NJERD, Vol. 8, No. 4, 2009

THE DEVELOPMENT AND EVALUATION OF A SOLAR-POWERED REFRIGERATOR USING ACTIVATED CARBON / METHANOL PAIR

I. F. Odesola
Department of Mechanical Engineering,
University of Ibadan,
Ibadan, NIGERIA.

ABSTRACT

A solar-powered adsorption refrigerator using activated carbon/methanol pair was designed and fabricated. The refrigerator has three major components: collector, condenser, and evaporator. A 3 mm thick flat glass was used as flat plate collector. The condenser was made of spirally coiled copper tube immersed in pool of stagnant water contained in a reinforced sancrete tank. The evaporator was fabricated from standard 15.6 mm diameter copper tubing. The activated carbon used as adsorbent was manufactured locally from shells of a palm kernel. The maximum temperature of 108°C attained in the solar collector was adequate for methanol generation, while maximum received insolation of 1000 kW/m^2 was sufficient for methanol desorption. The solar coefficient of performance (COP) of the refrigerator ranged from 0.0339 to 0.0345 compared to 0.03 to 0.055 recorded in the literature. The study shows that a solar powered adsorption refrigerator will operate in Nigeria's tropical climate with satisfactory coefficient of performance.

Keywords: Refrigeration, Solar, Adsorption, Activated Carbon, Methanol

NOMENCLATURE

C_p = specific heat capacity, kJ/kg/K
D = constant in Dubinin equation
h_w = wind heat transfer coefficient, $W/m^2/K$
h_{fg} = latent heat of vapourisation, kJ/kg
k = thermal conductivity, W/m/K
h_{sg} = isosteric heat of sorption, kJ/kg
L = length, m
m = mass, kg
n_g = number of glass cover
n_{pi} = number of pipes
P = pressure, bar
Q = heat flow rate, kJ/s
Q = heat energy, kJ
R = specific gas constant, kJ/kg/K
S = tilt correction factor
T = temperature, K
U_L = overall heat transfer coefficient, $W/m^2/K$
V_{pi} = volume of annular space, m^3
W = width, m
W_0 = maximum capacity adsorbent, L/kg
APD = adsorbent packing
Density, kg/m^3
X = concentration, kg/kg

1.0 INTRODUCTION

A country like Nigeria in tropical Africa has an attractive potential for solar energy applications. The demand for space cooling and refrigeration follows the pattern of availability of solar energy. It means that solar energy cooling is a useful technology in Nigeria where there is demand for cooling, high insolation, and no firm electricity supply to power conventional systems. The most promising applications are vaccine storage and food storage (Anyanwu and Ezekwe, 2003). Many agricultural products like fruits, vegetables, meat, milk, fish etc can be maintained in fresh conditions for significantly longer periods of time if they are stored at low temperatures. Unfortunately, in Nigeria many of these products are lost annually due to poor storage facilities. The worst cases are in rural areas where these products are produced. As a result of these problems, sharp differences exist in food supplies between the harvest and off harvest periods. High market value agricultural products are usually abundant and cheap during the harvest season but scarce and expensive at other times. Development of an appropriate refrigeration system will help in reversing this trend.

Another very important area where solar refrigeration plays very unique role is in the improvement of rural health care, including successful implementation of the national immunization programme for prevention of killer diseases. Vaccines require refrigeration during transportation and storage to remain effective. The use of solar refrigerators instead of conventional kerosene or liquefied petroleum gas (LPG) powered units, especially in remote areas, offers the following benefits (Anyanwu and Ezekwe, 2003):

- Elimination of fuel supply costs and delivery problems
- Reduced vaccine losses through improved refrigeration
- Reduced maintenance work load for technicians and medical personnel
- Overall cost savings for the vaccine cold chain equipment

A survey of literature on adsorptive processes / sorption refrigeration has shown that, in the early years of this century, refrigeration was used as frequently as the economy could allow. But some years later, with the development of cheap reliable compressors and electrical motors, the improvement in power station and the introduction of chlorofluorocarbon (CFC) in the 1930s, sorption refrigeration has carved a niche for itself in sorption technology business.

Khattab (2006) built a simple structure, low cost novel solar-powered adsorption refrigeration module with the solid adsorption pair of local domestic type charcoal and methanol. The module is unique in that it consists of a modified glass tube having a generator at one end and a combined evaporator and condenser at the other end. A simple arrangement of plane reflectors to heat the generator was employed. Glass shell was used to cover the beds in winter. The time duration during which the bed temperature is above 100°C was found to be 5h, with a maximum temperature of 120°C. In winter, the corresponding values are 6h and 133°C.The daily ice production is 6.9 kg/m^2 and 9.4 kg/m^2 and net solar COP is 0.136 and 0.159 for cold and hot climate respectively.

