A dynamic model for the heat transfer behavior of a cooling system[*]

by

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Abstract: For purposes of studying the heat transfer behavior of various fluids in a refrigeration system, a dynamic model is established, obtained on the basis of analysis concerning the effects of adsorption velocity, adsorbent bed temperature, condensing temperature, and heat transfer fluids, as well as changes of external conditions. It is demonstrated that adsorption velocity increases sharply in the initial phase of adsorption process and gradually declines after reaching a peak value, whereas condensing temperature increases sharply in the initial phase of desorption process and decreases after reaching a peak value with the desorption quantity decreasing. Furthermore, the increase of heat source temperature and the decrease of cooling water temperature can advance the adsorption process. The present study therefore suggests some ways of improving the performance of such a refrigeration system by increasing heat source temperature, decreasing ambient air temperature, increasing return air temperature and decreasing cooling water temperature.

Keywords: adsorption system; refrigerating system; desorption; simulation

Notation adopted in the paper

Notations are listed in the order of their appearance in the text.

R_f: heat capacity ratio of adsorbent bed to adsorbent;
M_a: mass of adsorbent;
c_{va}: adsorbent specific heat at constant volume;

T_b: adsorbent bed temperature;

c_{ve}: adsorbate heat capacity at constant volume;

x_0: full adsorption rate;

x_{conc}: adsorption rate in the isochoric heating process;

x: dynamic adsorption rate;

$\phi_{w \to b}$: quantity of heat transferred from fluid to adsorbent bed;

t : time;

K : a constant corresponding to working pairs;

T_{a1} : initial adsorption temperature;

T_m : saturation temperature of the adsorbate;

n : a constant corresponding to working pairs;

c_{pa} : adsorbent specific heat at constant pressure;

H_d : enthalpy of desorption;

c_{pc} : adsorbate specific heat at constant pressure;

T_{g2} : final desorption temperature;

x_{dil} : adsorption rate in the isochoric cooling process;

H_a : enthalpy of adsorption;

T_e : evaporation temperature;

$K_s a_P$: surface diffusion velocity coefficient;

D_{so} : surface diffusion coefficient;

R_P : average diameter of absorbent granules;

E_a : activation energy of surface diffusion;

m_f : mass flow of heat transfer fluid;

c_f : specific heat of heat transfer fluid;

$T_{f,in}$: entrance temperature of heat transfer fluid;

$T_{f,out}$: exit temperature of heat transfer fluid;

M_e : mass of adsorbate in the evaporator;

U : heat transfer coefficient between adsorbent bed and heat transfer fluid;

A_0 : heat exchange surface between adsorbent bed and heat transfer fluid;

m_c : mass flow of adsorbate that flows into the evaporator;

T_c : condensing temperature;

U_e : heat transfer coefficient of evaporator;

A_e : heat exchange surface of evaporator;

$T_{e,ai}$: return air temperature;

m_e : mass flow of adsorbate that runs off the evaporator;

L_e : latent heat of vaporization of adsorbate under evaporation temperature;

$T_{e,ao}$: supply air temperature;

$c_{e,air}$: supply air specific heat at constant pressure;

$m_{e,air}$: mass flow of supply air;

U_c : heat transfer coefficient of the condenser;

A_c : heat exchange surface of the condenser;

$T_{c,ai}$: entrance temperature of ambient air;

$T_{c,ao}$: exit temperature of ambient air;

$c_{c,air}$: ambient air specific heat at constant pressure;

$m_{c,air}$: mass flow of ambient air.

1.   Introduction

Adsorption refrigeration exhibits special advantages in terms of energy saving and environmental protection and is therefore developing rapidly nowadays (Halder and Sarkar, 2001; Yang and Chen, 2007; Wang and Wu, 2001). Douss, Sun and Meunier (1988) adopted the lumped parameter approach to simulate the absorption refrigeration system, while Hajji and Worek (1991) simulated the heat and mass transfer process in the adsorbent bed. Later on, Chen, Que and Chen (1996) and El-Sharkawy et al. (2006) have carried out some experiments, concerning the adsorption performance of the active carbon—ethanol.

