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Experimental study of the effect of enhanced mass transfer on the performance improvement of a solar-driven adsorption refrigeration system

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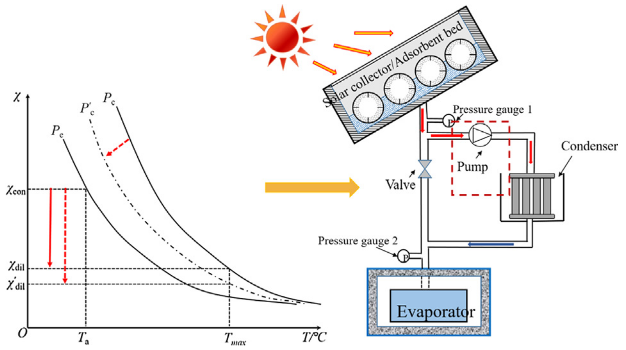
HIGHLIGHTS

- An enhanced mass transfer method based on the ideal adsorption cycle is proposed.
- A solar simulator was adopted to provide a light source for stable measurement.
- The comparative experiments between conventional and new systems were conducted.
- The average COP of the novel system has been improved by 35.9%.

GRAPHICAL ABSTRACT



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ABSTRACT

The current work demonstrates a novel prototype of a solar adsorption refrigeration system with enhanced mass transfer based on an ideal basic solid adsorption refrigeration cycle with activated carbon-methanol as the working pair. The working principle of the hypothesis was analysed, and the coefficient of performance (COP) was used to assess the system's performance. A solar simulator consisting of a halogen lamp light resource array was adopted to provide a light source for heating. Different comparative tests under different input radiation energy conditions were carried out to prove the hypothesis that a lower condensing pressure can be realized by using an enhanced mass transfer method and is good for increasing the amount of desorption. The variations of the adsorbent bed temperature, system pressure and ice production were analysed. The maximum COP and maximum ice-making capacity of the enhanced mass transfer adsorption refrigeration system were 0.142 and 7 kg, respectively. The average COP of the novel system showed an improvement of 35.9% compared with the average COP of the natural mass transfer adsorption refrigeration system when the input radiation energy was not less than 14.7 MJ during a refrigeration cycle.

1. Introduction

The utilization of energy from renewable sources has gained major interest during recent years, with the goal of reducing both the share of traditional fossil energy source consumption and energy-related environmental pollution. Among the innovative, environmentally friendly cooling technologies, solar cooling is seen as one of the most promising alternative solutions for the preservation of agricultural and dairy products as well as in areas with no electricity supply [1]. Based on solar heat collection and adsorption refrigeration techniques, solar-powered adsorption ice makers have received much attention in recent years [2,3]. Nevertheless, several disadvantages of adsorption

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Nomenclature

A_{ab}	area of the adsorbent bed, m^2
D	Dubinin-Astakhov constant
$I(t)$	solar radiation intensity, kW/m^2
L_e	latent heat of vaporization, $J{\cdot}kg^{-1}$
M_a	mass of adsorbent in the adsorbent bed, kg
Δm_a	desorbed refrigeration mass, kg
n	Dubinin-Astakhov constant
P	pressure, Pa
$P_s(T)$	saturation pressure corresponding to the adsorbent, Pa
Q_{evc}	refrigerating capacity, J
Q_{input}	total radiant energy absorbed by the adsorbent bed/collector, J
Q_{pump}	energy consumption of micro vacuum pump, J
Q_{tot}	total energy consumption, J
T	adsorbent temperature, °C
u_{COP}	root mean square error of the COP
u_{Qevc}	root mean square error of the refrigerating capacity
u_{Qtot}	root mean square error of the total energy consumption
χ_{con}	adsorbed phase concentration ratio at adsorbed state, $kg{\cdot}kg^{-1}$
χ_{dil}	adsorbed phase concentration ratio at desorbed state, $kg{\cdot}kg^{-1}$
χ'_{dil}	adsorbed phase concentration ratio at desorbed state in the enhanced mass transfer cycle, $kg{\cdot}kg^{-1}$
χ_o	the maximum limit of adsorbate concentration ratio, $kg{\cdot}kg^{-1}$
χ	adsorbate concentration ratio at equilibrium, $kg{\cdot}kg^{-1}$
$\tau\alpha$	transmittance-absorptance product

refrigeration have become obstacles for the practical application of adsorption refrigeration systems. These disadvantages include (1) a long adsorption/desorption time, (2) a small refrigeration capacity per unit mass of adsorbent, and (3) a coefficient of performance (COP) value that must be improved [4]. Currently, for large-scale applications of solar adsorption refrigeration, many research studies have been conducted to clear the obstacles.

