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PERFORMANCE EVALUATION OF A SOLAR POWERED SOLID ADSORPTION REFRIGERATOR UNDER A TROPICAL HUMID CLIMATE

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ABSTRACT

A solar powered intermittent cycle solid adsorption refrigeration system was developed and tested in Akure, Nigeria (Latitude 7.25^o N, Longitude 5.08^o E). The system utilized granular 70% $CaCl_2$ + 10% activated carbon + 20% $CaSO_4$ / NH_3 as an adsorbent/adsorbate pair. Initial and final condensate liquid volume, evaporator surface temperature, evaporator water temperature, adsorber plate surface temperature and ambient temperature were measured during adsorption. The adsorber plate surface temperature, condenser water temperature, condensate volume and ambient temperature were recorded during the generation of adsorbate. The data collected were reduced, using appropriate physical equations, to determine the Coefficient of Performance (C.O.P) of the Solar Refrigerator. Ambient temperatures during adsorption and generation ranged over 24^o – 29^{o}C. Performances of 1123.09 - 1186.2 kJ/m^2 per day of available cooling were obtained. The best cooling obtained was 438.57 kJ/m^2 per day of collector-exposed area. The refrigerator had an overall C.O.P of 0.021 - 0.033 whilst its daily ice production was 0.49 – 0.63 kg/m^2. The C.O.P and the daily ice production were higher than those reported in the literature for systems with solar collector plates coated with black paint and which utilized $CaCl_2/NH_3$ as working pair.

Keywords: Intermittent-cycle, solid-adsorption, solar-refrigerator, cooling, adsorbent, adsorbate, coefficient of performance, climate.

INTRODUCTON

Millions of people living in small communities in Nigeria do not have access to electricity; besides, the amount of kerosene and other petroleum products available to them is limited. An adsorption refrigeration system requiring no electrical power, and utilizing solar energy as the heat source for regeneration, offers the possibility of providing refrigeration for the preservation of food and other perishables to people who find energy sources too expensive. The need for ice making, vaccine and drug preservation in rural areas of developing countries where the supply of electricity is unavailable calls for the development of better refrigeration systems utilizing solar heat.

Adsorption heat pump and refrigeration systems are noiseless, non-corrosive and environmentally friendly. For these reasons the research activities in this sector are still increasing to solve the crucial points that make these systems not yet ready to compete with the well known vapor compression system (Wang et al, 2005^a). The expanding population and the energy crisis have brought serious problems to the world environment and sustainable development. The electric driven vapor compression refrigerators have faced challenges of CFCs and so are not suitable for sustainable development. Natural refrigerants such as water, ammonia, methanol etc will be welcome for future refrigeration industries (Wang et al, 2002).

Different kinds of adsorbent/adsorbate pairs have been investigated including activated carbon- methanol (Anyanwu and Ezekwe, 2003; Wang et al, 2002); activated carbon-ethanol (Chen et al, 1986); activated carbon- ammonia (Anyanwu and Ogueke, 2005); strontium chloride-ammonia (Chen et al, 2002); silica gel- ammonia (Zhou and Zhu, 2004); $CaCl_2$-NH_3 (Iloeje, 1985; Mei et al, 2005; Iloeje et al, 1995); charcoal- methanol (Headley et al,1994); active carbon fiber- methanol (Teng et al, 1997; Wang et al 1997); molecular sieve-water (Cui et al, 2005); carbon-methanol (Hu, 1998); compound adsorbent of activated carbon and calcium chloride- ammonia (Wang et al, 2005[b]; Wang et al, 2004) and zeolite-methanol (Waszkiewic et al, 2003).

Srivastava and Eames (1998) presented a review of adsorbents and adsorbates in solid-vapor adsorption heat pump systems. Among the adsorbents presented are the commercial hydrophilic solid adsorbents. These include silica gel, activated alumina, zeolites and calcium chloride. Commercial hydrophobic solid adsorbents such as activated carbons, metal oxides, specially developed porous metal hydrides and composite adsorbents were also reviewed. Muradov and Shadiev (1969[a], 1969[b]) constructed a $NaCl_2/NH_3$ system using a 2 m^2 double glazed flat plate collector. A cooling load of 1675 kJ/m^2 day and ice production of 1 kg/m^2 day were realized.

Iloeje (1985) designed, constructed and test ran a solar powered intermittent cycle solid absorption refrigerator. The intermittent system utilized $CaCl_2$ and NH_3 as absorbent and refrigerant, respectively. The absorbent was mixed with 20% by weight of $CaSO_4$, and prepared as hard porous granules of 5-10 mm sizes. The double glazed collector/absorber/generator unit used clear PVC and plane glass sheets, with the former as the outer cover. Overall collector plate exposed area was 1.41 m^2. Ambient temperatures during absorption and generation ranged over 25°C-35°C. Performances of 714- 826 kJ/m^2 per day of available cooling were obtained. The best useful cooling obtained was 472 kJ/m^2 per day of collector-exposed area, or the equivalent of 1 kg/m^2 per day of ice. Actual ice production so far was 0.58 kg per day, or 0.41 kg m^2 per day. The cycle COPs were compared with those predicted for such systems ($CaCl_2/NH_3$ with solar energy), as well as with other solar liquid systems (H_2O/NH_3 and $NaScN/NH_3$). The overall COPs were, however less than for the other systems.

