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2015 IOP Conf. Ser.: Mater. Sci. Eng. 88 012068

(http://iopscience.iop.org/1757-899X/88/1/012068)

Study of Solar Driven Silica gel-Water based Adsorption Chiller

K Habib[1], M K Assadi[1] and M H B Zainudin[1]
[1]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

*E-mail: khairul.habib@petronas.com.my

Abstract. In this study, a dynamic behaviour of a solar powered single stage four bed adsorption chiller has been analysed designed for Malaysian climate. Silica gel and water have been used as adsorbent-refrigerant pair. A simulation program has been developed for modeling and performance evaluation of the chiller using the meteorological data of Kuala Lumpur. The optimum cooling capacity and coefficient of performance (COP) are calculated in terms of adsorption/desorption cycle time and regeneration temperature. Results indicate that the chiller is feasible even when low temperature heat source is available. Results also show that the adsorption cycle can achieve a cooling capacity of 14 kW when the heat source temperature is about 85^{0}C.

1. Introduction

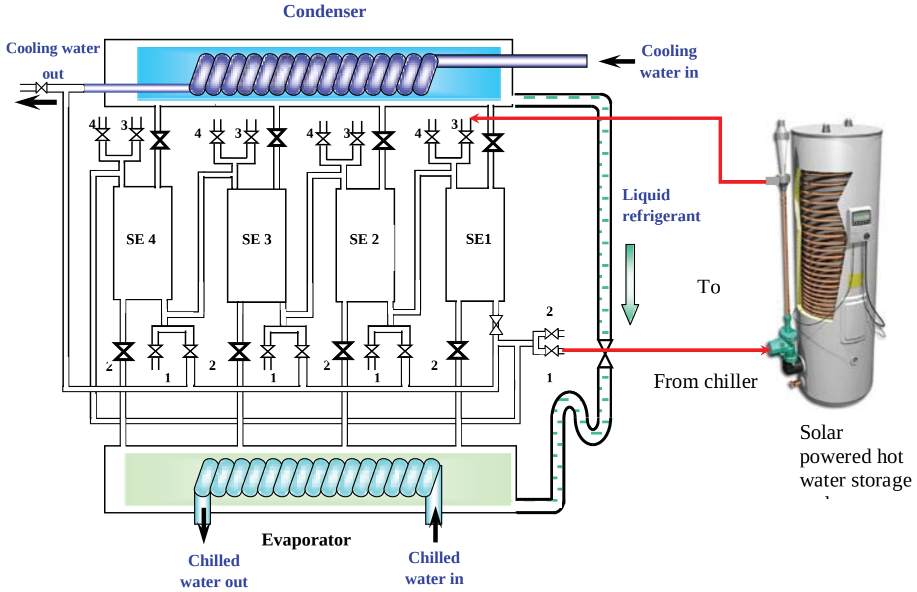
Environmental concerns and the rising energy costs necessitate looking for renewable energy driven environmentally benign cooling systems to meet the ever–increasing demand of refrigeration and air–conditioning. Heat driven sorption based cooling systems are gradually emerging as environmentally friendly alternatives to conventional vapour compression based refrigeration cycles. Since the detection of ozone holes in the stratosphere, caused by the CFCs and HCFCs of vapour compression based coolers, interest on adsorption cooling systems have increased a lot [1]. Adsorption cooling cycles are considered as environmentally benign, having zero ozone depletion potential (ODP) due to the use of natural refrigerants or alternative refrigerants. The other advantages of adsorption refrigeration systems are that they are free of vibration as they do not have any moving parts, simple control and lower operation costs.

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. Habib et al. [2] designed a solar driven dual mode chiller which can provide cooling load throughout the year. Zhai et al. [3] designed a 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. Pons and Guilleminot [4] worked on an activated carbon-methanol based solar adsorption refrigeration system to produce ice. Habib et al. [5] presented a solar driven combined adsorption refrigeration cycle which can deliver refrigeration load at -10C. Habib et al [6] used activated carbon fiber-ethanol pair to design a solar driven adsorption chiller. A cooling capacity of 12 kW can be achieved with a heat source temperature of 85C.

From the above perspective, the present study deals with the transient analysis of a single stage four-bed silica gel-water based adsorption cooling cycle. The novel cycle is driven by solar energy and the analysis of solar thermal system is carried out with TRNSYS software using the solar data of Kuala Lumpur (3.16^{0}N, 101.7^{0}E), Malaysia. A cycle simulation computer program of the novel adsorption cooling system is developed to analyze the cooling capacity and coefficient of performance (COP) variations by varying adsorption/desorption cycle times and regeneration temperatures. The present study can be useful to fabricate environmental friendly cooling cycle which can tackle global warming and ozone depletion problems.

