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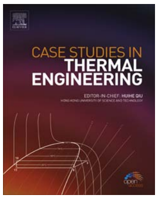

Measurements and theoretical modeling of effective thermal conductivity of particle beds under compression in air and vacuum

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ABSTRACT

Effective thermal conductivity experiments were carried out with spherical particle beds under low and high compressive pressure loading in vacuum and air. A theoretical model was proposed for the effective thermal conductivity of particle beds based on the experimental results. The model incorporates heat conduction by particles including contact thermal resistance between particles, conduction through the gas in between particles, and radiation between particles, and includes two fitting parameters, namely the coefficient of heat conducted through the fluid, and the macro-contact thermal resistance. The predictions from the theoretical model satisfactorily match the experimental data for the bed effective thermal conductivity over the range of applied loading pressures on particles with different Young's modulus and the gas environment. The model can be used generally to describe the effect of compression stress or pressure on effective thermal conductivity of particle beds.

1. Introduction

Effective thermal conductivity of particle beds is of great practical importance in many science and engineering applications such as packed bed reactors [1,2], drying processes [3], and regenerators [4]. Effective bed conductivity in the presence of a stagnant gas depends generally on the following factors [5]: particle thermal conductivity, gas thermal conductivity, gas pressure, packing fraction, particle size and shape, surface roughness, contact force and area between particles, and bed deformation. Existing analytical models, developed for calculating the effective thermal conductivity of particle beds as a function of compressive pressure loading on particles, all require complex fitting parameters [6–8]. More importantly, at relatively low applied compressive loads, these models tend to overestimate the effective thermal conductivity. Therefore, there is considerable motivation to refine the current theories and test them with experiments to improve our understanding of heat transfer in packed beds.

Available bed effective thermal conductivity models can generally be divided into the four categories: mixing law models, volume fraction models, packing structure models, and pressure-dependent or contact area-dependent models. Mixing law models combine values of the solid and fluid thermal conductivity, typically as a function of volume fraction, to determine the effective thermal conductivity. An extensive review was published by Abdulagatova et al. [9] on mixing law models and the dependence of effective thermal conductivity on temperature, porosity, and gas pressure. These models tend to be general in nature and have limited applicability. They can, however, provide convenient and rapid estimations for the physical bounds of effective thermal conductivity.

Volume fraction models are developed for different levels of solid volume fraction: low volume fraction materials (volume fraction of solids up to 10%), medium volume fraction materials (volume fraction of solids from 15% to 85%), and high volume

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Nomenclature

E	Young's modulus (Pa)
E_{star}	$(\frac{1-v_1^2}{E_1}+\frac{1-v_2^2}{E_2})^{-1}$(Pa)
F	Applied force (N)
H_0	Hertz coefficient, $\sqrt[3]{\frac{3r_{star}}{4E_{star}}}$
k_{eff}	Effective thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
k_{gas}	Thermal conductivity of gas ($\mathrm{W\,m^{-1}\,K^{-1}}$)
k_s	Bulk thermal conductivity of particles ($\mathrm{W\,m^{-1}\,K^{-1}}$)
m	Effective mean absolute surface slope
P	Compressive pressure (Pa)
$q_{contact}$	Heat transfer through contact area (W)
q_{gas}	Heat transfer through gas (W)
q_{rad}	Heat transfer by radiation (W)
r	Particle radius (m)
R_{gas}	Thermal resistance of gas ($\mathrm{K\,W^{-1}}$)
R_j	Combined micro-and macro-contact thermal resistance ($\mathrm{K\,W^{-1}}$)
R_{macro}	Effective macro-contact thermal resistance ($\mathrm{K\,W^{-1}}$)
R_{micro}	Effective micro-contact thermal resistance ($\mathrm{K\,W^{-1}}$)
R_{rad}	Thermal resistance of radiation ($\mathrm{K\,W^{-1}}$)
R_{sum}	Overall thermal resistance ($\mathrm{K\,W^{-1}}$)
r_{star}	$(\frac{1}{r_1}+\frac{1}{r_2})^{-1}$(m)
T	Temperature (K)

