Study of various adsorbent-refrigerant pairs for the application of solar driven adsorption cooling in tropical climates

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ABSTRACT

This article presents analytical investigation results on the performance of solar powered adsorption cooling systems for Malaysia and similar tropical regions. The studied adsorbent-refrigerant pairs are silica gel-water, activated carbon fiber-ethanol and activated carbon-methanol. A computer simulation program has been developed for modeling and performance evaluation for the solar driven adsorption cooling cycle using the meteorological data of Kuala Lumpur, Malaysia. The simulation is based on the experimentally confirmed adsorption isotherms, kinetics and isosteric heat of the adsorption data for the respective adsorbent-refrigerant pairs. The optimum cooling capacity and coefficient of performance (COP) of the different adsorbent-refrigerant pairs varying adsorption-desorption cycle time, regeneration temperature and chilled water inlet temperature are calculated and compared.

Keywords: activated carbon; adsorption; cooling; silica gel; solar thermal

Nomenclature

Symbols

α_0	coefficient in equation (1) [kg (kg of dry adsorbent) ⁻¹]
α_1	coefficient in eq. (1) [kg (kg of dry adsorbent, K) ⁻¹]
α_2	coefficient in eq. (1) [kg (kg of dry adsorbent, K ²) ⁻¹]
α_3	coefficient in eq. (1) [kg (kg of dry adsorbent, K ³) ⁻¹]
β_0	coefficient in eq. (1) [-]
β_1	coefficient in eq. (1) [K ⁻¹]
β_2	coefficient in eq. (1) [K ⁻²]
β_3	coefficient in eq. (1) [K ⁻³]
A	area [m ²]
A_c	collector area [m ²]
COP	coefficient of performance [-]
C_p	specific heat capacity [J/kg-K]
D_s	surface diffusion coefficient [m ² /s]
D_{so}	pre-exponential constant [m ² /s]
E_a	activation energy [J/kg]
h	enthalpy [J/kg]
M	mass [kg]

m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa]
P_s	saturation pressure [Pa]
Q	power [W]
Q_u	useful energy gain from collector [W]
R	gas constant [J/kg-K]
R_p	adsorbent fiber radius [m]
T	temperature [°C or K]
τ	time [s]
U	overall heat transfer coefficient [W/m ² -K]
U_L	overall heat transfer coefficient of collector to ambient [W/m ² -K]
F_R	collector heat removal factor [-]
I	incident solar radiation [W/m ²]
$T\alpha$	effective transmittance-absorptance product [-]
E	characteristic energy [J/kg]
n	heterogeneity constant [-]
x	instantaneous uptake [kg/kg]
x^*	equilibrium uptake [kg/kg]
x_0	limiting adsorption uptake [kg/kg]
Δh_{st}	isosteric heat of adsorption [J/kg]
η	efficiency [-]

Subscripts

<i>sg</i>	silica gel
<i>f</i>	liquid phase
<i>a</i>	adsorbent
<i>g</i>	gaseous phase
<i>in</i>	inlet
<i>out</i>	outlet
<i>w</i>	water
<i>bed</i>	sorption heat exchanger (adsorber/desorber)
<i>col</i>	collector
<i>amb</i>	ambient

Superscripts

<i>ref</i>	refrigerant
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1. Introduction

Thermally powered sorption cooling systems have attracted much attention as they appear to be promising from the view point of greenhouse gas emissions and ozone layer depletion problems [1]. Chlorofluorocarbons (CFCs) and Hydro-chlorofluorocarbons (HCFCs) have been considered as the major contributors to the environmental hazard. Thermally driven adsorption based chillers have zero ozone depletion potential due to the use of natural and/or alternative refrigerants like water, ammonia, methanol, ethanol, etc. As solar energy or low grade waste

heat can be effectively utilized to run these systems, it has the potential to reduce the peak load demand of electricity and the emission of greenhouse gases as well. The other advantages of adsorption refrigeration systems are that they are free of vibrations as they do not have any moving parts, simple control and lower operation cost. Thermally powered adsorption cooling cycle could be operated in both partial vacuum and pressurized conditions. The adsorbent-refrigerant pairs working at sub-atmospheric conditions are silica gel-water [1, 2], zeolite-water [3, 4], activated carbon fiber-ethanol [5, 6], activated carbon-methanol [7, 8], etc.

