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Experimental investigation and theoretical analysis of the solar adsorption cooling system in a green building

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Abstract

A solar adsorption cooling system was constructed in the green building of Shanghai Institute of Building Science. The system consisted of evacuated tube solar collector arrays of area 150 m^2, two adsorption chillers with nominal cooling capacity of 8.5 kW for each and a hot water storage tank of 2.5 m^3 in volume. A mathematical model of the system was established. According to experimental results under typical weather condition of Shanghai, the average cooling capacity of the system was 15.3 kW during continuous operation for 8 h. The theoretical analysis of the system was verified and found to agree well with the experimental results. The performance analysis showed that solar radiant intensity had a more distinct influence on the performance of solar adsorption cooling system as compared with ambient temperature. It was observed that the cooling capacity increased with the increase of solar collector area, whereas, solar collecting efficiency varied quite contrary. With the increase of water tank volume, cooling capacity decreased, while, the solar collecting efficiency increased. The system performances can be enhanced by increasing the height-to-diameter ratio of water tank. Additionally, it was observed that solar collecting efficiency decreased with the increase of the initial temperature of water in the tank; however, cooling capacity varied on the contrary. Also can be seen is that optimum nondimensional mass flow rate is 0.7 when the specific mass flow rate exceeds 0.012 kg/m^2 s.

Keywords: Solar energy; Adsorption cooling system; Performance analysis

1. Introduction

Solar cooling has been an attractive application for solar energy because of the near coincidence of peak cooling load with the available solar power. According to the main results of the EU project solar air-conditioning in Europe (SACE), Balaras et al. showed that solar air conditioning had a strong potential for significant primary energy savings. In particular, for southern European and Mediterranean areas, solar assisted cooling systems could lead to primary energy savings in the range of 40–50%. Related cost of saved primary energy lay at about 0.07 €/kWh for the most promising conditions [1].

The majority of solar cooling systems at present are solar absorption and solar adsorption cooling systems, which are based upon solar thermal utilization. Compared with the existing absorption systems, adsorption systems allow for somewhat lower driving temperatures but have a somewhat lower COP under the same conditions. The simplicity of the process, the wide range of driving temperatures and other advantages such as noiseless operation could lead to a large number of small solar assisted air-conditioning applications [1,2]. Tsoutsos et al. reported that the combination of an adsorption chiller with solar collectors offered a technically simple and energy saving solution [3].

Because of the intermittent nature of solar energy, intermittent adsorption refrigeration cycles have long been considered as logical approaches to solar cooling systems [4]. Therefore, up to now, the solar-powered adsorption

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Nomenclature

A	area (m^2)
COP	coefficient of performance
C_p	specific heat of water (J/kg °C)
$D1$	duration of the solar collecting system operation (s)
$D2$	duration of the adsorption chillers operation (s)
$D3$	working time (s)
F_i^C	collector control function
F_i^L	load return control function
I	solar radiant intensity ($W\,m^{-2}$)
m	mass flow rate ($kg\,s^{-1}$)
P	pressure (Pa)
Q	heat quantity (kW)
T	temperature (°C)
U	heat loss coefficient (W/m^2 °C)
Δm	net flow between nodes ($kg\,s^{-1}$)
Δx	distance between nodes (m)

Greek symbols

ρ	density of water ($kg\,m^{-3}$)
η	solar collecting efficiency

Subscripts

a	ambient
average	daily average
c	solar collector
chill	chilled water
co	cooling water
hp	heat pipe evacuated tubular solar collector
hw	hot water
i	node
o	outlet
se	section
si	side
ta	tank
U	U-type evacuated tubular solar collector
w	water

systems have mostly been intermittent and used only for ice making application. For applications such as air conditioning, two or more adsorption beds can be used to produce a cooling effect continuously.

Presently, both theoretical and experimental investigations were mainly based upon performance of adsorption chillers. Khattab developed a mathematical model to simulate and optimize the performance of a solar-powered adsorption refrigeration module with the solid adsorption pair of charcoal and methanol [5]. Saha et al. have analyzed a dual-mode silica gel–water adsorption chiller which utilized effectively low-temperature solar or waste heat sources of temperature between 40 and 95 °C. Two operation modes were possible for the advanced chiller. The first operation mode would be to work as a highly efficient conventional chiller where the driving source temperature was between 60 and 95 °C. The second operation mode would be to work as an advanced three-stage adsorption chiller where the available driving source temperature was very low (between 40 and 60 °C). Simulation results showed that the optimum COP values were obtained at driving source temperatures between 50 and 55 °C in three-stage mode, and between 80 and 85 °C in single-stage, multi-bed mode [6].

With regard to experimental investigations, Saha et al. have investigated a double-stage, four-bed, non-regenerative adsorption chiller powered by solar/waste heat sources between 50 and 70 °C. The prototype studied produced chilled water at 10 °C and had a cooling power of 3.2 kW with a COP of 0.36, when the heating source and sink had a temperature of 55 and 30 °C, respectively. Flat plate solar collectors could easily produce hot water to regenerate the adsorbent of the chiller at this level of temperature [7]. Liu et al. have developed an adsorption chiller with silica gel–water as the working pair and the system had no refrigerant valves. The elimination of valves reduced the cost of the chiller, and made it more reliable, as there were fewer moving parts, which could otherwise allow air infiltration. The sorption bed of such a chiller could be regenerated by hot water of between 75 and 90 °C. The whole chiller contained 52.8 kg of silica gel divided between two adsorbent beds, which operated out of phase and thus, produced constant cooling. Experiments with the first prototype showed that cooling power of 3.56 kW and COP of 0.26 could be obtained when the mass and heat recovery processes were employed under the follow operation conditions: evaporation temperature of 7 °C; heat sink temperature of 28 °C; and heat source temperature of 85 °C. The chiller was especially suitable for solar cooling systems with evacuated tubular solar collectors as thermal source [8].

For solar-powered adsorption cooling system, Yong et al. have established a lumped parameter model to investigate the performance of a solar-powered adsorption air-conditioning system driven by flat-type solar collectors. Their major contribution was the simplicity and convenience of the model in analyzing the performance of such hybrid systems. The proposed model could predict the dynamic response of adsorption systems well for the given operational conditions [9].

Few reports have been found on comprehensive experimental studies of solar-powered adsorption cooling system. In our previous article, we have introduced the solar integrated energy system for the green building of Shanghai research institute of building science. The design as well as partial experimental results of this system have been presented [10]. However, in the present work, the mathemati-