In the actual absorption refrigeration system, the fluctuation of adsorbent quantity and desorption quantity results in the changes of refrigeration quantity and of the condensing load (Wang and Wang, 2006). So, it is necessary to adopt the dynamic analysis method in order to simulate the actual functioning of the absorption refrigeration system and establish its operation characteristics (Restuccia et al., 2004; Kato, Sasaki and Yoshizawa, 2003; Sami and Tribes, 1996).

We take two-bed continuous adsorption refrigeration system as the object of our research. The two-bed continuous cycle consists of four processes (namely, the isochoric heating process, the isobaric desorption process, the isochoric cooling process and isobaric adsorption process), which take place in the adsorbent bed, and then also two processes, which take place in the evaporator and condenser, respectively, as this is shown in Fig. 1. The adsorbent bed is connected with the condenser in the desorption process and is connected with evaporator in the adsorption process.

2.   Dynamic model of the adsorbent bed

We assume that the adsorbent in the adsorbent bed is uniformly distributed, pressure and temperature are also uniform. According to the law of conservation of energy, we can develop the dynamic model of the adsorbent bed with regard to different respective processes.

For the isochoric heating process, the dynamic model of the adsorbent bed is shown in equations (1) and (2).

$$[(1 + R_f) M_a c_{va} + M_a x_{conc} c_{vc}] \frac{dT_b}{dt} = \phi_{w \to b} \tag{1}$$

$$x_{conc} = x_0 (T_m) \exp\left[-k \left(\frac{T_{a1}}{T_m} - 1\right)^n\right] \tag{2}$$
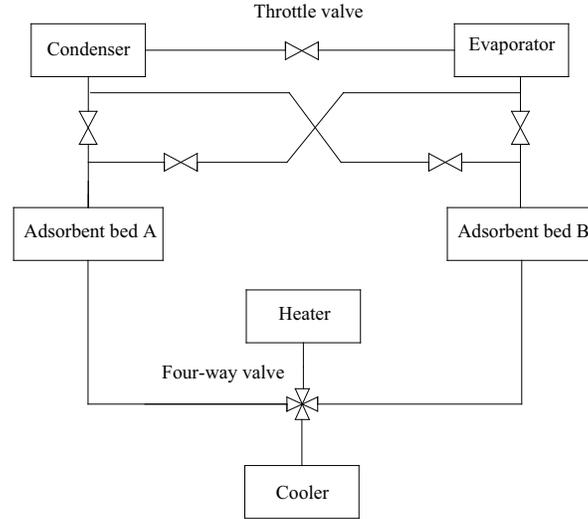
Figure 1. Schematic view of the system for two-bed continuous cycle

where R_f is heat capacity ratio of adsorbent bed to adsorbent, M_a is mass of adsorbent, c_{va} is adsorbent specific heat at constant volume, x_{conc} is adsorption rate in the isochoric heating process, c_{vc} is adsorbate heat capacity at constant volume, T_b is adsorbent bed temperature, t is time, $\phi_{w \to b}$ is quantity of heat transferred from fluid to adsorbent bed x_0 is full adsorption rate, K is the constant corresponding to working pairs (10.21 for active carbon—methanol), T_{a1} is initial adsorption temperature, T_m is saturation temperature of adsorbate, and n is another constant corresponding to working pairs (1.39 for active carbon—methanol).

For the isobaric desorption process, the dynamic model of the adsorbent bed is shown in Eq.(3):

$$[(1 + R_f) M_a c_{pa} + M_a x c_{pc}] \frac{dT_b}{dt} = \phi_{w \to b} + M_a H_d \frac{dx}{dt} \tag{3}$$

where c_{pa} is adsorbent specific heat at constant pressure, x is dynamic adsorption rate, c_{pc} is adsorbate specific heat at constant pressure and H_d is the enthalpy of desorption.

For the isochoric cooling process, the dynamic model of the adsorbent bed

is shown in equation (4) and (5):

$$[(1 + R_f) M_a c_{va} + M_a x_{dil} c_{vc}] \frac{dT_b}{dt} = \phi_{w \to b} \tag{4}$$

$$x_{dil} = x_0 \exp \left[-k \left(\frac{T_{g2}}{T_m} - 1 \right)^n \right] \tag{5}$$

where x_{dil} is adsorption rate in the isochoric cooling process, and T_{g2} is the final desorption temperature.

