Performance Testing and Analysis of Silica Gel-Water Adsorption Refrigerator

Hongxuan Li¹, Tonghua Zou¹*, Qingling Hui¹, Ting Li¹ and Walter Mittelbach²

¹Tianjin Key Laboratory of Refrigeration Technology, Tianjin University of Commerce, Tianjin 300134, China
²Sorption Technologies GmbH, Christaweg 52, 79114 Freiburg, Germany
*Corresponding author email: zthua@tjcu.edu.cn

Abstract. In recent years, adsorption refrigeration technology has attracted wide attention from experts and scholars at home and abroad due to its environmental friendliness and energy saving advantages. In order to study the effectiveness of adsorption refrigeration technology to recover low-grade energy, a silica gel-water adsorption refrigeration system was proposed, which can effectively utilize low-grade energy such as industrial waste heat. The structure and composition of the system are introduced. The operation performance of the unit is tested under different working conditions by orthogonal experimental method, and the experimental results are analyzed. The effects of hot water temperature and flow, chilled water temperature and flow on the refrigeration capacity and COP value of the system are obtained. The experimental results show that under the low-temperature heat source of 55-75°C, the cooling capacity of the system can reach 5.3-12 and the COP value can reach 0.36-0.56. Under the same hot water temperature difference, the cooling capacity and COP value of the system increase rapidly under the condition of changing the hot water temperature at low temperature, indicating that increasing the heat source temperature at low temperature has a greater impact on the system performance. Through the analysis of primary and secondary effects, it is concluded that the inlet temperature of hot water is the main factor affecting the refrigeration capacity and COP value of the system.

1. Introduction

At present, energy is one of the major challenges facing mankind. With the rapid development of the world economy and the rapid development of global industrialization, energy consumption is increasing[1]. Most of it is discharged in the form of waste heat at 70-200°C, resulting in serious waste of energy. The extensive use of fossil fuels such as coal, oil, and natural gas produces carbon dioxide, which also causes serious damage to the ozone layer [2]. How to effectively use low-grade heat sources such as industrial waste heat to improve energy utilization efficiency has become the focus of current research [3]. Adsorption refrigeration technology powered by low-grade heat sources came into being. This technology uses natural refrigerants, and its ozone depletion potential (ODP) and global warming potential (GWP) are both zero, which is very environmentally friendly [4]. At the same time, adsorption refrigeration has the characteristics of simple control, low operating cost, and non-corrosion. It is a good choice in places where waste heat is available such as low temperature space, automobile air conditioners, fishing boat ice making, solar air conditioners or heat pumps. Therefore, the adsorption refrigeration technology provides a favorable way for the recovery and efficient utilization of low-grade heat energy, and has received extensive attention from the international refrigeration community [5-6]. However, adsorption refrigeration systems generally have shortcomings with low COP values and low thermal energy utilization, so they have not yet entered
large-scale industrialization. Common adsorption working fluid pairs include activated carbon-methanol, silica gel-water, zeolite-water, etc. The silica gel-water can utilize waste heat at a lower temperature, which is more suitable for use in low-temperature heat source occasions. In recent years, scholars at home and abroad have carried out a lot of research on it. Liu Yanling [7] developed an improved silica gel-water refrigerator suitable for heat-recovery refrigeration cycle, and found that temperature has an important impact on system performance. J.Y. Wu et al. [8] studied the cyclic characteristics of the silica gel-water adsorption cooling system under general variable heat source conditions, and concluded that the heat source change rate is a key factor affecting system performance. In the silica gel-water refrigeration system, R. H. Mohammed et al. [9] placed silica gel particles in high-porosity aluminum foam, which significantly improved the effective thermal conductivity of the silica gel-water adsorption packed bed and increased the COP several times. In the same year, QW Pan et al. [10] designed adsorption air conditioners and conducted comprehensive tests on their performance under different conditions, proving that adsorption air conditioners have good performance in cooling and heating cogeneration in residential and solar applications. Performance.

