Journal of Thermal Science

https://doi.org/10.1007/s11630-022-1535-7

Heat Recovery for Adsorption Refrigeration System via Pinch Technology

PAN Quanwen[1,2*], SHAN He[1,2], TAMAINOT-TELTO Zacharie[3], WANG Ruzhu[1,2]

1. Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China
2. Engineering Research Center of Solar Power and Refrigeration, MOE, Shanghai 200240, China
3. School of Engineering, University of Warwick, Coventry CV4 7AL, UK

Abstract: An adsorption refrigeration system can be driven by low grade heat and uses natural refrigerant with the advantage of reducing the greenhouse gases emission. However, one of the weaknesses is its low efficiency and more importantly its high cost. The recovery of internal waste heat becomes therefore very important in order to improve the coefficient of performance (COP). Analysis based on pinch technology can be helpful to optimal heat recovery operation. In this paper, temperature-heat diagrams and problem tables for adsorption refrigeration systems are proposed and analyzed using Pinch Technology. The results show that pinch point is located between beds and the main waste heat needs to be recovered between beds. Dynamic characteristic (time factor) of adsorption refrigeration system is the main resistance for heat recovery. The effect of pinch point temperature difference on the system COP is not distinct. Furthermore, when the driving temperature is 90°C, the COP of adsorption refrigeration via optimization of pinch analysis is 0.73 which is fairly comparable to LiBr-water absorption refrigeration system. Pinch Technology can be adopted in different types of adsorption refrigeration systems (two-bed, four-bed, mass recovery, et al.).

Keywords: heat recovery, adsorption refrigeration, pinch point, pinch technology, silica gel-water

1. Introduction

The growth of cooling demand, for both domestic and industrial applications, is mainly driven by the global economic growth as well as the population growth. Continuously rising demand for cooling is putting enormous strain on electricity supply. According to a report of International Energy Agency, total electricity use for cooling worldwide is about 10% of global electricity use in 2016 [1]. In the cooling market, the dominating units are electrically driven mechanical compression refrigeration systems. Besides, refrigerant discharge of mechanical compression refrigeration system brings about ozone depletion issue. In the severe situation of energy and environment, the call for green refrigeration technology is urgent.

Adsorption refrigeration, one of the green refrigeration technologies, can be driven by low-grade heat and use natural refrigerants, so that it is a perfect solution to meet the increasingly strict requirements of energy saving and environmental protection [2]. Absorption refrigeration is another thermally driven refrigeration technology, but the use of solution pump brings about 5% electricity consumption and vibration [3]. Adsorption refrigeration system does not have any moving components and enjoys the advantages of no vibration and noise. The

Received: Apr 03, 2021 AE: WANG Lin Corresponding author: PAN Quanwen E-mail: panqw@zucc.edu.cn

Nomenclature

a	coefficient	ad	adsorbent
b	coefficient	bed	bed
C	specific heat capacity/kJ·kg^{-1}·K^{-1}	c	condensation
COP	coefficient of performance	CS	cold stream
H	heat load/kJ	d	desorption
L	latent heat of vaporization/kJ·kg^{-1}	e	evaporation
M	mass/kg	HS	hot stream
Q	heat/kJ	in	input driving heat
r	reaction heat/kJ·kg^{-1}	j, k	number
R723	ammonia blend refrigerant (40 wt% Dimethyl ether, 60 wt% Ammonia)	l	liquid
T	temperature/K	ou	output cooling capacity
t	temperature/°C	p	pinch point
X	refrigerant uptake/kg·kg^{-1}	r	recovered
X_0	maximum refrigerant uptake/kg·kg^{-1}	s	saturation
Subscripts		v	vapor
a	adsorption		

disadvantages of adsorption refrigeration, like low efficiency, however, limit its applications and product development.

The common refrigerants for adsorption refrigeration system are natural substances, like water, methanol and ammonia. The most common adsorbents are silica gel, activated carbon, zeolite, calcium chloride and metal organic framework (MOF). Among them, silica gel-water working pair is most used and developed because of its extremely low driving temperature [4] and low cost. A new class of zeolites, namely aluminophosphate base AQSOA (AQSOA-Z01, Z02 and Z05), also have similar low driving temperature but much larger adsorption capacity on water than silica gel because of its S-shaped adsorption isotherms [5]. So the commercial adsorption refrigeration units [6–10] adopt either silica gel-water or AQSOA zeolite-water with packed or coated beds. Besides, the adsorption refrigeration prototype with combined use of packed silica gel and coated AQSOA zeolite was built and investigated by Sapienza et al. [11]. MOF is a very promising adsorbent. Various types of MOFs have been developed, such as MOF-801 [12], MIL-100 [13], CAU-10 [14] and MIP-200 [15]. MIP-200 is reported to be the best MOF for adsorption refrigeration and its coefficient of performance (COP) was predicted to be over 0.6 at 60°C [15].

Advanced cycles are often proposed to enhance the adsorption refrigeration system performance. Heat and mass recovery cycle is considered to be an efficient way to recover the internal waste heat and enlarge the cyclic adsorption capacity, so that it is commonly used in practical systems [16]. Thermal wave cycle can make the most of the internal waste heat but it is hardly realized in practical systems while it requires suited heat and mass transfer properties of adsorbing/desorbing beds [17]. The reported experimental COP of active carbon-methanol thermal wave system is only 0.13 [18]. The adjustment of ads-/desorption times via three beds can also provide optimal operation of the adsorption refrigeration system due to the fact that the adsorption process requires more time than desorption process [19, 20]. Optimal cycle time is another factor to ensure the adsorption refrigeration system in good running state. Iguchi et al. [21] provided a method for estimating optimum cycle time based on adsorption chiller parameters, for example, hot water and chilled water temperature, heat transfer coefficient and heat capacities of beds. Performance optimization of solar adsorption cooling systems with adaptive cycle time was investigated [22, 23]. Pan et al. [24] proposed an operation strategy with varied cycle time based on solar hot water temperature and system performance was significantly improved.