For the isobaric adsorption process, the dynamic model of the adsorbent bed is shown in Eq.(6):

$$[(1 + R_f) M_a c_{pa} + M_a x c_{pc}] \frac{dT_b}{dt} = \phi_{w \to b} + M_a H_a \frac{dx}{dt} + M_a c_{pc} (T_e - T_b) \frac{dx}{dt} \tag{6}$$

where H_a is the enthalpy of adsorption and T_e is evaporation temperature.

It is better to take the non-equilibrium adsorption into consideration in dynamic simulation. Equations for dynamic adsorption rate are shown below as equations (7) and (8) (Sakoda and Suzuki, 1986):

$$\frac{dx}{d\tau} = K_s a_P (x_0 - x) \tag{7}$$

$$K_s a_P = \frac{15 D_{so}}{R_P^2} \exp (-E_a / RT) \tag{8}$$

where $K_s a_P$ is surface diffusion velocity coefficient, D_{so} is surface diffusion coefficient, R_P is average diameter of absorbent granules, E_a is activation energy of surface diffusion.

The energy balance equations of the heat transfer fluid in adsorbent bed are shown in equations (9) and (10):

$$\phi_{w \to b} = m_f c_f (T_{f,in} - T_{f,out}) \tag{9}$$

$$\phi_{w \to b} = U A_0 \frac{T_{f,in} - T_{f,out}}{\ln [(T_{f,in} - T_b) / (T_{f,out} - T_b)]} \tag{10}$$

where m_f is mass flow of heat transfer fluid, c_f is specific heat of heat transfer fluid, $T_{f,in}$ is entrance temperature of heat transfer fluid, $T_{f,out}$ is exit temperature of heat transfer fluid, U is heat transfer coefficient between adsorbent bed and heat transfer fluid and A_0 is heat exchange surface between adsorbent bed and heat transfer fluid.

On the basis of equations (9) and (10), the relationship between entrance temperature and exit temperature can be obtained, as shown in Eq. (11):

$$T_{f,out} = T_b + (T_{f,in} - T_b) e^{-\frac{U \bullet A_0}{m_f c_f}}. \tag{11}$$

3. Dynamic models of the evaporator and the condenser

The difference between heat input and heat output leads to the change of energy of the adsorbate in the evaporator. We assume that the pressure and the temperature in the evaporator are uniformly distributed. The dynamic model of the evaporator is presented in equations (12) and (13):

$$M_e c_{pc} \frac{dT_e}{dt} = m_c c_{pc} \left(T_c - T_e\right) + U_e A_e \left(T_{e,ai} - T_e\right) - m_e L_e \tag{12}$$

where M_e is mass of adsorbate in the evaporator, m_c is mass flow of adsorbate that flows into the evaporator, T_c is condensing temperature, U_e is heat transfer coefficient of the evaporator, A_e is heat exchange surface of the evaporator, $T_{e,ai}$ is return air temperature, m_e is mass flow of adsorbate that runs off the evaporator, L_e is latent heat of vaporization of adsorbate under evaporating temperature,

$$T_{e,ao} = T_e + \left(T_{e,ai} - T_e\right) \exp\left(-\frac{U_e A_e}{c_{e,air} m_{e,air}}\right) \tag{13}$$

where $T_{e,ao}$ is supply air temperature, $c_{e,air}$ is supply air specific heat at constant pressure and $m_{e,air}$ is mass flow of supply air.

Gaseous adsorbate is condensed to saturation liquid in the condenser, and then flows into the evaporator. The dynamic model of the condenser is given in equations (14) and (15):

$$M_a \left[c_{pcg} \left(T_b - T_c\right) + L_e\right] \frac{dx}{dt} = U_c A_c \left(T_c - T_{c,ai}\right) \tag{14}$$

where U_c is heat transfer coefficient of the condenser, A_c is heat exchange surface of the condenser, and $T_{c,ai}$ is entrance temperature of ambient air:

$$T_{c,ao} = T_c + \left(T_{c,ai} - T_c\right) \exp\left(-\frac{U_c A_c}{c_{c,air} m_{c,air}}\right) \tag{15}$$

where $T_{c,ao}$ is exit temperature of ambient air, $c_{c,air}$ is ambient air specific heat at constant pressure, and $m_{c,air}$ is mass flow of ambient air.

