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Experimental Evaluation of a Thermally Driven Adsorption Refrigeration System in Ogbomoso Environs

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Abstract
Solar energy is the most promising among the available green energy sources and also the remedy to the increasing global warming potential and ozone depletion. This paper presents an experimental evaluation of an adsorption refrigeration system uses solar energy as a source of heat gain to drive the refrigeration system. It consists of a solar collector, an adsorbent bed, a condenser and an evaporator. The effect of variation of the ambient, condenser, evaporator and desorption temperatures on the COP system and SCP cycle with local weather parameters were investigated. A parabolic solar concentrator was built to collect the solar energy to heat the combination of adsorbent, Activated carbon and adsorbate, methanol and the system employed solar energy as the main power supply. The experimental results revealed that the ambient, condenser, evaporator and desorption temperatures were increased by 25%, 4%, 13% and 265% respectively with solar time from 9hr to 13hr. The response of COP and SCP with variation in solar radiation and desorption temperature had higher influence compare to other weather parameters. The collector and thermal efficiencies were 0.014 and 6.98% respectively at the peak inner adsorber temperature of 114.1 ^{o}C. The respective cycle and net solar COPs of the ARS were 0.408 and 0.00080 at an evaporator temperature of 17.1 ^{o}C. This study showed that the solar thermal-driven ARS performed well in south-western climatic conditions of Nigeria and can be used to replace conventional refrigeration system to reduce the effect of global warming and environmental pollutions caused chlorofloro-refrigerants.
Keywords: Solar, Adsorption, Refrigeration, COP, Concentrator

1. Introduction

Cooling and refrigeration are needed to provide the human comfort in the modern day technology. In tropical countries like Nigeria, which experience extreme in the land mass, demand for electricity shoots up due to the need for cooling (Bansal *et al*. 1997). The high electricity requirement overworks the national grid and harms the environment due to the burning of fossil fuels, which are the primary source of power. Recently, the top technologies provide cooling by using vapour compressor technology. Nevertheless, the vapour compressor refrigeration device is one of the techniques accountable for ozone layer destruction because most of these use HCFCs and HFCs refrigerants (Dieng and Wang, 2001). In refrigeration applications, solar energy presents an avenue to trim down this problem. The quantity of solar intensity impacted on the surface of Earth is much higher than the yearly total energy expenditure. The energy obtainable from the sun is more than 5200 times the entire world energy needed in 2006 (Habib *et al.*,2013).

In recent times, several encouraging technologies have been built to utilize the Sun's energy. These technologies facilitate the protection of the environment, enhance the energy economization and accelerate the sustainable developments which are the main concerns in the 21st century. The cooling demand is proportional to the accessibility of solar energy has caused the researchers to utilize more of the solar energy. In refrigeration applications, adsorption refrigeration uses solar energy as well as waste heat as a source of power to thermally drive the refrigeration system (Sumathy *et al*., 2003). The use of thermal driven systems aids to trim down the carbon dioxide emission from combustion of fossil fuels in power plants. Adsorption systems utilize a natural working fluid such as water and methanol, which have zero ozone depletion potential (Enibe and Iloeje, 1997[a] and 1997[b])

2. Previous Works

The adsorption systems are driven by the heat sources of lower temperatures makes the application of solar energy more feasible on the adsorption system. Tchernev, (1985) studied robust adsorption refrigeration technology driven by solar power, and he developed the refrigeration system with zeolite– water as the working pair. Pons and Guilleminot (1986) studied activated carbon-methanol and zeolite–water adsorption systems driven by solar energy. The COP of the activated carbon-methanol ice maker was 0.12–0.14 with a collector area of 6 m^2 (four collectors) and adsorbent mass of 20–24 kg/m^2, and the COP of a zeolite–water refrigerator (Grenier *et al*.,1988) is about 0.10 with the collector area of 20 m^2 (24 collectors) and the adsorbent mass of 360 kg. Sumathy and Li. (1999) examined an activated carbon-methanol ice maker powered by solar energy, and results revealed that the daily ice production is 4–5 kg and the COP is 0.1–0.2 when the area of flat plate collector is 0.92 m^2.