The amount of solar cooling achieved by a refrigerating machine per unit of heat supplied is usually given by the coefficient of performance (COP).

Table 1 shows the COP for some solar sorption refrigerators with different adsorption pairs.

Table 1 COP for Some Intermittent Solar Sorption Refrigerators

Adsorption Pair	Solar collector area (m^2)	Solar radiation intensity (MJ/m^2)	COP	Ice produced	Source / Investigator(s)
Carbon-Ammonia	1.4	-	0.05	-	Critoph (1993)
Charcoal-Methanol	-	-	0.136	6.9 kg/m^2	Khattab (2004)
	-	-	0.159	9.4 kg/m^2	Khattab (2004)

AC-Methanol	0.94	17.10	0.13	4.5 kg	Li et al (2004)
	0.94	16.28	0.12	4.0 kg	Li et al (2004)
$CaCl_2$-Methanol	-	-	0.28	-	Lai et al (1993)
$CaCl_2/CaSO_4$-NH_3	1.41	12.1	0.020 – 0.028	0.41 kg/m^2 day	Iloeje (1985)
$CaCl_2$-NH_3	1.6	20	0.08	3.2 kg	Lin et al (1993)
$CaCl_2/CaSO_4$-NH_3	-	25	0.0026	-	Desouza (1997)

MATERIALS AND METHODS

DESIGN, CONSTRUCTION AND TESTING OF THE SOLAR POWERED REFRIGERATOR

DESIGN OF SYSTEM COMPONENTS

Design parameters:

Global solar radiation	520 Wm^{-2} (Anjorin, 2008)
Average ambient temperature	30^{o}C
Maximum generation temperature	100^{o}C
Adsorbent/adsorbate pair	Granular (70%$CaCl_2$+10%Activated carbon +20%CaSO4)/NH_3
Condensing temperature	35^{o}C (Iloeje, 1985)
Evaporating temperature	-10^{o}C (Iloeje, 1985)
Generation Period	6 hours (Iloeje, 1985)
Adsorption period	12 hours (Iloeje, 1985)
Overall Coefficient of Performance	0.1
Percentage swell for adsorbent	10% (Anjorin, 2008)
Final Ice temperature	-5^{o}C
Crushing strength of adsorbent	4.8 - 8.3 N/mm2 for 7 cycles (Anjorin, 2008)
Porosity of adsorbent	40 – 42% over 7 cycles (Anjorin, 2008)

Description of the solar solid adsorption refrigerator

Fig.1 shows a schematic diagram of the solar solid adsorption refrigerator. It consists of three major parts, namely the adsorbent bed, 3; the condenser, 7; and the evaporator, 10. The adsorbent bed is enclosed in a metal shell, 1; which is in turn enclosed in a double glazed flat plate solar collector with double glass, 4. The upper part of the metal shell is coated with a black paint. Other components of the solar refrigerator include: fins, 5; insulated box, 12;

level indicator, 8; liquid receiver,9; ice box,13; valves, 14,15; a pressure gauge, 16; a connecting pipe, 17; and a frame bracket, 11. The adsorbent bed, made of a galvanized steel plate box with the dimensions of 1.0 m x 1.0 m x 0.035 m, is the major component of the solar refrigerator. The top surface of the stainless steel box is covered with a flat plate painted with black paint. The bottom and four sides of the stainless steel box are insulated by 0.03 m thickness styrofoam chips. 5 kg of the adsorbent (70% $CaCl_2$ + 10% Activated Carbon + 20% $CaSO_4$) is enclosed in the galvanized steel box. In order to enhance the heat transfer effect between the solar collecting surface and the adsorbent, 3 aluminium fins are fixed in the stainless steel box. The collector was double glazed with clear glass as the inner layer and Perspex as the outer layer.

The condenser consists of a 3.2 m long spiral condensation heat exchanger immersed in a cooled water tank having the dimension 850 mm × 440 mm × 1130 mm. It is placed in the space between the adsorbent bed and the evaporator in order that the solar refrigerator becomes more compact and the condensed refrigerant can flow into the evaporator by gravity easily. The condensation heat exchanger was made of ∅ 21 mm galvanized steel pipe. The cylindrical liquid receiver (223 mm diameter and 306 mm height) is made of galvanized steel. It served as storage for liquid ammonia. A liquid level indicator gauge was fitted to indicate the level of ammonia. The evaporator is made of 1.5 mm galvanized steel plate. In order to enhance the heat transfer effect, the heat exchange surface was designed as a series of four trapezoidal cells, the dimension of the evaporator is 450mm x 300mm x 100 mm. The evaporator was immersed in a water tank with the dimensions 550 mm × 400 mm × 190 mm, which was placed inside an insulated box. During the adsorption process, ice was formed in the water tank. The water tank had a draining cock at its bottom to drain the water after each test. The difference in the volume of water initially in the tank and the volume drained gave the amount of ice frozen.