Solar adsorption refrigeration system seems to be a promising alternative refrigeration device since cooling load of buildings is roughly in phase with solar energy availability. During the past decades much research has been performed on solar adsorption refrigeration. Table 1 lists solar driven adsorption refrigeration systems using various adsorbent-refrigerant pairs.

The present study introduces a comparison of solar driven adsorption cooling systems using the meteorological data of Kuala Lumpur. A cycle simulation computer program has been developed to analyze cooling capacity and COP by varying adsorption/desorption cycle time, regeneration temperature and chilled water inlet temperature. Performance data of silica gel-water, activated carbon fiber-ethanol and activated carbon-methanol based adsorption systems have been presented and compared. The results obtained from this analysis will be useful in selecting a suitable adsorbent-refrigerant pair for adsorption cooling in tropical climates.

2. Working principle of the solar adsorption chiller

In the present study, a two bed solar powered adsorption cooling cycle has been studied. The schematic diagram of the adsorption cycle is shown in the Figure 1. The chiller is composed of four heat exchangers namely two adsorber/desorber heat exchangers, an evaporator and a

condenser. Four refrigerant valves are used for the operation four pre-determined processes namely, adsorption, pre-heating, desorption and pre-cooling. As can be seen from Fig. 1, refrigerant evaporates from the evaporator and adsorbed by the adsorber bed through refrigerant valve V4. At the same time desorbed refrigerant goes to the condenser through refrigerant valve V2 which is known as the desorption-condensation process. The desorber bed is powered by solar thermal heat which is the only heat source of the studied system. The details of the working principle of adsorption chiller have been described in detail elsewhere [1].

3. Adsorbent-refrigerant pair

In the present study, three different adsorbent-refrigerant pairs have been selected and these are silica gel-water, activated carbon fiber (ACF)-ethanol and activated carbon (AC)-methanol. The porous properties of silica gel, ACF and AC are listed in Table 2. It is evident from Table 2 that ACF possesses largest surface area which is followed by activated carbon. ACF also has higher adsorption capacity than the other two studied adsorbents. On the other hand, silica gel has higher apparent density compared to ACF and AC, which indicates that it is easier to pack relatively larger amount of silica gel into the adsorbent bed of the silica gel-water based adsorption chiller.

4. Mathematical modeling

4.1 Adsorption kinetics

Adsorption rates of silica gel-water, ACF-ethanol and AC-methanol pairs are estimated from the linear driving force equation.

$$\frac{dx}{d\tau} = 15 \frac{D_{s0} \exp\left(-\frac{E_a}{RT}\right)}{R_p^2} (x^* - x) \quad (1)$$

The numerical values of D_{so} and E_a for silica gel water [1], ACF-ethanol [5] and AC-methanol [26] are evaluated experimentally.

4.2 Adsorption isotherms

For silica gel-water system, the S-B-K isotherm model [27], which is expressed by Eq. (2), is used to estimate the equilibrium uptake.

$$x^* = \alpha(T_{sg}) \left[\frac{P_s(T^{ref})}{P_s(T_{sg})} \right]^{\beta(T_{sg})} \quad (2)$$

Where,

$$\begin{aligned} \alpha(T_{sg}) &= \alpha_0 + \alpha_1(T_{sg}) + \alpha_2(T_{sg})^2 + \alpha_3(T_{sg})^3 \\ \beta(T_{sg}) &= \beta_0 + \beta_1(T_{sg}) + \beta_2(T_{sg})^2 + \beta_3(T_{sg})^3 \end{aligned}$$

The Dubinin- Radushkevich (D-R) equation is used to estimate the equilibrium uptake of ACF - ethanol pair.

$$x^* = x_0 \exp \left[-D \left\{ T \ln \left(\frac{P_s}{P} \right) \right\}^2 \right] \quad (3)$$

Dubinin-Astakhov (D-A) model is used to estimate the uptake of AC-methanol pair.

$$x^* = x_0 \exp \left[-D \left\{ T \ln \left(\frac{P_s}{P} \right) \right\}^n \right] \quad (4)$$

Table 3 lists the numerical values of α_0 to α_3 and β_0 to β_3 of silica gel-water pair, x_0 and D for ACF-ethanol pair and x_0 , D and n for AC-methanol pair.

