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EXPERIMENTATION OF AN ACTIVATED CARBON/METHANOL SOLAR REFRIGERATOR

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Abstract. Adsorption refrigeration systems become promising alternative cooling technology for refrigeration and air conditioning applications. Thermal energy is a primary source of such systems for producing cooling capacity with less electricity usage compared to vapour compression systems. Solar energy with free-access and abundant availability in the tropics have great potential as a renewable heat source to drive the adsorption refrigeration systems through direct conversion from solar irradiation to the thermal energy. This paper describes experimental work on the performance of a solar adsorption refrigerator working with activated carbon/methanol pair in Bali area. The solar refrigerator has an adsorber with an effective surface area of 0.259 m^2 enclosed in a double-glazed collector box. The cooling load of the evaporator is 1 kg of water sited inside a cooler box of 0.37 x 0.25 x 0.345 m size. The experimental tests were performed outdoor to determine system cooling capacity and solar COP. Test results indicated that the refrigerator capable of bringing down water temperature at 18 ºC, while the system cooling capacity and COP reach 47.5 kJ and 0.046. Moreover, it is supposed that the solar adsorption refrigerator can be applied to pre-cooling post-harvest agricultural products, mainly tomatoes, before distribution to the grocery stores or end consumers.

Keywords : Activated carbon/methanol, Adsorption refrigerator, Intermittent, Solar energy

1. INTRODUCTION

Refrigeration machines, which mostly work based on vapour compression cycles, have been known as intensive electricity equipment. The electricity supply mainly comes from fossil-energy based power generators, which contribute indirectly to global warming by CO_2 gas emissions. Moreover, the refrigerant types used, namely chlorofluorocarbons (CFCs), hydrofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs), have a significant ozone-layer depletion potential that very harmful to the environment [1-2].

Solar adsorption refrigeration (SAR) systems offer an attractive solution to provide more environmentally friendly cooling by using natural refrigerants (e.g., water, methanol, ethanol, and ammonia) and easily accessible renewable energy resources. Solar thermal energy, which delivered with or without heat transfer fluids, becomes a primary driving power to run such systems instead of electricity. Importantly, the solar irradiation availability period is coincident with the cooling demands and potential to reduce the peak load of electricity [3-5].

The SAR systems employ refrigerant and adsorbent as a working pair and operate under pressurised or partial vacuum conditions [5]. Some important working pairs are silica gel/water, zeolite/water, activated carbon/ammonia, activated carbon/ethanol, and activated carbon/methanol [6-7]. The activated carbon/methanol can be driven with a heat source of low-grade temperatures, such as solar energy [8]. Its maximum desorption temperature is 120 ºC, and working at a high vacuum pressure [9]. Activated carbon is a sorbent material that has a large adsorption capacity of 0.45 kg/kg with a specific surface of 400-2500 m2/gram and low desorption heat of 1800-2000 kJ/kg [10-11]. Methanol is a refrigerant with the high latent heat of evaporation and freezing point lower than water, which is suitable for ice-making and refrigeration applications [12].

Many researchers reported experimental works on the activated carbon/methanol SAR system. Buchter et al. [13] built and tested an adsorptive solar refrigerator equipped with a 2 m^2 of single-glazed solar collector/adsorber in Burkina-Faso. The gross solar COP obtained was 0.09-0.13, with the water of 40 L immersed in the evaporator. The solar irradiance during the test was 19-25 MJ/m^2. Santori et al. [14] carried out a field test of a stand-alone solar adsorption refrigerator for vaccine storage in Messina, Italy. They used a solar collector exposed area of 1.2 m2. A solar COP of 0.08 was achieved by producing 5 kg of ice.

Anyanwu and Ezekwe [15] conducted an experimental test on a solid adsorption solar refrigerator in Nsukka, Nigeria. The refrigerator used a flat type collector with an effective exposed area of 1.2 m^2. The best cooling capacity yielded of 266.8 kJ/m^2 per day, and the useful cycle COP achieved of 0.056-0.093. Li et al. [16] developed a no valve flat plate solar ice maker in the West of China. The solar collector area was 1 m2, which produce 4-5 kg ice under solar irradiation of 18-22 MJ/m^2. The solar COP obtained was 0.12-0.14. Leite et al. [17] tested a solar adsorptive ice maker in Brazil. The collector-adsorber used multi-tubular with transparent insulation material and a projected area of 0.61 x 1.65 m. The solar COP gained was 0.085 at solar irradiation of 23.7 MJ/m^2. The ice produced was 6.05 kg.

