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Thermodynamic analysis of single-stage and multi-stage adsorption refrigeration cycles with activated carbon–ammonia working pair

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ABSTRACT

Activated carbon–ammonia multi-stage adsorption refrigeration cycle was analyzed in this article, which realized deep-freezing for evaporating temperature under −18 °C with heating source temperature much lower than 100 °C. Cycle mathematical models for single, two and three-stage cycles were established on the basis of thorough thermodynamic analysis. According to simulation results of thermodynamic evaluation indicators such as COP (coefficient of performance), exergetic efficiency and cycle entropy production, multi-stage cycle adapts to high condensing temperature, low evaporating temperature and low heating source temperature well. Proposed cycle with selected working pair can theoretically work under very severe conditions, such as −25 °C evaporating temperature, 40 °C condensing temperature, and 70 °C heating source temperature, but under these working conditions it has the drawback of low cycle adsorption quantity. It was found that both COP and exergetic efficiency are of great reference value in the choice of cycle, whereas entropy production is not so useful for cycle stage selection. Finally, the application boundary conditions of single-stage, two-stage, and three-stage cycles were summarized as tables according to the simulation results, which provides reference for choosing optimal cycle under different conditions.

1. Introduction

Adsorption refrigeration technology keeps receiving considerable attention and significance for decades, as it enjoys the merit of environmentally benign and can be driven by low-grade thermal energy [1]. Nowadays low-grade thermal energy with temperature lower than 100 °C is abundant as the forms of solar energy and industrial waste heat. Utilization of such low-grade thermal energy can improve the energy utilization efficiency as well as can decrease the waste of direct thermal energy emission to the environment. As a result, adsorption cooling system, especially freezing system driven by heating source with temperature below 100 °C is a promising technology for energy conservation and sustainable development.

Currently, for the applications under freezing conditions, thermal energy with temperature higher than 100 °C is usually used to drive adsorption refrigeration systems. The physical adsorption working pair of activated carbon–methanol is widely used for ice-making with satisfactory performances. Wang, Wang [2] developed an activated carbon–methanol ice maker for fishing boat with a productivity of about 20 kg h^{-1} when the evaporating temperature was as low as −15 °C and the driving heat source temperature was 110 °C. Zhao, Zhang [3] investigated a freeze proof solar powered adsorption cooling tube using active carbon–methanol working pair, with the highest adsorption temperature below 110 °C and −4 °C evaporating temperature, performing at a COP (coefficient of performance) more than 0.11.

Nevertheless, the capability of utilizing thermal energy with low temperature for adsorption freezing system is desired and prospective. For the utilization of thermal energy with temperature lower than 100 °C, Ji, Song [4] constructed a solar hot water driven adsorption ice-making system with activated carbon–methanol working pair, which had the lowest evaporating temperature of −8.6 °C when the heating source temperature was maintained at 94 °C. As for chemical adsorption, the driving temperature can usually be lower. Wang, Wang [5] investigated a two-stage chemical adsorption refrigeration cycle employing $CaCl_2$/$BaCl_2$–NH_3 working pair, which could generate refrigerating power at −15 °C when the cooling source temperature was 25 °C and the heating source temperature was as low as 75 °C. Le Pierrès, Mazet [6] studied a new type of cascaded thermochemical system using $BaCl_2$–NH_3 working pair with two reactors, two condensers, and two

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Nomenclature

A	parameter of Clausius–Clapeyron equation (K)
COP	coefficient of performance
c	specific heat capacity (kJ kg^{-1} K^{-1})
h	specific enthalpy (kJ kg^{-1})
k, n	parameter of D–A equation
m	mass (kg)
p	pressure (kPa)
Q	heat (kJ)
R	ideal gas constant (kJ kg^{-1} K^{-1})
S	entropy (kJ K^{-1})
T	temperature, temperature in adsorption bed (K)
x	adsorption ratio (kg kg^{-1})
x_0	parameter of D–A equation (kg kg^{-1})

Greek letters

Δx	cycle adsorption quantity (kg kg^{-1})
ε	exergetic efficiency
σ	specific entropy production (kJ kg^{-1} K^{-1})

