Study of a silica gel-water based dual mode adsorption chiller

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***Abstract*— This article presents analytical investigation results on the performance of dual-mode multi-bed adsorption cooling systems using silica gel-water pair. This novel adsorption chiller utilizes effectively low-temperature solar or waste heat sources of temperature between 40 and 85°C. Two operation modes are possible for the advanced chiller. The first operation mode will be to work as a highly efficient conventional chiller where the driving source temperature is between 60 and 85°C. The second operation mode will be to work as an advanced two-stage adsorption chiller where the available driving source temperature is very low (below 60°C). In the present work, a simulation study of a dual-mode, four-bed silica gel-water adsorption chiller is undertaken. For a driving source temperature above 60°C, the chiller functions as a single stage four-bed adsorption chiller. However, the chiller works as a two stage four-bed adsorption chiller when the driving source temperature falls within the range from 40°C to 60°C. With a cooling water temperature of 30°C. It has been found that this dual mode adsorption chiller is capable to provide cooling throughout the year via measuring the coefficient of performance and the cooling capacity of the system.**

***Keywords*—**silica gel; water; dual-mode; adsorption chiller

I. Introduction

Developing a highly clean and renewable sources of energy has become the main concern for the researchers to reduce the severity of the environmental problems, such as depletion of the ozone layer as a result of using chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) in vapor compression based coolers [1], rising in the energy cost and the depletion of fossil fuel sources like oil, coal and natural gas.

Thermally powered adsorption based chillers have zero ozone depletion potential due to the use of natural refrigerants like water, methanol, ethanol, ammonia, etc. As solar energy or low grade waste heat can be effectively utilised to run these systems, it has the potential to reduce the peak load demand of electricity and the emission of greenhouse gases as well. Besides, the construction of these systems is simpler, as there are almost no moving parts, and they require low electricity usage. Examples of various adsorption cooling cycles using different adsorbent-refrigerant pairs may be found in the Refs. [2-18].

One of the problems of adsorption chillers is that the chiller cannot provide sufficient cooling load throughout the year due to low temperature achieved in a number of months. To overcome this problem dual-mode, multi-bed type adsorption chiller has been introduced [19-20]. The main advantage of dual mode multi-bed chiller is that it is able to provide sufficient cooling load throughout the year.

With this perspective, the present study analyses the performance of a dual-mode multi-bed adsorption chiller. Performance simulation of the novel dual-mode adsorption cooling system is done to analyse the changes in cooling capacity and coefficient of performance (COP) with variations in regeneration temperature and cooling water inlet temperature.

II. WORKING PRINCIPLE OF DUAL-MODE ADSORPTION CHILLER

A. *Single stage four – bed scheme*

The schematic diagram of the dual-mode four-bed adsorption chiller shown in Fig. 1. The working principle and operation schedule of dual mode adsorption chiller have been described by Saha et al [19].

B. *Two stage four-bed scheme*

Fig. 2 illustrates the schematic diagram of a two-stage four-bed adsorption chiller. The working principle of two stage adsorption chiller has been described elsewhere [19].

III. MATHEMATICAL MODELING

C. Adsorption Isotherms

The modified Freundlich equation which is expressed by Eq. (1), is selected to calculate the equilibrium uptake of silica gel-water pair [2] and to provide a brief analytical expression of the data that was found experimentally.

$$q^* = A(T_{sg})\left[\frac{P_s(T_{ref})}{P_s(T_{sg})}\right]^{B(T_{sg})} \quad (1)$$

$$\begin{aligned} A(T_{sg}) &= A_0 + A_1 T_{sg} + A_2 T_{sg}^2 + A_3 T_{sg}^3 \\ B(T_{sg}) &= B_0 + B_1 T_{sg} + B_2 T_{sg}^2 + B_3 T_{sg}^3 \end{aligned} \quad (2)$$

The numerical values of A_0 to A_3 and B_0 to B_3 are determined by the least square fit to experimental data [2] and are given in Table I.