Based on the above research, a silica gel-water adsorption refrigeration unit system structure is introduced. This system can be effectively combined with a low-temperature heat source, so energy such as industrial waste heat and solar energy can be effectively used. At the same time, the performance of the system was experimentally studied, and the effects of different working conditions such as hot water temperature, chilled water temperature, hot water flow rate and chilled water flow rate on cooling capacity and COP of the system were tested, the primary and secondary effects of four factors on cooling capacity and COP of the system were analyzed.

2. Adsorption Refrigeration System
The physical structure of the system is shown in Figure 1. The main equipment of the whole system includes adsorption refrigerator, cooling tower, plate heat exchanger, thermostatic water tank, heating water tank, four water pumps, four turbine flowmeters, and six temperature sensors. The system is divided into three circuits, namely hot water circuit, cooling water circuit and chilled water circuit. The heating water tank is built with 45W electric heating wire and the hot water in the water tank flows into the adsorption refrigeration unit through the heat source heat pump to provide heat source for the refrigerator. The cooling tower is a mechanically ventilated cooling tower. The cooling water is cooled by the cooling tower and then enters the refrigeration unit through the cooling water pump. The adsorption heat and condensation generated by the refrigerator are discharged out of the refrigerator, and finally flowed back to the cooling tower. The addition of plate heat exchanger makes the three water circuits into a closed system, and also prevents the dirt in the cooling tower from entering the refrigerator and affecting the performance of the unit. The thermostatic water tank can provide a constant cold source for the refrigerator, the chilled water generated by the refrigerator flows into the thermostatic water tank to simulate the cold end. Both the heating water tank and the thermostatic water tank control the temperature of the water tank through the digital temperature control meter to control the on-off of the contactor, so as to meet the water temperature conditions of different working conditions.
3. Working Principle
This system uses a continuous refrigerator, consisting of two adsorption beds, evaporator, condenser and eight valves (V1~V8). Figure 2 shows the working principle of the system. The red, green and blue lines in the figure respectively represent the three water paths of hot water, cooling water and frozen water. The direction of the arrow is the flow direction of water in the refrigerator. The flow direction of the water in the refrigerator is changed by switching the valve, so as to change the working state of the adsorption bed. Since the adsorption refrigeration system works under vacuum, the two working chambers in the figure are both vacuum chambers.

3.1 Refrigeration Process 1 (Adsorption on Bed A1, Desorption on Bed A2)
When the adsorption bed A1 is in the adsorption state and the adsorption bed A2 is in the desorption state, as shown in Figure 2 (a). The heat exchanger in the same working chamber with adsorption bed A1 is used as evaporator, and the heat exchanger in the same working chamber with adsorption bed A2 is used as condenser. Hot water enters the adsorption bed A2 through V3 to provide desorption heat for the desorption process of the adsorption bed. The temperature of A2 gradually rises to produce a
desorption reaction, and the refrigerant gas is continuously desorbed. The gas goes into the condenser to condense. The cooling water enters the adsorption bed A1 and the condenser through V1 and V7 to take away the heat of adsorption and condensation, the temperature of A1 gradually drops to produce adsorption reaction. Chilled water enters the evaporator through V5, and takes out the circulation of cold generated in the evaporator.

3.2 Refrigeration Process 2 (Desorption on Bed A1, Adsorption on Bed A2)

As shown in Figure 2 (b), the adsorption bed A1 is in the desorption state and the adsorption bed A2 is in the condensation state. The heat exchanger in the same working chamber as the adsorption bed A1 is used as the condenser. The heat exchanger in the same working chamber as the adsorption bed A2 acts as the evaporator. Hot water enters the adsorption bed A1 through V1 to provide desorption heat for the desorption process of the adsorption bed, the temperature of A1 gradually increases to produce desorption reaction, continuous desorption of refrigerant gas, The temperature of A1 gradually rises to produce a desorption reaction, and the refrigerant gas is continuously desorbed. The cooling water enters the adsorption bed A2 and the condenser through V3 and V5 to take away the heat of adsorption and condensation, the temperature of A1 gradually drops to produce adsorption reaction. The chilled water enters the evaporator through V7 and circulates out the cold capacity produced in the evaporator.