Fend and Tan. (1990[a], 1990[b], and 1991) and Li *et al*. (1991) developed the solid adsorption refrigeration system driven by solar energy with the integrated solar collector–adsorption generator, multi types of solar energy powered adsorption refrigeration systems were developed. Enibe and Iloeje (1997[a] and 1997[b]) used a tubular type of absorber, for which the adsorbent filled inside the metal pipes. The concentric tube arranged at the center of the metal pipe served as the mass transfer channel of the refrigerant, and the metal tube is boned on the collector surface. Erhard *et al*. (1998) arranged the condensation part of the horizontal heat pipe inside the adsorbent bed to enhance the heat flux density. Headley *et al*. (1994) studied the activated carbon-methanol adsorption refrigerating system using the compound parabolic concentrator (CPC) as the heat source. The system could realize refrigeration even if the solar radiation is very meager, but the efficiency of the refrigeration system is very low.

Vasiliev (2005) developed a continuous adsorption heat pump with heat recovery process driven by solar energy and natural gas, using a parabolic concentrator for collecting the solar energy to heat the circulating water. The system utilized solar energy as the main power supply, and the natural gas served as a supplementary heat source when solar energy is not sufficient. The system can achieve continuous refrigeration with the cycle time of 12 minutes. Liu *et al*. (1998 and 2000) presented the refrigeration system which combined the unit adsorption tube with the collector for the solar energy. For such a design the adsorbent bed is heated by direct solar energy. Wang *et al*. (2000) built a compound system of water heater and refrigerator driven by solar power to improve energy efficiency and also developed the silica gel–water adsorption chiller which had been applied to the building and grain storage hall with solar energy as the driving power.

3. Basic Adsorption Refrigeration System

Adsorption refrigeration system uses solid adsorbent beds to adsorb and desorb a refrigerant to obtain the cooling effect. These adsorbent beds filled with solid material, adsorb and desorb an adsorbate vapour in response to changes in the temperature of the adsorbent. The primary adsorption refrigeration system consists of four main components: a solid adsorbent bed, a condenser, an expansion valve and an evaporator. The adsorbent bed desorbs refrigerant when heated and adsorb refrigerant vapour when cooled. The adsorbent was packed in a hermetically sealed adsorber painted black for solar radiation absorption at a particular temperature in compliance with its condensing pressure. The primary adsorption cycle consists of four thermodynamic steps is as presented in Figure 1

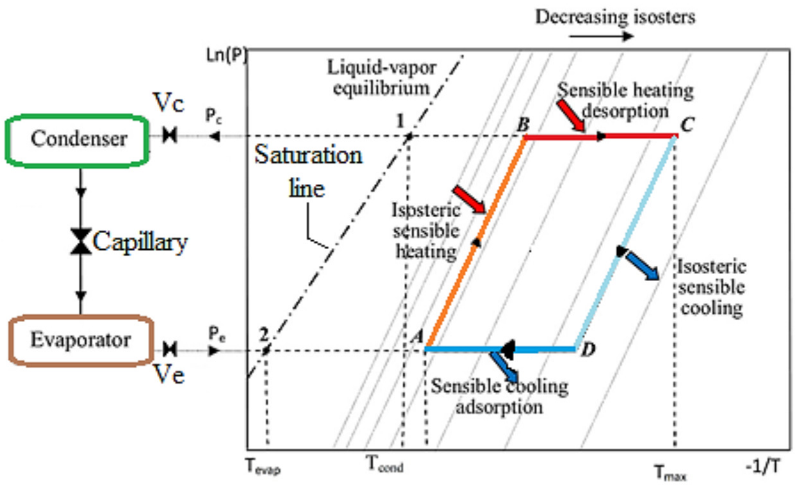

Fig. 1: Clayperon curve of basic adsorption refrigeration cycle (Khattab,2004).

3.1 Performance Parameters

From the Clapeyron diagram in Fig. 1, the total energy gained by the system during the heating period Q_T is the sum of the power Q_{AB} used to raise the temperature of the Activated carbon (AC) + methanol from point A to B and the energy Q_{BD} used for progressive heating of the AC and desorption of methanol are expressed in equations (1,2 and 3)(Khattab, 2004 and 2006).

$$Q_T = Q_{AB} + Q_{BD} \quad (1)$$

$$Q_{AB} = (m_{AC} C_{PAC} + C_{Pm} m_{mA})(T_B - T_A) \quad (2)$$

$$Q_{BD} = [m_{AC} C_{PAC} + C_{pm} \{(m_{mA} + m_{mD})/2\}](T_D - T_B) + (m_{mA} - m_{mD})h \quad (3)$$

The gross heat released during the cooling period, Q_{e1} is the energy of vapourization of methanol is expressed in equation (4)

$$Q_{e1} = (m_{mA} - m_{mD})L \quad (4)$$

The net energy used to produce ice Q_e is expressed in equation (5)

$$Q_e = Q_{e1} - Q_{e2} \quad (5)$$

where Q_{e2} is the energy necessary for cooling the liquid adsorbate from the temperature at which it is condensed to the temperature at which it evaporates is given in equation (6).

