International Journal of Heat and Mass Transfer 68 (2014) 435–443

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermal conductivity, pore structure and adsorption performance of compact composite silica gel

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ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form 30 September 2013
Accepted 30 September 2013
Available online 15 October 2013

Keywords:
Thermal conductivity
Pore parameters
Expanded natural graphite
Silica gel
Composite adsorbents

ABSTRACT

A novel composite solid desiccant material is proposed in this study to enhance thermal conductivity and adsorption performance of silica gel. This desiccant material is fabricated by combining silica gel with expanded natural graphite treated with sulfuric acid (ENG-TSA) as a host matrix. The performance of this composite material with respect to different densities and different silica gel ratios was investigated. Experimental results showed that the highest thermal conductivity of consolidated composite adsorbents is 19.1 W m^{-1} K^{-1}. This is an increase of more than 270 times as compared to that of pure silica gel. Analysis on pore parameters demonstrated that the compression of simple mixture of ENG-TSA with silica gel does not destroy the morphology of silica gel. In addition, both non-equilibrium and equilibrium adsorption performance of composite silica gel and pure silica gel were evaluated. Non-equilibrium adsorption performance indicated prominent enhancement of heat transfer, whilst equilibrium adsorption performance indicated a reasonable mass transfer.

1. Introduction

Increased need for indoor comfort has led to an increase demand in cooling. However, according to International Institute of Refrigeration in Paris, about 15% of global electricity generated is used for cooling [1]. Solid desiccant cooling are regarded as energy-saving cooling technologies because they are driven by low grade heat such as waste heat and solar energy [2]. These systems are also considered eco-friendly since they employ natural working fluids, i.e. water vapor, as refrigerants [3]. As one of the most common desiccant material, silica gel is widely used for dehumidification because of its high porosity, stable adsorption characteristics and low cost [4]. However, poor heat transfer property of silica gel leads to smaller amount of adsorption for a given cycle time, which consequently results in lower refrigeration power as well as the specific cooling power (SCP) [5,6]. Measures to achieve high thermal conductivity without or with minimal reduction in water uptake are among some of the solutions considered to overcome this problem.

Consolidation or addition of thermal conductive materials including metal [7], expanded natural graphite (ENG) [8], polymer matrix [9], expanded vermiculite [10] and so forth, is taken as an effective solution to improve the thermal properties of original materials. Among these mentioned materials, ENG had been widely investigated to enhance the heat transfer properties of adsorbents for its high thermal conductivity, porous structure and inert chemical property [11–14]. In early research, Mauran et al. [11], and Han et al. [12] used ENG as a heat transfer additive in adsorption and chemical heat pumps. Later, Eun et al. [13] manufactured composite blocks consisting of silica gel and ENG in a silica gel-water adsorption heat pump system. Their results revealed a considerable enhancement of thermal conductivity and refrigeration performance with the use of ENG in the composite blocks. Wang et al. [14] also confirmed that a simple composite consolidated adsorbent of Active Carbon (AC) and ENG could lead to better heat and mass transfer performance. Bonnissel et al. [15] and Wang et al. [16] reported a new type of ENG that had a much lower bulk density and higher thermal conductivity. Wang et al. [16] found out that its maximum thermal conductivity was 337 W m^{-1} K^{-1} at a bulk density of 831 kg m^{-3} and named it expanded natural graphite treated with sulfuric acid (ENG-TSA). To convince better heat transfer property of ENG-TSA as a host matrix, Wang et al. [17] conducted the thermal conductivity tests of AC/ENG-TSA and AC/ENG composite adsorbents, which showed that the former was about 7 times higher than the optimal value of AC/ENG composite adsorbents.

Previous research shows that compressed ENG-TSA has much higher thermal conductivity than the compressed ENG [17]. In this paper, consolidated and composite adsorbents of silica gel and ENG-TSA with different ratio and different density are investigated to enhance the thermal conductivity and adsorption performance of silica gel. Firstly, the thermal conductivity, surface area and pore parameters of composite blocks are discussed. Then both the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.075

Nomenclature

T	sample temperature, K
λ	thermal conductivity, W m^{-1} K^{-1}
α	thermal diffusivity, m^2 s^{-1}
c_p	specific heat, kJ kg^{-1} K^{-1}
ρ	density, kg m^{-3}
ε	porosity
V_P	porous volume, cm^3
V_t	overall volume, cm^3
$\rho_{i,m}$	ideal maximal density of compacted composite blocks, kg m^{-3}
ρ_{sg}	bulk density of granular silica gel, kg m^{-3}
$\rho_{m,G}$	maximum density of consolidated ENG-TSA blocks, kg m^{-3}
W_{sg}	weight fraction of silica gel in composite blocks, %
ρ_m	real maximum density of the compacted composite blocks, kg m^{-3}
ρ_i	bulk density of silica gel/ENG-TSA, kg m^{-3}
M_i	mass of silica gel/ENG-TSA in composite adsorbents, g
$\triangle V_P/\triangle d_p$	derivative pore volume calculated by BJH method, cm^3 g^{-1} Å^{-1}
q_t	water uptake on silica gel at time, kg kg^{-1}
q_∞	water uptake on silica gel at equilibrium, kg kg^{-1}
d_p	diameter of pore, Å
T	sample temperature, K

equilibrium and non-equilibrium adsorption performance of composite silica gel blocks and pure silica gel are evaluated.

