Comparative performance analysis of a two-bed adsorption cooling system with adsorption of different adsorbates on silica-gel

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This study presents a comparative performance analysis of a two-bed adsorption cooling system in which various working fluids are used with silica-gel as adsorbent pairs. An adsorption cycle simulation program has been developed to investigate the influence of different operating conditions on the cooling power and COP of the system. For the configuration of the adsorption cycle in the present simulation, two adsorption bed design is used. Different working fluids as adsorbate are considered in this study. These are water, methanol, R134a and R404a. They can be employed in the adsorption refrigeration systems driven by heat sources such as solar energy or waste heat with a temperature lower than 100°C. It is observed that the parameters that have the most significant effect on COP and SCP are, in decreasing order, the adsorption heat of adsorbate-adsorbent pair, cooling source temperature, heating source temperature, condensation temperature at the condenser and evaporation temperature at the evaporator. These results are valid for all working pairs. In general, increasing evaporation temperature and decreasing adsorption bed temperature during the adsorption process increases COP and SCP for all working pairs. In addition to that different design parameter such as specific cooling power, the mass of adsorbent and adsorbate etc. are calculated, compared and discussed for each working pairs.

Keywords: Adsorption cooling, adsorbate-adsorbent pair, silica gel, COP, SCP

INTRODUCTION

Among the thermally driven refrigeration systems, adsorption systems, which can be powered by low-grade renewable energy and waste heat resources, are of great interest and considerable research and development studies have been performed by numerous researchers in recent decades[1]. The primary heat sources for adsorption cooling/refrigeration systems are waste heat and solar energy. The systems in which the physical adsorption working pairs employed are usually preferred when solar energy is used as the heat source [2]. The physical adsorption process of the gas occurs mainly within the pores and surface of the solid adsorbent [3]. The adsorbed amount and concentration of refrigerant in the pores are strongly dependent on pressure and temperature variations as well as the operating conditions of the system [4]. The design of an adsorption refrigeration system requires the knowledge of adsorption characteristics of the employed adsorbent-adsorbate pair when the temperature and pressure are varying.

The isosteric heat of adsorption is a specific combined property of an adsorbent/adsorbate combination. The equilibrium adsorption properties at several adsorbent temperatures and adsorption chamber adsorbate pressures were studied for a wide range of pairs by several researchers [5-9].

Silica gel is a silicon dioxide (SiO_2), an amorphous form of silica which is manufactured from silicate and sulfuric acid. It is a naturally occurring mineral that is purified and processed into beaded or granular form, and is also non-corrosive and chemically inert. Silica gel can be used as a primary desiccant or blended with other desiccants in any application where control of moisture is required.

Silica gel belongs to low temperature working adsorbent, which can be driven by heat source with the temperature lower than 100°C [2]. The silica gel is a type of amorphous synthetic silica. Each kind of silica gel has only one type of pore, which usually is confined in narrow channels. The pore diameters of ordinary silica gel are 2, 3 nm (A type) and 0.7 nm (B type), and the specific surface area is about 100–1000 m^2/g [3, 9].

Sah et al. [10] summarize the performances of the potential adsorption cooling systems which use silica gel and carbon as adsorbents. It is stated that the systems with silica gel as absorbent have higher COP than the systems with carbon as the adsorbent. However, the applications of both types of systems are different. The system with silica gel has the advantage of relatively low driving temperature. In the adsorption cooling systems, refrigerants like methanol, ammonia, ethanol, carbon dioxide, nitrogen, R134a, R114 are paired with activated carbon. These systems operate with comparatively higher driving temperatures. However, methanol

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based adsorption cooling systems cannot operate above 150°C as methanol would decompose and the adsorption power of activated carbon decreases sharply at that high temperature. These methanol systems are used for ice making and air-conditioning purposes [9]. The R134a (tetrafluoroetan CF3CH2F) and R404a (CHF2CF3 / CH3CF3 / CF3CH2F) can be employed as a working fluid in the systems operate above atmospheric pressure which ensures that the system leakages are very small and can be used to several cooling applications [7].

The adsorption characteristics of each adsorbent-adsorbate pair are usually entirely different than each other. Detailed specification about the adsorption isotherms of the different adsorbent/adsorbate pair as well as the isosteric heat of adsorption must be known to design the adsorption based cooling cycle system. Detailed literature reviews on adsorption working pairs for refrigeration/cooling applications can be found in the references [3, 4].

