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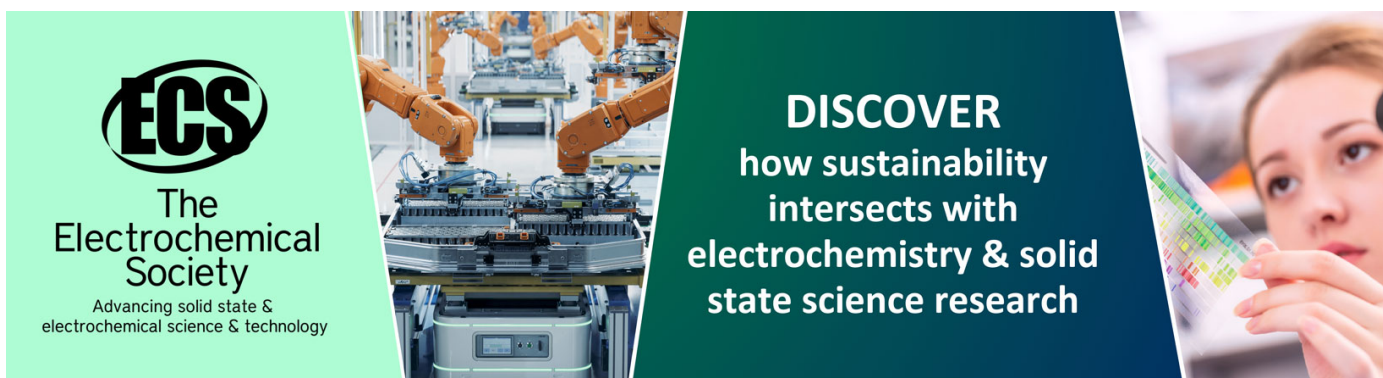
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Design of solar adsorption refrigeration system with CPC and study on the heat and mass transfer performance

W P Du¹, M Li¹, Y F Wang^{1,3}, J H He² and J X He¹

¹Solar Energy Research Institute, Yunnan Normal University, Kunming, Yunnan, China

²School of Physics and Electronic Sciences, Chuxiong Normal University, Chuxiong, Yunnan, China

E-mail: wangyf@ynnu.edu.cn

Abstract. To overcome the problem that the heat source temperature is limited and the lower part of the adsorption tube cannot effectively absorb the solar radiation when solar radiation as the heat source of the adsorption refrigeration system. From the perspective of enhancing the adsorption refrigeration unit tube to absorb solar radiation, thereby strengthening the heat transfer characteristic of adsorption bed, which can improve the efficiency of the refrigeration unit refrigerating capacity and system refrigeration efficiency. Solar adsorption refrigeration system based on CPC was designed and constructed in this paper. The heat and mass transfer performance of the adsorption refrigeration system were studied. The experimental results show that the temperature of the adsorption bed with parabolic concentrating structure can rise to 100 °C under low irradiation condition. When the irradiation intensity is 600 w/m² and 400 w/m², the average temperature rising to desorption temperature reaches 0.67 °C/min and 0.50 °C/min, respectively. It can effectively solve the problem that the conventional adsorption bed is difficult to reach the required desorption temperature due to the low power density of the sunlight. In the experiment, the system COP were 0.166 and 0.143 when the system in the irradiance of 600 w/m² and 400 w/m².

1. Introduction

The use of renewable energy for refrigeration is one of the important ways to solve the energy and environmental problems [1]. The universal existence of solar energy, the greenhouse effect coefficient of solar refrigeration and the ozone depletion potential are zero. What's more, due to the change of solar radiation with time and the geographical distribution of solar radiation are highly consistent with air conditioning demand, solar refrigeration has been widely studied. Adsorption refrigeration can effectively use solar energy, industrial waste heat and other low-grade heat source and has no moving parts, low noise, long life and other advantages. So, solar adsorption refrigeration has been widely concerned [2]. However, the low refrigeration efficiency has become the bottleneck of commercial development of adsorption refrigeration technology currently [3].