The adsorbent bed, condenser, evaporator were checked for leakage and then were connected with each other using galvanized steel pipe of ∅ 21mm. The whole system was mounted on a frame bracket installed with wheels, so that it can be moved easily when necessary. Only one valve was installed beside condenser, which helped to vacuumize the whole system as well as to charge the system with refrigerant. A pressure gauge was installed behind adsorbent bed to check for the pressure conditions in the system. The solar adsorption refrigerator is shown in Plate 1.

Plate 1: The Solar Refrigerator

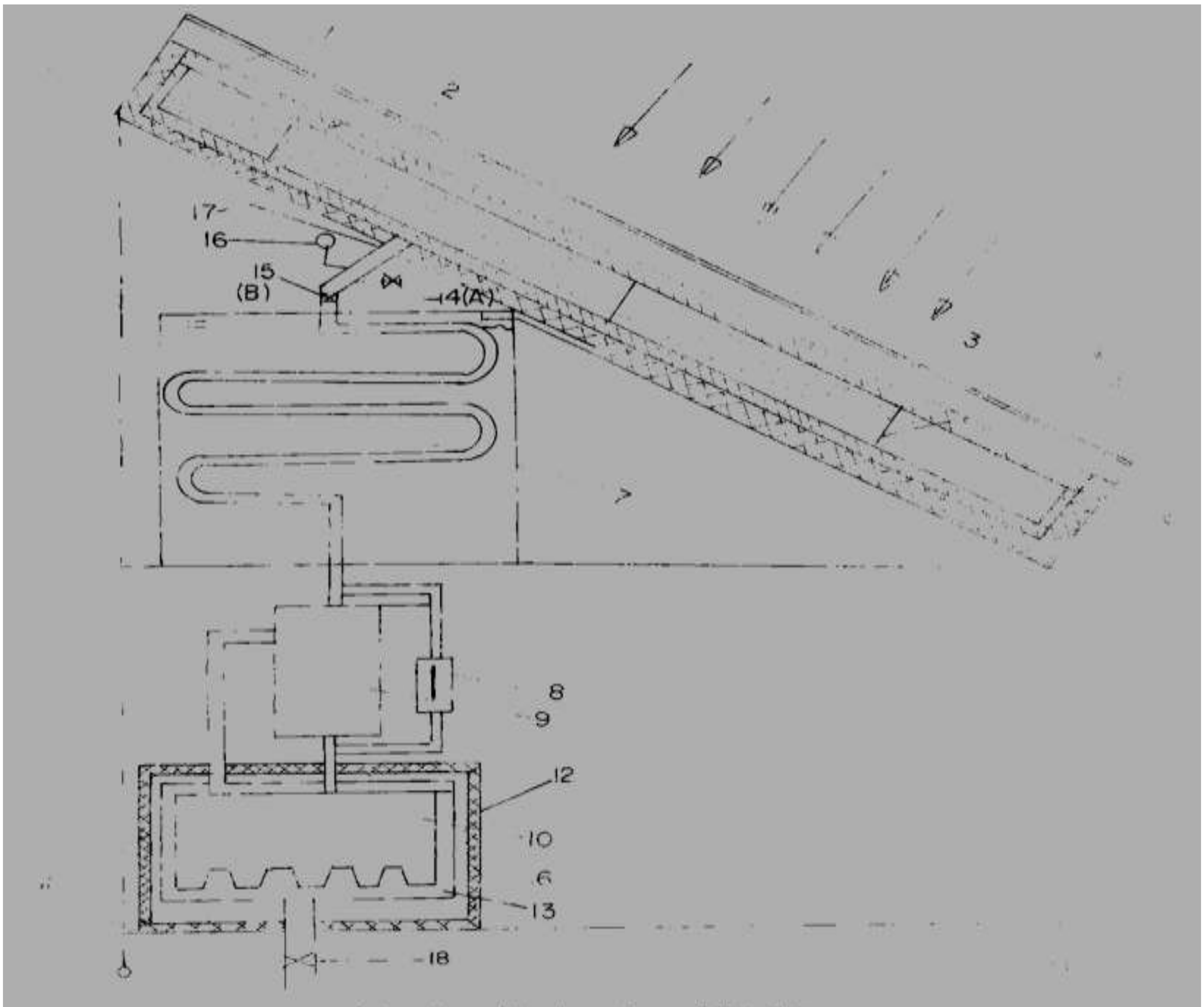

Fig 4.1: Schematic diagram of the solar solid adsorption refrigerator
1...metal shell, 2...coating, 3...adsorbent, 4...glass cover, 5...fins, 6...insulation
7...water cooled condenser, 8...level indicator, 9...liquid receiver, 10...evaporator
11...bracket, 12...Insulated box, 13...Ice box, 14,15...valves, 16...pressure gauge,
17...connecting pipe, 18...Drain valve

