam insulation, respectively, had the lowest temperature difference of 6°C and 19°C, respectively. Thus, they retain the highest temperature at those respective intervals of time.

5. CONCLUSIONS

This work provides manufacturers of refrigerators with means of improving on energy consumption of household refrigerator. Having conducted the experiments, the conclusions therein are presented below:

i. A household refrigerator was constructed and improvement on its energy consumption was examined.

ii. Different insulation materials, namely rigid polyurethane foam, expanded polyurethane foam, styro foam, fibre glass, and composite insulations (which is a combined rigid polyurethane and fibre glass insulation) were used in succession for the cooler of the refrigerator to perform the experiments on energy consumption, heat flux, and instantaneous temperature.

iii. The results obtained from the experiments revealed that of all the insulations considered, the refrigerator with composite insulation consumed the lowest amount of energy and also had the highest capacity to retain heat.

iv. Overall, there was improvement on energy consumption of the refrigerator by means of the composite insulation.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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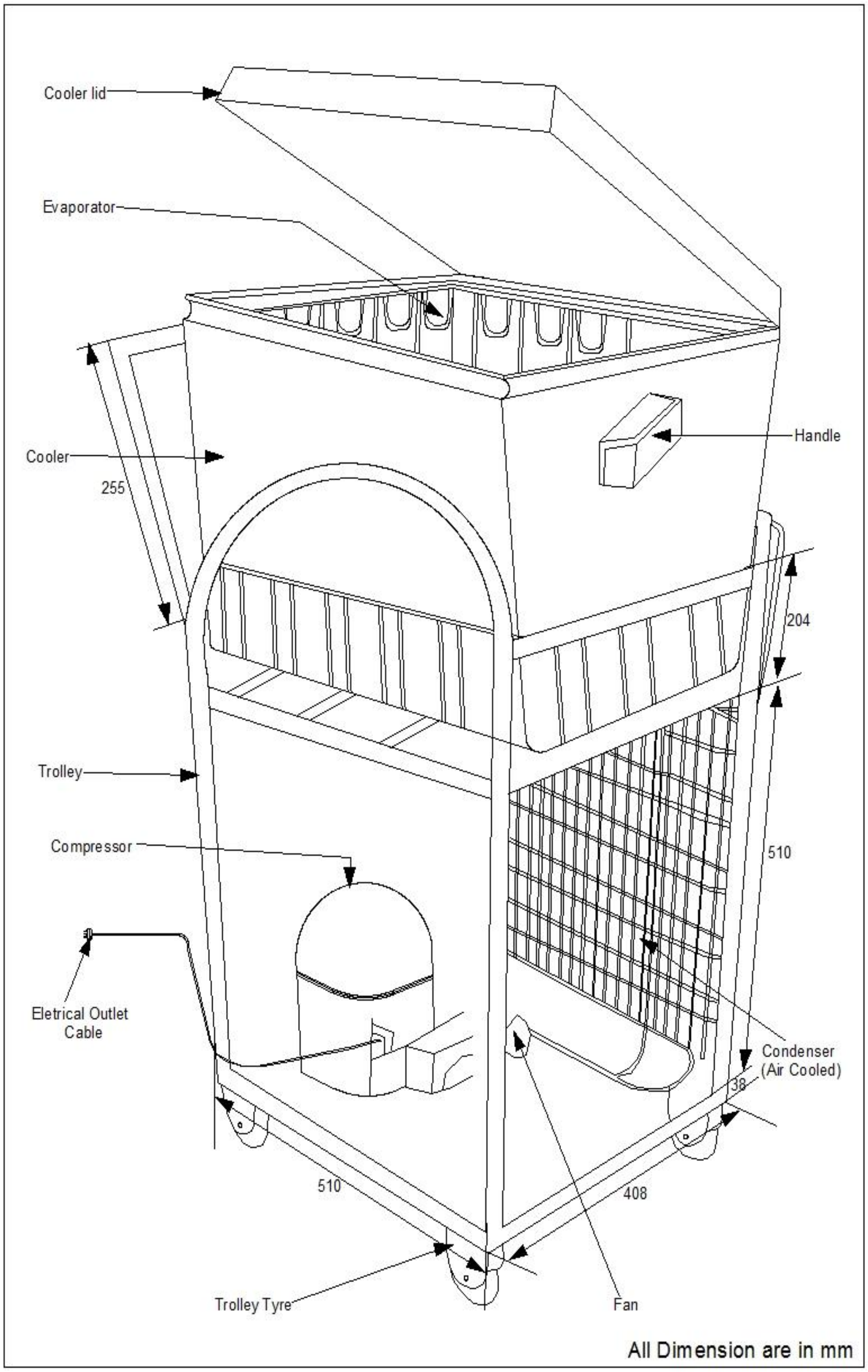
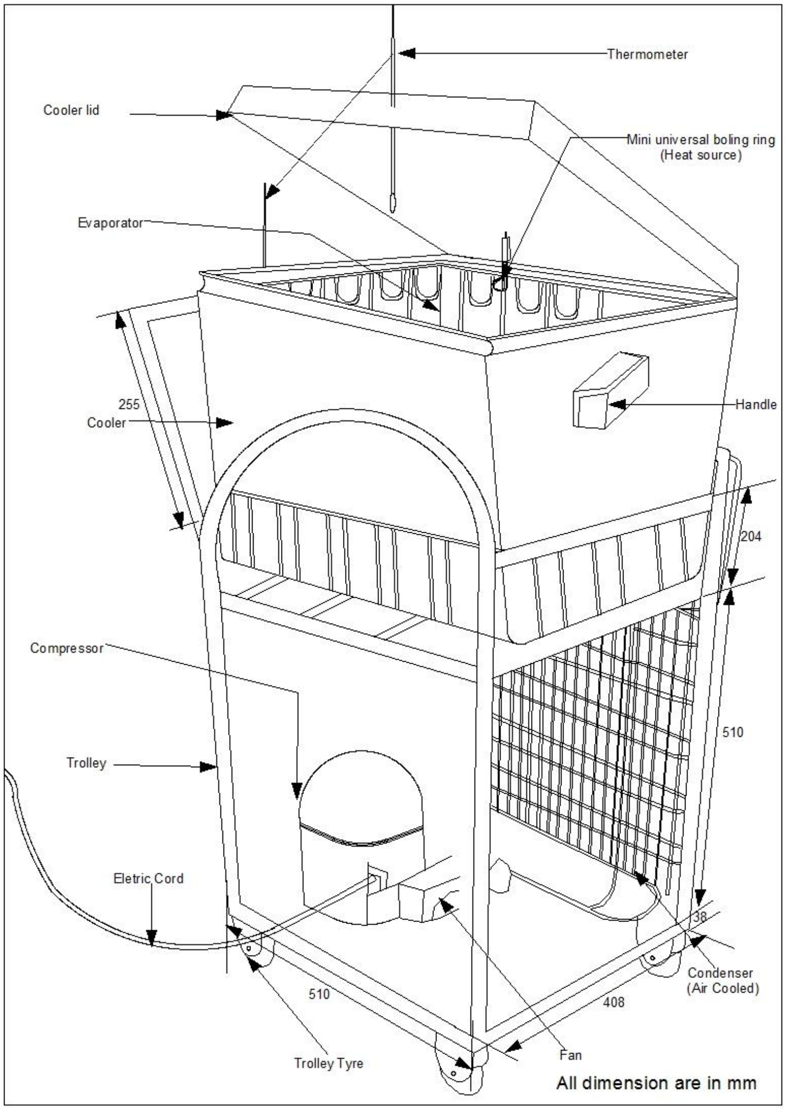
APPENDICES



Appendix I. Isometric drawing of the refrigerator



Appendix II. Schematic diagram of the reverse heat loss experiment

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