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Multi-sphere Unit Cell model to calculate the effective thermal conductivity in packed pebble beds of mono-sized spheres

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ABSTRACT

This paper presents a new approach to the calculation of the effective thermal conductivity in packed pebble bed reactors, namely the Multi-sphere Unit Cell model. The model specifically accounts for the porous structure, which is characterised using the radial variation in porosity, coordination number and contact angles between adjacent spheres. It also accounts for solid and gas thermal conduction, contact area, surface roughness as well as the thermal radiation for pebble temperatures up to 1200 °C. This more rigorous approach to characterising the porous structure enables improved prediction of the effective thermal conductivity in the near-wall and wall regions, resulting in better prediction of the temperatures at the reflector interface. Results obtained with the Multi-sphere Unit Cell model are compared with existing correlations and experimental data including those from the SANA-I experimental test facility.

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1. Introduction

Packed beds are used in various industrial systems that are associated with energy transfer, such as pebble bed reactors (PBRs), due to the high solid surface area to volume ratio. Therefore, a proper knowledge of the thermal properties, especially the effective thermal conductivity, is essential to enable the correct design of these systems (Zhou et al., 2007).

The bed effective thermal conductivity is a lumped parameter which is representative of the overall radial or axial heat transfer through a packed bed of spheres, and is a summation of various components of the overall heat transfer. The effective thermal conductivity is of importance because it forms, amongst others, a vital part of the self-acting decay heat removal chain, which is directly related to the PBR safety case. Van Antwerpen et al. (2010) presented a comprehensive review of the correlations generally employed by the thermal fluid design community for PBRs to simulate the effective thermal conductivity in packed pebble beds.

The concept of the overall bed effective thermal conductivity (k_{bed}) in a bed saturated with a stagnant gas can be split up into three components (Bauer, 1990). The first is that of the effective thermal conductivity (k_{eff}) consisting of four distinct heat transfer mechanisms namely: (1) conduction through the solid; (2) conduction through the contact area between adjacent spheres; (3) conduction through the stagnant gas phase; and (4) thermal radiation between the solid surfaces. The second component is the enhanced fluid effective conductivity ($k_{f,eff}$) due to the turbulent mixing in the highly irregular flow paths while the solid phase is motionless, also referred to as the braiding effect or dispersion. The third component is when the gas phase as well as the solid phase is in motion ($k_{s,eff}$) because of stirring or vibrations in the packing. The bed effective thermal conductivity is therefore given by:

$$k_{bed} = k_{eff} + k_{f,eff} + k_{s,eff} \tag{1}$$

This paper presents a new Multi-sphere Unit Cell model to calculate the first component namely the effective thermal conductivity k_{eff}. Results obtained with the new model are compared with existing correlations and available experimental data from the SANA-I experimental test facility.

2. Analysis of the effective thermal conductivity

Most of the difficulties encountered in predicting the effective thermal conductivity are associated with the fact that it is a phenomenological characterisation of a solid-fluid medium rather than a thermo-physical property (Aichlmayr and Kulacki, 2006). Therefore, before any heat transfer analysis is attempted, one should have a thorough understanding of the underlying physics and the structural arrangement of the packed bed under consideration.

Nonetheless, for the bulk and near-wall regions of a randomly packed bed the Multi-sphere Unit Cell model consists of two primary components:

