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Investigation on thermal characteristics of novel composite sorbent with carbon coated iron as additive

L. Jiang [a,b,*], R.Z. Wang [b], A.P. Roskilly [a]

[a] Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK
[b] Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Carbon coated iron and expanded natural graphite are selected as the additives in developing novel consolidated composite strontium chloride, which is attempted to improve heat and mass transfer performance. Due to anisotropic characteristics, both disk and plate samples are investigated which are parallel and perpendicular to compression direction respectively. It is worth noting that thermal conductivity of composite sorbent increases with the increase of density and the decrease of mass ratio whereas permeability shows a reverse trend. Results demonstrate that the highest thermal conductivity of composite strontium chloride with carbon coated iron could reach 2.95 W m^{-1} K^{-1}, which is improved by 14 times when compared with granular salt. Permeability of composite sorbent ranges from 1.2×10^{-9} m^2 to 4.5×10^{-14} m^2 when density is in the range between 400 kg m^{-3} and 600 kg m^{-3}. Sorption characteristic of composite sorbent with carbon coated iron is also investigated and compared with that not adding carbon coated iron. Under the condition of −10 °C evaporation temperature, sorption reaction rate of composite sorbent with carbon coated iron is better than that without carbon coated iron due to the improved mass transfer performance. Sorption rates of composite sorbents are almost the same when evaporation temperature reaches 10 °C.

1. Introduction

Sorption reaction process is regarded as one of the most prospective approaches for low grade heat utilization due to its various applications of refrigeration [1,2], heat pump [3,4], power generation [5,6], thermal energy storage (TES) [7,8], carbon capture [9], desalination [10], etc. An eternal challenge is how to further realize desirable heat and mass transfer performance [11], which will have a great influence on sorption characteristic [12]. To address this problem, a main solution depends on the improvement of sorption reactor which consists of heat and mass transfer enhancement of heat exchanger and sorbent [13].

Various researches have been investigated to intensify heat transfer of heat exchanger by increasing heat transfer areas of finned tube [14]. Nonetheless, the larger heat transfer area inevitably increases thermal capacity which results in a low system efficiency [15]. In fact, heat transfer enhancement of heat exchanger has a limited improvement on sorption reactor due to the fact that the largest thermal resistance lies in sorbent side [16]. Therefore, heat and mass transfer enhancement of sorbent is essential for sorption systems. It is extensively acknowledged that composite sorbent is an effective method for heat and mass transfer intensification. Different matrices such as expanded natural graphite (ENG) [17], vermiculite [18,19] and carbon nanoparticle [20] have been selected as the additives in developing composite sorbents. Among them, ENG has been widely investigated which could be classified into different types in term of its intercalation compound. Considering ENG without intercalation compound, early study of composite sorbent was carried out by Mauran et al. Results indicated that ENG could improve heat transfer of metal chloride [21]. Later, Tamainot-Telto et al. investigated thermal conductivity of composite sorbent by mixing activated carbon and ENG, and analyzed its possible application for sorption refrigeration and heat pump [22,23]. Jiang et al. [24,25] evaluated thermal conductivity and permeability of eight different metal chlorides with ENG, and compared their properties in the sorption process. As for ENG with intercalation compound, expanded natural graphite treated with sulfuric acid (ENG-TSA) is quite representative, and sulphuric acid is adopted as graphite intercalation compound in the exfoliation process to obtain a lower density [26,27]. Jiang et al. developed composite $CaCl_2$ with ENG-TSA as matrix. Results

* Corresponding author at: Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK.
E-mail addresses: maomaojianglong@sjtu.edu.cn, Long.jiang@newcastle.ac.uk (L. Jiang).

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Nomenclature

A	area of cross section (m^2)
Al@C	carbon coated aluminum
B	shape factor
C	specific heat ($J\ g^{-1}\ K^{-1}$)
EDX	energy dispersive X-ray
ENG	expanded natural graphite
ENG-TSA	expanded natural graphite treated with sulfuric acid
Fe@C	carbon coated iron
GF	graphite flake
K	permeability (m^2)
m	mass flow rate ($kg\ s^{-1}$)
MWCNT	multi-walled carbon nanotube
Ni@C	carbon coated nickel
P	pressure (Pa)
q	gas volume flow rate ($L\ min^{-1}$)
R	gas constant ($J\ mol^{-1}\ K^{-1}$)
SCP	specific cooling power ($W\ kg^{-1}$)
SEM	scanning electron microscopy
T	temperature (°C)
TES	thermal energy storage
t	time (s)
V	axial velocity ($kg\ s^{-1}$)
x	sorption capacity ($kg\ kg^{-1}$)