Overall, the recovery of system internal waste heat is the best way to improve the system performance. Optimal heat recovery operation needs appropriate arrangement of heat exchanger networks which can be optimized by Pinch Technology [25]. Pinch Technology was proposed by Linhoff and Boland [26] and now has been widely applied in chemical engineering and absorption refrigeration areas [27]. Compared to simulation or experiment methods, pinch technology is a convenient and efficient method which is suitable for new heat exchanger networks design or existing heat exchanger networks optimization. Atuonwu et al. [28]

used Pinch Technology to optimize energy efficiency for a zeolite adsorption drying system but the internal heat exchanger network was not analyzed. Xu et al. [29] developed a temperature-heat (t-Q) diagram analysis method for the heat recovery adsorption cycle. Though this method uses t-Q diagram as what pinch technology uses, it is only suitable for evaluation on the heat exchanger network in existing systems. Pinch technology used in analysis or optimizing of heat exchanger network for adsorption refrigeration and heat pump system has not yet been reported in the literature. The main objective of this paper is therefore to adapt the method of pinch analysis to adsorption refrigeration and heat pump systems. In order to evaluate the proposed method, the t-Q diagram of a silica gel-water adsorption refrigeration system is analyzed using Pinch Technology and predicted performance are also given.

2. Mathematical Modeling

A conventional two-bed adsorption refrigeration system including the associated thermodynamic cycle, illustrated in Fig. 1, is taken as an example (in the figure, V means valve.). This system has four working processes: precooling, adsorption, preheating and desorption (Fig. 1(b)). These working processes can be described as follows.

(1) Bed1 in precooling & Bed2 in preheating

V1–V4 are closed and V5 is the throttle valve. Bed1 is cooled and Bed2 is heated.

(2) Bed1 in adsorption & Bed2 in desorption

V1 and V4 are closed and V2 and V3 are open. Bed1 is cooled and adsorbs the refrigerant vapor from evaporator. Bed2 is heated and desorbs the refrigerant vapor which flows into condenser.

(3) Bed1 in preheating & Bed2 in precooling

After above processes, cooling and heating operation of Bed1 and Bed2 is switched. V1–V4 are closed. Bed1 is heated and Bed2 is cooled.

(4) Bed1 in desorption & Bed2 in adsorption

V1 and V4 are open and V2 and V3 are closed. Bed1 is heated and desorbs the refrigerant vapor which flows into condenser. Bed2 is cooled and adsorbs the refrigerant vapor from evaporator.

Though beds are fixed, their temperatures change periodically and a large number of heat streams are transferred within the system. In the prospect of using Pinch Technique, the beds are regarded as "stream". Adsorbing bed, refrigerant from desorbing bed to condenser, refrigerant in condensation process and refrigerant from condenser to evaporator are considered as hot streams which can be marked by HS1, HS2, HS3 and HS4, respectively. Desorbing bed, refrigerant from evaporator to adsorbing bed and refrigerant in condensation process are cold streams which can be marked by CS1, CS2 and CS3, respectively. The hot and cold streams are summarized in Table 1. The working processes of adsorption refrigeration system switch periodically and they are transient. The energy equations of all streams are based on the full working period and then time factor is considered.

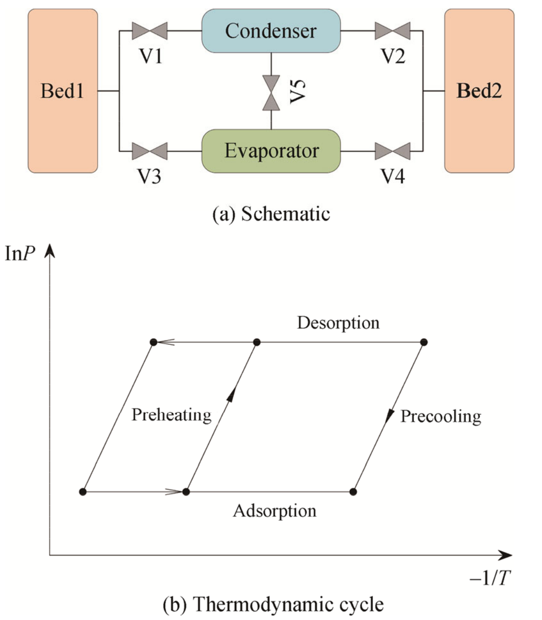


Fig. 1 Two-bed adsorption refrigeration system

Table 1 Hot and cold streams of two-bed system

Category	Name	Label
Hot stream	Adsorbing bed	HS1
	Refrigerant flow from desorbing bed to condenser	HS2
	Condensing refrigerant	HS3
	Refrigerant flow from condenser to evaporator	HS4
Cold stream	Desorbing bed	CS1
	Refrigerant flow from evaporator to adsorbing bed	CS2
	Evaporating refrigerant	CS3

Energy equation of HS1 and CS1 is expressed by the following equation:

$$H_j = H_{j-1} + \left|(M_{\text{bed}}C_{\text{bed}} + M_{\text{ad}}C_{\text{ad}} + M_{\text{ad}}X_jC_1)\Delta T_j - M_{\text{ad}}r\Delta X_j\right| \tag{1}$$

where H is the heat load (kJ). M_{bed} and M_{ad} are the mass of the bed metal and adsorbent (kg), respectively. C_{bed}, C_{ad} and C_1 are the specific heat of the bed metal, adsorbent and refrigerant liquid (kJ·kg^{-1}·K^{-1}), respectively. ΔT and ΔX are the difference of temperature

(K) and refrigerant uptake ($kg \cdot kg^{-1}$), respectively; r is the adsorption/desorption reaction heat ($kJ \cdot kg^{-1}$).

