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Development of a 1 Kw Prototype Kerosene-Powered Vapour Absorption Refrigerator for Domestic Refrigeration Applications

Taiwo Semiu Amosun[1*] and Paul Omoniyi Kaffo[2]
[1]Department of Mechanical and Mechatronic Engineering, Federal University Otuoke, Nigeria
[2]Department of Mechanical Engineering, Ogun State Institute of Technology, Igbesa, Nigeria
*Corresponding author: amosunts@fuotuoke.edu.ng

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Abstract
Vapour absorption is an attractive method of utilizing low grade energy directly for cooling. This work attempts to develop a kerosene-powered vapour absorption refrigerator for domestic refrigeration applications. It is designed to comprise five major components: evaporator, absorber, generator, pump and condenser and their capacities were determined to be 80W, 350W, 180W, 20W and 90W respectively. The refrigerator is a medium-size one and is designed for domestic purposes only. It uses lithium bromide and water and water combination. Parts were designed, fabricated and assembled accordingly. Finally, the performance test was carried out. The refrigerator was able to achieve an evaporative temperature of 7°C and had theoretical coefficient of performance (COP_t) and experimental (COP_e) of 0,25 and 0.24 respectively. It also takes 35 minutes to cool 1litre of water at ambient temperature to 0oC. The operating temperature of the refrigerator is between 7°C to 43°C.

Keywords: *Vapour; Absorption; Generator; Evaporator; Condenser*

Abstrak
Penyerapan uap merupakan metode yang menarik dalam memanfaatkan energi tingkat rendah secara langsung untuk pendinginan. Penelitian ini mencoba mengembangkan lemari es penyerap uap menggunakan tenaga minyak tanah untuk aplikasi pendinginan rumah tangga. Sistem Ini dirancang yang erdiri dari lima komponen utama diantaranya : evaporator, penyerap, generator, pompa dan kondensor dan kapasitasnya yang ditentukan masing-masing sebesar 80W, 350W, 180W, 20W dan 90W. Kulkas berukuran sedang dan dirancang untuk keperluan rumah tangga. Sistem ini menggunakan lithium bromida dan air serta kombinasi air . Bagian-bagiannya dirancang, dibuat, dan dirakit sesuai kebutuhan. Akhirnya dilakukan tes kinerja. Kulkas mampu mencapai suhu penguapan 7°C dan memiliki koefisien kinerja teoretis (COP_t) dan eksperimental (COP_e) masing-masing sebesar 0,25 dan 0,24. Dibutuhkan waktu 35 menit untuk mendinginkan 1 liter air pada suhu sekitar hingga 0°C. Suhu pengoperasian lemari es antara 7°C hingga 43°C.

