Low Grade Heat Driven Adsorption System For Cooling and Power Generation Using Advanced Adsorbent Materials

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Abstract

Globally there is abundance of low grade heat sources (around 150 °C) from renewables like solar energy or from industrial waste heat. The exploitation of such low grade heat sources will reduce fossil fuel consumption and CO₂ emissions. Adsorption technology offers the potential of using such low grade heat to generate cooling and power. In this work, the effect of using advanced adsorbent materials like AQSOA-Z02 (SAPO-34) zeolite and MIL101Cr Metal Organic Framework (MOF) at various operating conditions on power and cooling performance compared to that of commonly used silica-gel was investigated using water as refrigerant. A mathematical model for a two bed adsorption cooling cycle has been developed with the cycle modified to produce power by incorporating an expander between the desorber and the condenser. Results show that it is possible to produce power and cooling at the same time without affecting the cooling output. Results also show that for all adsorbents used as the heat source temperature increases, the cooling effect and power generated increase. As for increasing the cold bed temperature, this will decrease the cooling effect and power output except for SAPO-34 which shows slightly increasing trend of cooling and power output. As the condenser cooling temperature increases, the cooling effect and power output will decrease while for the chilled water temperature, the cooling load and power generated increased as the temperature increased. The maximum values of average specific power generation (SP), specific cooling power (SCP) and cycle efficiency are 73 W/kg_{ads}, 681 W/kg_{ads} (using SAPO-34) and 67% (using Silica-gel) respectively. However, MIL101Cr can generate SP and SCP of 95 W/kg_{ads} and 1367 W/kg_{ads} respectively, but this case cannot consider to be practical operating conditions, because of using relatively low cooling source temperature, but this material still offers potential of generating power.

Keywords Adsorption System, Cooling and Power, AQSOA-Z02 (SAPO-34), MIL101Cr.

Nomenclature

Symbols		Subscript	
A	adsorption potential, J/mol	ads,a	adsorbent
c_p	specific heat capacity, J/kg.K	ads	adsorption
k_o	empirical constant in Eq. (8), 1/s	bed	adsorbent bed
E_a	activation energy, J/kg	chill	chilled water
h	enthalpy, J/kg	des	desorption
h_{fg}	evaporation latent heat J/kg	ex	expander
M	mass, kg	eff	effective
$\dot{m}$	mass flow rate, kg/s	evap	evaporator
P	pressure, Pa	f	liquid
Q_{st}	isosteric heat of adsorption, J/kg	g	gas
R	gas constant, J/kg.K	i	adsorption/desorption
R_p	adsorbent practice radius, m	in	inlet
U	overall heat transfer coeff., W/m ² K	j	cooling / heating source
W	power generated W	o	outlet
SP	specific power generated W/kg _{ads}	ref	refrigerant
SCP	specific cooling power W/kg _{ads}	r	ratio
t	time, s	s	saturation
T	temperature, K	cond	condenser
x	adsorption uptake, kg/kg _{ads}	w	water
x_{eq}	equilibrium uptake, kg/kg _{ads}		
ϕ	flag		

1. Introduction

Global electricity demand has increased significantly over the last few decades leading to increase fossil fuel consumption and CO₂ emissions. Global warming, climate change and energy security lead researchers towards developing more environmentally friendly energy systems and real change in the energy policy [1]. Dependence on the fossil fuel can be reduced by using low grade heat sources such as solar energy, geothermal energy and waste heat. A number of researchers have investigated the use of sorption technologies to exploit low grade heat sources for cooling applications. Cai et al [2] studied experimentally a single effect absorption system and results show that NH₃-LiNO₃ presents COP of 0.15 and minimum evaporation temperature of -13.1 °C utilizing regeneration temperature of 94.6 °C, while using NH₃-NaSCN presents COP of 0.2 and minimum evaporation temperature of -7.5 °C utilizing regeneration temperature of 97.6 °C. Gomri [3] simulated a solar/natural gas single effect lithium bromide absorption chiller and results show that COP of 0.82, exergy efficiency of 30% and 5 °C of evaporator temperature can be achieved utilizing 54-83 °C of heat source temperature. Aiming to improve the adsorption cooling technology different system configurations, working pairs and heat and mass transfer enhancing technologies have been used [4]. Huizhong et al [5] tested experimentally a solar powered adsorption cooling tube using active carbon/methanol and utilizing heat source temperature of around 110 °C and results show that COP is about 0.11 and the evaporator temperature reached -4 °C. Jribi et al [6] have set up a mathematical model of a 4-bed adsorption chiller using Maxsorb III -CO₂ utilizing heat source temperature of 95 °C and results show that COP of 0.1 can be achieved. Low-grade heat sources, can be used to produce power (electricity) using Organic Rankine cycle (ORC) and Kalina cycle technologies. Lecompte et al [7] examined ORC using zeotropic mixtures and results show that the second law efficiency can be increased in the range of 7.1% and 14.2% compared to pure working fluids using heat source temperature of 150 °C. Elsayed et al [8] numerically studied Kalina cycle system 11 (KCS11) and results show that efficiency can be improved by up to 40% using ammonia and up to 20% using R134a compared to ORC.

