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Development of a Combustible solid waste powered vapour absorption Refrigerator

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ABSTRACT

The electricity crisis, food storage has become very expensive as individuals as well as producers need to pay a lot of money to run generators to power refrigerators. In order to address the aforementioned problem an alternative means of energy source would be required. This study aims to reduce the problem encountered in refrigeration by using vapour absorption refrigeration (VAR) powered by combustible solid waste. A combustible waste refrigerator was designed and fabricated. The combustible vapour absorption refrigerator uses ammonia as its refrigerant, and water is used as the absorbent. The temperatures of the evaporator, generator and condenser were measured and recorded periodically. The performance of the system was evaluated using Carnot Cycle efficiency. The results obtained shows that the refrigerator proved quite functional, achieving a coefficient of performance (COP) of 1.57. This validates the functionality of the system but it was observed that it took 2 hours of heating to produce a 2.1 °C drop (from 34.2 °C to 32.1°C) in evaporator temperature. After 5 hours of heating, there was a 9.1°C drop (from 34.2 °C to 25.1 °C) in evaporator temperature. However, the atmospheric temperature was 27 °C which means the cooling achieved was less appreciable. Thus, it is recommended that the waste powered VARS application will be viable and suitable for domestic and commercial usage.

1. Introduction

Refrigeration generally refers to the process of cooling a substance or an enclosed space and it is no doubt an integral part of our lives. The household refrigerator is one of the most common and needed household kitchen appliance, and among the domestic appliances used today, it consumes a considerable amount of the electrical energy being supplied to residents. A refrigerator (colloquially fridge) consists of a thermally insulated compartment and a heat pump (mechanical, electronic or chemical) that transfers heat from the inside of the fridge to its external environment so that the inside of the fridge is cooled to a temperature below the ambient temperature of the room. Refrigeration is an essential food storage technique in developed countries [1]. The low temperature reduces the reproduction rate of bacteria, so the refrigerator reduces the rate of spoilage. Optimum temperature range for perishable food storage is 3 to 5 °C (37 to 41 °F) [2]. Refrigeration freezes the water contained in the food fibers, thus slowing bacteria growth [3]. Extensively, refrigeration is used for safety, storage and preservation of perishable food items like food and its products, vegetables, fruits, milk, beverages, chilling of water, ice formation etc. including industrial applications like in chemical manufacturing, petroleum refinery, petrochemical plants, paper and pulp industry, pharmaceutical industry, etc. [4].

Refrigeration is defined as the process of extracting heat from a lower-temperature substance (heat source) or cooling medium and transferring it to a higher-temperature substance (heat sink) [5]. It is the use of mechanical or thermally activated devices to produce and maintain a temperature in a region below the temperature of its surrounding [6]. A refrigeration system (refrigerator) as such is a combination of components connected in a particular defined order to produce the refrigeration effect. Naturally, heat flows from high temperature regions to low temperature regions as in a heat engine – work is done by the system; therefore, the refrigeration process is a reverse heat engine such that work is done on the system. Thus, the refrigeration process is a cyclic process which is the inverse of the thermodynamic power cycle and it is known as the Refrigeration Cycle. Mechanically powered refrigerator is known as vapour compression refrigerator system (VCRs), while thermally powered refrigeration is called vapour absorption refrigeration systems (VARs). The VARs are powered by different heat sources such as kerosene, natural gas, geothermal, solar and waste heat etc. Waste to energy in VARs application need to be encourage to reduce issues cause by fossil fuel.

Waste-to-energy (WTE) or energy-from-waste (EFW) is the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source – it is a form of energy recovery [7]. There is a rapid increase in the amount of solid waste generated yearly. In Nigeria alone, about 1.4 million tons of combustible solid waste are generated annually [8,9]. Due to limited knowledge on modern technologies for WTE, these wastes are largely deposited in landfills. Solid waste management is by far one of the greatest challenges facing environmental bodies in the country [10,11]. WTE technologies seek to not only solve the problem of waste disposal but also many other challenges such as shortages in power generation, greenhouse gases from inappropriate waste disposal and reduction in land for waste depot.

