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Experimental investigation of a solar-powered adsorption refrigeration system with the enhancing desorption

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ABSTRACT

The paper proposes a novel solar adsorption refrigeration system employing an active enhancing mass transfer method based on the typical basic cycle. In essence, the new method is to drop the internal pressure of the system in the desorption process. The working principle of the hypothesis and the cycle description are explained in detail and analyzed by laboratory experiments. The novel solar adsorption refrigeration system prototype with activated carbon-methanol as working pair was designed and built. Some different comparative tests under different weather conditions were conducted to prove the hypothesis and evaluate the performance of the novel adsorption refrigeration system. The experimental results show that the system employing an active enhancing mass transfer method will increase the mass of desorbed refrigerant by about 20% if compared with a natural desorption refrigeration system. It was also proved that the novel method is very effective for low adsorbent temperature operation, which may help to obtain a COP_{solar} increase of at least 16.4%. And about one and half hours can be saved by enhancing desorption refrigeration system to get the same desorbed refrigerant with the natural desorption refrigeration system. The results of experiments show that the novel system has improvements in the coefficient of performance, the mass of desorption and desorption rate, and the characters of the solar adsorption refrigeration system can be a benefit to further application.

1. Introduction

Solar adsorption refrigeration technology has received a lot of attention due to their noiseless and environmentally friendly refrigerants, especially, the solar energy utilization since the cold demand coincides most the time with the solar irradiation availability [1]. However, certain drawbacks have become obstacles to its real applications and commercialization. Such as the discontinuous operation of the cycle; the large volume and weight relative to traditional refrigeration systems; the low specific cooling capacity; the low coefficient of performance; the long adsorption/desorption time; the poor heat transfer performance of the adsorbent bed. In these decades, a lot of theoretical and experimental works on the solar adsorption refrigeration technology have been conducted and improved. Tremendous improvements in the refrigeration performance have been gotten by making significant progress mainly in two aspects: the first is to enhance heat and mass transfer in the adsorbent bed, the second is to apply new cycles which can recover more heat and mass.

As is known to us, the heat transfer of the adsorbent is inferior and the main way of heat transfer is conduction in the adsorbent. So the thermal conductivity enhancement of the adsorbent is one effective way to improve the heat transfer in adsorption systems [2]. At present, adding fins are the simplest and effective way to increase the effective heat transfer area in the adsorbent bed and further improve heat transfer performance. Some works in this aspect are reported in the literature on the development of various adsorbent bed [3]. The effects of different solar collector/ adsorbent bed design parameters on the performances of a solar-powered solid adsorption refrigerator had been studied by Ogueke and Anyanwu [4]. They used a plate collector with inner tubes as an adsorbent bed, where the adsorbent was packed in the annular space between two co-axial tubes. An improvement of more than 30% in COP (the coefficient of performance) and condensate yield was obtained through the optimal choices of tube spacing, adsorbent packing density, and collector plate tube material combinations. Louajari studied a system with fins in solar collector/adsorber, which is composed of many cylindrical tubes welded using external fins [5]. The result showed that the maximal temperature reached in the adsorber with fins attains 97 °C while in the adsorber without fins reached 77 °C, and the performance of the solar adsorption refrigerating machine with an adsorber of fins was 0.11which are higher than the one without fins. While in terms of parameter optimization, Brites completed a parametric improvement study according to a numerical study based on a

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Nomenclature

T_a	adsorption temperature,°C
T_c	condensation temperature, °C
T_e	evaporation temperature, °C
T_g	starting desorption temperature, °C
T_{ads}	starting adsorption temperature, °C
T	temperature, °C
P_e	evaporation pressure, Pa
Q_{ref}	refrigerating capacity, J
L_e	latent heat of vaporization, J·kg^{-1}
I(t)	solar radiation intensity, kW/m^2
A_{ab}	area of the adsorbent bed, m^2
A_{pv}	area of the PV panel, m^2
D	Dubinin-Astakhov constant
n	Dubinin-Astakhov constant
m_a	desorbed refrigerant mass, kg
P_c	condensation pressure, Pa
P'_c	condensation pressure in the enhancing mass transfer cycle, Pa
T'_g	starting desorption temperature in the enhancing mass transfer cycle, °C
T'_{ads}	starting adsorption temperature in the enhancing mass transfer cycle, °C
T_{max}	the maximum temperature, °C
P	pressure, Pa
χ	adsorbed phase concentration ratio, kg·kg^{-1}
χ_{con}	adsorbed phase concentration ratio at adsorbed state, kg·kg^{-1}
χ_{dil}	adsorbed phase concentration ratio at desorbed state, kg·kg^{-1}
χ'_{dil}	adsorbed phase concentration ratio at desorbed state in the enhancing mass transfer cycle, kg·kg^{-1}
Q_{cc}	energy used to cool down the refrigerant liquid, J
Q_s	total radiant energy absorbed by the adsorbent bed/collector, J
$Q_{s\text{-}pump}$	total energy consumption of the micro vacuum pump, J
M_a	mass of adsorbent in the adsorbent bed, kg