Saha et al. [11] studied analytically silica gel–water based advanced adsorption cooling system driven by the low-grade waste heat source of 50°C and cooling source of 30°C. Simulation software was developed to study the effects of operating temperatures, flow rates, and adsorption/desorption cycle times on cooling output, COP and chiller efficiency [12].

A large number of studies such as refs. [13-16] have been published about adsorption cooling systems employing the pair of silica gel and water. Only a few studies such as refs.[17,18] considered silica gel-methanol pair as an adsorbent/adsorbate pair. However, to the best of our knowledge, there is not any published study that has been devoted to studying on the adsorption cooling system with the refrigerants R134A and R404A as adsorbate fluid onto the silica gel as adsorbent solid.

From this mentioned perspective, the present study aims to perform a comparative investigation on the performance of the two-bed adsorption cooling cycle with the adsorbate fluids of water, methanol, R134A and R404A on the commercially available silica gel employed as the adsorbent solid. To realize the aimed research, a cycle simulation program is developed according to the mathematical model proposed in this study to perform realistic simulation and detailed investigation for the design of the adsorption based refrigeration and cooling systems. The presented results can be used on the design of adsorption based cooling cycle systems in which a silica gel is employed as an adsorbent with the one of the working fluid among water, methanol, R134A and R404A.

MATHEMATICAL MODELLING

The adsorption cooling system is similar to the known mechanical vapour compression systems and the system components such as the evaporator, condenser and expansion valve are the same. The main difference is that the thermal compressor takes the place of the mechanical compressor. This section deals with the operating principle of the thermal compressor operating according to the adsorption refrigeration cycle.
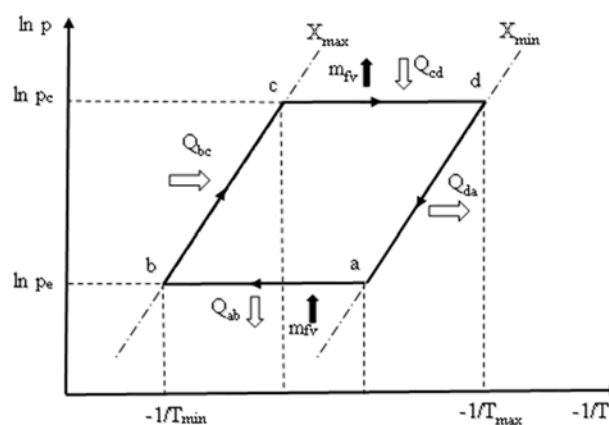

Fig.1. Basic adsorption cycle for an adsorption bed

It is possible to study the system by dividing it into four main sections according to the operating principle of adsorption cooling cycle. According to this, heating and cooling processes in which mass change is not observed are isosteric, whereas adsorption and desorption processes made under constant pressure are isobaric characteristic transports. The $\ln P - 1 / T$ diagram of the adsorption refrigeration cycle is given in Fig.1.

Isobaric adsorption, (a-b): In this process, the vapour of the adsorbate supplied from the evaporator is adsorbed by the adsorbent in the bed; meanwhile heat rejection occurs from the bed. The process is completed when the temperature of the bed falls to the value of T_b at constant evaporator pressure.

Isosteric heating process (b-c): Adsorbent bed temperature is increased from T_b to T_c by heat input from the outside (when the evaporator and condenser valves are in the closed position). No desorption occurs during the process, and gas pressure increases in the bed.

(a)