Both cooling and power have been recently investigated by a number of researchers to enhance the overall efficiency of utilising low grade heat sources. Table (1) summarises the research work carried out for producing cooling and power simultaneously. It can be seen that using absorption technology, cycle thermal efficiency of almost 27.7% can be achieved using low grade heat sources of temperature ranging from 57 to 465 °C and ammonia-water as working pair, however ammonia is toxic material and can cause serious health risk. Also, it can be seen that adsorption technologies have been used to produce cooling and power with COP of 0.77 and exergy efficiency of 90%.

Table 1 technologies used for cooling and power.

Absorption technology			
Author	Working pair/fluid	Source temp. °C	System performance
Vijayaraghavan, and Goswami [9]	Ammonia/water	87-207	First law efficiency is 25% higher than the basic combined power and cooling cycle.
Hasan et al [10]	Ammonia/water	57-197	Maximum second law efficiency of 65.8%
Liu and Zhang [11]	Ammonia/water	450	Exergy efficiency of 58% (22.3% increase) and 18.2% reduction in energy consumption.
Zheng et al [12]	Ammonia/water	350	Overall thermal efficiency of 24.2%, and exergy efficiency of 37.3%.
Zhang and Lior [13]	Ammonia/water	450	Cycle thermal and exergy efficiencies of 27.7%, and 55.7%.
Jing and Zheng [14]	Ammonia/water	465	Equivalent heat-to-power and exergy efficiencies reached 41% and 58%.
Wang et al [15]	Ammonia/water	200	About 36 kW of power and 75 kW of refrigeration. Thermal and exergy efficiencies reached 13.72% and 5.4%.
Adsorption technology			
Author	Working pair/fluid	Source temp. °C	System performance
Jiang et al [16]	5 different salts/ammonia	100-400	Electrical efficiency of 15.8%, COP of 0.691 and exergy efficiency of 82%.
Wang et al [17]	PbCl ₂ / ammonia BaCl ₂ / ammonia CaCl ₂ / ammonia	100-400	Exergy efficiency of 90% (40-60% higher than Gaswami cycle) and COP of 0.77.
Bao et al [18]	MnCl ₂ /ammonia	150-210	COP of 0.57 and exergy efficiency of 62%
Bao et al [19]	CaCl ₂ /ammonia	120-130	Power of 490 W and chilled water at 5.4 °C.
Jiang et al [20]	MnCl ₂ - CaCl ₂ /ammonia	130	Power of 300 W and cooling of 2 kW and the efficiency of cogeneration system increases from 31.6% to 37.6%.
Lu et al [21]	12 different salts/ammonia	100-300	COP increased by 38%, electricity efficiency improved from 8% to 12% and second law efficiency reached 41%.
AL-Mousawi et al [22]	MIL101Cr/water	70-90	Overall cycle efficiency increased from 47% to 50%.
Adsorption technology and ORC			
Author	Working pair/fluid	Source temp. °C	System performance
Jiang et al [23]	CaCl ₂ /BaCl ₂ and R245fa	< 100	Energy and exergy efficiencies were 10.1%-13.1% and 18.5%-20.3
Wang et al [24]	Silica-gel-water and R600	78 -98	1 kW of electricity and 6.3 kW of refrigeration from 15 kW of heat

The integration of adsorption system with Organic Rankine cycle to produce cooling and power was investigated by Jiang et al [23] and Wang et al [24] showing the possibility of generating cooling and power at the same time. However, the adsorption materials used by Jiang et al is a chemical salt and that used by Wang et al is the conventional silica-gel with limited water adsorption capability. There is a limited work to produce cooling and power by incorporating an expander in the adsorption system using chemical adsorbent materials such as MnCl₂ and CaCl₂ with ammonia as refrigerant [14][15] [16][17][18][19], while no similar work was

reported using physical adsorption materials. Chemical adsorbents have lower stability than a physical adsorbents, where chemical molecules do not keep their original state which limits its practical applications. Swelling and agglomeration are additional problems of chemical adsorbents which affect the mass and heat transfer performance of the system negatively [25].