set of experimental results [6]. The number of metallic fins in adsorbent bed, the thermal contact resistance between silica-gel and the collector plate and so on had been analyzed for determining the optimum value. The heat and mass diffusion time, solid phase thermal conductivity, particle diameter, bed height and the vapor channel width in a new compact adsorbent bed of adsorption cooling system were simulated and analyzed by Mohammed [7]. The thermodynamic cycle study of the solar adsorption refrigeration system at a steady temperature was taken by Hadj Ammar et al. [8] in which it showed that the optimal COP was 0.73 whereas a total daily ice production of 13.65 kg. Li and Ji designed and optimized a large-diameter aluminum-alloy finned-tube adsorbent bed collector for enhancing the heat transfer and reducing the uneven temperature distribution in the collector/adsorber [9]. The adsorbent bed efficiency was improved between 31.64% and 42.7%, the maximum COP was 0.122 and maximum daily ice-making can achieve 6.5 kg. The finned-tube adsorbent bed also has been mounted in a water tank which can be driven by a domestic solar hot water system [10]. With the solar hot water temperature of 94 °C, the maximum daily ice-making capacity can reach 8.4 kg and the maximum COP was 0.139. Another kind of tubular adsorber was presented and designed for a solar adsorption refrigeration system by Hadj Ammar [11]. Some important parameters of the adsorber, such as adsorber tube size, tube wall material and collector glazing cover, were investigated, finally, the solar adsorption refrigeration system has a solar COP about 0.21. For the similar tubular adsorbent bed, many researchers are interested in it in recent years. Bouzeffour designed a solar adsorption refrigeration module with the tubular adsorbent bed, the experiment was conducted in the weather conditions of Bou-Ismail and a solar COP ranging from 0.083 to 0.09 could be achieved [12]. In view of the kind of tubular adsorbent bed, besides of the experiments, the dynamic modeling and simulation also were developed to provide an insight into the daily thermal behavior of the tubular adsorber [13]. Many other works also emphasized the increase in heat transfer by proper contact between the adsorbent bed and the metal [14–16].

On the other hand, the earliest adsorption refrigeration cycle is based on the typical basic cycle or the single-bed intermittent cycle, the efficiency of the basic cycle is low and the cooling output is not continuous. So other researchers proposed some new cycles, such as heat recovery cycle, mass recovery cycle, both heat and mass recovery cycle, thermal wave cycle, forced convection thermal wave cycle, cascade cycle, multi-bed cycle, etc. Akira investigated the performance of two-bed adsorption refrigeration cycle with mass recovery process [17]. The mass recovery cycle was compared with conventional cycle such as the single stage adsorption cycle regarding cooling capacity, the results showed the performance of mass recovery cycle was better than that of the regular cycle and more efficient as being driven by low regenerating temperature. Shelton is one of the researchers that early proposed the concept of thermal wave cycle and the cycle utilized a simple heat transfer fluid circulating loop for heating and cooling of two solid adsorbent beds [18]. The 80% heat required in desorption process can be provided by the heat released in the adsorption process. Critoph put forward the idea of the forced convective thermal wave cycle early, which used heat transfer intensification to achieve both high efficiency and small size from a solid adsorption cycle [19,20]. According to his research results and thermodynamic modeling, the system can attain a COP of 0.90 at evaporating temperature of 5 °C and condensing temperature of 40 °C. Based on the concept, Wang provided a performance improvement of adsorption cooling by heat and mass recovery operation, and the theoretical analyses on the COP have been completed for various heat and mass recovery cycles, such as basic intermittent adsorption cycle, continuous two-adsorber heat recovery cycle, mass recovery cycle, mass recovery with sensible heat recovery, and mass recovery with both sensible heat and heat of adsorption recovery [21]. Due to the integrated application of heat and mass recovery processes can get better performance of adsorption refrigeration system, Wang selected a serial heat recovery process between two adsorbers and a mass recovery-like process between two evaporators to study the operating features in a practical silica gel-water adsorption refrigeration system [22]. Then, a temperature-heat diagram analysis method for heat recovery physical adsorption refrigeration cycle was developed by Wang et al. to analyze the experiment related results of process temperature and estimate the performance for heat recovery cycle [23]. Li and Wang et al. presented a solar-powered multi-mode thermochemical sorption refrigeration system which consisted of three sorption refrigeration thermodynamic cycles [24]. The system could switch its working mode according to the available solar energy insolation so that the working reliability of the sorption system had been improved and the scope of application also had been widened. Saha applied the multi-bed cycle scheme to improve the performance of thermally activated silica gel-water adsorption refrigeration cycle [25]. For a two-bed, single-stage, silica gel-water adsorption chiller, the effect of variation of the collector area and the adsorption cycle time on the system performance had been studied by Dutta, and a cyclic and daily averages of solar COP were used as key performance indicators to evaluate the system [26]. Also for a two-bed adsorption refrigerator based on activated carbon/ethanol working pair, the different management strategies which mean heat recovery between adsorbers and re-allocation of phase durations was evaluated to identify their influence on the system