(b)
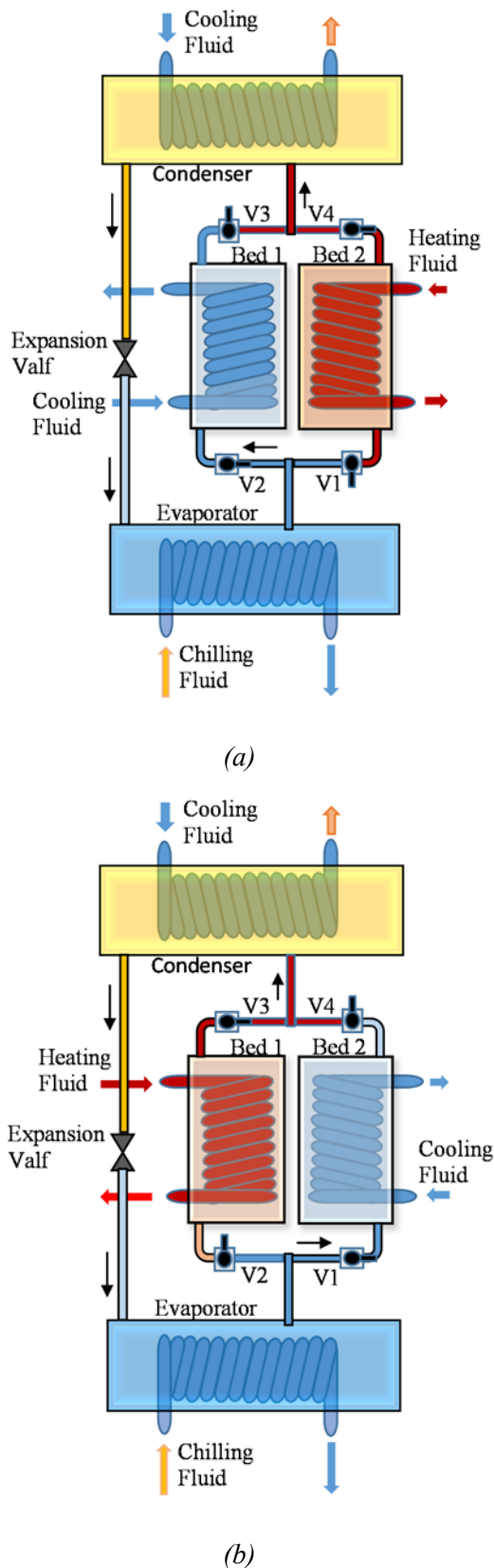
Fig.2. Schematic of the two-bed adsorption cooling cycle: (a) Bed 1 in adsorption phase, Bed 2 in desorption phase ; (b) Bed 1 in desorption phase, Bed 2 in adsorption phase

Isobaric desorption, (c-d): At this stage, the heat input to the adsorbent bed continues. However, the desorption starts and the desorption-induced vapour is condensed in the condenser. The pressure in the adsorbent bed is considered constant at condenser pressure. At the end of the stage, bed temperature reaches the maximum value (T_d).

Isosteric cooling process (d-a): After the desorption process is completed, the adsorbent bed (when the evaporator and condenser valves are in the closed position) is cooled down to T_a temperature, so the pressure is reduced and the adsorption bed is ready for the next cycle.

It can be seen that the cooling effect can be produced during the isobaric adsorption process. In order to provide continues cooling, it is common to use two (or multiple) adsorption beds in the system. In a working cycle, one of the chambers is used for the adsorption while other for the desorption. The role of each chamber is interchanged in another cycle, to maintain a pseudo-continuous production of the cooling effect. Schematic of the two-bed adsorption cooling cycle system is given in Fig.2.

It is essential to know the isotherms and the adsorption heat of the adsorption pairs used to calculate the yield and the capacity in the cooling cycles. A lumped parameter approach is used in the study. The main assumptions applied in the mathematical model are given as follows:

(1) The temperature and the pressure are uniforms throughout the whole adsorber bed.

(2) The refrigerant is adsorbed uniformly in the adsorber bed and is liquid in the adsorbent.

(3) The pressure difference between the adsorber bed and the condenser or the evaporator is neglected.

(4) The heat conduction of the shell connecting the adsorber to the condenser or the evaporator is neglected, and the heat exchange between two beds is entirely isolated.

(5) The system has no heat losses (or refrigerating output loss) to the environment.

Adsorption isotherms

It becomes a common approach that the use of Dubinin–Astakhov (D–A) model for the calculation of the adsorbate uptake value on the adsorbent as a function of temperature and pressure in the adsorption bed [1, 5]. Dubinin–Astakhov (D–A) equation may be written in the form given as follow:

$$W = W_0 \, exp \left\{ -\left[\frac{RT}{E} ln\left(\frac{p_s}{p}\right) \right]^n \right\} \qquad (1)$$

with

$$W = X v_a \quad \text{and} \quad W_0 = X_0 v_0 \qquad (2)$$

In Eq.(1), E may be expressed as the specific characteristic energy of the adsorbent-adsorbate pair which may be evaluated from the experimental measurements. R is the gas constant. Pressure is represented by p, and suffix s is referring to the saturation state. Temperature is represented by T. The parameter n is a power constant which results in the best fitting of the experimental isotherms. The quantity X represents the specific adsorbed mass of adsorbate (kg of adsorbate per kg of adsorbent), and v_a is the specific volume of the adsorbed phase, which is given by

