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Investigation on thermal conductive consolidated composite $CaCl_2$ for adsorption refrigeration

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Properties such as thermal conductivity, permeability, adsorption concentration of adsorbents are paramount for adsorption refrigeration. A novel consolidated composite $CaCl_2$ with the matrix of expanded natural graphite treated with sulfuric acid (ENG–TSA) was investigated and the samples were developed according to different mass ratio of salt and different density. Results indicate that samples have very perspective heat and mass transfer performance. The highest thermal conductivity was 88.1 W/(m K), which is 22 times higher than that with the matrix of expanded natural graphite (ENG) and 400 times higher than ordinary granular $CaCl_2$. Permeability of adsorbent was between 9.31×10^{-10} to 3.05×10^{-14} m^2 while the density ranged between 300 and 500 kg/m^3. Adsorption performance of composite $CaCl_2$ was tested, and the results showed that for the samples with different density and salt mass ratio adsorption quantity ranged between 0.364 g/g to 0.4492 g/g while the cooling temperature and evaporating temperature changed from 25 to 35 °C and −10 to 15 °C, respectively. Furthermore, under the conditions of same heat source, cooling water and evaporating temperature, the heating time for the tube adsorber of composite $CaCl_2$ with ENG–TSA as the matrix was almost 2.5 times less than that with ENG as the matrix.

1. Introduction

As one environmental benign and energy saving technology, solid–gas chemisorption is prospective for converting the low grade thermal energy into the high grade refrigeration power [1–3]. Adsorbents like activated carbon (AC), silica gel, and chlorides are widely used in adsorption refrigeration and heat pump systems. The heat and mass transfer performance is regarded as one key indicator for adsorption refrigeration systems because it influences the adsorption/desorption rate and as well as the power density significantly [4]. In order to improve thermal conductivity, consolidated composite adsorbents that were characterized as high thermal conductivity have been investigated by various researchers. For example, Eun [5] and Wang et al. [6] manufactured silica gel and AC compound blocks by mixing the adsorbents with expanded natural graphite (ENG) powders, and both achieved reasonable highly improved thermal conductivity and permeability. Tamainot-Telto and Critoph [7] made use of monolithic AC leading to the thermal conductivity up to 0.44 W/(m K). K Wang [8] et al. also developed a new type of compound adsorbent mixed by $CaCl_2$ and ENG, which greatly improved thermal conductivity of granular $CaCl_2$ by about 36 times. Jiang et al. [9] investigated thermal conductivity and permeability of eight different chlorides with ENG, and compared the properties of different consolidated composite adsorbents. Previous research work showed that expanded natural graphite treated by sulfuric acid (ENG–TSA) is a prospective heat transfer matrix, and the highest thermal conductivity for this matrix could reach 337 W/(m K) at a bulk density of 831 kg/m^3 [10]. Consequently, Wang et al. [11] evaluated the thermo-physical properties of composite AC with the matrix of ENG–TSA, and the results showed that the highest effective thermal conductivity was 34.2 W/(m K), that is 150 times higher than ordinary granular AC. However, for chemical adsorbent such as $CaCl_2$, the research work mainly concentrated on the matrix of ENG. There is little research work on the performance of consolidated adsorbent with ENG–TSA as the matrix. In order to investigate such type of novel adsorbents, different consolidated composite samples were developed, and the thermal conductivity, permeability, and adsorption performance of the adsorbents were studied.

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Nomenclature

B_r	shape factor of the samples
C_p	specific heat, kJ/(kg K)
D_1	inside diameters of cylinder, m
D_2	outside diameter of cylinder, m
d	thickness of testing sample, m
d_1	tube external radius, m
d_2	tube thickness, m
g	gravity acceleration, m/s^2
K_r	permeability, m^2
L	axial length of heating wall, m
L_1	distance between pipe end and fin, m
L_2	fin thickness, m
L_3	distance between fins, m
L_4	fin height, m
m_a	gas mass flow rate, kg/s
m_{rd}	mass flow rate of gas for radial diverging mode, kg/s
m_{rc}	mass flow rate of gas for radial converging mode, kg/s
m_{salt}	mass of adsorbent, kg
N	fin number
p_1	inlet pressure of air, Pa
p_2	outlet pressure of air, Pa
q_v	volume flow rate of gas, L/min
Q	heat flux, W
R_1	inner radius of sample, m
R_2	outer radius of sample, m
S	effective heating area, m^2
T	sample temperature, K
t_{50}	half cycle time, s

