DESIGN AND PERFORMANCE SIMULATION OF NEW SOLAR CONTINUOUS SOLID ADSORPTION REFRIGERATION AND HEATING HYBRID SYSTEM

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Rezumat. In this paper, the design of a new continuous solid adsorption refrigeration and heating hybrid system driven by solar energy was presented, and its performance simulation and analysis were made under the normal working conditions. Some performance parameters of the system were obtained, and the effects of water mass in water tank on the system’s COP\text{cooling}, COP\text{heating} etc. were discussed.

Cuvinte cheie: Solar energy; Continuous type; Adsorption refrigeration; Hybrid system.

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INTRODUCTION
The coefficient of performance of solid adsorption refrigeration system has been improved greatly due to a great number of experimental and theoretical researches since the recent years. But the commercialization of solid adsorption refrigeration system is retarded by low thermal conductivity of adsorbent and low specific cooling power of the system [1]. By application of water, methanol, and ammonia, the solar adsorption refrigeration system employs the intermittence of solar energy and adsorption refrigeration. But such cooling type only refrigerates during the night, and in the summer day when larger cooling capacity is needed, the method of cold storage must be adopted which will lead the larger volume and higher cost of solar adsorption refrigeration system. In this paper, based on lots of experimental and theoretical researches of solid adsorption refrigeration system, the design and performance analysis of a new continuous solid adsorption refrigeration and heating hybrid system driven by solar energy was proposed. By comparison with the intermittent solar solid adsorption refrigeration system, the new hybrid system has many advantages such as refrigerating continuously even in the daytime, cooling as well as heating, and higher energy efficiency.

1. DESIGN AND PRINCIPLE OF THE HYBRID SYSTEM
1.1. Design of the hybrid bed
Solar solid adsorption bed is always designed according to the fabrication of plate type heat collector. Such design has two disadvantages as following: (1) The encapsulation thickness of adsorbent is so large that the temperature difference of adsorbent between surface layer and bottom in the bed is too big for adsorb or desorb evenly; (2) Only be used in intermittent cycle with desorbing in the daytime and adsorbing at night.

To overcome the two disadvantages of traditional adsorption bed, the hybrid adsorption bed is combined by two adsorption beds which are covered by glass layer similar with solar collector shown in Fig. 1. To avoid the mutual thermal effect, an adiabatic layer is placed between the two beds. Black lacquer is coated on the surface of the bed. A U-type flume is devised as the bed wall through which the cold water flows to cool adsorbent that is adsorbing. When the two beds are in a state of saturated adsorption/desorption respectively, the two beds exchange their positions through a rotation of 180° by an axis, still with the upper bed desorbing and the lower bed adsorbing for refrigerating continuously.

![Fig. 1. The design of hybrid adsorption bed.](image-url)
1.2. Working principle of the hybrid system

The schematic design of solar continuous solid adsorption refrigeration and heating hybrid system is shown in Fig. 2. The system consists of a hybrid adsorption bed array, water tank, condenser, evaporator, liquid receiver, throttle valve, valves and so on.

In an ideal process, the working principle is shown in Fig. 3. In the morning, the upper bed absorbs solar energy as a heat collector. When the temperature of adsorbent rises up to a temperature \( T_{a2} \rightarrow T_{g1} \) which causes the vapor pressure of the desorbed refrigerant up to the condensing pressure \( p_{cv} \rightarrow p_{co} \), desorption at constant pressure is initiated, the desorbed vapor is condensed in the condenser and collected in the receiver. The temperature of adsorbent in upper bed continues rising due to solar heating. After 2 h, when the temperature of adsorbent reaches the expected desorption temperature 80–90°C \( T_{g1} \rightarrow T_{g2} \), the first heating of upper bed ends, and the hybrid bed is rotated by 180°. The upper bed is substituted for the lower bed, which is heated by solar energy now, and the upper bed is cooled by cold water in water tank which will circulates from tank to bed by its natural convection.