4. Dynamic characteristics of the operating parameters of components

The values of the parameters, adopted in the calculation process are shown in Table 1.

Table 1. Parameter values adopted for calculations

Parameter	Value	Unit
Temperature of hot water	80	$^\circ$C
Mass flow of hot water	5.94	kg s^{-1}
Temperature of cooling water	40	$^\circ$C
Mass flow of cooling water	5.94	kg s^{-1}
Temperature of ambient air	35	$^\circ$C
Cycle time	40	minute
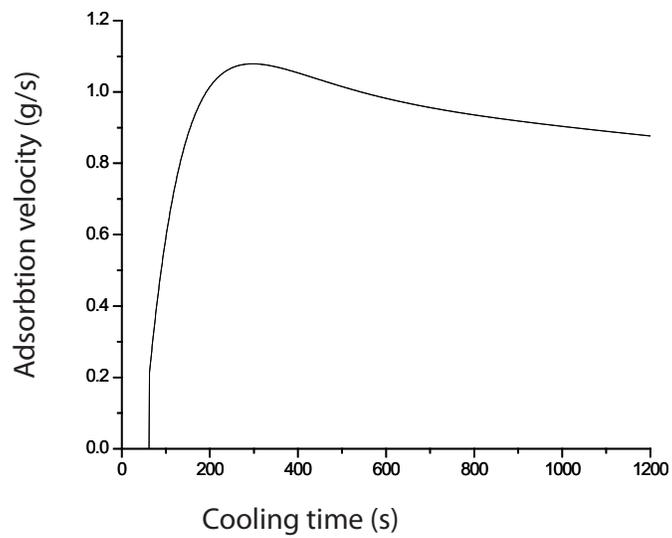
Figure 2. Change of adsorption velocity with the progress of cooling time

4.1. Dynamic changes of the adsorption velocity

The course of the adsorption velocity is shown in Fig. 2.

It can be easily seen that the adsorbent bed goes into the adsorption process after a short isochoric cooling process and the adsorption velocity is changing all the time. The adsorption velocity increases sharply in the initial phase of the adsorption process and gradually declines after reaching a peak value.

4.2. Dynamic changes of adsorbent bed temperature

The course of the adsorbent bed temperature is shown in Fig.3.
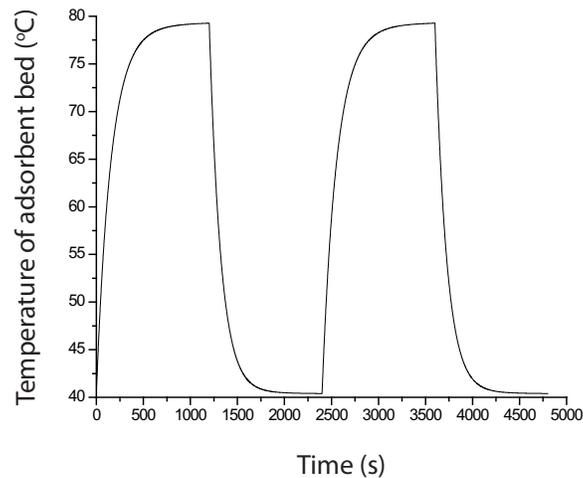
Figure 3. The change of temperature of adsorbent bed with the lapse of time

It can be easily seen that the adsorbent bed temperature increases sharply in the initial phase of the heating process, but its rate of increase slows down when the temperature is close to the heat resource temperature. Heat supplied to the adsorbent bed is mainly used to desorb the adsorbate and increase sensible heat of the adsorbent bed. But in the initial phase of the heating process, the desorption process does not take place, and the heat transferred from heat transfer fluid is all used to increase the sensible heat of the adsorbent bed. After adsorbent bed temperature reaches the desorption temperature, heat transferred from heat transfer fluid is firstly used to supply the enthalpy of desorption.

