Renewable Energy 74 (2015) 287–297

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Experimental study on working pairs for two-stage chemisorption freezing cycle

L. Jiang, L.W. Wang*, W.L. Luo, 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

ARTICLE INFO

Article history:
Received 23 April 2014
Accepted 4 August 2014
Available online 27 August 2014

Keywords:
Two-stage cycle
Chemisorption
Freezing
Ammonia

ABSTRACT

Recently $CaCl_2$–$BaCl_2$–NH_3 chemisorption freezing cycle driven by low temperature heat source has been successfully developed. In order to develop one working pair with more desirable performance than $CaCl_2$–$BaCl_2$–NH_3, working pairs of $CaCl_2$–NaBr–NH_3, $CaCl_2$–$BaCl_2$–NH_3, $SrCl_2$–$BaCl_2$–NH_3 and $SrCl_2$–NH_4Cl–NH_3 were investigated and compared. Most of composite adsorbents were developed with new type matrix of expanded natural graphite treated with sulfuric acid (ENG-TSA), leaving one working pair with expanded natural graphite (ENG) for comparison. For $SrCl_2$–NH_4Cl–NH_3 and $CaCl_2$–NaBr–NH_3, experimental results show that the maximum adsorption quantities are 95.4% and 88.6% of theoretical values, respectively. Simulation results show that for different working pairs coefficient of performance (COP), cooling capacity, and specific cooling power (SCP) range from *0.215 to 0.285*, *2 to 3.65 kW* and 161.4–260.74 W kg^{-1}, separately. The best results are obtained from $CaCl_2$–NaBr–NH_3, and its *SCP and COP are as high as 260.74* W kg^{-1} *and 0.285, which are improved by 15.1% and 5.6% if compared with the values for CaCl2–BaCl2–NH3. Comparisons also show that the matrix of ENG-TSA improves SCP effectively. Taking CaCl2–BaCl2–NH3 as an example*, *its* SCP is improved by 76.9% if compared with the result obtained from working pair with the matrix of ENG.

1. Introduction

With the increasingly prominent problems of energy crysis and environmental pollution, adsorption refrigeration as one kind of green energy conversion technologies is gathering the momentum because of its zero ozone depletion potential (ODP) and global warming potential (GWP) [1]. Furthermore, adsorption refrigeration is also one type of energy saving technologies because it is driven by the low grade heat, such as waste heat from the factory, geothermal [2] and solar energy [3].

For the traditional single-stage adsorption freezing cycle, the reactor usually requires the heat source with the temperature higher than 100 °C in the desorption process while the ambient temperature is about 30 °C. Otherwise the coefficient of refrigeration performance (COP) will be lower than 0.1. Various researchers investigated on the adsorption freezing cycles. Pons et al. [4] utilized the working pairs of $SrCl_2$ and NH_3 for freezing conditions. Results showed that COP of the system was 0.22 under the conditions of 130 °C heat source temperature, 40 °C cooling water temperature and −25 °C evaporation temperature. T.X. Li et al. [5] researched on working pairs of $MnCl_2$–NH_3, and results showed that heat source temperature was as high as 177 °C when the evaporation temperature and cooling temperature were −25 °C and 30 °C, respectively. Erhard et al. [6] acquired the evaporation temperature of −10 °C with the $SrCl_2$–NH_3 working pair; however, the COP was only about 0.045–0.082 when the heat source temperature was as high as 100–120 °C. Oliveira et al. [7] studied a resorption system with NH_4Cl as LTS and $MnCl_2$ as HTS for simultaneous heating and cooling effect production. The COP was as low as 0.02 when the cooling and heating effects were obtained at −5 °C and 50 °C, respectively. Generally, for single-stage adsorption system, evaporation temperature cannot reach −15 °C when heat source temperature is lower than 100 °C and cooling temperature is higher than 30 °C. Le Pierre et al. [8] developed a cascading system using $BaCl_2$–NH_3 for applications driven by low-temperature heat source. A deep-freezing temperature was able to be obtained as low as −33 °C when the ambient temperature was 25 °C. Nonetheless, COP was as low as 0.031.

