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Performance evaluation of a zeolite–water adsorption chiller with entropy analysis of thermodynamic insight

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HIGHLIGHTS

- An adsorption chiller using novel adsorbent Zeolite FAM Z01 is presented.
- Chiller's highest COP was achieved at low grade heat source of 65 °C.
- Second law equations were developed to study the chiller's irreversibilities.
- Entropy generation against heat source temperature and cycle time is presented.
- 'Specific entropy generation' is used to reveal the trend of the chiller's COP.

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ABSTRACT

This paper presents an environment-friendly adsorption chiller using Zeolite FAM Z01–water pair as opposed to the conventional silica gel and water pair. The adsorbent, zeolite, is thinly coated onto the surfaces of fin-tube heat exchanger for faster rates of heat and mass transfer. Another feature of the adsorption chiller is the use of a lever-countered weighted valve which can be open or closed by the pressure difference between the reactors and the condenser or evaporator. Experiments are conducted to evaluate the performance of zeolite-based chiller in terms of total heat input, cooling capacity, and coefficient of performance (COP) with respect to heat source temperature and adsorption/desorption cycle time where an optimal operational zone can be determined: (i) hot water inlet temperatures range from 65 °C to 85 °C, (ii) adsorption/desorption cycle times of 200–300 s at optimum cooling and COP, Entropy analyses have been conducted to understand the irreversibility contributed by both the desorption and adsorption beds at assorted hot water inlet temperatures and cycle time.

1. Introduction

In recent decades, increasing cooling demand in the industrial and residential sectors aggravates energy consumption leading to a corresponding deterioration of environment from higher fossil fuel utilization. Cooling by the conventional vapor compression chillers consumes much electricity at 0.8–1.2 kW h/Rtons. Improvements to energy efficiency of key chiller components have been reported to have reached their asymptotic peaks, and huge investment is needed for only marginal improvements of chiller's energy efficiency. An alternative method to improving energy efficiency is to focus on the development of thermally-driven cycles that can be powered by low temperature waste heat which is available in abundance from exhaust of industrial processes or from renewable energy sources such as solar or geothermal heat [1]. Concerning such issues, scientists and engineers have studied green alternative solutions, and amongst such approaches, the adsorption cycle has been mooted as one of the most attractive technologies [2,3]. Being low-grade waste heat driven, maintenance free and environment benign are main advantages of adsorption chillers [4–8]. A proper designed such system operates in the heat source temperature as low as 55 °C. No major moving parts present in the chiller structure, requesting only minimum maintenance. High durability of adsorbent material added as a plus for its long lasting performance. Furthermore, the green nature of the technology comes from the utilization of non-ozone-depleting refrigerants and waste heat by which no additional CO_2 is emitted.

Extensive work has been conducted to study the adsorption cooling systems. The system can be constructed by implementing various adsorbent–adsorbate pairs, for example, silica gel–water [9], zeolite–water [10–12], activated carbon–ammonia [13] or

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Nomenclature

Abbreviations

ADS	adsorption bed
Cond	condenser
COP	coefficient of performance
DES	desorption bed
Evap	evaporator
FAM Z01	Functional Adsorbent Material, Zeolite Z01

Symbols

A	area (m^2)
C_p	specific heat capacity (kJ/kg K)
D_{so}	pre-exponential factor for surface diffusion (m^2/s)
E_a	activation energy (kJ/kmol)
M	mass (kg)
$\dot{m}$	mass flow-rate (kg/s)
P	pressure (Pa)
Q_E	cooling capacity (kW)
Q_H	heat input (kW)
Q_{st}	heat of adsorption (kW/kg)
R	universal gas constant (kJ/kmol K)
R_p	average radius of adsorbant particles (m)
q	adsorbate uptake (kg/kg of adsorbent)
q^*	equilibrium adsorbate uptake (kg/kg of adsorbent)
T	temperature (K)
t	time (s)
t_{cycle}	cycle time (s)
S_{gen}	entropy generation (kJ/K)
U	overall heat transfer coefficient (kW/m^2 K)
W_s	power input of spray pump (kW)
θ	operation indicator (–)
δ	operation indicator (–)