4.3 Solar collector energy balance

The energy balance of the energy balance of the evacuated tube collector can be expressed as,

$$\dot{m}C_{pf}(T_{out} - T_{in}) = A_c F_R [I(\tau\alpha) - U_L(T_{in} - T_{amb})] \quad (5)$$

The left hand side of eq. (5) indicates energy output from the collector. The first term of the right hand side of eq. (5) represents energy recovery from the collector and the second term shows the energy loss from the collector.

Thus the instantaneous collector efficiency at steady state can be defined as the ratio of the useful energy output to the product of solar radiation and collector surface area.

$$\eta_{col} = \frac{Q_u}{IA_c} = \frac{F_R [I(\tau\alpha) - U_L(T_{in} - T_{amb})]}{I} \quad (6)$$

4.4 Adsorption and desorption energy balance

Using the lumped approach, the energy balance for the sorption bed of three various adsorbent/refrigerant pairs can be expressed as [5]

$$\left[m_a (C_{p,a} + C_p^{ref} x) + m_{hex} C_{p,hex} \right] \frac{dT_{bed}^{ref}}{d\tau} = m_a \Delta h_{st} \frac{dx_{bed}^{ref}}{d\tau} + \gamma m_a C_{p,v}^{ref} \frac{dx_{bed}^{ref}}{d\tau} + \dot{m}_f C_{p,f} (T_{bed,in} - T_{bed,out}) \quad (7)$$

where $\gamma = 1$ for reactor working as adsorber, and $\gamma = 0$ for reactor working as desorber. The left hand side of adsorber/desorber energy balance equation (Eq. 7) indicates the rate of change of internal energy due to the thermal mass of adsorbent(s), the refrigerant and adsorber /desorber heat exchanger during adsorption and desorption. The first term on the right hand side of Eq. (7) represents the adsorption or desorption heat, the second term for energy transport due to refrigerant vapor transfer from evaporator to adsorbent bed during adsorption-evaporation process. The third term on Eq. (7) defines the total amount of heat released to the cooling water

upon adsorption or provided by the heating source (hot water) for desorption. For a small temperature difference across heating/cooling fluid such as water, the outlet temperature of the heat source or heat sink is sufficiently accurate to be modeled by the log mean temperature difference (LMTD) method and it is given by:

$$\frac{T_{bed,out} - T_{bed}}{T_{bed,in} - T_{bed}} = \exp \left[- \frac{(UA)_{bed}^{ref}}{\dot{m}_f C_{p,f}} \right] \quad (8)$$

Similarly condenser and evaporator energy balances can be obtained.

The cooling capacity, Q_{eva}^{cycle} of this can be defined as,

$$Q_{eva}^{cycle} = \frac{1}{\tau_{cycle}} \int_0^{\tau_{cycle}} (\dot{m} C_p)_w (T_{chill,in} - T_{chill,out}) d\tau \quad (9)$$

The driving source temperature can be expressed as,

$$Q_{hot}^{ref} = \frac{1}{\tau_{cycle}} \int_0^{\tau_{cycle}} (\dot{m} C_p)_{des} (T_{hot,in} - T_{hot,out}) d\tau \quad (10)$$

Here τ_{cycle} denotes total cycle time.

The coefficient of performance (COP) can be obtained as,

$$COP = \frac{Q_{hot}^{ref}}{Q_{eva}^{cycle}} \quad (11)$$

5. Weather data

An accurate climatic database is required for the performance evaluation of solar powered energy conversion technologies. In this regard, the accuracy of solar radiation and ambient air temperature is crucial. The climatic data based on the typical year concept for Kuala Lumpur,

Malaysia (3.16°N, 101.7°E) have been used in the present study. Figure 2 shows the variation of hourly average global solar radiation of Kuala Lumpur on a particular day [29]. It can be seen from Fig. 2 that the highest solar radiation on a particular day is about 650 W/m² which is obtained at around noon.

6. Results and discussion

6.1 Hot water supply

Figure 3 depicts the variation of the hot water storage tank temperature for Kuala Lumpur climate throughout a day three years back from now (1st May, 2011). Hot water temperature from tank never falls below 60°C because of the automatic operation of the auxiliary heater. It can be seen from Fig. 3 that during noon the maximum temperature of the hot water is achieved, which is around 88°C.

