SOLAR-POWERED ADSORPTION REFRIGERATION CYCLE OPTIMIZATION
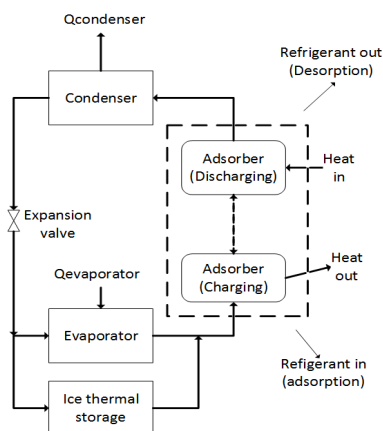
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Graphical abstract

Abstract

Solar energy is an attractive energy source among various renewable energy resources in Malaysia as relatively high solar radiation is available throughout the year. This solar energy can be utilized for air-conditioning by using solar-powered adsorption refrigeration cycle. Intermittent nature of the solar radiation leads to a challenge for continuous air-conditioning operation. In the present study, a combination of solar adsorption refrigeration system based on activated carbon-ammonia or activated carbon-methanol working pairs, and thermal storage is studied. Analytical calculation results show that activated carbon-methanol pair indicates higher coefficient of performance (COP) than activated carbon-ammonia pair, while adsorption chiller system with hot water thermal storage has higher COP than the system with ice thermal storage. For the activated carbon-methanol case with hot water thermal storage, the COP is 0.79. Since this COP analysis is based on the ideal case with uniform temperature distribution within the reactor beds, which achieve equilibrium states at the end of reactions. In more realistic situation, the reaction process will be terminated before reaching to the equilibrium states because of the non-uniform temperature distribution and the time required for the reaction. Transient simulation in which heat transfer and reaction equation are combined will be performed to model actual reactors.

Keywords: solar-powered; adsorption refrigeration; adsorption capacity; thermal storage

1.0 INTRODUCTION

The development of solar refrigeration technologies became the worldwide interest because the air-conditioning demand increases in parallel with the availability of the solar radiation [1]. Solid adsorption refrigeration system is a green technology to reduce the dependency on electricity from fossil fuels and producing cooling for air-conditioning from solar energy. Solid adsorption refrigeration is achieved by adsorbing gaseous refrigerant onto the porous surface of solid adsorbent. When solar energy is used as the main energy source, activated carbon, zeolite, and silica gel are the common materials used as an adsorbent. Environmental-friendly materials including ammonia, methanol, or water can be a refrigerant. The adsorbent-refrigerant pairs that employ these

materials are considered as zero ozone depletion potential as well as zero global warming potential.

The solar adsorption refrigeration system consists of a solar collector, adsorber reactors, a condenser, and an evaporator. The adsorption refrigeration cycle is shown in Figure 1. When solar radiation is available, the solar collector captures the solar thermal energy, which is transferred to the adsorber reactors. The heated adsorber reactor releases the refrigerant from its adsorbent in desorption process. The released refrigerant is liquefied in the condenser and sent to the evaporator. At the same time, heat is removed from another adsorber reactor, which adsorbs the refrigerant vapor from the evaporator. As the pressure in the charging adsorber reactor reduces, the refrigerant vaporizes in the evaporator. As a result, heat is removed from the anti-freeze solution used as the air-conditioning working fluid at

the evaporator. These processes of desorption and adsorption will be performed alternately between the two adsorber reactors.

The solar adsorption refrigeration processes show low coefficient of performance (COP) and low specific cooling effect (SCE). These drawbacks are caused by the thermal inertia of the adsorbent beds, and can be improved by enhancing the heat and mass transfer in the adsorbent beds [2]. Solar radiation is available intermittently during the daytime due to the humidity in the air, while solar radiation is not available during the night. Some form of thermal storage has to be introduced to provide air-conditioning even when solar radiation is low or not available. The COP of the adsorption refrigeration system is calculated by dividing the cooling capacity gained by the heating capacity required to heat the adsorbent reactors, as in Eqn.(1) below.

$$COP = \frac{Cooling\ capacity\ gained}{Heating\ required\ by\ the\ system} = \frac{Q_{evaporator}}{Q_{regeneration}} \quad (1)$$