Lemmini and Errougani [18] experimentally tested a flat plate solar adsorption refrigerator in Marocco under Mediterranean climate. They found that solar COP achieved was 0.05-0.08 at 12-28 MJ/m^2 solar insolation and daily mean ambient temperature of 20 ^oC. The lowest evaporator temperature was at -11 ^oC. Ambarita et al. [19] reported the experimental test of a flat plate type solar-power adsorption refrigeration cycle with adsorbent of activated alumina and activated carbon in Medan city. The solar collector area used was 0.25 m^2. They concluded that the pair of activated carbon/methanol was better than activated alumina/methanol. The solar COP yield was 0.074 with solar irradiation of 13.63 MJ/m^2. The lowest evaporator temperature achieved was 7.3 ^oC, while the maximum generator temperature was 110.1 ^oC.

To the author's knowledge, only a few research reported performances of an intermittent solar adsorption refrigeration system under Indonesia's climate conditions, particularly in Bali island. Accordingly, this paper presents an experimental investigation of a solar adsorption refrigerator by utilising activated carbon/methanol pair with an intermittent working cycle in the Bali area. The system performance in terms of cooling capacity, solar COP, and the evolution of the pressure and temperature during the adsorption cycle are discussed. Furthermore, the developed refrigerator prototype is expected to be used as a pre-cooling device for post-harvest agricultural products, mainly tomatoes, before distribution to the grocery stores or end consumers.

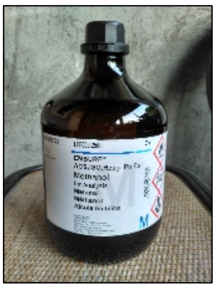
2. METHODS

2.1 Experimental Setup and Materials

Figure 1 shows a photograph of the prototype of an experimental setup. It composes of three major parts, namely a solar collector/adsorber, a condenser, and an evaporator/cooler box. The solar collector is a flat plate type made of steel plate with a 0.259 m^2 effective exposed area and tilt angle of 9 ^{o}. The solar collector is insulated with polyurethane of 40 mm and 60 mm thickness for the side and bottom walls, respectively, to prevent heat losses and painted using black-doff colour to absorb more heat. The top side of the solar collector is covered by double glass layer of 3 mm thickness each with a 40 mm gap.

The adsorber is placed inside the solar collector and connected to the condenser through a pipe header. The adsorber consists of 10 rows copper pipe with the outer pipe size of 41.3 mm OD, 39.1 mm ID, and 420 mm long, whereas the coaxial inner one is a perforated copper pipe of 2 mm in diameter with a dimension of 9.5 mm OD, 8 mm ID, and 480 mm long. The activated carbon is loaded about 5.4 kg in between of the two pipes. The condenser is made of copper pipe of 19.05 OD, 175 mm long arranged in five rows vertically, and connected to the two headers. The evaporator uses a copper plate of 1.8 mm thickness with a trapezoidal surface and a heat transfer area of 0.119 m^2. The cooler box has 16 L capacity and 0.37 x 0.25 x 0.345 m size.

Figure 2 shows a working pair of activated carbon/methanol employed for the experimental prototype. The activated carbon is a granular type of coconut-based carbon, and the methanol is a product of Merck with a purity of 99.9%.



(a)

(b)