6.2 Ideal cooling cycle

Using the isotherm data, the conceptual ideal adsorption cooling systems of silica gel-water, ACF-ethanol and AC-methanol pairs are illustrated in Figure 4. One can understand from Fig. 4 that for the same operating temperature conditions, the difference between the maximum and minimum uptake $\{\Delta x = x_{\max} - x_{\min}\}$ of ACF-ethanol cycle is higher than that of AC-methanol and silica gel-water cycles. The Δx values for ACF-ethanol cycle is 0.44 kg/kg, which is followed by AC-methanol and silica gel-water cycles (0.4 kg/kg and 0.08 kg/kg), respectively.

6.3 Adsorption /desorption cycle time

Table 4 shows the rated conditions for silica gel-water, ACF-ethanol and AC-methanol based adsorption cooling cycles. The values adopted in the present simulation model are furnished in Table 5. The simulated results of cooling capacity variations with adsorption/desorption cycle time for adsorption cooling cycle of the studied pairs are depicted in Fig. 5. The switching (pre-heating or pre-cooling) time is chosen as 50 s. As can be seen from Fig. 5, when the cycle time is smaller than 400 s, adsorption or desorption cannot occur sufficiently. As a result, cooling capacity decreases abruptly. On the other hand, when cycle time is longer than 700 s, the cooling capacity decreases gradually due to the less intense of adsorption after the first 10 minutes as the adsorbent reaches towards equilibrium. From Fig. 5 it is also observed that among the three studied systems, silica gel-water system has the highest cooling capacity, which is around 13 kW for the cycle time between 450 and 500 s. But it is also noticeable that there is a sharp drop of cooling capacity of silica gel-water system when the cycle time is around 800s. The maximum cooling capacity of AC-methanol and ACF-ethanol systems are 11.5 and 11 kW, respectively. Figure 6 demonstrates the variation of COP with adsorption/desorption cycle time for the studied three pairs. It can be seen from Fig. 6 that the COP of all three pairs increase with the increase of adsorption/desorption cycle time. However, after 900 s, the increase of COP values becomes marginal. It is also noticeable that ACF-ethanol system has the highest COP (around 0.62). The optimum values of COP for ACF-ethanol, silica gel-water and AC-methanol system are around 0.5, 0.45 and 0.43, respectively when the cycle time is around 450-500 s.

6.4 Regeneration temperature

Figure 7 shows the variation of cooling capacity of the studied three systems with driving heat source temperature supplied from the hot water storage tank for Kuala Lumpur climate

conditions. Heat transfer fluid flow rates and cycle times are taken as the rated values which are shown in Table 3. It can be observed from Fig. 7 that the cooling capacities of all the three systems maintain a linear relationship with the driving heat source temperature. The relationship between cooling capacity and driving heat source temperature of zeolite-water based adsorption chiller is also shown in Fig. 7. The experimental results of zeolite-water based chiller are taken from Singapore climate conditions which are similar to those of Kuala Lumpur. From Fig. 7 it is evident that the zeolite-water system has the highest cooling capacity followed by silica gel-water system, AC-methanol and ACF-ethanol system. The cooling capacity of silica gel-water system varies from 6 to 16 kW with the heat source temperature varies from 60 to 95°C. This is due to the amount of refrigerant circulation increases when the amount of desorbed refrigerant increases with the higher driving heat source temperature.

The variation of COP with regeneration temperature for the four systems is depicted in Figure 8. It is observable from Fig. 8 that for Kuala Lumpur climate conditions, when the heat source temperature is below 70°C, silica gel-water system has the highest value of COP which is around 0.5 which is followed by the COP values of ACF-ethanol and AC-methanol systems. But when the heat source temperature is more than 70°C, the COP of ACF-ethanol system reaches up to around 0.55. It is noticeable from Fig. 8 that the COP values of all three studied systems increase with increase in regeneration temperature until the temperature reaches 75°C. After that the COP increases slightly with the increase in regeneration temperature.

6.5 Chilled water inlet temperature

The effects of chilled water inlet temperatures on cooling capacity of the studied three pairs are illustrated in Fig. 9. It can be observed from Fig. 9 that silica gel-water cycle has the highest

cooling capacity varying from 12 to 19 kW when the chilled water temperature varies from 10 to 20°C. The variation of COP with chilled water inlet temperatures is depicted in Fig. 10. It can be observed from Fig. 10 that ACF-ethanol has the highest COP varying from 0.5 to around 0.6, followed by AC-methanol and silica gel-water pairs.