Experimental setup and instrumentation

By connecting the adsorbent bed, the condenser and the evaporator with ∅ 21mm galvanized steel pipes; the solar refrigerator was built. The refrigerator was evacuated to flush out the air and moisture that may degrade the working process of the adsorption pair. In order to facilitate evacuating the solar refrigerator and charging it with refrigerant, a valve was installed above the condenser. Furthermore, a pressure gauge with a reading accuracy of ±0.5 kPa was installed to show the pressure in the adsorbent bed. The adsorbent bed was inclined at an angle of 7.25^{o} towards the South. The absorbent was charged with NH_3 gas. During charging, valve B was shut while valve A was opened (Fig. 1). The cover for the collector/ adsorber assembly was removed to facilitate adsorber plate cooling.

During generation, the cover for the absorber/collector assembly was replaced. The adsorber plate surface temperature, condenser water temperature, condensate volume and ambient temperature and pressure were recorded. Generation was allowed to proceed until no appreciable further increase in the condensate volume was observed. After generation, the cover of the collector/adsorber assembly was removed, and the collector/adsorber allowed to cool down. The adsorber plate surface temperature and ambient temperature were recorded during the cool-down period.

Before the start of adsorption, a measured volume of water was introduced into the evaporator vessel. The cover plate was removed. Initial and final condensate liquid volume, evaporator cell surface temperature, evaporator water temperature, plate surface temperature, ambient temperature were recorded. The evaporator water volume was measured at the end of adsorption. The mass of ice obtained was determined from the volume of water in the evaporator before and after adsorption. In order to collect the data necessary to evaluate the performance of the solar refrigerator, a series of sensors and instruments were employed. All tube surface temperatures and evaporator water temperatures were measured with digital thermometers having Type K thermocouple sensors, having accuracy of $\pm(0.75\%+2^{o}C)$. Condenser water and ambient temperature were measured with a mercury-in-glass thermometer, with a reading accuracy of $\pm$ $0.5^{o}C$. Gauge pressures were taken with 0-20 bar pressure gauges with a reading accuracy of ± 0.1 bar. Evaporator water volume was determined with a measuring cylinder graduated in cm^3.

The total radiant energy per unit area on a horizontal surface was determined using a pyranometer having a sensitivity of 17 $\mu V/Wm^2$. The output of the Pyranometer was given in millivolts. The readings were converted to W/m^2 using a calibration constant, 60.83×10^3 A/m^2. The cumulative incident energy was read at 30-minute intervals.

Results and Discussion

Table 2 shows the system operating condition of the solar refrigerator whilst Tables 3, 4 and 5 depict the data reduction for three runs of the refrigerator (on 20th, 21st and 22nd August 2007 respectively).

Figs. 2 - 4 show the temperature and condensate (profiles) during generation on 20th, 21st and 22nd August 2007 respectively whilst Figs 5 - 7 show the temperature profile during cooling and absorption on the said days respectively. It is evident from Figs. 2 - 4 that the temperature profile of the adsorber plate depends on the solar flux. The ambient, collector plate temperatures closely followed the solar radiation pattern. The collector plate temperatures depend on solar level radiation levels and the rate of heat loss from the system to the immediate environment. A steep rise in the collector plate temperature occurred between 9.00 and 12.00 noon for the three runs of the solar refrigerator. The heating resulted in increasing the temperature of the system. The solar collector glazing was covered with dew for most of the mornings thus contributing to the delayed heating of the system and the onset of condensation.

The maximum temperature attained by the collector plate was 90°C. After the peak, the collector plate temperature decreased with decreasing solar radiation intensity. The sensible heat of the collector plate and of the absorbent (70% $CaCl_2$ + 10% Activated Carbon + 20% $CaS0_4$) permitted desorption to continue even during the period when the solar flux and collector plate were consistently decreasing. During generation the amount of Ammonia condensate collected ranged between 0.60 - 0.98 kg below ambient temperature. Ambient temperature during ammonia generation ranged between 27 – 28 °C. This implies that the condensing temperatures for a water-cooled condenser must of necessity be lower than those of an air-cooled condenser which must dissipate heat to the surroundings, even at the hottest time of the day. The generation period was constant at 8 hours for the three runs of the solar refrigerator.