$$Q_{e2} = (m_{mA} - m_{mD}) C_{Pm} (T_c - T_e) \quad (6)$$

Q_{ice1} is the energy required to cool water from T_A to 0°C to produce ice is expressed in equation (7)

$$Q_{ice1} = M^* (L^* C_{P,water} (T_A - 0)), \quad (7)$$

where M^* and L^* are the mass and latent heat of fusion of ice and net cooling produced is expressed in equation (8)

$$Q_{ice} = M^* L^* \quad (8)$$

3.2 Performance Estimates

The performance estimates of the closed type adsorption refrigeration system could be expressed in terms of collector and evaporator efficiencies (Khattab, 2004 and 2006)

The collector efficiency is the ratio of the total energy gained by the system during the heating period (Q_T) to the total solar energy input to the system during the day (Q_I) is calculated using equation (9)

$$\eta_1 = Q_T / Q_I \quad (9)$$

The evaporator efficiency is the ratio of the energy required to cool water from ambient temperature ($T_{A)}$ to evaporator temperature (T_e = 0 °C) (Q_{ice1}) to the net energy used to produce ice (Q_e) is obtained using equation (10)

$$\eta_2 = Q_{ice1} / Q_e \quad (10)$$

where Cp is specific heat capacity in kJ/kgK, H is the heat of desorption in kJ/kg, L is latent heat of evaporation of the methanol in kJ/kg, M is mass in kg, Q is energy in kJ, T is the temperature in °C.

The desorbed refrigerant is condensed in the condenser from where it flows into the evaporator. At night, the temperature of the adsorber reduces to the minimum, and subsequently, the pressure of the adsorbent bed drops to below the evaporation pressure, causing the refrigerant liquid in the evaporator to vapourize resulting in the refrigeration effect. The refrigeration effect is measured by the system performance efficiency. It is described by the coefficient of performance (COP) as presented in equation (11)

$$COP = \frac{Q_{ref} - Q_{cc}}{Q_g} \quad (11)$$

The effectiveness of a cooling device is called the "coefficient of performance'. It is the ratio of the cooling effect to the heat input, that is how much energy is removed from a cold space, ($Q_{ref} - Q_{cc}$) for each unit of energy expended (Q_u). The amount of refrigeration, Q_{ref} is calculated using equation (12)

$$Q_{ref} = \Delta x \, m_{ac} L_e \quad (12)$$

Where L_e is the latent heat of vapourization of adsorbate, Q_{cc} is the amount of energy assumed to be utilized in cooling the refrigerant liquid from the condensing temperature T_c to the evaporation temperature T_e. Q_{cc} is estimated as

$$Q_{cc} = m_{ac} \Delta x \, C_{P,m} (T_{co} - T_{ev}) \quad (13)$$

Q_u is the heat required for the regeneration of the adsorption bed, and it was calculated using equation (1)

The specific cooling power, SCP is an efficiency indicator defined as the ratio of the cooling production to the product of cycle time and unit of adsorbent mass. It is calculated using equation (14)

$$SCP = \frac{Q_{ref} - Q_{cc}}{t_{cycle} \cdot m_{ac}} \quad (14)$$

The gross solar coefficient of performance (COPs) is the ratio of the cooling effect to the incident solar energy on the surface of the solar collector during the whole day. It is calculated using equation (15)

$$COP_S = \frac{Q_{ref} - Q_{cc}}{Q_I} \quad (15)$$

where $Q_I = \int A_c I(t) \partial t$ is the solar heat input by the collector, A_c is the collector aperture area, I(t) is the solar intensity over time, t and ∂t is the differential time

4. Experimental Set Up

4.1 Design Considerations

The layout of the prototype systems designed in this study was very simple involving only three main components; the combination collector-adsorber for heating the activated carbon-methanol mixture, condenser coil in a water bath and an evaporator where distilled methanol collects during desorption. This system used a parabolic trough concentrator to heat the receiver at its focal point. The receiver formed the adsorber for the adsorption system giving it direct heating from the sun. Methanol and activated carbon were used as a refrigerant and adsorbent material respectively in this study.