It can also be easily seen that adsorbent bed temperature decreases sharply in the initial phase of the cooling process, but its rate of decrease slows down when the temperature is close to the cooling water temperature. Heat taken by the cooling water mainly includes enthalpy of adsorption and sensible heat

of the adsorbent bed. But the adsorption process does not take place in the initial phase of the cooling process, so the heat transferred to cooling water is all from sensible heat of the adsorbent bed. After adsorbent bed temperature reaches the adsorption temperature, the heat transferred to cooling water is mainly from enthalpy of adsorption.

4.3. Dynamic changes of condensing temperature
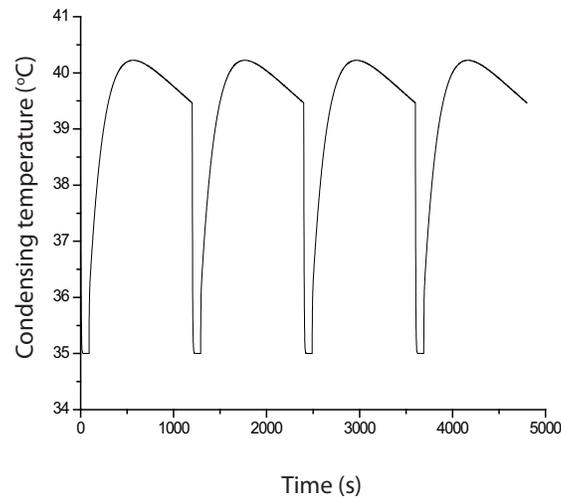
The course of the condensing temperature is shown in Fig.4.

Figure 4. The course of the condensing temperature with the progress of time

It can be easily seen that in the initial phase of the heating process, desorption process does not take place and the condensing temperature is close to the ambient air temperature. In the initial phase of the desorption process, the desorption quantity increases sharply and the adsorbate enters the condenser. The heat released by the adsorbate brings the increase of condensing temperature. With the continuation of the desorption process, the desorption velocity decreases and the mass of adsorbate entering the condenser also decreases, which results in the decrease of the condensing temperature. When the adsorbent bed is changing its working status, the desorption process does not take place and the condenser is cooled by ambient air, so that the condensing temperature is close to ambient air temperature.

4.4. Dynamic changes of evaporation temperature

The temporal course of the evaporation temperature is shown in Fig. 5.

It can be easily seen from Fig. 5 that the changes of evaporation temperature can be divided into three processes. The first process (a-b in Fig. 5) starts when the adsorbent bed enters the cooling process, but the adsorption process does not occur. The adsorbent bed is not connected with the evaporator and there is no cooling capacity output before adsorbent bed temperature decreases to the initial adsorption temperature. The evaporation temperature gradually increases because of the input of heat load. After the adsorbent bed temperature decreases to the initial adsorption temperature, it enters the second process (b-c in Fig. 5). The evaporation temperature decreases, because of the effect of the adsorption process. The evaporation temperature decreases until the refrigeration capacity equals the heat load. The third process (c-d in Fig. 5) starts when the evaporation temperature begins to increase and ends when the new cycle begins. The length of the third process mainly depends on the evaporation temperature, the refrigeration capacity and the cycle time. The third process should be possibly short in the actual system.
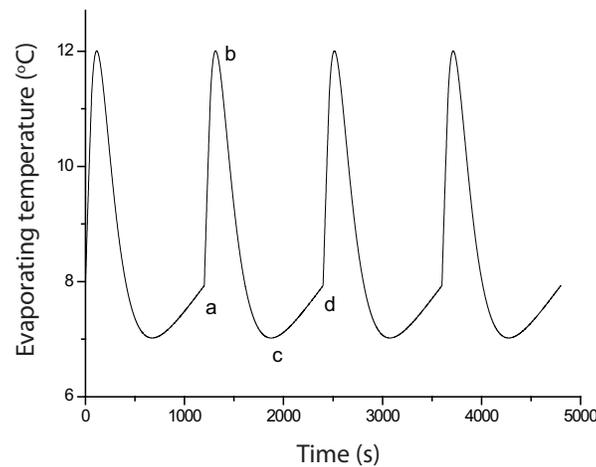

Figure 5. The course of the evaporation temperature with the passage of time

4.5. Dynamic changes of heat transfer fluid temperature

The temporal course of the exit temperature of cooling water is shown in Fig. 6.