Greek letters

α	thermal diffusivity ($mm^2\ s^{-1}$)
β	mass ratio of ENG
γ	mass ratio of Fe@C
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	gas viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)
v'	specific volume of saturated liquid ammonia ($m^3\ kg^{-1}$)
v''	specific volume of saturated vapor ammonia ($m^3\ kg^{-1}$)
v	sorption rate ($kg\ kg^{-1}\ s^{-1}$)

Subscripts

a	axial
c	cross section
con	condensation
de	desorption
e	evaporation
in	inlet
max	maximum
out	outlet
$SrCl_2$	strontium chloride
sorb	sorbent

demonstrated that the highest thermal conductivity was able to reach 88.1 $W\ m^{-1}\ K^{-1}$ while permeability decreased to the magnitude of $10^{-14}\ m^2$ [28]. One remarkable fact is that ENG is a good additive to improve heat transfer performance of the sorbent whereas mass transfer is slightly weakened.

Vermiculite has been verified to improve mass transfer performance of composite sorbent. However, heat transfer is not able to be further improved by using vermiculite as matrix since it has a relatively low thermal conductivity [29]. In recent years, carbon nanoparticles are expected to improve heat transfer performance due to its distinguished characteristic. Yan et al. investigated sorption performance of multi-walled carbon nanotubes (MWCNT) and revealed that MWCNT could be selected as an additive for metal chlorides in the development of composite sorbent [30]. After that, a novel composite $CaCl_2$ with MWCNT as matrix was developed for investigating thermal conductivity and sorption kinetic. Results indicated that MWCNT was conducive to mass transfer performance with a limited improvement for thermal conductivity [31]. Comparably, carbon coated metal is also investigated for developing composite sorbent because of its wrapped structure. Carbon coating protects external condition for metal inside with excellent thermo-physical properties remained, which could prevent serious swelling and agglomeration in mass transfer process [32,33]. Since ENG and carbon nanoparticles have respective influence on granular sorbent, it tends to consider a coupling enhancement of composite sorbent by using both of the additives. Our previous work verified that additives of ENG and carbon coated aluminum (Al@C) had a positive influence on heat and mass transfer performance of sorbent [34]. Nonetheless, various carbon coated metals have a different influence on heat and mass transfer of sorbents. This may result in a diversity of sorption and desorption performance, which could be used for different applications.

This paper aims to further investigate novel composite $SrCl_2$ which is impregnated with ENG and carbon coated iron (Fe@C). Composite sorbents with different matrices i.e. carbon coated nickel (Ni@C), Al@C and Fe@C are comprehensively compared and analyzed in term of heat and mass transfer performance. Also sorption characteristic is investigated and analyzed based on the improved heat and mass transfer performance.

2. Development of novel composite $SrCl_2$

Thermochemical reaction process of $SrCl_2$ with ammonia could be according to Eqs. (1) and (2). Table 1 indicates the main parameters of $SrCl_2$ in term of equilibrium desorption temperature, molar mass, maximum cycle sorption capacity, thermal conductivity and permeability, reaction enthalpy and entropy. To simplify the description of chemisorption process of $SrCl_2$, phrase of $SrCl_2$ 8/1 is used in the rest of this paper, which represents that $SrCl_2$ ammoniate reacts with ammonia from 1 mol to 8 mol. As for reaction process from 0 mol to 1 mol, it is difficult to be used in general temperature range of low grade heat i.e. lower than 300 °C.

$$SrCl_2 \cdot NH_3 + 7NH_3 \leftrightarrow SrCl_2 \cdot 8NH_3 + 7\Delta H_{SrCl_2} \quad (1)$$

$$NH_3\ (gas) \leftrightarrow NH_3\ (liq) + \Delta H_{con} \quad (2)$$

ENG is beforehand expanded by the optimal expanding process, i.e. heating expandable natural graphite in an oven at the temperature of 600 °C for 8 min [35]. Detailed developing processes of novel composite $SrCl_2$ with ENG and Fe@C are illustrated in

Table 1
The main parameters of granular $SrCl_2$.

Sorbent	$SrCl_2$ 8/1
Equilibrium desorption temperature (°C)	96 (30 °C condensation temperature)
Molar mass ($g\ mol^{-1}$)	158.4
Reaction enthalpy ΔH ($J\ mol^{-1}$)	41,432
Reaction entropy ΔS ($J\ mol^{-1}\ K^{-1}$)	228.6
Maximum cycle sorption capacity Δx_{max} ($kg\ kg^{-1}$)	0.75
Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	0.21
Permeability (m^2)	10^{-9}