Waste-to-Energy covers a very wide range of technologies of different scales and complexity. This can include the production of cooking gas from organic waste, the heat treatment of waste in large size incinerators, co-processing of Refuse Derived Fuel in cement plants, etc. [12]. The basic principle for WTE applied to this study is that the heat energy generated from the combustion of this solid waste materials as heat energy input into the vapor absorption refrigerator rather than the conventional vapor compression cycle which uses mechanical energy as input.

In the current Nigerian society, the issues that continue to plague the power generation sector which result in instability and unreliability of electricity supply presents a stumbling block for industries and individuals who wish to utilize the process of refrigeration for various purposes; this as a result of the fact that majority of the refrigerators are powered by electricity. To cope with this challenge, the industries and individuals result to using big generators which are expensive to purchase and have a high running cost due to cost of fuel and maintenance. Nigeria also has an inherent waste problem and it is the most pressing environmental challenge faced by urban and rural areas of Nigeria. Nigeria, with population exceeding 170 million, is one of the largest producers of solid waste in Africa [13]. Despite a host of policies and regulations, solid waste management in the country is assuming alarming proportions with each passing day. The use of the combustible waste vapour absorption refrigeration system helps to offset the cost that would have been incurred using the electrical refrigerator since combustible waste is an ever present and cheap source of fuel. In order to curb the situation, Kerosene powered refrigerator was used in past for cooling food and drinks where electricity was not available [14,15]. This is a very convenient refrigerator used in local and rural areas of the country where gas or electricity is not supplied at all or adequately.

Waste is generally a material which consists of different kinds of substances which include organic substances, metals, minerals and water, and energy from waste simply involves the generation of electrical energy and/or thermal energy from waste treatment. Globally, the management of solid waste is a huge problem and this is even more so in developing countries as Nigeria [16]. In Nigeria, there exist poor waste management resulting from inefficient collection and unsafe disposal of waste materials generated [10]. Also, the efficiency of collecting solid waste in Nigeria ranges from 5% in some semi-urban cities to 50% in urban cities [10] and the amount of solid waste being produced in the country is fast increasing compared to the capacity of its agencies improving on the resources required to level up this growth [17]. It is therefore necessary to promote trends which would add to improving waste management and utilization in the country.
The latent energy available from the organic fragment is retrieved for beneficial usage by adopting appropriate Waste Processing and Treatment technologies which also leads to; reduction of the solid waste material to over 90%, reduction in environmental pollution, reduction in land usage for dumps which is scarce in cities, etc. [18]. Solid waste contains a large fraction of paper, food waste, wood waste, cotton and leather, all of which are renewable materials, hence, they serve as a renewable source of energy [19,20]. The thermal treatment of waste in order to recover energy can be done by three major ways; pyrolysis, gasification and combustion [21].

The demand for energy continues to increase rapidly as a result of increased economic growth. The conventional way to generate transportable and useable energy from solid waste is through the direct combustion of the waste. This technology is well-established and has been in existence for 100 years [22]. The combustion of carbon-based materials in an environment of excess oxygen at very high temperatures liberates heat energy and produces a waste gas composed majorly of carbon dioxide (CO_2) and water (H_2O) [23,24]. The net amount of energy to be recovered depends on factors such as; the density and composition of the waste, the relative moisture percentage, the combustion system design, etc. and practically only 65 to 80% of the energy content of the waste organic matter can be recovered as heat energy to be used for heat required applications [25].
Also, wood is one of the most common and used multipurpose raw materials. It undergoes processing in different wood processing facilities and industries; Saw mill, plywood, furniture,

pulp and paper industries, etc [26]. Wood waste is thus generated as a result of forest activities and processes carried out by these wood processing industries. In Nigeria, 5.2 million tons of wood residues are generated per annum [27,28], while 1.8 million tons of sawdust are generated annually [29,30]. This waste generated by the wood industries in Nigeria become pollutants to the environment as a result of burning or improper dumping [31]. Sawmills generate a lot of waste in the form of sawdust, wood off-cuts, wood rejects, etc. and as a result of improper disposal methods, these wastes are burnt openly, dumped along river banks or dumped and left to root in an open space [32,33].

Wood as a source of energy contributes to the energy systems on different levels, which ranges from use in residents to use in industries. Significant in Nigeria is the use of wood waste to produce energy for heating and cooking especially in rural areas, which is referred to as firewood. Wood is therefore very important as it serves as a substitute energy source for heating requirements during power outages [34].