2. Experiment work

2.1. Production of the consolidated blocks

ENG-TSA used in this paper was manufactured by Mersen Company in France, while silica gel was purchased from a Chinese company named Shanghai Chang Quan Silica Gel Desiccant Co., Ltd. Silica gel, which is powder like, with small grain size of 100–200 mesh was used.

The preparation process of consolidated composite adsorbent of silica gel and ENG-TSA was done according to the designed procedure. Firstly, both the granular ENG-TSA and granular silica gel were dried in the oven at the temperature of 120 °C for 4 h to ensure sufficient dryness, after which they were carefully weighed. Silica gel was then moisturized with water by the mass ratio of 1:1 before mixing with ENG-TSA for uniformity in the mixture. The composite of silica gel, ENG-TSA, and water was then uniaxially compressed by a pressing machine. Finally the consolidated samples were dried in the heater at the temperature of 120 °C for 4–5 h.

2.2. Test of thermal conductivity and thermal diffusivity

Thermal conductivity and thermal diffusivity are important thermodynamic parameters for heat transfer performance in desiccant cooling. In this paper, both the thermal conductivity and diffusivity of compact composite adsorbents and silica gel were measured using Xenon flash apparatus, which employs the principle of Laser flash measuring method [18]. In this method, a light pulse is transmitted to the rear side of a testing sample, resulting to a temperature rise on the front surface. Thermal diffusivity is then determined by analyzing the resulting temperature–time curve. With the measured specific heat and density, the thermal conductivity of the test sample is given by the following equation:

$$\lambda(T) = \alpha(T) \times C_p(T) \times \rho(T) \quad (1)$$

where T is temperature (K), λ is the thermal conductivity (W m^{-1} K^{-1}), α is thermal diffusivity (m^2 s^{-1}), C_p is the specific heat (J kg^{-1} K^{-1}), and ρ is the density (kg m^{-3}).

The thermal conductivity of consolidated composite adsorbents was measured perpendicular to the direction of compression due to its high anisotropic performance. This was in agreement with experiments done in compressed ENG-TSA which showed a higher perpendicular thermal conductivity of about 50 times higher than the parallel thermal conductivity [16].

2.3. Test of surface area and pore parameters

In this test, silica gel was used as desiccant for water vapor in composite blocks. For this reason, porosity of the material plays an important role to evaluate the potential volume for water vapor uptake. Pore size also plays a significant part in determining the rate at which water vapor will flow through the porous media in adsorption process.

In order to analyze the influence of consolidation with ENG-TSA, surface area and pore parameters, such as pore volume, pore size and porosity of compact composite adsorbents were tested and compared with pure silica gel by an Accelerated Surface Area and Porosimetry System (ASAP 2020). The system utilizes the principle of static volumetric technique [19] to obtain adsorption and desorption isotherms and applies multiple gas sorption laws to get the information of surface area and pore parameters of a solid material.

Pore volume measurement helps predict the capacity of a porous media, while porosity describes the fraction of void space in it, as defined by the ratio [19]:

$$\varepsilon = V_P/V_t \quad (2)$$

where ε is used to denote porosity, V_P is the porous volume (m^3), and V_t is the overall volume of the porous medium (m^3), including the solid and void components.

Surface area and pore structure were tested and analyzed under the temperature of 77 K, with nitrogen used as adsorbate gas. Surface area was calculated with BET equations, whilst pore volume and pore size distributions were calculated according to the BJH theory [20].

2.4. Test of adsorption performance

To confirm better heat transfer in composite silica gel the non-equilibrium adsorption tests were conducted. Meanwhile the equilibrium adsorption tests were also proceeded to prove the favorable water uptake properties of composite silica gel with the addition of ENG-TSA. Both the non-equilibrium and equilibrium adsorption tests were conducted in a thermo-humidistat chamber, with granular silica gel as contrast sample. Each of them has two processes, i.e. preparation and measurement processes.

In preparation process of non-equilibrium adsorption performance tests, samples were heated to 100 °C in the oven for more than 4 h to remove moisture, after which measurements were taken. Dry samples were taken out from the oven and quickly weighed in an electronic balance with measurement accuracy of 0.001 g. A recorder was used to ensure the whole weighing time as short as 30 s. As soon as the weighing process completed, the