Study on Hybrid of Solar Powered Water Heater and Adsorption Ice Maker

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Abstract

Based on the vacuum tube type solar collector, a system of hybrid solar powered water heater and adsorption ice maker was designed and a prototype was built. Energy analysis of the hybrid system was presented, and the prototype was experimental tested in different season. The results of analysis and experiment show that, compared with the traditional solar powered water heater and cooling machine, the hybrid system is more suitable for household usage.

Keywords: solar energy; adsorption refrigeration; water heater

Introduction

The utilization of solar energy is a major characteristic of modern “green building”, it is concerned by scientists around the world and some progress is made. There exist two types of solar collector: photovoltaic cell and purely thermal collector, the latter is more common in the application of solar energy. Based on the purely thermal collector, solar powered heating and cooling system of building are developed, some products are used.

The technology of solar powered heating system is developed successfully, it is widely used in solar powered water heater. The product of solar powered water heater is popularly used in China, nearly 10% of water heaters in China is powered or partly powered by solar energy, the percentage is still increasing quickly. The solar powered water heater has advantages of environmental friendliness and energy conservation, but it has some disadvantages. The main disadvantage of it is that the supply of solar energy and the need of heated water do not agree with each other in the same season. In summer, the supply of solar energy reaches maximum level, but the need of heated water is minimum, in winter, it is in the opposite situation. So the utilization of solar energy of water heater is not sufficient.

The technology of solar powered cooling system is developed too. It is an excellent application of solar energy, because the supply of solar energy and the need of refrigeration both reach maximum level in the same season (summer), and the utilization of solar energy is sufficient in that season. Liquid absorption system has been proposed and tested at first, solid adsorption system is researched and tested latter. One characteristic of solid adsorption system is that there is no need of rectifying column, so it has advantages of simple construction, no-moving parts and no-noise. On the other hand, non-freon refrigerant is used in adsorption refrigeration, so it is environmental friendly. Worsoe-Schmidt has developed adsorption solar refrigerator which has been used in many countries of Africa. The main shortcoming of adsorption solar refrigeration system is that its operation is limited by weather conditions. So the solar powered cooling machine could only be used seasonal, that is to say, it is expensive compared with the cooling machine which can be used in the whole year. Requirements for cooling and heating of household are dissimilar in different season. Purely solar powered heating or cooling machine could not meet those requirements.

The work described below is to combine the solar powered water heater and adsorption refrigeration machine, to meet the requirements of household in different season, and to improve the efficiency of utilization of solar energy.

Hybrid of Solar Powered Water Heater and Adsorption Ice Maker

Vacuum tube is widely used as collector in solar powered water heater. The technology of vacuum tube type collector is mature, absorb rate of glass vacuum tube is more than 93%, and thermal radiation rate at 100°C is less than 6%, its temperature when exposed to sun without water can reach 250°C, temperature of water in the collector can reach 98°C easily by adjusting the quantity of water in it. Water at that temperature can be used as heat source of adsorption refrigeration system.

According to above discussion, a hybrid of solar powered water heater and refrigerator is designed. The
schematic of system is shown in Figure 1. It is just a combination of a solar water heater and an adsorption refrigerator. Heating of the vacuum tube type solar collector is started in the morning, water in the solar collector is heated slowly. When temperature of water in the collector is 5-7°C over than that in the storage tank, the water circulation pump works to pump up cold water in the tank into the collector, warm water in the collector flows through the adsorber, goes back into the storage tank. When the warm water flows through, the adsorber is heated, temperature of the adsorbent in it rises. In an ideal process, temperature of the adsorbent could be very close to the maximum temperature of water in the tank at last. When temperature in the adsorbent rises up to the reaction temperature of desorption, the refrigerant is desorbed from the adsorbent, and the vapor pressure in the adsorber rises too. When the pressure reaches the condensing pressure, the desorbed refrigerant vapor is condensed in the condenser and collected in the receiver. At night, with the reduction of ambient temperature, the adsorber is cooled by nature convection, temperature of the adsorbent in it is reduced, and pressure in the adsorber drops to value below the evaporation pressure, evaporation begins, ice is made slowly in the refrigeration box. Refrigeration will continue for the whole night until the next morning.