Energy equation of HS2 and CS2 is expressed by the following equation:

$$H_j = H_{j-1} + M_{ad} C_v \Delta T_j \sum_{k=j-1}^{n-j+1} \left(X_{k+1} - X_k \right) \tag{2}$$

where C_v is the specific heat capacity of refrigerant vapor, $kJ \cdot kg^{-1} \cdot K^{-1}$. X is the refrigerant uptake, $kg \cdot kg^{-1}$.

Energy equations of HS3, HS4 and CS3 can be expressed by Eqs. (3)–(5), respectively.

$$Q_c = M_{ad} \left[X\left(T_{d1}, T_c\right) - X\left(T_{d2}, T_c\right) \right] L \tag{3}$$

$$Q_{c \to e} = M_{ad} \left[X\left(T_{d1}, T_c\right) - X\left(T_{d2}, T_c\right) \right] C_l \left(T_c - T_e\right) \tag{4}$$

$$Q_e = M_{ad} \left[X\left(T_{a2}, T_e\right) - X\left(T_{a1}, T_e\right) \right] L \tag{5}$$

where, Q is heat exchange capacity, kJ. L is the latent heat of vaporization, $kJ \cdot kg^{-1}$. T_{d1} and T_{d2} are initial and final temperature of desorption process, K. T_{a1} and T_{a2} are initial and final temperature of adsorption process, K. T_c and T_e are condensation and evaporation temperature, K.

Silica gel-water is the working pair of the adsorption refrigeration system. Its adsorption equilibrium is expressed by a modified Dubinin-Astakhov (D-A) equation [30] as:

$$X = X_0 \exp\left[-a \left(\frac{T_{ad}}{T_s} - 1 \right)^b \right] \tag{6}$$

where, T_s is saturation temperature of refrigerant, K. The value of D-A coefficient is: X_0=0.346 kg (Water)$\cdot kg^{-1}$ (Silica gel); a=5.6 and b=1.6.

Preheating and precooling processes are isochoric so that the refrigerant uptake of adsorbent is constant. The refrigerant uptake of adsorbent in heating (preheating and desorption) and cooling (precooling and adsorption) processes are given by the following equations:

For heating process,

$$X_j = \begin{cases} X_{j-1}, & T_d < T_{ad}\left(T_c, X_{j-1}\right) \\ X\left(T_d, T_c\right), & T_d \ge T_{ad}\left(T_c, X_{j-1}\right) \end{cases} \tag{7}$$

For cooling process,

$$X_j = \begin{cases} X_{j-1}, & T_a > T_{ad}\left(T_e, X_{j-1}\right) \\ X\left(T_a, T_e\right), & T_a \le T_{ad}\left(T_e, X_{j-1}\right) \end{cases} \tag{8}$$

The main performance index is the coefficient of performance (COP):

$$\mathrm{COP} = Q_{ou} / Q_{in} \tag{9}$$

where, Q_{in} and Q_{ou} are input driving heat and output cooling capacity, respectively, kJ.

The value of parameters in the mathematical model are listed in Table 2. The heat capacity of bed metal, mass of adsorbent, specific heat capacity of adsorbent, adsorption/desorption reaction heat and latent heat of vaporization of refrigerant are referred by previous study [24]. In order to solve the above equations, a program is written in MATLAB. For the calculations, the temperature increment used is 0.25 K. The operating temperatures of hot and cold streams are listed in Table 3.

Table 2 Value of parameters in the mathematical model of two-bed system

Parameters	Value	Unit
$M_{bed}C_{bed}$	77 720	$kJ \cdot K^{-1}$
M_{ad}	47	kg
C_{ad}	0.92	$kJ \cdot kg^{-1} \cdot K^{-1}$
C_l	4.18	$kJ \cdot kg^{-1} \cdot K^{-1}$
C_v	1.9	$kJ \cdot kg^{-1} \cdot K^{-1}$
H_r	2550	$kJ \cdot kg^{-1}$
L	2520	$kJ \cdot kg^{-1}$
T_{d2}, T_{a1}	85+273.15	K
T_{d1}, T_{a2}	30+273.15	K
T_c	30+273.15	K
T_e	5+273.15	K

Table 3 Operating temperatures of streams

Label	Supply temperature/°C	Target temperature/°C
HS1	85	30
HS2	85	30
HS3	30	30
HS4	30	5
CS1	30	85
CS2	5	85
CS3	5	5

3. Analysis

3.1 *t-Q* diagram

t-Q diagram is one of the most used methods in pinch analysis to analyze the heat exchanger network. *t-Q* diagram of the adsorption refrigeration system is shown in Fig. 2. All the stream curves are displayed in the figures. Red color represents hot stream and blue color represents cold stream. All the hot stream curves are located on upper left of the figure and all the cold stream curves are located on the lower right of the figure. HS2, HS4 and CS2 curves are almost vertical because their heat capacities are very small. HS3 and CS3 curves are horizontal because they are the isothermal condensation and evaporation processes of refrigerant, respectively. HS1 and CS1 curves are polylines and their slopes change obviously at about median of medium temperature and driving temperature because they include precooling (or preheating) and adsorption (or desorption) processes. Heat load difference of both ends of HS1 and CS1 curves are the biggest, which indicates that the beds have the biggest heat exchange capacity.

For the original figure, CS2 curve is between HS1 and CS1 curves so the CS2 must be processed to demonstrate the pinch point. CS2 stream represents refrigerant flow from evaporator to adsorbing bed. In the adsorption refrigeration system, adsorbent of bed directly adsorbs the refrigerant vapor from the evaporator. So the CS2 curve segment from the medium temperature to the driving temperature is integrated in HS1 curve and the new t-Q diagram is shown in Fig. 2(b). The pinch point is located between HS1 and CS1 curves, so that heat exchanger should be placed between adsorbing and desorbing beds to recover the heat. This is the reason why heat recovery cycle is adopted.

