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Performance investigation of a solar hot water driven adsorption ice-making system

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ABSTRACT

A solar hot water driven solid adsorption ice-making system with heat storage was designed and constructed. The finned-tube absorbent bed in the water tank, which also acted as heat storage unit, was heated by the hot water from the solar vacuum tube collector in desorption process. The water in the tank was also auxiliary heated by electric heater to keep at the set desorption temperature. Activated carbon–methanol was utilized as the working pairs in the system. Effects of heat source temperature on system performance were experimentally investigated under four conditions: maintaining the water temperature in the tank at 94 °C (boiling point), 85 °C, 75 °C, respectively, and heating the water to reach 94 °C then naturally cooling the hot water without maintaining heating in desorption process. The experimental results showed that the temperatures around the finned-tube of the adsorbent bed was homogeneous, which was beneficial for desorption of the adsorbate. The maximum daily ice-making capacity of 8.4 kg and the lowest temperature of −8.6 °C were achieved when the hot water temperature was maintained at 94 °C. The maximum refrigeration cycle coefficient of performance (COP) of 0.139 was obtained under the condition of heating the water to reach 94 °C then cooling naturally the hot water without maintaining heating. The system heat utilization efficiency decreased with the increase of heat source temperature due to the greater heat loss in desorption process.

1. Introduction

With development of human society, the increasing energy needs and environmental crisis are attracting great attention across the world. The requirements for air conditioning and refrigeration consume a large quantity of conventional energy resources and often lead to power shortage in peak period, especially in summer. Solar energy is a clean energy, and its total quantity is approximately infinite [1]. Moreover, the summer, which demands the greatest cooling capacity, is usually the season with the strongest solar radiation [2]. The abundant solar radiation resources in summer could meet the great energy consumption demand for refrigeration in this season. Therefore, development and utilization of solar energy in refrigeration field were of great practical significance. Solar refrigeration technology includes mainly the solar-driven ejector refrigeration, the solar absorption refrigeration and the solar adsorption refrigeration. All these technologies utilize environmental friendly refrigerant and do not employ compressor, thus these systems have low noise in operation. To promote the system coefficient of performance (COP) is the common objective for these solar-driven refrigeration technologies. Solar absorption refrigeration technology was developed early, and was relatively mature now. Its system volume and cooling capacity were ordinarily large, thus was suitable for central cooling in large scale buildings. Lithium bromide was usually used as refrigerant in solar absorption refrigeration system. However, lithium bromide was easy to crystallize, and lithium bromide solution has strong corrosion to general metals, which would shorten the system lifetime. In addition, the solar absorption refrigeration system could only provide cooling capacity above 0 °C. Solar-driven ejector refrigeration system adopted ejector to replace compressor in traditional refrigeration system, and produced cooling capacity by liquid evaporation. The low system performance was the main problem for such system. Steam jet refrigerator with water as the working fluid could not produce ice too. Current studies on ejector refrigeration technology focused on structure optimization of the ejectors, performance improvement of the working medium, and sustaining performance under unstable solar irradiation. Combination of ejector refrigeration and absorption/adsorption refrigeration was an effective way to promote performance of the ejector refrigeration system.

The earliest experiment on adsorption refrigeration was conducted in 1848. When ammonia was adsorbed by silver chloride,

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Nomenclature

A_{SC}	surface area of solar vacuum tube collector (m^2)
C_{water}	specific heat of water J/(kg K)
COP_{cycle}	coefficient of performance of the refrigeration cycle
M_{water1}	the mass of water in solar vacuum tube water heating system (kg)
M_{water2}	the mass of water in water tank (kg)
M_{water_los}	mass of the evaporated water (kg)
$I(t)$	solar radiation intensity (J/m^2 S)
q_{water_los}	evaporating latent heat of water (J/kg)
Q_{cc}	sensible heat given off by the refrigerant liquid (J)
$Q_{electric}$	heat supplied by the electric heater (J)
Q_{e_ice}	refrigeration quantity for ice in ice box from initial temperature (in liquid phase) to final temperature, including sensible heat and latent heat (J)
Q_{e_water}	refrigeration quantity for remaining water in ice box from initial temperature to final temperature (J)
Q_{e_M}	sensible heat of the metal evaporator from ambient temperature to final temperature (J)
Q_{e_L}	cooling quantity loss of the ice box (J)
Q_g	heat for regeneration of adsorbent bed (J)
Q_I	total solar radiation incident to the collector (J)
Q_{ref}	refrigeration quantity (J)
Q_u	all heat to the adsorber (J)
Q_{water1}	sensible heat to heat the water in solar vacuum tube water heating system (J)
Q_{water2}	heat obtained by the water in water tank (J)
Q_{water_eva}	latent heat of the evaporated water into ambient
T_a	ambient temperature (°C)
T_c	condensing temperature (°C)
T_e	evaporating temperature (°C)
T_g	generating temperature (°C)
η_{SC}	collection efficiency of solar water heating system (%)
η_{system}	system heat utilization efficiency (%)