The system was constructed using locally sourced materials, and the assembled unit is shown in Figure 2. The following design conditions were used to fabricate the experimental rig:

Parabolic trough: The size of the parabolic mirror and framework were formed using a segmented mirror, maco, plywood, and gum were used gummed it to form the curve having length, 2200 mm of adsorber copper pipe diameter of 32.5 mm. All the piping joints and fittings used in the system were capable of preventing leakages by using different nipples

Condenser tank: The condenser tank was positioned such that the outlet of the collector tube was below the outlet of the condenser coil and this would force the hot methanol into the condenser. The size and specifications of the condenser coil are as follow condenser coil is made up copper pipe diameter is 0.09525 mm and half of the 50-litre stainless drum. The outlet condenser coil is connected to the evaporator box of 40 mm x40 mm x 40 mm.

Supporting frame: The frame supporting the condenser tank has been designed so that the majority of the weight would be placed on the central support structure through two legs. The third leg was placed on an outrigger to provide balance for the construction as well as additional support for the mass of condenser tank once filled. The frame was also made to be removed for disassembly and transportation purposes. The entire unit was placed on a single frame with wheels attached to the frame to allow easy short-range transportation such as in and out of the laboratory for testing. A jockey wheel was mounted to assist with the short-range transport of the device and positioning for testing. A threaded strut was built to hold the mirror frame at any desired angle for the correct alignment to the sun in any location.

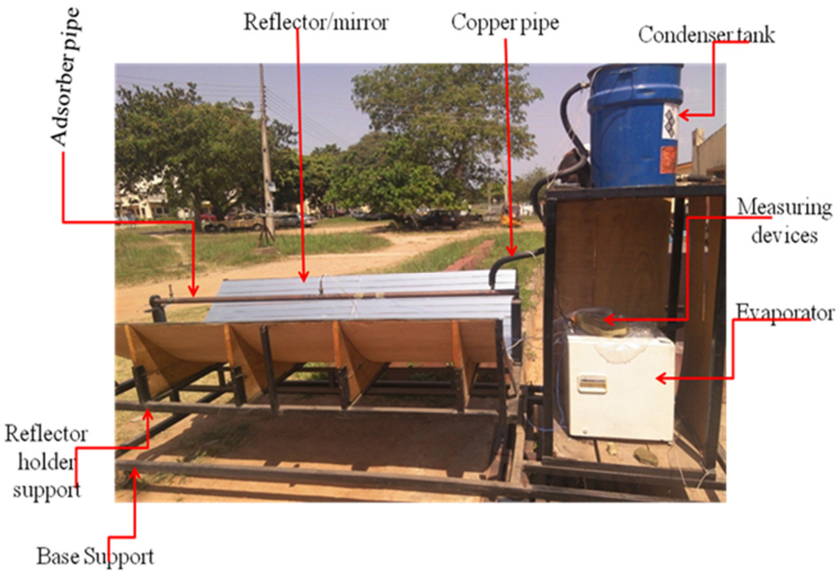

Figure 2: Photograph of the developed solar adsorption refrigeration system powered by parabolic trough solar concentrator

4.2. Experimental Procedures

An experimental rig was set up in the front of Mechanical Engineering workshop, Department of Mechanical Engineering, LAUTECH OGBOMOSO (Latitude of 8.1227° N, Longitude of 4.2436° E at Elevation of 347 m).The photograph of the experimental rig of the system is shown in Fig. 2. The experiment was conducted to observe and record the temperature of different components of the system, solar intensity and relative humidity which allows calculation of performance estimate of the system. The prototype was tested and the system collector being aligned East-West and facing North. The mirror was tilted to align with a median position of the suns inclination during the hottest part of the day approximately 10:00 to 16:00 hrs. It provided greater exposure of sunlight normal to the mirror surface. This light applied directly to the collector tube. The collector tube temperature, the temperature at the condenser inlet, the condenser water temperature, the temperature at the condenser outlet, and the evaporator temperature were observed and recorded for the period at the interval of 2 minutes. The adsorber was charged with methanol as adsorbate and activated carbon as the adsorbent.

The system operation begins its cycle during the day when the reflector is directed to the sun and the light striking the parabolic mirror is redirected to the collector tube to heat-up the tube. This heat is applied to the adsorbent/refrigerant combination. The heat releases the refrigerant as a gas which rises and makes its way to the water cooled condenser. The liquid refrigerant travels under gravity to the refrigerant receiver located in an evaporator (fridge) compartment. This process was continued throughout the day until the heat being applied can no longer release the refrigerant.

After the sun sets the temperature and the pressure in the adsorber tube reduces, and the refrigerant begins to boil. Refrigerants boil at much lower temperatures than most of the other liquids and therefore draw energy from the surroundings and produce cold. The boiling refrigerant returns to a gaseous state and can be returned to the adsorber (generator) to be reabsorbed ready for the next day. It is this process which gives the intermittent refrigerator its name the process of heating and cooling occurs in different stages where a continuous cycle requires heating on a constant basis to maintain a constant cooling effect.

