An efficient solar-powered adsorption chiller and its application in low-temperature grain storage

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Abstract

A novel solar-powered adsorption cooling system for low-temperature grain storage has been built, which consists of a solar-powered water heating system, a silica gel–water adsorption chiller, a cooling tower and a fan coil unit. The adsorption chiller is composed of two identical adsorption units, each of them containing an adsorber, a condenser, and an evaporator/receiver. The two water evaporators have been incorporated into one methanol evaporator by the use of the concept of a gravity heat pipe. In order to improve the system efficiency and achieve continuous cooling production, the adsorbers are operated out-of-phase, and heat and mass recovery processes have been used. During the period from July to September of 2004, the system was put into experimental operation to cool the headspace (i.e., the air volume above the grain) of a grain bin. Three months of operation showed promising performance. The chiller had a cooling power between 66 and 90 W per m² of collector surface, with a daily solar cooling coefficient of performance (COPsolar) ranging from 0.096 to 0.13. The electric cooling COP was between 2.6 and 3.4.

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1. Introduction

The temperature inside the storage facility is one of the most important factors to ensure the quality of the stored grain. Low temperatures can prevent insect infestations, mould growth, and can also reduce the respiration of the grain, which leads to an extended storage time. Mechanical vapor compression refrigeration systems can be used for controlling the storage temperature during hot summer seasons in China (Hao et al., 2001). High capacity chillers are effective in controlling the grain storage temperature, but such an approach can be economically prohibitive in some cases because of the high electric power consumption and operation costs. Hence, it would be interesting to develop an alternative refrigeration device with minimal electric power consumption, possibly to use solar energy efficiently.

Solar-powered adsorption refrigeration systems seem to be a reasonable alternative, since the cooling load inside the storage room is roughly in phase with the solar energy availability. Many researches on solar adsorption refrigeration have been conducted in the last two decades, and a number of solar adsorption refrigeration systems were successfully developed. Pons and Guilleminot (1986) experimentally investigated a solar adsorption icemaker with 6 m² solar collector/adsorber, which produced 30–35 kg of ice per day under the solar radiation of about 22 MJ/m² day. Critoph (1988) comprehensively studied the performance limitations of adsorption cycles for solar cooling.
Headley et al. (1994) constructed a solar adsorption refrigerator powered by a combined parabolic concentrating solar collector with a solar COP of about 0.02. Boubakri et al. (2000) studied the limits of ice production by means of adsorptive collector–condenser technology. Tamaniot-Telto and Critoph (2000) investigated the thermophysical properties of two types of monolithic activated carbons, in order to design and manufacture a high performance generator for solid sorption refrigeration. Recently, Hildbrand et al. (2004) introduced a new solar-powered adsorption refrigerator with a mean solar COP of 0.16. In China, some experimental solar adsorption refrigeration systems have been also developed and studied (Wang et al., 2000; Luo et al., 2005). However, most of the systems were intermittent with a small cooling output and mainly used for ice making. Solar adsorption cooling for air conditioning is an important area which has great expectations in the near future.

This study focus in the development of an efficient and economically acceptable continuous solar-powered air conditioning system. Performance tests of the system were carried out during July to September 2004. The system employed a new design of solar-powered adsorption chiller and it was used to chill the headspace of a grain bin in Jiangsu Province, China.

2. System design and operation description

2.1. The components of the system

Fig. 1 shows the schematic layout of the studied solar-powered air conditioning system and Fig. 2 shows a photograph of the facilities. The solar cooling system includes a solar-powered water heating system, a silica gel–water adsorption chiller, a cooling tower and a fan coil unit. No auxiliary heat source was provided in order to reduce costs. The characteristics of the main components are detailed below.

2.1.1. Solar-powered water heating system

The solar heating unit consists of 49.4 m² of all-glass evacuated tube solar collectors, a 290 W water pump and 0.6 m³ partitioned hot water tank. The water pump was switched on and off by a differential temperature controller, and it works independently of the adsorption chiller operation. In the early morning of summer sunny days, valve 12 and it was used to chill the headspace of a grain bin in Jiangsu Province, China.
was kept open, and valve 13 was closed. The upper portion of the water inside the tank was quickly heated by the energy absorbed from the solar collectors and it could be used to regenerate the bed of the adsorption chiller. When the temperature of the water in the upper part of the tank exceeded 70°C, valve 13 was opened and the whole tank was used as heat reservoir for the adsorption chiller. Such a design allowed the operation of the adsorption chiller to start as early as possible in the morning.