Kata Kunci: Uap; Penyerapan; Generator; Alat Penguap; Kondensator

1. Introduction

Vapour absorption refrigeration (VAR) method is a preferable option in industrial applications where heat that would otherwise be wasted serves as a heat source for the absorption machine. Low grade energy such as solar or fossil fuel is used for refrigeration in VAR systems, which is less expensive to generate than vapour compression refrigeration systems. Apart from being advantageous from this perspective of energy use, such systems also provide other advantages over vapour compression. For example, the system gives quite running with no vibration and their silent operation is unmatched when compared to the latter systems (Liu and Wang, 2018). VAR systems are ideal for regions where low-cost thermal energy is accessible. As absorption units become more popular not only in industry but also on a domestic level, their continuous development becomes more important. This will enable better improvement in their performance characteristics. Many research works had been carried out by researchers in the field of refrigeration technology especially in the area of vapour absorption refrigeration systems focused on improving the efficiency of VARs. One of the ways this is being done is by using alternative working fluids. For instance, Chen and Wang (2019) performed a comprehensive analysis of a vapor absorption refrigeration system for domestic refrigeration applications. Khan et al (2019) also designed and analysed the performance of a kerosene-fired vapor absorption refrigerator using ammonia-water system. Kim (2017) examined the performance of a vapor absorption refrigeration system using propane as the refrigerant. Mukhopadhyay (2016) performed a comprehensive review on kerosene-based vapor absorption refrigeration systems. A detailed performance analysis of a vapor absorption refrigeration system using a salt hydrate as the working fluid was also carried out by Zou and Huang, 2016. The researchers found that the system had a high COP and that it was able to operate effectively at low temperatures. This research demonstrates the potential for VARS to be developed using low-cost and sustainable materials, which could make them more accessible to a wider range of users. Li et al. (2016) investigated the use of a mixture of lithium bromide and water as the working fluid in a VARS. It was found out that the use of this mixture led to an increase in the coefficient of performance (COP) of the system, which is a measure of its efficiency. Osta-Omar and Micallef (2016) developed a mathematical model for thermodynamic analysis of an absorption refrigeration system equipped with an adiabatic absorber using a lithium-bromide/water pair as the working fluid. Micallef and Micallef (2010) proposed a mathematical model for a vapour absorption refrigeration unit employing either water-lithium bromide or ammonia-water refrigerant-absorbent pairs. Chen (2018) also presented a thermodynamic analysis of a kerosene-powered vapour absorption refrigeration system. Pan and Wang (2018) evaluated the performance analysis of a vapour absorption refrigeration system using waste heat from an industrial process. This work developed a kerosene-powered vapour absorption refrigeration system and used the working temperatures of the generator, adiabatic absorber, condenser, evaporator as input data to evaluate the coefficient of performance of the system.

Working Principle of Vapour Absorption Refrigeration System

Absorption cooling dissolves a vapour in a liquid, pumps the solution to higher pressure in the generator and then uses heat to evaporate working fluid. The working fluid in an absorption refrigeration system is a binary solution consisting of refrigerant and absorbent. In Figure 1, two evacuated vessels are connected to each other. The left vessel contains liquid refrigerant while the right vessel contains a binary solution of absorbent/refrigerant. The solution in the right vessel will absorb refrigerant vapor from the left vessel causing pressure to reduce. While the refrigerant vapor is being absorbed, the temperature of the remaining refrigerant will reduce as a result of its vaporization. This causes a refrigeration effect to occur inside the left vessel. At the same time, solution inside the right vessel becomes more dilute because of the higher content of refrigerant absorbed. This is called the "absorption process". Normally, the absorption process is an exothermic process, therefore, it must reject heat out to the surrounding in order to maintain its absorption capability.

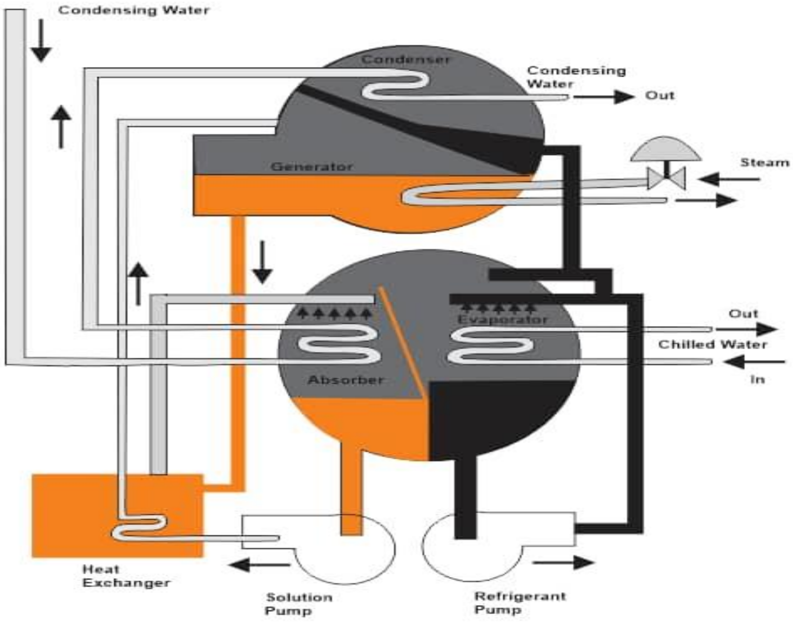

Figure 1. Working of Vapour Absorption Refrigeration System.

