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# Effective thermal conductivity modeling of consolidated sorption composites containing graphite flakes

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ABSTRACT

Thermal conductivity of $CaCl_2$-silica gel composites adsorbent, which is generally used in water-based adsorption cooling systems, can be enhanced by adding natural flakes graphite and consolidating the mixture with a binder. In this study, a bound conduction model with a unit cell approach is employed to predict the effective thermal conductivity of consolidated composite. The model takes the volume fraction, flake size and orientation of the graphite flakes as input, and calculates the effective thermal conductivity of the consolidated mixture. To validate the model result with experimental data, consolidated adsorbents with 0–20 wt% graphite flakes were prepared and their thermal conductivity was measured by Transient Plane Source (TPS) method. The results show that the addition of graphite flakes into consolidated adsorbent increases thermal conductivity from 0.13 to 0.57 $W \cdot m^{-1} \cdot K^{-1}$ when tested at 2% RH and 35 °C. The predictions of the model at steady-state condition qualitatively agreed with the experimental data.



## 1. Introduction

Heat-driven sorption technology, as a sustainable and clean solution for thermal management and heat storage, has drawn significant interest in academic and industrial research community. This interest has been intensified in the last decade as environmental and climate changes issues are becoming major global challenges. Numerous studies aim to improve material sorption performance, as it is at the core of sorption cooling or storage systems [1]. Due to the nature of sorption process, heat transport properties, e.g. thermal diffusivity and thermal conductivity, of the adsorbent material plays an important role in their performance, since increasing thermal diffusivity can enhance the heat transfer rate that leads to faster sorption/desorption cycles thus more efficient (more compact) heat-driven sorption chillers [2]. A key part of the sorption chillers design is developing adsorbent materials (or composites) with superior hydrophilicity, high water uptake capacity, low regeneration temperature (60–150 °C) [3], and high thermal diffusivity. Silica gel [4] and silicoaluminophosphate [5] have suitable adsorption properties at operating conditions of water-based sorption cooling systems, i.e. low temperature (30–90 °C) and pressure (1.2–5.6 kPa); however, these highly porous sorbents have low effective thermal conductivity 0.13 $W \cdot m^{-1} \cdot K^{-1}$ [6]. Methods used to improve heat transfer in sorption beds include: (i) coating heat exchanger with adsorbent material [2], this will reduce the thermal contact resistance at the interface between the heat exchanger and the coated sorption material; (ii) growing adsorbent on the adsorber bed surface [7]; (iii) adding thermally conductive materials such as metals [8] and consolidating adsorbents in a thermally conductive porous matrix [9], which lead to an increase in the bulk thermal conductivity of sorption composite. The effective thermal conductivity of a wide range of adsorbents reported in the literature is shown in Table 1.

Tanashev et al. [9] measured the thermal conductivity of hygroscopic salts ($CaCl_2$ [10], LiBr and $MgCl_2$) confined silica gel (KSK) with 0.1–0.8 g/g water content using the transient hot wire method at 290–300 K and observed an increase in thermal conductivity from 0.1 to 0.5 $W \cdot m^{-1} \cdot K^{-1}$ with increasing water content. Aristov et al. [11] measured the thermal conductivity of consolidated sorbents, silica gel (KSK) with 36.6 wt% $CaCl_2$ and silica gel (KSK) with 42.7 wt% LiBr and reported that the thermal conductivity increased significantly as the water uptake of the sorbent increased, while the effect of temperature and pressure on thermal conductivity was almost negligible. Restuccia et al. [12] developed and experimentally validated a theoretical model to predict the effective thermal conductivity of wet zeolite. The effective thermal conductivity of zeolite 4A was measured by a hot wire method at different temperatures and water content. All the above-

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**Nomenclature**

| | |
|---|---|
| TPS | Transient Plane Source |
| RH | Relative Humidity |
| k | thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$ |
| b | basic cell half side, m |
| $r_p$ | particle radius, m |
| r | disk radius, μm |
| t | disk thickness, μm |
| w | unit cell width, μm |
| a | unit cell dimension, μm |
| R | thermal resistance, $K \cdot W^{-1}$ |
| T | temperature, K |
| $\dot{Q}$ | heat flow rate, W |
| $k_{eff}$ | effective thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$ |
| PVP | polyvinylpyrrolidone |
| $t_{sample}$ | sample thickness, mm |
| A | sensor area, $mm^2$ |
| ΔT | temperature rise between sensor and sample, K |