Methanol refrigerants generally have higher COP as compared with ammonia refrigerants in adsorption reactions with activated carbon adsorbents.
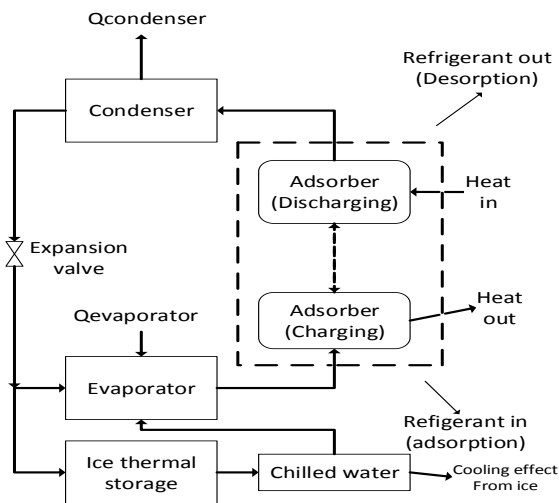

Fig.1. Solar adsorption refrigeration system

Many studies on adsorption refrigeration have been focused on mathematical modeling of heat and mass transfer in the adsorbent beds. The major concerns were on adsorption working pairs' reaction performances, heat transfer in adsorbent beds, and the coupled heat and mass transfer processes. The modeling techniques of heat and mass transfer process of a local thermal equilibrium among the adsorbent and refrigerants in uniform and non-uniform temperature-based models have been reported [3-4]. Recently, continuous operations of cooling production by solar adsorption refrigeration were simulated and the results were validated with thermodynamic analysis [1, 5]. Hassan also suggested a new adsorption refrigeration system concept, in which adsorption process occurs at a constant

temperature of adsorption, achieved at a minimum pressure. The introduction of minimum pressure for adsorption process is used as the adsorption pressure and this pressure is lower than the evaporator pressure [1]. However, additional methods are required to prove this theoretical system because the system needs another parameter called minimum pressure, which is lower than evaporator pressure as in ideal adsorption refrigeration cycle. Furthermore, finned-tube adsorber reactors design was optimized and the mass transfer of the whole system was simulated [6-8]. Experimental results on the performance of the working pairs of adsorbent refrigerants were reported. The results were used to study the adsorption capacity and adsorption kinetics of the working pairs for solar-powered cooling [9-10].

The motivation of this research is to study the transient effects on the reaction rate, and temperature and pressure distribution inside the adsorbent bed. The studies on such transient analysis are very limited. The transient process in the literature proved that the pressure distribution inside the adsorbent beds is uniform during adsorption and desorption processes [11-12]. However, the temperature in the adsorbent beds is not uniform, and thus affecting the reaction rate of adsorption and desorption processes.

In this paper, activated carbon-ammonia and activated carbon-methanol adsorbent-refrigerant working pairs are used to study the time-dependent adsorption and desorption reactions in adsorbers to provide cooling continuously for thermal comfort in buildings. To enhance the performance of the solar-powered adsorption refrigeration system, a methodology to optimize the solar-powered adsorber reactor design is developed taking its transient performance into account. Simulation of time-dependent reaction in the adsorption reactors of the adsorption system is investigated to study the temperature distribution inside the adsorbent bed and its effect to the reaction rate and heat transfer inside the adsorber. In Malaysia, sunlight is available twelve hours a day on average. The solar energy from sunlight will be used as thermal energy supply for the adsorption refrigeration system.

2.0 SOLAR ADSORPTION REFRIGERATION AND THERMAL STORAGE

2.1 Adsorption capacity of reaction working pairs

A good adsorbent has a large adsorption capacity and strong affinity for refrigerant with wide operating temperature and pressure ranges [15]. Meanwhile, a good refrigerant for solar adsorption cooling system should have high latent heat of vaporization to increase refrigerant adsorption capacity. The suitable refrigerants for solar adsorption refrigeration system are including water, ammonia and methanol. Water refrigerant is limited for air-conditioning applications, since it cannot operate in subzero temperatures. In this study, the adsorption capacity of activated

carbon adsorbent with ammonia or methanol refrigerants is determined analytically. The adsorption capacity of ammonia and methanol refrigerants at their saturated pressure and system temperature are calculated from adsorption isotherm equation with the conditions listed in Table 1 and the results are plotted in Figure 2, and this data will be compared with the experimental results. The adsorption isotherm equation is in Eqn.(2) as follows [2]:

$$X = X_o \exp\left\{-K\left(\frac{T}{T_s(P)} - 1\right)^n\right\} \quad (2)$$

Table 1. Variables for D-A equation [1]