Conveniently, we still call the up bed upper bed, and the low bed lower bed. The temperature of adsorbent in lower bed is reduced rapidly \( T_{g2} \rightarrow T_{a1} \), and the vapor pressure of refrigerant drops too \( p_{co} \rightarrow p_{ev} \). Evaporation, i.e. refrigeration could happen if the connecting valve is open. The cooling by cold water and air natural convection causes the temperature of adsorbent in lower bed to drop \( T_{a1} \rightarrow T_{a2} \). In the evening, by several cycles the water will reaches high temperature, and can be used by the family.

The thermodynamic cycle for adsorption refrigeration can be demonstrated in a \( p-T-x \) diagram shown as Fig. 3. But in such hybrid cycle, because the temperature of cooling water in water tank is rising after every cycle, \( T_{a2}, T_{g1}, T_{g2}, \) and \( T_{a1} \) will have increasing values. So the cycle will not be repeated exactly due to the dynamic change of the several parameters. In general, when the upper bed desorbs, the lower bed adsorbs, and the hybrid system refrigerates and heats simultaneously and continuously.

Based on the same design parameters of the two beds and the homogeneous temperature of adsorbent in the adsorbing/desorbing process, this paper will make a theoretical analysis on the system of a single hybrid adsorption bed. There are five subsystems in the hybrid system: (1) the upper bed (signed by bed 1), (2) the lower bed (signed by bed 2), (3) condenser, (4) evaporator, (5) and water tank.

At night, because the ambient temperature is low, all the two beds will adsorb refrigerants and have refrigeration effects.
adsorbent in upper bed (kg/kg), \(c_{pl}\) is the isobaric specific heat of adsorbate liquid (J/kg K), \(M_h\) is the mass of adsorber material (kg), \(c_{pb}\) is the specific heat of adsorber material (J/kg K), and \(h_d\) is the desorption heat (J/kg). \(x_1\), \(h_d\) can be calculated by the two following equations [6]:

\[
x_1 = x_0 \exp \left[ -k_1 \left( \frac{T_1}{T_{co}} - 1 \right) \right]
\]

(2)

which is called D-A equation, where \(k_1\), \(n_1\) are the adsorption parameters related with desorbing of the working pair, \(x_0\) is the maximum of adsorption capacity (kg/kg), and \(T_{co}\) is the condensing temperature equal to the ambient temperature (K), and

\[
h_d = L \times \frac{T_1}{T_{co}}
\]

(3)

where \(L\) is latent heat of vaporization of adsorbate (J/kg).

For the lower bed, the unsteady energy equation is

\[
\dot{m}_w c_{pw} (T_{w,in} - T_{w,out}) + \alpha A (T_{am} - T_2) = \left( M_{a2} c_{pa} + x M_{a2} c_{prl} + M_b c_b \right) \frac{dT_2}{dt} + h_u M_a \frac{dx_2}{dt}
\]

(4)

where \(\dot{m}_w\) is the mass flow rate of cooling water (kg/s), \(c_{pw}\) is the isobaric specific heat of cooling water (J/kg K), \(T_{w,in}\) is the inlet temperature of cooling water (K), \(T_{w,out}\) is the outlet temperature of cooling water (K), \(T_{am}\) is the ambient temperature (K), \(\alpha\) is the heat-transfer coefficient between lower bed and ambient (W/m\(^2\) K), \(x_2\) is the adsorption capacity of adsorbent in lower bed (kg/kg), and \(h_u\) is the adsorption heat (J/kg).