$$v_a = v_b \, exp\big(\Omega(T - T_b)\big) \tag{3}$$

where v_b is the saturated liquid specific volume at the normal boiling point, b represents the van der Waals volume, and Ω is given as:

$$\Omega = \ln(b/v_b)/ \ (T_c - T_b) \tag{4}$$

T is the temperature. The critical and normal boiling point temperatures of the refrigerant are represented by suffixes c and b, respectively. The parameter v_0 can be obtained by using Eq.(2) at T = 273.15 K. Tab.1 shows the properties and parameters of the adsorbates used in the present study.

Table 1. Properties and parameters of the adsorbates [19]

	Unit	Water	Methanol	R134A	R404A
MW	kg/kmol	18.02	32.04	102.03	97.60
T_b	K	373.15	338.15	247.09	226.70
T_c	K	647.25	513.40	374.23	345.22
R	kJ/kg K	0.4615	0.2595	0.08149	0.08519
P_c	kPa	22064	8104	4059	3729
ρ_c	kg/m³	322.00	281.50	515.30	484.50
b	m³	0.001692	0.002055	0.000939	0.000986
v_b	m³/kg	0.001043	0.001337	0.000726	0.000766
v_0	m³/kg	0.000875	0.001140	0.000766	0.000845
Ω		0.001764	0.002452	0.002018	0.002125
*h_{fg}	kJ/kg	2454	1178	181	146
*ΔH_{ads}	kJ/kg	2701	1373	242	262
W_0	m³/kg	0.000303	0.000399	0.000402	0.000344
X_0	kg/kg	0.346	0.350	0.525	0.407
E	kJ/kg	227.6	172.84	68.15	83.52
n		1.35	1.7	1.237	1.613
E_a	kJ/kg	2330	1311	412	430

*Values at T=293,15 K

Adsorption kinetics

Adsorption and desorption rates of the adsorbate onto adsorbent can be calculated by the use of Linear Driving Force (LDF) approach. Adsorption kinetics (dX/dt) equation is given in Eq.(5).

$$\frac{dX}{dt} = F_o \frac{D_o}{r_p^2} exp \left(-\frac{E_a}{RT} \right)(X_{eq} - X) \tag{5}$$

where X_{eq} is the equilibrium concentration at the given pressure and temperature; F_o is a constant characteristic of adsorbent's shape. The equilibrium concentration is calculated using the Dubinin-Astakhov equation given in Eq.(1). X is the instantaneous concentration of the adsorbent bed. The values of the adsorption kinetic parameters used in the present study are given in Table (1, 2).

Table 2. Values of the parameters used in the present study.

Parameter	Values	Unit
D_o	2.54E-4	m²/s
F_o	15	
R_p	1.7E-4	m
$M_{bm}c_{p,bm}$	78	kJ/K
M_s	47	kg

Adsorption heat

Isosteric heat of adsorption is traditionally expressed as a function of concentration due to its dependence on temperature is relatively weaker. For adsorption of fluids below their thermodynamic critical point, its magnitude is larger than the heat of vaporization of the adsorbate, which has a strong temperature dependence [5, 6]. As a result, the difference between the adsorption heat and the vaporization heat is a property of relevance in the design of adsorption refrigeration systems. By the use of this common evaluation procedure, it has been shown that isosteric heat of adsorption can be approximated as a function of relative adsorption uptake for adsorbent-adsorbate pair combinations which broadly follow the Dubinin's isotherms [5]. However, the gas phase of the adsorbent is not ideal, during the adsorption of the adsorbate molecules onto the assorted adsorbent is affected by the pressure and temperature changes. Therefore, the heat of adsorption may be calculated by using the following Eq.(9) as suggested by El-Sharkawy et al. [20].

$$\Delta H_{ads} = h_{fg} + (E)[ln(W_0/W)]^{1/n} + (ET\Omega/n)[ln(W_0/W)]^{((1-n))/n} \qquad (9)$$

Energy balance equations

The energy balance equation in the adsorbent bed for the pre-cooling and the adsorption processes can be expressed as given in Eq. (10).

