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Performance analysis on a novel compact two-stage sorption refrigerator driven by low temperature heat source

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A B S T R A C T

A novel two-stage sorption refrigeration system is established and analyzed, which is driven by heat source with the temperature lower than 100 °C. $CaCl_2$-$BaCl_2$-NH_3 is selected as working pair whereas matrix of expanded natural graphite treated with sulfuric acid (ENG-TSA) is used for the improved heat and mass transfer performance of composite sorbent. The non-fin filling technique is adopted to decrease mass and volume of sorption reactor, which further improves system compactness. Results show that two-stage sorption refrigeration system is flexibly adapted to different heat source with temperature below 100 °C. *COP* and *SCP* of the novel system range from 0.185 to 0.22 and from 50 W kg^{-1} to 76 W kg^{-1}, respectively under the condition of 70 °C–90 °C heat source temperature and 5 °C–10 °C evaporation temperature. Performance of novel two-stage sorption refrigeration system is also compared with that of previous type by using the conventional fin tube sorption reactor based on mass and volume of the whole system. It is indicated that the highest improvement of SCP_{sys} and VCP_{sys} for the novel system are able to reach 28.1% and 32.5%, respectively when heat source temperature is 70 °C.

1. Introduction

Low grade heat with the temperature lower than 100 °C can be easily obtained, which extensively exists in industrial waste heat, geothermal and solar power [1]. For efficient utilization of low temperature heat source, sorption refrigeration characterized with simple structure, easy operation and good adaptability to heat source, is regarded as a prospective energy conversion technology [2]. The main research fields of sorption refrigeration lie on three aspects, i.e. heat and mass transfer enhancement of the sorbent [3], cycle innovation and optimization [4] as well as thermal design of sorption system [5].

For evaluating the performance of the sorbent, different parameters such as thermal conductivity, permeability and sorption rate etc. are required to be considered comprehensively [6]. Among them thermal conductivity usually plays a leading role, which greatly influences system performance [3,7]. To further improve thermal conductivity, composite sorbent has been introduced and developed. As a major matrix of composite sorbent, expanded natural graphite (ENG) has been widely investigated [8], which was first invented by Carburet company in US [9]. It is developed from the expandable graphite which is prepared by methods of electrochemistry and chemistry oxidation [10]. Early study about the consolidated composite sorbent impregnated with ENG as the matrix was investigated by Mauran et al. [11], who verified the better heat transfer performance of composite sorbent for granular $CaCl_2$. Wang et al. [12] measured the effective thermal conductivity of ENG-$CaCl_2$-nNH_3 (n = 2, 4, 8) composite sorbent by using hot wire method at a fixed pressure and temperature under ammonia atmosphere, and results were in the range from 7.05 W m^{-1} K^{-1} to 9.2 W m^{-1} K^{-1}. Recent researches have indicated that composite sorbents could remarkably improve thermal conductivity of the granular sorbent through various matrix, whereas the best matrix was expanded natural graphite treated with sulfuric acid (ENG-TSA) [13], and it was able to improve thermal conductivity of granular $CaCl_2$ from 0.3 W m^{-1} K^{-1} up to about 88 W m^{-1} K^{-1} [14].

Additionally, refrigeration performance could also be improved by various advanced cycles such as heat recovery cycle, mass recovery cycle [15], thermal wave cycle [16], two-stage sorption cycle [17], resorption cycle [18], etc. Among them two-stage sorption refrigeration cycle is able to effectively reduce desorption temperature and increase sorption temperature, which demonstrates a good flexibility to external conditions. Hu et al. [19] proposed a

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Nomenclature

AV	ammonia valve
c	specific heat (kJ kg^{-1} K^{-1})
COP	coefficient of performance
HTS	high temperature salt
LTS	low temperature salt
m	mass flowrate (m^3 h^{-1})
P	pressure (Pa)
Q	heating power (kW)
SCP	specific cooling power (W kg^{-1})
t	time (s)
T	temperature (K)
V	valve
VCP	cooling power per unit volume (W m^{-3})
W	heating or cooling power (kW)