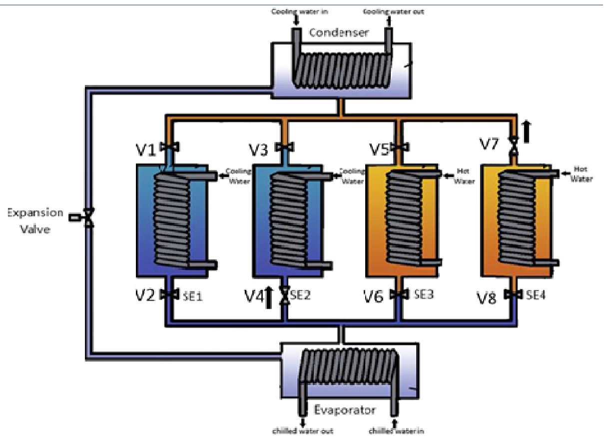

Fig.1: Schematic diagram of single stage four bed adsorption chiller

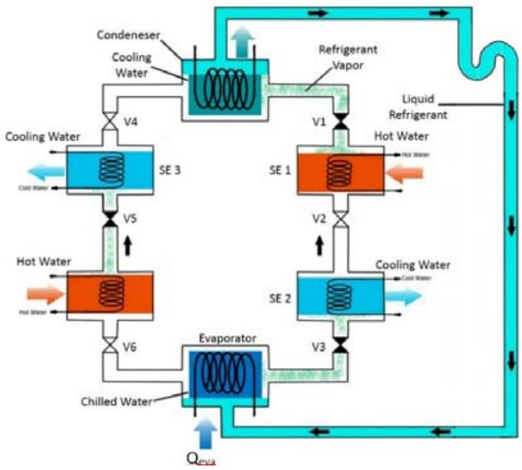

Fig. 2: Schematic diagram of two stage four bed adsorption chiller

D. Adsorption kinetics

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

$$\frac{dq}{dt} = k_s a_v (q^* - q) \quad (3)$$

$$k_s a_v = 15\frac{D_s}{R_p^2}$$
$$D_s = D_{so}\exp\left(-\frac{E_a}{RT}\right) \quad (4)$$

TABLE I. Values adopted for simulation [2]

Parameter	Value
A_0	- 6.5314 kg (kg of dry adsorbent) $^{-1}$
A_1	0.72452 × 10^{-1} kg (kg of dry adsorbent, K) $^{-1}$
A_2	0. 23951 × 10^{-3} kg (kg of dry adsorbent, K^2) $^{-1}$
A_3	0.25493 × 10^{-6} kg (kg of dry adsorbent, K^3) $^{-1}$
B_0	15.587
B_1	0.15915 K
B_2	- 0.5061 × 10^{-3} K^{-2}
B_3	0.5329 × 10^{-1} K^{-3}

E. Energy balance equations

Assuming the uniform temperature, pressure and refrigerant concentration throughout the bed, the heat transfer and energy balance equations for the bed can be written as,

$$\frac{d}{dt}\left\{\left(m_{sg}C_{sg} + m_{sg}C_{p,w}q + m_{hex}C_{hex}\right)T_b\right\} = m_{sg}Q_{st}\frac{dq}{dt}$$
$$-\delta m_{sg}C_v\left\{\gamma\left(T_b - T_e\right)\frac{dq}{dt} + \left(1-\gamma\right)\left(T_b - T_e\right)\frac{dq}{dt}\right\}T_b$$
$$+\dot{m}_w\left(T_{in} - T_{out}\right)$$
(5)

In Eq. (5) the values of δ and γ value ranges from 0 or 1. The value of δ depends on the function of bed (adsorber or desorber). Value of γ is governed by the interaction of the bed; either on the evaporator or another bed.