It can be easily seen from this diagram that in the initial phase of the cooling process, the exit temperature of cooling water is rather high and that it decreases gradually with time. This is because in the initial phase of the process, the adsorbent bed temperature is rather high and the quantity of transferred heat is big. This leads to a high exit temperature of cooling water. With adsorbent bed temperature decreasing, the temperature difference decreases and the exit

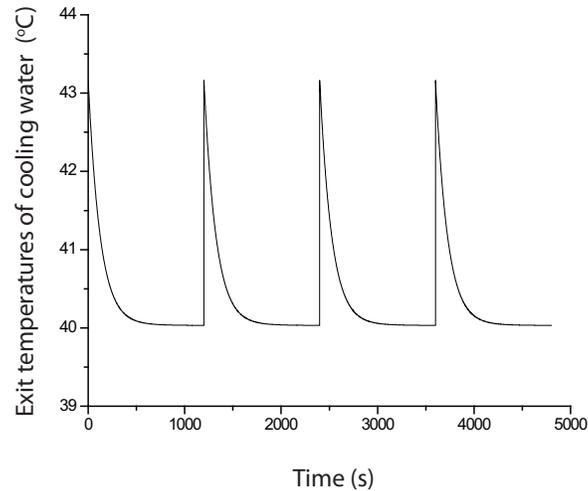temperature of cooling water decreases gradually.

Figure 6. The course of the exit temperature of cooling water with the passage of time

The temporal course of the exit temperature of hot water is shown in Fig. 7.

With regard to this process, it can be easily seen that in the initial phase of the heating process, the exit temperature of hot water is quite low and it increases gradually with time. This is so because in the initial phase of the process, the adsorbent bed temperature is rather low and the quantity of transferred heat is big. The effect thereof is the low exit temperature of hot water. With adsorbent bed temperature increasing, the temperature difference decreases and the exit temperature of hot water increases gradually.

5. Dynamic characteristics of the adsorption refrigeration system

5.1. Cycle time

If cycle time is so short that there is not enough time for the adsorbent bed to be appropriately heated or cooled, the desorption process and the adsorption process cannot be performed adequately. The choice of the cycle time is related not only to the heat and mass transfer performance of the adsorbent bed, but also to the performance of the condenser and of the evaporator. The dependence
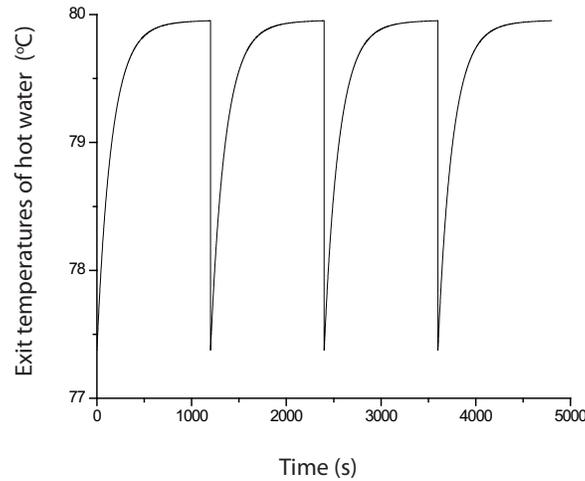
Figure 7. The course of the exit temperature of hot water with the passage of time

of the SCP (specific cooling capacity*) upon the change of cycle time is shown in Fig. 8.

It can be easily seen from Fig. 8 that there is a peak value of SCP along the cycle time duration. Hence, the cycle time should not be too long nor too short. One should choose the cycle time value possibly close to the point when the SCP value reaches its peak value.

5.2.   Heat source temperature

The dependence of the adsorption velocity upon the change of heat source temperature is shown in Fig. 9.

It can be easily seen from Fig. 9 that with the increase of heat source temperature, the time for adsorption process is accelerated and the adsorption velocity increases very fast. Increasing of the heat source temperature will cause the increase of the adsorbent bed temperature and of the initial adsorption temperature. Thereby, the adsorption volume under the same cycle time will get increased and adsorption process would be accelerated. Hence, it can be concluded that increasing the heat source temperature is good in terms of improving the performance of the system.