*Subscripts*

| | |
|---|---|
| *e* | effective |
| *p* | particle |
| *m* | medium |
| *L* | lower bound |
| *U* | upper bound |
| *g* | graphite flake |
| *s* | continuous medium |

*Greek symbols*

| | |
|---|---|
| φ | volume fraction |
| n | shape factor |
| ψ | sphericity |
| ρ | density, $g \cdot cm^{-3}$ |
| θ | angle, degree |

mentioned studies showed a significant effect of water content on the thermal conductivity of sorption composites.

Fayazmanesh et al. [16] synthesized consolidate composite with addition of copper powder and graphite flakes. Graphite flake particles are distributed evenly in composite adsorbent when copper powder particle inhomogeneously distributed at the bottom surface of samples.

As shown in Table 1, composite adsorbent with expanded graphite has higher thermal conductivity compared to silica or zeolite based composites. This is while the thermal conductivity

**Table 1**
Thermal conductivity of some adsorbent materials.

| Adsorbent | Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$ | Measurement method and conditions | Ref. |
|---|---|---|---|
| Calcined silica gel (KSK)/$CaCl_2$ | 0.1–0.5 | - Transient hot wire method<br>- Water content (0–0.8 g/g)<br>- Temperature 16–27 °C | [10] |
| - Consolidated silica gel (KSK)/$CaCl_2$ (36.6 wt%)<br>- Consolidated silica gel (KSK)/LiBr (42.7 wt%) | 0.12–0.16<br>0.1–0.13 | - Transient hot wire method<br>- Air pressure: 10–1,000 mbar<br>- Binder: 20 wt% aluminium hydroxide | [11] |
| Consolidated silica gel (15 wt% binder) | 0.24–0.26 | - Guarded-hot plate apparatus<br>- Silica gel coated between copper plates<br>- Temperature: 35–50 °C<br>- Contact pressure: 0–90 bar<br>- Polyvinylpyrrolidone used as binder | [6] |
| - Compressed silica gel (KSK)/$CaCl_2$<br>- Compressed silica gel (KSK)/LiBr<br>- Compressed silica gel (KSK)/$MgCl_2$<br>- Alumina/$CaCl_2$ | 0.12–0.5<br>0.16–0.4<br>0.14–0.42<br>0.12–0.41 | - Transient hot wire method<br>- Measurements took place at 16–27 °C<br>- Water content (0–0.9 g/g)<br>- No binder used | [9] |
| Wetted zeolite 4A | 0.17–0.25 | - Transient hot wire method<br>- Filling gas: air at 1 bar<br>- Measurement temperatures (50–200 °C)<br>- Water content (0.02–0.2 g/g) | [12] |
| Consolidated composite activated carbon | 1–4 | - ASTM E1530 guarded thermal flow meter method<br>- Samples with different ratio of activated carbon were made (33–50%) | [15] |
| Consolidated silica gel (15 wt% binder)-graphite flake (0–20 wt%) | 0.13–0.42 | - Transient Plane Source (TPS)<br>- Connected to humidifier<br>- Measurement temperature 35 °C<br>- Relative Humidity 2–20% RH | [16] |
| Consolidated composite activated carbon | 0.9–2.5 | - Guarded hot plate method<br>- Samples with different ratio of activated carbon and expanded graphite were made | [17] |
| - $CaCl_2$ (powder)<br>- $CaCl_2$ (pellet)<br>- Composite-KP50 expanded graphite (20%) and $CaCl_2$<br>- Consolidated composite- KP50 expanded graphite (20) and $CaCl_2$ | 0.31–0.39<br>0.11–0.14<br>0.4–0.47<br>0.31–0.47 | - Transient hot wire method<br>- Filling gas: air at 1 bar<br>- Measurement take place at different temperature<br>- Different pressure applied for making consolidated samples (0–0.67–20)<br>- Dry samples | [18] |