Recently, advanced adsorption materials were developed like AQSOA-Z02 and various Metal Organic Framework materials like MIL101Cr with superior adsorption characteristics. Therefore this work investigates the performance of these advanced materials using two bed adsorption system to simultaneously produce cooling and power. In addition, the water adsorption characteristics of AQSOA-Z02 (SAPO-34) and MIL101Cr were measured using DVS analyser (dynamic vapour sorption analyser).

2. Basic adsorption cooling system

Figure (1a) shows a schematic diagram of a basic two-bed adsorption cooling system which consists of adsorber, desorber, condenser and evaporator. As the adsorption is an exothermic process a cooling source is used to extract heat from the adsorber and sustain cooling during adsorption process which helps to desorb the refrigerant from the evaporator and produce cooling effect. Desorption is an endothermic process, and a heat source (low grade heat source) is used to add heat to the desorber and sustain heating during the process which helps to release the refrigerant (water vapour) from the hot bed. After that, the hot refrigerant will be cooled in condenser to feed the evaporator with the refrigerant liquid and keep the cooling process continuous. Figure (1b) shows the basic adsorption cycle on an isosteric diagram; process 1-2 is an adsorbent isosteric heating where a low grade heat source is used and this heating is still continuous during the process 2-3' while the valve 4 is opened, after that, an adsorbent isosteric cooling is started (process 3'-4') using cooling source and this cooling is still continuous during the process 4'-1 while the valve 1 is opened and the same processes are repeated for the other bed.

Figure 1: shows a basic two-bed adsorption cooling system (a) schematic diagram (b) isosteric diagram

3. Adsorption system for cooling and power generation

Figure (2a) shows a schematic diagram of the modified two-bed adsorption cycle for cooling and power generation which consists of adsorber, desorber, condenser, evaporator and expander (turbine) which located between the hot bed (desorber) and the condenser. Adding an expander to the adsorption cycle is not enough to generate power without a significant pressure difference between the inlet and the outlet of the turbine which comes from reducing the pressure of the condenser to a lower pressure and keep the original pressure of the desorber at $P_{\max}$. The modified adsorption cycle can work in two different modes; the first mode as shown in figure (2b) is for cooling only (1-2-x-4-5-1) which works exactly as the basic adsorption cycle and the second mode is for cooling and power generation (1-2-3-4-5-1). In the second mode (cooling and power generation) the process 1-2 is an adsorbent isosteric heating and heat is needed to reach $P_{\max}$ by utilising low grade heat source such as solar energy or waste heat. Through process 2-x' the adsorbent is still heating up while the solenoid valve is opened and desorption process is started which generate the cycle maximum pressure $P_{\max}$ at point 2. Producing energy will start when the water vapour with the enthalpy of h_2 expands through an expansion process to produce mechanical work and leaves the turbine at h_3 as shown in figure (2). This process releases

heat before the refrigerant enters the condenser where it is condensed to liquid at point 4. As the condensate refrigerant (water) passes through the evaporator; it will take heat from the surrounding producing cooling effect by evaporation process. During switching time, all the solenoid valves V1, V2, V3, and V4 are closed, then the isosteric desorption process starts in bed 1, while the isosteric adsorption process starts in bed 2 as shown in figure (2).

Figure (3) shows the expansion process through the expander on a T-s diagram and the process 2-3s is an isentropic process and the process 2-3 is the real expansion process while in this investigation the ideal case only is to be considered. The value of the maximum pressure in the cycle (P_2) as shown in figures (2b) and (3) depends on the temperatures of the heat source (hot bed) and the condenser. As in figure (3) the entropy of the point 3s can be taken from the saturation properties of the water at the condenser temperature and from the entropy and temperature (hot bed temperature) at point 2, the value P_2 (maximum pressure) can be calculated and as a result, the value of P_2 is variable during this investigation and depends on the applied operating conditions.