Combustible solid waste are organic materials such as wood, paper and fabrics that generate waste heat when they are burnt. The waste heat exhaust into the environment when not reused for useful and economic purposes. Unachukwu and Anyanwu [35]; Igbinomwanhia et al. [36] and Aliu et al. [37] indicated in their works that about 25% of most urban wastes generated in Nigeria consist of paper and other non - toxic materials, which can be combusted in suitably designed incinerators. These waste materials are either burnt uncontrollably to reduce volume or disposed of in landfills, which causes ecological problems such as emission of noxious harmful gases, soil contamination, other form of pollution. Egware et al. [38] had established that the flame temperature of combustible solid waste to be 178 – 621 ^{0}C, which can be used for medium range temperature heat recovery devices. Energy production, waste disposal and minimization of pollution are key problems that must be look into to sustain cities in country future. Incineration had been increasingly used to treat waste that are not recycled economically. In order to recover the waste heat from solid waste for useful purposes in Nigeria. Unachukwu & Anyanwu [35]; Igbinomwanhia et al. [36]; Egware et al. [39] and Okoye et al. [40] have in various ways studied and analyzed the used of incinerator in waste to energy (WTE) application for electricity and hot water generation in Nigeria in addressing the problems caused by uncontrollable burning. Again, this did not proffer solution for using the WTE potential for vapour absorption refrigeration. To solve the problem combustible solid waste and reduced the problems caused by mechanical vapour compression. Therefore, a properly designed experimental investigation study assessing the utilization of combustible solid waste for vapour refrigerator in Nigeria is need. Thus, this study focus on the development of a combustible solid waste powered vapour absorption refrigerator and determine its performance.

2. Materials and Methods

2.1 Combustible Waste Powered Vapor Absorption Refrigerator Description

Here aqua-ammonia solution settles in the accumulator from the absorbent and acts as a suction to the generator. As heat is applied to the generator from burning of combustible solid waste (sawdust of firewood in this case), the temperature of the aqua-ammonia solution rises. This rise in temperature causes the ammonia vapor to separate from the aqua-ammonia solution since the solubility of ammonia decreases as temperature increases and it also boils at a much lower temperature than the absorbent. The ammonia vapor is then air cooled in a condenser to a liquid state and it is passed through a capillary tube which bring the pressure and temperature down. Ammonia is evaporated to vapor state as it absorbs heat from the refrigerated space.

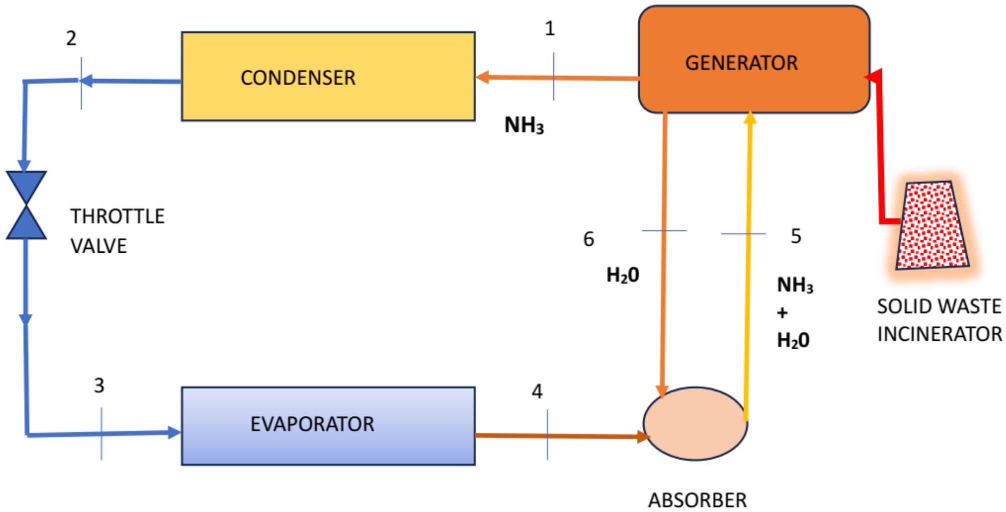

Figure 1. Combustible waste powered VAR Schematic Diagram

2.2 Materials

The first step taken in the development of this project was in selecting the materials that would be able to withstand the corrosive actions of ammonia. This was done by selecting the materials to be used from a variety of available materials such as aluminum, copper, steel, alloys of steel, other alloys, etc. The material carrying the refrigerant has to be able to withstand a temperature load of under 150ºC. This was carried out by carefully and categorically defining the requirements of the desired components, followed by checking these determined requirements so as to ensure the easy availability of the materials that have been selected for use.