7. Conclusions

The aim of the present study is to compare three different adsorption cooling cycles driven by solar thermal energy suitable for tropical climates. Meteorological data of Kuala Lumpur have been used in this study. The main conclusions are as follows:

- i. ACF-ethanol cycle shows the highest adsorption uptake followed by AC-methanol and silica gel-water pairs.
- ii. Simulation results indicate that for Kuala Lumpur climate, cooling capacity of silica gel – water system is highest among the studied three different adsorbent-refrigerant pairs. For all three studied pairs, cooling capacity increases with the increase in cycle time.
- iii. Silica gel-water cycle demonstrates the highest COP values when regeneration temperature is below 70°C. However, the COP of ACF-ethanol based adsorption cycle is found to be highest when the regeneration temperature is above 70°C.
- iv. The present study may provide useful information in designing adsorption based cooling cycles for Malaysia and similar tropical regions.

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References

- [1] H. T. Chua, K.C. Ng, A. Malek, T. Kashiwagi, A. Akisawa, B.B. Saha, Modeling the performance of two-bed silica gel-water adsorption chillers, *International Journal of Refrigeration* 22 (1999) 194-204.
- [2] D. Wang, J. Zhang, Q. Yang, N. Li, K. Sumathy, Study of adsorption characteristics in silica gel-water adsorption refrigeration, *Applied Energy* 113 (2014) 734-741.
- [3] A. Myat, K.C. Ng, K. Thu, Y-D. Kim, Experimental investigation on the optimal performance of zeolite-water adsorption chiller, *Applied Energy* 102 (2013) 582-590.
- [4] I. Solmus, B. Kaftanoglu, C. Yamali, D. Baker, Experimental investigation of a natural zeolite-water adsorption cooling unit, *Applied Energy* 88(11) (2011) 4206-4213.
- [5] B.B. Saha, I.I. El-Sharkawy, A. Chakraborty, S. Koyama, Study on an activated carbon fiber-ethanol adsorption chiller: Part I-system description and modeling, *International Journal of Refrigeration* 30 (2007) 86-95.
- [6] B.B. Saha, I.I. El-Sharkawy, A. Chakraborty, S. Koyama, Study on an activated carbon fiber-ethanol adsorption chiller: Part II- performance evaluation”, *International Journal of Refrigeration* 30 (2007) 96-102.
- [7] E.E. Anyanwu, C.I. Ezekwe, Design, construction and test run of a solid adsorption solar refrigerator using activated carbon/methanol as adsorbent/adsorbate pair, *Energy Conversion Management*, 44 (18) (2003) 2879-2892.

- [8] D.J. Miles, S.V. Shelton, Design and testing of a solid sorption heat pump system, *Applied Thermal Engineering*, 16 (5) (1996) 389-394.
- [9] K. Habib, B.B. Saha, Performance evaluation of solar driven activated carbon fiber-ethanol based adsorption cooling system in Malaysia, *Asian Journal of Scientific Research* 6(3) (2013) 146-156.
- [10] A. El Fadar, A. Mimet, A. Azzabakh, M. Perez-Garcia, J. Castaing, Study of a new solar adsorption refrigerator system powered by a parabolic trough collector, *Applied Thermal Engineering* 29 (2009) 1267-1270.
- [11] K. Habib, B.B. Saha, A. Chakraborty, S.T. Oh, S. Koyama, Study on solar driven combined adsorption refrigeration cycles in tropical climates, *Applied Thermal Engineering* 50(2013) 1582-1589.
- [12] K. Habib, B. Choudhury, P.K. Chatterjee, B.B. Saha, Study on a solar heat driven dual-mode adsorption chiller, *Energy* 63(2013) 133-141.
- [13] Z. Lu, R. Wang, Z. Xia, Experimental analysis of an adsorption air-conditioning with micro-porous silica gel, *Applied Thermal Engineering* 50(2013) 1015-1020.
- [14] X.Q. Zhai, R.Z. Wang, J.Y. Wu, Y.J. Dai, Q. Ma, Design and performance of a solar-powered air-conditioning system in a green building, *Applied Energy* 85(2008) 297-311.
- [15] Z.S. Lu, R.Z. Wang, Z.Z. Xia, Q.B. Wu, Y.M. Sun, Z.Y. Chen, An analysis of the performance of a novel solar silica gel-water adsorption air-conditioning, *Applied Thermal Engineering* 31(2011) 3636-3642.
- [16] K.C.A. Alam, B.B. Saha, A. Akisawa, Adsorption cooling driven by solar collector: A case study for Tokyo solar data, *Applied Thermal Engineering* 50 (2013) 1603-1609.