Figure 2: shows a two bed adsorption cycle for cooling and power (a) schematic diagram (b) isosteric diagram

Figure 3: shows T-s diagram of the expansion process.

4. Mathematical Formulation

4.1 Adsorbent material characteristics

In this study, two advanced adsorption materials, AQSOA-Z02 (SAPO-34) and MIL101Cr are compared to silica-gel. Figures (4a) to (4c) show scanning electron microscope SEM images of these three materials. AQSOA-Z02 has solid regular cubic or brick shape with a uniform particle size while MIL101Cr has smaller particles. DVS analyser by (Surface Measurement System Ltd) has been used to experimentally examine the adsorption isotherms of AQSOA-Z02 (SAPO-34)-water and MIL101Cr-water at the laboratories of the University of Birmingham. This DVS analyser comprises of a temperature controlled chamber that contains a sensitive recording microbalance for measuring the adsorbent weight. A dry nitrogen purge system is applied before packing the sample to ensure precise readings. The vapour pressure in the chamber is regulated by mass flow controller which determines the amount of dry and saturated vapour gas. The microbalance is connected to a computer to record mass readings every 4 s while vapour pressure sensor and RTD temperature sensor are used to measure testing conditions. A sample of 10 mg (± 0.05 mg) is located in the sample pan and then dried at certain temperature until no change in the mass is recorded. Then, at various partial pressures (0.1–0.95) adsorption is started. This test is repeated at three different temperatures (25°C, 35°C and 45°C). Figures (5a) and (5b) show the measured isotherms of AQSOA-Z02 (SAPO-34)-water and MIL101Cr-water at three temperatures (25 °C, 35 °C and 45 °C) and the corresponding curve fitting lines. Figures (6a) to (6c) show the

kinetics fitting of experimental uptake for MIL101Cr-water at 25 °C, 35 °C and 45 °C and the corresponding curve fitting lines.

For AQSOA-Z02 (SAPO-34)-water, the experimental data is fitted to the thermodynamic formulation that developed by Sun and Chakraborty [26] and the constants is listed in table (2). The equation is given by:

$$x_{eq} = x_o \left[\frac{k \left(\frac{P_s(T_w)}{P_s(T_a)} \right)^m}{1 + (K-1) \left(\frac{P_s(T_w)}{P_s(T_a)} \right)^m} \right] \quad (1)$$

$P_s(T_w)$ and $P_s(T_a)$ are the saturation vapour pressure at water vapour temperature and adsorbent temperature respectively.

$$k = \alpha \exp[m(Q_{st} - h_{fg})/RT] \quad (2)$$

Table 2: Values of parameters used in Eqs. (1) and (2)

Property	Value	Unit	Source
x_{eq}	0.285	kg/kg _{ads}	Fitting
α	1032	-	Fitting
m	3.18	-	Fitting
Q_{st}	3420	kJ/kg	[27]

For MIL101Cr-water, the experimental data is fitted to equation (3) which is divided into three zones as shown in table (3) due to the S-shape isotherms of the material as shown in figure (5b). This three zones fitting helps to fit the data directly using polyfit MATLAB function.

$$x_{eq} = f(A) \quad (3)$$

Where

$$A = -RT \ln \left(\frac{P_s(T_w)}{P_s(T_a)} \right) \quad (4)$$

Table 3: MIL101Cr-water isotherms of Eq. (3)

$A < 1774.9$	$x_{eq} = 1.46 - 5.76E-5A - 1.34E-08A^2 + 6.65E-12A^3$
$A > 2498.7$	$x_{eq} = 0.475 - 2.29E-04A + 4.79E-08A^2 + 3.36E-12A^3$
$1774.9 \leq A \leq 2498.7$	$x_{eq} = 2252.774 - 5.567A + 0.0055A^2 - 2.66E-06A^3 + 6.42E-10A^4 - 6.14E-14A^5$

The modified Freundlich equation is used to present the adsorption isotherms of Silica-gel- water [28][29][30] as:

$$x_{eq} = A(T_s) \left[\frac{P_s(T_w)}{P_s(T_a)} \right]^{B(T_s)} \quad (5)$$

Where

$$A(T_s) = A_o + A_1 T_s + A_2 T_s^2 + A_3 T_s^3 \quad (6)$$

$$B(T_s) = B_o + B_1 T_s + B_2 T_s^2 + B_3 T_s^3 \quad (7)$$

The constants of equations (6) and (7) are listed in table (4).

