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Research Paper

Investigation on heat and mass transfer performance of novel composite strontium chloride for sorption reactors

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HIGHLIGHTS

- A novel type composite strontium chloride ($SrCl_2$) is developed with ENG and Al@C.
- Anisotropic heat and mass transfer performance is investigated and compared.
- Samples with Al@C enjoys the higher permeability than that without Al@C.
- Both plate and disk samples show their respective advantages for the sorption reactor.

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ABSTRACT

A novel composite strontium chloride ($SrCl_2$) is developed with porous material of expanded natural graphite (ENG) and nanoparticle of carbon coated aluminum (Al@C) as the additives. Samples with different densities and mass ratios of salt are produced and classified into disk and plate types which are parallel and perpendicular to the compression direction, respectively. Thermal conductivity is investigated by laser flash measuring method whereas permeability is tested through Ergun model. It is indicated that with regard to thermal conductivity and permeability, plate samples show the better performance than that of disk samples. The highest thermal diffusivity could reach 5.7 $mm^2 \cdot s^{-1}$ when the density is 800 $kg \cdot m^{-3}$. Correspondingly the highest thermal conductivity is 2.96 $W \cdot m^{-1} \cdot K^{-1}$, which is about 15 times higher than that of ordinary granular $SrCl_2$. Permeability of plate and disk samples range from 9.9×10^{-10} m^2 to 9.89×10^{-14} m^2 and 2.91×10^{-10} m^2 to 2.46×10^{-14} m^2 when the density ranges between 400 $kg \cdot m^{-3}$ and 600 $kg \cdot m^{-3}$. The possible applications are presented and compared by using heat and mass properties of novel composite $SrCl_2$, which show their respective advantages when simulating the performance for the different reactors.

1. Introduction

Sorption reaction process has drawn a burgeoning number of attentions due to its advantages of simple structure and utilizing green refrigerants without Ozone Depletion Potential (ODP) and Global Warming Potentials (GWP) [1,2]. It is worth noting that sorption reaction process can be applied to both refrigeration and thermal energy storage (TES). For sorption refrigeration, specific cooling power (SCP) plays a leading role when considering the system compactness. As for sorption thermal energy storage (STES), heat releasing power is paramount with regard to the different demands of end users. Both SCP and heat releasing power are relevant with cycle time, which is mainly determined by the heat and mass transfer performance of the sorbent.

For heat and mass transfer enhancement, composite sorbent is considered as one effective method which has been widely investigated. As a major matrix of composite sorbent, expanded natural graphite (ENG) has been selected for physical and chemical sorbents [3], which was first invented by Carburet Company in US [4]. Mauran et al. [5] introduced ENG as a matrix to the consolidated composite sorbent, which demonstrated the better thermal conductivity for composite metal chlorides. Tian et al. [6] investigated the heat and mass transfer performance for $CaCl_2$ composite sorbents. Results revealed that the highest thermal conductivity was able to reach 1.66 $W \cdot m^{-1} \cdot K^{-1}$ in term of different densities and mass ratios of salt. Tamainot-Telto and Critoph [7,8] tested the thermal conductivity of activated carbon by using the steady-state heat source method, and evaluated the performance for heat

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Nomenclature

A	area of sample cross section (m^2)
Al@C	carbon coated aluminum
B	shape factor
C	specific heat ($J \cdot g^{-1} \cdot K^{-1}$)
d	thickness of sample (mm)
ENG	expanded natural graphite
ENG-TSA	expanded natural graphite treated with sulfuric acid
K	permeability (m^2)
m	mass flow rate ($kg \cdot s^{-1}$)
MWCNT	multi-walled carbon nanotube
p	pressure (Pa)
q	gas volume flow rate ($L \cdot min^{-1}$)
R	gas constant ($J \cdot kg^{-1} \cdot K^{-1}$)
SCP	specific cooling power ($W \cdot kg^{-1}$)
STES	sorption thermal energy storage
T	temperature (°C)
TES	thermal energy storage
t	time (s)
Greek letters	
α	thermal diffusivity ($mm^2 \cdot s^{-1}$)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
μ	gas viscosity (Pa·s)
v	axial velocity ($m \cdot s^{-1}$)
Subscripts	
a	axial
con	condensation
de	desorption
in	inlet
out	outlet
$SrCl_2$	strontium chloride
sorb	sorbent

pump application. Later, Jiang et al. [9,10] investigated thermal conductivity and permeability of eight different chlorides with ENG, and compared the properties of different consolidated composite sorbents in the sorption process. Besides, expanded natural graphite treated by sulfuric acid (ENG-TSA) was recently introduced to further improve the thermal conductivity of metal chlorides [11,12]. The highest thermal conductivity of the composite sorbent was able to reach 88.1 $W \cdot m^{-1} \cdot K^{-1}$ while the permeability decreased to the magnitude of 10^{-14} m^2 [13]. Nonetheless, one drawback is that price of ENG-TSA was about 60 times higher than that of ENG, and the limited improvement could be achieved for the real sorption refrigeration system [14,15]. It is worth noting that thermal conductivity of the composite sorbent has improved significantly through various matrix when compared with that of granular chlorides. Comparably, mass transfer performance is stagnated or even slightly backwards.