Subscripts

c	cycle
cond	condensation
chi	chilled
dsH	desorption of HTS
dsL	desorpiton of LTS
e	evaporation
h	heating
in	inlet
out	outlet
ref	refrigeration
sH	sorption of HTS
sL	sorption of LTS
sorb	sorbent
sys	system
tot	total
w	water

two-stage solid sorption freezing cycle, and composite sorbents of $CaCl_2$ and $BaCl_2$ were selected as the working pair. Cycle sorption performance of this working pair was investigated and analyzed by using the test unit which was specially designed. After that, Wang et al. [20] established a $CaCl_2$-$BaCl_2$-NH_3 two-stage sorption freezing machine. Experimental results revealed that compared with $CaCl_2$-NH_3 single-stage sorption freezing cycle, desorption temperature of two-stage cycle decreased from 98 °C to 75 °C when condensation temperature was 30 °C. Compared with $BaCl_2$-NH_3 single-stage sorption freezing cycle, sorption temperature of two-stage cycle increased from 16 °C to 43 °C when evaporation temperature was −20 °C. Jiang et al. [21] investigated and compared sorption characteristics of various two-stage working pairs i.e. $CaCl_2$-NaBr-NH_3, $CaCl_2$-$BaCl_2$-NH_3, $SrCl_2$-NH_4Cl-NH_3 as well as $SrCl_2$-$BaCl_2$-NH_3, and pointed out the optimal working pair for different heat source temperatures.

It is also worth noting that the proposed sorption cycle is required to be combined with good thermal design so that the desirable performance could be obtained. Sorption reactor usually acts as the core component of sorption system which should be given the priority in term of thermal design. Fin tube sorption reactors are common to be used for real sorption refrigeration systems, which have been investigated by various researches [22]. Two different reactor concepts, i.e. an external and integrated reactor for thermochemical energy, were investigated by Mette et al. [23]. It was indicated that performance could be improved by concepts of the developed reactor. Wang et al. investigated three different types of sorption working pairs i.e. activated carbon-methanol, chemical sorbent-ammonia and composite sorbent-ammonia, which were applied to fin tube sorption reactors for fishing boat ice maker. Results demonstrated that the highest specific cooling power (*SCP*) was as low as 35 W kg^{-1} [24]. Conventionally, *SCP* is calculated based on the mass of sorbent. But considering for the real world application of sorption refrigeration and thermal energy storage, mass and volume of the whole system should be taken into account [25]. Under this scenario, non-fin filling technology by compressing is conducive for system compactness. From this viewpoint, Bao et al. [26] attempted to investigate a resorption refrigeration system for cold storage through electric heating. The compressing technique for sorption reactor was expected for the improved system performance. Results indicated that *SCP* of the resorption refrigeration system ranged from 87 W kg^{-1} to 125 W kg^{-1}. Gao et al. [27] investigated a two-stage sorption freezing system for a refrigerated truck, and composite $CaCl_2$ and $MnCl_2$ were compressed into each unit sorption reactor. It was indicated that although the maximum *SCP* were obtained as 108 W kg^{-1}, hot air inlet temperature was as high as 270 °C. Our previous work had also verified the feasibility of gradient thermal cycle by using compressing technology of composite sorbent. Results mainly demonstrated a good system performance for power and refrigeration cogeneration [28]. Nonetheless, it still remains unknown the degree of improvement between sorption reactors by using compressing technology and conventional fin tube.

In this paper, a novel two-stage sorption refrigeration system is established and analyzed with heat source temperature lower than 100 °C. Composite sorbents with the matrix of ENG-TSA are developed for heat and mass transfer enhancement, and $CaCl_2$-$BaCl_2$-NH_3 is selected as the working pair. For system compactness, compressing technique is applied for sorption reactor. Performance of two-stage refrigeration system with non-fin tube sorption reactor is also compared with that of fin tube reactor.

2. System description of two-stage sorption refrigerator

2.1. Sorbents and reactors

For two-stage sorption refrigeration, $CaCl_2$ is selected as high temperature salts (HTS) whereas $BaCl_2$ is chosen as low temperature salts (LTS). Thermochemical reaction processes of these two salts with ammonia can be referred to Equations (1)–(3). Developing processes of composite sorbents could be referred to reference [14]. First, 2.03 kg ENG-TSA is dried in the oven with controlled temperature of 120 °C for two hours, and the duration is sufficient to eliminate the mass error caused by moisture variation between samples. The oven with model of SX-20-10 is produced by Shanghai Huayan company with working temperature from environmental temperature to 1000 °C. Then 4.67 kg $CaCl_2$ and 5.6 kg $BaCl_2$ are dissolved in the water, respectively. Afterwards, ENG-TSA is mixed in the salt solution separately. As composite sorbent is mixed thoroughly, the mixture is transferred into an oven and dried 7–8 h at the temperature of 160 °C. Finally composite sorbent is compressed into the reactor by pressing machine, which is produced by Rongmei hydraulic company with the maximum force of 10 tons.

Mass ratio of salt and density are often considered to be two major factors in the development of composite sorbents. The higher