Refrigerant	X_{max} (g/g)	K	n
Methanol	0.356	32.65	2
Ammonia	0.29	3.1853	1.0957

Carbon pellets: Type 208C
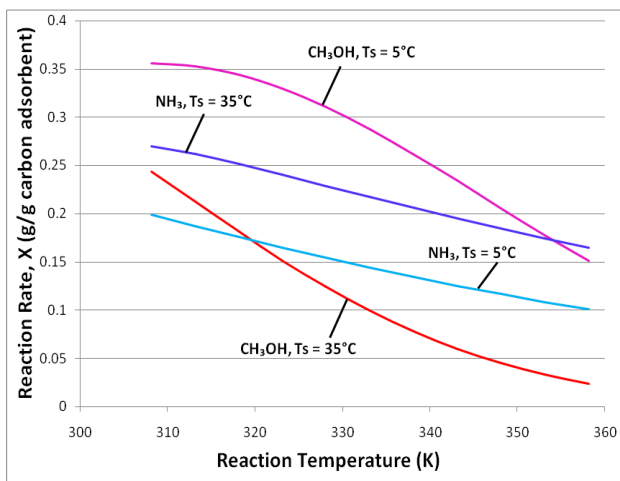
Fig.2. Calculated adsorption capacity of ammonia and methanol for hot water thermal storage

From the adsorption capacity shown in Figure 2, methanol refrigerant shows higher adsorption capacity compared to ammonia refrigerant. Ammonia refrigerant operates at pressure higher than the atmospheric pressure, which is between 0.5 bars to 5 bars, while methanol refrigerant operates at pressure lower than atmospheric pressure. Too low operating pressure of refrigerant may draw outside air into the system and degrade its performance. For long term usage, ammonia may corrode the surface of the reactor while methanol refrigerant is not corrosive.

2.2 Solar collector and thermal storage for continuous operations of chillers

Most of the previous work for solar adsorption refrigeration is focused on flat plate solar collectors, while very few studies are reported on using parabolic trough collector (PTC). A standard flat plate solar collector provides thermal energy at temperatures between 60°C to 80°C, while PTC can provide solar thermal energy up to 350°C.

In this study, solar energy is utilized as the heat source for the adsorption refrigeration system. In order to provide cooling when solar radiation is not available, thermal storage is used with the solar adsorption chillers. There are three possible configurations of thermal storage integrated into the adsorption refrigeration systems; using hot water thermal storage, using increased capacity of adsorbent beds, and ice thermal storage.

In the first case, hot water is used to store heat energy in the form of sensible heat. When solar radiation more than the adsorption reactors require is available, the excess thermal energy is stored in the form of hot water in a tank. The hot water thermal storage extends the operation hours of the adsorption reactors. This configuration is a combination of the existing technologies: conventional waste heat-operated adsorption chiller and the hot water thermal storage. Further technology development is not needed in terms of refrigeration system configuration.
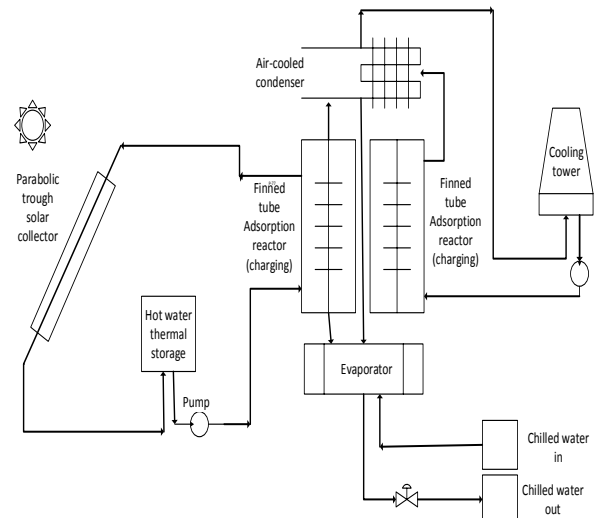