2. Working principle of silica gel-water adsorption cooling cycle

Figure 1 shows the schematic diagram of the four bed adsorption cooling cycle which consists of a condenser, an evaporator, four sorption beds filled with silica gel. The details of the adsorption cooling system have been presented by Habib et el. [2].



1: Hot water outlet; **2**: Coolant inlet to the adsorber; **3**: Hot water inler; **4**: Coolant outlet from the adsorber

Figure 1. Schematic diagram of four bed adsorption chiller [2].

3. Mathematical modeling

3.1 Adsorption isotherms

The modified Freundlich model, which is expressed by equation (1), is used to estimate the equilibrium uptake of silica gel-water pair [2].

$$x^* = \alpha(T_{sg})\left[\frac{P_s(T^{ref})}{P_s(T_{sg})}\right]^{\beta(T_{sg})} \quad (1)$$

Where,

$$\alpha(T_{sg}) = \alpha_0 + \alpha_1(T_{sg}) + \alpha_2(T_{sg})^2 + \alpha_3(T_{sg})^3$$

$$\beta(T_{sg}) = \beta_0 + \beta_1(T_{sg}) + \beta_2(T_{sg})^2 + \beta_3(T_{sg})^3$$

3.2 Adsorption kinetics

The rate of adsorption or desorption is governed by the linear driving force model [2].

$$\frac{dx}{dt} = 15D_{so}\frac{\exp\left(-\frac{E_a}{RT}\right)}{R_p^2}\left(x^* - x\right) \quad (2)$$

3.3 Adsorption and desorption energy balance

Using the lumped approach for the adsorption bed, which comprises silica gel, the heat exchanger fins and tubes, the energy balance equation is given by [2],

$$\left[m_{sg}C_{p,sg} + m_{sg}C_p^{ref}x^{ref} + m_{Al}C_{p,Al} + m_{Cu}C_{p,Cu}\right]\frac{dT_{ads/des}^{ref}}{dt} = \delta m_{sg}\left\{h_g\left(P_{eva/cond}^{ref}, T_{ads/des}^{ref}\right) - h_g\left(T_{eva/cond}^{ref}\right) + \Delta h_{st}^{ref}\right\}\frac{dx_{ads/des}^{ref}}{dt} + \dot{m}_w C_{p,w}\left(T_{w,in,ads/des}^{ref} - T_{w,o,ads/des}^{ref}\right) \quad (3)$$

The outlet temperature of the source is to be modeled by the log mean temperature difference (LMTD) method and it is given by,

$$T_{w,o,bed}^{ref} = T_{bed}^{ref} + \left(T_{w,in,bed}^{ref} - T_{bed}^{ref}\right)\exp\left[-\frac{(UA)_{bed}^{ref}}{(\dot{m}C_p)_w}\right] \quad (4)$$

3.4 Evaporator energy balance

The evaporator energy balance of adsorption cycle can be expressed as [2]:

$$\left[m_{eva}^{ref}C_{p,eva} + m_{hex}C_{p,Cu}\right]\frac{dT_{eva}^{ref}}{dt} = -\delta\left\{h_g\left(P_{eva}^{ref}, T_{ads}^{ref}\right) - h_g\left(T_{eva}^{ref}\right) + h_{fg}^{ref}\right\}m_{sg}\frac{dx_{ads}^{ref}}{dt} + (\dot{m}C_p)_{chill}\left(T_{chill,in} - T_{chill,o}\right) \quad (5)$$

The water outlet temperature can be expressed as,

$$T_{chill,o} = T_{eva}^{ref} + \left(T_{chill,in} - T_{eva}^{ref}\right)\exp\left[-\frac{(UA)_{eva}^{ref}}{(\dot{m}C_p)_w}\right] \quad (6)$$

3.5 Condenser energy balance

The condenser energy balance of adsorption cycle can be expressed as [2]:

$$(m_{cond}^{ref} C_{p,cond} + m_{hex}^{ref} C_{p,Cu}) \frac{dT_{cond}^{ref}}{dt} = -\delta \left\{ h_g \left(P_{cond}^{ref}, T_{des}^{ref} \right) - h_g \left(T_{cond}^{ref} \right) + h_{fg}^{ref} \right\} m_{sg} \frac{dx_{des}^{ref}}{dt} + \dot{m}_w C_{p,w} \left(T_{w,in,cond}^{ref} - T_{w,o,cond}^{ref} \right)$$