- [17] H.Z. Hassan, A.A. Mohamad, Thermodynamic analysis and theoretical study of a continuous operation solar-powered adsorption refrigeration system, *Energy* 61(2013) 167-178.
- [18] H.R. Ramji, S.L. Leo, M.O. Abdullah, Parametric study and simulation of a heat-driven adsorber for air-conditioning system employing activated carbon-methanol working pair, *Applied Energy* 113(2014) 324-333.
- [19] A. Mahesh, S.C. Kaushik, Solar adsorption refrigeration system using different mass of adsorbents, *Journal of Thermal Analysis and Calorimetry* 111(2013) 897-303.
- [20] H.Z. Hassan, A.A. Mohamad, R. Bennacer, Simulation of an adsorption solar cooling system, *Energy* 36 (2011) 530-537.
- [21] M. Pons, J.J. Guilleminot, Design of an experimental solar powered, solid adsorption ice maker, *Journal of Solar Energy Engineering (Trans. ASME)* 103(4) (1986) 332-337.
- [22] E.E. Anyanwu, N.V. Ogueke, Transient analysis and performance prediction of a solid adsorption solar refrigerator, *Applied Thermal Engineering* 27 (2007) 2514-2523.
- [23] K. Sumathy, H.L. Yong, M. Steinhagen, H. Kerskes, Performance analysis of a modified two-bed solar adsorption air-conditioning system, *International Journal of Energy Research* 33(2009) 675-686.
- [24] Y.J. Dai, K. Sumathy, Heat and mass transfer in the adsorbent of a solar adsorption cooling system with glass tube insulation, *Energy* 28(2003) 1511-1527.
- [25] Y. Hamamoto, K.C.A. Alam, B.B. Saha, S. Koyama, A. Akisawa, T. Kashiwagi, Study on adsorption refrigeration cycle utilizing activated carbon fibers. Part 1. Adsorption characteristics, *International Journal of Refrigeration* 29 (2006) 305-314.

- [26] E.F. Passos, J.F. Escobedo, F. Meunier, Simulation of an intermittent adsorptive solar cooling system, *Solar Energy* 42(1989) 103-111.
- [27] B.B. Saha, E. Boelman, and T. Kashiwagi, Computer simulation of a silica gel water adsorption refrigeration cycle - the influence of operating conditions on cooling output and COP, *ASHRAE Transactions*, 101 (1995) 348-357.
- [28] Y. Zhao, E. Hu, A. Blazewicz, A comparison of three adsorption equations and sensitivity study of parameter uncertainty effects on adsorption refrigeration thermal performance estimation, *Heat Mass Transfer* 48(2012) 217-226.
- [29] C.K. Tang, Chapter 2-Malaysia's weather data,
http://bseep.weebly.com/uploads/8/0/7/2/8072374/chapter_2_malaysia_weather_data_draft_01.pdf

Table captions

Table 1. Summary of solar driven adsorption cycles for cooling application.

Table 2. Porous properties of silica gel, ACF and AC.

Table 3. Adsorption parameter of silica gel-water, ACF-ethanol and AC-methanol pairs.

Table 4. Rated conditions.

Table 4. Values adopted for simulation.

Table 1. Summary of solar driven adsorption cycles for cooling application.

