

Research Paper

Finding optimal conductive additive content to enhance the performance of coated sorption beds: An experimental study

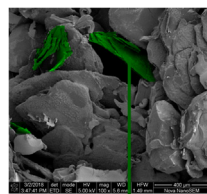
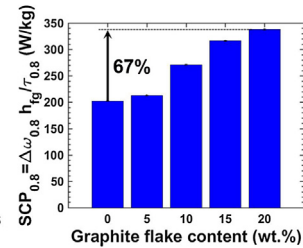
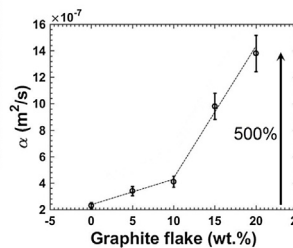
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HIGHLIGHTS

- Transient measurement using custom-built gravimetric large pressure jump test bed.
- Graphite flake additives in CaCl_2 -silica gel composite sorbents.
- Enhancement of sorbent thermal diffusivity by 500% with 20 wt% graphite flake.
- 65% increase in SCP and 17% increase in COP with 20 wt% graphite flake.

GRAPHICAL ABSTRACT

Graphite flake in CaCl_2 -silica gel composite

ARTICLE INFO

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ABSTRACT

Adding natural graphite flakes to sorbents of sorption cooling systems can significantly enhance the overall thermal diffusivity, while reducing the active material and increasing mass transfer resistance. To find an optimum compromise between these counteracting trends, the sorption performance of CaCl_2 -silica gel composite sorbents with 0–20 wt% graphite flakes content are tested using a custom-built gravimetric large pressure jump (G-LPJ) test bed. It is observed that in the early stages of sorption, i.e. sorption time less than 20 min, graphite flakes additives increase the specific cooling power (SCP) (from 365 to 604 W/kg for 5 min sorption time, a 65% increase) and coefficient of performance (COP) (from 0.46 to 0.54 for 5 min sorption time, a 17% increase) due to the enhanced sorbent thermal diffusivity (from 0.23 to 1.38 m^2/s , a 500% increase). Over time, as the sorbent approaches equilibrium, the performance enhancement deteriorates by increasing graphite flakes content since there is less active material in the composite. Furthermore, adding 20 wt% graphite flakes to the composite sorbent has led to a 67% increase in $\text{SCP}_{0.8}$ (SCP when the sorbent reaches 80% of equilibrium).

1. Introduction

Vapor compression refrigeration systems (VCR) consume approximately 15% of global electrical energy and use environmentally harmful refrigerants, i.e. hydrofluorocarbon [1–3]. Moreover, vehicle air conditioning (A/C) systems, VCR, significantly increases fuel consumption, in fact vehicle A/C is the second largest consumer of fossil energy after vehicle propulsion [4]. As an alternative to VCR, sorption

cooling systems are eco-friendly since they employ natural working fluids, i.e. water vapor, as refrigerants [5,6]. Furthermore, sorption cooling systems utilize materials with low regeneration temperatures and can be powered by low-grade heat sources, i.e. temperature sources around 80 °C, including solar thermal energy and industrial waste heat [5]. In addition, in an internal combustion engine (ICE) vehicle, almost 70% of total fuel energy is dissipated through the ICE coolant and exhaust gas in the form of waste heat [7], which can be used to regenerate

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Nomenclature		sorber)	
c	specific heat capacity, J/kg K	<i>Subscripts</i>	
h_{ads}	enthalpy of adsorption, J/kg	evap	evaporator/evaporative
h_{fg}	enthalpy of evaporation, J/kg	eq	equilibrium
p	pressure, Pa	sorb	sorbent
p_0	saturation pressure, Pa	sorp	sorption
Q	energy, J	<i>Abbreviations</i>	
T	temperature, K	COP	coefficient of performance
t	time (s)	HEX	heat exchanger
<i>Greek symbols</i>		G-LPJ	gravimetric large pressure jump
α	thermal diffusivity, m^2/s	SCP	specific cooling power
τ	cycle time, s	TCR	thermal contact resistance
φ	graphite flake content in the sorbent (g H_2O/g dry		

the sorbent and generate cooling for air conditioning.