For a long time, researchers have carried out extensive studies to improve the performance of the adsorption refrigeration system. In the refrigerant performance, in order to improve the heat transfer performance of the adsorbent and overcome the problem of expansion and caking in the process of adsorption cycle, scholars developed all kinds of high thermal conductivity of adsorbent [4-7]. In the improvement of the structure of the adsorbent bed, there are ways to increase the heat transfer fins, to



promote heat exchange with heat pipes and to prepare heat exchange coatings [8,9]. Solar Energy Research Institute of Yunnan Normal University used activated carbon-methanol as working pair in the adsorption refrigeration system and designed a kind of fin tube solar adsorption collector bed for solar adsorption refrigeration system by increasing the diameter and adding heat transfer fins, have been obtained some research results [10,11,12]. But the fin tube adsorbent bed is not uniformly heated, only the upper part can receive sunlight during the desorption process, and the lower part of the fin tube inside of the insulating layer cannot effective absorption of solar radiation, so the refrigerant desorption is not sufficient, which result in affect the efficiency of system.

In order to overcome the problem that the heat source temperature is limited and the lower half of the fin tube cannot absorb solar radiation effectively and to increase the cooling capacity of the unit and the cooling efficiency of the system, the absorption of the solar by the adsorption refrigeration unit tube and the heat transfer characteristics of the adsorbent bed need to be enhanced. Combining no tracking focused composite parabolic (CPC) reflector panel with solar adsorption refrigeration, a solar adsorption refrigeration system based on CPC was constructed and its heat and mass transfer performance were studied.

2. Design of solar adsorption refrigeration system based on CPC

The solar adsorption refrigeration system based on CPC is shown in figure 1. The system is mainly composed of adsorption bed, condenser, evaporator and vacuum valve, vacuum pressure gauge and mass transfer channel. The main components of the system are introduced below.



Figure 1. The solar adsorption refrigeration system based on CPC.

2.1. Adsorption refrigeration tube with fin

The adsorption refrigeration tube adopts the fin adsorption tube as shown in figure 2, and the parameters of each part are shown in table 1. The length of adsorption refrigeration tube in the system is 1 meter, the average of each refrigeration tube filled 2.05 kg activated carbon. The fin adsorption refrigeration tube is shown in figure 1, and its structural parameters are shown in table 1.

Table 1. Structure parameters of finned tube.

Structure parameters	Size (mm)
Outer diameter /Inner diameter	90/40
Wall thickness (fin thickness)	1.5
Long fin / Short fin	25/10
Gap width of mass transfer	6

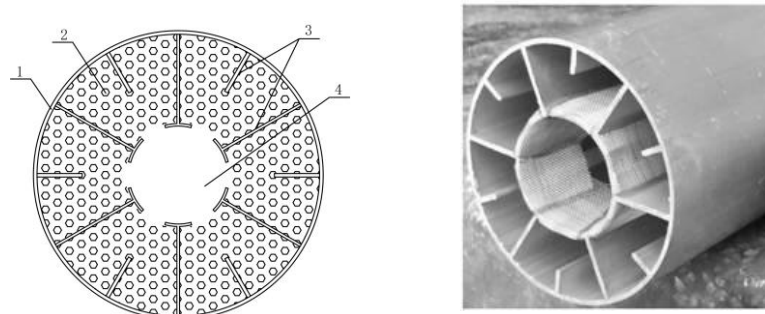


Figure 2. Structure diagram and physical map of finned adsorption tube.
1. Outer tube; 2. Adsorbent; 3. Heat transfer fins; 4. Mass transfer channel.

2.2. The adsorption bed design

In order to overcome the solar energy as heat source of the adsorption refrigeration system, heat source temperature is limited and the lower part of the fin tube cannot effectively absorb the solar radiation problems, by increasing the desorption temperature of the adsorption tube, the adsorption bed designed with a composite parabolic trough condenser structure (as shown in figure 3). In order to ensure that the light direct into the adsorbent bed can be full utilized, two parabolic focal points are located at F1 and F2 as shown in figure 4, and the two paraboloids are connected to the surface of the heat absorbing tube at point A. The urethane foam filled between the parabolic trough surface and the back of the adsorbent bed, which can effectively reduce the heat loss at the bottom of the adsorbent bed. According to this design, adsorption bed parabolic trough concentrating ratio $\zeta=1.24$. The parameters of the condensing surface of the adsorption bed are shown in table 2.

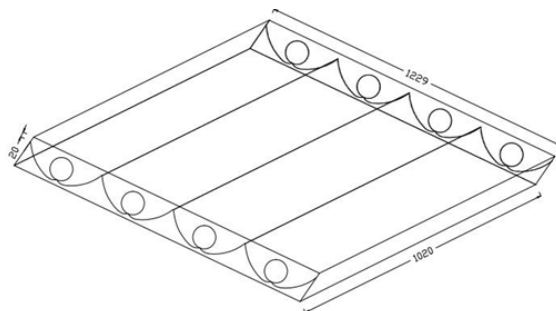


Figure 3. Adsorption bed of CPC solar adsorption refrigeration.