Figure 2. Working pair: (a) methanol, (b) activated carbon

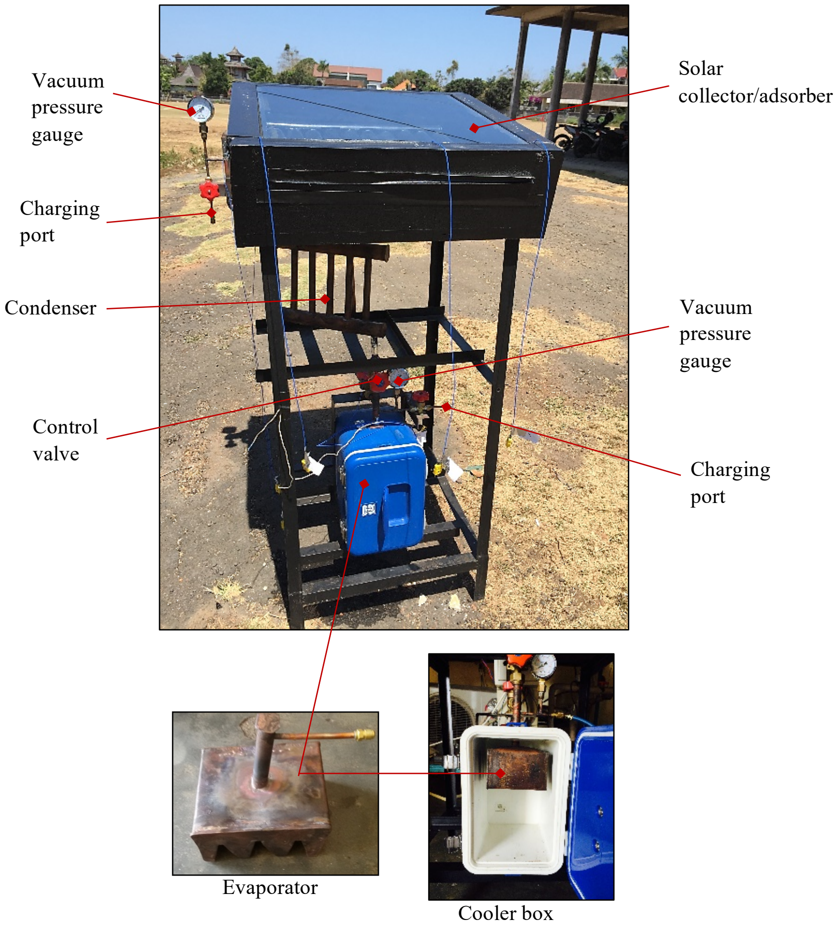


Figure 1. Experimental prototype

2.2 Procedures

The adsorption refrigerator prototype is firstly heated up to the adsorber temperature of 110 ºC using 2 x 500 W halogen lamps. At the same time, deeply vacuum to the pressure of -76 cmHg using a vacuum pump to ensure no gases trapped inside the system. This step is called degassing process to achieve proper system vacuum by releasing non-condensable gases, which bonded to the activated carbon in the adsorber. The system vacuum condition is maintained and monitored for 48 hours to ensure that no leakage occurs. Subsequently, 425 ml of methanol is charged into the system via a charging port closed to the evaporator/cooler box. The system is then ready for the outdoor performance test.

The performance test has been carried out on 21 July 2019 at Politeknik Negeri Bali for one day at the local time started from 08.30 to 05.30 the next day by using 1 kg of water as a cooling load. The evaporator is immersed in the water. The control valve between the condenser and the evaporator is kept fully opened during the test period to perform a no valve adsorption cycle operation.

The experimental data is collected from the reading of measurement instruments in 30 minutes interval. The K-type thermocouples measure the temperature in the adsorber, condenser, evaporator, water, and ambient air, and the readings are displayed on a Krisbow (KW-06-283 model) digital thermometer. Two analog vacuum pressure gauges are placed adjacent to the adsorber and evaporator. For solar irradiation measurement, a solar power meter (SM206 model) is employed.

The system cooling capacity is calculated by using Eq. 1, while solar energy received by the collector/adsorber and the solar COP calculation refer to Eq. 2 and Eq. 3 [10], [15]. The cooling capacity is determined from the product of water quantity (mw), specific heat of water (cp,w) and temperature change from initial temperature (Ti) to final temperature (Tf).

$$Q_c = m_w \, x \, c_{p,w} \, x \, (T_i - T_f) \quad (1)$$

The total solar irradiation energy incident (E_s) to the collector is determined by the product of solar irradiation intensity over the whole day from sunrise (tsr) to sunset (tss) and the collector exposed surface area (A_c).

$$E_s = \int_{tsr}^{tss} I_{s(t)}\, x\, A_c\, dt \quad (2)$$

$$COP_s = \frac{Q_c}{E_s} \quad (3)$$

3. RESULTS AND DISCUSSION

The temperature evolution of the adsorber and evaporator with the solar irradiation profile in a day are depicted in Figure 3. The solar irradiation reaches the peak of 866 W/m^2 at 12.00. The partly cloud is observed at 10.30, and the solar irradiation drops to 101 W/m^2. From 15.30 to 18.00, the solar irradiation decreases gradually from 479 W/m^2 to 87 W/m^2. The total solar irradiation energy received by the solar collector in a day is 14.35 MJ/m^2. The ambient temperature fluctuates 28.3-35 ºC during day time from 08:30 to 18.00. Accumulated heat in the solar collector increases the temperature of the adsorber along with the solar radiation evolution, reaching the maximum adsorber temperature of 77.8 0C from the start point of 37 ºC at 08.30. However, the condenser temperature fluctuates slightly, achieving a peak of 38.2 ºC at 12.00. The maximum temperature difference between condenser and ambient air is 5 ºC at 12.30. The response of the adsorber temperature increment is slower than that of the solar radiation received by the solar collector, due to the low thermal conductivity of the activated carbon and heat losses in the solar collector.