Adsorbent-refrigerant pair(s)	System description	System performance	Source
Activated carbon fiber-ethanol	A theoretical analysis of a two-bed adsorption chiller for Malaysian climate	A cooling capacity of 12 kW can be achieved when the heat source temperature is 85°C.	Habib and Saha [9]
Activated carbon-ammonia	Adsorption refrigeration system powered by parabolic trough solar collector coupled with a heat pipe	Use of concentrated collector and high flux density made the system more compact and lighter compared to the systems with flat plate or evacuated tube collectors	El Fadar et al. [10]
Activated carbon-R134a + Activated carbon-R507A	Solar driven combined adsorption refrigeration cycle with AC-R134a as topping cycle and AC-R507A as bottoming cycle	The system can achieve a refrigeration load -10°C.	Habib et al. [11]
Silica gel-water	A solar heat driven dual mode chiller able to provide cooling throughout the year	For a driving source temperature above 60°C, the chiller works as a single stage four-bed adsorption chiller; while the chiller functions as a two stage adsorption chiller when the driving source temperature falls	Habib et al. [12]

		below 60°C.	
Silica gel-water	One novel heat pipe solar adsorption chiller with mass-heat recovery was designed. With 65 kg of micro-porous silica gel was used as adsorbent in each adsorbent bed. The chiller was applied in Green Building in Dezhou city, China	The average thermal efficiency of solar collector, the average COP of the adsorption refrigerator and the average solar COP of the system are 0.36, 0.44 and 0.16, respectively	Lu et al. [13]
Silica gel-water	Solar powered air conditioning system which consisted of a 150 m ² solar collector and two adsorption chillers with a capacity of 8.5 kW each under the typical weather condition of Shanghai	$COP_{solar} = 0.15$ $COP_{system} = 0.35$	Zhai et al. [14]
Silica gel-water	The chiller with self-balance of refrigerant is investigated. The performance of the chiller may be influenced by different heating strategy.	The cooling capacity and COP obtained was 3.6 kW and 0.32 when driving source temperature, cooling water inlet and chilled water inlet temperatures were 57°C, 27°C and 15°C, respectively.	Lu et al. [15]
Silica gel-water	An analytical investigation has been performed to study the	At least 15 collector (each of 2.415 m ²) is required to achieve the required heat	Alam et al. [16]

	possibility of application of solar cooling for the climatic condition of Tokyo, Japan.	source temperature (around 85°C) to run the cooling unit. It is also observed that the solar powered adsorption cooling unit provides cooling capacity around 10 kW at noon with base run conditions, while the system provides solar COP around 0.3.	
Activated carbon-methanol	A solar powered theoretical adsorption cooling system is introduced which is able to produce cold continuously about 24-h of the day	The chiller is able to produce a daily mass of 2.63 kg of cold water at 0°C from water at 25°C per kg of adsorbent. COP obtained was 0.66.	Hassan and Mohamad [17]
Activated carbon-methanol	A parametric study adsorption air-conditioning system employing computational fluid dynamics (CFD) technique	In CFD study, an input exhaust gas of 200°C would have bed temperature of 120°C while employing 20 mm tick of wall made of stainless steel.	Ramji et al. [18]
Activated carbon-methanol	A prototype model of solar adsorption refrigeration system was constructed and its performance was evaluated with different mass ratios ranging from 0.25 – 2.50 of adsorbent	When mass ratio is 1.0, a minimum cooling temperature of 12.2°C was obtained.	Mahesh and Kaushik [19]

Activated carbon-methanol	A theoretical analysis of a tubular solar adsorption refrigeration system which takes into account the variations of ambient temperature and solar radiation along the day	COP and SCP obtained are 0.211 and 2,326 kW, respectively. Pressure distribution inside the adsorption bed was found nearly uniform and varying with time.	Hassan et al. [20]
Activated carbon-methanol	Solar adsorption refrigeration system to produce ice	Ice at -3 °C was produced at the rate of about 6 kg per m ² of collector area. $COP_{solar} = 0.12$ $COP_{system} = 0.43$	Pons and Guillemot [21]
Activated carbon-methanol	A finite element based transient analysis of a solar powered adsorption refrigerator	Numerically the performance of the refrigerator improved with the decrease in condenser pressure and increase in evaporator pressure	Anynawu and Ogueke [22]
Activated carbon-methanol	Lumped parameter analysis of an adsorption air-conditioning system driven by simple flat-plate solar collectors	Optimum values of adsorbent mass and collector area to get a maximum SCP of 150 Wm ⁻²	Sumathy et al. [23]
Activated carbon-methanol	Performance of a solar adsorption cooling system with tubular adsorber in evacuated glass tube insulation	No significant pressure difference in the 80 mm diameter adsorber tubes during the heating period	Dai and Sumathy [24]

Table 2. Porous properties of silica gel, ACF and AC.