the cooling effect was produced. In 1920s, Hulse proposed a refrigeration system with silica gel–sulfur dioxide as working pairs [3]. In 1960, Plank and Kuprianoff utilized activated carbon–methanol as refrigeration working pairs [4]. In 1978, Tchernev in American Zeolite Power Company developed the first solar-powered intermittence adsorption refrigeration equipment with zeolite–water as the working pairs [5]. Critoph [6] and Meunier [7] compared the performance of activated carbon–methanol (water) and molecular sieve–water (methanol) in adsorption refrigeration systems, and concluded that the activated carbon–methanol had a higher cooling efficiency when the desorption temperature was below 150 °C. Wang used different silica gel samples as adsorbates, and found solid particulate pollution deteriorated greatly the adsorption capacity [8]. Jiang developed successfully $CaCl_2$–NaBr–NH_3 working pairs for two-stage chemisorption freezing cycle driven by low temperature heat source [9].

In 1997, Wang [10] prepared an activated carbon fiber adsorbent, with cooling capacity 2–3 times higher than that of the regular activated carbon. The adsorption/desorption time was shorten to 1/10 of that with the regular activated carbon. Since then, developing novel composite adsorbent with high thermal conductivity became a research focus. In 2012, Wang [11] demonstrated a consolidated composite activated carbon with higher thermal conductivity and thermal diffusivity. In 2014, Jiang [12] investigated a consolidated composite $CaCl_2$ with a matrix of expanded natural graphite treated with sulfuric acid. The composite had very perspective heat and mass transfer performance. Compared with zeolite molecular sieve, the foamed aluminum composite resulted in shorter cycle period and higher COP [13]. By utilizing calcium chloride/expandable graphite composite adsorbent, the average heat transfer coefficient of the system in process of cooling and heating increased by 265% and 300% respectively [14]. Lu [15] did experimental research on adsorption chillers using micro-porous silica gel–water and compound adsorbent–methanol. Li [16] studied the adsorption performance of composite adsorbent of $CaCl_2$ and expanded graphite with ammonia as adsorbate.

Another important way for improving performance of solar adsorption refrigeration system was to enhance heat and mass transfer in the adsorbent bed. Hong [17] built a fin-tube type adsorption chiller and found that the fin thickness and the hot water temperature were the dominant parameters for COP and SCP. Leite [18] designed a copper tube solar powered adsorption refrigeration system using the transparent honeycomb material kneading board. The daily ice-making capacity was 7–10 kg/(m^2 d). Hildrand [19] developed a metal tube adsorbent bed and the solar cooling COP was between 0.10 and 0.25. Bao [20] presented a small refrigerator based on resorption technique to utilizing low grade thermal energy. CPC collectors were also adopted to improve the system performance [21,22]. Hassan [23] and Jribi [24] simulated and improved the adsorption refrigeration cycle. Lu [25] developed a novel solar silica gel–water adsorption air conditioning and analyzed its performance. Hamdeh [26] optimized solar adsorption refrigeration system by experimental and statistical techniques. However, the flat plate collector, which was usually adopted as heat collecting unit of solar solid adsorption refrigeration system, inevitably resulted in the inhomogeneous heating on the adsorbent bed.

In this paper, the proposed solar adsorption refrigeration system employed activated carbon–methanol as working fluid, which was noncorrosive and had stable performance under 0 °C. The heat collected by vacuum tube was stored in water bath, and provided stable energy input for the adsorbent bed at the desorption stage. The adsorbent bed consisted of large-diameter aluminum-alloy finned tubes with excellent heat and mass transfer performance and was kept in water bath. Thus temperature around the adsorbent bed was homogeneous, beneficial to sorption/desorption of refrigerant. The performance experiments of the solar hot water driven adsorption ice-making system were conducted.

2. System descriptions

The schematic diagram of a solar hot water driven solid adsorption ice-making system with heat storage was shown in Fig. 1. The system consisted of solar collector, adsorbent bed, condenser, evaporator, vacuum valves, vacuum pressure gauge, circulating water pumps and electric heater. Solar radiation projected on the solar collector in the daytime and the water temperature in solar water heating system rose. The adsorbent bed in water bath was heated by the hot water, which was pumped from solar water heating system to the water tank at the beginning of desorption process. With increasing of the adsorbent bed temperature, the refrigerant was gradually desorbed from the adsorbent in the adsorbent bed. When the vapor pressure of refrigerant in the adsorbent bed reached the condensing pressure, the vacuum valve was opened. Then refrigerant vapor was condensed and flowed into the evaporator. The electric heater was also utilized to