2.1.2. Adsorption chiller

Boelman et al., 1995 mentioned that silica gel–water is a suitable adsorption pair to be regenerated by low-grade heat sources. Since the available hot water temperature from a solar-powered water heater is between 60 and 90°C, this pair is employed in the adsorption chiller. The adsorption chiller (shown in Fig. 1) includes two identical adsorption units and a second stage evaporator with methanol as working fluid (Wang, in press). Each adsorption unit consists of one adsorber, one condenser and one evaporator/receiver (the first stage evaporator), which are housed in a chamber to simplify the chiller construction and to enhance the mass transfer of the water vapor. The adsorber is a compact tube-fin heat exchanger with refrigerant mass transfer channels, filled with about 50 kg of micro-porous silica gel, and enclosed in a metallic chamber. The upper and bottom surfaces of the metallic chamber are constructed with metal meshes to facilitate the refrigerant mass transfer. The two condensers, similar to tube and shell heat exchangers, are connected in series. There is a second stage evaporator under the two first stage evaporators, as shown in Fig. 1, which is not found in the conventional two-adsorber refrigeration systems. During the operation of the adsorption chiller, the chilled water releases heat to the liquid methanol that evaporates in the second stage evaporator. The vapor is condensed on the surface of the first stage evaporator of the adsorption unit, which is running under the adsorption phase, and drops back to the bottom of the second stage evaporator. In this way, the heat from the chilled water is transferred indirectly to the refrigerant inside the adsorption unit. As can be seen in Fig. 1, there are three flow circuits in the adsorption chiller, namely: hot water, cooling water and chilled water circuits. Each of them contains a water pump. The rated powers of the three pumps are 250 W, 370 W and 120 W, respectively.

2.1.3. Cooling tower and fan coil unit

A cooling tower, which has an axial flow fan with 250 W of rated power, is utilized as heat sink for the adsorption chiller.

The heat from the grain bin is transferred to the adsorption chiller through a fan coil unit. An air damper is employed to control the temperature of the air leaving the fan coil. A centrifugal fan with 750 W of rated power is used in the fan coil unit, due to the size of the grain bin.

2.1.4. Instrumentation and data acquisition

A number of sensors and instruments are utilized to acquire the data necessary to evaluate the performance of the solar adsorption chiller (see Fig. 1). A pyranometer (TBQ-2 Type) with an accuracy of ±2% is used to measure the solar radiation on the surface of the collectors. The temperature measurements are performed with platinum resistors (PT100) with an accuracy of ±0.2°C. Turbine flow meters are used to measure the water flow rate of each pump. The pyranometer, hygrometers, flow meters and temperature sensors are connected to a Keithley 2700 multi-meter/data logger. A RS232 bus is used as the communication link between the latter and the computer.

2.2. The adsorption cycle

2.2.1. Continuous adsorption cycle with heat and mass recovery

The advantages of mass recovery have been demonstrated in previous literatures (Pons and Poyelle, 1999; Wang, 2001). With the aid of a vacuum valve (V11) and eleven water valves (V0–V10), the adsorption chiller can be operated under a continuous refrigeration cycle with heat and mass recovery between two adsorbers. The operation scheme is listed in Table 1. Differing from the conventional two-adsorber heat recovery process, in this chiller, the heat recovery only last while the resident hot water inside the adsorber, that started to be cooled, was being pushed into the other adsorber by the cooling water. Hence, the heat recovery time is determined by the flow rate of the cooling water. A programmable logic controller is used to control the on/off state of all valves.
Evaluation of the performance of the solar-powered adsorption chiller

3.1. Performance indexes

The cooling power ($Q_c$) and the specific cooling power per collector area (SCP) are calculated by the following two equations, respectively:

$$Q_c = \dot{m}_{cw} C_{pw} \left( T_{cw-in} - T_{cw-out} \right)$$

$$SCP = \frac{\dot{m}_{cw} C_{pw} \left( T_{cw-in} - T_{cw-out} \right)}{A_c}$$

The cooling coefficient of performance (COP) during one cycle is defined as:

$$COP_{cycle} = \frac{\int \dot{m}_{cw} C_{pw} \left( T_{cw-in} - T_{cw-out} \right) dt}{\int \dot{m}_{hw} C_{pw} \left( T_{hw-in} - T_{hw-out} \right) dt}$$

The solar cooling COP of the system ($COP_{solar}$) is assumed to be the ratio between the useful cooling output in the second stage evaporator (cooling load) and the total incident solar energy on the surface of the solar collectors.

$$COP_{solar} = \frac{\int \dot{m}_{cw} C_{pw} \left( T_{cw-in} - T_{cw-out} \right) dt}{\int A_c I dt}$$

The electrical COP was calculated by

$$COP_{electric} = \frac{\int \dot{m}_{cw} C_{pw} \left( T_{cw-in} - T_{cw-out} \right) dt}{\int \sum P_{electric} dt}$$

where $\int \sum P_{electric} dt$ is the electric power consumption of the four water pumps and the cooling tower fan.

4. Results and discussions

4.1. All-glass evacuated tube collector

The efficiency of the all-glass evacuated tube collectors employed in this system have excellent high temperature thermal performance.

4.2. Adsorption chiller COP and cooling power

The flow rates of all water circuits and the cycle time were kept constant to improve the reliability and to simplify the operation of the chiller. The operation parameters for this adsorption chiller are listed in Table 2. The cooling performance of the chiller according to the hot water inlet temperature is presented in Fig. 4. The hot water temperature required to regenerate the adsorption chiller is between 70 and 90 °C, which can be achieved by the solar water heating system.