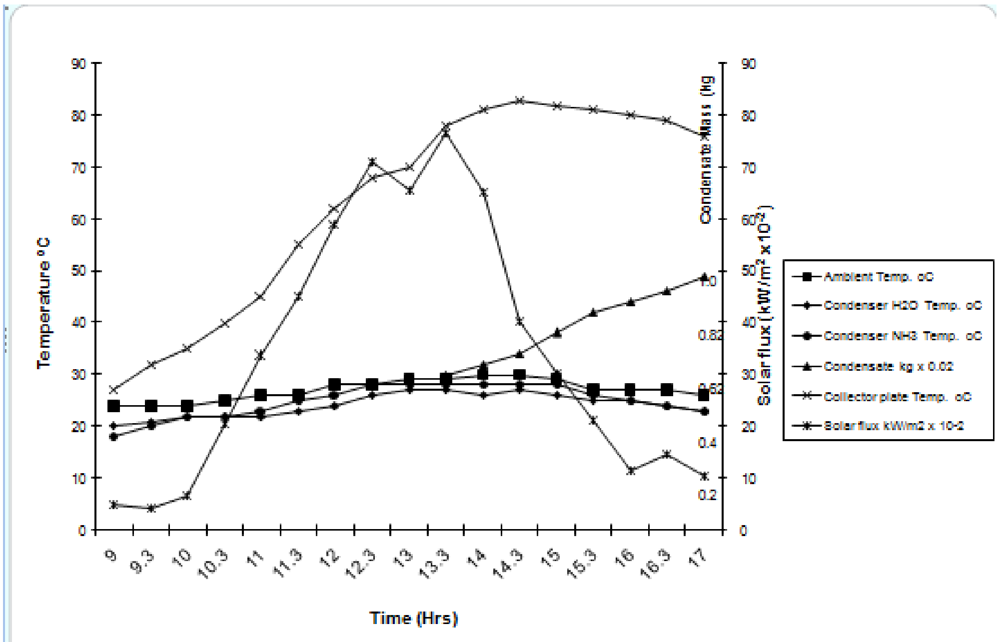

Fig. 2: Temperature and Condensate (profiles) during generation (run no. 2)

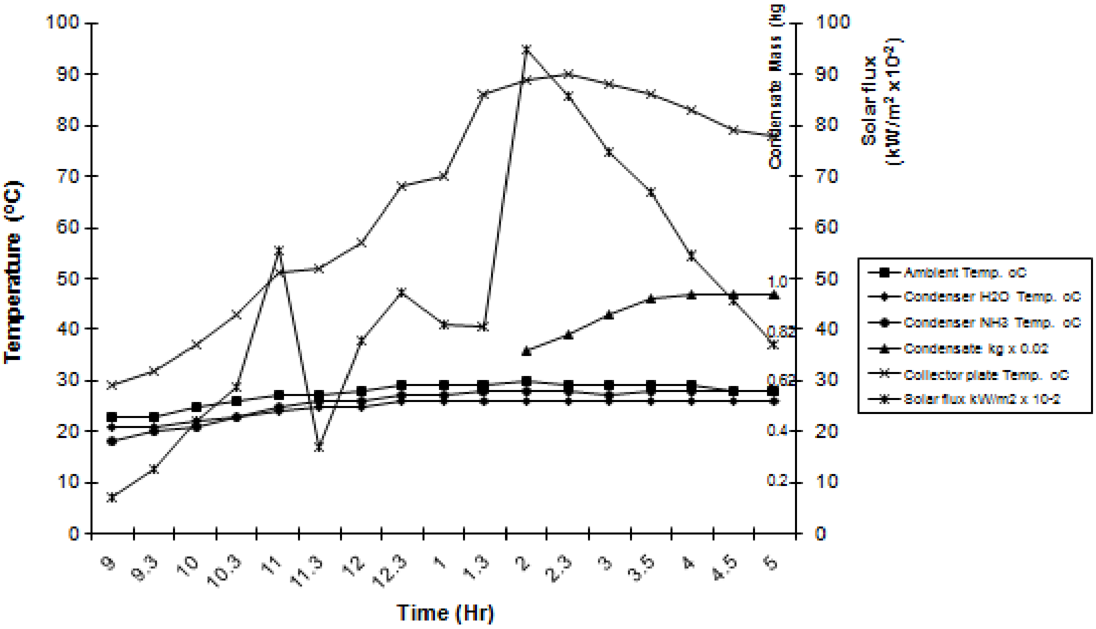

Fig. 3: Temperature and Condensate (profile) during generation (run no. 3)

