Dynamic simulation and experiments of a heat regenerative adsorption heat pump

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Abstract

The dynamic behavior of a heat regenerative adsorption heat pump employing an activated carbon–methanol pair has been studied. The mathematical models to simulate the system are presented. Curves of the system’s Specific Cooling Power and Coefficient of Performance versus evaporating temperature for the system’s variables are obtained by numerical calculation. To assess the validity of the model, experimental data with different operational parameters is furnished. The experimental results are in close agreement with the calculated data of the dynamic simulation. Therefore, by means of dynamic simulation, the performance of the system can be predicted, and the optimum operational parameters can be selected. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Dynamic simulation; Adsorption heat pump; Specific cooling power; Coefficient of performance

1. Introduction

The heat regenerative adsorption heat pump has many advantages, such as no moving components and the ability to use waste heat. But there are also many problems, for example, the refrigerating capacity per unit mass of the adsorbent is low, the size of the system is large, etc. Therefore, extensive studies have been concentrated on how to improve the performance of the system in recent years. The cycle process of the system chiefly depends on the dynamic
behavior of heating and cooling fluids in the system, so it is important to obtain the dynamic behavior of every component in the system.

Douss [1], Suzuki [2], Cho [3] and Sami [4] have contributed to dynamic simulation. They studied dynamic behavior for some different adsorption refrigeration systems and obtained some good results.

In this paper, a heat regenerative adsorption heat pump employing an activated carbon–methanol pair is taken as an example, in which the adsorbers adopt a novel shell and tube type heat exchanger. The mathematical models to simulate dynamic behavior of the system are presented. The curves of the system’s SCP (Specific Cooling Power) and COP (Coefficient Of Performance) versus the evaporating temperature for the system’s variables, such as the temperature of the heating source, temperature of the cooling water, cycle time, overall heat transfer coefficient of adsorbers, and so on, are obtained by a numerical method. Some experiments have been done, and the experimental conditions have been simulated by using the

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proposed model. The experimental and calculated data have been compared. Thus, the simulation methods have been verified, and the performances of the system can be predicted by comparison.

2. The heat regenerative adsorption heat pump

A continuous heat regenerative adsorption refrigerator/heat pump using activated carbon–methanol, developed in recent years, is shown in Fig. 1 [5]. It is an improved prototype that has been modified several times. In the improved system, the adsorbers are contained in a novel shell and tube type heat exchanger. The diameter of the tubes is 9.5 mm and the distance between the tubes is 25 mm. The adsorbent is placed in the space outside the tubes, and water

![Diagram of an improved continuous heat regenerative adsorption refrigeration system.](image)

Fig. 1. An improved continuous heat regenerative adsorption refrigeration system.
or oil of the heating or cooling medium flows through the tubes. The heat source is a boiler of about 100 l capacity, heated by a combination of several electric heaters such that the highest heating power is 30 kW.

For setting up the numerical model of the system, some essential assumptions are made as follows:

1. The cooling ability of the condenser is unlimited.
2. The evaporation temperature can be fixed at any desired constant value.
3. The adsorption and desorption capacities are only dependent on the local temperature.
4. The flow of the fluid is homogeneous in the components.
5. The refrigerant is adsorbed uniformly in the adsorber, and the adsorbent is uniformly distributed in the adsorber.

3. Dynamic model of system

A basic cycle of a continuous heat regenerative adsorption refrigeration/heat pump system is shown in Fig. 2. The cycle path of one adsorber goes along a-b-c-d in Fig. 2. The heating phase can be divided into two processes. In the isosteric regeneration process, the adsorber is heated from $T_{a2}$ to $T_{g1}$. The heat absorbed by the adsorber includes the sensible heat of the adsorber material, the adsorbent, and the adsorbate. In the isobaric desorption process, the adsorber is heated from $T_{g1}$ to $T_{g2}$. In addition to the sensible heat, the absorbed heat also includes the heat of desorption.

Similarly, the cooling phase is also divided into two processes. In the isosteric cooling process, the adsorber is cooled from $T_{g2}$ to $T_{a1}$. The heat released by the adsorber includes the sensible heat of the adsorber material, the adsorbent, and the adsorbate. In the isobaric

![Fig. 2. A basic cycle of continuous heat regenerative adsorption refrigeration system.](image-url)
adsorption process, the adsorber is cooled from $T_{a1}$ to $T_{a2}$. In addition to the sensible heat, the released heat also includes the heat of adsorption.

In view of the balance of energy, some relevant equations are given as follows.