\(x_2\), \(h_u\) can be calculated by the two following equations:

\[
x_2 = x_0 \exp \left[ -k_2 \left( \frac{T_2}{T_{ev}} - 1 \right) \right]
\]

(5)

which is called D-A equation, where \(k_2\), \(n_2\) are the adsorption parameters related with adsorbing of the working pair, \(x_0\) is also the maximum of adsorption capacity (kg/kg), and \(T_{ev}\) is the evaporating temperature (K); and

\[
h_u = L \times \frac{T_2}{T_{ev}}
\]

(6)

For the water tank, the unsteady energy equation is

\[
\dot{m}_w c_{pw} (T_{w,out} - T_{w,in}) = M_{wt} c_{pw} \frac{dT_{wt}}{dt}
\]

(7)

where \(M_{wt}\) is the mass water in water tank (kg), \(T_{wt}\) is the mean water temperature in water tank (K). For the condenser, the unsteady energy equation is

\[
\dot{Q}_{co} = M_a \left[ c_{prl} (T_{co} - T_1) - L \right] \frac{dx_1}{dt}
\]

(8)

where \(\dot{Q}_{co}\) is the heat loss of adsorbate in condenser (W), \(c_{prl}\) is the isobaric specific heat of adsorbate vapor (J/kg K). For the evaporator, the unsteady energy equation is

\[
\dot{Q}_{cooling} = M_a \left[ L - c_{prl} (T_{2} - T_{ev}) \right] \frac{dx_2}{dt}
\]

(9)

where \(\dot{Q}_{cooling}\) is the cooling capacity of adsorbate in evaporator (W).

2.2. Coefficient of performances of the hybrid system

The solar cooling coefficient of performance of the hybrid system is expressed as:

\[
COP_{cooling} = \frac{\int \dot{Q}_{cooling} d\tau}{\int \dot{H}(\tau) d\tau}
\]

(10)

The solar heating coefficient of performance of the hybrid system is expressed as:

\[
COP_{heating} = \frac{\int M_{wt} c_{pw} \frac{dT_{wt}}{dt} d\tau}{\int \dot{H}(\tau) d\tau}
\]

(11)

3. PERFORMANCE ANALYSIS OF THE HYBRID SYSTEM

In the performance process of the hybrid system, there exist optimal tradeoffs between cooling and heating and between design and performance. During the day because water in the water tank will not be extracted to reach an appropriate water temperature for the family use at night, with rising of water temperature in the water tank, the final temperature of adsorbent in lower bed \(T_{a2}\) is equal to the mean water temperature in water tank \(T_{wt}\) after heat exchanging between the cooling water and the lower bed. With the mean water temperature in water tank \(T_{wt}\) rising, \(T_{a2}\) is raised after every cycle. Fortunately in the next process of solar heating the final temperature of adsorbent in upper bed \(T_{a2}\) is raised too, which will offset the drop of COP\(_{cooling}\) due to the rising of final temperature of adsorbent in lower bed \(T_{a2}\). As the water mass in water tank rises, the COP\(_{cooling}\), COP\(_{heating}\), SCP\(_a\), SCP\(_c\), and SHP\(_c\) also rise during the day.

As the water mass in water tank rises, the temperature \(T_{a2}\) and \(T_{wt}\) in the daytime, the cooling capacity of per kg adsorbent at night, and the cooling capacity of per m\(^2\) heat-collecting area at night will reduce. Therefore an optimal value of water mass in water tank exists, which will make the COP\(_{cooling}\), COP\(_{heating}\), SCP\(_a\), SCP\(_c\), and SHP\(_c\) in the daytime, the water temperature in water tank after 1 day and the cooling capacity at night be appropriate values for an optimal design.
Fig. 4. COPcooling variable with water mass in water tank in the daytime.

Fig. 5. COPheating variable with water mass in water tank in the daytime.

Fig. 6. Specific cooling power of adsorbent SCP_{a} variable with water mass in water tank in the daytime.

Fig. 7. Specific cooling power of heat-collecting area SCP_{c} variable with water mass in water tank in the daytime.

5. CONCLUSION

This paper has proposed a design scheme of new solar continuous solid adsorption refrigeration and heating hybrid system and has made a performance simulation and analysis on the system. The relations between cooling/heating coefficient and solar radiation time and the optimal value of water mass in water tank of the hybrid system are found. This paper shows that such hybrid system has a great-applied value and the theoretical work on the system in this paper will make for the optimization of performance parameters of the next experimental prototype.

REFERENCES