The outlet temperature of the bed can be modelled using log mean temperature method (LMTD) and it is given by,

$$T_{out} = T_b + \left(T_{in} - T_b\right)\exp\left(-\frac{U_b A R_b}{\dot{m}_w C_w}\right) \quad (6)$$

The energy balance equations of condenser (Eq. 7 and 8) and evaporator Eq. 9 and 10) are shown below.

$$\frac{d}{dt}\left\{\left(m_{con}C_w + m_{hex}C_{hex}\right)T_e\right\} = -Lm_{sg}\frac{dq}{dt}$$
$$-m_{sg}C_v\left(T_{des} - T_{con}\right)\frac{dq_{des}}{dt} + \dot{m}_w C_w\left(T_{cw,in} - T_{cw,out}\right)$$

(7)

$$T_{cw,out} = T_c + \left(T_{cw,in} - T_c\right)\exp\left(-\frac{U_c A R_c}{\dot{m}_w C_w}\right) \quad (8)$$

$$\frac{d}{dt}\left\{\left(m_e C_w + m_{hex} C_{hex}\right) T_e\right\} = -L m_{sg} \frac{dq_{ads}}{dt} - m_{sg} C_w \left(T_{con} - T_e\right)\frac{dq_{des}}{dt} + \dot{m}_{chill} C_w \left(T_{chill,in} - T_{chill,out}\right) \quad (9)$$

$$T_{chill,out} = T_e + \left(T_{chill,in} - T_e\right)\exp\left(-\frac{U_e A R_e}{\dot{m}_{chill} C_w}\right) \quad (10)$$

F. Cooling capacity and COP

The COP and cooling capacity can be defined as,

$$Q_{chill} = m_{chill} C_{p,w} \int_0^{t_{cycle}} \left(T_{chill,in} - T_{chill,out}\right) dt \quad (11)$$

$$Q_{hot} = m_{hot} C_{p,w} \int_0^{t_{cycle}} \left(T_{hot,in} - T_{hot,out}\right) dt \quad (12)$$

$$COP = \frac{Q_{chill}}{Q_{hot}} \quad (13)$$

IV. RESULTS AND DISCUSSION

G. Chiller transient response

Fig. 3 and Fig. 4 show the temperature profiles of the different components of the single stage and the two stage four beds adsorption chiller, respectively. In Fig. 3 the hot water inlet temperature has been taken as 82ºC in combination with a coolant of temperature 30ºC, while in Fig. 4 the hot water temperature has been chosen as 60ºC along with a coolant of temperature 30ºC. The chilled water temperature is taken as 15ºC.

H. Heat source temperature

The effects of regeneration temperature on cooling capacity and COP are shown in Figs. 5 and 6 with fixed cooling water and chilled water inlet temperatures, respectively for both single stage and two stage operation mode. When the driving source temperature is below 60°C, the chiller operates in two–stage, four–bed mode. However, when the regeneration temperature becomes more than 60°C while chiller should be changed to single stage four bed mode in order to achieve higher performance. From Figs. 5 and 6 it is clear that both the cooling capacity and COP increase linearly with the increase of driving source temperature in both the operation modes.

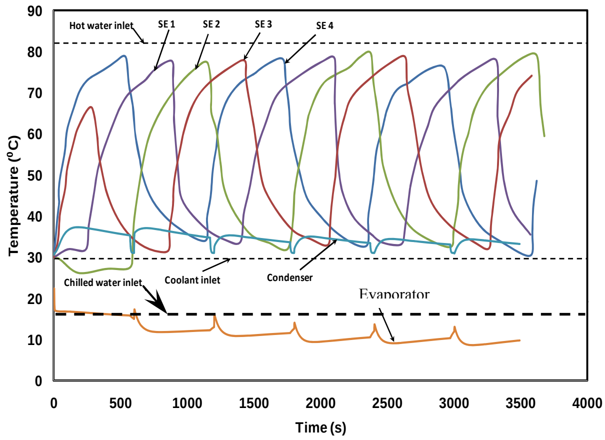

Fig. 3. Temperature profile of different components of single stage four bed adsorption chiller.

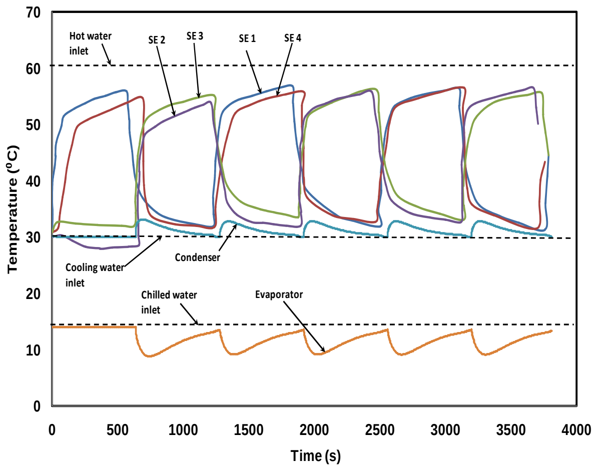

Fig. 4. Temperature profile of different components of two stage four bed adsorption chiller