The reflector, ambient, condenser, evaporator inner and the outer surface of adsorber temperatures were measured using a 12 channel temperature recorder with SD data logger. Solar radiation intensity and relative humidity were measured using a solar meter recorder and environmental meter recorder with SD data logger respectively.

5. Results and Discussions

The results obtained in the experimental analysis of the solar parabolic trough collector for the adsorption refrigeration system are presented in graphical forms.

The variation of ambient, reflector, adsorber outer and inner temperatures with the solar time is as presented in Figure 3 The internal adsorber temperature was increased from 31 ºC at 9.00 h to 114.1 ºC around noon. It revealed that the internal temperature of the adsorber increased with the solar time from 9:00 am to 12:19 pm when the peak internal adsorber temperature of 114.1 ºC was reached, after which it began to decrease. The reflector and the outer surface temperature of the adsorber followed the same pattern.

Figure 4 shows that the solar intensity increases with the local time, with a very sharp increase from 122.9 W/m^2 to 817.1 W/m^2 between 11:25 am-11:49 am. A gross increase and decrease also occurred between 11:47 am to 3:59 pm, with the solar intensity reaching its peak value of 836.8 W/m^2 at 1:37 pm. The fluctuation in the solar energy from 9:00 am to 4:00 pm, had significant impacts on the temperatures achieved for the day.

The plot of evaporator temperature against solar time for different days at the solar time of 16.00 - 24.00 hr and 0.00 - 7.00 am are presented in figures 5 and 6. One of the day, Figure 5 showed that after the whole cycle for the day ended at 4 pm, the evaporator temperature was 38.6 ºC, which later decreased to 19.9 ºC at 11:17 pm. This temperature was almost maintained till 1:06 am, when it was 19.6 ºC, and later decreased to 17.1 ºC at 6:30 am. This implied that cooling was achieved at a minimum evaporator temperature of 17.1 ºC.

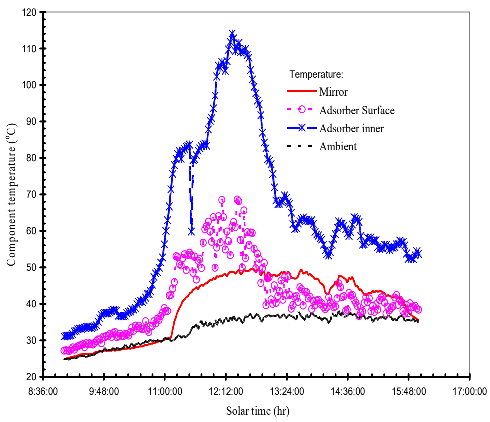

Figure 3: Graph of the ambient, reflector, adsorber outer and inner temperatures against the solar time

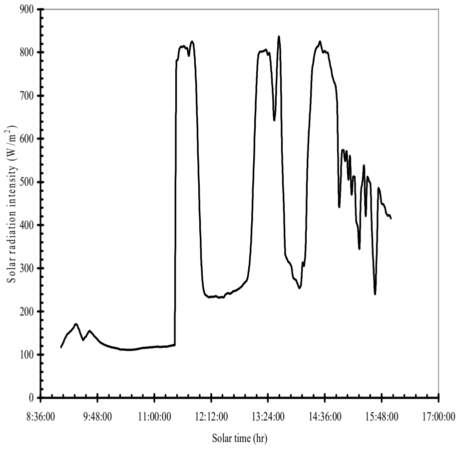

Figure 4: Plot of solar radiation intensity against solar time on 19 11 2015

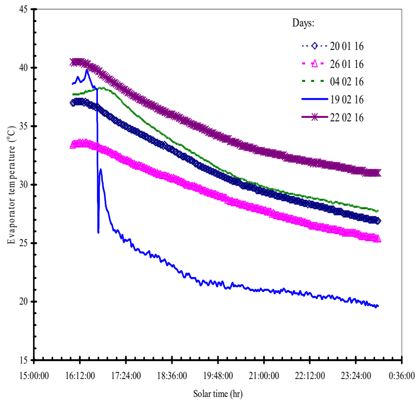

Figure 5: Plot of evaporator temperature against solar time on different days (day-cycle, 16.00 – 24.00 hr)