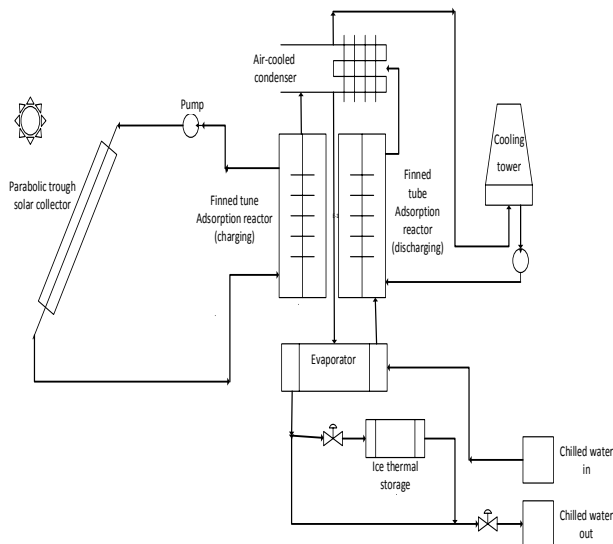**Fig.3.** Adsorption chillers with hot water thermal storage

Figure 3 shows the adsorption chiller system with hot water thermal storage. Although the boiling temperature of hot water is 100°C, the hot water temperature is limited to 85°C. This is because the highest operating temperature for water pumps is 85°C to avoid cavitations. As a result, the desorption temperature of the discharging adsorber reactor is lower than 85°C. The lower the temperature for desorption, the lower the amount of refrigerant that flows out of the adsorbent bed, which leads to lower COP of the refrigeration cycle. For hot water thermal storage, the evaporator temperature for the studied system is set to 5°C considering the demand side temperature requirement for air-conditioning.

For the second case, adsorption beds with extended capacity are used as thermal storage as shown in Figure 4. Transient analysis and performance prediction studies were reported for three adsorber beds, in which cold energy is stored in the form of refrigerant in a separate refrigerant storage tank at ambient temperature in one large bed, and the other two beds perform adsorption and desorption alternately [3]. This approach makes the configuration and operation of the adsorption cycle

complex. The commercially available adsorption chiller units cannot be used as they are.
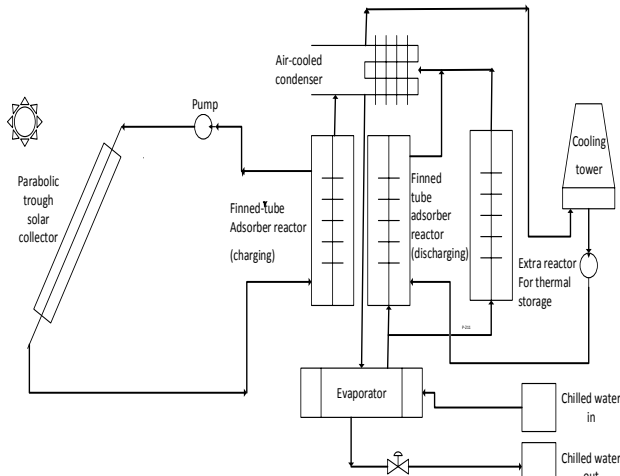
**Fig.4.** Adsorption chillers with extended capacity adsorber beds

Fig.5. Adsorption chillers with ice production thermal storage

In the third case, ice thermal storage is integrated into the adsorption refrigeration system as shown in Figure 5. During the daytime, ice is created using the extra solar thermal energy. Whenever solar energy is unavailable, the thermal energy stored in the ice can be utilized to respond to the air-conditioning demand. Ice thermal storage allows solar radiation fluctuations that do not agree with the demand for thermal energy for air-conditioning. The volume of the ice thermal storage is smaller than other forms of thermal storage because of the large latent heat of fusion of water.

In Figure 6, a comparison of adsorption capacity based on experiment, which is calculated from Equation (2) based on material properties in Table 1, for ammonia and methanol refrigerants towards carbon adsorbents. For ice thermal storage, the evaporator temperature for the studied system is set to -15°C. Ice is created in ice thermal storage using the chilled water, which is antifreeze solution. The discharging capacity for the adsorption reactors