Regarding research on the high-performance working pair aspect, activated carbon is considered the most commercialized adsorbent material due to its large surface area, high adsorption capacity and high surface reactivity [5]. Therefore, activated carbon has been one of the most extensively studied adsorbents. A thermodynamic framework for the surface-energy and surface-structural interaction factors of activated carbon materials with various nonpolar adsorbate molecules was developed for a better understanding of the adsorption/desorption mechanism of the refrigeration working pair [6]. The adsorption characteristics of two commercially available activated carbon samples (207EA granules and WS-480 pellets) were acquired by experimenting with nitrogen sorption at 77 K [7]. Allouhi et al. studied and compared the details of 7 working pairs intended for use in solar adsorption cooling systems. The activated carbon fibre/methanol working pair with the maximal adsorption capacity was found through a MATLAB program computation [8]. The adsorption characteristics of the activated carbon adsorbent were obtained through broader study, including the activated carbon/R134a pair (a temperature range of 20–60 °C and pressure up to 10 bars) [9], the activated carbon/CO_2 pair (a temperature range of −18–80 °C and pressure up to 10 MPa) [10], the activated carbon/HFC-152a pair (a temperature range of 25–75 °C) [11], and the activated carbon/HFC-404A pair (a temperature range of 25–75 °C) [12]. In addition to the inexpensive activated carbon adsorbent, attention has also directed at water. The research on water as an adsorbate has also been in-depth, including study on the silica gel/water pair [13,14] and the zeolite/water pair [15–17]. Additionally, some novel composite adsorption working pairs have emerged recently. Wang et al. studied a $MnCl_2/CaCl_2\text{-}NH_3$ working pair; then, a two-stage solid sorption freezing cycle was designed and adopted in a refrigerated truck [18,19]. New adsorption working pairs are able to improve the refrigeration capacity per unit mass of adsorbent and the coefficient of performance, admittedly, but activated carbon/methanol is still the most economical and most stable adsorption working pair. The operating temperature of the activated carbon/methanol pair is especially suitable for working in a solar adsorption refrigeration system. Many researchers are still struggling to improve the solar adsorption refrigeration system with an activated carbon/methanol working pair by designing and studying some new refrigeration cycle styles and new methods of heat and mass transfer enhancement.

Moreover, some new thermodynamic cycles or multi-stage systems were proposed to improve the COP or achieve a continuous refrigeration. Such as the thermal wave cycle utilizing a simple heat transfer fluid circulating loop for heating and cooling of two solid adsorbent beds [20], the cascade cycle with a solid adsorption heat pump system [21], and the forced convective thermal wave cycle [22]. Recently, Wang [23] established the cycle mathematical models for single, two and three-stage cycles on the basis of the thorough thermodynamic analysis. According to the simulating results, the proposed cycle with selected working pair could work under very severe conditions and some application boundary conditions also were summarized. An in-depth numerical and thermodynamic study of a two-stage, 2-bed silica gel/water adsorption system was presented, the thermodynamic analysis provided a theoretical limit for minimum desorption temperature and optimal inter-stage pressure for a two-stage adsorption cycle [24]. The management strategies of a two-bed activated carbon/ethanol refrigerator were studied, both strategies of heat recovery between adsorbers and re-allocation of phase durations were evaluated and confirmed the possibility of increasing COP and SCP up to 40% and 25% [25]. A 3-beds adsorptive chiller prototype was designed based on different durations of adsorption and desorption isobaric steps of a basic temperature driven adsorptive cooling cycle, and the performance and the potential of the new cycle management strategy have been demonstrated through experimental analysis [26]. Lots of new adsorption refrigeration cycles also were proven to be efficient by various researchers [27,28]. Although these newly proposed cycles are good for the improvement of COP, some of them are difficult to realize in a real operation, or some of their systems are too complex to operate and maintain, and most of the others are just laboratory studies [29]. While the overall performance of the thermal adsorption cooling systems is mainly limited by heat and mass transfer inside the adsorbent bed, due to the low thermal conductivity of the adsorbent particles and the low mass diffusivity of adsorbent-adsorbate pairs [30].

Thus, during the last decades, various prototype machines have been developed to enhance the heat transfer of the adsorbent bed. An adsorption cooling machine with a solar collector/adsorber composed of many welded cylindrical tubes using external fins was developed, and the results of the simulation model showed that the performances of the solar adsorption refrigerating machine with an adsorber equipped with fins were indeed higher than those of the machine without fins [31]. An adsorption ice production machine with a large-diameter finned-tube adsorbent bed collector was designed and optimized for reducing the uneven temperature distribution in the adsorber, and the experimental results showed that a maximum COP of 0.122 and a maximum daily ice-making capacity of 6.5 kg could be achieved [32]. An adsorption ice-maker with flat plate solar collector and optimal configuration parameters was proposed and optimized, and the optimized results showed that the system can produce from 5 kg up to 13 kg of ice per day per square meter of collector area, with solar coefficients of performance (SCOP) of 0.12 and 0.24 in the hot and the