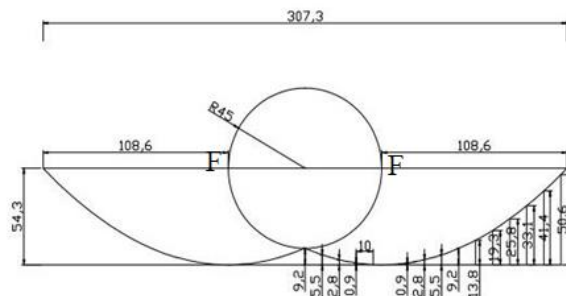


Figure 4. The unit tube of the adsorbed bed.

Table 2. Structural parameters of adsorption refrigeration unit tube and adsorbent bed.

Structural parameters	Size (mm)
Parabolic focal radius p	108.64
Parabolic trough depth H	99.32
Radiation width of a focusing unit D	307.28
The adsorption bed size (length * width * height)	1229*1020*80

2.3. Condenser design

The desorption of the refrigerant vapor is condensed into liquid through heat exchange with the condenser. Therefore, the condensing load of the system should be considered when designing the condenser. The calculation formula of condensing load is:

$$Q_{cond} = M(L_e + c_p \Delta t) \quad (1)$$

Q_{cond} is condensing load; M is the amount of desorbed refrigerant; L_e is the latent heat of vaporization of refrigerant; c_p is specific heat capacity of refrigerant steam at constant pressure; Δt is the temperature difference before and after condensation.

The required heat transfer area for condenser is:

$$A = \frac{Q_{cond}}{U_c \Delta t} \quad (2)$$

U_c is the condenser heat transfer coefficient; Δt is a temperature difference between refrigerant and water; A is the required heat transfer area for the condenser.

The system uses the copper-aluminum composite finned tube water-cooled condenser, composed of four copper-aluminum composites finned tube and two copper tubes placed up and down, they all placed in the condensate tank. During the desorption process, the refrigerant vapor passes through the inner tube and exchanges heat with the cold water outside of the finned tube and then condense into liquid. The condenser structure is shown in figure 5. The structural parameters of the condenser are shown in table 3.

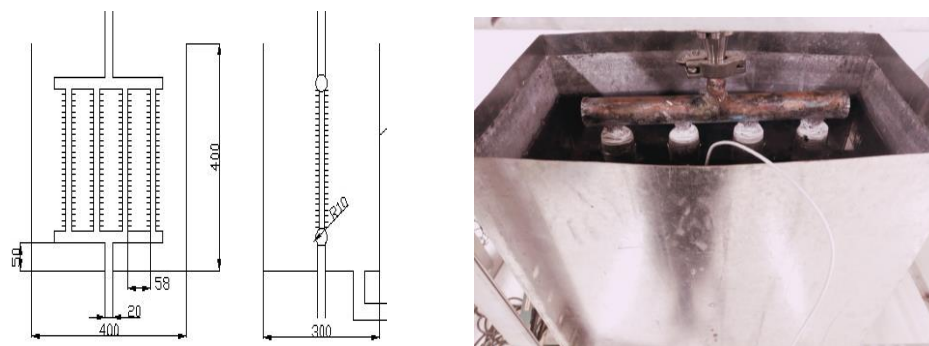


Figure 5. Condenser structure diagram and physical map.

Table 3. Structural parameters of condenser.

Name	Specifications
Fin tube inner / outer diameter	15.5 mm/32.5 mm
Fin net height / gap / thickness	8 mm/2.5 mm/0.3 mm
Condenser tank (length × width × height)	400 mm × 300 mm × 400 mm

2.4. Evaporator design

While ensuring that the volume of the evaporator meets the requirements of the storage of the liquid refrigerant, the surface heat exchange area of the evaporator needs to be increased. It also needs to be considered that the convenience of ice taking and the maneuverability of manufacturing. The evaporator is designed as an aluminum alloy container as shown in figure 6. Evaporator parameters are as follows:

Table 4. Structural parameters of evaporator.