3.1. Heating phase

3.1.1. Isosteric regeneration process

The equation of the heat flux across the adsorber can be given by:

$$ (M_1c_{v1} + M_2c_{v2} + M_2x_{conc} \cdot c_{p3}) \frac{dT_a}{dt} = \phi_{w \rightarrow a} $$

$$ x_{conc} = x_0 \exp \left[ -k \left( \frac{T_{a2}}{T_c} - 1 \right)^n \right] \tag{1} $$

3.1.2. Isobaric desorption process

The equation of the heat flux across the adsorber is presented as follows:

$$ (M_1c_{p1} + M_2c_{p2} + M_2x \cdot c_{p3}) \frac{dT_a}{dt} = \phi_{w \rightarrow a} + M_2(-\Delta H) \frac{dx}{dt} $$

$$ \Delta H = RA \frac{T_a}{T_c}, x = x_0 \left[ -k \left( \frac{T_{a2}}{T_c} - 1 \right)^n \right] \tag{2} $$

3.2. Cooling phase

3.2.1. Isosteric cooling process

The equation of the heat flux across the adsorber is presented as follows:

$$ (M_1c_{v1} + M_2c_{v2} + M_2x_{dil} \cdot c_{p3}) \frac{dT_a}{dt} = \phi_{w \rightarrow a} $$

$$ x_{dil} = x_0 \exp \left[ -k \left( \frac{T_{a2}}{T_c} - 1 \right)^n \right] \tag{3} $$

3.2.2. Isobaric adsorption process

The equation of the heat flux across the adsorber is presented as follows:

$$ (M_1c_{p1} + M_2c_{p2} + M_2x \cdot c_{p3}) \frac{dT_a}{dt} = \phi_{w \rightarrow a} + M_2(-\Delta H) \frac{dx}{dt} + M_2c_{p3}(T_e - T_a) \frac{dx}{dt} $$

$$ \Delta H = RA \left( \frac{T_a}{T_c} \right), x = x_0 \exp \left[ -k \left( \frac{T_a}{T_c} - 1 \right)^n \right] \tag{4} $$
The last term in Eq. (4) considers the thermal effects due to the flow of refrigerant vapor from the evaporator to the adsorber.

### 3.3. Heating and cooling medium

According to the balance of energy, some related equations describing the flow of the heating or cooling medium are presented as follows:

\[ \phi_{w \rightarrow a} = m_w c_{pw} (T_{w, \text{in}} - T_{w, \text{out}}) \]  
\[ \phi_{w \rightarrow a} = \alpha A_0 \frac{T_{w, \text{in}} - T_{w, \text{out}}}{\ln((T_{w, \text{in}} - T_a)/(T_{w, \text{out}} - T_a))} \]

If the heat losses in the heating medium loop are neglected, we have the equations \( T_{w, \text{in}} = T_{w, \text{out}} \), \( T_{a, \text{out}} \), and \( T_{a, \text{in}} \). When one adsorber is heated in the beginning, the heat comes from another adsorber that is being cooled with a heat regenerative adsorption refrigeration system. Therefore, the heat flux \( \phi_{w \rightarrow a, 1} \) of adsorber 1 equals the heat flux \( -\phi_{w \rightarrow a, 2} \) of adsorber 2, according to the balance of energy. The heat regenerative energy chiefly depends on the time of the heat regenerative process.

### 3.4. Heating and cooling source

It has been assumed that the heating power provided by the electric resistance can be changed to any power from 0 to 30 kW. At the beginning of the adsorber heating, the required power for the adsorber is more than 30 kW. In such case, with the boiler’s heating power limited to 30 kW, the outlet temperature of the boiler is lower than the required temperature for the required heating source. As the adsorber heating continues, the power required by the boiler decreases, with the outlet temperature of the boiler finally becoming the same as the required temperature for the heating source and the heating power of the boiler becomes lower than 30 kW.

Therefore, the following heat balance is employed to calculate the outlet temperature of the boiler heating medium.

\[ M_0 c_w \frac{d T_{w, \text{out}}}{dt} = Q_{\text{out}} + m_w c_{pw} (T_{w, \text{in}} - T_{w, \text{out}}) \]

The cooling source for the adsorber is the cooling tower. To simplify the calculations, the inlet temperature of the cooling medium in the adsorber is fixed at a constant value under the supposition that the cooling capacity of the cooling tower is unlimited.

### 3.5. COP and SCP of system

The refrigerating capacity of the system in one cycle is presented as follows:

\[ Q_{\text{ref}} = 2 \left[ M_2 (x_{\text{cond}} - x_{\text{dil}}) L(T_e) - M_2 (x_{\text{cond}} - x_{\text{dil}}) c_3 (T_e - T_e) \right] \]
The COP of the system is given as follows:

\[
\text{COP} = \frac{Q_{\text{ref}}}{\left(2 \cdot \int_{\text{cycle}/2}^{\text{cycle}} Q_{\text{la}} \, dt\right)}
\]  

(9)

The SCP of the system is presented as follows:

\[
\text{SCP} = 2 \left[ (x_{\text{cond}} - x_{\text{dil}}) L(T_e) - (x_{\text{cond}} - x_{\text{dil}}) c_v (T_e - T_c) \right] / t_{\text{cycle}}
\]  