The major materials used include:

i. Carbon steel pipes; for the cycle components where pure ammonia flow through like, condenser and evaporator. This was selected because it is less costly compared to stainless steel.
ii. Galvanized Sheet: for the construction of the refrigerator body frame.
iii. Ammonia/Water (NH_3/H_2O); where ammonia is the refrigerant and water is the absorbent for the absorption refrigerator.
iv. Fiber; for insulation of the metal components where necessary.

2.3 Detailed Design

To design a single stage vapor absorption refrigerator based on NH_3/H_2O. This consists of the following modules; Determination of the various mass flow rates through the system, design of the evaporator, design of the condenser, design of the generator, design of the. Also, the design and construction of the burner and the refrigerator body frame was carried out.
The first and second law of thermodynamics and the principle of conservation of mass are used for the thermodynamic analysis of the designed combustible waste VAR system. The heat and work interactions occurring in the different components of the system are also considered in applying the principles above. The assumptions carried out in the system analysis are as stated by Anand *et al*. [41] and Amosun & Kaffo [42]:

i. The system operates at the steady state.
ii. The heat loss through the components of the system is taken as negligible.
iii. The refrigerant vapor at generator exit is considered to be superheated
iv. The state of the refrigerant at other components is considered to be saturated states at their respective temperatures.
v. The temperature and pressure of the environment is considered to be 30°C and 1 bar respectively.

2.3.1 Working Fluid Parameters

The various parameters values used for the design of the NH_3/H_2O vapor absorption system are given as shown in Table 1.

Table 1. Working Fluid Parameters

S/N	Parameters	Values
1	Capacity of system, Q_E	1.75 kW
2	Concentration of NH3 in refrigerant, X_r	0.98
3	Concentration of NH3 in Solution, X_s	0.42
4	Concentration of NH3 in absorbent, X_w	0.38
5	Temperature of the evaporator, T_E	2ºC
6	Generator or condenser pressure, P_1	10.7 bar
7	Evaporator pressure, P_3	4.7 bar
8	Temperature of the Condenser, T_C	54ºC
9	Temperature of the Absorber, T_A	52ºC
10	Temperature of the Generator, T_G	120ºC

Using the thermodynamics tables by Rogers and Mayhew [43] for the state properties of the ammonia refrigerant corresponding to the temperatures and pressures, and the enthalpy-concentration diagram for aqua ammonia, at various concentrations of ammonia/water and corresponding saturation pressure, the corresponding enthalpy (kJ/kg) and temperature (ºC) can be calculated and on the basis of this enthalpy and various mass flow rates calculated. The heat transfer in the various components of the combustible waste vapors absorption system is also calculated, on which basis the various components are designed. The corresponding enthalpy values obtained as explained are presented in Table 2. The states presented in the table are also corresponding to the states presented in Figure 1 earlier mentioned.

Table 2. Enthalpy Values of the Different States

States	Pressure (bar)	Temperature (ºC)	Specific Enthalpy (kJ/kg)
1	10.7	54	1135
2	10.7	54	200
3	4.7	2	200
4	4.7	2	1220
5	10.7	52	180
6	10.7	120	255

2.3.2 Determination of Mass Flow Rates

The mass flow rate of refrigerant ($\dot{m}_r$) to be used was computed using Equation (1) as stated by Payne and O'Neal [44].

$$\dot{m}_r = \frac{Q_E}{h_4 - h_3} \tag{1}$$

where Q_E = The refrigeration capacity, h_3 and h_4 are specific enthalpies are evaporator entry and exit respectively.