Project	Dimensions
Evaporator size	410mm*180mm*105mm
Evaporator volume	4.95L
Evaporator surface area	0.255 m ²

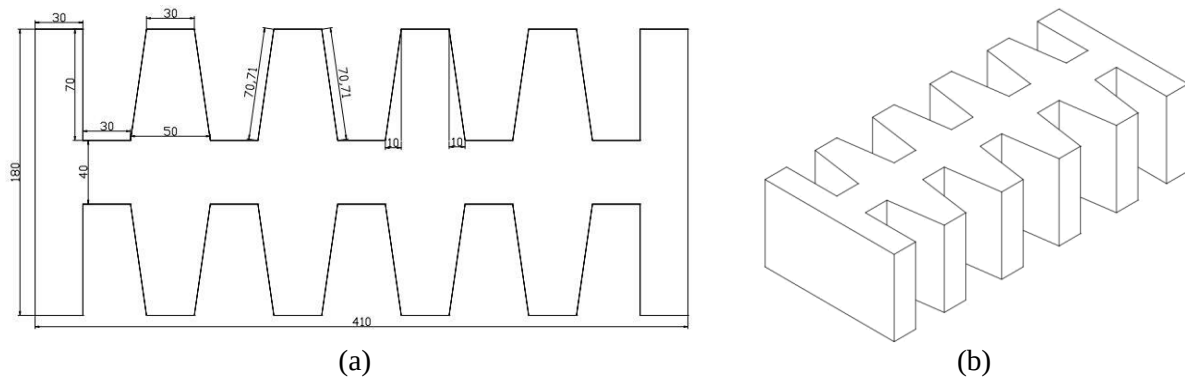


Figure 6. Evaporator structure diagram, (a) Axonometric drawing of evaporator and (b) Top view of evaporator.

3. Performance analysis

The process of the system is accompanied by the heat and mass transfer process, and the performance of heat and mass transfer determines the performance of the system. The performance of the system will be analyzed for two aspects of mass transfer performance and refrigeration performance.

3.1. Mass transfer model

The D-A equation applies to activated carbon-methanol working pair for adsorption refrigeration in equilibrium adsorption (Dubinin Astakhov equation) [13]

$$x = x_0 \exp \left[-K \left(\frac{T}{T_s} - 1 \right)^n \right] \quad (3)$$

x —Adsorption rate, kg kg^{-1} , the ratio of adsorbent refrigerant quality and adsorption quality; x_0 —Ultimate adsorption rate, kg kg^{-1} ; K —A constant determined only by the structure of the adsorbent; T_s —The temperature of the liquid refrigerant, K; T —Adsorbent temperature, K; n —Characteristic parameters of working pairs.

In order to analyze desorption performance of the system conveniently, corresponding to adsorption rate x . The ratio of the mass of the desorbed refrigerant to the mass of the adsorbent charged in the system is defined as desorption rate λ , and it is expressed as:

$$\lambda = x_0 - x \quad (4)$$

Take equation (3) into equation (4):

$$\lambda = x_0 \left\{ 1 - \exp \left[-K \left(\frac{T}{T_s} - 1 \right)^n \right] \right\} \quad (5)$$

In the low-pressure adsorption refrigeration system with methanol as a refrigerant, when the methanol is in the liquid-gas phase equilibrium and the temperature range is not large, the change of pressure with temperature can be expressed by Clausius-Clapeyron equation:

$$\ln P = -\frac{A}{T_s} + B \quad (6)$$

A, B —The parameters of Clausius-Clapeyron equation of refrigerant.

By the deformation of the equation (6), T_s can be obtained:

$$T_s = \frac{A}{B - \ln P} \quad (7)$$

By taking formula (7) in (5), the equation of desorption rate is obtained:

$$\lambda = x_0 \left\{ 1 - \exp \left\{ -K \left[\frac{T(B - \ln P)}{A} - 1 \right]^n \right\} \right\} \quad (8)$$

3.2. Refrigeration performance

Solar refrigeration system refrigerating efficiency COP is used to measure the performance of refrigeration system, which is expressed by the ratio of the effective refrigerating capacity of the system Q_{ref} to the solar radiation energy received by the adsorbent bed Q_s :

$$COP = \frac{Q_{ref}}{Q_s} \quad (9)$$

3.2.1. The effective refrigerating capacity of the system. After the desorption process, the adsorbent bed carries on radiation heat transfer and convection heat transfer with surroundings continuously. At the same time, the system pressure is also reduced, when the system pressure drops to the evaporation pressure, adsorption-evaporation stage start, the refrigerant is adsorbed to produce cooling effect Q_{ref} . The amount of cooling from refrigerant evaporation can be calculated by the following formula:

$$Q_{ref} = \Delta X M a L_e \quad (10)$$

$$\Delta X = X_{conl} - X_{dil} \quad (11)$$

L_e —The latent heat of vaporization of refrigerant; X_{conl} —Adsorption amount of adsorbent to refrigerant before desorption; X_{dil} —Adsorption amount of adsorbent to refrigerant before adsorption.