The condenser outlet temperature can be expressed as:

$$T_{w,o,cond}^{ref} = T_{cond}^{ref} + \left(T_{w,in,cond}^{ref} - T_{cond}^{ref} \right) \exp\left[-\frac{(UA)_{cond}^{ref}}{(\dot{m}C_p)_w} \right] \quad (7)$$

3.6 Cooling Capacity and coefficient of performance
The cooling capacity is obtained at the evaporator of adsorption cycle.

$$Q_{eva}^{cycle} = \frac{1}{t_{cycle}} \int_0^{t_{cycle}} (\dot{m}C_p)_w (T_{chill,in} - T_{chill,o}) dt$$

The coefficient of performance (COP) of adsorption cycle can be expressed as:

$$COP = \frac{\int_0^{t_{cycle}} (\dot{m}c_P)_{chill} (T_{chill,in} - T_{chill,o}) dt}{\int_0^{t_{cycle}} (\dot{m}c_P)_{des} (T_{h,in} - T_{h,o}) dt} \quad (8)$$

4. Weather data
An accurate climatic database is necessary in solar energy technologies. Habib et al. [5] showed the variation of monthly average solar radiation of Kuala Lumpur, Malaysia.

Table 1. Rated conditions.

Hot water inlet		**Cooling water inlet**		**Chilled water inlet**	
Temperature (°C)	Flow rate (kg/s)	Temperature (°C)	Flow rate (kg/s) (ads+cond)	Temperature (°C)	Flow rate (kg/s)
85	1.28	30	(1.25+1.25)	14	0.71
Adsorption/desorption cycle time: 600s			**Switching time: 30s**		

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Table 2. Values adopted for simulation [2].

Symbols	Values	Units
m_{sg}	40	Kg
UA_{bed}	3500	W/K
UA_{eva}	4870	W/K
UA_{cond}	15330	W/K
m_{cond}	24.28	Kg
m_{eva}	12.45	Kg
h_{fg}	2.8x106	J/Kg
$C_{p,hex}$	950	J/Kg-K
$C_{p,sg}$	960	J/Kg-K

5. Results and discussion

5.1 Hot water temperature variation

Figure 2 depicts the variation of hot water supply from the tank to the adsorption chiller Kuala Lumpur climate throughout a day (1st May, 2013). It can be seen from Fig. 2 that the maximum temperature of hot water temperature is achieved from 12-2 pm and the temperature is around 85°C.

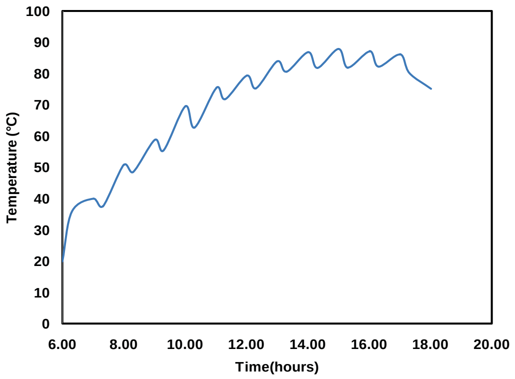

Figure 2. Variation of hot water supply from the tank to the chiller in Kuala Lumpur in May 2013.

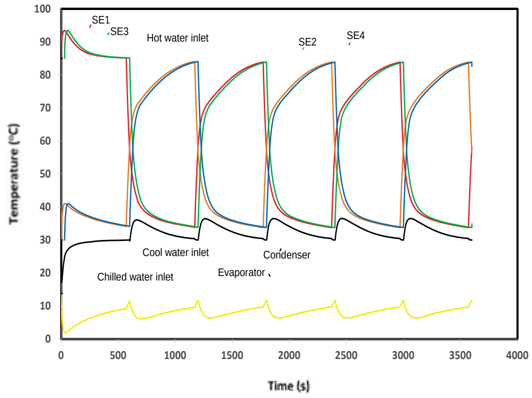

Figure 3. Temperature profiles for various components of silica gel-water cycle at rated conditions