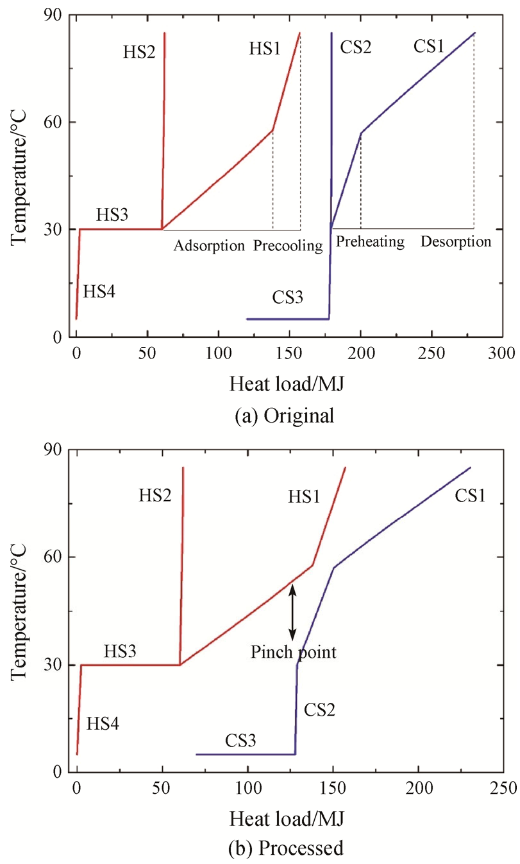


Fig. 2 t-Q diagram of the adsorption refrigeration system

3.2 Problem table

The most used method in pinch analysis is problem table. The pinch point temperature difference is chosen as 5°C. The operating temperature of hot streams should minus half of pinch point temperature difference and the operating temperature of cold streams should plus half of pinch point temperature difference. In the actual adsorption refrigeration system, the heat of HS4 is dissipated by CS3. As a result, HS4 is integrated into CS3. The problem table of the adsorption refrigeration system is shown in Table 4. The pinch point is located at 32.5°C with zero input and output heat flux, which is consistent with the result of t-Q diagram. If the adsorption system is steady, about (82.39+1.59) MJ internal waste heat can be recovered in one adsorption refrigeration cycle. In this case, the output capacity is 55.41 MJ and input driving heat is 17.52 MJ. The potential COP of adsorption refrigeration system is 3.16.

But the actual adsorption refrigeration system is unsteady and the time factor should be considered. The pinch technology should be modified when it is used for adsorption refrigeration. The temperatures of HS1 and HS2 rise up from the bottom to top but the temperature of CS1 changes in opposite way, from top to bottom. So the recovered heat (exchanged heat between HS1-HS2 and CS1) can be given by the following equations while considering the time factor and pinch point temperature difference. Eqs. (10)–(12) are the modified pinch technology expressions for two-bed adsorption refrigeration system.

$$Q_{\mathrm{r}}=\min\big(H_{\mathrm{CS1}}(T_1)-H_{\mathrm{CS1}}(T_{\mathrm{d1}}),\ H_{\mathrm{HS1}}(T_{\mathrm{a1}})-H_{\mathrm{HS1}}(T_2)+H_{\mathrm{HS2}}(T_{\mathrm{d2}})-H_{\mathrm{HS2}}(T_2)\big) \tag{10}$$

Table 4 Problem table of adsorption refrigeration system

Temperature/°C	Streams	HS1/MJ	HS2/MJ	HS3/MJ	CS1/MJ	CS2/MJ	CS3/MJ	Deficient heat/MJ	Accumulated heat/MJ		Heat flux/MJ	
									Input	Output	Input	Output
87.5					14.64			14.64	0	−14.64	17.52	2.87
82.5		82.39	1.59		86.86			2.87	−14.64	−17.52	2.87	0
32.5		14.59	0.22			0.22		−14.59	−17.52	−2.93	0	14.59
27.5				57.81				−57.81	−2.93	54.88	14.59	72.40
27.5						0.87		0.87	54.88	54.01	72.40	71.53
7.5							55.41	55.41	54.01	−1.40	71.53	16.11
7.5												

$$T_1 = T_{a1} - \frac{T_{a1} - T_{a2} + T_p}{2} \tag{11}$$

$$T_2 = T_{a2} + \frac{T_{a1} - T_{a2} + T_p}{2} \tag{12}$$

Comparison of cases with and without time factor is shown in Table 5. When considering the time factor, the recovered heat is much less than that of case without time factor. Hence, more input driving heat is required and the COP reduces from 3.16 to 0.66. The COP drop is the result of unsteady characteristics of adsorption refrigeration system. The effect of unsteady characteristics on the system should be reduced for enlarging the recovered heat and improving the system performance.

Table 5 Comparison of cases with and without time factor

	Recovered heat/ MJ	Input driving heat/ MJ	Cooling capacity/ MJ	COP
Without time factor	83.98	17.52	55.41	3.16
With time factor	18.04	83.46	55.41	0.66

3.3 Effect of pinch point temperature difference

Fig. 3 shows the effect of pinch point temperature difference on COP of adsorption refrigeration system. When the adsorption refrigeration system is assumed to be steady (without time factor), pinch point temperature difference has a significant impact on COP. COP reduces significantly from 3.16 to 0.66 when pinch point temperature difference increases from 5°C to 30°C, because recyclable internal heat of HS1 is concentrated in the low temperature area (generally lower than 60°C for this specific adsorbent). When the pinch point temperature difference increases, recovered heat from the low temperature area becomes less so the COP decreases greatly. When the time factor is taken into account, pinch point temperature difference has little impact on COP. The COP slightly drops down with increasing pinch point temperature difference. Internal heat of HS1 in the low temperature area becomes unrecyclable when time factor is taken into account. So recovered heat amount is without significant change when the pinch point temperature difference increases. When the pinch point temperature difference is 30°C, the COPs of two cases are very close. Therefore, internal heat of HS1 in the low temperature area is unrecyclable at 30°C pinch point temperature difference.