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*SPC or specific cooling capacity is defined as the cooling capacity of the given system per 1 kg of the absorbent. It is one of the two basic measures of system efficiency, see, e.q. Wang, Wang and Oliveira (2009) (eds.).
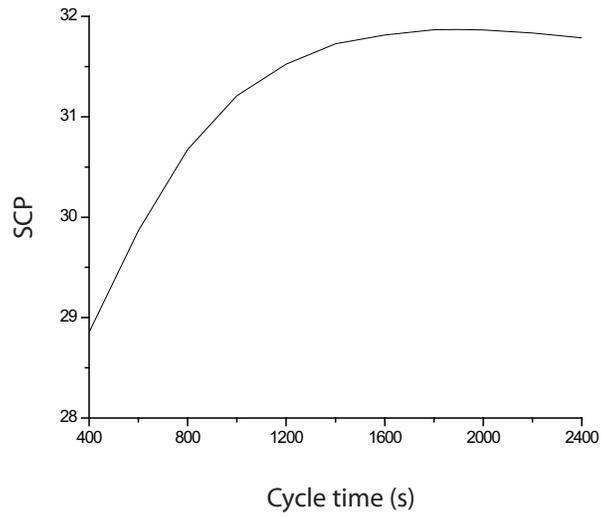
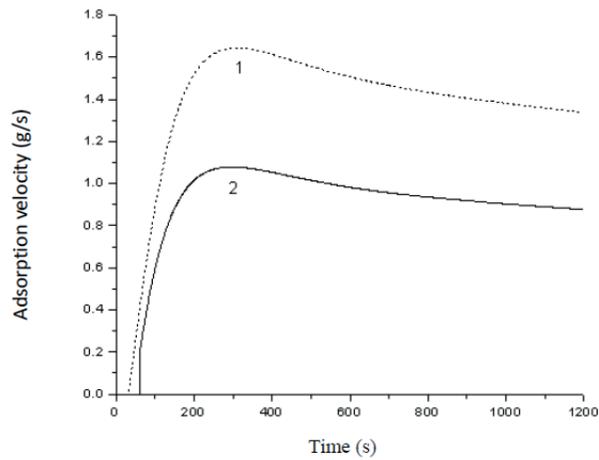Figure 8. Dependence of the SCP on the change of cycle time

Figure 9. Dependence of the adsorption velocity on the change of heat resource temperature

5.3.   Ambient air temperature

The condenser is cooled by ambient air. The change of ambient air temperature will affect the heat transfer of the condenser. The dependence of the condensing temperature upon the change of ambient air temperature is shown in Fig. 10.
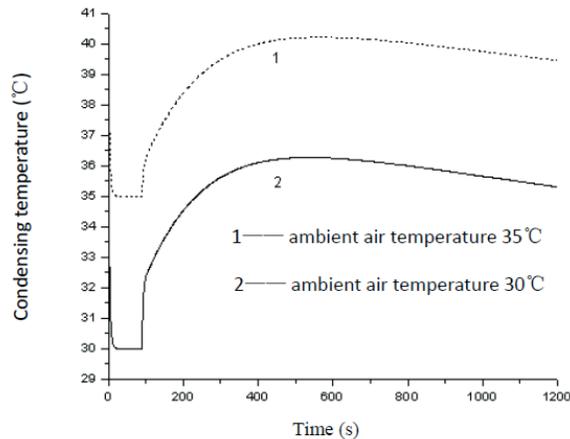

Figure 10. Dependence of the condensing temperature upon the change of ambient air temperature

It can be easily seen now that with the increase of ambient air temperature, the condensing temperature also increases. With the increase in the ambient air temperature, the condensing pressure increases and the force driving mass recovery increases, so the adsorption rate increases slightly. However, increase of the condensing temperature results in the reduction of the initial adsorption temperature and will delay the adsorption process. Overall, therefore, the increase of ambient air temperature is not good for the performance of the system.

5.4.   Return air temperature

Changes of the return air temperature reflect the changes of the heat load. The dependence of the evaporation temperature upon the change of return air temperature is shown in Fig. 11.