Li et al (2002) presented a no valve, flat plate solar ice maker on the basis of previous research achievements. The indoor experiments with quartz lamps instead of real solar radiation showed that the solar ice maker can produce 7-10 kg ice when the total insolation accepted by 1.5 m^2 collector was 28-30 MJ. The solar ice maker can produce about 4-5 kg of ice per day when the solar insolation received is 18-22 MJ/m^2.

Luo et al (2005) developed a solar ice maker with activated carbon-methanol pair for rura application in Kunming, China. A year round tes was performed on the refrigerator. Test results show that the COP of the solar ice maker i between 0.083 and 0.127 with daily ice productio in the range 3.2-6.5 kg/m^2 when the solar radiatio received falls between 15-23 MJ/m^2. The dail average ambient temperature was in range 7.7 21.1°C.The minimum daily solar radiation for ic maker to perform effectively in Kunming is aroun 16 MJ/m^2.

Khattab (2006) developed a mathematic model to simulate and optimize the performance a solar-powered adsorption refrigeration modu with the solid adsorption pair of domestic type charcoal and methanol. The module employed modified glass tube having a circular genera (sorption bed) at one end and a combin evaporator and condenser at the other end. T charcoal is mixed with small pieces of blacker steel to enhance the heat transfer in the sorpt bed. A simple arrangement of plane reflectors v adopted to heat the generator. The effects of us steel additives inside the sorption bed investigated. The percentage increase in desor methanol ranges from 3% in the hottest mont about 19% in the coldest month as a resul using a mass of steel pieces equal to about of the mass of charcoal. These improvem increase to 7% and 43% in the hottest and col months respectively when glass shell is use the bed. The effect of climatic conditions or performance of the module showed that 28 the cooling energy is lost as a result of clir effect in hot months and this ratio reaches 1 in cold climate.

Mohammed (2007) reported a dynamic mo simulate the adsorption-desorption proc associated with intermittent heat pump syste mathematical model that is based on the c volume approach was first developed and discretised using the finite difference scheme. The equations for the conservat mass, momentum, and energy in the bed derived, for higher pressure and low pr segments, including the adsorbate (refrig the adsorbent, and the vessel. The pre temperature distribution / evolution is very c the experimental values. The deviatic predicted results from the experimental findings are within the maximum relative error (0.8%).

Antonio et al (2007) presented experimental thermodynamic cycles and performance analysis of a solar-powered adsorptive icemaker that uses activated carbon - methanol pair in hot humid climate. The collector - adsorber is multi-tubular with an opaque black radiation - absorbing surface which was thermally insulated by means of transparent insulation material (TIM). The maximum regenerating temperatures were 100.1, 87.3, 92.7°C, with an ice production of 6.02, 2.10 and 0 kg by square meter of projected area, for cycles of clear sky, partially cloudy and overcast days.

The objective of this study is to develop and evaluate a solar-powered refrigerator using activated carbon methanol pair.

2.0 WORKING PRINCIPLE OF THE ADSORPTION REFRIGERATOR

Two distinct periods have been identified in solar adsorption refrigeration cycle; the first period consists of regeneration of the adsorbent by solar energy when the adsorbate is condensed and the second period occurs during the night when evaporation of the adsorbate and the adsorption back into the adsorbent takes place. Ideal adsorption cycle is normally shown on Clapeyron diagram (InP versus -1/T). This cycle has four thermodynamic steps: isosteric (constant concentration) heating, isobaric (constant pressure) desorption, isosteric (constant concentration) cooling, isobaric (constant pressure) adsorption.

3.0 CONSTRUCTION OF THE ADSORPTION REFRIGERATOR

The adsorption refrigerator consists of three major components: collector / generator / adsorber, condenser and evaporator. Other accessories that are associated with this machine are: liquid collector, valves, piping system and pressure gauges. There are three collector tubes each 800 x 400 x 7mm long steel pipe, having a coaxial perforated inner tube. The perforations were 3 mm in diameter spaced 40 mm axially and four per circumference in an alternating manner. Each annular space between the inner and the outer tube was charged with locally manufactured activated carbon. Thereafter, the grill of pipes was positioned centrally onto the collector plate.