The refrigerant is cooled from the condensing temperature T_c to the evaporating temperature T_e , The sensible heat of emission is:

$$Q_{CC} = \int_{T_e}^{T_c} M a \Delta X C_{pl} dT \quad (12)$$

In this system with activated carbon-methanol as working pairs, the latent heat of vaporization of methanol can be calculated using the following equation:

$$L = 1252.43 - 1.596t - 0.0088t^2 \quad (13)$$

t : Temperature of methanol, °C.

3.2.2. Solar radiation energy absorbed by adsorption bed. The energy received by the adsorbent bed during the heating process is used to increase the sensible heat of the metal adsorbent of the adsorbent bed itself, the sensible heat of the adsorbent, providing desorption heat and heat dissipation. The transient heat balance equation of the adsorption bed is:

$$A_e I(t) \tau \alpha = (M_m C_{pm} + M_a C_{pa}) \frac{dT}{dt} + x M_a C_{pl} \frac{dT}{dt} + h_d M_a \frac{dx}{dt} + Q_{Hloss} \quad (14)$$

$I(t)$ —The total solar radiation energy projected onto the unit surface area of the collector, which

can be measured by a solar radiometer; A_e —heat collector area; τ —Sunlight transmittance of glass cover panels; α —Sunshine absorption rate of adsorption bed; M_m : The quality of a metal shell of adsorption collectors; C_{pm} : the specific heat of the metal shell adsorber; M_a : The quality of the adsorbent, C_{pa} : Specific heat of adsorbent; C_{pl} : The specific heat of refrigerant; $x(kg.kg^{-1})$: The adsorption quality of the refrigerant for the unit adsorbent; h_d : Heat desorption of refrigerant; Q_{Hloss} : The heat dissipation of the collector to the external environment.

4. Experimental results and analysis

In order to test the performance of solar adsorption refrigeration system based on CPC, the adsorption refrigeration system is placed under the TYD-PD4 matrix steady state solar simulator (The solar simulator consists of 15 xenon lamps, mainly used for solar water heaters, heat collectors and other products to test the light performance). The performance of the system is experimentally studied when the irradiance is 600 W/m² and 400 W/m². The experimental tests are shown in figures 7 and 8.

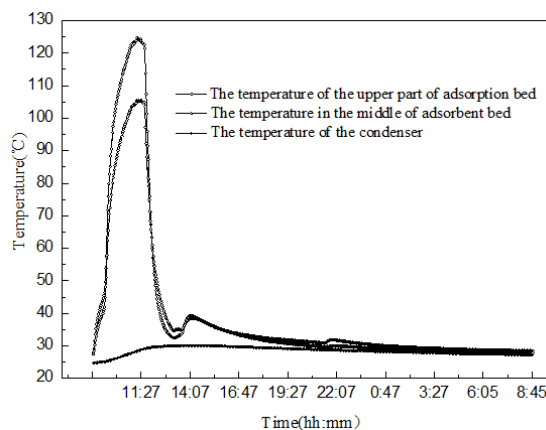


Figure 7. Temperature variation of adsorption bed and condenser at 600 W/m².

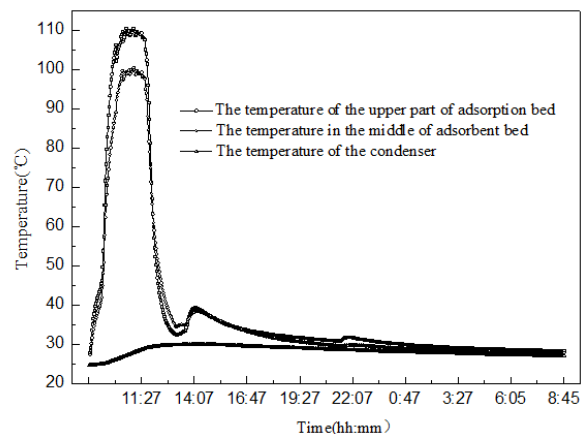


Figure 8. Temperature variation of adsorption bed and condenser at 400 W/m².