The principle of mass conservation was applied at absorber to determine the mass flow rate of absorbent ($\dot{m}_w$) and mass flow rate of solution ($\dot{m}_s$) using Equations (2) and (3) respectively as stated by Payne and O'Neal [44].

$$\dot{m}_w = \frac{\dot{m}_r\left(X_r - X_s\right)}{\left(X_s - X_w\right)} \tag{2}$$

$$\dot{m}_s = \dot{m}_w + \dot{m}_r \tag{3}$$

2.3.3 Design of Evaporator

The evaporator was considered to be made of tubes that air cooled. To determine the logarithmic mean temperature difference, tubes surface area and tubes diameter for the evaporator tubes, Equations (4) to (6) respectively were used as stated by Du et al. [45].

The logarithmic mean temperature for evaporator (θ_{me}) is given as

$$\theta_{me} = \frac{\theta_{1e} - \theta_{2e}}{\ln\left(\frac{\theta_{1e}}{\theta_{2e}}\right)} \tag{4}$$

Where $\theta_{1e} = T_{ai} - T_E$ (4a)

$\theta_{2e} = T_{ao} - T_E$ (4b)

T_{ai} and T_{ao} are the air inlet and outlet temperatures to and from the evaporator, which are 30 ^{0}C and 5 ^{0}C respectively.

The evaporators tubes surface area (A_E) is expressed as

$$A_E = \frac{Q_E}{FU\theta_{me}} \tag{5}$$

Where F and U are the correction factor and overall heat transfer coefficient respectively. The overall heat transfer coefficient of 1000W/m^2 and correction factor of 1 were assumed [46].
The evaporators tubes surface diameter (D_E) is expressed as

$$D_E = \frac{A_E}{n_e \pi l_e} \quad (6)$$

Where ne and le are number and length of evaporator tubes. The number of evaporator tubes of 6 and length of evaporators of 455mm were used.

2.3.4 Design of Condenser

To determine the condenser tube diameter, the heat rejected by the condenser (Q_C) was evaluated as shown in Equation (7) as expressed by Doğan et al. [47]. The cooling medium to used is air.

$$Q_C = \dot{m}_r \times (h_1 - h_2) \quad (7)$$

Also, the logarithmic mean temperature difference (θ_{mc}) for the condenser tubes was computed using Equation (8) is stated by Wei et al. [48].

$$\theta_{mc} = \frac{\theta_{1c} - \theta_{2c}}{\ln\left(\frac{\theta_{1c}}{\theta_{2c}}\right)} \quad (8)$$

Where $\theta_{1c} = T_C - T_{aic}$ (8a)

$\theta_{2c} = T_C - T_{aoc}$ (8b)

T_{aic} and T_{aoc} are the air inlet and outlet temperatures to and from the condenser, which are 30 ^{0}C and 45 ^{0}C respectively.
The values obtained in Equations (7) and (8) was used to determine the surface area (A_C) of the condenser tubes as shown in Equation (9).

$$A_C = \frac{Q_C}{FU\theta_{mc}} \quad (9)$$

Where F and U are the correction factor and overall heat transfer coefficient respectively. The overall heat transfer coefficient of 1000W/m^2 and correction factor of 1 were assumed [46].
Equation (10) was used to evaluated the diameter (D_C) of the condenser tube as expressed by (Vaisi et al. [49].

$$D_C = \frac{A_C}{n_c \pi l_c} \quad (10)$$

Where n_c and l_c are number and length of condenser tubes. The number of condenser tubes of 6 and length of condenser of 455mm were used.

2. 4 Manufacture Specification of Developed VAR

The Table 3 shows the manufacture specific of the materials and processes used in carrying out the project. The values obtained from Equations (1) were used to the manufacturing specification to produce the developed combustible vapour absorber refrigerator.

Table 3. Specification of VAR system

S/N	Components	Specifications	Quantity
1	Refrigerated Space (Galvanized Sheet)	52 x 34.2 x 53.5 (L x B x H) cm^3	1
2	Evaporator (Aluminum)	2 x 45.5 (D x L) cm^2	1
3	Condenser (Carbon Steel)	1.5 x 45.5 (D x L) cm^2	1
4	Generator (Boiling ring section)	1 x 27 (D X L) cm^2	1
5	Absorber and Accumulator	5 x 15 (D x L) cm^2	1
6	Heat Sink (Steel sheet)	9 x 1 (L x B) cm^2	50
7	Refrigerant	0.2kg of NH_3 gas	1
8	Burner (Steel Plates)	100 x 100 x 0.5(L x B x H) cm^2	1
9	Copper rod	1.5 cm (D) (Hollow)	1
10	Thermometer		1
11	Copper Wire	4 yards	1
12	Fiber Glass		1
13	Kerosene		1 liter

2.5 Geometric Modeling of Components

This stage was carried out the use of a CAD software, AutoCAD 2016. The component parts of the system to be fabricated were first modeled to size to give us the view of how they should look like in reality. The draft of the developed Vapour absorption refrigeration system evaporator space and refrigerator door is presented in Figure 2. The evaporated space measures 0.52 m x 0.342m x 0.535m given it a maximum volumetric capacity of $0.0951444m^3$.

