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Study on gradient thermal driven adsorption cycle with freezing and cooling output for food storage

F.P. Song, L.X. Gong, L.W. Wang*, R.Z. Wang

Institute of Refrigeration and Cryogenics, Key Laboratory of Power Machinery and Engineering of Ministry of Education, Shanghai Jiao Tong University, Shanghai 200240, China

HIGHLIGHTS

- A gradient thermal driven cycle for food storage is proposed and tested.
- The total thermal COP and exergy efficiency of the cycle are 0.13–0.26 and 11%–13%.
- The total thermal exergy efficiency for heat utilization of the cycle is 31%–42%.

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ABSTRACT

An gradient thermal driven adsorption cycle powered by low grade heat, such as geothermal, solar energy, or waste heat from factories, is constructed for the food storage both under the conditions of freezing (around −15 °C) and the refrigeration (around 5 °C). The cycle is combined by the $CaCl_2$–$BaCl_2$ adsorption freezer (first stage) and silica-gel/lithium chloride adsorption air conditioner (second stage) and it is driven by the heat source with gradient temperature that is lower than 100 °C.The cycle produces cooling and freezing power simultaneously with the implementations of adsorption and resorption processes. In the experiments the heat source temperature ranges from 70 to 90 °C, condensing temperature is controlled at 25 °C. The results show that thermal coefficient of performance (thermal COP) of gradient thermal driven cycle ranges from 0.13 to 0.28, which improves 87% compared with the adsorption freezing cycle under the heat source of 90 °C and evaporating temperature of −15 °C. The refrigerating capacity is 4.56 kW under driving heat source at 70 °C and the improvement is 76.5% if the heat source temperature increases to 90 °C. The exergy efficiency of the cycle are calculated to be 0.11 −0.13 under the above conditions, and the exergy efficiency for heat utilization varies from 0.31 to 0.42, which is improved 90.3% and 75.6% compared with the adsorption freezing cycle and adsorption cooling cycle, respectively when the heat source temperature is 90 °C.

1. Introduction

Solar energy and industrial waste heat, which are abundant in the environments and processing industries, are huge untapped resources and have great potential to be recovered. The Energy Efficiency Directive (EED) has stressed the importance of the use of industrial waste energy as a way to reach the EU target [1]. Refrigeration has become an essential part of food storage, until recently, vapor compression refrigeration systems using different working fluids have been predominantly used in food storage, which has resulted in a significant increase of electric power demand. The International Institute of Refrigeration in Paris (IIF/IIR) has estimated that approximately 15% of all the electricity produced in the whole world is employed for refrigeration and air conditioning processes of various kinds [2,3]. The conventional vapor compression refrigeration machines contribute significantly in an opposite way to the policy of sustainable development, leading to the depletion of precious fossil fuels and the production of greenhouse gases. Consequently, the adsorption refrigeration cycle driven by low grade energy will be an effective solution to both energy and environmental pollution problems.

The research on adsorption refrigeration can be classified into two conditions, one is for the refrigeration temperature above 0 °C that is a common technology for the air conditioning, and the other is for the refrigeration temperature below 0 °C that is generally for the freezing requirements such as making ice [4]. Extensive studies

* Corresponding author. Tel.: +86 21 34208038.
E-mail address: lwwang@sjtu.edu.cn (L.W. Wang).

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Nomenclature

COP	coefficient of performance
SCP	specific cooling power, kW/kg
T	temperature, °C
t	time, s
Q	quantity of heat, kW
m	mass, kg
c	specific heat capacity, kJ/(kg K)
E	exergy of heat, kW
η	exergy efficiency
Subscripts	
ref	refrigeration
ad	adsorption
de	desorption
LTS	low temperature salt
MTS	middle temperature salt
e	evaporation
av	average
h	heating
in/out	inlet/outlet
eth	ethanol
wat	water