2. Method

This single stage kerosene–powered vapour absorption refrigeration system that uses Lithium-bromide and water combination is designed to possess a refrigeration capacity of 1kilowatt and comprise five major components: evaporator, absorber, generator, pump and condenser. *In operation, the system employs two fluids, namely the refrigerant and the absorbent, as its principal working fluids.* The selection of material that best suits the work was duly considered bearing in mind, the desired engineering properties of the material and their effect on the environment and the man. The kerosene refrigerator is capable of converting the chemical energy of volatile substance (kerosene) to cooling energy for the purpose of cooling drinks and food items such as bread, cake etc. The system operates at an evaporator temperature of 3^{o}C and a condensing temperature of 43^{o}C. Fabrication of this kerosene-powered refrigerator was done at the Engineering Workshop of the Faculty of Engineering, Federal University Otuoke, Bayelsa, Nigeria. Based on the design specifications, pressurized water tank stands, refrigerating stand, and kerosene tank stand were fabricated and assembled. The major factors that affect the sufficiency of a vapour absorption refrigeration system are the evaporating temperature, the condensing temperature, the type of refrigerant used, the type of equipment used such as evaporator, pump, generator, absorber, etc. Different design factors were considered and taken into consideration standard refrigerator sizes. The standard refrigerator sizes range from 0.6096 to 1.0160 metres in width, 1.5748 to 1.8288 metres in height and 0.7366 to 0.9144 metres in depth. Areas are determined using the equation (1).

$$\text{Area} = \text{Length} \times \text{Width} \tag{1}$$

Thus the area of the refrigerator was obtained from equation (1) to be 0.32 m^2, Similarly, volumes were determined using equation (2).

$$\text{Volume} = \text{length} \times \text{width} \times \text{height} \tag{2}$$

Hence, volume of the kerosene tank = 0.06 m^3, and pressurized water tank = 0.09 m^3. The components are attached to a frame made of 18 mm thick plywood frame shown below. The generator is clamped by two 150mm mild steel strips with the help of 25 mm screws firmly. The absorber is also clamped with a single similar 150mm mild steel strip which is screwed to the frame and a support at the bottom. The condenser is similarly fixed to frame and the frame is cut behind the condenser to enhance the convection heat transfer from the condenser. The evaporator is supported at its base with a wooden frame. The pump is screwed to the frame with two small screws. The heating coil is fixed to the frame below the generator.

2.1. Design Analysis

a. Selection of Refrigerant Absorbent Pair

Lithium-bromide and water combination is adopted for this work. In this combination, water is the refrigerant and lithium-bromide is the absorbent. Since the freezing temperature of water is 0^{o}C, a lithium-bromide/water absorption system is only limited to applications where the least temperature in the system is above 0^{o}C. Hence, the choice of the refrigerant/absorbent pair selected is dependent primarily on the condenser and evaporator temperatures. Other performance characteristics considered during selection of refrigerant/absorbent pair are high solubility of the refrigerant in the absorbent, less volatility of the absorbent than the refrigerant, Strong affinity of the absorbent for the refrigerant vapour, refrigerant possessing high latent heat of vaporization. Finally, the pair of the two working fluids selected are non-toxic, non-irritant, non-flammable and possess adequate stability against corrosion and decomposition.

A desirable refrigerant should not give rise to either unduly high condenser pressure or very low evaporator pressure. Having desired and determined the refrigerant to be used in the condensing and evaporating temperatures respectively, the pressures are directly obtained from the table for the saturation pressures corresponding to these two temperatures.

b. Determination of Flow Rate

In determining the flow rate of refrigerant, the capacity of the refrigerator, the cooling effect and temperature of operation measured at the evaporator and condenser are required. Refrigerant load is commonly expressed in the unit of tons of refrigeration. Figure 2 depicts the Ph diagram for the system.