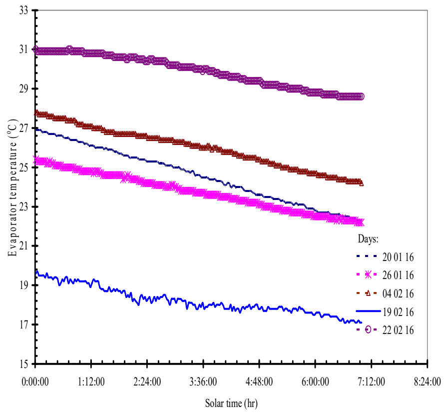

Figure 6: Plot of evaporator temperature against solar time for different days (night-cycle, 0.00 – 7.00 hr)

The variation of ambient, condenser, evaporator and desorption temperatures with the sidereal time is presented in Figure 7. The desorption temperature was increased from 23 ºC at 9.00 h to 84 ºC around noon. It revealed that the desorption temperature of the adsorber increased with the solar time from 9:00 am to 12:19 pm when the peak desorption temperature of 84 ºC was reached, after which it began to decrease. During the day, between the solar time of 9:00 am to 12:19 pm, the results revealed that the ambient, condenser, evaporator and desorption temperatures were increased by 25%, 4%, 13%, and 265% respectively.

The effect of the desorption temperature varied between 24 and 82 ºC on the system Coefficient of Performance, COPc and gross solar Coefficient of Performance, COP_{GS} for the activated carbon-methanol pair is as shown in Figure 8. The results showed that the COPc and COP_{GS} reduced by 13% and 75% respectively as the desorption temperature was increased by 242%

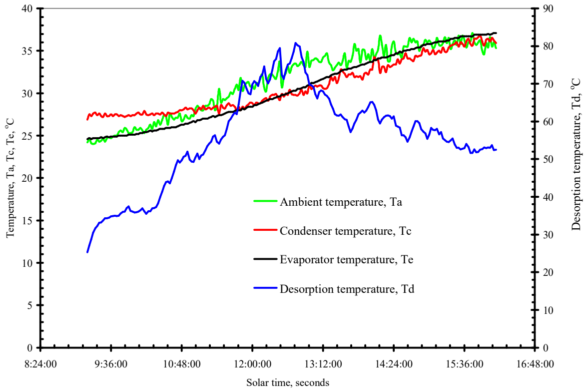

Figure 7: Graph of the ambient, condenser, evaporator and desorption temperatures against the solar time

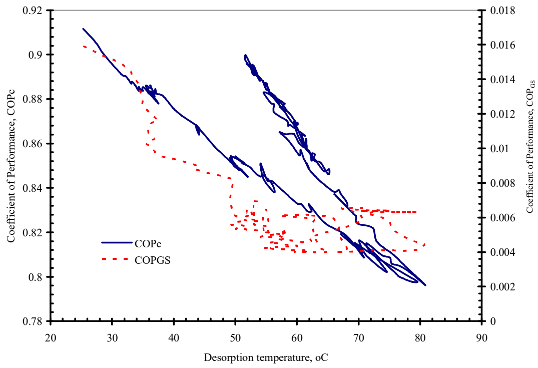

Figure 8: Variation of the coefficient of performance with desorption temperature

The effect of the ambient temperature varied between 24 and 34 °C on the system Coefficient of Performance, COPc and gross solar Coefficient of Performance, COP_{GS} is as shown in Figure 9. The results revealed that the system COP and Gross solar COP reduced by 12% and 75% respectively as the ambient temperature was increased by 55%.

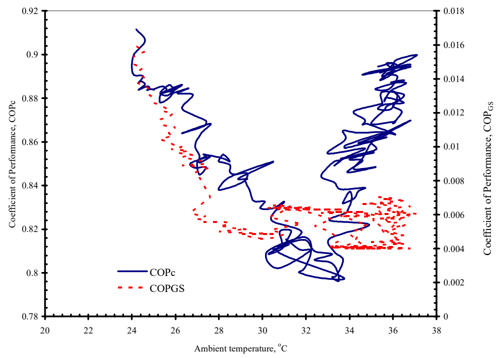

Figure 9: Effect of ambient temperature on the coefficient of performance

The effect of the desorption temperature varied between 24 and 82 °C and ambient temperature varied between 24 and 37.2 °C on the specific cooling power, SCP is as presented in Figure 10. The SCP increased by 0.8% with the percentage increment in ambient and desorption temperatures of 55% and 242% respectively because desorption temperature influenced directly with the ambient temperature.