**Energy Analysis**

Solar energy absorbed by the collector will be used in three way\(^{(3)}\): (1)\(Q_u\) energy to heat the water in storage tank and adsorber. (2)\(Q_s\) energy storage in the collector. (3)\(Q_l\) energy lost due to various losses. The energy conservation equation is:

\[
A_e G(\tau \alpha) = Q_u + Q_s + Q_l
\]  

Where \(G\) is the solar flux density to the collector, \(\tau\) is the transmittance of solar radiation through the cover of the collector, \(\alpha\) is the collector efficiency, \(A_e\) is the area of the collector.

For a solar collector, the heat quantity \(Q_u\) is used to heat the water and adsorber, which is mainly determined by the efficiency of collector; the heat quantity \(Q_s\) is determined by the sensible heat of collector and depends on the collector material; \(Q_l\) is the heat losses composed of the face loss, the bottom loss, the four sides loss of collector and the loss of heat exchange in the adsorber when warm water flows through the adsorber (this loss does not exist in purely solar water heater).

The useful heat from the collector \(Q_u\) contributes both to the heating of the water in the tank and to the heating of the adsorber which will cause the desorption of refrigerant from the adsorbent bed. The energy equation is:

\[
Q_u = M_{water} C_{water} (T_h - T_l) + (M_m C_m + M_a C_a) (T_h' - T_0) + M_R C_R (T_e - T_0) + H_R M_R
\]

In which the first term represents the heat added to the water in the storage tank, \(M_{water}\) – mass of water in tank, \(C_{water}\) – specific heat of water, \(T_h\) – the last temperature of water after heating, \(T_l\) – temperature of city water; the second term represents the sensible heat of material and adsorbent in adsorber, \(M_m\) – mass of adsorber material, \(C_m\) – specific heat of material, \(M_a\) – mass of adsorbent, \(C_a\) – specific heat of adsorbent, \(T_h'\) – the last temperature of adsorber after heating, \(T_0\) – ambient temperature; the third term represents the sensible heat of refrigerant in adsorber, \(M_R\) – mass of refrigerant in adsorber, \(C_R\) – specific heat of refrigerant, \(T_e\) – critical temperature of reaction; term 4 is the heat of desorption, \(H_R\) – heat of adsorption per kilogram.
The desorbed refrigerant is condensed in the condenser and flows into the evaporator. When pressure in the adsorbent bed is lower than the evaporation pressure, the refrigerant liquid in the evaporator will evaporate which causes the refrigeration effect. The refrigeration quantity is:

\[ Q_{\text{ref}} = M_R L_e \]  

where \( L_e \) is the latent heat of refrigerant vaporization.

Refrigeration cycle \( COP \) can be defined as:

\[ COP_{\text{cycle}} = \frac{Q_{\text{ref}}}{Q_g} \]  

where \( Q_g \) is the heat absorbed by the adsorber, which is shown as:

\[ Q_g = Q_u - Q_{\text{water}} = ( M_{\text{m}} C_{\text{m}} + M_{\text{c}} C_{\text{c}} ) ( T_h - T_0 ) + M_R C_R ( T_e - T_0 ) + H_e M_R \]

In which \( Q_{\text{water}} = M_{\text{water}} C_{\text{water}} ( T_h - T_e ) \)

The hybrid system has two useful output, one is refrigeration, its system \( COP \) (solar efficiency) is:

\[ COP_{\text{system}} = \frac{Q_{\text{ref}}}{A_g G(\tau a)} \]  

The other is heating the water in the storage tank, its system efficiency (solar efficiency) is:

\[ \eta_{\text{system}} = \frac{Q_{\text{water}}}{A_c G(\tau a)} \]

**Experimental Results**

A prototype of hybrid system for water heating and ice-making has been developed. The solar energy collector is consisted of 30 \( \phi 47 \times 1 \times 1200 \) glass vacuum tubes whose collect area of solar energy is 4.2 \( \text{m}^2 \). \( \text{SrCl}_2 - \text{NH}_3 \) is used as working pair of adsorption refrigeration (\( \text{SrCl}_2 \) is used as the adsorbent, and \( \text{NH}_3 \) is used as refrigerant \(^{3)} \), structure of adsorber adopted by this paper is shown in Fig 2. It is made up of unit generating tubes. Configuration of unit generating tube is shown in Fig 3. Unit generating tube is made up of aluminum fin in which \( \text{SrCl}_2 \) is filled, ammonia-conducted tube and stainless steel tube. Ammonia-conducted tube is the passage of ammonia vapor flowing into/out generating tube, and stainless steel tube is a heat exchanger in which heat exchange is conducted when warm water is flowing.