(10)

4. Results and analysis

We have presented the mathematical models to describe the dynamic behavior of the adsorption cycle. By means of dynamic simulation, some factors affecting COP and SCP, such as the cycle time, the temperature of the heat source, the temperature of the cooling water, the overall heat coefficient of the adsorber, etc., are analyzed. To assess the validity of the model, the experimental conditions have been employed in order to simulate the performance by using the proposed model, and the experimental data and calculated results have been compared. In the simulation calculation, some operational parameters, as above mentioned, were determined in accordance with the experimental data. An overall heat transfer coefficient for the adsorber, \( z = 90 \, \text{W/m}^2 \, ^\circ\text{C} \) was obtained during the experiments.

4.1. Influence of overall heat transfer coefficient on COP and SCP

Fig. 3 shows the effect of the overall heat transfer coefficient of the adsorber on the COP and SCP of the system as a function of the evaporating temperature. Some experimental data is also shown in Fig. 3.

From analysis of these curves, we realize that the overall heat transfer coefficient of the adsorber influences the performance of the system greatly. If the overall heat transfer coefficient can be increased, the SCP can be greatly increased. For example, at the same cycle time, the SCP increases by about 25% when \( z \) is doubled, but the effect on COP is smaller. This is the reason that quick heating and cooling of the adsorbent increases the desorption temperature and decreases the adsorption temperature at the same cycle time. On the other hand, at the same desorption and adsorption temperature, the cycle time can be shortened in order to raise the SCP and COP. Therefore, it is important to enhance the heat transfer rate in the adsorbers.

4.2. Influence of temperature of heat source on COP and SCP

Usually, the higher the temperature of the heat source, the faster is the rate of heating of the activated carbon, and the higher is the desorption temperature. Therefore, the SCP will be increased greatly by increasing the temperature of the heat source, but for the COP, the increase is smaller. Fig. 4 shows the effect of the temperature of the heat source on the COP...
and SCP of the system as a function of the evaporating temperature. Some experimental data also shown in Fig. 4.

4.3. Influence of cycle time on COP and SCP

Usually, the shorter the cycle time, the higher is the SCP, but if the cycle time is too short, the adsorbent cannot be heated or cooled to the desired temperature in the available time. Obviously, this will affect the desorption and adsorption capacity. Thus, the selection of the
cycle time is very important to improve the performance of the system. Fig. 5 shows the effect of cycle time on the COP and SCP of the system as a function of evaporating temperature. Some experimental data are also shown in Fig. 5. From the calculations made and the shown data, it appears that the best cycle time is about 40 min.

4.4. Influence of temperature of cooling water on COP and SCP

The adsorption temperature is related to the temperature of the cooling water at the
adsorber inlet. The lower the temperature of the cooling water, the faster is the rate of cooling of the activated carbon, and the lower is the adsorption temperature, as a result of the lower condensing temperature. Fig. 6 shows the effect of the temperature of the cooling water on the COP and SCP of the system as a function of the evaporating temperature. Some experimental data are also shown in Fig. 6. This figure clearly shows the advantages of a lower cooling water temperature for increasing the COP and SCP of the system.
Comparing the calculated results with the experimental data, there is a small difference in the SCP, but there is a much larger difference in the COP, the test data being significantly below the calculated results. The reasons are analyzed as follows:

1. According to the dynamic behavior of the system, the SCP depends chiefly on the temperature of the heat source, the temperature of the cooling water, the condensing temperature, the evaporating temperature, the overall heat transfer coefficient of the adsorber, and the adsorption capacity of the adsorbent–adsorbate pair. In the simulation
calculations, most of these parameters are selected in accordance with the local experiments. The overall heat transfer coefficient of the adsorber was measured in the experiment, therefore only the experimental mass transfer in the adsorbers can cause the difference between theory and practice. Mass transfer in the adsorbers has a small influence on the SCP because the gas flow channels were taken into consideration during designing the adsorbers, and the cycle time is longer in the experiments.

2. The heat losses of the system were neglected in the simulation calculations, but they will cause the measured COP to be less than the calculated one. The heat losses of the system are about 10% of the total heat input, according to the test of the real prototype.

3. Usually, there is the highest COP along the path of the ideal cycle as mentioned above, but real systems operate along real cycles. The required heat of the real cycle is larger than that of the ideal cycle. Therefore, this results in a lower COP in the real system than in the simulated system.

Therefore, the calculation methods should be improved in further work: many factors, such as the real cycle, heat losses, cooling ability of the condenser, the time of adsorption and desorption, etc., should be considered in the simulation. The experimental prototype should be improved: the prototype should decrease the heat losses of the components as much as possible. Through this work, the calculated performance and the experimental performance will become closer to each other.

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References