$$\left[\left(M_{bm}c_{p,bm}\right)_{bed,m} + \left(M_s c_{p,s}\right)_{bed,s}\right]\frac{dT_{bed}}{dt} + (M_s X_{ad,f})\frac{dh_{ad,f}}{dt} + (m_{bed,v})\frac{dh_{bed,v}}{dt} = M_s\frac{dX_{ad,f}}{dt}\left(\Delta H_{ads} + \gamma h_{evap,out} - h_{ad,f}\right) + \frac{dm_{bed,v}}{dt}(\gamma h_{bed,in} - h_{bed,v}) - \dot{Q}_{cool} \qquad (10)$$

where the value of $\gamma = 0$ in the pre-cooling process; $\gamma = 1$ in the adsorption process.

The energy balance equation in the adsorbent bed for the pre-heating and the desorption process can be expressed as given in Eq.(11).

$$\left[\left(M_{bm}c_{p,bm}\right)_{bed,m} + \left(M_s c_{p,s}\right)_{bed,s}\right]\frac{dT_{bed}}{dt} + (M_s X_{ad,f})\frac{dh_{ad,f}}{dt} + (m_{bed,v})\frac{dh_{bed,v}}{dt} = M_s\frac{dX_{ad,f}}{dt}\left(\Delta H_{ads} + \gamma h_{cond,in} - h_{ad,f}\right) + \frac{dm_{bed,v}}{dt}(\gamma h_{bed,out} - h_{bed,v}) + \dot{Q}_{heat} \qquad (11)$$

where the value of $\gamma = 0$ in the pre-heating process; $\gamma = 1$ in the desorption process.

Mass balance equations

Amount of adsorbate in the adsorbent bed can be calculated from the following expression (Eq.(12)) at any instant.

$$M_{bed,f} = M_s X_{ad,f} + m_{bed,v} \qquad (12)$$

The mass transfer rate between the bed and the evaporator during the adsorption process can be obtained from Eqs.(13) and (14).

$$\frac{dM_{bed,f}}{dt} = M_s\frac{dX_{ad,f}}{dt} + \frac{dm_{bed,v}}{dt} \qquad (13)$$

$$\frac{dm_{eva,out}}{dt} = \frac{dm_{bed,in}}{dt} = \frac{dM_{bed,f}}{dt} \qquad (14)$$

Similarly, the mass transfer rate between the bed and the condenser during the desorption process can be obtained from Eqs.(13) and (15).

$$\frac{dm_{cond,in}}{dt} = \frac{dm_{bed,out}}{dt} = \frac{dM_{bed,f}}{dt} \qquad (15)$$

The cycling mass of the adsorbate in the system can be obtained from Eq.(16) or Eq.(17). The non-cycling mass of the adsorbate in the system can be obtained from Eq.(18).

$$M_{f,cyc} = \int_{des}\frac{dm_{cond,in}}{dt}dt = \int_{ads}\frac{dm_{eva,out}}{dt}dt \qquad (16)$$

$$M_{f,cyc} = M_s(X_{max} - X_{min}) + V_{bed,void}(\rho_{v,max} - \rho_{v,min}) \qquad (17)$$

$$M_{f,ncyc} = M_s X_{min} + V_{bed,void}\rho_v(P_c, T_{max}) \qquad (18)$$

where $V_{bed,void}$ shows the void volume occupied by adsorbate in the vapor phase in the adsorbent bed. $\rho_{v,max}$ represents the maximum vapor density at the condenser pressure (P_{cond}) and the maximum bed temperature (T_{max}); $\rho_{v,min}$ represents the minimum vapor density at the evaporator pressure (P_{eva}) and the minimum bed temperature (T_{min}).

Finally, Eq.(19) gives the total mass of the adsorbate employed in the system.

$$M_{f,sys} = M_{f,cyc} + M_{f,ncyc} \qquad (19)$$

System performance parameters

Adsorption cooling system performance is commonly defined by its specific cooling power (SCP) in W/kg adsorbent and the coefficient of performance (COP). The two parameters are the most critical data among the technical specifications of such products. COP and SCP are expressed by Eq.(20) and Eq.(21) respectively.

$$COP = \frac{Q_{eva}}{Q_{heat}} \qquad (20)$$

$$SCP = \frac{Q_{eva}}{t_{cycle}M_s} \qquad (21)$$

Where cooling capacity of the evaporator (Q_{eva}) and heat load of the system (Q_{heat}) in a cycle can be calculated by Eq.22 and Eq.23, respectively.

$$Q_{eva} = \oint_0^{t_{cycle}}\frac{dm_{eva,out}}{dt}\left(h_{exv,o} - h_{eva,sv}\right)dt \qquad (22)$$

$$Q_{heat} = \oint_0^{t_{cycle}}\dot{Q}_{heat}dt \qquad (23)$$

It should be mentioned that the electrical power consumption of chilled water, cold water and hot water pumps are relatively small so can be neglected.