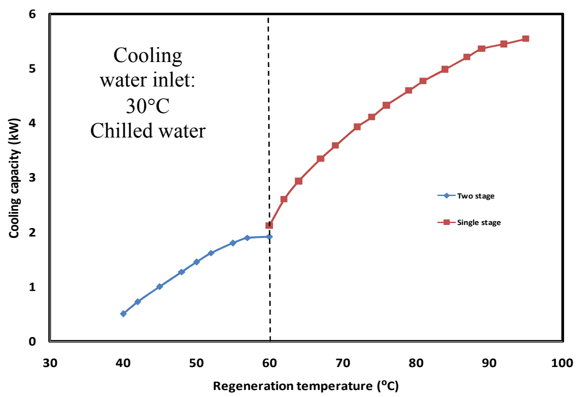

Fig. 5.Effects of cooling capacity on heat source temperature

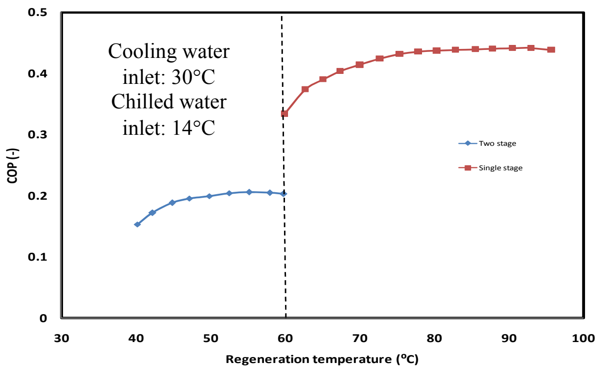

Fig. 6. Effects of COP on heat source temperature

I. *Cooling water inlet temperature*

Figs. 7 and 8 show the effects of cooling water temperature on cooling capacity and COP in both single–stage four–bed and two–stage four–bed modes. Hot water temperature is chosen as 80 and 50°C for single–stage and two–stage operation modes, respectively. Chilled water inlet temperature is taken as 14°C. For both the single–stage and two–stage mode, cooling capacity increases as the cooling water temperature is lowered. This is because of the lower adsorption temperature, causing higher amount of refrigerant being adsorbed and desorbed during each cycle.

J. *Dühring diagram*

Fig. 9 shows the Dühring diagram for adsorption cycle in single–stage, four–bed and two–stage four–bed operations. It can be seen from Fig. 9 that there is a high regeneration temperature. In Fig. 9, the heat source temperature is taken as 80°C for single–stage, four–bed operation mode. On the other hand, for two–stage, four–bed operation mode, the heat source temperature is taken as 50°C.