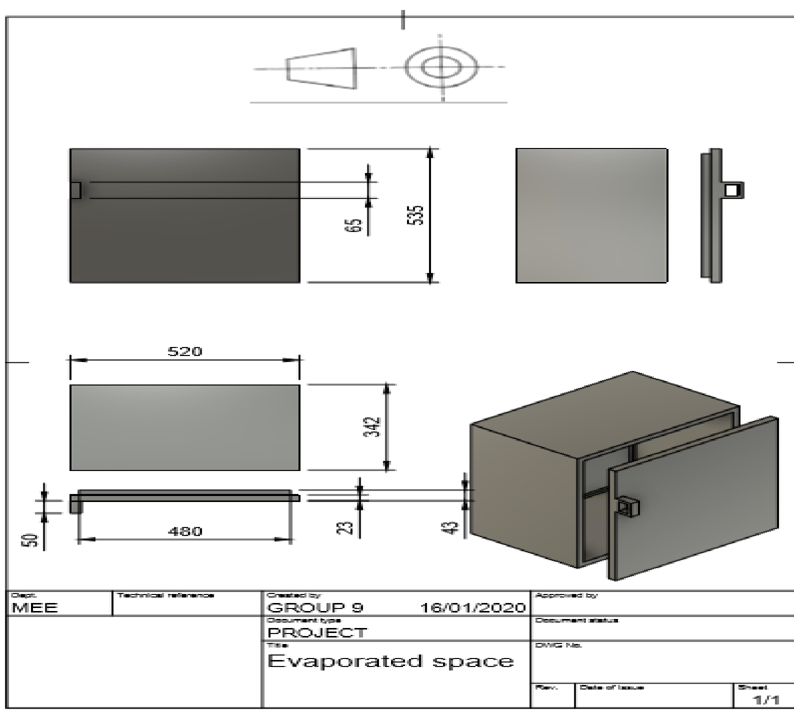

Figure 2. The Evaporated space and Refrigerator door

2.6 Fabrication Process of the Absorption Refrigerator System

These are the activities and operations carried out during the undertaking of this study. They include:

i. Cutting metal sheets to size
ii. Gas welding
iii. Electric arc welding.
iv. Drilling of holes on metal plates.

Some of the components of the refrigerator designed could not be fabricated due to factors such as non-feasibility of fabrication process and non-availability of technical know-how. These components include; generator, evaporator, condenser and absorber of the fridge compartment. The pictorial view of fabricated combustible vapour absorption refrigerator is presented in Figure 3.

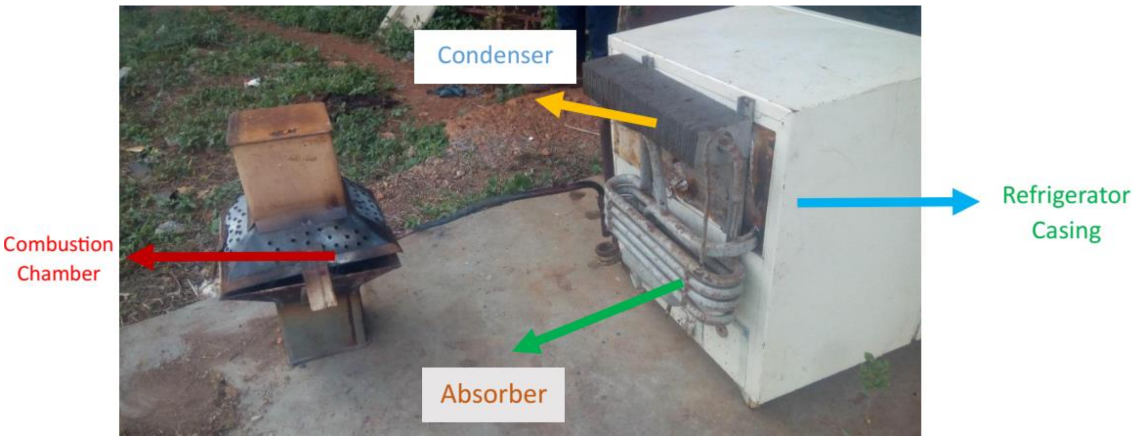

Figure 3: Pictorial view of the fabricated Combustible waste powered refrigerator