Greek symbols

a	Coefficient of heat conducted through fluid
a_L	Contact radius, $H_0\cdot\sqrt[3]{F}$ (m)
β	Accommodation factor for macro-contact thermal resistance
σ	Stefan-Boltzmann constant ($\mathrm{W\,m^{-2}\,K^{-4}}$)
σ_s	Average surface roughness (μm)
υ	Poisson's ratio
Λ_{bulk}	Mean free path (nm)

Subscripts

star	Effective

fraction materials (volume fraction of solids larger than 90%). Tavman [10] reviewed models predicting effective thermal conductivity based on porosity, particle thermal conductivity, and gas thermal conductivity. Maxwell's model [11] for the effective thermal conductivity of randomly distributed and non-interacting spherical particles in a homogeneous continuous medium is known to predict the thermal conductivity of low volume fraction materials very well. Chiew and Glandt [12] proposed an improved form of Maxwell's equation for medium volume fraction materials. Gonzo [13] presented an equation for high volume fraction materials. Argento and Bouvard [14] proposed a model for partially sintered spheres, which reduces to Batchelor and O'Brien [15] model when the contact area between spheres is small. Volume fraction models could be used for particle beds under compression; however, the uncertainty is often large because these models usually neglect the thermal resistance of the contact area between particles.

Packing structure models are based on the different packing structures of spheres. Batchelor and O'Brien [15] proposed a general formula to determine the effective thermal conductivity of a random packing of particles considering particles in random packing arrangements are more likely to be statistically isotropic in thermal conductivity. Cheng et al. [16] presented a method to evaluate the packing structure of mono-sized spheres by using Voronoipolyhedra. Finney [17] measured the structure of the packed bed and showed that when the solid to fluid conductivity ratio is low, the dominant heat transfer mechanism is the solid-fluid-solid conduction between particles. Dietz [18] modeled particle beds as hexagonally packed planes of spheres. Effective thermal conductivity was calculated as a function of particle and surrounding medium thermal conductivities. Siu and Lee [19] found that the ratio of effective thermal conductivity to bulk particle thermal conductivity for simple cubic (SC), body centered cubic (BCC), and face centered cubic (FCC) packing arrangements is a linear function of the ratio of contact radius to particle radius. This result shows that the effective thermal conductivity of randomly packed beds can be modeled by the SC packing model multiplied by a constant. The method is valid for particle thermal conductivities much greater than gas thermal conductivities or in vacuum.

Pressure-dependent or contact area-dependent models take the compressive pressure on particles into account and consider thermal contact resistance between particles. Effective thermal conductivity in a particle bed has been shown [20–22] to increase as the contact area between particles increases with increasing applied compressive pressure. The Schlünder, Zehner, and Bauer model [1,23,24] simulated the particle bed with a standard unit cell containing two contacting particles. Heat flow in the unit cell is divided into three parallel paths. The first path consists of conduction and radiation through the gas filled voids. The second path consists of conduction through solid and gas phases with radiation between solid surfaces. The third path consists of the solid-solid conduction path. The model is suitable for high solid to gas thermal conductivity ratios. Garrett and Ban [8] developed a similar resistance network model in predicting anisotropic effective thermal conductivity of particle beds under applied compressive pressures. Models for thermal contact resistance, which incorporate factors including mechanical loads, surface roughness, and gas pressure have been proposed [25–27]. It has been proposed that overall thermal contact resistance of non-conforming rough contacting surfaces was the combination of macro-and micro-contact thermal resistances [28,29]. However, it is difficult to determine the geometrical properties of particles in order to calculate the micro-contact thermal resistance.

Extensive studies on the effective thermal conductivity of particle beds under high compressive pressures have been published, yet no data is available to compare with theoretical models in the low compressive pressure regime. Furthermore existing models tend to over predict effective thermal conductivity in the low compressive pressure regime. The objective of this study was to first obtain experimental data of particle beds in air and vacuum with low uniaxial compressive loading. Mono-sized particles of similar conductivity but different Young's modulus were used in experiments to show the effect of compressive force. Secondly, we developed a generic resistance network model for predicting effective thermal conductivity of particle beds as a function of compressive pressure