Calculation procedure of the mathematical model

The home-made-software is written in the RAD Studio 10 environment using the Delphi 10 program language. The thermophysical fluid properties used in the model are obtained as real-fluid properties by including the CoolProp library, which is provided as a high accuracy open-source property package for pure and pseudo-pure fluids, as well as humid air. The CoolProp library, written in the C++ programming language, can calculate properties for 110 different pure and pure fluids, detailed information about the software can be found in Bell et al.[21]. Besides, adsorption heat is calculated as a function of pressure, temperature and concentration when it is not taken as a fixed value as it is in most studies. The equations given in the model are solved by iterative manner.

Validation of the mathematical model

Several studies have been already reported about the adsorption cooling systems for the use of the water-silicagel pair. Di et al. [16] conducted an experimental and theoretical simulation work by the use of the water-silicagel pair. In order to validate present mathematical model computations performed according to their parameters and working conditions used in their study. The mass of the adsorbent (M_s) used in a bed is = 47 kg silica gel. The heat capacity ($M_{bm}c_{p,bm}$) of the adsorption bed metal materials is taken as 78 kJ/K. The cooling water inlet temperature ($T_{cool,in}$) to the bed or the condenser is equal to 30 °C. The chilling water inlet temperature ($T_{chill,in}$) to the evaporator is equal to 20 °C. Evaporation temperature at the evaporator is the function of the cooling power. Other temperature settings are applied as follow:

Condenser temperature $\quad T_{cond} = T_{cool,in} + 3$ °C ;
Evaporator temperature $\quad T_{eva} = T_{chill,o} - 3$ °C;
Bed maximum temperature $T_{bed,max} = T_{heat,in} - 2$ °C ;
Bed minimum temperature $T_{bed,min} = T_{cool,in} + 2$ °C .

Tab.4 shows the comparisons between the present predicted results and the findings of Di et al.[16] for the three different heating fluid inlet temperatures as 65, 75 and 85°C. It can be seen that the predicted COP and SCP values are in a good agreement with the experimental and simulation data of Di et al. [16]. As the temperature increases from 65 to 85 °C, there is slight increase at COP values,

whereas, SCP increases sharply with the rising heating fluid temperature. Tab.4 also shows the relative differences between the calculated results and the experimental data. Largest relative difference percentages are 8.1% and 6.5% for COP and SCP, respectively. Considering the experimental uncertainties in the measurements and the assumptions made in the calculations, the agreement of the results is quite well.

Table 3. Physical characteristics of the silicagel used in the present study.

Chemical Composition	$SiO_2.n(H_2O)$
SiO_2 content (%)	99.7
Diameter (mm)	2-5
Density (kg/m³)	750
Micro Pore Volume(cm³/g)	0.343
Specific Surface Area (m²/g)	693
Pore Diameter (Å)	17.4
Specific Heat (c_p) (kJ/kgK)	0.92
Shape	Spherical
Colour	White

Table 4. Comparisons the present model results with the data given in Di et al.[16] for the silicagel-water pair. ($T_{cool,in}$ = 30°C , $T_{chill,in}$ = 20°C)

| $T_{heat,in}$	COP			SCP		
	Exp. [16]	Sim.[16] (RD¹%)	Present (RD¹%)	Exp. [16]	Sim.[16] (RD²%)	Present (RD²%)
85°C	0.43	0.40(7.5)	0.42(2.3)	99.8	93.3(6.5)	101.0(1.2)
75°C	0.37	0.39(5.4)	0.40(8.1)	80.2	78.8(1.7)	78.2(2.5)
65°C	0.37	0.39(5.4)	0.39(5.4)	63.9	65.1(1.9)	62.4(2.3)

$RD^1 = |COP_{exp} - COP_{sim}|/COP_{exp}$; $RD^2 = |SCP_{exp} - SCP_{sim}|/SCP_{exp}$