3.4 Effect of pinch point temperature difference

Fig. 4 shows the effect of different working temperature conditions on COP of adsorption refrigeration system. COP increases with the increasing

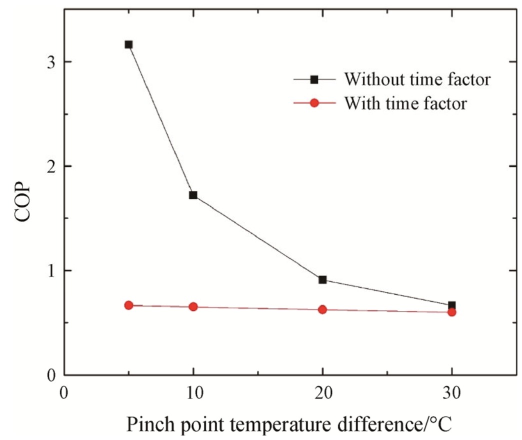


Fig. 3 Effect of pinch point temperature difference on COP

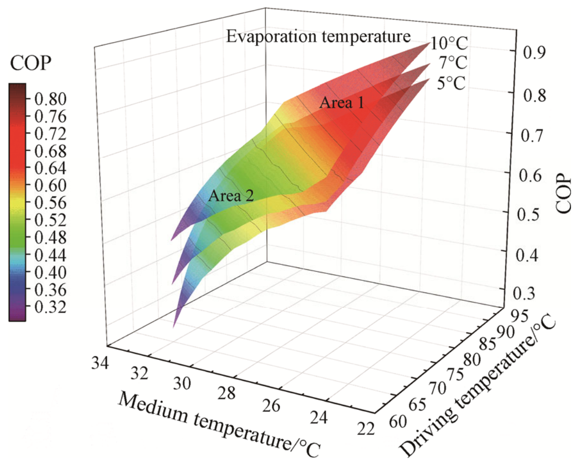


Fig. 4 Effect of different working temperature conditions on COP

driving temperature, increasing evaporation temperature and decreasing medium temperature (adsorption and condensation temperature). The gradient of the COP surface is relatively large and it indicates that the driving temperature and medium temperature have remarkable effect on COP. In the case of 5°C evaporation temperature, COP can be as high as 0.83 (90°C driving temperature and 25°C medium temperature) and as low as 0.28 (65°C driving temperature and 32°C medium temperature). Gradient of the COP surface has obvious change between two areas: (1) high driving temperature and low medium temperature area (Area 1); (2) low driving temperature and high medium temperature area (Area 2). In the case of 5°C evaporation temperature, separation line between two areas starts on 73.5°C/25°C driving/medium temperatures and ends on 89.5°C/30°C driving/medium temperatures. Gradient of the COP surface in Area 1 is generally larger than that in Area 2. Hence, driving temperature and medium temperature have greater effect on COP in Area 1 than Area 2. Shape of COP surfaces at three evaporation temperatures (5°C, 7°C and 10°C) are similar so that the effect of driving temperature and medium temperature on COP is not affected by the evaporation temperature.

3.5 Comparison between pinch analysis and other methods

Simulation and experiment methods are widely used in adsorption refrigeration study. The comparison between pinch analysis and other methods (simulation and experiment) has been investigated and the results are shown in Fig. 5. The experimental data used are from the previous studies [24, 31]. The evaporation temperature and medium temperature are set to be 7°C and 30°C, respectively. In Fig. 5, the COP via optimization of pinch analysis is higher than the other two methods. For simulation and experiment of adsorption chiller, the heat and mass transfer performance and heat exchanger effectiveness have significant influence on system COP. However, these factors are not considered for pinch analysis, and they, of course, contribute to higher COP.

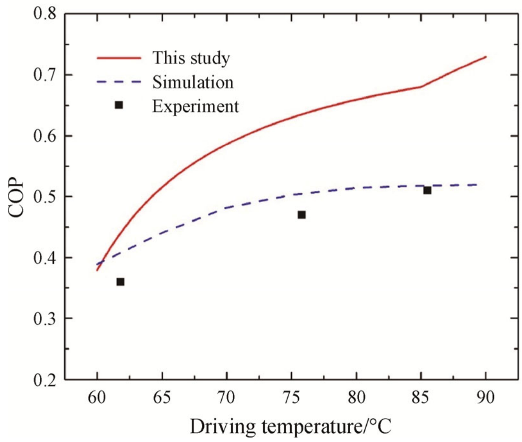


Fig. 5 Comparison between pinch analysis and other methods (simulation and experiment)

When the driving temperature is 90°C, the COP of adsorption refrigeration via optimization of pinch analysis is 0.73 which is comparable to LiBr-water absorption refrigeration system [32]. The COPs via optimization of pinch analysis and simulation are very close at low driving temperature but the gap grows when the driving temperature increases. So the performance of previous adsorption refrigeration unit is close to its upper limit and there is few potential in performance improvement under the low driving temperature condition. However, under the relatively high driving temperature conditions, the previous adsorption refrigeration still has sufficient performance potential and more improvement should be taken in adsorption/desorption reaction and heat and mass transfer. Besides, adsorption refrigeration system performance prediction by pinch analysis is feasible with the advantages of quick response.

4. Other Kinds of Adsorption Refrigeration System

4.1 Four-bed system

The proposed modified pinch technology can also be used in other configurations of adsorption refrigeration system. A four-bed system is shown in Fig. 6. Compared to two-bed adsorption refrigeration system, the four-bed system has two more beds and two more valves. When one desorbing bed is connected with condenser and one adsorbing bed is connected with evaporator, the other two (desorbing and adsorbing) beds are connected with each other. The desorbed refrigerant vapor in the desorbing bed is directly adsorbed by the adsorbent in the adsorbing bed, which are named as medium desorption and adsorption processes. The benefit of four-bed system is to expand the operating temperature boundary conditions and improve the system performance under the extremely poor working conditions [33]. The detailed working processes can be described as follows:

(1) Bed1 & Bed4 in desorption and Bed2 & Bed3 in adsorption

V1, V3 and V7 are open while V2, V3 and V6 are closed. V5 is the throttle valve. Bed1 is heated and desorbs the refrigerant vapor which flows into Condenser. Bed2 is cooled and adsorbs the refrigerant vapor from Evaporator. Bed3 is also cooled and adsorbs the refrigerant vapor which is desorbed by Bed4 while Bed4 is heated.