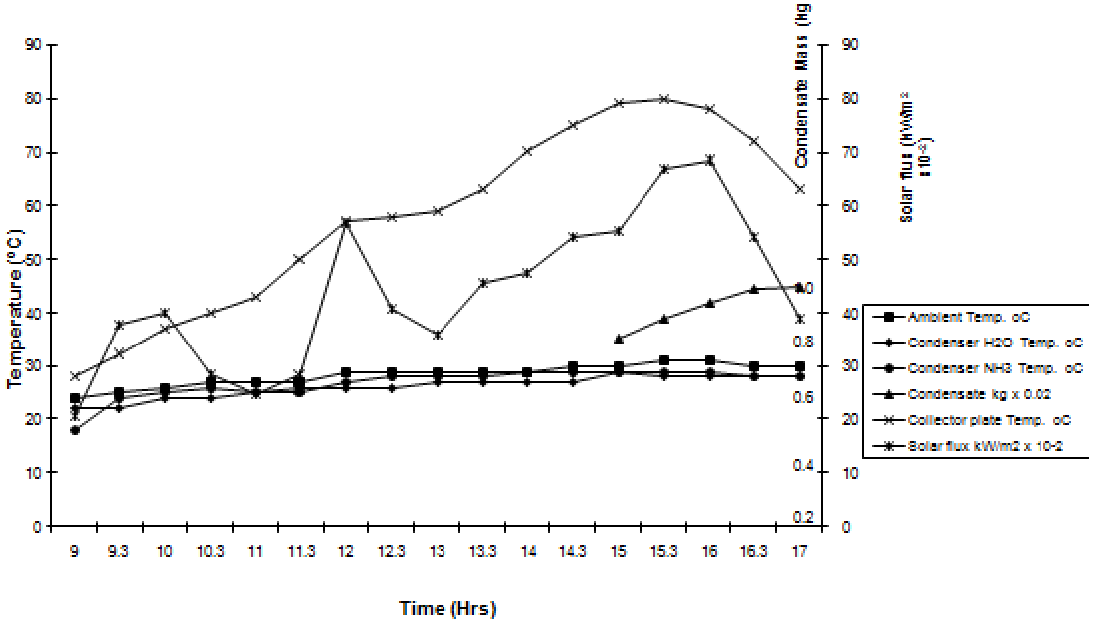

Fig. 4: Temperature and Condensate (profiles) during generation (run no. 4)

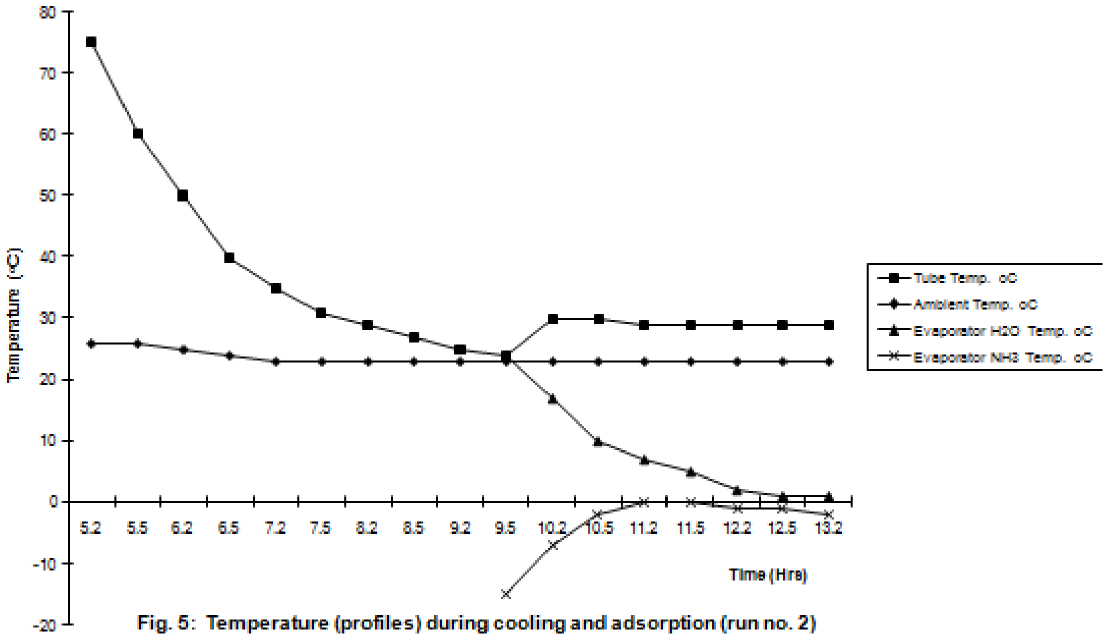

Fig. 5: Temperature (profiles) during cooling and adsorption (run no. 2)