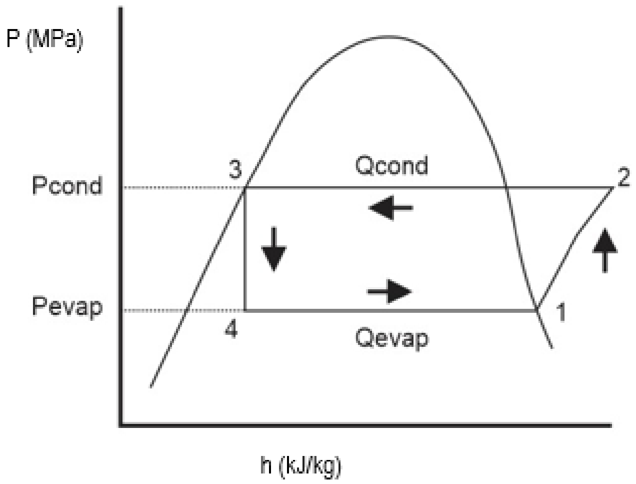

Figure 2. Ph Diagram of the System.

From the thermodynamic table of properties: h_1 = 178.73kJ/kg, h_2= 206.5 kJ/kg, h_3= h_4 = 64.49kJ/kg, Assuming no sub-cooling of the liquid leaving the evaporator, refrigerating effect = h_1- h_2= h_1- h_2 = 178.73 – 64.59 = 114.4 kJ/kg

$$M_f = \frac{B}{\epsilon} = 18.924\ kg/min = 0.3154\ kg/s \quad (3)$$

Where M_f , B, ϵ are mass flow rate of the refrigerant, total cooling load and refrigerating efficiency. The ton of refrigeration is sometimes defined on the basis of long ton or taken equal to a cooling water of one kilocalorie per second. Figure 3 shows the schematic diagram of the system.

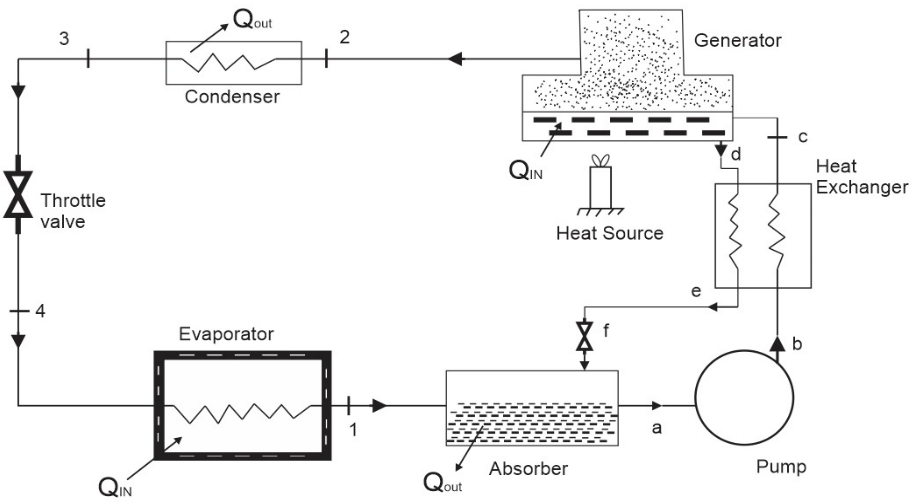

Figure 3. Schematic diagram of the kerosene-powered vapour absorption refrigerator.

c. Condenser

Condenser removes the heat from the hot vapor refrigerant. A household refrigerator's condenser size is normally determined by considering some variables, including the necessary cooling capacity, heat transfer characteristics, and efficiency concerns. It is designed to allow the cooling medium to maintain effective temperature difference over all areas of the transfer concerns. The refrigerant employed the system which generally governs the kind of medium employed for cooling the condenser which in turn limits the selection of condenser type. The heat rejected by the condenser is calculated by equation (4) in line with the method used by Prash et al (2017).

