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Testing of a lab-scale four-bed adsorption heat pump

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HIGHLIGHTS

- We tested the performance of a lab-scaled four-bed adsorption heat pump.
- A maximum *SCP* of 93 W/kg was found at cycle time of 11 min.
- A maximum *COP* of 0.55 was found at cycle time of 35 min.
- The liquid evaporation rate in the evaporator was much smaller than the vapor adsorption rate in the adsorber.

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ABSTRACT

A lab-scale adsorption heat pump with four adsorbers was tested. The core structure of the adsorber is aluminum alloy finned tubes. Water was the adsorbate (refrigerant) and a fine silica gel granule was the adsorbent. At the regeneration temperature of 77.5 °C, a maximum *SCP* value of 93 W/kg silica gel was found. The corresponding optimum cycle time is 11 min and the *COP* value is 0.31. The *COP* value considerably increases with the cycle time. At the cycle time of 35 min, the *COP* value reaches a maximum of 0.54 and the corresponding *SCP* value is 73 W/kg silica gel. In the adsorption process, the evaporation rate of the liquid refrigerant in the evaporator was found to be much smaller than the vapor adsorption rate of the adsorbent in the adsorber. This resulted in a slow adsorption process and thus a descent of the maximum *SCP* value.

1. Introduction

Adsorption heat pump (chiller) has several advantages over conventional vapor-compression air-conditioning system. Firstly, it can use water, which is an environmental friendly substance, as refrigerant. Thus its operation does not cause any negative impact on the environment. Secondly, it can convert low-grade thermal energy (<80 °C) into a cooling effect without consuming a large amount of electricity. This low-grade thermal energy can be solar energy, waste heat in industrial processes or waste heat exhausted by internal combustion engines. Hence, for producing cooling effect, it is an energy-saving device. Due to the above two reasons, in the recent years, many researchers put a lot of efforts into this research subject [1–3].

Zheng et al. [4,5] investigated the effect of operating parameters on the performance of multi-bed adsorption heat pumps. San et al. [6–8] used a solid-side resistance model to analyze the performance of a four-bed adsorption heat pump. Wang et al. [9,10] tested the performance of an adsorption heat pump in which activated carbon and methanol were selected as adsorption pair. Wang et al. [11] experimentally investigated the performance of an adsorption heat pump for heating purposes. Tokarev et al. [12] found that using a composite adsorbent (MCM-41) can largely increase the *COP* value of adsorption heat pump. Aristov et al. [13,14] and Gordeeva et al. [15] investigated sorption characteristics of various composite adsorbents. Freni et al. [16] tested the performance of an adsorber in which finned tubes were coated with a composite adsorbent (SWS-1L). Kubota et al. [17] proposed an adsorber with fin-tube module for enhancing the cooling power and *COP* value of an adsorption heat pump. Hirota et al. [18] tested the performance of an adsorption heat pump incorporated with a mechanical booster pump. Daou et al. [19] theoretically and experimentally investigated the performance of a single-bed adsorption heat pump using a composite adsorbent as adsorbent. Lo et al. [20] analyzed the performance of an ideal single-stage adsorption cooling cycle and a single-effect double-lift adsorption cooling cycle. Wu et al. [21] experimentally and analytically investigated variations of condensing temperature and evaporating

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Nomenclature

ads	adsorption process
c_p	specific heat, J/kg-K
COP	coefficient of performance
$\dot{m}$	mass flowrate, kg/s
p	vapor pressure, kPa
prec	precooling process
preh	preheating process
Q_C	specific condensing heat load per cycle, kJ/kg-cycle
$\dot{Q}_{ch}$	average cooling power of adsorption heat pump, *W*
Q_E	specific cooling capacity per cycle, kJ/kg-cycle
reg	regeneration process
RH	relative pressure (p/p_{sat})
SCP	specific cooling power, W/kg adsorbent
$\bar{T}$	average fluid temperature, °C
$\dot{V}_{cond}$	condensing-water volumetric flowrate, L/min
$\dot{V}_{cw}$	chilled-water volumetric flowrate, L/min
$\dot{V}_{hc}$	hot/cold-water volumetric flowrate, L/min
W	moisture content of adsorbent, kg H_2O/kg adsorbent

temperature in an adsorption cooling module. Grisel et al. [22] successfully developed an adsorption heat pump rated at a cooling power of 3.6 kW by employing automobile plate-fin heat exchangers in the adsorbers. Mahdavikhah et al. [23] analyzed the effect of fin spacing and fin height of a plate-fin type adsorber on the performance of an adsorption heat pump. Lu et al. [24] examined improvement in cooing capacity and *COP* value by arranging a mass and heat recovery process in an adsorption heat pump.