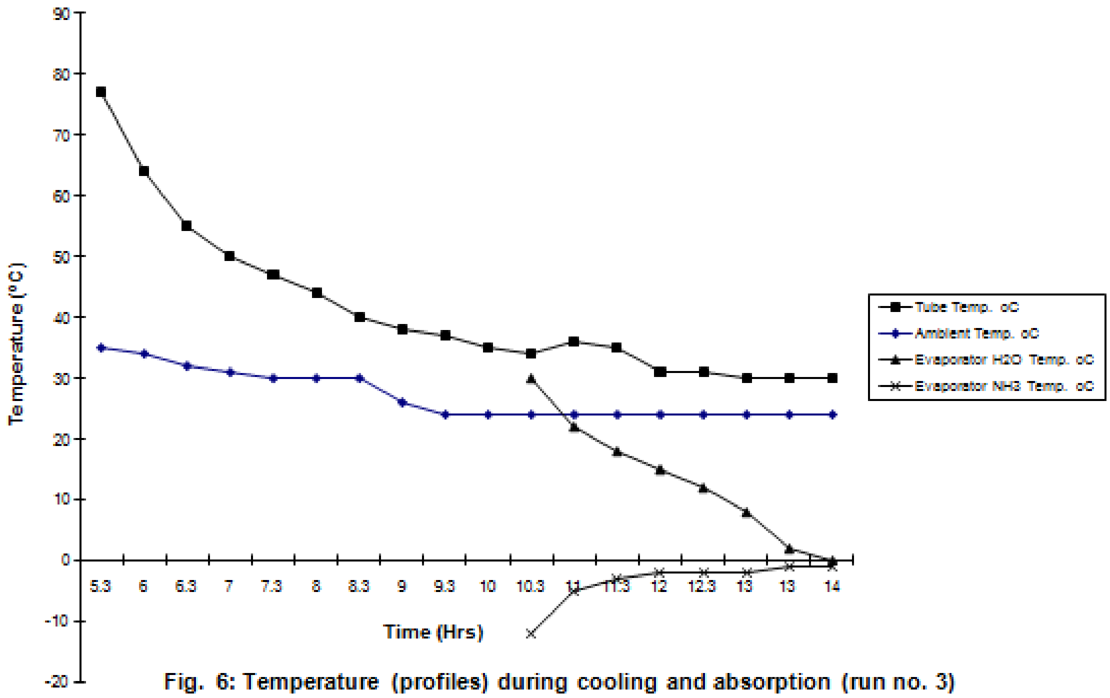

Fig. 6: Temperature (profiles) during cooling and absorption (run no. 3)

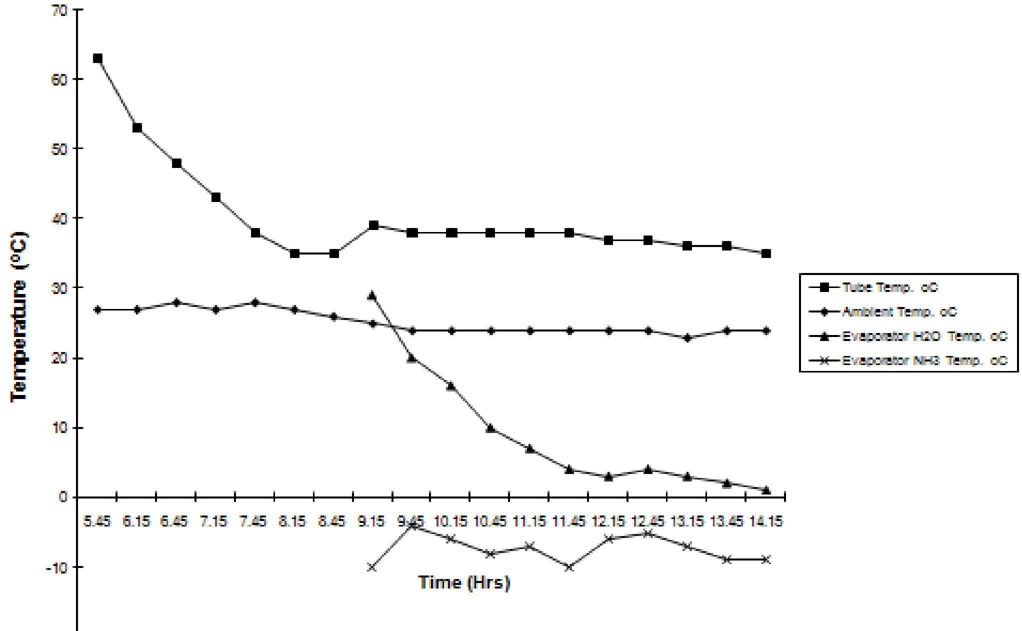

Fig. 7: Temperature (profiles) during cooling and absorption (run no. 4)