$$k_{eff} = k_e^{g,c} + k_e^r \tag{2}$$

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Nomenclature

A_j	joint conduction area, m^2
A_m	summation of microcontacts, m^2
A_r	radiation conduction area, m^2
A_s	surface area of sphere, m^2
$a_1 - a_4$	empirical constants
a_T	thermal accommodation coefficient
c_1	Vickers micro-hardness coefficient, GPa
c_2	Vickers micro-hardness exponent
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
c_v	specific heat at constant volume, J kg^{-1} K^{-1}
D_{tot}	total geometrical distance between two spheres, m
d	distance of corresponding voids, *m*; distance between two spheres, m
d_p	diameter of sphere, m
E_p	Young's modulus, Pa
E'_p	effective Young's modulus, Pa
F	collinear force, N
F_{1-2}	diffuse view factor between two surfaces
F^L_{1-2}	long-range diffuse view factor
$F^L_{1-2,avg}$	average long-range diffuse view factor
f_k	dimensionless non-isothermal correction factor
H^*	$= c_1(\sigma'/m_{RMS})^{c_2}$, GPa
H_B	Brinell hardness, GPa
H_{BGM}	hardness constant $H_{BGM} = 3.178 \quad GPa$
H_{Vic}	Vickers hardness, GPa
j	temperature jump parameter
Kn	$(\equiv\lambda/d)$ Knudsen number
k_{bed}	total bed effective thermal conductivity, W m^{-1} K^{-1}
k_e^c	effective thermal conductivity through contact area, W m^{-1} K^{-1}
k_e^g	effective thermal conductivity through fluid/gas and point contact, W m^{-1} K^{-1}
$k_e^{g,c}$	effective thermal conductivity though gas, point contact and contact area in the bulk and near-wall region, W m^{-1} K^{-1}
$k_e^{g,c,W}$	effective thermal conductivity though gas, point contact and contact area in the wall region, W m^{-1} K^{-1}
k_e^r	effective thermal conductivity due to radiation in the bulk and near-wall region, W m^{-1} K^{-1}
$k_e^{r,L}$	effective thermal conductivity due to long-range radiation, W m^{-1} K^{-1}
$k_e^{r,S}$	effective thermal conductivity due to short-range radiation, W m^{-1} K^{-1}
$k_e^{r,W}$	effective thermal conductivity due to radiation in the wall region, W m^{-1} K^{-1}
k_{eff}	effective thermal conductivity due to thermal conduction and radiation in the bulk and near-wall region, W m^{-1} K^{-1}
k_{eff}^W	effective thermal conductivity due to thermal conduction and radiation in the wall region, W m^{-1} K^{-1}
$k_{f,eff}$	effective thermal conduction due to fluid mixing (braiding effect), W m^{-1} K^{-1}
k_g	thermal conductivity of gas phase, W m^{-1} K^{-1}
k_s	thermal conductivity of solid phase, W m^{-1} K^{-1}
$k_{s,eff}$	effective thermal conduction due to solid particle movement, W m^{-1} K^{-1}
k_s^*	effective solid conductivity, W m^{-1} K^{-1}
L_{bed}	length of bed, m
L_{bulk}	length of bulk region of bed, m
L_j	length between centres of two sphere, m
L_r	radiation distance, m
$L_{r,avg}$	average radiation distance, m
M_g	molecular mass of gas, kg kmol^{-1}
R_i	inner radius of annulus, m
M_s	molecular mass of solid surface, kg kmol^{-1}
M^*	effective molecular mass, kg kmol^{-1}
m_{rms}	combined root mean squared surface slope
m_1,m_2	surface slopes of surfaces 1 and 2
$\bar{N}_c$	average coordination number
$\bar{n}$	average coordination flux number
$\bar{n}_{long}$	average coordination flux number for long-range radiation
$P_{0,c}$	maximum contact pressure, Pa
$P_{0,H}$	Hertzian contact pressure, Pa
P'_b	base gas pressure, Pa
P_g	current gas pressure, Pa
Pr	Prandtl number
Q_r	heat flux, W
q''_g	heat flux through gas, W m^{-2}
R_G	resistance of the interstitial gas in the macro-gap, K W^{-1}
R_g	resistance of the interstitial gas in the micro-gap, K W^{-1}
$R_{HERTZ,1,2}$	Hertzian micro-contact resistance, K W^{-1}
$R_{in,1,2}$	inner solid material resistance, K W^{-1}
R_j	thermal resistance of joint, K W^{-1}
$R_{L,1,2}$	macro-contact constriction/spreading resistance, K W^{-1}
$R_{mid,1,2}$	middle solid material resistance, K W^{-1}
R_o	outer radius of annulus, m
$R_{out,1,2}$	outer solid material resistance, K W^{-1}
R_s	micro-contact constriction/spreading resistance, K W^{-1}
R_λ	resistance of the interstitial gas in the Knudsen regime (Smoluchowski effect) of the macro-gap, K W^{-1}
r	radial coordinate, m
r_a	radius of the micro-contact area, m
r_c	radius of the contact area, m
r_{eq}	equivalent pebble radius, m
r_p	radius sphere, m
r_λ	mean free-path radius between two spheres, m
$\bar{T}$	average surface temperature of interacting spheres, K
T'_b	base temperature, K
T_g	gas temperature, K
T_0	≡237 K
T_s	solid surface temperature, K; $s = 1$ surface 1, $s = 2$ surface 2
x	coordinate in the x direction
Z_{depth}	depth into packed bed, m
z	particle diameters from a wall
z_r	geometrical length (non-dimensional distance)
$z_{r,avg}$	average geometrical length (non-dimensional distance)

Greek symbols

α	non-dimensional parameter defined by Bahrami et al. (2006)
γ_g	specific heat ratio = c_p/c_v
ε	porosity or void fraction
ε_b	bulk porosity
ε_r	emissivity

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