2.7 Test and Coefficient of Performance (COP_{ref}) Evaluation

After fabrication of the combustible VARs, it was tested to determine its performance. The heating was tracked on about 300 minutes. The temperature readings from the evaporator in the refrigerated space, the condenser and the generator were recorded with the aid of a digital thermometer at intervals of 30 minutes.

The temperatures values obtained for evaporator, condenser and generator was used to evaluated Carnot COP_{ref} of the developed combustible VAR as expressed in Equation (11) [50].

$$COP_{ref} = \left(1 - \frac{T_C}{T_G}\right) \times \left(\frac{T_E}{T_C - T_E}\right)$$

(11)

3. Results and Discussion

3.1 Results

During the operation of the system, temperature readings were gotten from the evaporator in the refrigerated space, the condenser and the generator, with the aid of a thermometer. Also, the heating was tracked on a 60-minute basis after initially observing that the generator did not heat up reasonably for the first 2 hours (120 minutes). Hence the readings taken include variation of generator, evaporator and condenser temperature with time. Considering the system result after 5 hours (300 mins) are presented in Figure 4 and 5.

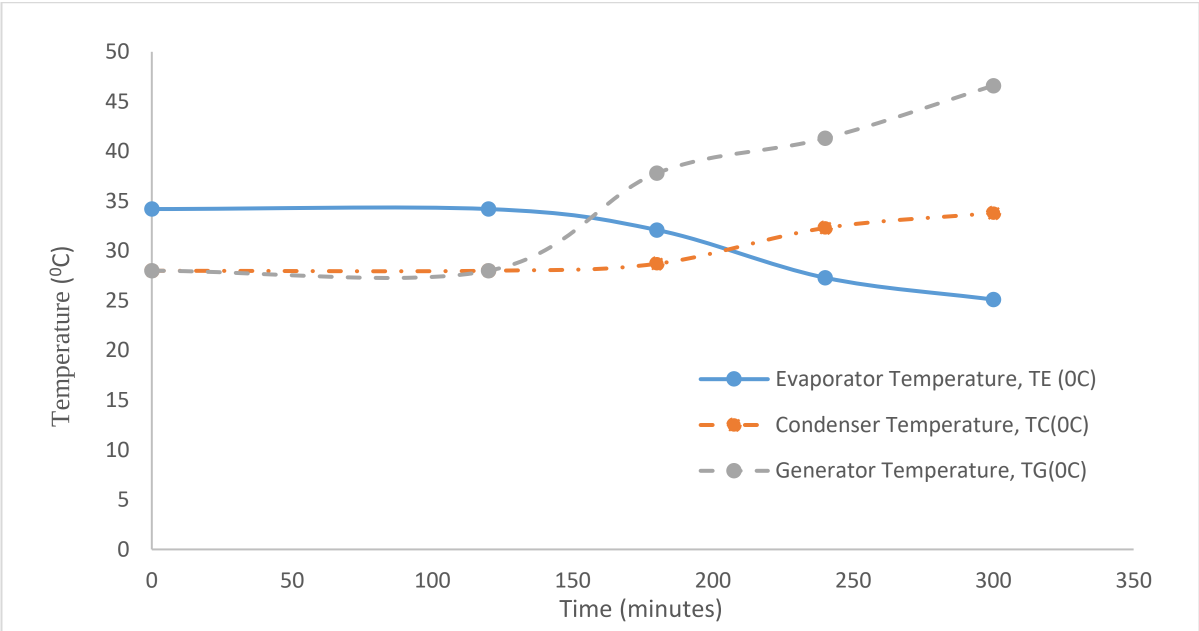

Figure 4. Variation of Generator, Evaporator and Condenser Temperatures with Time