Adsorption heat pump is an attractive device for producing cooling effect. Yet, up-to-date, its development still faces many challenges in order to meet the requirement for commercial applications. Adsorber is the key component in an adsorption heat pump. Previous computer analyses [6–8] reveal that overall heat transfer coefficient, total heat transfer area and heat capacity of adsorbent heating/cooling elements (core structure) are three important factors governing the characteristics of an adsorber. The specific cooling power (*SCP*) and *COP* value of an adsorption heat pump tend to increase with the overall heat transfer coefficient and total heat transfer area, but decreases with an increase of the heat capacity of adsorbent heating/cooling elements. In this work, a lab-scale four-bed adsorption heat pump (Fig. 1) was tested. For enhancing the heat transfer in the adsorbers, finned tubes with a large heat transfer area and a low heat capacity were adopted as the adsorbent heating/cooling elements. In addition to acquiring the *COP* and *SCP* values, the measured data were also expected to yield strategies for improving the performance of the adsorption heat pump.

2. System description

There are seven basic components, including four adsorbers, one evaporator, one condenser and one capillary tube (U tube), in the four-bed adsorption heat pump (Fig. 2). During a cyclic operation, each adsorber consecutively proceeds to four different modes - adsorption, preheating, regeneration and precooling (Fig. 3). The adsorption time and preheating time are arranged the same as the regeneration time and precooling time respectively. But the preheating/precooling time is set to be shorter than the adsorption/regeneration time. The cycle time of the adsorption heat pump equals the sum of the four mode times.

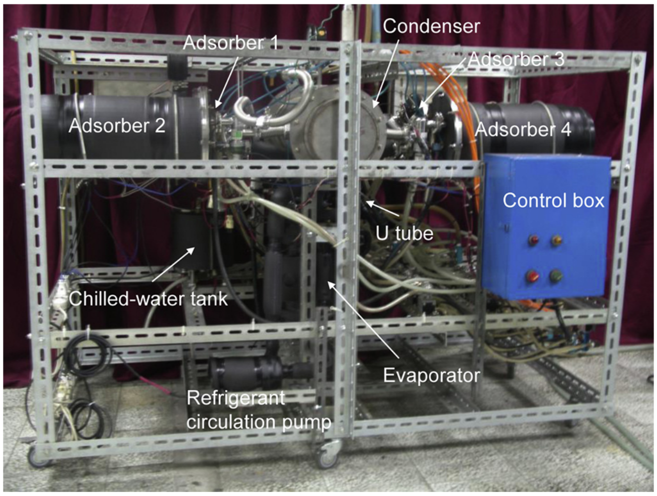

Fig. 1. Configuration of a four-bed adsorption heat pump.

In the beginning of a cycle, valves (1a) and (3b) shown in Fig. 2 are opened and the other valves are closed. Adsorbers (1), (2), (3) and (4) are in the adsorption, precooling, regeneration and preheating modes respectively (Fig. 3). While adsorber (2) accomplishes the precooling mode, adsorber (4) also accomplishes the preheating mode. At this time, valves (2a) and (4b) are opened. Adsorbers (2) and (4) would switch from the precooling and preheating modes to the adsorption and regeneration modes respectively. In the meanwhile, valves (1a) and (3b) remain opened. That means adsorbers (1) and (3) are still in the adsorption and regeneration modes respectively.

While adsorber (1) accomplishes the adsorption mode, adsorber (3) also accomplishes the regeneration mode. At this time, valves (1a) and (3b) are closed. Adsorbers (1) and (3) would switch from the adsorption and regeneration modes to the preheating and precooling modes respectively. In the meanwhile, valves (2a) and (4b) remain opened. Adsorbers (2) and (4) are still in the adsorption and regeneration modes respectively.

While adsorbers (1) and (3) accomplish the preheating and precooling modes respectively, adsorbers (2) and (4) also accomplish the adsorption and regeneration modes respectively. At this time, the adsorption heat pump completes the first half cycle and it starts to enter the second half cycle. As shown in Fig. 3, the processes in the second half cycle are similar to those in the first half cycle.

After all the four adsorbers accomplish the four modes, adsorber (1) will return to the adsorption mode. Adsorbers (2), (3) and (4) would return to the precooling, regeneration and preheating modes respectively. At this time, the system proceeds to the next cycle.

As indicated in the above, at any time in a cycle, there is at least one adsorber undergoing the adsorption process. Hence, the four-bed adsorption heat pump is capable of producing a continuous cooling effect.

3. Components and process control

3.1. Adsorber

In the adsorption heat pump, the four adsorbers are identical. One of the adsorbers (adsorber (1) in Fig. 2) was installed with a pressure gauge for monitoring the variation of vapor pressure in each process. The adsorber is composed of a shell and a core structure (Fig. 4). The shell was made of a stainless steel pipe with a