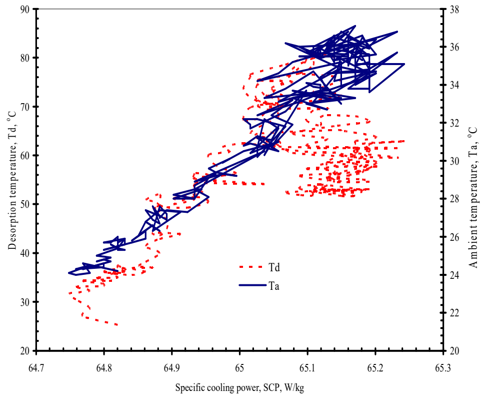

Figure 10: Effect of desorption and ambient temperature on the Specific Cooling Power

The effect of the condensation temperature varied between 28 and 38 °C and evaporation temperature varied between 26 and 37 °C on the specific cooling power, SCP during the day is as presented in Figure 11. The results showed that the SCP increased by 0.8% with the percentage increment in evaporation and condensation temperature of 42% and 36% respectively.

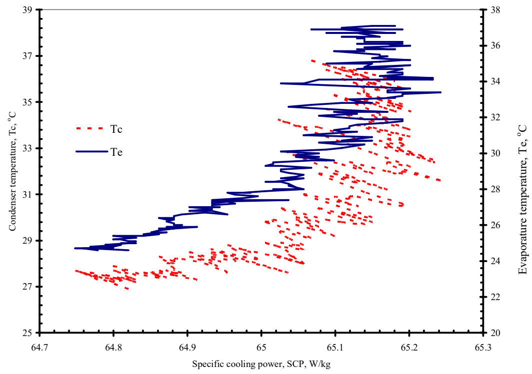

Figure 11: Effect of the condensation and evaporation temperatures on the Specific Cooling Power, SCP

The effect of the evaporation temperature varied between 24.2 and 37 °C on the solar collector, and evaporator efficiencies are as presented in Figure 12. The results showed that the solar collector efficiency reduced by 78% and the evaporator efficiency increased by 24% with evaporation temperature until 30 °C reaching maximum after that it began to change the effects

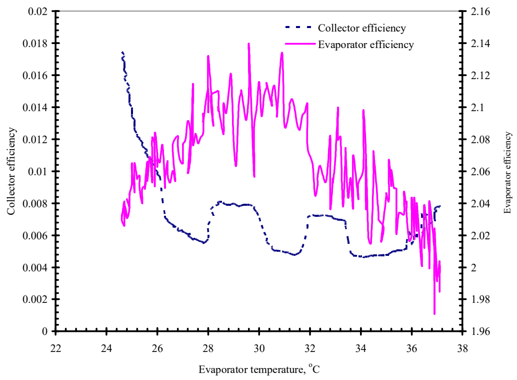

Figure 12: Effect of the evaporation temperature on the solar collector and evaporator efficiencies

The impact of the desorption temperature varied between 24 and 80 °C on the solar collector, and evaporator efficiencies of the system are as presented in Figure 13. The evaporator efficiency increased by 6% and the solar collector efficiency reduced by 78% as desorption temperature was increased by 233%.

The effect of the solar radiation intensity varied between 160 and 640 W/m^2 on the solar collector, and evaporator efficiencies of the system are as presented in Figure 14. The evaporator efficiency increased by 6% and the solar collector efficiency reduced by 78% as the solar radiation intensity was increased by 300%. It is deduced that solar power has the direct effect on solar concentrator performance.

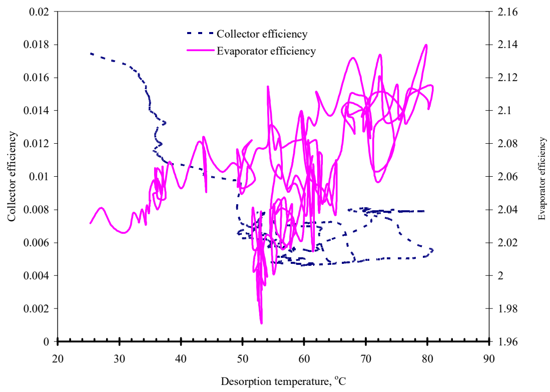

Figure 13: Effect of the desorption temperature on the solar collector and evaporator efficiencies of the system

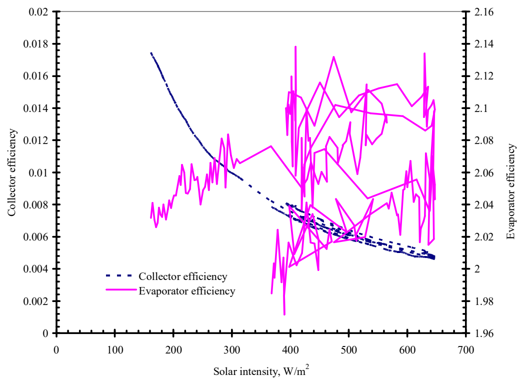

Figure 14: Effect of the solar radiation intensity on the solar collector and evaporator efficiencies of the system

The effect of the solar radiation intensity varied between 160 and 640 W/m^2 on the total heat gained by the system is as presented in Figure 15. The full temperature obtained by the system increased by 15% as the solar radiation intensity was increased by 300% and the value fluctuated to signify the dynamic nature of solar radiation intensity during the day.