RESULTS AND DISCUSSION

The present study aims to perform a corporative work on the adsorption cooling system using silica gel with different working fluids as constitute adsorbent-adsorbate pairs. Four different widely used fluid (water, methanol, R134A and R404A) are chosen as the adsorbate. Two-bed adsorption cooling system as described in previous sections with the conditions described in the validation section are used in the calculations. In the computations, evaporation temperature at the evaporator is set as T_{eva} = 5°C; two different cooling fluid inlet temperature is considered as $T_{cool,in}$ = 20°C or 30°C; heating fluid inlet temperature is changing between 60 to 95°C. Adsorption/desorption time is taken as 600

seconds, precooling/preheating time is taken as 50 seconds. Therefore, the cycle time is taken as 1300 second. Computations are performed at the same working conditions for the four different adsorbates.

Fig.3, and Fig.4, show the computed results of the coefficient of performance (COP) and specific cooling power (SCP) respectively. For the all working fluids COP and SCP values at $T_{cool,in} = 20°C$ is higher than ones at $T_{cool,in} = 30°C$. It is resulted by more adsorbate is adsorbed by the adsorbent at lower temperatures, and the temperature difference between the heating and the cooling is also increased. These results more working fluid circulates in the system, and the cooling power rises considerably.
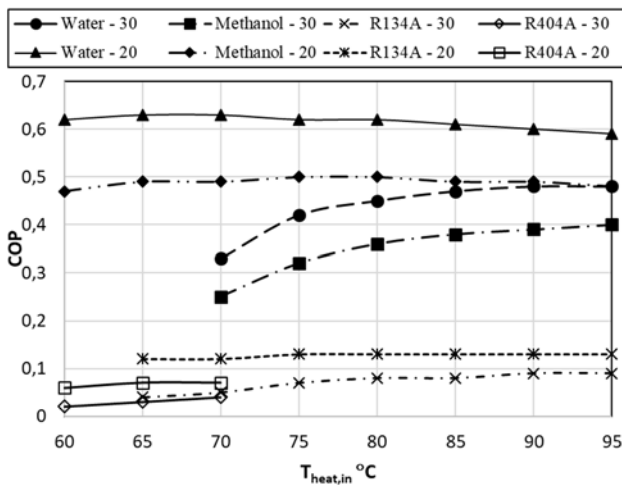
Fig.3. Comparisons of COP for the different heating and cooling fluid inlet temperatures. (T_{eva}=5°C; $T_{cool,in}$ = 20 or 30°C)
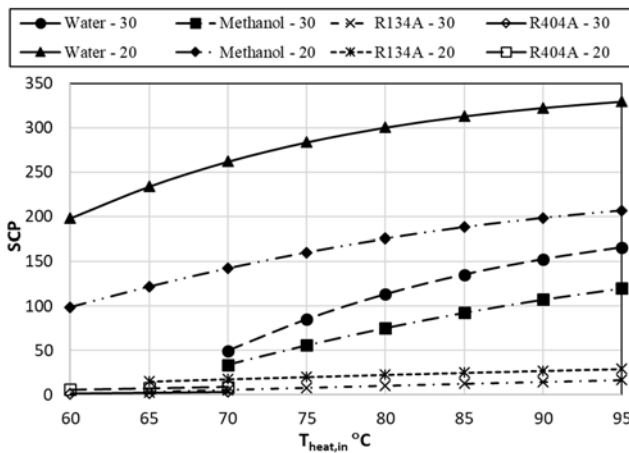
Fig.4. Comparisons of SCP for the different heating and cooling fluid inlet temperatures. (T_{eva}=5°C; $T_{cool,in}$ = 20 or 30°C)

Comparing COP and SCP for the working fluids, it can be seen that the highest COP (=0.63) and SCP (=329 W/kg) are obtained for the water, and the lowest ones are found for the R404A (as 0.02 and 1.3 W/kg, respectively).

The variations of COP and SCP with hot water inlet temperature shows similar behaviour for water and methanol. It can be seen from Fig.3 that COP values for methanol are about 80% of the value for water at the same operating conditions. COP values of R134A increase slightly with rising hot water inlet temperature, it rises up to 0.13 for $T_{cool,in}$ = 20°C and 0.09 for $T_{cool,in}$ = 30°C. In the meantime, SCP values for water and methanol increase significantly with increasing hot water inlet temperature as well as decreasing cooling water inlet temperatures, as shown in Fig.4. SCP values for methanol are about 70% and 60% of the water's values at $T_{cool,in}$ = 20°C and 30°C, respectively. SCP values of R134A increase slightly with rising hot water inlet temperature, it rises up to 30 W/kg for $T_{cool,in}$ = 20°C and 17 W/kg for $T_{cool,in}$ = 30°C.