(2) Bed2 & Bed3 in desorption and Bed1 & Bed4 in adsorption

V2, V3 and V6 are open while V1, V3 and V7 are closed. Bed1 is also cooled and adsorbs the refrigerant vapor which is desorbed by Bed4 while Bed2 is heated. Bed3 is heated and desorbs the refrigerant vapor which flows into Condenser. Bed4 is cooled and adsorbs the refrigerant vapor from Evaporator.

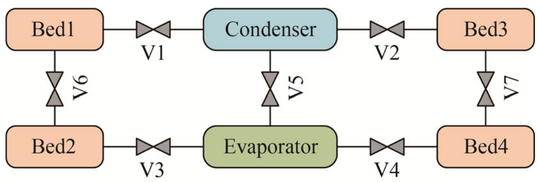
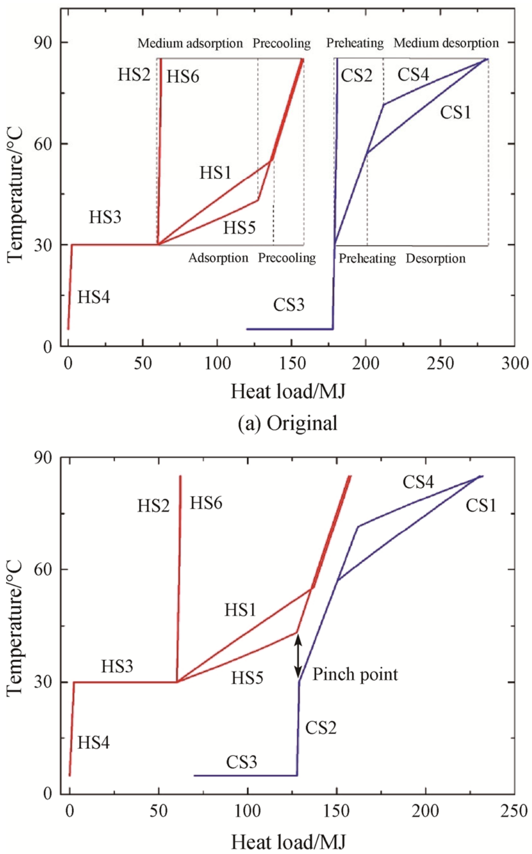


Fig. 6 Schematic of the four-bed adsorption refrigeration system

All streams of the four-bed systems are shown in Table 6. Compared to the two-bed system, four-bed system has two more hot streams and one more cold stream. The stream equations of HS5, HS6 and CS4 can be referred by the equations of HS1, HS2 and CS1, respectively. The adsorption equilibrium of medium desorption and adsorption processes is expressed by Eq. (6) where the saturation temperature is replaced by the other bed temperature. The parameters of all the equations and operating temperature adopt the same value in Table 2 and Table 3, respectively.

Table 6 Hot and cold streams of the four-bed system

Category	Name	Label
Hot stream	Adsorbing bed	HS1
	Refrigerant flow from desorbing bed to condenser	HS2
	Condensing refrigerant	HS3
	Refrigerant flow from condenser to evaporator	HS4
	Medium adsorbing bed	HS5
	Refrigerant flow from medium desorbing bed to medium adsorbing bed	HS6
Cold stream	Desorbing bed	CS1
	Refrigerant flow from evaporator to adsorbing bed	CS2
	Evaporating refrigerant	CS3
	Medium desorbing bed	CS4



(b) Processed

Fig. 7 *t*-*Q* diagram of the four-bed adsorption refrigeration system

All the stream equations of four-bed system have been solved in MATLAB and all stream curves are illustrated in Fig. 7. HS2 and HS6 are very closed because the mass of desorbed refrigerant vapor from the different desorbing beds are almost the same. Two adsorption processes curves (HS1 and HS5) are polynomial-lines but their inflection points are different which indicates the adsorption process starts at higher temperature in adsorbing bed than medium adsorbing bed. Though adsorbing bed has lower corresponding saturation temperature (condensation temperature) than medium adsorbing bed (medium desorbing bed temperature), its initial refrigerant uptake is much lower, so that its adsorption process starts at relatively higher temperature. Despite this, the starting and ending points heat load difference of HS1 and HS5 are almost the same. This proves that the mass of adsorbed refrigerant vapor of the different adsorbing beds are equivalent. Two desorption processes (CS1 and CS4) are in the same situation. Similar with the two-bed system, the pinch point of four-bed system is located between adsorbing beds and desorbing beds.

4.2 Adsorption refrigeration system with mass recovery

Fig. 8 shows an adsorption refrigeration system with mass recovery. Compared to two-bed adsorption refrigeration system, the mass recovery system has one more valve connecting two beds. Therefore, the mass recovery process can be implemented when the mass recovery valve (Valve V6) is opened before the adsorption and desorption switch. In this case, the adsorbing bed directly adsorbs the refrigerant vapor from the desorbing bed when the system is in mass recovery process. The application of mass recovery process can enhance the cyclic adsorption uptake of refrigerant and improve the system performance [34].

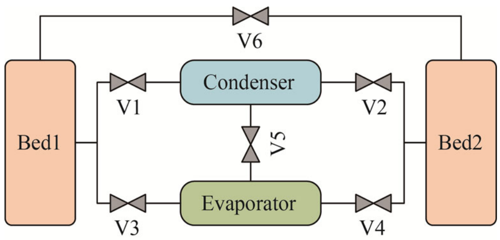


Fig. 8 Schematic of the mass recovery adsorption refrigeration system

Mass recovery system has the same streams and stream equations with two-bed system. But the saturation temperature of adsorption equilibrium equation should be replaced by the other bed temperature once the system is in mass recovery process. The working pair of mass recovery system is activated carbon 208C-R723. The constants in adsorption equilibrium equation of this working pair are: X_0=0.354; a=3.7342; b=1.187 [35]. The bed details and physical properties of activated carbon are referred to the previous studies [36, 37]. The physical properties of R723 are referred to the database of REFPROP software. Values of parameters in the mathematical model of mass recovery system are shown in Table 7.