The collector plate and tubes assembly was mounted on the rear plate insulation inside a 16G galvanized steel box. The glazing was a clear plain glass while the insulation consists of 70 mm fibre glass and 60 mm Styrofoam chip which is capable of withstanding the expected temperature of about 100°C. The top and bottom headers were 12.7 mm steel tube. Adsorbent cooling during charging, cooling and adsorption processes was both by natural convection of air over the collector plate and tubes and night sky radiation which was made possible by manually operated removable collector box end Each of these components (condenser, evaporator, and adsorbent bed) was checked to be sure that it is free of air. Copper tubing (Φ12mm) was used to connect them together for easy flow of methanol vapour and liquid as the case may be. The whole system was mounted on a frame bracket installed with wheels for ease of movement. Valves were installed on the system in order to monitor, vacuum and charge the system with the refrigerant. A pressure gauge was installed behind the adsorbent bed so as to monitor and record the pressure conditions of the system during operation. The photograph of the whole system is shown in Fig.1.

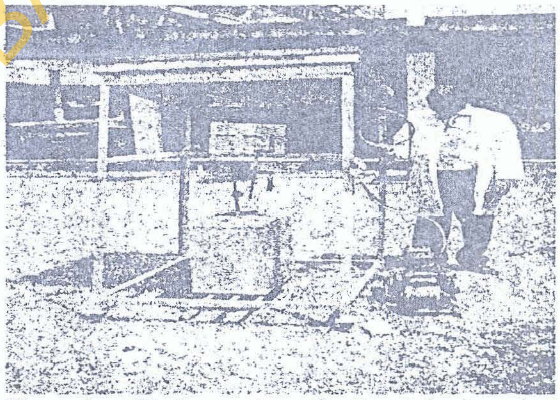

Fig. 1: Photograph of the designed solar adsorption refrigerator

4.0 EXPERIMENTAL RESULTS

Tables 1 and 2 show the solar insolation incident on the collector plate per unit area and the predicted plate, tube and adsorbent temperatures respectively on the day indicated in Ibadan, Nigeria. Figs. 2 and 3 show the variation of solar insolation with local time in Ibadan on clear and cloudy days respectively. Fig. 4 shows the measured plate temperatures versus solar time on a relatively clear day.

Table 1: Solar insolation (total) incident on the collector plate per unit area (17/02/2006)

S/N	Local time (hr)	Solar time (hr)	Insolation (W/m^2)
1	8.30	7.56	126.00
2	9.00	8.26	236.00
3	10.00	9-26	552.00
4	10.30	9.56	662.00
5	11.30	10.56	789.00
6	12.00	11.26	789.00
7	12.30	11.56	789.00
8	13.00	12.26	757.00
9	13.30	12.56	757.00
10	14.00	13.26	584.00
11	14.30	14.56	631.00
12	15.00	14.26	346.00
13	15.30	14.56	442.00
14	16.00	15.26	316.00
15	17.00	16.26	0.00
16	18.00	17.26	0.00
17	19.00	18.26	0.00
18	20.00	19.26	0.00
19	21.00	20.26	0.00
20	22.00	21.26	0.00
21	23.00	22.26	0.00
22	24.00	23.26	0.00
23	25.00	24.26	0.00
24	26.00	25.26	0.00

Table 2: Predicted plate, tube and adsorbent temperatures (17/02/2006)

S/N	Local time (hr)	Solar time (hr)	Plate Temp. (°C)	Tube Temp. (°C)	Adsorbent Temp. (°C)
1	8.30	7.56	27	27	27
2	9.00	8.26	27	27	27
3	10.00	9.26	27	27	27
4	10.30	9.56	27	27	27
5	11.30	10.56	27	27	27
6	12.00	11.26	27	27	27
7	12.30	11.56	27	27	27
8	13.00	12.26	39.0	37	36.0
9	13.30	12.56	49.0	45.0	45.0
10	14.00	13.26	80.0	70.0	68.0
11	14.30	13.56	73.0	64.0	63.0
12	15.00	14.26	102.0	88.0	86.0
13	15.30	14.56	99.0	85.0	84.0
14	16.00	15.26	83.0	72.0	71.0
15	17.00	16.26	60.0	54.0	53.0
16	18.00	17.26	57.0	51.0	51.0
17	19.00	18.26	27	27	27
18	20.00	19.26	27	27	27
19	21.00	20.26	27	27	27
20	22.00	21.26	27	27	27
21	23.00	22.26	27	27	27
22	24.00	23.26	27	27	27
23	258.00	24.26	27	27	27
24	27.00	25.26	27	27	27