During test days, the chiller began to run in the morning when the water temperature in the upper part of the partitioned hot water tank exceeded 68 °C. The outlet temperature of chilled water was controlled to be within 12–18°C.

Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating/cooling time (s)</td>
<td>900</td>
</tr>
<tr>
<td>Mass recovery time (s)</td>
<td>60</td>
</tr>
<tr>
<td>Heat recovery time (s)</td>
<td>40</td>
</tr>
<tr>
<td>Hot water flow rate (m³/s)</td>
<td>0.001</td>
</tr>
<tr>
<td>Cooling water flow rate (m³/s)</td>
<td>0.0014</td>
</tr>
<tr>
<td>Chilled water flow rate (m³/s)</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

Fig. 3. Instantaneous efficiency of the all-glass evacuated tube collector.
The chiller stopped running in the afternoon when the water temperature in the upper part of the partitioned hot water tank was below 65 °C. Typical daily performance of the chiller is presented in Table 3. The solar-powered water heater could supply hot water to the adsorption chiller for about 6.5–8.5 h during the sunny day. The chiller gave an average SCP between 66 and 90 W/m² with a solar cooling COP ranging from 0.096 to 0.13. According to Hao et al. (2001), the COP of a conventional chiller used for grain cooling in China is about 1.5–2.1. As shown in Table 3, the electrical COP of the solar-powered adsorption chiller is far higher than that of a mechanical compression chiller.

4.3. The cooling of the grain depot with the solar-powered system

In most grain depots of China, during cold winters, the stored grains are cooled thoroughly to below 5 °C by mechanical ventilation with ambient air. During hot seasons, the middle and bottom grain layer temperatures in the bin are usually maintained below 15–20 °C. However, in the upper layer, the grain temperature increases quickly; even exceeding 32 °C in some hot areas, and to maintain this temperature between 15 and 20 °C is one of the key problems in the grain storage (Zhou et al., 2002).

At present, the usual method for dealing with this problem is to employ mechanical vapor compression refrigerators to cool the stored grain to below 14 °C in a short time. The temperature is reduced by blowing chilled air inside the bin when the temperature of the top layer of the grain exceeds a certain value. The ambient air is first cooled and dehumidified to avoid condensation of moisture in the grain stack, and then reheated to a suitable temperature before enters into the bin. Hence, the energy consumption is relatively high and the system COP is relatively low. Moreover, ventilation with dry and cold air may lead to the loss in the grain quality.

A different approach to this problem could be the cooling of only the headspace inside the bin. The cold air above the upper layer of grain may inhibit the increase of its temperature.

In the experiments, the air from the headspace of the grain bin was cooled by the fan coil unit and then distributed into various ventilation pipes, which are shown in Fig. 5. The experiments were carried out from July 28 to
September 30 of 2004. To avoid condensation of moisture on the grain surface, the temperature difference between the inlet and outlet air of the fan coil unit was controlled, by regulating the opening of the damper, to be within 8 °C.

**Fig. 6** shows the variations of ambient temperature (\(T_{am}\)), headspace and grain upper layer temperatures in the chilled grain bin (\(T_{a-test}\) and \(T_{tg-test}\), respectively). The corresponding temperatures in a similar grain bin without cooling (\(T_{a-check}\) and \(T_{tg-check}\), respectively) are shown in the same figure to allow a comparison. The results in both bins were obtained during the same test day. Although the ambient temperature was quite high, the headspace temperature was lower than the grain upper layer temperature in the chilled bin during most of the time. **Fig. 7** shows the variations of the grain upper layer temperature inside the bin during the whole experimental period. It can be seen that the increase of the grain upper layer temperature could be effectively inhibited during hot seasons by cooling the grain bin headspace with the solar-powered adsorption chiller. If the adsorption chiller starts to run before the grain upper layer temperature rises to above 15 °C, the temperature can be maintained to about 15–20 °C during the whole year in most of the areas in China.

### 5. Conclusions

A solar-powered adsorption air conditioning system with heat and mass recovery processes between the absorbers was built and put into experimental operation to inhibit the temperature increase of grain inside a storage bin. The following conclusions can be drawn based on the test results:

1. The solar-powered adsorption chiller had an average SCP between 66 and 90 W/m² with a solar cooling COP ranging from 0.096 to 0.13, in the studied conditions. Its performance compares favorably to most of the previous published results.

2. The corresponding electrical COP of the adsorption air conditioning system is between 2.6 and 3.4, which is far higher than that of the usual mechanical vapor compression chillers employed in China to cool grains. The solar-powered adsorption chiller presented in this study was only a demonstration prototype, but if a larger chiller and solar collector array were used, the corresponding electrical cooling COP could be further increased.

3. Cooling the bin headspace with the solar-powered adsorption chiller during hot seasons could inhibit the temperature increase of the grain upper layer inside the bin. Thus, this kind of solar adsorption air conditioning system could be considered as an alternative for low-temperature grain storage in most of the areas of China.

Up to August 2006, there are four such systems installed in China and it is confirmed that such systems are acceptable for grain storage.

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