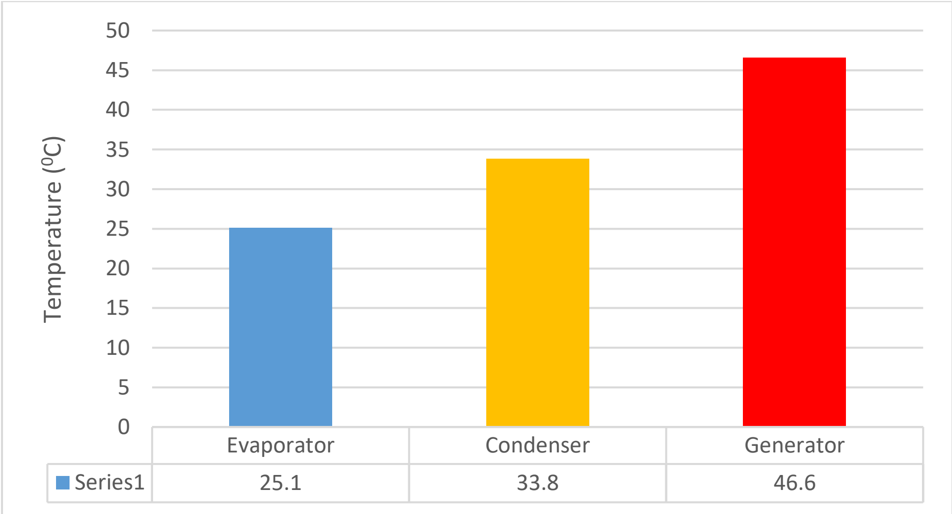

Figure 5. Summary of Evaporator, Condenser and Generator Temperatures

Based on the values obtained, which were presented in Figure 5 and using Equation (11) the Carnot cycle COP_{ref} was computed as 1.574.

3.2 Discussion

The results obtained from testing for this system as shown in Figures 4 and 5, the generator achieved the highest temperature as the operation proceeded, followed by the condenser temperature which became higher than the temperature of the atmosphere (27 ^{0}C). After the 5 hours (300 minutes) of heating, the temperature of the refrigerated space drops to a measured value of 25.1 ^{0}C with a change in temperature of 9.1 ^{0}C from the original value. This was a promising observation considering the temperature of the atmosphere was given at 27 ^{0}C. Additionally, it was observed from Figure 4 that the condenser and generator temperatures obtained increase with time while the evaporator decrease with time. The result obtained from the performance experiment of the combustible waste powered refrigerator showed its COP_{ref} was 1.574. Although this is the Carnot value of the COP and it would be lower if the enthalpy at the different states were used. The actual COP_{ref} would still be in line with the standard performance of a single effect refrigerator with COP set between 1.00 – 2.00 as mentioned by Dorgan & Anderson, [51] and Boelsen [52]. With respect to the obtained COP_{ref} results, the feasibility of the combustible waste powered refrigeration is hence proved.

3.3 Challenges

The level of cooling (temperature drop) achieved in the refrigerated space was not as expected and challenges were met during the undertaking of this study. Among these challenges was the inefficient combustion of saw dust as opposed to literature views. The used of extra fuel (kerosene) to initiate the sawdust burn was adopted. Another challenge was that the generator did not burn to the expected temperature of above 80 ^{0}C and this reduced the work input to the system which led to less effective cooling in the evaporator for the refrigerator. Also, the generator took a lot of time to heat up after the combustion process had already begun (over 2 hours) and this was the major challenge when carrying out the performance experiment of the system.

4. Conclusion

The refrigerator system was designed, fabricated and shown to be functional after testing. Performance evaluation of the system was carried out and the coefficient of performance obtained was low compared to competing VCRSs, which implies that the system uses a large amount of energy for the low cooling effect it offers. This is not a disadvantage in the case of our refrigerator because the energy used was the heat energy derived from the burning of wood waste which is easily and cheaply available. Also, the functionality and performance of this system shows a positive step in its contribution to the society since the operational cost of the refrigerator very low. The application of this study safeguards the interest of the rural areas with inadequate electricity to meet refrigeration needs, as well as urban areas where it would help reduce electricity tariffs for food stores and the likes.

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