$$Q_c = m_f (h_2 - h_3) = 0.45 \text{ kw} \tag{4}$$

Where Q_c, m_f, h_2 and h_3 are heat rejected by the condenser, mass flow rate ($0.3154\ kg/s$) and enthalpies at the inlet (64.49kJ/kg) and exit (206.5 kJ/kg) of the compressor. The inlet temperature of air is 31^{0}C while the exit temperature of air is 38^{o}C. Air is used as the cooling medium. Considering the number of Condenser tubes (n) = 10, Length of each tube (l) = 0.4 m and the diameter of the condenser = 0.002 m. The effective area of condenser is evaluated with the aid of equation (5) and in line with the method used by Prash et al (2017).

$$\mathrm{A_c} = \mathrm{n\pi dl} = 0.025\ \mathrm{m^2} \tag{5}$$

Where A_c, n, d and l are area of the condenser, number of tubes (10), diameter of the condenser (0.002 m) and length of each tube (0.4 m). The pipe was bent into several turns with the help of 180 degrees bending tool to make it compact and also to enhance the drop in pressure which eliminates the requirements of any throttling device such as a capillary tube.

d. Evaporation

This is another important part within which cooling and freeing takes place. And it is located within the low pressure side of which the refrigerant vaporizes in it as it absorbs heat. The direct dry type of evaporator is used based on the following factors: The cost requirement, fabrication procedure, material availability, size of unit. The surface area of evaporator is derived from the heat transfer formula. A 6mm thick glass container (240 x 150 x 60 mm) was ordered. This container is used as an evaporator cabin which is filled with water and the water is expected to be cooled to 10 degrees centigrade as a result of the refrigeration cycle. The same 6 mm mild steel tube is wounded in the form of a coil and sent through this evaporator cabin. The effective area of evaporator is calculated with the aid of equation (6) as given below:

$$A_e = n\pi dl = 0.1257\ m^2 \tag{6}$$

Where A_e, n, d and l are effective area of the evaporator, number of tubes (10), diameter of the evaporator (0.01 m) and length of the tube (0.4 m) Similarly, heat extracted by the evaporator is evaluated with the aid of equation (7) in line with the method used by Prakash et al (2017).

$$Q_e = m_f\,(h_1 - h_4) = 0.36kW \tag{7}$$

Where Q_e , m_f , h_1 , h_4 are heat extracted from the evaporator, mass flow rate of the refrigerant (0.3154 kg/s), and enthalpies at the inlet (64.49kJ/kg) and exit (178.73kJ/kg) of the evaporator.

e. Generator

A 3, 000 cm^3 mild steel cylinder which is usually used to carry refrigerants is used as generator. Drilling of four holes of diameter 1.5cm at the specified spots for the inlet and outlets and one hole of diameter 2.5 cm for the connection of thermocouple was performed on a vertical drilling machine. Arc welding was used to weld four 1.5cm and one 2.5 cm mild steel, internally threaded nuts which get mated with the bronze adapters for inlet and outlet connections and one for the thermocouple. From the first law of thermodynamic, in any thermodynamic process, there is no gain or loss of energy to each process of the cycle. It should be noted, in applying the steady flow energy equation the kinetic and potential energy terms were omitted. This is almost justifiable because the velocity of flow is slow, to avoid undesirable pressure loses and variation in length noting the system is small for heat balance in the system and the heat rejected in the condenser. Heat supplied is assumed to be uniform. Using energy balance for the generator, the quantity of heat supplied to the generator is given by equation (8) in line with the method used by Donald and Khandwawala (2014).

$$Q_g = \text{Heat added to generator} = mc\theta = 1.44 \text{ kW} \tag{8}$$

Where Q_g, m, c and θ are the quantity of heat supplied, mass of kerosene (2.25 kg), specific heat capacity of kerosene (2.01 kJ/kgk) and temperature difference between final and initial temperatures (32 K).