Subscript

abe	adsorbed phase of adsorbate
ads	adsorption bed
c	condenser
chi	chilled water
cw	cooling water
des	desorption bed
e	evaporator
f	liquid phase
g	gaseous phase
hw	hot water
hx	heat exchanger
i	inlet
o	outlet
zl	zeolite

R134a [14], in which the latter substances play the role of refrigerant. A multistage design from Saha et al. [15] effectively brought down the minimum heat source temperature to near ambient from a single stage type silica gel–water adsorption chiller. Saha and co-workers experimentally tested a three stage [16] and later a two stage chiller [17], and achieved 50 °C heat source temperature from the former, and 55 °C from the latter with 30 °C cooling water in both situations. Saha et al. [18], Wang et al. [19], Alam et al. [20], and Ng et al. [21] investigated operational strategies of multi-bed adsorption systems. Chen et al. [22] tested an adsorption chiller that eliminates the vacuum valves in the structure. Shahzad et al. [23] and Thu et al. [24] creatively hybridized adsorption chiller technology with multi-effect desalination (MED), which break through the conventional MED lower temperature limit to below ambient condition. Simulation and numerical studies [25–28] on the adsorption refrigeration systems at the same time helped to establish theoretical frame work, and explore the behavior of such machine in extreme as well as optimal conditions. Given the research activities conducted in the adsorption cooling field, Choudhury et al. [29] comprehensively summarized the development of this technology from three aspects, i.e., thermal energy harvesting, heat and mass transfer enhancement, and lastly advanced cycles and stages.

However, the vast application of this green technology is bottlenecked by low coefficient of performance (COP) and relatively larger foot-print. The existing adsorption chillers operate well below the theoretical Carnot limit. Meunier et al. [30] explained the reason through thermodynamic second law analysis. Meunier and co-authors suggested that in the conditions of isothermal heat reservoirs and ideal transfer, a temperature gap exists between the reactor sorption cycles and heat reservoirs, which is responsible for the thermal irreversibilities. Even infinite cascades of sorption reactors yield no more than 68% of the ideal efficiency [31]. Chua et al. [32] pointed out that the largest portion of entropy is generated by sorption heat transfer. Ng [33] has suggested that the COP of such thermally driven adsorption systems is normally lower than 1. On the other hand, the size of the chiller is bounded by the characteristics of the adsorbent–adsorbate pair. In order to achieve desired cooling capacity, the amount of evaporated refrigerant must be adsorbed simultaneously by the solids. This requires large amount of adsorbent and sufficient void space to be introduced into reactors.

This paper presents an adsorption chiller using a novel adsorbent, FAM Z01 Zeolite (composition: $Fe_xAl_yP_zO_2 \cdot nH_2O$, $x = 0.02$–0.10, $y = 0.35$–0.5, $z = 0.4$–0.6, $n = 0$–1), with water as adsorbate. The chiller is equipped with adsorbent coated reactor heat exchangers and lever mechanism valves. The performance of the system is evaluated experimentally with respect to various parameters, namely, adsorption/desorption cycle time and hot water inlet temperature. A further investigation of the thermodynamic insight of the chiller is carried out by entropy analysis.

2. System characteristics

2.1. Adsorbent–adsorbate pair

The adsorbent introduced in the current work, namely Functional Adsorbent Material (FAM Z01), is a novel aluminophosphate based water sorption zeolite developed by Kakiuchi et al.[34]. The material has a one-dimensional AFI type molecular sieve structure with a molecular window of diameter 0.73 nm. Only molecules smaller than this dimension, such as water molecules, are permitted free migration though the window. FAM Z01 owns S-shape water vapor sorption isotherms with excellent durability over 200,000 adsorption–desorption cycles and little hysteresis behavior. Sorption takes place dramatically in a narrow range of relative pressure (defined as the ratio of sorption pressure to the saturation pressure of vapor at the same temperature), while out of which the amount of vapor uptake possesses little changes with respect to the relative pressure [35]. This translates to a much larger adsorption capacity over conventional silica gel at normal chiller operation conditions, and further results in a compact chiller design. On the other hand, owning big latent heat, being absolutely