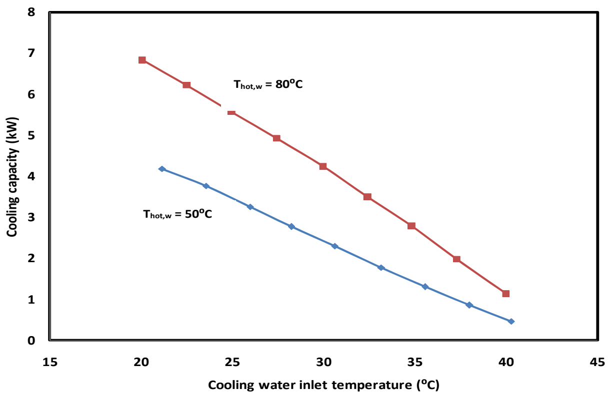

Fig.7. Effects of cooling capacity on cooling water inlet temperature

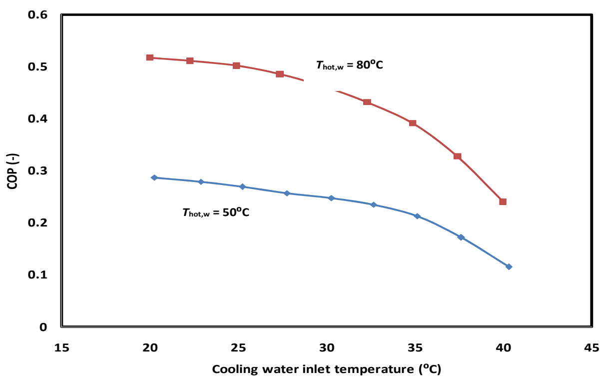

Fig.8. Effects of cooling capacity on cooling water inlet temperature

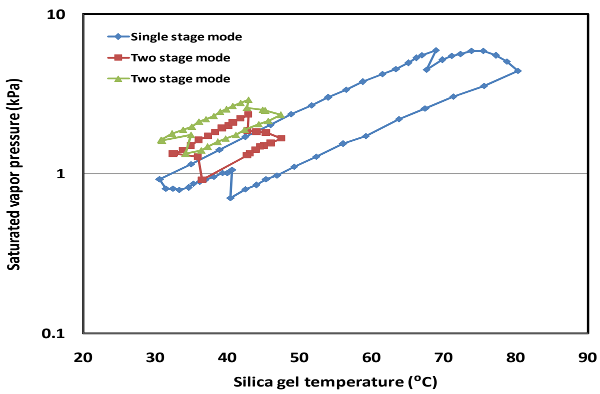

Fig.9. Dühring diagram of the dual mode adsorption chiller

V. CONCLUSIONS

The main target of this study is to investigate the performance characteristics of the dual mode, four bed adsorption chiller. The conclusions are as follows:

i. The main advantage of the dual–mode adsorption cooling cycle is its ability to utilize effectively a wide range of driving heat source of temperature between 40 to 85°C.

ii. The chiller works in two stage four bed mode when the regeneration temperature is below 60°C while when the driving source temperature is more than 60°C, the chiller changes to single stage four bed mode.

iii. The results can be useful in designing air conditioning system which can provide cooling load throughout the year.

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Nomenclature

A_0	coefficient in equation (1), kg (kg of dry adsorbent)$^{-1}$
A_1	coefficient in eq. (1), kg (kg of dry adsorbent, K)$^{-1}$
A_2	coefficient in eq. (1), kg (kg of dry adsorbent, K^2)$^{-1}$
A_3	coefficient in eq. (1), kg (kg of dry adsorbent, K^3)$^{-1}$
B_0	coefficient in eq. (1), (–)
B_1	coefficient in eq. (1), K^{-1}
B_2	coefficient in eq. (1), K^{-2}
B_3	coefficient in eq. (1), K^{-3}
AR	area, m^2
COP	coefficient of performance
C_p	specific heat capacity, J/kgK
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^{-1}
Q_{st}	isosteric heat of adsorption/desorption, J/kg
$k_s a_v$	mass transfer coefficient, 1/s
m	mass, kg
P	pressure, Pa
P_s	saturation pressure, Pa
q^*	equilibrium uptake, kg/kg
q	refrigerant amount adsorbed, kg/kg
Q_{chill}	cooling output, kW
Q_{hot}	driving heat, kW

T	temperature, K
t	time, s
U	heat transfer coefficient, W/m^{2}K
L	latent heat, kW
R	gas constant, J/kgK
R_p	average radius of adsorbent particle, m

Subscripts

ads	adsorber
b	sorption bed
chill	chilled water
con	condenser
des	desorber
e	evaporator
hot	hot water
in	inlet
out	outlet
sg	silica gel
ref	refrigerant
w	water
cw	cooling water
hex	heat exchanger

References

[1] D.C. Wang, Y.J. Wang, J.P. Zhang, X.L. Tian and J.Y. Wu, "Experimental study of adsorption chiller driven by variable heat source", Energy Conv. and Manage., vol. 49, pp. 1063-1073, 2008.

[2] H.T. Chua, K.C. Ng, A. Malek, T. Kashiwagi, A. Akisawa and B.B. Saha, "Modeling the performance of two-bed silica gel-water adsorption chillers", Int. J. Refrig., vol. 22, pp. 194-204, 1999.