have been conducted to investigate the adsorption air conditioning technology powered by the heat source temperature below 100 °C. Saha et al. [5] experimentally investigated a double-stage, four-bed, non-generative adsorption chiller powered by solar/waste heat sources between 50 and 70 °C. The prototype produced cold water at 10 °C and had a cooling power of 3.2 kW with a COP of 0.36 when the heating and condensing source had a temperature of 55 and 30 °C, respectively. Ng et al. [6] had reported the cooling cum desalination cycles driven by low temperature waste heat which employ adsorption processes. Saha et al. [7] numerically researched a new generation cooling device employing $CaCl_2$ in silica gel-water systems, and it was found that the cooling capacity and COP could be increased up to 20% and 25%, respectively when compared with the silica gel-water adsorption chiller. Restuccia et al. [8] developed an adsorption chiller employing silica gel impregnated with $CaCl_2$ as adsorbent, for which the COP was close to 0.6 when the generating temperature was 85–95 °C and cooling temperature was 35 °C. Tamainot-Telto and Critoph [9] studied a modular adsorption air conditioner, which was powered by hot air, the experimental results with this module showed that the cooling power was about 100 W, the SCP was 600 W/kg, the COP was 0.20 without any heat regenerative process when the heat source, the condenser and the evaporator had a temperature of 100, 30 and 15 °C, respectively. Gong et al. [10] had tested the adsorption chiller employing lithium chloride in silica gel and methanol, and the experimental results showed that the COP is 0.41, the cooling capacity was 5 kW when the temperature of hot water inlet, cooling water inlet and chilled water outlet was 85,30 and 15 °C, respectively.

Meanwhile, the freezing conditions with the refrigeration temperature below 0 °C have been researched for the heat source temperature below 100 °C with different working pairs and adsorption cycles. Critoph [11] mentioned a solar vaccine refrigerator studied in his laboratory in the early 1990s, such a machine could maintain the cold box at 0 °C during the daytime, after one adsorption cycle, performed during the previous night. Oliveira [12] tested an adsorption icemaker with mass recovery process, which had a daily ice production of 1.2 and 1.6 kg per kg of adsorbent when the generating temperature was 75 and 85 °C, respectively. Wang et al. [4] designed a two-stage adsorption freezing machine driven by the heat source temperature below 100 °C, for which the COP and SCP at −15 °C refrigerating temperature were 0.13 and 100W/kg with the heat source of 85 °C and the coolant temperature of 25 °C. Erhard et al. [13,14] researched a solar powered adsorption ice making unit utilizing $SrCl_2$–NH_3 as working pair and the COP is about 0.05–0.08 when the heat source temperature was as high as 100–120 °C.

However, for food storage generally both freezing and air conditioning technologies are required. The food needs to be cooled from ambient temperature to the temperature above 0 °C in the manufacturing process and below −10 °C in the distribution process to slow the physical, microbiological and chemical activities that cause deterioration in foods [15]. Until recently, few papers have been focused on the research of the cycle combining both air conditioning and freezing technologies. In order to develop a type of adsorption refrigeration machine for food storage application that can be driven by the heat source temperature below 100 °C, in this manuscript a gradient thermal driven cycle is presented. The experimental performance of this cycle is analyzed and the results are discussed.

2. System description of the gradient thermal driven cycle

2.1. Design of the gradient thermal driven cycle

The newly designed gradient thermal driven cycle integrating the adsorption freezing cycle and adsorption refrigeration cycle is shown in Fig. 1. This cycle, for which a $CaCl_2$–$BaCl_2$–NH_3 freezer is chosen as the first stage, and the single stage cycle employing silica gel impregnated with lithium chloride as the adsorbent and methanol as refrigerant is selected as the second stage for refrigeration, can be driven by the low temperature heat source (below 100 °C). From the schematic layout of the cycle in Fig. 1(a), it can be seen that the chief components of the test system include one hot water tank, one adsorption freezing machine, one adsorption cooling machine, one chilled methanol tank, one chilled water tank and two cooling water tanks. The test unit is equipped with monitoring sensors, these sensors are installed at the inlet and outlet of the evaporator, condenser and inside the adsorber. The picture of the test unit is presented in Fig. 1(b).

The interconnection between the adsorption freezing cycle and adsorption air conditioning cycle is through the heating and cooling water fluid pipelines. The working processes are:

(1) The hot water from the water tank firstly flows into the adsorption freezing machine, and then goes into the adsorption cooling machine. By such a way the energy from the heat source can be used gradiently by two machines, and the temperature between the inlet and outlet of the heat source can be consequently enlarged for the improvement of the heat utilization efficiency. In the experiments the heating fluid at the outlet of the system flows back into the hot water tank, whereas for the real application such as the waste heat from factories always exhausted to the environment.
(2) Meanwhile, the cooling water with the temperature of 25 °C from the two cooling towers flows into the adsorption freezing machine and cooling machine, respectively. After that the cooling water flows back into the cooling water tank. Simultaneously, the circulating methanol is used for transporting the refrigeration quantity out of the adsorption freezing machine, and the cooling power produced by the adsorption cooling machine is taken out by the cyclic flowing water.