Table 7 Values of parameters in the mathematical model of the mass recovery system

Parameters	Value	Unit
$M_{bed}C_{bed}$	0.15	$kJ\cdot K^{-1}$
M_{ad}	1	kg
C_{ad}	0.923	$kJ\cdot kg^{-1}\cdot K^{-1}$
C_l	4.131	$kJ\cdot kg^{-1}\cdot K^{-1}$
C_v	3.164	$kJ\cdot kg^{-1}\cdot K^{-1}$
H_r	1100	$kJ\cdot kg^{-1}$
L	880	$kJ\cdot kg^{-1}$
T_{d2}, T_{a1}	80+273.15	K
T_{d1}, T_{a2}	30+273.15	K
T_c	30+273.15	K
T_e	5+273.15	K

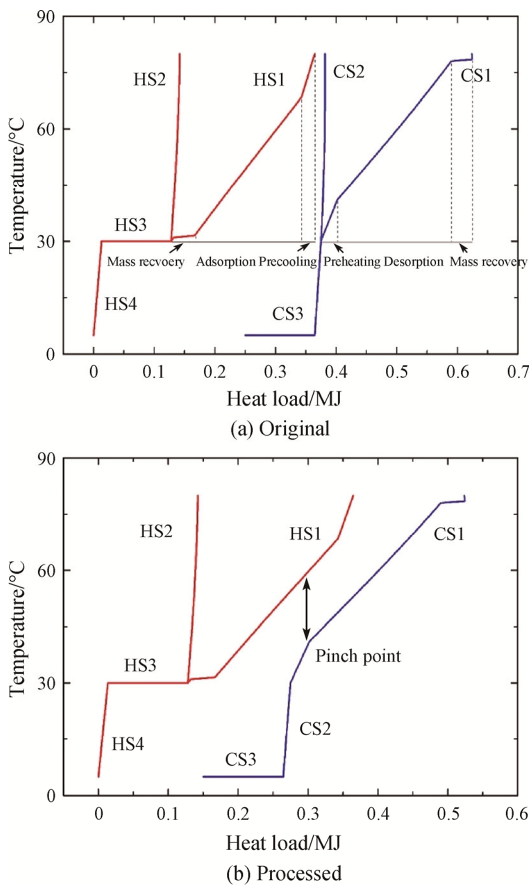


Fig. 9 *t-Q* diagram of the mass recovery adsorption refrigeration system

All the stream equations of mass recovery system have been solved in MATLAB software and all the stream curves have been illustrated in Fig. 9. The stream curves of mass recovery are similar to those of four-bed system except adsorbing and desorbing beds (HS1 and CS1 curves). For the adsorbing bed, there are three stages which are precooling, adsorption and mass recovery, respectively. The curve's slope is quite different at each stage. The mass recovery stage has the minimum slope and the precooling stage has the maximum slope. The heat load difference is larger at very narrow temperature interval. This phenomenon reveals the adsorption reaction rate is very large because the corresponding saturation temperature (another bed's temperature) is high. The desorbing bed has the same situation with the adsorbing bed. Similar with the previous systems, the pinch point of mass recovery system is located between adsorbing and desorbing beds.

5. Conclusions

In this paper, heat recovery of adsorption refrigeration systems is analyzed by the means of Pinch Technology. Mathematical model including all stream equations is elaborated for pinch analysis. Problem tables and *t-Q* diagrams of the adsorption refrigeration systems are constructed. Through analysis on the problem tables and the *t-Q* diagrams of the different adsorption refrigeration systems, some of the key conclusions are obtained:

(1) Pinch point is located between beds and the main waste heat needs to be recovered between beds. Dynamic characteristics of adsorption refrigeration system are the main resistance for heat recovery.

(2) The effect of pinch point temperature difference on the system COP is not distinct when pinch point temperature difference increases from 5°C to 30°C.

(3) When the driving temperature is 90°C, COP of adsorption refrigeration via optimization of pinch analysis is 0.73 which is comparable to LiBr-water absorption refrigeration system.

(4) Pinch Technology can be adopted in different adsorption refrigeration system types.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 51906136), the Institute of Advanced Studies (IAS) of the University of Warwick in the UK (Grant No C5E3X56470T) and Shanghai Sailing Program (Grant No. 19YF1423100).

References

[1] The future of cooling. https://www.iea.org/futureofcooling/ (accessed Jan 22, 2021).

[2] Pan Q., Peng J., Wang H., et al., Experimental investigation of an adsorption air-conditioner using silica

gel-water working pair. Solar Energy, 2019, 185: 64–71.

[3] Li H., Lin P., Du S., et al., Modelling and thermodynamic analysis of a hot-cold conversion pipe using R134a-DMF-He as the working pair. Journal of Thermal Science, 2021, 30(1): 64–75.

[4] Pan Q., Peng J., Wang R., Experimental study of an adsorption chiller for extra low temperature waste heat utilization. Applied Thermal Engineering, 2019, 163: 114341.

[5] Wei Benjamin Teo H., Chakraborty A., Fan W., Improved adsorption characteristics data for AQSOA types zeolites and water systems under static and dynamic conditions. Microporous and Mesoporous Materials, 2017, 242: 109–117.

[6] Adsorptions chiller Typ NAK-C. http://www.gbunet.de/indexe.html (accessed Jan 22, 2021).

[7] InvenSor LTC 10 plus. https://invensor.com/en/products/ (accessed Jan 22, 2021).