Except for selecting ENG as the matrix, quite a lot of researchers have also focused on improving heat and mass transfer performance by using carbon nanomaterials in recent years. Due to the excellent heat transfer performance, nanoparticles such as multi-walled carbon nanotubes (MWCNT), graphite nanoplatelets, and carbon coated copper were attempted to be selected as the additives for the development of compound organic materials [16–18]. However, less research of composite sorbents is reported to improve heat and mass transfer performance by using carbon nanomaterials as the additives. The sorption performance of ammonia on the packed multi-walled carbon nanotubes was studied by Yan et al. Results indicated that pure MWCNT could be selected as additive for chemical sorbents to improve their heat transfer characteristics though it was not suitable for solid–gas sorption refrigeration owing to its relatively low sorption quantity [19]. Later, Yan et al. [20] investigated sorption characteristics of composite $CaCl_2$ with MWCNT as the matrix, and found that adding MWCNT into chemical sorbents could avoid the agglomeration phenomenon and prevent the sorption performance attenuation of the pure salt. Since carbon nanotubes are usually aggregated and entangled together, it is not easy to be dispersed homogeneously. Compared with carbon nanotubes, nanoparticles such as carbon coated metal with core-shell structure indicate large potentials for developing the composite sorbents. It reveals that carbon coating is able to protect the external condition for the metal core, and the metal core can take a promoting effect while maintaining the excellent thermo-physical properties [21,22]. The granular shape in nanometer size tends to be easy to occupy the porous structure of composite sorbents with ENG. As a result, it could avoid great swelling and agglomeration in the mass transfer process.

In this paper, strontium chloride ($SrCl_2$) impregnated with both ENG and carbon coated Aluminum (Al@C) as the additives is investigated for the comprehensive heat and mass performance since there is little research work about the composite $SrCl_2$ with these two additives. Due to the anisotropic thermal conductivity and permeability of compact ENG [23], novel composite $SrCl_2$ is investigated and compared in term of disk and plate samples, which are parallel and perpendicular to the compression direction respectively.

2. Development of novel composite $SrCl_2$

Compared with the conventional composite sorbent, the novelty is to introduce the nanoparticle and porous material i.e. Al@C and ENG into the sorbent for the improvement of heat and mass transfer performance. Al@C is expected to further improve mass transfer of the sorbent whereas ENG is conducive to the heat transfer performance. The thermochemical reaction process of $SrCl_2$ with ammonia can be according to the Eqs. (1) and (2).

The development processes of the novel composite $SrCl_2$ can be referred to the Ref. [24]. ENG is expanded by the optimal expanding process, i.e. heating untreated natural graphite in an oven at the temperature of 600 °C for 8 min [25]. First, ENG is dried in the oven with controlled temperature of 120 °C. Meanwhile, the nanoparticle i.e. Al@C is dispersed in ethanol with ultrasonic bath for 30 min to prevent the aggregation of Al@C in the mixing process. $SrCl_2$, ENG and Al@C are stirred and mixed together by the ultrasonic treatment for another 30 min. The mixture will be dried in an oven at 120 °C for 48 h. Finally, the mixture is put into a vessel and pressed by the compression machine.

In the development of the novel composite $SrCl_2$, mass ratio of salt and density are two major factors. The crack will easily happen if the density is lower than 400 $kg \cdot m^{-3}$, which results in the poor mechanical stability of the composite sorbent. Also worth noting that the higher density and lower mass ratio of salt are, the lower permeability and the higher thermal conductivity will become. For testing the thermal properties, density of the novel composite $SrCl_2$ is selected in the range from 500 $kg \cdot m^{-3}$ to 800 $kg \cdot m^{-3}$ for good mechanical stability. The mass ratio between $SrCl_2$ and ENG ranges from 50% to 83% i.e. from 1:1 to 5:1 whereas the ratio between ENG and Al@C is adopted as 20:1 [24]. Since anisotropic