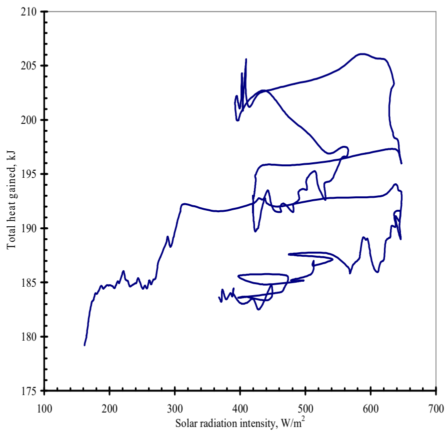

Figure 15: Effect of the solar radiation intensity on the total heat gained by the system

The effect of the solar radiation intensity varied between 160 and 640 W/m^2 on the SCP of the system is as presented in Figure 16. The SCP increased by 0.8% as the solar radiation intensity was increased by 300% and the value fluctuated to signify the dynamic nature of solar radiation intensity.

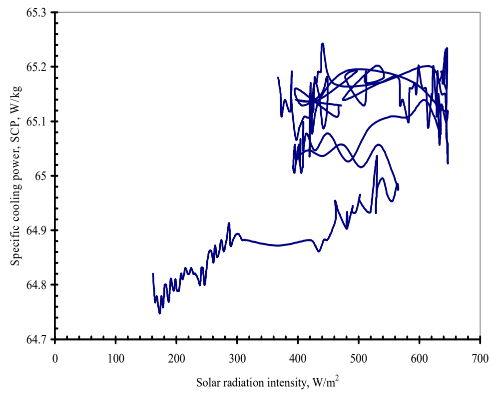

Figure 16: Effect of the solar radiation intensity on the SCP of the system

The effect of the solar radiation intensity varied between 160 and 640 W/m^2 on the COP of the system is as presented in Figure 17. The COPc reduced by 13% and COP_{GS} reduced by 75% as the solar radiation intensity was increased by 300 %. It is deduced that solar radiation intensity has a strong indirect effect on COP_{GS}

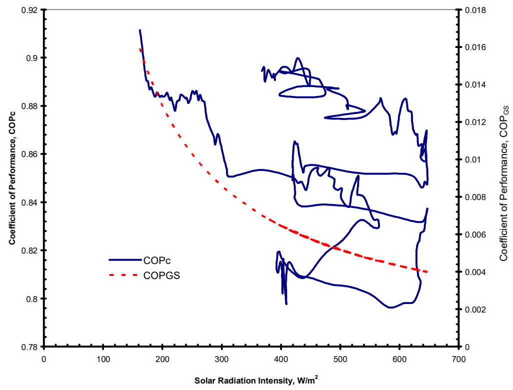

Figure 15: Effect of the solar radiation intensity on the COPc and COP_{GS} of the system

5. CONCLUSIONS

Adsorption cooling systems have received substantial attention during the last few decades to satisfy the market demand for cooling systems and cope with the current environmental issues. This work presented an experimental evaluation of an adsorption refrigeration system which uses solar energy as a source of heat gain to drive the refrigeration system and activated carbon and methanol as the working pair driven by the parabolic solar concentrator; the following conclusions were drawn:

The experimental results revealed that the ambient, condenser, evaporator and desorption temperatures were increased by 25%, 4%, 13% and 265% respectively with solar time from 9hr to 13hr. The response of COP and SCP with variation in solar radiation and desorption temperature had higher influence compare to other weather parameters. The collector and thermal efficiencies were 0.014 and 6.98% respectively at the peak internal adsorber temperature of 114.1 °C. The respective cycle and net solar COPs of the ARS were 0.408 and 0.00080 at an evaporator temperature of 17.1 °C. This study showed that the solar thermal-driven ARS performed well in south-western climatic conditions of Nigeria and can be used to replace conventional refrigeration system to reduce the effect of global warming and environmental pollutions caused chlorofloro-refrigerants.

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