It can be easily seen that when the return air temperature increases, the evaporation temperature also increases. With the increase of the return air temperature, the evaporation pressure increases and the force, driving mass recovery, decreases, so that the adsorption rate decreases a bit. However, the increase of evaporation temperature results in the increase of the initial adsorption temperature, which will accelerate the adsorption process. Overall,
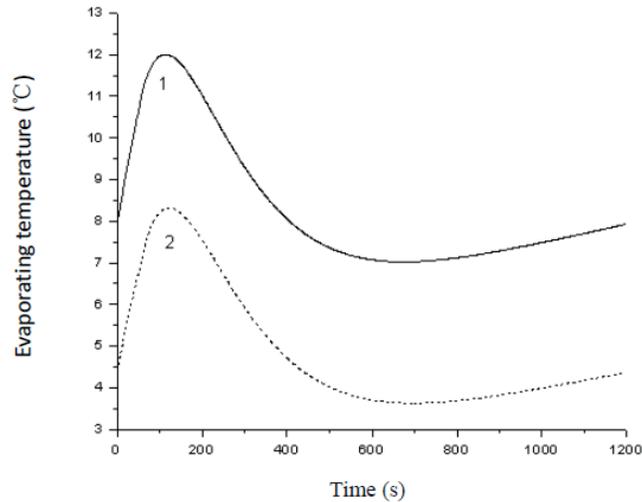
Figure 11. Dependence of the evaporation temperature on the change of return air temperature

the increase of return air temperature is good in terms of improvement in the performance of the system.

5.5. Cooling water entrance temperature

Dependence of the adsorption velocity upon the change of the cooling water entrance temperature is shown in Fig. 12.

It can be easily seen from this figure that when the cooling water entrance temperature increases, the adsorption velocity decreases. With the increase of the cooling water entrance temperature, the initial adsorption temperature decreases, the initial desorption temperature increases and, consequently, the adsorption process will be delayed. The increase in the cooling water entrance temperature is, therefore, not good for the performance of the system.

6. Conclusions

We shall now summarise the findings, which were illustrated and commented upon in the preceding sections of the paper.

1. Adsorption velocity increases sharply in the initial phase of the adsorption process and gradually declines after reaching a peak value.

2. Change of the adsorbent bed temperature is well pronounced in the initial phase of the heat transfer process, but this change becomes smaller

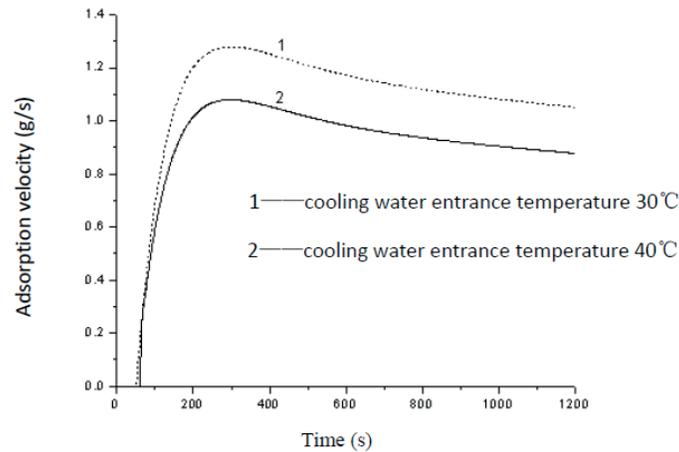with the continuation of the heat transfer and the temperature tends to stabilise.

Figure 12. Dependence of the adsorption velocity on the change of cooling water entrance temperature

3. Condensing temperature increases sharply in the initial phase of the desorption process and declines after reaching a peak value with the volume of desorption decreasing.

4. The changes in the evaporation temperature include three processes. The first process starts when the two beds change their working status and the evaporation temperature gradually increases. After the adsorbent bed temperature decreases to the initial adsorption temperature, the evaporation temperature enters the second process and the rate of decrease of this temperature is quite significant. The third process starts when the evaporation temperature begins to increase and ends when the new cycle begins.

5. The increase of heat source temperature and the decrease of cooling water temperature will accelerate the adsorption process.

6. The results obtained suggest some ways to improve the performance of the system, namely such as increasing the heat source temperature, decreasing the ambient air temperature, increasing the return air temperature and decreasing the cooling water temperature.

Acknowledgments

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