[8] Green adsorption chiller. http://www.greenchiller.biz/ (accessed Jan 22, 2021).

[9] chillii® Adsorption Kits. http://www.solarnext.eu/eng/the/chillii_ads_kits.shtml (accessed Jan 22, 2021).

[10] Silica Gel Chiller eCoo 2.0. https://fahrenheit.cool/en/ (accessed Jan 22, 2021).

[11] Sapienza A., Gullì G., Calabrese L., et al., An innovative adsorptive chiller prototype based on 3 hybrid coated/granular adsorbers. Applied Energy, 2016, 179: 929–938.

[12] Kim H., Yang S., Rao S.R., et al., Water harvesting from air with metal-organic frameworks powered by natural sunlight. Science, 2017, 356(6336): 430–434.

[13] Cui S., Qin M., Marandi A., et al., Metal-Organic Frameworks as advanced moisture sorbents for energy-efficient high temperature cooling. Scientific Reports, 2018, 8(1): 15284.

[14] Lenzen D., Bendix P., Reinsch H., et al., Scalable green synthesis and full-scale test of the metal-organic framework CAU-10-H for use in adsorption-driven chillers. Advanced Materials, 2018, 30(6): 1705869.

[15] Wang S., Lee J.S., Wahiduzzaman M., et al., A robust large-pore zirconium carboxylate metal-organic framework for energy-efficient water-sorption-driven refrigeration. Nature Energy, 2018, 3(11): 985–993.

[16] Pan Q.W., Wang R.Z., Experimental study on operating features of heat and mass recovery processes in adsorption refrigeration. Energy, 2017, 135: 361–369.

[17] Meunier F., Adsorption heat powered heat pumps. Applied Thermal Engineering, 2013, 61(2): 830–836.

[18] Grzebielec A., Rusowicz A., Laskowski R., Experimental study on thermal wave type adsorption refrigeration system working on a pair of activated carbon and methanol. Chemical and Process Engineering, 2015, 36(4): 395–404.

[19] Sapienza A., Palomba V., Gullì G., et al., A new management strategy based on the reallocation of ads-/desorption times: Experimental operation of a full-scale 3 beds adsorption chiller. Applied Energy, 2017, 205: 1081–1090.

[20] Rouf R.A., Alam K.C.A., Saha B.B., et al., Utilizing accessible heat enhancing cooling effect with three bed solar adsorption chiller. Heat Transfer Engineering, 2019, 40(12): 1049–1059.

[21] Iguchi K., Nakayama M., Akisawa A., Method for estimating optimum cycle time based on adsorption chiller parameters. International Journal of Refrigeration, 2019, 105: 66–71.

[22] ul Qadir N., Said S.A.M., Mansour R.B., Performance prediction of a two-bed solar adsorption chiller with adaptive cycle time using a MIL-100(Fe)/water working pair—influence of solar collector configuration. International Journal of Refrigeration, 2018, 85: 472–488.

[23] Basdanis T., Tsimpoukis A., Valougeorgis D., Performance optimization of a solar adsorption chiller by dynamically adjusting the half-cycle time. Renewable Energy, 2021, 164: 362–374.

[24] Pan Q.W., Wang R.Z., Study on operation strategy of a silica gel-water adsorption chiller in solar cooling application. Solar Energy, 2018, 172: 24–31.

[25] Du S., Wang R.Z., Xia Z.Z., Optimal ammonia water absorption refrigeration cycle with maximum internal heat recovery derived from pinch technology. Energy, 2014, 68: 862–869.

[26] Linhoff B., Boland D., User guide on process integration for the efficient use of energy. Chemical Engineering Journal, 1982, 26: 260–261.

[27] Jawahar C.P., Raja B., Saravanan R., Thermodynamic studies on NH_3-H_2O absorption cooling system using pinch point approach. International Journal of Refrigeration, 2010, 33(7): 1377–1385.

[28] Atuonwu J.C., Straten G.V., Deventer H.V., et al., Optimizing energy efficiency in low temperature drying by zeolite adsorption and process integration. Chemical Engineering Transactions, 2011, 25: 111–116.

[29] Xu S.Z., Wang R.Z., Wang L.W., Temperature-heat diagram analysis method for heat recovery physical adsorption refrigeration cycle—Taking multi-stage cycle as an example. International Journal of Refrigeration, 2017, 74: 254–268.

[30] Di J., Wu J.Y., Xia Z.Z., Wang R.Z., Theoretical and experimental study on characteristics of a novel silica gel-water chiller under the conditions of variable heat

source temperature. International Journal of Refrigeration, 2007, 30(3): 515–526.

[31] Pan Q.W., Wang R.Z., Wang L.W., et al., Design and experimental study of a silica gel-water adsorption chiller with modular adsorbers. International Journal of Refrigeration, 2016, 67: 336–344.

[32] Xu Z.Y., Wang R.Z., Wang H.B., Experimental evaluation of a variable effect LiBr-water absorption chiller designed for high-efficient solar cooling system. International Journal of Refrigeration, 2015, 59: 135–143.

[33] Sah R.P., Choudhury B., Das R.K., Study of a two-bed silica gel-water adsorption chiller: performance analysis. International Journal of Sustainable Energy, 2018, 37(1): 30–46.

[34] Pan Q., Wang R., Vorayos N., et al., A novel adsorption heat pump cycle: Cascaded mass recovery cycle. International Journal of Refrigeration, 2018, 95: 21–27.

[35] Tamainot-Telto Z., Novel method using Dubinin-Astakhov theory in sorption reactor design for refrigeration and heat pump applications. Applied Thermal Engineering, 2016, 107: 1123–1129.

[36] Lychnos G., Tamainot-Telto Z., Prototype of hybrid refrigeration system using refrigerant R723. Applied Thermal Engineering, 2018, 134: 95–106.

[37] Pachoa Á.M.R., Thermodynamic and heat transfer analysis of a carbon-ammonia adsorption heat pump. University of Warwick, Coventry, UK, 2014.