Subscripts

1, 2	beginning and ending state points, respectively
a	adsorption, adsorbent
$a1$, $a2$	maximal and minimal adsorption (temperature), respectively
b	boundary
c	condensing, cooling
cond	condensation
d	desorption
e	evaporating
eva	evaporation
fg	liquid–gas phase change
g	generation, desorption
$g1$, $g2$	minimal and maximal desorption (temperature), respectively
h	heating, heating source
I, II, III	the first, second and third stage of multi-stage cycle, respectively
m	middle parameter for two-stage cycle
$m1$, $m2$	middle parameters for three-stage cycle
min	minimum
opt	optimum
r	refrigerant
ref	refrigeration
rf	refrigerant liquid
s	saturated
sys	closed system

Superscripts

$'$	two-stage cycle
$''$	three-stage cycle

evaporators, whose experimental prototype reached the evaporator temperature as low as −30 °C when the heating source temperature ranged from 55 °C to 80 °C, with a rough solar COP of about 0.031.

Physical adsorption has the advantage of high stability compared to chemical adsorption. However, till now, there is little research work focusing on physical adsorption refrigeration under deep-freezing conditions with evaporating temperature lower than −18 °C and heating source temperature much lower than 100 °C. Actually, for applications under air-conditioning conditions, multi-stage adsorption refrigerators with silica gel–water working pair have already been commercialized, including two-stage [7] and three-stage systems [8], which can be driven by 60 °C heating source temperature, with a COP of approximately 0.1–0.2 [9]. Multi-stage cycle can be adopted to decrease the required driving heat source temperature of adsorption refrigerator. Furthermore, recently, the novel adsorbent of consolidated activated carbon (AC) combined with expanded natural graphite treated with sulfuric acid (ENG-TSA) has been developed for the improvement of heat and mass transfer performance. The thermal conductivity of consolidated AC/ENG-TSA can be as high as 34.2 W m^{-1} K^{-1}, which is almost the highest thermal conductivity gotten from consolidated physical adsorbents, and the corresponding specific heat capacity at constant pressure is 2.75 kJ kg^{-1} K^{-1} in average [10]. Such an adsorbent provides the possibility for the practical use of activated carbon adsorbent in physical adsorption refrigerators, and pressure system also has the advantages of high mass transfer performance and reliability. Thus the selected activated carbon–ammonia working pair was chosen for multi-stage adsorption refrigeration cycle to be analyzed in this article.

On the other hand, in the design and assessment of adsorption refrigeration systems, COP is usually analyzed based on the first law of thermodynamics, and SCP (specific cooling power) is usually analyzed with simulation or experiment for specific designed systems. For example, Wang, Wang [11] investigated the performances of several working pairs with activated carbon as adsorbents for the mass recovery adsorption ice making test units by comparing the COP and the SCP. Tamainot-Telto, Metcalf [12] studied various activated carbon–ammonia pairs with a thermodynamic cycle model considering COP to determine the optimum working pair. As for the second law of thermodynamics, there exist exergy analysis and entropy analysis tools, and these tools can help assess adsorption refrigeration systems from the viewpoint of energy grade. However, these methods are not adopted so frequently. Analysis of exergetic efficiency can be found in the study of refrigeration and electricity cogeneration systems, such as chemisorption cogeneration system [13] and resorption cogeneration cycle [14]. In the recent years, the model of artificial neural network has also been adopted to predict the performance of adsorption refrigeration systems [15]. The exergy performance prediction with the application of artificial neural network is also promising to simplify the analysis [16]. Entropy analysis mainly includes calculation of entropy production for specific system. It generally comes to the conclusion that heat transfer at the beds generates the most entropy [17], and the proportion of the cycle entropy production contributed by adsorption beds can be 90% of the total [18]. Academics also analyzed entropy production of specific cycle and different working pairs [19]. However, they didn't give suggestions about the selection of optimum cycle and working conditions, or guidance for system control. There usually lacks useful information after thermodynamic analysis.

In summary, the aim of this article was to realize and optimize the utilization of low-grade thermal energy with temperature much lower than 100 °C to fulfill the cooling requirements of both air-conditioning and freezing. Consolidated AC/ENG-TSA–ammonia multi-stage adsorption refrigeration cycle was selected on a number of considerations. The novel combination of the newly developed working pair and multi-stage cycle possesses several advantages compared with current systems, such as the capability of deep-freezing, low heating source temperature, relatively high heat and mass transfer performance, and reliability, which significantly raise the practical value of the study. On the