must be large enough to provide cooling for the air-conditioning and ice generation simultaneously. At the same time, the heat provided to the discharging adsorption reactor fluctuates due to the intermittency of solar radiation. The transient heat transfer and resulting desorption reaction within the reactor influences its performance.
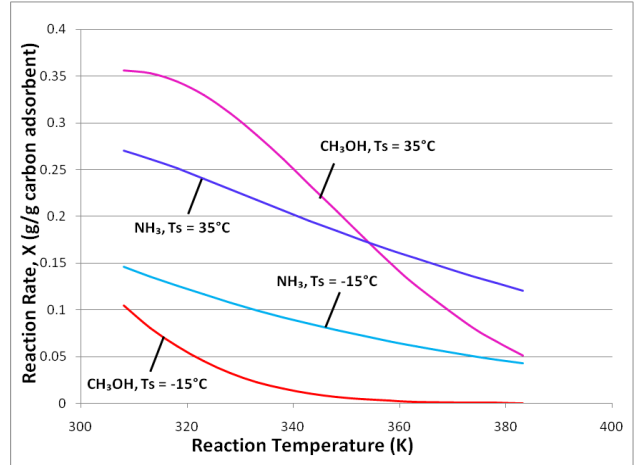
Fig.6. Adsorption capacity for system with ice thermal storage

Table 2. COP of the studied system using hot water and ice thermal storage

| Reaction working pairs	COP of the system	
	Hot water thermal storage	Ice thermal storage
Activated carbon-ammonia	0.72	0.66
Activated carbon-methanol	0.79	0.74

From Figure 6, the desorption temperature of hot water thermal storage is up to 85°C, while in ice production the desorption temperature is up 100°C. A performance comparison of the refrigeration system using two forms of thermal storages using hot water and ice thermal storages are shown in Table 2. In the COP calculation, the mass of adsorbent used is 10 kg, the mass flow rate of ammonia refrigerant is 1.495 kg/s, while the mass flow rate of methanol refrigerants is 3.045 kg/s.

From the COP calculations, it is shown that activated carbon-methanol working pair shows higher COP when using both hot water and ice thermal storage compared to activated carbon-ammonia. This calculation is made in ideal conditions assuming uniform temperature distribution within the adsorbers. The adsorption refrigeration system with hot water thermal storage has higher COP than that of ice thermal storage case for both of the reaction pairs. For the ice thermal storage case, the higher discharging adsorber reactor temperature leads to higher COP. Still, the lower evaporator temperature causes lower COP. Combining these two effects the ice thermal storage case has lower COP than the hot water thermal storage case.

According to the analytical calculation results shown in Table 2, the solar-powered adsorption refrigeration cycle with hot water thermal storage for activated carbon-methanol working pair case has the highest COP. Although the volume is larger than ice thermal storage, hot water thermal storage is less expensive and easier to design. Since silica gel-water adsorption pair, which operates with negative pressure, is frequently used for the conventional adsorption chillers, the existing technology can be used for the activated carbon-methanol pair, which also operates with negative pressure.

Due to the intermittent nature of solar radiation, it is not practical to design the refrigeration system that responds all of the air-conditioning demands only by solar thermal energy all year around even if thermal storage is integrated into the refrigeration system. A backup heat source is required for stable operation. As the backup heat source, a boiler may be used to supply heat energy to the adsorbers.

2.3 Adsorber reactor
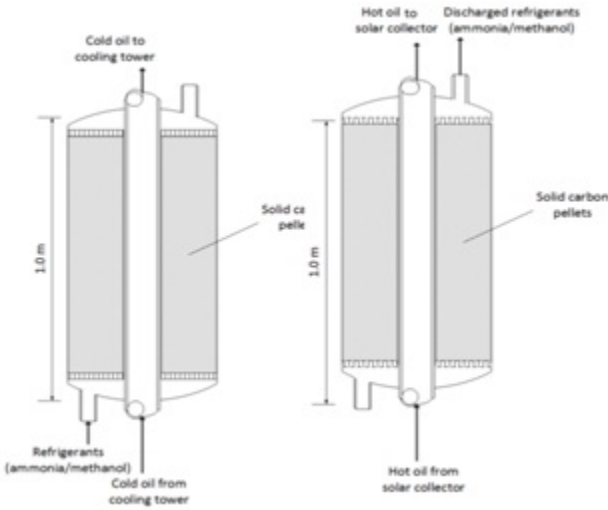
From left: **Fig.7(a)** Adsorber model in charging mode, **Fig.7(b)** Adsorber model in discharging mode

Figure 7(a) and (b) show the adsorber reactor model in charging and discharging modes for the future prototype test. In the refrigeration system, two adsorber reactors are used to perform adsorption and desorption alternately for air-conditioning.

