Effective thermal conductivity of packed bed adsorbers: Part 1 – Experimental study

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ARTICLE INFO

ABSTRACT

Low thermal conductivity in packed bed adsorbers is a crucial challenge facing widespread adoption of low-grade heat adsorption thermal energy storage systems. In this work, thermal conductivities of 2-mm diameter AQSOA FAM-Z02 packed bed adsorbers with different numbers of adsorbent layers are measured, using a NETZSCH HFM 436/3/1E Lambda, in the temperature range of 10–80 °C and under atmospheric pressure. Effects of thermal contact resistance (TCR) between the adsorbent particles and the bed metal surfaces are deconvoluted from the total thermal resistance. Effective thermal conductivities of the adsorber packed bed are 0.188 and 0.204 W m^{-1} K^{-1} at temperatures of 10 and 80 °C, respectively. It is observed that the relative importance of TCR compared to the total thermal resistance of a monolayer FAM-Z02 packed bed, is 67% at 25 °C and under contact pressure of 0.7 kPa, which is significant and should be considered in the design of adsorption systems.

1. Introduction

Concerns over increase in global primary energy consumption [1], greenhouse gas emissions, climate change [2], enormous amount of wasted energy [3], and dependency on the conventional fossil fuel energy resources [4] have made researchers eager for seeking low-grade heat driven sustainable heating and cooling methods. Adsorption technologies, including adsorption thermal energy storage (ATES) [5], adsorption cooling systems [6], adsorption heat pumps [7], and desiccant air conditioning systems [8], can steer the energy sources toward low-carbon sustainable alternatives, e.g., thermal solar, industrial low-grade waste-heat and geothermal energy. ATES can contribute to a significant reduction in the global energy consumption by storing energy of heat sources with intermittent nature, such as solar energy or waste heat, offering high energy storage density and low heat loss. Using non-toxic and non-polluting refrigerants are other environmental benefits that increase attractiveness of ATES. However, the low thermal conductivity of adsorbent materials (0.1–0.8 W m^{-1} K^{-1} [9]) and high thermal contact resistance between adsorbent and adsorber bed heat exchanger surfaces, hereinafter called TCR, suppress the overall performance and reduce the competitiveness of the available ATES systems.

To tackle the low heat transfer inside the adsorber beds, using composite adsorbents with high thermal conductive additives was found a practical solution [10]. To this end, granular activated carbon with aluminum additives [11], activated carbon with CaCl$_2$ [12], consolidated NaX Zeolite with expanded natural graphite [13], and silica gel-expanded graphite [14] were studied. Consolidated composite adsorbents increase the heat transfer rate in the adsorber beds, however, they may decrease the mass transfer rate [10]. In contrast, a thin layer (less than 1 mm) of coated adsorbent on the metal surface of an adsorber bed: (i) increases the mass transfer between the adsorbate and coated adsorbent, (ii) reduces the pressure drop inside the bed, and (iii) provides a higher heat transfer rate by reducing the TCR between the adsorbent and metal surface of adsorber bed [15].

Consolidated high conductive composites and coated adsorbent increase the heat transfer, whereas granular packed beds provide higher performance in terms of volumetric cooling power (i.e. cooling power divided by volume) and energy storage density (i.e. stored energy divided by volume) for adsorption systems [16]. Freni et al. [16] compared identical heat exchangers, one with 0.1 mm thickness coated adsorbent and the other one with 0.6–0.7 mm diameter loose grain AQSOA FAM-Z02 and showed that even though coated bed provided faster water uptake rate, the granular adsorber offered higher volumetric cooling power.

To study the heat transfer performance of a packed bed adsorber, TCR and effective thermal conductivity of the packed bed should be measured and modeled properly. Importance of TCR