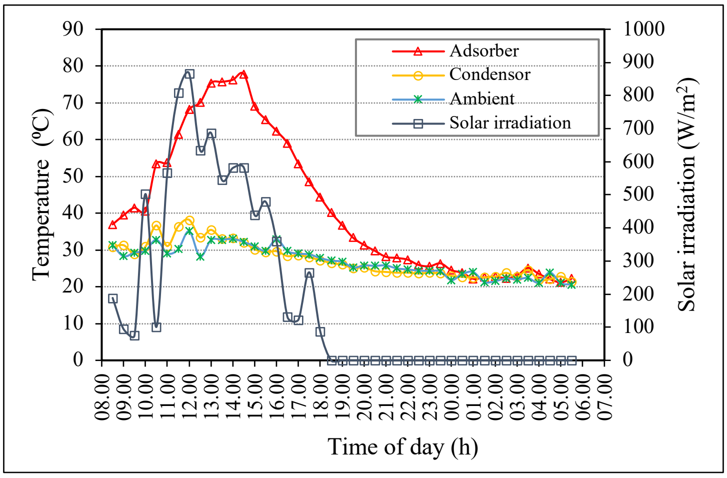


Figure 3. Variation of adsorber and evaporator temperatures, and solar irradiation with time

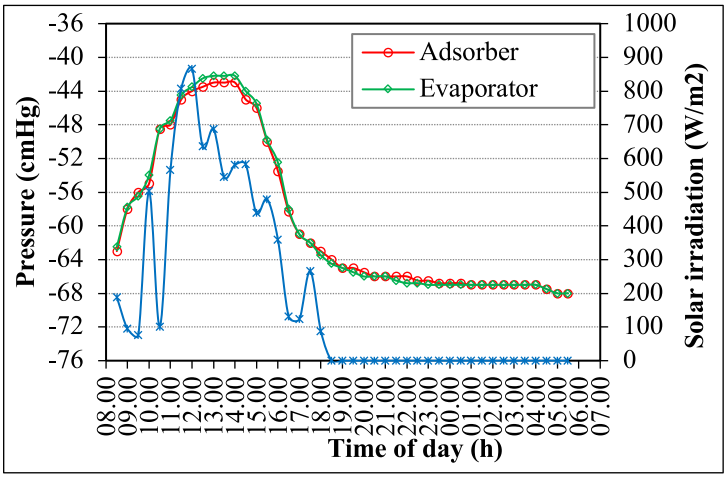


Figure 4. Variation of adsorber and evaporator pressures, and solar irradiation with time

Figure 4 shows the variation of the adsorber and evaporator pressure with the solar irradiation in a day. At th e starting point at 08.30, the adsorber pressure is -62.5 cmHg and increases upon the peak of -43 cmHg at 14.00. The adsorber pressure increases dramatically between 08.30 and 12.00 and stable at -43 cmHg for about 2 hours and then decreases significantly to -64.5 cmHg at 18.00. The stable period of the adsorber pressure indicates the condensation of the vapor methanol occurs. The evaporator pressure increases proportionally with the adsorber pressure. A slight pressure difference of 0.5 cmHg between the adsorber and the evaporator observed during the exposure of the solar irradiation. It is the effect of no valve operation, and pressure drop occurs in the adsorption system line. During the night-time (18:30-05:30), the adsorber and evaporator pressure decrease following the decrease of ambient temperature from 27.8 ºC down to 20.6 ºC.