However, commercialization of sorption cooling systems is limited by fundamental challenges, including low specific cooling power (SCP) and low coefficient of performance (COP) due to poor heat transfer between the sorber bed heat exchanger (HEX) and the sorbent material [8–10]. Sorber beds need to be cooled/heated during the sorption/desorption process to maintain efficient uptake. As such, improving heat transfer characteristics of the sorbent and HEX are crucially important to the overall performance of the sorption systems. It has been shown in our previous studies [11,12] that the sorbent thermal diffusivity is the main limiting factor in the heat transfer from the sorbent to the heat transfer fluid through the heat exchanger. Hence, developing composite sorbents with higher thermal conductivity and lower specific heat and density (low thermal inertia) can enhance the overall performance of adsorbent beds [13,14]. Addition of high thermal diffusivity material can form higher conductivity paths by filling up the pores in the microstructure of the adsorbent particles to increase the overall thermal diffusivity. However, in general, these additives decrease the active material fraction and increase the vapor transport resistance [15]. Moreover, many microporous adsorbents have open pore structures and high total pore volumes [16]. As a result, significant improvements in thermal diffusivity of microporous adsorbent materials have been limited to high additive fractions (> wt%), compromising the total adsorption capacity.

Demir et al. [17] used metallic particle additives to enhance heat transfer rate through an unconsolidated adsorbent bed. Silica gel with metallic additives of copper, brass and aluminum (strips with 0.1 mm thickness, 2 mm width and 10 mm length) up to 15% in mass basis has been investigated. They noticed that the addition of 15 wt% of aluminum pieces to silica gel enhanced thermal conductivity of a pure silica gel bed by 242% (from 0.106 to 0.363 W/m K). They did not study the effects of the additives on the overall performance of

adsorption cooling systems. Askalany et al. [18] studied the effect of using metallic additives on thermal conductivity of granular activated carbon (1–2 mm). Fillings of iron, copper and aluminum at different mass concentrations ranging from 10 to 30% have been studied. They reported that thermal conductivity increased with an increase in metallic additives concentrations. However, metallic additives are not suitable for corrosive sorbents such as salt/porous matrix composites. Therefore, graphite particles/additives might be a better candidate when a corrosive sorbent is used. Compared to most metals, graphite has higher intrinsic thermal conductivity, lower molecular weight and excellent stability at high working temperatures [15], and therefore can be a suitable additive to enhance the sorbent thermal diffusivity.

Graphite is by far the most studied additive when developing composite sorbents with the purpose of enhancing thermal conductivity [19]. When comparing different host matrices or/and additives, graphite presents the highest conductivity values [20]. For instance, Mauran et al. [21] reported thermal conductivities of about 10–40 $W(m\cdot K)^{-1}$ for a $CaCl_2$ -expanded natural graphite (ENG) composite.

Summary of the existing studies on the effect of graphite additives on the heat and mass transfer of sorbent materials and the gaps in the open literature are presented in Table 1. It can be seen that some of the studies did not report the water uptake, whereas the effect of graphite additive on water uptake is crucial in sorption performance and should be investigated. The majority of the studies that reported the water uptake, investigated the equilibrium uptake using small-scale measurements, i.e. where sorbents in the order of milligrams are tested, which reaches equilibrium quickly because of the low heat and mass transfer resistances. However, due to the transient behavior of sorber beds and relatively larger heat and mass transfer resistances in sorption chillers, the sorbent does not reach equilibrium to become fully saturated/dried during sorption/desorption in large-scale sorption cooling systems [22]. Hence, in this paper, a gravimetric large pressure jump

Table 1

Summary of the existing studies on the effect of graphite additive on heat and mass transfer of the sorbent and the gap in the research.

Ref. No.	Sorbent	Thermally conductive additive	Increase in thermal conductivity $W(m\cdot K)^{-1}$	Uptake ($g\cdot g^{-1}$)	Gap in the research
[23]	Packed bed zeolite	Expanded graphite	0.09 to 10	Not reported	Uptake not reported.
[16]	4A-zeolite-based composite	Graphite (40%)	0.1 to 0.35	Equilibrium uptake decreased from 0.23 to 0.13	Equilibrium uptake reported.
[24]	$CaCl_2$	Expanded graphite	Up to 9.2	Not reported	Uptake not reported
[25]	$CaCl_2$ and silica gel	Graphite flakes (20%)	0.57 to 0.78	Equilibrium uptake decreased from 0.32 to 0.15	Equilibrium uptake reported
[26]	silica gel	Expanded graphite (40%)	Up to 19	Transient uptake increased	Graphite weight was not included in calculations
[27]	silica gel	Expanded natural graphite treated with sulfuric acid (ENG-TSA)	Up to 20	Transient uptake increased	Graphite weight was not included in calculations

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