In order to obtain the deep freezing effect under the condition of heat source temperature lower than 100 °C, a novel design of two-

* Corresponding author. Tel.: +86 21 34208038; fax: + 86 21 34206814.
E-mail address: lwwang@sjtu.edu.cn (L.W. Wang).

http://dx.doi.org/10.1016/j.renene.2014.08.011
0960-1481/

Nomenclature

A	area (m^2)
c	specific heat (kJ/kg K)
D	diameter(m)
GWP	global warming potential
g	gravity acceleration(9.8 m/s^2)
h	enthalpy (kJ/kg)
L	latent heat of vaporization (kJ/kg)
m	mass (kg)
ODP	ozone depletion potential
p	pressure (Pa)
Q	energy (kW)
q	mass flow rate (kg/s)
R	Heat resistance(m^2 K/W)
s	fin thickness(m)
t	time(s)
T	temperature(K)
v	fin spacing(m^3)
w	power(W)
x	cycle adsorption quantities(kg kg^{-1}MTS)

Greek

ρ	density of adsorbent(kg/m^3)

Subscripts

ad	adsorption
am	ammonia
al	aluminum
c	cycle
ca	$CaCl_2$
chill	chilled water
con	condenser
cool	cooling water
des	desorption
eth	ethanol solution
eva	evaporation
f	working fluid
g	ENG-TSA
h	hot water
heat	heating
in	inlet
L	LTS adsorbent
Lq	liquid
M	MTS adsorbent
m	metal
max	maximum
eth	ethanol solution
min	minimum
NH_3	ammonia
o	outer
out	outlet
p	pressure
ref	refrigeration
s	steel
t	tube
tot	total
w	water
y	reaction process

stage adsorption refrigeration cycle on the basis of the adsorption process and resorption process [9] was proposed. In the research [9] working pair of $CaCl_2$–$BaCl_2$–NH_3 was studied, and the matrix of expanded natural graphite (ENG) was used for the improvement of the heat and mass transfer performance. Results showed that the cycle was able to generate the cooling power at the freezing temperature lower than −20 °C while the heat source temperature was as low as 70 °C and the cooling temperature was higher than 30 °C. However, there was no detailed study on the performance of other working pairs with other matrixes for such type of two-stage adsorption freezing cycle. Recently the study on the expanded natural graphite treated with the sulfuric acid (ENG-TSA) showed the great improvement for heat transfer performance [10]. In order to have a comprehensive understand of new type of adsorbents for the further research, as well as to develop a type of the working pair with higher performance, in this paper we studied four working pairs for two-stage adsorption cycle, and the matrix of ENG-TSA was chosen for heat transfer intensification. The adsorption and resorption performance, as well as the thermal conductivity of the adsorbents were tested, and the optimum working pair was chosen for the design and simulation of a two-stage adsorption freezer.

2. Choice of working pairs and materials for the experiment

2.1. Introduction of principle of two-stage adsorption refrigeration cycle

The diagram of two-stage adsorption refrigeration cycle is shown in Fig. 1. For this two-stage adsorption cycle the first working process is desorption phase of low temperature salt (LTS) as well as adsorption phase of middle temperature salt (MTS); these two phases are proceeded at the same time. For desorption process of LTS, the LTS is heated by the heat source (Q_{des-2}), and desorbs refrigerant at a high-pressure P_c to the condenser, for which the refrigerant rejects heat (Q_{cond}) to the environment at T_c. For the adsorption phase of MTS, the heat of adsorption (Q_{ads-2}) in the MTS bed is taken away by the heat sink, and adsorbs the refrigerant from the evaporator at a low-pressure P_e, providing the refrigeration effect (Q_{ref}) at T_e. The performance of this process is related with the equilibrium drop [11,12], i.e. temperature difference between the adsorption/desorption temperature and equilibrium temperature. A large equilibrium drop will enhance the kinetics and consequently decrease the adsorption time.

The second working process is the resorption process between the MTS and LTS. During the resorption process, MTS bed is heated by the external heat source at high temperature T_{g1} with the heat

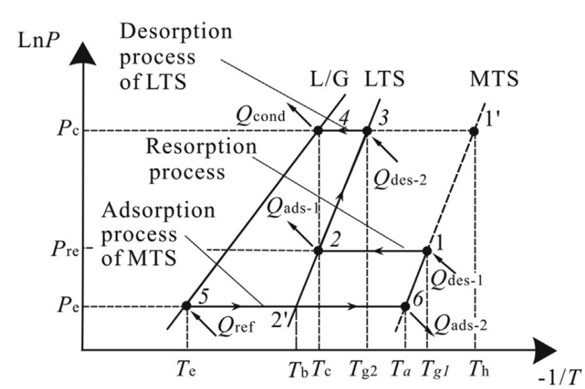

Fig. 1. P-T diagram of two-stage adsorption refrigeration cycle.