f. Absorber

A 3,000 cm^3 mild steel cylinder similar to the generator is also used for the purpose of absorber. Drilling of three holes of diameter 1.5 cm at the specified spots for the inlet and outlet was performed on a vertical drilling machine. Arc welding was done to weld four 1.5cm mild steel plates, internally threaded nuts which get mated with the bronze adapters for inlet and outlet connections. Heat interaction occurs across the heat exchanger through the absorber resulting in a decrease in temperature of the evaporator chamber. Heat rejected in the absorber is evaluated with equation (9) as used by Prash et al (2017) :

$$Q_a = m_f\,(h_a - h_1) = 0.852kW \tag{9}$$

Where Q_a , m_f , h_1 , h_a are heat rejected from the absorber, mass flow rate of the refrigerant (0.3154 kg/s), and enthalpies at the inlet (178.73kJ/kg) and exit (448.91kJ/kg) of the absorber.

g. Design for Pressurized Kerosene Tank

The design and construction of atomized kerosene compartment showed Figure 4 is made of three main parts, namely; (a) Chamber (b) The insulator, and (c) the casing. Key design factors were considered in the selection of materials for the three main parts of pressurised kerosene tank to enhance its effectiveness, reliability, stability, workability, and sustainability. Some other components which form part of the atomized kerosene compartment are standard parts that are readily available in the market. It was found that buying them is cheaper than producing them in-house. These components include; valve, pipes, pneumatic pump, lock, hinge, galvanized steel pipe, hoist, nipple, and door handle. The kerosene tank is a vessel that has a rectangular shape and the determination of the volume of the tank determined using equation (10).

$$V = lwh = 0.5958 \text{ m}^3 \quad (10)$$

Where V, I, w and h are the volume (m^3), length (0.62m), width (0.31m) and height (0.31m) of the kerosene tank respectively. The volume of the pressurized water tank is large enough to avoid constant refilling during the process.

h. The Design of Burner

The volume of the burner is given in equation (11).

$$V = \pi r^2 h = 0.002061 \text{m}^3 \quad (11)$$

Where V, r and h are the volume (m^3), radius (0.04 m) and vertical height (0.41 m) of the burner respectively. Also, the surface area from the analysis is given in equation (12).

$$S = 2\,\pi r\,(h + r) = 0.00113 \text{ m}^3 \quad (12)$$

Where S, r and h are the surface area (m^2), radius (0.4 m) and height (0.41m) of the burner.

i. Material Selection for Insulation

Asbestos, Polystyrene, Glass fibre are used as insulators based on the following requirements for insulation: strength, fire proof, Low thermal, conductivity, Performance, Light, weight and Water repellant.

j. Design for the Glass Fibre

From the design analysis, the area of the glass fibre selected is given in equation (13).

$$A = lw = 0.005551\ m^3 \quad (13)$$

Where A, l and w are the area (m^2), length (0.91m) and width (0.61m) of the glass fibre. Also, the volume of the glass fibre used is given in equation (14).

$$V = lwh = 0.0027755\ m^3 \quad (14)$$

Where V, l, w and h are the volume (m^3), length (0.91m), width (0.61m) and height (0.005) of the glass fibre.

k. Design for the Plywood

The area of the plywood selected is evaluated in equation (15).

$$A = lw = 0.005551\ m^3 \quad (16)$$

Where A, l and w are the area (m^2), length (0.91m) and width (0.61m) of the glass fibre. Also, the volume of the glass fibre selected is given in equation (17)

$$V = lwh = 0.0005551 m^3 \quad (17)$$

l. Design for Pipes

The size of pipe used throughout the system is ¼ th inch (6.35 mm), mild steel pipe. The volume of the galvanized pipe linking kerosene tank to the burner is given in equation (18).

$$V = \pi d^2 l/4 = 0.003676\ m^3 \quad (18)$$

Where V, d and l are volume (m^3), diameter (0.02m) and length (1.17m) of the galvanized pipe. Table 1 presents a summary of the materials selected for the construction of three main sections of atomized kerosene compartment.