4. Experimental Results and Performance Analysis

As the driving force of the adsorption refrigeration system, hot water provides heat for the desorption of the adsorption bed. When the hot water provides more heat for the adsorption bed, the adsorbent can desorption more adsorbent, more cooling capacity is generated. The influence of hot water on system performance will be explored by changing the temperature and flow rate of hot water. Similarly, as the evaporating end of chilled water, its temperature and flow rate also have a certain impact on system performance, so the influence of chilled water on system performance will also be explored by changing the temperature and flow rate of chilled water. The experimental conditions designed by orthogonal experiment method in this paper are shown in Table 1.

| Working conditions | Hot water inlet temperature(°C) | Hot water flow(m³·h⁻¹) | Chilled water inlet temperature(°C) | Chilled water flow(m³·h⁻¹) |
|--------------------|---------------------------------|------------------------|-----------------------------------|--------------------------|
| 1                  | 55                              | 2.5                    | 12                                | 4.5                      |
| 2                  | 55                              | 3.0                    | 17                                | 5.0                      |
| 3                  | 55                              | 3.5                    | 22                                | 5.5                      |
| 4                  | 65                              | 2.5                    | 17                                | 5.5                      |
| 5                  | 65                              | 3.0                    | 22                                | 4.5                      |
| 6                  | 65                              | 3.5                    | 12                                | 5.0                      |
| 7                  | 75                              | 2.5                    | 22                                | 5.0                      |
| 8                  | 75                              | 3.0                    | 12                                | 5.5                      |
| 9                  | 75                              | 3.5                    | 17                                | 4.5                      |

4.1 Influence of Hot Water Temperature and Flow on System Performance

Figure 3 shows the variation of cooling capacity and COP of the system with hot water temperature. As can be seen from the figure, when the hot water temperature increases from 55°C to 75°C, the cooling capacity of the unit increases from 5.3kW to 12.53kW, and the COP increases from 0.36 to 0.5. The increase of heat source temperature can effectively improve the system performance. When the hot water increased from 55°C to 65°C, the cooling capacity increased by 88 % and COP increased by 30.56 % while when the hot water increased from 65°C to 75°C, the cooling capacity increased by 25 % and COP increased by 6.4 %. Under the same temperature difference of 10°C, the growth rate of cooling capacity and COP under low temperature condition is much larger than that under high temperature condition, This indicates that increasing the heat source temperature at a low temperature has a greater impact on the performance of the refrigeration system than increasing the heat source
temperature at a high temperature.

**Figure 3.** Influence of hot water temperature on cooling capacity and COP of the system

**Figure 4.** Influence of hot water flow on cooling capacity and COP of the system

In order to explore the influence of hot water flow on system performance, the hot water flow was controlled at 2.5 m³/h, 3.0 m³/h and 3.5 m³/h respectively. The cooling capacity and COP value of the unit were recorded. As can be seen from Figure 4, with the increase of hot water flow, cooling capacity gradually increases. The hot water flow increased from 2.5 m³/h to 3.0 m³/h, the cooling capacity increased by 1.74 kW. The hot water flow increased from 3.0 m³/h to 3.5 m³/h, the cooling capacity increased by 0.17 kW. It shows that the increase of hot water flow can increase the cooling capacity of the unit. The COP value firstly increases and then decreases with the increase of hot water flow. When the hot water flow increases from 2.5 m³/h to 3.0 m³/h, COP increases by 0.076. When the hot water flow increases from 3.0 m³/h to 3.5 m³/h, COP decreases by 0.026. This shows that system performance can be improved by increasing the hot water flow. However, when the hot water flow increases to a certain value, the cooling capacity does not increase significantly, COP also decreased, resulting in heat waste, so the hot water flow should be properly controlled.