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Nomenclature

A	surface area of the packed bed, cm^2	R_p	thermal resistance of adsorbent particle, K W^{-1}
ATES	adsorption thermal energy storage	R_{p-p}	thermal contact resistance between the particles, K W^{-1}
d_p	adsorbent particle diameter, mm	R_{tot}	packed bed total thermal resistance (including the TCR), K W^{-1}
f_{calib}	calibration factor of the heat flux transducer, W m^{-2} V^{-1}	t	time, s
HFM	heat flowmeter	T	temperature, K
k	thermal conductivity, W m^{-1} K^{-1}	T_1	temperature of the upper hot plate of the heat flowmeter, K
k_{tot}	packed bed total thermal conductivity (effects of TCR is included.), W m^{-1} K^{-1}	T_2	temperature of the lower cold plate of the heat flowmeter, K
$k_{eff,bed}$	packed bed effective (medium) thermal conductivity (effects of TCR is not included.), W m^{-1} K^{-1}	TCR	thermal contact resistance, K W^{-1}
L	packed bed length (thickness), mm	V	heat flux transducer output, V
ω	water uptake, kg kg$_{ads}^{-1}$		
n	number of adsorbent layers	*Subscripts*	
P	gas pressure, Pa	*as*	aluminum sheet
$P_{contact}$	contact pressure at the contact of adsorbent particle and the metal surface, Pa	*bed*	packed bed
$\dot{Q}$	heat flow, W	*contact*	at the contact of adsorbent particles and the heat exchanger metal surface
R	thermal resistance, K W^{-1}	*eff*	effective
R_{as-p}	thermal contact resistance between the aluminum sheet and the particles, K W^{-1}	*p*	adsorbent particle
		tot	total
R_{bed}	packed bed effective thermal resistance (excluding the TCR), K W^{-1}	*w*	water

has been raised in the literature [17–19], but little has been shown regarding the measurement and modeling of TCR inside the adsorber bed. Based on the test procedure for flat surfaces developed by Antonetti and Yovanovich [20], Wang et al. [21] measured the TCR between the heat exchanger surface and zeolite granule adsorbent with diameters of 0.297, 0.149 and 0.074 mm by heat flux ratio-measuring instrument, under vacuum pressure. A correlation fitted to their experimental data [21] was fed into an empirical lumped analytical model for thermal conductivity of a silica gel packed bed, developed by Rezk et al. [22]. Sharafian et al. [19] experimentally showed that the ratio of TCR to the total thermal resistance could be as high as 26% at 37 °C, for a consolidated block of silica gel-PVP on a metal substrate.

Thermal conductivity measurement methods used for various adsorbent materials are listed in Table 1. Bjurström et al. [23] measured thermal conductivity of moist silica gel particles by transient hot strips method and effective thermal conductivity of a dry packed bed of silica gel through a steady-state measurement, using a custom-built annular test bed. Tanashev and Aristov [24] measured thermal conductivity of a composite of KSK silica gel and CaCl$_2$ by the transient hot wire method at 290–330 K and atmospheric pressure. They showed that thermal conductivity of the composite increased from 0.112 to 0.216 W m^{-1} K^{-1} when water uptake was raised from 0.01 to 0.58 kg kg$_{ads}^{-1}$. Tanashev et al. [25] later showed that their reported thermal conductivity of the composites of silica gel and salts, under atmospheric pressure, could be used in the closed adsorption systems as well, since their results showed that thermal conductivity was a stronger function of uptake rather than vapor pressure and temperature.

Due to the adsorption heat released by adsorbents, the measured temperature difference in the unsteady thermal conductivity measurement is smaller than that of the test with no adsorption

Table 1
Thermal conductivity measurement techniques used for adsorbent materials in the literature.

Ref.	Measurement method	Standard	Adsorbent	Adsorbent configuration	Uptake, kg kg$_{ads}^{-1}$	Temperature, K	Thermal conductivity, W m^{-1} K^{-1}	Importance of TCR (TCR R$_{tot}^{-1}$)
[23]	Transient hot strip/ transient plane source	ISO22007-2	Silica gel	Packed bed (silica gels are poured in a cell (40 × 60 × 10 mm)	0	295	0.147	–
					0.329	295	0.265	–
[26]			Silica gel + CaCl$_2$ + 20 wt% graphite flakes	Composite	0.18	308	0.41	–
[24]	Transient hot wire	ASTM C1113	Silica gel KSK + 20 wt% CaCl$_2$	Composite	0.01	293	0.112 ± 0.007	–
					0.58	293	0.216 ± 0.012	–
[27]			Silica gel + 36.6 wt% CaCl$_{2+}$ binder Al(OH)$_3$	Composite	0.053	363	0.12	–
					0.286	363	0.227	–
[28]			AQSOA FAM-Z02	–	–	303	0.117	–
					–	363	0.128	–
[29]	Laser flash	ASTM E1461-13	AQSOA FAM-Z01	Coated (0.3 mm thickness)	–	293	0.376	–
[30]	Guarded-hot plate	BS-874	Monolithic carbon (sample LM127)	Monolithic with coarse powders	–	293	0.45	–
					–	393	0.4	–
[19]		ASTM E1530	Silica gel + PVP with a metallic substrate	Composite	–	310	0.282	0.26
					–	321	0.240	0.05