Table 4: Values of parameters used in Eq. (5) [29][30]

Parameter	Value
A_o	-6.5314
A₁	0.072452
A₂	-0.23951×10 ⁻³
A₃	0.25493×10 ⁻⁶
B_o	-15.587
B₁	0.15915
B₂	-0.50612×10 ⁻³
B₃	0.5329×10 ⁻⁶

Adsorption and desorption is a time dependant process and are assumed to be controlled by macroscopic diffusion. For all pairs, the linear driving force (LDF) equation is used to describe the adsorption/desorption rate as [28][29][31]

$$\frac{dx}{dt} = k_o \exp(-E_a/RT)(x_{eq} - x) \quad (8)$$

For AQSOA-Z02(SAPO-34)-water, the kinetics constants of equation (8) is listed in the table (5) [32][33]. While, for MIL101Cr-water the values of kinetics constants are calculated from fitting the data of the DVS machine tests to the LDF model at three different temperature (25 °C, 35 °C and 45 °C) and a range of pressure ratio of (0-0.95). The values of these constant are listed in the table (6).

Table 5: LDF equation constants of SAPO-34-water [32][33]

Symbol	$P_r > 0.1$	$P_r^b \leq 0.1$	Unit ^a
E_a	17709.8	44423.5	J/mol
k_o	3.23E+04	1.85E+04	1/s

^a Units are: s=second, Joule, mol=mole.

Table 6: Fitted LDF equation constants of MIL101Cr-water

Symbol	$0.5 \geq P_r \geq 0.4$	Else	Unit
E_a	27612	19610	J/mol
k_o	10	3.25	1/s

For Silica-gel-water the values of kinetics constants used in equation (8) are : $k_o = 1.3183 \text{ E}+05 \text{ 1/s}$ and $E_a = 42000 \text{ J/mol}$ [28][30].

Figure 4: SEM images for (a) Silica gel[34](b) AQSOA Z02 (SAPO-34)[35](c) MIL101Cr Water[36].

(a) SAPO-34-water.

(b) MIL101Cr-water.

Figure 5: Isotherm fitting of experimental uptake from DVS machine and predicted uptake.

(a) 25 °C.

(b) 35 °C.

(c) 45 °C.

Figure 6: Kinetics fitting of experimental uptake from DVS machine and predicted uptake for MIL101Cr-water.

4.2 System energy balance

The lumped model technique is used to describe the energy balance equations in the two adsorbent beds used in this study, where the adsorbent, the refrigerant and the bed materials are assumed to be at the same temperature at all time of the cycle [37][38][39].

$$\left(M_{C_{p_{eff}}}^{bed}\right) \frac{dT_i^{bed}}{dt} + \left(M_a x_i^{bed} c_p\right) \frac{dT_i^{bed}}{dt} = \varphi M_a \left(\frac{dx_i^{bed}}{dt}\right) (Q_{st}) - (mc_p)_j (T_{j,o} - T_{j,in}) \quad (9)$$

Flag φ equals to 0 at switching time and equals to 1 at adsorption/desorption process. The first term on the left side of the equation (9) shows the internal energy change in heat exchanger material, including the fins and the tubes, while the second term represents the change in internal energy of the refrigerant (water). On the other hand, the first term on the right side of equation (9) represents the heat generated/rejected during the adsorption/desorption process respectively. The last term describes heat added/rejected to the coolant during the adsorption / desorption process. The bed outlet temperature is given by [37][38][39]

$$T_{j,o} = T_i^{bed} + (T_{j,in} - T_i^{bed}) \exp \left[\frac{-(UA_r)_i^{bed}}{(mc_p)_j} \right] \quad (10)$$

The energy balance equations for the condenser can be expressed by [29][40][41]

$$\left(Mc_{p_{eff}}^{cond}\right)\frac{dT^{cond}}{dt} = \varphi h_{fg} M_a \frac{dx_{des}^{bed}}{dt} - (mc_p)_{cond}(T_{w,o} - T_{w,i}) - (c_p)_w (T^{ex} - T^{cond}) M_a \frac{dx_{des}^{bed}}{dt} \quad (11)$$