### 4.2 Impact of Chilled Water Temperature and Flow on System Performance

Figure 5 shows the variation trend of system cooling capacity and COP with the temperature of chilled water entering the adsorber. It can be seen from the experimental results that the cooling capacity and COP of the system increase with the increase of chilled water temperature. When the chilled water temperature is 22°C, the cooling capacity can reach 10.42 kW and COP can reach 0.47. When the chilled water temperature increases from 12°C to 17°C, the cooling capacity increases by 12.4% and COP increases by 7.5%. When the chilled water temperature increased from 17°C to 22°C, the cooling capacity and COP increased by 15.1% and 9% respectively. It can be concluded that the higher the inlet temperature of chilled water, the better the performance of the refrigeration system. The experimental results show that the chilled water temperature has a certain effect on the performance of adsorption refrigerator. When the application conditions permit, the performance of the refrigeration system should be improved as much as possible by increasing the temperature of the chilled water in the refrigerator, which is consistent with the performance of our common vapor compression refrigeration.
Figure 5. Influence of chilled water temperature on cooling capacity and COP of the system

As can be seen from Figure 6, the cooling capacity increases with the increase of the chilled water flow. The chilled water flow increases from 4.5 m$^3$·h$^{-1}$ to 5.5 m$^3$·h$^{-1}$, and the cooling capacity increases from 8.74 kW to 9.5 kW by 8%. From 5.0 m$^3$/h to 5.5 m$^3$/h, the cooling capacity increased by 9.7% from 9 to 10.42 kW. However, the change of chilled water flow has little impact on COP of the system. In the process of changing the flow of chilled water, COP is 0.43 at the minimum and 0.45 at the maximum, it is basically unchanged. Therefore, the method to improve the performance of adsorption refrigeration system by increasing the flow of frozen water is not very ideal.

5. Analysis of the Primary and Secondary Effects of Four Factors on the Performance of Adsorption Refrigeration System

5.1 Analysis of Primary and Secondary Effects of Cooling Capacity

The range analysis of the four factors' influence on the cooling capacity of the adsorption refrigeration system is shown in Table 2. It can be seen from the table that the range of each factor is not equal, the maximum range of hot water inlet temperature is 7.227, and the minimum range of chilled water flow is 0.833. It shows that the changes of various factors have different impacts on the cooling capacity of adsorption refrigeration system. The greater the range, the greater the impact of the factors on the cooling capacity of the refrigeration system [10]. The order of extreme values of various factors is hot water inlet temperature > chilled water inlet temperature > hot water flow > chilled water flow. The four factors affect the cooling capacity of adsorption refrigeration system in the order from main to second: hot water inlet temperature, chilled water inlet temperature, hot water flow rate and chilled water flow rate.

The determination of the optimal level of each factor is related to the mean value [11], and the evaluation index is the mean value of cooling capacity, the larger the cooling capacity, the better adsorption refrigeration system. In the table, the mean value 1, mean value 2 and mean value 3 respectively represent the mean value of each factor and each level. It can be seen from the table that when the inlet temperature of hot water is 75°C, the flow rate of hot water is 3.0 m$^3$·h$^{-1}$, the inlet temperature of chilled water is 22°C, and the flow rate of chilled water is 5.0 m$^3$/h, the system cooling capacity can reach the maximum, which is the optimal working condition.
### Table 2. Analysis of primary and secondary effects affecting system cooling capacity

| Working conditions | Hot water inlet temperature /°C | Hot water flow m³·h⁻¹ | Chilled water inlet temperature /°C | Chilled water flow m³·h⁻¹ | Refrigerating capacity kW |
|--------------------|---------------------------------|------------------------|-------------------------------------|---------------------------|---------------------------|
| 1                  | 55                              | 2.5                    | 12                                 | 4.5                       | 4.74                      |
| 2                  | 55                              | 3.0                    | 17                                 | 5.0                       | 4.50                      |
| 3                  | 55                              | 3.5                    | 22                                 | 5.5                       | 6.67                      |
| 4                  | 65                              | 2.5                    | 17                                 | 5.5                       | 8.26                      |
| 5                  | 65                              | 3.0                    | 22                                 | 4.5                       | 12.27                     |
| 6                  | 65                              | 3.5                    | 12                                 | 5.0                       | 9.38                      |
| 7                  | 75                              | 2.5                    | 22                                 | 5.0                       | 12.33                     |
| 8                  | 75                              | 3.0                    | 12                                 | 5.5                       | 13.78                     |
| 9                  | 75                              | 3.5                    | 17                                 | 4.5                       | 11.48                     |
| Mean value1        | 5.303                           | 8.443                  | 9.300                              | 9.497                     | —                         |
| Mean value2        | 9.970                           | 10183                  | 8.080                              | 8.737                     | —                         |
| Mean value3        | 12.530                          | 9.177                  | 10.423                             | 9.570                     | —                         |
| Range              | 7.227                           | 1.740                  | 2.343                              | 0.833                     | —                         |