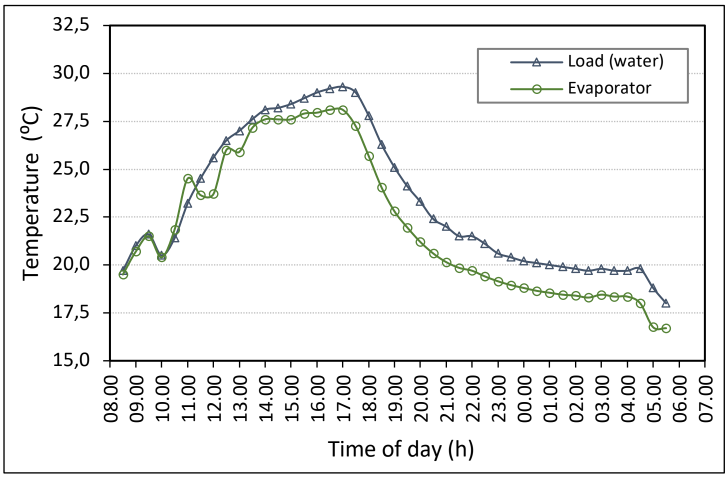


Figure 5. Variation of evaporator and water temperatures with time

The fluctuation of the evaporator and water temperature during the test period are shown in Figure 5. At the beginning of the test at 08.30, both of the temperatures is at 19.5 ºC. The evaporator and water temperature increase to a maximum of 28.1 ºC and 29.3 ºC, respectively, at 17.00. Accordingly, both of the temperatures decrease significantly down to 19.2 ºC and 20.6 ºC, at 23.00, and being stable for about 5 hours at 18 ºC and 19.8 ºC. It indicates that the evaporation process is being completed. The minimum temperature by the evaporator and water is 16.7 ºC and 18 ºC and keep stable for about 1 hour.

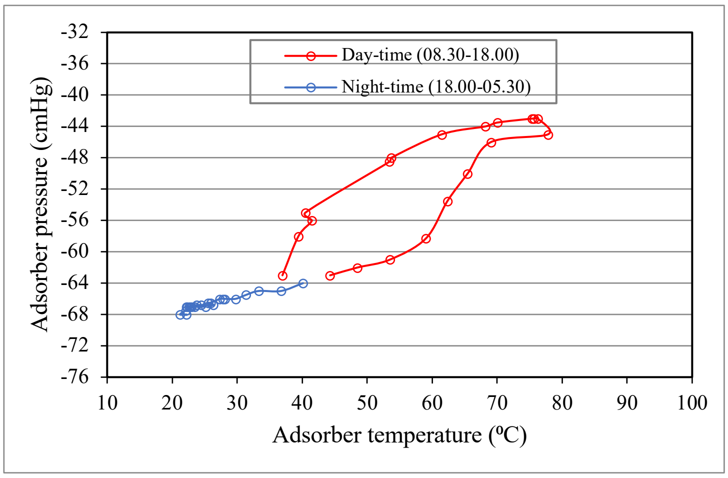


Figure 6. Actual characteristics of a solar adsorption refrigeration cycle

Figure 6 shows actual characteristics of the no valve solar adsorption refrigerator represented by the evolution of temperature and pressure in the adsorber. Referring to stages of the process of the theoretical adsorption cycle (Fig.2), the heating, desorption, and part of the cooling processes occur during day-time (08.30-18.00). It is apparent that the condensation process starts at the adsorber temperature of 61.5 ºC (-45 cmHg) until the respected temperature reaches a maximum of 77.8 ºC (-43 cmHg). During the night-time (18.00-05.30), the adsorber temperature drops about 18.9 ºC from starting at 40.1 ºC then ends close to the ambient temperature. It can be seen from the figure that the solar adsorption prototype works appropriately, similar to the theoretical adsorption cycle.

The cooling capacity is calculated based on the temperature changes of the water from a maximum of 29.3 ºC to a minimum of 18 ºC. Taking specific heat of the water is 4.2 kJ/kgK, the cooling capacity obtained is 47.5 kJ. The solar coefficient of performance (COP) is the ratio of the cooling capacity to the solar irradiation received by the solar collector. The solar COP obtained is 0.046 based on the effective exposed area of the solar collector of 0.259 m^2 and total solar irradiation energy of 14.35 MJ/m^2.

4. CONCLUSION

The experimental prototype of an activated carbon/methanol solar refrigerator has been built and tested with the exposure of solar irradiation in Bali Province, Indonesia. The solar adsorption refrigerator works up to a maximum adsorber temperature of 77.8 ºC by receiving total solar energy of 14.35 MJ/m^2. The cooling capacity produced is 47.5 kJ, and the solar COP yields 0.046. The minimum temperature by the water as a cooling load medium is 18 ºC. Further investigation is needed to improve the solar collector design to capture more heat, thus increasing the adsorber temperature to obtain more methanol flowing to the evaporator and optimising the system cooling capacity and solar COP.

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