The first term on the left side of equation (11) shows the internal energy change in condenser tubes. On the other hand, the first term on the right side of equation (11) represents the latent heat of vaporization. The second term represents the total rate of heat rejected to the cooling water, while the last term shows the rate of sensible heat required to cool the income vapour from expander outlet temperature to condenser temperature. The condenser outlet temperature is given by [29][40][41]

$$T_{w,o} = T^{cond} + (T_{w,in} - T^{cond}) \exp \left[\frac{-(UA_r)^{cond}}{(mc_p)_{cond}} \right] \quad (12)$$

The energy balance in the evaporator is expressed as [29][40][41]

$$\left(Mc_{p_{eff}}^{evap}\right)\frac{dT^{evap}}{dt} = \varphi h_{fg} M_a \frac{dx_{ads}^{bed}}{dt} - (mc_p)_{evap}(T_{chill,o} - T_{chill,i}) - (c_p)_w (T^{cond} - T^{evap}) M_a \frac{dx_{des}^{bed}}{dt} \quad (13)$$

The first term on the left side of the equation (13) shows the internal energy change of the evaporator tubes. On the other hand, the first term on right side of equation (13) represents the latent heat of evaporation while the second term gives cooling effect of the adsorption cogeneration cycle. The last term shows the rate of sensible heat required to cool down the incoming condensate to the evaporation temperature. The outlet temperature of the chilled water can be written as [29][40][41]

$$T_{chill,o} = T^{evap} + (T_{chill,in} - T^{evap}) \exp \left[\frac{-(UA_r)^{evap}}{(mc_p)_{evap}} \right] \quad (14)$$

The mass balance of liquid refrigerant in the evaporator is given as [29][37][41]

$$\frac{dM_{ref}}{dt} = -M_a \left[\frac{dx_{des}^{bed}}{dt} + \frac{dx_{ads}^{bed}}{dt} \right] \quad (15)$$

The water vapour enters the expander with the maximum cycle pressure P_2 , (as shown in figure 3), the refrigerant mass flow rate, the temperature T_2 , mass flow rate m and the enthalpy h_2 . Through the expander a mechanical work is produced and then, the refrigerant vapour leaves the expander with the condition of point 3 as in figure (3). The thermodynamic equation for the power generation is:

$$W = \dot{m}_{ref}(h_2 - h_3) \quad (16)$$

The overall performance of the cogeneration cycle is evaluated using the specific cooling power (SCP), specific generated power (SP), the cooling coefficient of performance (COP) and overall cycle efficiency as expressed in equations (17-20).

$$SCP = \frac{(mc_p)_{\text{evap}} \int_0^{t_{\text{cycle}}} (T_{\text{chill,o}} - T_{\text{chill,i}}) dt}{M_a t_{\text{cycle}}} \quad (17)$$

$$SP = \frac{\int_0^{t_{\text{cycle}}} m_{\text{ref}} (h_2 - h_3) dt}{M_a t_{\text{cycle}}} \quad (18)$$

$$COP = \frac{(mc_p)_{\text{evap}} \int_0^{t_{\text{cycle}}} (T_{\text{chill,o}} - T_{\text{chill,i}}) dt}{(mc_p)_h \int_0^{t_{\text{cycle}}} (T_{h,o} - T_{h,i}) dt} \quad (19)$$

$$\text{Cycle efficiency} = \frac{(mc_p)_{\text{evap}} \int_0^{t_{\text{cycle}}} (T_{\text{chill,o}} - T_{\text{chill,i}}) dt + \int_0^{t_{\text{cycle}}} m_{\text{ref}} (h_2 - h_3) dt}{(mc_p)_h \int_0^{t_{\text{cycle}}} (T_{h,o} - T_{h,i}) dt} \quad (20)$$

Where, SCP is the specific cooling power per unit mass of adsorbent (kW/kg), SP is the specific power per unit mass of adsorbent (kW/kg), COP is the ratio of the cooling effect to the total heat consumed and the cycle efficiency refers to the total energy efficiency of the adsorption cycle for cooling and power.

4.3 System modelling

A two bed adsorption system for cooling and power generation is simulated using MATLAB Simulink software to study the feasibility of producing cooling and power simultaneously utilizing three different adsorbents. The main system components such as beds, condenser, evaporator and expander (turbine) are presented in a flow chart as shown in figure (7) which shows the main steps used to solve the system equations (1-20).