**5.2 Analysis of Primary and Secondary Effects of Influencing Factors Of COP**

The range analysis of the four factors’ influence on the COP of the adsorption refrigeration system is shown in Table 3. It can be seen from the table that the range of each factor is not equal. The maximum range of hot water inlet temperature is 0.141, and the minimum range of chilled water flow is 0.027. It shows that the changes of various factors have different impacts on COP of adsorption refrigeration system. The greater the range, the greater the impact of the factors on COP of the refrigeration system. The order of extreme values of various factors is hot water inlet temperature > hot water flow > chilled water inlet temperature > chilled water flow. The four factors affect COP of adsorption refrigeration system in the order from main to second: hot water inlet temperature, hot water flow, chilled water inlet temperature and chilled water flow.

The determination of the optimal level of each factor is related to the mean value, and the evaluation index is the mean value of COP, the larger the COP, the better adsorption refrigeration system. In the table, the mean value 1, mean value 2 and mean value 3 respectively represent the mean value of each factor and each level. It can be seen from the table that when the inlet temperature of hot water is 75°C, the flow of hot water is 3.0 m³·h⁻¹, the inlet temperature of chilled water is 22°C, and the flow rate of chilled water is 5.5 m³·h⁻¹, COP can reach the maximum, which is the optimal working condition.
### Table 3. Analysis of primary and secondary effects affecting COP of the system

| Working conditions | Hot water inlet temperature/°C | Hot water flow /m³·h⁻¹ | Chilled water inlet temperature /°C | Chilled water flow /m³·h⁻¹ | COP |
|--------------------|--------------------------------|------------------------|------------------------------------|---------------------------|-----|
| 1                  | 55                             | 2.5                    | 12                                 | 4.5                       | 0.339 |
| 2                  | 55                             | 3.0                    | 17                                 | 5.0                       | 0.330 |
| 3                  | 55                             | 3.5                    | 22                                 | 5.5                       | 0.397 |
| 4                  | 65                             | 2.5                    | 17                                 | 5.5                       | 0.399 |
| 5                  | 65                             | 3.0                    | 22                                 | 4.5                       | 0.535 |
| 6                  | 65                             | 3.5                    | 17                                 | 5.0                       | 0.481 |
| 7                  | 75                             | 2.5                    | 22                                 | 5.0                       | 0.463 |
| 8                  | 75                             | 3.0                    | 12                                 | 5.5                       | 0.561 |
| 9                  | 75                             | 3.5                    | 17                                 | 4.5                       | 0.462 |
| Mean value 1       | 0.355                          | 0.400                  | 0.460                              | 0.445                     |     |
| Mean value 2       | 0.472                          | 0.475                  | 0.397                              | 0.425                     |     |
| Mean value 3       | 0.496                          | 0.447                  | 0.465                              | 0.452                     |     |
| Range              | 0.141                          | 0.075                  | 0.068                              | 0.027                     |     |

6. Conclusion

1. The cooling capacity of the system increases with the increase of hot water temperature, hot water flow, chilled water temperature and chilled water flow. Under the same temperature difference of hot water, the growth rate of cooling capacity at low temperature is much higher than that at high temperature. It shows that increasing the heat source temperature has a greater impact on the performance of the refrigeration system when the temperature is low.

2. The COP of the system increases with the increase of hot water temperature and chilled water temperature. With the increase of the hot water flow, it firstly increases and then decreases, which shows that the system performance can be improved by increasing the hot water flow appropriately. But when the flow is too large, the heat cannot be fully utilized. The change of frozen water flow rate has little effect on COP value. Therefore, changing the chilled water flow rate is not ideal for improving the operation effect of the unit.

3. The order of the primary and secondary factors of the sound cooling capacity is hot water temperature, chilled water temperature, hot water flow and chilled water flow; The order of the primary and secondary factors affecting COP is hot water temperature, hot water flow, chilled water temperature, chilled water flow.

7. References

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