The prototype was built in Changsha, a city in south China, it was installed on the roof of a five-storied building. A typical experiment was demonstrated at the end of August, 2000. Overall insolation was measured by a pyranometer parallel to the collector. Temperatures of water in tank, inlet and outlet of adsorber and temperature of evaporator were measured by thermocouple, ambient temperature, temperatures of city water and adsorber were measured also. Weight of the removed ice can be determined as the last quantity of refrigeration. The sun began shining normally at 7:00 am, the initial temperature of water was 18\(^\circ\)C, the initial temperature of adsorber was 32\(^\circ\)C (the same temperature as environment), after 6 hours, temperature of water in the tank reached 85\(^\circ\)C, temperature of the adsorber reached 80\(^\circ\)C, temperature of water inlet the adsorber was 91\(^\circ\)C, the desorption process began obviously. After 5 hours continuously heating, temperature of water in the tank reached maximum value, 93\(^\circ\)C, temperature of water inlet the adsorber was 98\(^\circ\)C, temperature of the adsorber was nearly 90\(^\circ\)C. Heating and desorption stopped at that time (6:00 pm). Total solar heat density was 20 \( \text{MJ} / \text{m}^2 \), that is to say, about 84 \( \text{MJ} \) solar heat was collected. At night temperature of the adsorber reduced slowly, at about 11:00 pm, the temperature reduced to 28\(^\circ\)C, adsorption took place. 1 hour later, temperature of the evaporator reduced to -15\(^\circ\)C, ice was made obviously at 6:00 pm. Total solar heat density was 20 \( \text{MJ} / \text{m}^2 \), that is to say, about 84 \( \text{MJ} \) solar heat was collected. At night temperature of the adsorber reduced slowly, at about 11:00 pm, the temperature reduced to 28\(^\circ\)C, adsorption took place.

Here \( COP_{\text{system}} \) and \( \eta_{\text{system}} \) defined by (6), (7) were 0.069 and 0.67, \( COP_{\text{cycle}} \) defined by (5) was 0.21. At similar weather condition, \( COP_{\text{system}} \) of the same solar powered water heater system without refrigerator was 0.72. \( COP_{\text{system}} \) of other kinds of solar power adsorption refrigerator varied from 0.05 – 0.12\(^{\dagger}\).

Table 1 shows the experimental result discussed above and another experimental result of hot water and ice output in a typical season (summer). Obviously with the reduction of collected solar energy, system efficiency of heating and cooling become smaller. The value of refrigeration efficiency (COP) reduces more relatively. On the other hand, system efficiency without adsorption refrigerator is almost not changed. It is due to poor heat transfer in the adsorber. Technology of heat transfer enhancement should be adopted in the adsorber in order to improve the efficiency of refrigeration. But generally, the results of refrigeration is acceptable. The refrigeration quantity produced after one day operation can be used to keep a 100 liter cold box for more than 48 hours with temperature less than 5\(^\circ\)C.

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\( \text{Fig. 2. Schematic of Adsorber (cross – section)} \)

\( \text{Fig. 3. Schematic of Unit Generating Tube} \)
Table 1. Experimental Results of the Hybrid System

| Date          | Energy Collected (MJ) | Hot water Output °C | Ice out kg | \( COP_{\text{system}} \) | \( COP_{\text{cycle}} \) | \( \eta_{\text{system}} \) without refrigerator |
|---------------|-----------------------|----------------------|------------|---------------------------|--------------------------|-----------------------------------------------|
| Aug. 23-24, 2000 | 84                    | 93                   | 180        | 11.6                      | 0.069                    | 0.21                                          | 0.67                                          | 0.72                                          |
| Oct. 15-16, 2000 | 63                    | 92                   | 120        | 8.0                       | 0.064                    | 0.163                                         | 0.61                                          | 0.70                                          |

Conclusions

1) The hybrid system of solar powered water heater and refrigerator uses one solar collector as heating and refrigeration source, it is suitable for household application.

2) The adsorber is separated from the collector, thus high efficiency glass vacuum tube can be used for solar energy collection. The adsorber is also separated from the water tank\(^3\), thus the refrigeration quantity is not influenced by the consumption of hot water. It can meet different household requirements for heating and cooling in different season.

3) Compared with purely solar powered water heater and refrigerator, the system efficiency of heating and cooling is lower\(^1\), but the hybrid system has two useful output, so the level and efficiency of solar energy utilization are higher.

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