Figure 7: System modelling flow chart.

5. Results and discussion

The main purpose of this study is to investigate the feasibility of producing power as well as cooling at the same time by modifying the two bed adsorption system to generate cooling and electricity simultaneously. Table (7) shows the main operating conditions and the characteristics of bed, condenser and evaporator used in this study. The basic two bed adsorption cycle shown in figure (1a) is validated against experimental data of a two bed adsorption cooling system [42]. Figure (8) shows the simulated and experimental outlet temperature of heat transfer fluids for the two bed silica-gel-water adsorption system. The predict outlet temperature profile of heat transfer fluids show deviation from the experimental data of the bed, condenser and evaporator by an average error less than 12%. Figure (9) shows the output of the adsorption cycle for cooling and power generation using AQSOA-Z02 (SAPO-34)-water as a working fluid and utilising a heat source temperature of 140 °C. The cycle can produce maximum cooling and power of almost 1 kW (average of 0.4 kW) and 5.3 kW (average of 4.6 kW) respectively. Figure (10) shows a comparison of the COP and cycle energy efficiency of the three used pairs using cooling only and cooling and power generation. Results show that the proposed cycle can improve the original adsorption cycle up to 11% by producing power in addition to cooling. Figure (11) compares of the

SCP generated in each cycle for the three pairs. Results show that generating power did not affect the producing of cooling.

Table 7:
Parameters used in the simulation.

Parameter	Value
Bed heating fluid temperature °C	120
Bed cooling fluid temperature °C	26
Condenser cooling temperature °C	26
Chilled water temperature °C	18
Bed hot fluid mass flow rate kg/s	1.2
Bed cold fluid mass flow rate kg/s	1.3
Condenser mass flow rate kg/s	0.75
Evaporator mass flow rate kg/s	0.75
Half cycle time s	320
Switching time s	12

Bed heat exchanger characteristics.	
Parameter	Value
Fin length m	172E-3
Fin width m	30E-3
Fin pitch m	1.2E-3
Module length m	450E-3
No. of module	4
No. tubes/module	6
Tube OD m	15.875E-3
Tube thickness m	0.8E-3

Condenser/evaporator characteristics.	
Parameter	Value
Pipe length m	5.5
No. tubes	4
Tube OD m	15.875E-3
Tube thickness m	0.8E-3

Figure 8: Simulated and experimental outlet temperature of heat transfer fluids for the two bed silica-gel-water adsorption system.

Figure 9: Two bed SAPO-34-water adsorption system for cooling and power generation utilising 140 °C heat source temperature and 4.13 kg/bed adsorbent.

Figure 10: COP/efficiency Comparison between using the first mode and the second mode of the proposed adsorption cycle utilising 120 °C heat source temperature.

Figure 11: SCP Comparison between using the first mode and the second mode of the proposed adsorption cycle utilising 120 °C heat source temperature.

Figure (12) shows the effect of heat source temperature on the average specific power (SP), specific cooling power (SCP) and efficiency of Silica-gel-water, AQSOA-Z02 (SAPO-34)-water and MIL101Cr-water. As heat source temperature increases the SP increases due to the increase in water uptake which leads to increase the mass flow rate and the increase in enthalpy difference which again increases the SP as shown in figure (12a). As heat source temperature increases, the average SCP increases for Silica-gel-water, AQSOA-Z02 (SAPO-34)-water and it is still stable for MIL101Cr-water and this is due to how the water uptake is affected with heat source temperature for each pair. For SAPO-34-water, as the heat source temperature increases the efficiency increases, while for Silica-gel-water and MIL101Cr-water it decreases due to more heat consumption that happens at high temperatures.