[3] D. Wang, J. Zhang, Q. Yang, N. Li and K. Sumathy, "Study of adsorption characteristics in silica gel–water adsorption refrigeration", Appl.Energy, vol. 113, pp. 734-741, 2014.

[4] X. Wang, Z. He and H.T. Chua, "Performance simulation of multi-bed silica gel-water adsorption chillers", Int. J. Refrig., vol. 52, pp. 32-41, 2015.

[5] R. M. Rezk Ahmed and K. Al-Dadah Raya, "Physical and operating conditions effects on silica gel/water adsorption chiller", Appl. Energy, vol.89(1), pp. 142–149, 2012.

[6] Z. Xia, D. Wang and J. Zhang, "Experimental study on improved two-bed silica gel–water adsorption chiller", Energy Conv. Manage., vol. 49, pp. 1469-1479, 2008.

[7] A. Sadeghlua, M. Yarib and H. B. Dizaj, "Simulation study of a combined adsorption refrigeration system", Appl. Therm. Eng., vol. 87, pp. 185-199, 2015.

[8] A. Myat, K.C. Ng, K. Thu K and Y.-D. Kim, "Experimental investigation on the optimal performance of zeolite–water adsorption chiller", Appl. Energy, vol. 102, pp.582-590, 2013.

[9] I. Solmus, B. Kaftanoglu, C. Yamali and D. Baker, "Experimental investigation of a natural zeolite–water adsorption cooling unit", Appl. Energy,vol. 88(11), pp.4206–13, 2011.

[10] B. B. Saha, I.I. El-Sharkawy, A. Chakraborty and S. Koyama,"Study on an activated carbon fiber-ethanol adsorption chiller: Part I–system description and modeling", Int. J. Refrig., vol. 30, pp.86–95, 2007.

[11] B. B. Saha, I.I. El-Sharkawy, A. Chakraborty and S. Koyama, "Study on an activated carbon fiber–ethanol adsorption chiller: Part II–performance evaluation", Int. J. Refrig., vol. 30, pp.96–102, 2007.

[12] K. Habib, B. B. Saha, A. Chakraborty, S.T. Oh and S. Koyama, "Study on solar driven combined adsorption refrigeration cycles in tropical climates", Appl. Therm. Eng., vol. 50, pp. 1582-1589, 2013.

[13] W. S. Loh, B. B. Saha, A. Chakraborty, K.C. Ng and W. G. Chun, "Performance analysis of waste heat driven pressurized adsorption chiller", J. Therm. Science & Tech., vol. 5, pp. 252-265, 2010.

[14] S. Jribi, B.B. Saha, S. Koyama and H. Bentaher, "Modeling and simulation of an activated carbon–CO2 four bed based adsorption cooling system", Energy Conv. & Manage., vol. 78, pp. 985-991, 2014.

[15] S. Jribi, B.B. Saha, S. Koyama, A. Chakraborty and K. C. Ng, "Study on activated carbon/HFO-1234ze(E) based adsorption cooling cycle", Appl. Therm. Eng., vol. 50, pp. 1570-1575, 2013.

[16] N.D. Banker, K. Srinivasan and M. Prasad, "Performance analysis of activated carbon + HFC-134a adsorption coolers", Carbon, vol. 42, pp. 117-127, 2004.

[17] 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", Appl. Energy, vol. 113, pp.324-333, 2014.

[18] H.Z. Hassan, A.A. Mohamad and R. Bennacer, "Simulation of an adsorption solar cooling system", Energy, vol. 36, pp. 530-537, 2011.

[19] B.B. Saha, S. Koyama, T. Kashiwagi, A. Akisawa, K.C. Ng and H.T. Chua, "Waste heat driven dual–mode, multi–stage, multi–bed regenerative adsorption system", Int. J. Refrig. vol.26, pp.749–757, 2003.

[20] B. B. Saha, S. Koyama, K.C. Ng, Y. Hamamoto, A. Akisawa and T. Kashiwagi, "Study on a dual-mode, multi-stage, multi-bed regenerative adsorption chiller" Renew. Energy, vol. 31, pp. 2076-2090,2006.