Adsorbent	Surface area (m^2g^{-1})	Pore volume (ccg^{-1})	Apparent density (kgm^{-3})	Source
Silica gel (type A)	715	0.28	730	Chua et al. [1]
ACF (A-20)	1900	1.028	300	Hamamoto et al [25]
AC	1450	0.5	350	Hamamoto et al. [25]

Table 3. Adsorption characteristics of silica gel-water, ACF-ethanol and AC-methanol pairs.

Silica gel-water pair [2]	α_0	$-6.5314 \text{ kg (kg of dry adsorbent)}^{-1}$
	α_1	$0.72452 \times 10^{-1} \text{ kg(kg of dry adsorbent, K)}^{-1}$
	α_2	$-0.23951 \times 10^{-3} \text{ kg(kg of dry adsorbent, K}^2)^{-1}$
	α_3	$0.25493 \times 10^{-6} \text{ kg(kg of dry adsorbent, K}^3)^{-1}$
	β_0	-15.587
	β_1	0.15915 K^{-1}
	β_2	$-0.50612 \times 10^{-3} \text{ K}^{-2}$
	β_3	$0.5329 \times 10^{-6} \text{ K}^{-3}$
ACF-ethanol pair [5]	x_0	$0.797 \text{ kg ethanol/kg ACF}$
	D	$1.716 \times 10^{-6} \text{ K}^{-2}$
AC-methanol pair [28]	x_0	0.28 kg/kg
	D	$8.45 \times 10^{-7} \text{ K}^{-2}$
	n	2.08

Adsorption Cycle	Hot water inlet		Cooling water inlet		Chilled water inlet	
	Temperature (°C)	Flow rate (kg/s)	Temperature (°C)	Flow rate (kg/s) (ads+con)	Temperature (°C)	Flow rate (kg/s)
Silica gel-water cycle	85	1.5	30	(1.5+1.5)	14	0.6
ACF-ethanol cycle	85	1.5	30	(1.5+1.5)	14	0.6
AC-methanol cycle	85	1.5	30	(1.5+1.5)	14	0.6
Adsorption/desorption cycle time: 500 s			Switching time for both cycles: 50 s			

Table 4. Rated conditions.

Table 5. Values adopted for simulation.

Symbols	Silica gel-water	AC- methanol	ACF- ethanol	Unit
m_a	40	40	40	kg
UA_{bed}	3500	3600	3300	W/K
UA_{eva}	4870	4890	4860	W/K
UA_{con}	15330	15340	15320	W/K
m_{con}	24.28	25.28	23.28	kg
m_{eva}	12.45	11.45	13.45	kg
$C_{p,a}$	960	889	895	J/kg-K
h_{fg}	2.8×10^6	1.15×10^6	2.0×10^6	J/kg
$C_{p,hex}$	950	950	950	J/kg-K

Figure captions

Figure 1: Schematic diagram of the solar driven two-bed adsorption cooling cycle.

Figure 2: Hourly variation of solar radiation on a particular day in Kuala Lumpur.

Figure 3: Hourly variation of storage tank temperature on a particular day in Kuala Lumpur.

Figure 4: Adsorption isotherms for ACF-ethanol, silica gel-water and AC-methanol pairs.

Figure 5: Adsorption/desorption cycle time effect on cooling capacity for ACF-ethanol, silica gel-water and AC-methanol adsorption cycles.

Figure 6: Adsorption/desorption cycle time effects on COP for ACF-ethanol, silica gel-water and AC-methanol adsorption cycles.

Figure 7: Regeneration temperature effects on cooling capacity for zeolite-water [3], ACF-ethanol, silica gel-water and AC-methanol adsorption cycles.

Figure 8: Regeneration temperature effects on COP for zeolite-water [3], ACF-ethanol, silica gel-water and AC-methanol adsorption cycles.

Figure 9: Chilled water inlet temperature effects on cooling capacity for ACF-ethanol, silica gel-water and AC-methanol adsorption cycles.

Figure 10: Chilled water inlet temperature effects on COP for ACF-ethanol, silica gel-water and AC-methanol adsorption cycle.

Figure 1

Figure 2

Figure 3

$$\Delta x (\text{ACF-ethanol}) = 0.44; \Delta x (\text{AC-methanol}) = 0.4; \Delta x (\text{Silica gel-water}) = 0.08$$

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10