Greek symbols

λ	thermal conductivity, W/(m K)
α	thermal diffusivity, m^2/s
ΔT	average temperature gradient, K
Δx	cycle adsorption quantity, kg/kg
Δz	thickness of the samples, m
$v'(T_e)$	specific volume of saturated liquid ammonia, m^3/kg
$v''(T_e)$	specific volume of saturated vapor ammonia, m^3/kg
μ	gas viscosity, Pa s
ρ	density, kg/m^3
v_{rc}	velocity of the refrigerant vapor of radial converging, m/s
v_{rd}	velocity of the refrigerant vapor of radial diverging, m/s

2. Preparation of the consolidated adsorbents

ENG–TSA is manufactured by Mersen in France. The sample is manufactured from natural graphite soaked in sulfuric acid, which becomes intercalated in the layered structure of the graphite. Finally the sample is exfoliated by heating in flame, forming expanded graphite with much lower density than normal expanded natural graphite whilst the intercalated acid element is removed [10]. The anisotropic thermal conductivity and permeability of consolidated ENG–TSA matrix have already been studied [6], and results indicated that both optimal heat and mass transfer directions were perpendicular to the compression direction. Therefore, in the experiments only plate samples were utilized.

The manufacturing process is shown in Fig. 1. Firstly the ENG–TSA is dried in the oven at the temperature of 120 °C. Secondly the $CaCl_2$, water and ENG–TSA are mixed together. Then the composite of $CaCl_2$, ENG–TSA, and water are dried in the oven at the temperature of 120 °C for 4 h to make sure there is no retained water. After that the composite of $CaCl_2$, ENG–TSA, and water is dried in the oven at the temperature of 260 °C for 4 h to remove the crystal water. Finally the composite is compressed by a pressing machine into a block.

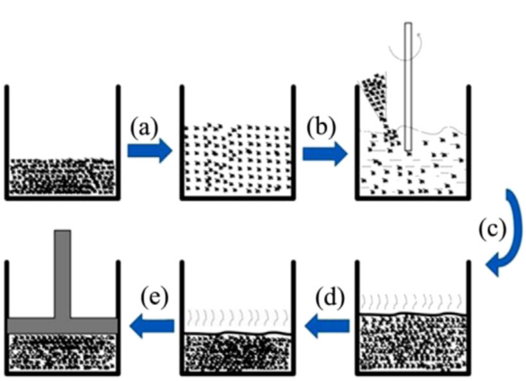

Fig. 1. Producing processes of consolidated composite salts, (a) drying process of granular ENG–TSA, (b) mixture of granular $CaCl_2$, ENG–TSA, and water, (c) drying the composite adsorbent of $CaCl_2$, ENG–TSA, and water, (e) drying process of the consolidated adsorbent (f) compressing process of composite adsorbent.

Experiments showed that the mechanical stability of the consolidated composite adsorbents is related with the ratio of the ENG–TSA and the density. The cracks easily happen on the composite adsorbents when the mass ratio of $CaCl_2$ is larger than 80% and the density is larger than 800 kg/m^3. Thus in the experiments the mass ratio of the salt lower than or similar to 80% is chosen. Considering that the mass ratio of the salt cannot be too small otherwise the SCP (specific cooling power per kilogram adsorbent) will be small, the mass ratio of the salt in the experiments is larger than 50%. I.e. the percentage of salt in the composite adsorbent in the experiments is 50%, 67%, 75%, 80% and 83%, respectively. Since the refrigerant is ammonia and working pressure is positive for the adsorbents, the density of the consolidated adsorbent in the experiments ranges from 300 to 600 kg/m^3 because the lower density will influence SCP as well as the thermal conductivity and too high density will influence the permeability of the adsorbents [12].

The bulk density of pure salt in compact adsorbent was calculated by dividing the whole volume with the mass of $CaCl_2$, and the results were shown in Table 1. Different serials are divided by the mass ratio of salt in the composite adsorbents. For example, serial 1 is for the salt mass ratio of 50%. Different samples are divided by different bulk density of composite adsorbents that ranges from

Table 1
Samples with different bulk density of adsorbent and different bulk density of $CaCl_2$.

Serial No.	Mass ratio of $CaCl_2$ %	Density of composite adsorbent						
		Sample No. 1	2	3	4	5	6	7
		300	350	400	450	500	550	600
		Bulk density of $CaCl_2$						
		Sample No. 1	2	3	4	5	6	7
1	50	150	175	200	225	250	275	300
2	67	200	233.3	266. 7	300	333.3	366.7	400
3	75	225	262.5	300	337.5	375	412.5	450
4	80	240	280	320	360	400	440	480
5	83	250	291. 7	333. 3	375	416. 7	458.3	500