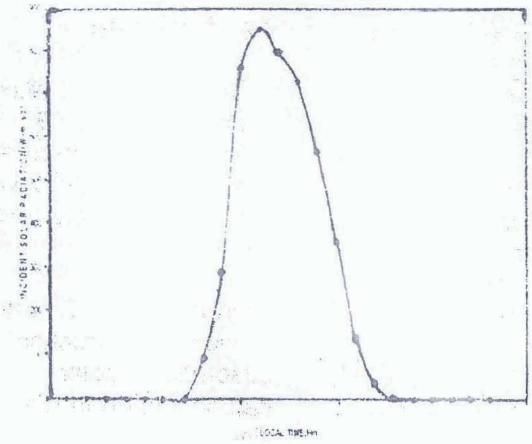

Fig. 2: Variation of solar insolation with local time at Ibadan on a clear day (18/02/06)

Fig. 3: Variation of solar insolation with local time Ibadan on a cloudy day (27/03/06)

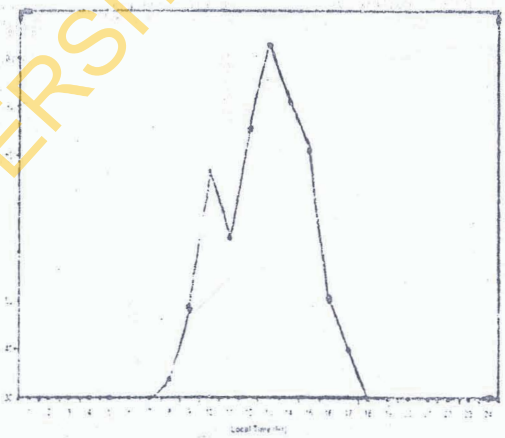

Fig. 4: Measured plate temperature versus solar time on a relatively clear day (18/03/06)

The bulk densities of the activated carbon samples ranged from 0.62 g/cm^3 to 0.67 g/cm^3 ad the surface area ranged from 870 m^2/g to 906 m^2/g, thus classifiable as medium grade carbons. The maximum temperature of 108°C received in the solar collector was adequate for methanol generation, while maximum received insolation of 1000 kW/m^2 was sufficient for methanol desorption. Ambient temperatures during the adsorbate generation and adsorption ranged from 28°C to 34°C, while the minimum temperature inside the evaporator ranged from 23°C to 26°C. For water initially in the temperature range of 28°C - 34°C, this represents a 5 - 8°C cooling.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the studies carried out on the design of solar powered adsorption refrigerator:

i. A solar powered solid adsorption with activated carbon/methanol pair was successfully designed, fabricated and evaluated in the tropical climate of Nigeria.

ii. This work has established the fact that purely thermal pump can be built in tropical climate using locally activated carbon for chilled water production.

iii. Activated carbon, which is the principal component for this solar powered refrigerator can be locally sourced without compromising standards.

iv. This is an ongoing project and efforts are being made to improve the performance of the machine.

REFERENCES

Antonio P. F. L., Marcelo B. G., Rodrigo R. D., Franscisco A. B. and Francis M. (2007): "Experimental thermal cycles and performance analysis of a solar-powered adsorptive icemaker in hot humid climate", *Renewable Energy*. Vol. 32, pp. 697-712.

Anyanwu E. E. and Ezekwe C. I. (2003):" Design, construction and test run of a solid adsorption solar refrigerator using activated carbon / methanol as adsorbent /adsorbate pair". *Energy Conversion and Management* . Vol. 44, pp. 2879-2892.

Khattab N. M. (2006): "Simulation and optimization of a novel solar-powered adsorption refrigeration module". *Solar Energy. Vol.* 80, pp. 823-833.

Li M., Wang R. Z., Xu Y. X. and Dieng A. O. (2002): "Experimental study on dynamic performance analysis of a flat - plate solar solid - adsorption refrigeration for ice maker". *Renewable Energy* . Vol. 27, pp.211-221.

Luo H. L., Dai Y. J., Wang R. Z., Runsheng T. and Li M. (2005): "Year round test of a solar adsorption ice maker in Kunming China". *Energy Conversion and Management. Vol.* 46, pp. 2032 – 2041.

Mohamed A. G. (2007): " Simulation of intermittent thermal compression processes using adsorption technology". *Journal of the Franklin Institute. Vol.* 344, pp. 725-740.