The adsorber reactors are cylindrical and built vertically. Heat transfer fluid will flow into and from the adsorber inside the heat transfer tube. Perforated plates are placed at the top and bottom of the adsorbent beds to allow the refrigerant vapor to flow into and out from the adsorbent beds. Fins are built along the length of the cylinder to enhance the heat transfer within the adsorber reactors. The adsorber dimensions and fin configuration will be identified from the simulation results.

The distribution of pressure is almost uniform within the beds [10], while the temperature distribution within the adsorbers is not uniform. The rate of reaction will be simulated using finite element

analysis software. The performance of the reactors can be improved by enhancing the heat transfer within the adsorbent beds by introducing fins.

3.0 EXPERIMENT AND SIMULATION

3.1 Adsorption capacity experiment
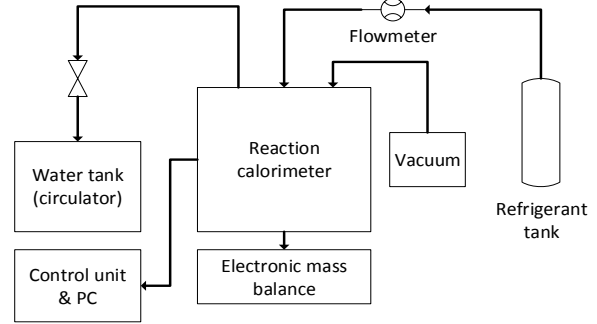
Fig.8. Reaction calorimetry experimental set up.

The adsorption performance of selected adsorbent-refrigerant working pairs is important to the performance of solar adsorption refrigeration systems. As a future work, the adsorption capacity experiment is planned using a reaction calorimeter as shown in Figure 8.

The operating parameters of ammonia refrigerant is as follow; evaporating pressure, P_e = 5.339bars at evaporating temperature, T_e = 5°C, and condensing pressure, P_c = 15.0bars at condensing temperature, T_c = 35°C. Meanwhile, the operating parameters of methanol; the evaporating pressure, P_e = 0.4bars at evaporating temperature, T_e = 5°C, and condensing pressure, P_c = 1.3bars at condensing temperature, T_c = 35°C. The total surface area, the apparent density, and the average particle size of the granular activated carbon are to be measured. The reactor is always kept at predetermined temperature throughout the experiment. The heat of adsorption reaction is obtained from the latent heat of vaporization of the respective refrigerants. The reaction calorimetry experiment is designed from the experimental procedure in [14] by using ammonia and methanol as refrigerants.

The measured adsorption capacity, X_{exp} is calculated as mass of adsorbent after adsorption process divided by the initial mass of adsorbent, m_1 as in Eqn.(3):

$$X_{exp} = \frac{m_{ref}}{m_1} \qquad (3)$$

The measured results, X_{exp} will be used for adsorption reactor simulation.

3.2 Simulation of adsorber model

The analytical solution shown in Table 2 is based on ideal cases where reactions in equilibrium are achieved at the ends of adsorption and desorption processes with uniform temperature distributions. In more realistic situations, it is hard to achieve the

uniform temperature distribution within time. As a result, the reactions are terminated before they reach equilibrium state. Since the reaction rate is a function of reaction temperature as expressed in Eqn. (2), heat transfer within the reactors plays an important role to enhance the reaction. In addition, the reactions are time dependent. The charging reaction occurs from fully discharged state to fully charged state, while discharging reaction proceeds in the opposite direction.

The transient reaction within the adsorber reactors will be simulated using finite element method. Heat transfer and reaction rate relation in Eqn. (2) are combined in the simulation model. The dependent variables will be temperature distribution within the bed, pressure of the refrigerant and amount of refrigerant adsorbed by the adsorbent. To enhance the heat transfer within the adsorber for more reaction, radial circular fin will be designed in the adsorbent bed.

4.0 CONCLUSION

The reaction rate and COP for activated carbon-ammonia and activated carbon-methanol reaction pairs used for solar-powered adsorption refrigeration system is studied. Activated carbon-methanol reaction pair showed higher COP than activated carbon-ammonia pair, while an adsorption refrigeration system with hot water thermal storage has higher COP than the system with ice thermal storage. As a future work, a simulation model with heat transfer and reaction capabilities is discussed.

Acknowledgement

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