Considering the adsorption heat values (at 20°C) given at Tab.1, water has the largest one (2751 kJ/kg), methanol has less than half of water's value (as 1373 kJ/kg), R134A and R404 have quite lower than water and methanol values (as 242 and 262 kJ/kg, respectively). When the computed result for COP and SCP are considered together with the adsorption heat values of the adsorbent-adsorbate pairs, it can be seen that the performance parameters show a strong relationship with the adsorption heat magnitude of adsorbate. Therefore, it can be concluded that the adsorption heat has a significant effect on the COP and SCP.

CONCLUSIONS

This study presents a comparative study on a two-bed adsorption cooling system with silica gel as adsorbents and four different working fluids (water, methanol, R134A and R404A) as the adsorbate. These four adsorbent-adsorbate pairs and various cycle operating conditions are investigated at the heating source temperature range from 60 to 95°C. The performance indicators are the COP and the SCP. Among the adsorbent-adsorbate pairs considered in this study, the best performance values are obtained for the silica gel-water pair. The silica gel-methanol pair shows similar behavior to the silica gel- water pair with about 20% and 40% less performance regarding COP and SCP, respectively. However, the silica gel-methanol has the advantage of evaporator temperature can be below 0 °C. It

should be mentioned that the adsorption cycles using these two fluids as adsorbate can be operated under atmospheric pressures. On the other hand, positive pressure refrigerants R134 and R404 pairs with silica gel shows shallow performances compared to the water and the methanol ones. The maximum COP and SCP values for the R134A are 0.13 and 30 W/kg respectively. Since the critical temperature is relatively low to the other fluids, R404A can be used the operating temperature less than 72 °C. The maximum COP and SCP values for the R404A are 0.07 and 9 W/kg respectively.

It is shown that the parameters that have the most considerable effect on COP and SCP are, in decreasing order, the adsorption heat of adsorbate-adsorbent pair, cooling source temperature, heating source temperature, condensation temperature at the condenser and evaporation temperature at the evaporator. These results are valid for all working pairs. In general, increasing evaporation temperature and decreasing adsorption bed temperature during the adsorption process increase COP and SCP for all working pairs.

It should be mentioned that the basic adsorption cycle used in this study. The performance of the adsorption cooling systems has been improving by the use of more advanced design optimization and simulation models such as heat recovery, mass recovery, multi-bed and multi-stage technologies as well as improving more efficient adsorbent-adsorbate pairs. It is a promising technology for the use of low-grade renewable energy sources.

NOMENCLATURE

b- the van der Waals volume, m^3;
c_p- specific heat, kJ/kgK;
COP – coefficient of performance, - ;
D_0 – surface diffusion coefficient, m^2/s;
E – characteristic energy of adsorption pair, kJ/kg;
E_a – activation energy of adsorption pair, kJ/kg;
F_o - a constant characteristic of adsorbent's shape.
h_{fg}- vaporization enthalpy, kJ/kg;
ΔH_{ads}- adsorption heat, kJ/kg;
M - mass, kg;
MW- molecular weight of fluid, kg/kmol;
n- exponential constant, -.
p- pressure, kPa;
p_s- saturation pressure, kPa;

R – gas constant, kJ/kgK;
RD- relative difference;
SCP – specific cooling power, W/kg;
Q - heat, kJ;
$\dot{Q}$ - heat rate, kW;
t - time, s;
T - temperature, K;
X – adsorption capacity on mass basis, kg/kg;
v_a – adsorbed phase specific volume, m^3/kg;
v_b – saturated liquid specific volume at normal boiling temperature, m^3/kg;

Subscripts

a- adsorbed phase;
ad- adsorption;
b- boiling point;
bed- adsorber bed;
bm- bed material;
c- critical point;
cyc- cycle;
cond- condenser;
eva- evaporator;
f- fluid;
fg- phase change from liquid to gas;
in- inlet
out- outlet
min- minimum;
max- maximum;
s- sorbent;
s- saturation;
l- liquid phase;
v- vapour phase;

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