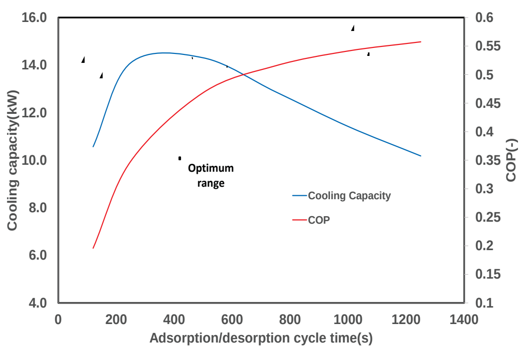

Figure 4. Effects of adsorption / desorption cycle time on cooling capacity and COP

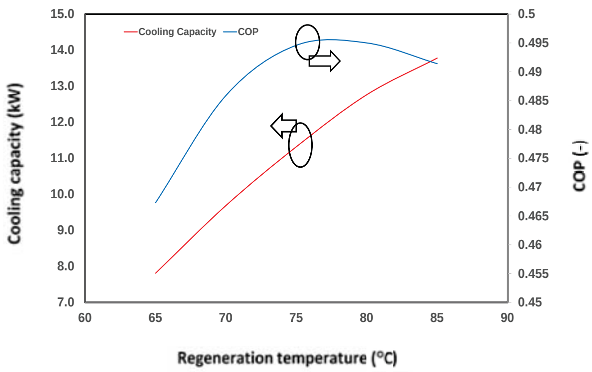

Figure 5. Effects of regeneration temperature on cooling capacity and COP

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5.2 Chiller transient response

Figure 3 shows the chiller temporal histories for all the components (adsorber, desorber, evaporator and condenser) by using the mathematical model presented herein. Table 1 depicts the rated conditions for adsorption cycle. Table 2 lists the values adopted for simulation [2]. It can be seen from Fig. 3, the four bed silica gel-water based adsorption chiller is able to reach from transient to nearly steady state within three half cycles or 1900s, where adsorption/desorption cycle time is taken as 600 s and switching time is taken as 30s.

5.3 Adsorption/desorption cycle time

The simulated results of cooling capacity and COP variations with adsorption/desorption cycle time for silica gel-water cycle are shown in Fig. 4. From the Fig. 4, it is observed that for four bed silica gel-water cycle, the highest cooling capacity is around 14 kW for cycle times between 460 and 600s. From the Fig. 4 it is noted that the COP increases uniformly with the increase of adsorption/desorption cycle time and after reaching a certain value (around 600 s) it becomes steady. When the cycle time is less than 450s, there is not enough time for adsorption/desorption to occur satisfactorily. As a result, the cooling capacity decreases abruptly. On the other hand, when the cycle time is longer than 650s, the cooling capacity decreases gradually due to the less intention of adsorption after the first 10 min as the adsorbent reaches towards equilibrium or near equilibrium.

5.4 Regeneration temperature

Figure 5 shows the effects of heat source temperature on cooling capacity and COP for silica gel-water cycle. From Fig. 5, it is noticeable that the cooling capacity increases linearly from 8 to 14 kW with heat source temperature varies from 65 to 85ºC. This is due to the fact that the amount of refrigerant circulation increases with the amount of desorbed refrigerant increases with the higher driving heat source temperature. The optimum COP value is around 0.495 for silica gel-water system when the regeneration temperature is between 80 to 85ºC.

6. Conclusion

The paper investigates the transient analysis of a solar heat driven four-bed single stage silica gel-water based adsorption cooling cycle. The solar system is modeled with TRNSYS program using the meteorological data of Kuala Lumpur. Simulation results indicate that both the cooling capacity and COP increase with the regeneration temperature. The proposed four bed adsorption system can achieve cooling capacity of 14 kW and COP of 0.49 when the driving heat source temperature is 85^0C. The present study can be useful to fabricate environmental friendly cooling cycle which can tackle global warming and ozone depletion problems.

7. Nomenclature

Symbols		**Subscripts**	
A	Area (m^2)	sg	Silica gel
m	Mass (kg)	eva	Evaporator
COP	Coefficient of performance (-)	cond	Condenser
C_p	Specific heat capacity (J/kg-K)	W	water
h	Enthalpy (J/kg)	in	inlet
$\dot{m}$	Mass flow rate (kg/s)	out	outlet
P	Pressure (Pa)		
T	Temperature (K)	**Subscript**	
t	Time (s)	ref	refrigerant
Q	Power (W)		

U	Overall heat transfer coefficient (W/m^2-K)
h_{fg}	Isosteric heat of adsorption (J/kg)

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