Table 1. Materials Selection for the constructed Component Parts of Atomized Kerosene Compartment.

S/N	Components	Materials Selected	Reason
1.	The chamber	Mild Steel	High thermal conductivity, Minimum heat loss, toughness, low cost, availability
2.	Insulators	a. Asbestos	Low thermal conductivity, low cost, suitability
		b. Polystrene	Low thermal conductivity, low cost, suitability
		c. Glass fibre	Low thermal conductivity, low cost, suitability
3.	Casing	Mild Steel	High Toughness, low cost, good tensile strength.

m. The Selection of Pump

A special purpose 20 w dc pump used in air-conditioning equipment is used for this cycle. The purpose of this device is to pump the solution which is strong in water from the absorber to the generator. This is the only mechanical device being used in the whole system.

n. Capillary Tube

The capillary tube is employed as a throttling device on a small commercial and domestic refrigerator unit only. It is a small diameter tube that forms a permanently open artery between the high and side of the system. It is necessary to design the capillary tube length or mass flow rate for refrigerant. Equation (19) was used to determine the size of the capillary tube.

$$Q = F(P_2 - P_1) \tag{19}$$

o. Coefficient of Performance

The coefficient of performance is the ratio of useful cooling provided to work required. It is the performance of a refrigerating system. Higher COPs equate to lower operating costs. Thus neglecting work done by pump the theoretical COP_t of the system is evaluated by equation (20).

$$COP_t = \frac{refrigerating\ effect}{network\ input} = \frac{Q_e}{Q_g} = 0.25 \tag{20}$$

Where Q_e $(0.36\ kW)$ and Q_g $(1.44\ kW)$ are the heat extracted by the evaporator and heat added to the generator.

Figure 4. Isometric view of the prototype kerosene-powered vapour absorption refrigerator.

3. Results and Discussion

The experiments were carried out in a test room where the ambient temperature and humidity were almost maintained constant and recorded (32°C ± 2 °C, and 50 – 60% RH). The temperatures of evaporator and condenser with the help of thermocouple installed in the experimental setup. Experimental COP_e is then calculated from the measured temperatures as shown in Table 2 below. Thus, the average experimental COP_e is 0.24 which is very close to the value obtained for theoretical COP_t that is, 0.25.

Table 2. Results obtained during performance testing by cooling 1000 cm^3 of water from Ambient temperature to 0°C.

No.	Time (minutes)	Refrigeration chamber temperature (°C) Ambient	Condensing temperature Tc (°C)	Generator temperature (°C)	Evaporating temperature Te (°C)	Experimental $\mathbf{COP_e}$
1.	0	0	40.2	30.0	10.0	0.33
2.	15	16.0	40.2	30.5	9.0	0.29
3.	30	14.0	42.4	31.0	8.9	0.29
4.	45	10.9	42.4	31.0	7.2	Ŏ0.25
5.	60	9.9	42.4	31.0	7.5	0. 25
6.	75	9.5	43.1	31.0	6.7	0.22
7.	90	8.7	43.1	32.0	6.7	0.21
8.	105	7.7	44.7	32.0	6.7	0. 21
9.	120	7.6	44.7	33.0	6.0	0.18
10.	135	6.6	44.7	33.0	6.0	0.18
11.	150	6.6	44.8	33.0	6.0	0. 18
$\bar{X}$	76	8.9	42.97	31.6	7.3	0.24

Similarly, Figure 5 shows temperature levels at different stages of cooling. It depicted condensing, absorber, evaporating and refrigeration chamber temperatures at different time intervals. These temperatures continued to increase until they reached the maximum and then remained constant.