The experimental results show that the design of parabolic structure for adsorption bed condensing can make the adsorption bed temperature exceed 100°C and the irradiation intensity is lower, while the non-concentrating adsorption bed generally needs more than 900 W/m² radiation intensity to achieve the same effect. In view of the low solar power density, conventional adsorption bed is difficult to achieve the required desorption temperature problem, condenser adsorption bed can be an effective solution. In 600 W/m² and 400 W/m² of the radiation intensity, the average temperature rise rate reached 0.67°C/min, 0.50°C/min to the desorption temperature. With the increase of the irradiation intensity, the difference between the top temperature and the bottom temperature of the adsorbent bed increase, which make the desorption rate in the adsorption tube different with the position. In the desorption process, due to the radiation power density fall too fast, so that in the desorption process there are two temperature fluctuations, moreover, the first one is larger than the second one. The temperature range of the condenser is very small, indicating that the condenser meets the cooling load.

In the desorption process, the desorption rate and the system pressure are changed in a similar trend, but the change of the desorption rate is lagging behind the change of the system pressure, in different irradiation experiments, the rate of change showed first slow, then quick, and then gradually stable trend. As can be seen from figures 9 and 10, the higher the irradiance is, the higher the final desorption rate reached. When the irradiance upgrade from 400 W/m² to 600 W/m², the desorption rate can be increased by 4.1%, and in the 600 w/ m² the experiments show the desorption process is long and

stable, and finally the desorption rate reached 12.5%. Compared with the non-condensing adsorbent bed, the desorption rate of the adsorption bed is improved, and the cooling capacity of the unit tube is effectively improved. When the irradiation intensity is 600 W/m^2 and 400 W/m^2 , it was calculated by the experimental data that the COP were 0.166 and 0.143, respectively.

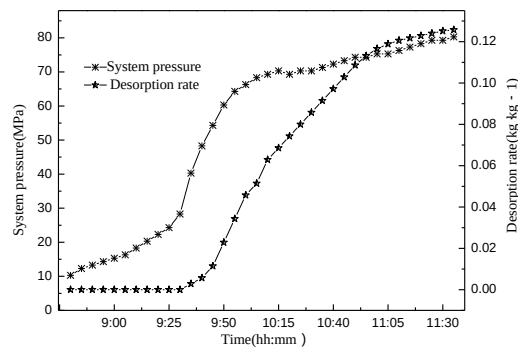


Figure 9. The process of desorption system pressure and desorption rate changes at 600 W/m^2 .

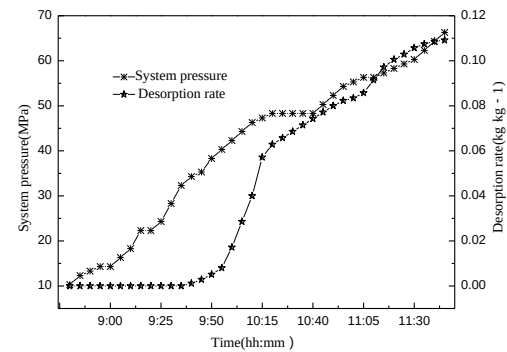


Figure 10. The process of desorption system pressure and desorption rate changes at 400 W/m^2 .

5. Conclusion

Improving the heat and mass transfer performance in the adsorption refrigeration system is the key to improve the coefficient of performance of the system, in order to overcome the problem that the heat source temperature is limited and the lower part of the adsorption tube cannot effectively absorb the solar radiation when solar radiation as the heat source of the adsorption refrigeration system. From the perspective of enhancing the adsorption refrigeration unit tube to absorb solar radiation, thereby strengthening the heat transfer characteristic of adsorption bed, which can improve the efficiency of the refrigeration unit refrigerating capacity and system refrigeration efficiency. Solar adsorption refrigeration system based on CPC was designed and constructed in this paper. The heat and mass transfer performance of the adsorption refrigeration system were studied. The experimental results show that the temperature of the adsorption bed with parabolic concentrating structure can rise to 100°C under low irradiation condition. When the irradiation intensity is 600 W/m^2 and 400 W/m^2 , the average temperature rising to desorption temperature reaches 0.67°C/min and 0.50°C/min , respectively. It can effectively solve the problem that the conventional adsorption bed is difficult to reach the required desorption temperature due to the low power density of the sunlight. In the experiment, the system COP were 0.166 and 0.143 when the system in the irradiance of 600 W/m^2 and 400 W/m^2 .

Acknowledgments

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