Figure (13) shows the effect of cold bed temperature on the average SP, SCP and efficiency for the three pairs. As the cold bed temperature decreases the SP, SCP and efficiency increases except for SAPO-34-water which decreases as cold temperature decreases and this is due to the isotherms shape of each material. MIL101Cr-water shows a good performance at low cold temperature, because it has S shape isotherms and when the pressure ratio at adsorption mode approaches the 0.6, the water uptake reaches the highest value. Figure (14) show the effect of condenser temperature on the average SP, SCP and efficiency for the three pairs. When the condenser temperature increases the average specific power generation decreases for Silica-gel and AQSOA-Z02 (SAPO-34) while it is almost constant for MIL101Cr. For all pairs, as the condenser temperature increases the efficiency decreases. This is mainly because of the low water uptake at high condenser temperature. Also, as

the condenser temperature increases the turbine pressure ratio and enthalpy difference decreases leading to decrease in power generation. Figure (15) show the effect of inlet chilled temperature on the average SP, SCP and efficiency of the three pairs studied in this work. When the chilled temperature increases the average SP, SCP and efficiency increase for Silica-gel and MIL101Cr while it is almost constant for AQSOA-Z02 (SAPO-34).

MIL101Cr-water is superior adsorption pair in terms of isotherms water uptake and it can achieve maximum uptake value of almost 1.4 kg/kg_{ads} as shown in figure (5b), however this high uptake can only be achieved if the pressure ratio $P_s(T_w)/P_s(T_a)$ during adsorption mode is greater than 0.6 and this can be achieved either by decreasing the adsorption temperature i.e. bed cold temperature or increasing the evaporator temperature i.e. using high chilled temperature, that is why this pair shows the highest values of the average SP and SCP in figures (12a) and (12b) and good values in figures (14a) and (14b). In addition, this high uptake value needs relatively fast kinetics to achieve the maximum uptake within the half cycle time. As a result, MIL101Cr-water produce the maximum SP and SCP over this investigation of 1367 W/kg_{ads} and 95 W/kg_{ads}, but with relatively low cold bed temperature and this case cannot be considered as a practical engineering case for cooling and power generation, however MIL101Cr offers potential of generating power only. AQSOA-Z02 (SAPO-34) produced the maximum SP and SCP of 681 W/kg_{ads} and 73 W/kg_{ads} respectively for the case of cooling and power generation using acceptable operating conditions. Silica-gel shows dominantly the highest energy cycle efficiency with a maximum value of 67%.

(a) Average specific power generation.

(b) Average specific cooling power.

(c) Efficiency

Figure 12: Effect of bed heat source temperature.

(a) Average specific power generation.

(b) Average specific cooling power.

(c) Efficiency

Figure 13: Effect of bed cold temperature.

(a) Average specific power generation.

(b) Average specific cooling power.

(c) Efficiency

Figure 14: Effect of condenser cooling temperature.

(a) Average specific power generation.

(b) Average specific cooling power.

(c) Efficiency

Figure 15: Effect of inlet chilled temperature.

6. Conclusion

AQSOA-Z02 (SAPO-34)-water, MIL101Cr-water and Silica-gel-water are used as a working pairs for an adsorption system to generate cooling and power at the same time. The modified adsorption system includes two adsorbent beds, condenser, evaporator and an expander placed between the desorber and the condenser. The refrigerant leaves the hot bed (after the desorption process) to enter the expander at high pressure and temperature to produce mechanical power and then enters the condenser. After that, the condensed refrigerant passes through the evaporator to produce the cooling effect. This study show the possibility of utilising the adsorption technology to generate power as well as cooling. In addition, the current study has investigated the effect of heat source temperature, cold bed temperature, condenser cooling temperature and chilled water temperature on the power generated and the cooling capacity obtained by the system. The main results can be summarised as:

1. The adsorption cycle for cooling and power generation is feasible and can produce up to 73 W/kg_{ads} of SP, 681W/kg_{ads} of SCP using SAPO-34, while MIL101Cr can generate SP and SCP of up to 95 W/kg_{ads} and 1367 W/kg_{ads} respectively, but this case cannot consider to be practical operating conditions, because of using relatively low cold bed temperature, however this material still offers potential of generating power.

2. Adding an expander to the adsorption cooling cycle help to increase the overall cycle efficiency by up to 11% and Silica-gel achieved the maximum efficiency of 67%.
3. As the heat source temperature increases, the average specific cooling power and the power generation by the system increase.
4. As bed cooling temperature increases, the average specific cooling power and the power generation decrease except for SAPO-34-water which slightly increases due to different isotherm shape.
5. Increasing the condenser cooling temperature will decrease the average specific cooling power and the power generation through the system except for MIL101Cr-water which is not affected.
6. As for the chilled water temperature, the average specific cooling power and power generation through the system increase, as the temperature increases for MIL101Cr and Silica-gel, while it remains relatively constant for SAPO-34.

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