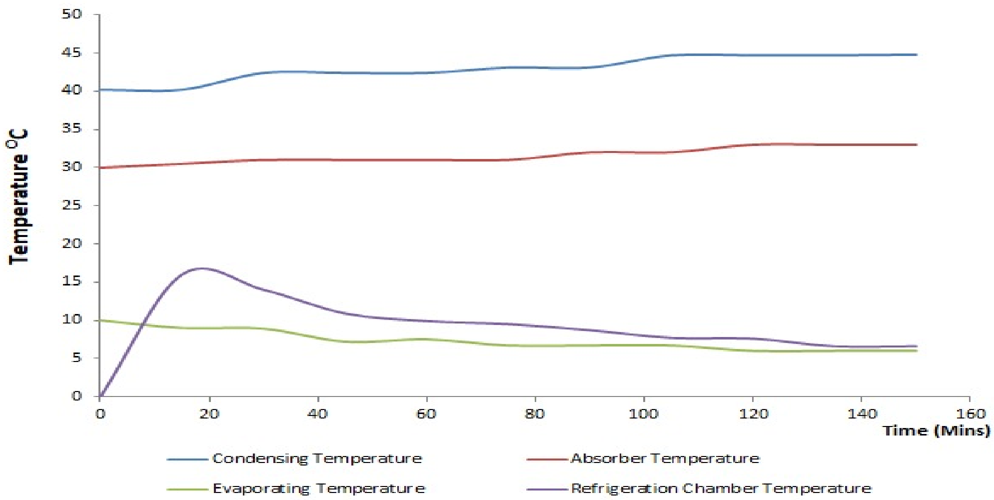

Figure 5. A graph showing the temperature levels at different stages of cooling.

Figure 6 also showed the value obtained experimentally for COP at different time interval. The maximum experimental COP obtained being 0.24.

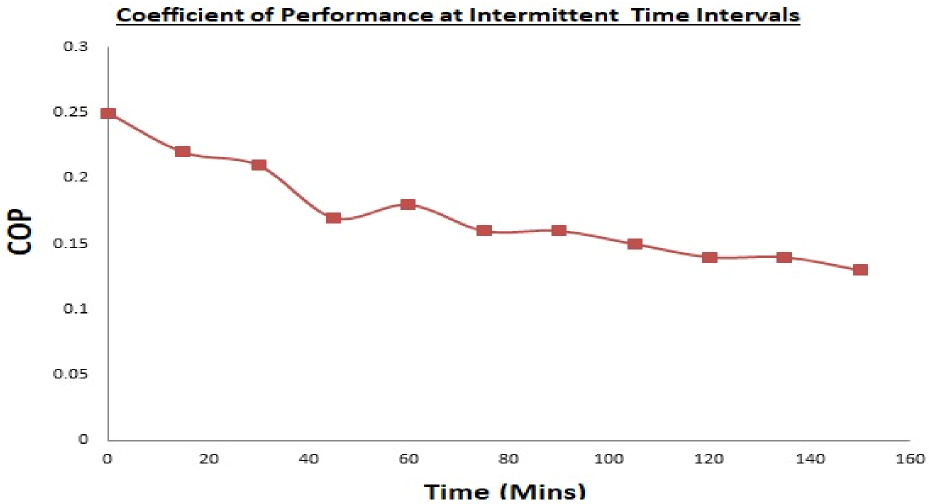

Figure 6. Coefficient of Performance at Intermittent Time Interval

4. Conclusion

A prototype of a kerosene powered absorption refrigerating system that operates within evaporating and condenser temperatures of 7.3 and 43^{0}C, respectively was developed and its performance evaluated. The theoretical $\mathrm{COP_t}$ of the system is evaluated to be 0.25 while the experimental $\mathrm{COP_e}$ of this refrigerator is found to be 0.24. This value is similar to the ones previously obtained by other researchers in vapour absorption refrigeration systems. For instance, Prash et al, 2017 obtained COP of 0.42 for their design which is about two times higher in size and capacity when compared to this design. It can be concluded that the system was functional with COP of 0.25 and can be used for domestic applications.

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