TABLE 2: System Operating Conditions

	Run 2	**Run3**	**Run 4**
Generation time (Hrs)	8	8	8
Cool down time (Hrs)	4	4.50	3
Adsorption time (Hrs)	3.33	3.50	5
Average Ambient Temperature during generation (^{0}C)	27	27	28
Average Ambient temperature during adsorption (^{0}C)	23	24	24
Average condenser water temperature (^{0}C)	25.5	24.8	26.1
Nominal evaporation temperature (^{0}C)	-10	-10	-10
Period evaporator below ^{0}C (hours)	2	2.30	5
Total mass of evaporator water (kg)	3.2	4.0	2.5
Initial water temperature (^{0}C)	24	30.0	29
Final water temperature (^{0}C)	1	0.0	1
Mass of ice produced (kg)	0.51	0.63	0.49
Overall COP	0.029	0.033	0.021

TABLE 3: Data Reduction for 20 August 2007

Parameter	**Value**
Amount of NH_3 generated	= 0.98 kg
Heat of evaporation (h_{fg} at 0^0C)	= 1261.9 kJ kg^{--1}
Amount of cooling available	= 0.98 x 1261.9 = 1236.7 kJ
Amount of cooling obtained $m_w\ C_w\ \Delta T_w$	= 3.2x 4.217 x 23 = 310.37 kJ

COP cooling process	= 310.37/1236.7 = 0.25
Mean direct radiation	= 319 W/m^2
Total direct radiation (total 8.00 – 7.00)	= 9 x 3600 s. 319 W/m^2 x $1m^2$ = 10335.6 kJ
(COP) $_{\textbf{Total}}$	= 310.37/10335.6 = 0.030

TABLE 4: Data Reduction for 21 August 2007

Parameter	**Value**
Amount of NH_3 generated	= 0.94 kg
Heat of evaporation (h_{fg} at 0^0C)	= 1261.9kJ kg^{--1}
Amount of cooling available	= 0.94 x 1261.9 = 1186.2 kJ
Amount of cooling obtained $m_w C_w \Delta T_w$	= 4 x 4.217 x 30 = 506.04 kJ
COP cooling process	= 506.04/1186.2 = 0.43
Mean direct radiation	= $471W/m^2$
Total direct radiation (total 8.00 – 7.00)	= 9 x 3600 s. $471W/m^2$ x $1m^2$ = 15620.4 kJ
(COP) $_{\textbf{Total}}$	= 506.4/15260.4 = 0.033

TABLE 5: Data Reduction for 22 August 2007

Parameter	**Value**
Amount of NH_3 generated	= 0.90 kg
Heat of evaporation (h_{fg} at 0^0C)	= 1261.9kJ kg^{--1}
Amount of cooling available	= 0.90 x 1261.9 = 1135.7 kJ
Amount of cooling obtained $m_w C_w \Delta T_w$	= 2.5 x 4.217 x 28 = 295.19 kJ
COP cooling process	= 295.19/1135.7 = 0.26
Mean direct radiation	= $431W/m^2$
Total direct radiation (total 8.00 – 7.00)	= 9 x 3600 s. $431W/m^2$ x $1m^2$ = 13964.4 kJ
(COP) Total	= 295.19/13964.4 = 0.021

The period for which evaporator water was below 0°C ranged between 2 - 5 hours. The evaporator water temperature decreased gradually until it reached a final value at the end of the test. The lowest temperatures obtained varied over 0 - 1°C. The mass of ice produced was 0.49 - 0.63kg/m^2 per day whilst the useful overall COP of the solar refrigeration system ranged between 0.021 - 0.033. This is a significant achievement when compared to work of Iloeje [8] where the daily ice production was between 0.42 - 0.58 kg/m^2 per day and the overall COP ranged between 0.02 - 0.028.

Higher COPs may be realized during the dry season when solar radiation intensities are higher. Again higher COPs may be realized at a solar collector angle of tilt 10° plus local latitude, 17.25^o (Kalogirou, 2003.

CONCLUSIONS

A solar adsorption refrigeration system utilizing granular 70% $CaCl_2$ + 10% activated carbon + 20% $CaSO_4$ / NH_3 as an adsorbent/adsorbate pair was designed, constructed and tested. The mass of ice produced was 0.49 - 0.63kg/m^2 per day whilst the overall COP of the solar refrigeration system ranged between 0.021 - 0.033. The solar refrigerator may provide an alternative way for cold storage of food and vaccine in this Country where most towns/villages/cities receive an abundant solar radiation annually.

The present solar refrigerator is advantageous in that it has no moving parts and there is no need for electricity to power it although it has lower COP when compared with the conventional vapour compression refrigerator. The development of adsorption system for refrigeration is promising. The performance of adsorption systems depends on both adsorption pairs and processes. The cost of energy produced by thermal adsorption systems is much lower than that for conventional refrigeration systems considering the cost of fuels, electricity transmission and system maintenance involved in the latter. If solar adsorption systems are to complete favourably with conventional and vapour compression technologies, efforts should be made in enhancing the Coefficient of Performance (COP) and Specific Cooling Power (SCP). Heat recovery, mass recovery, multi-bed and multistage technologies could improve the COP and SCP of solar adsorption refrigeration systems.

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