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A review of methods to predict the effective thermal conductivity of packed pebble beds, with emphasis on the near-wall region

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ABSTRACT

The effective thermal conductivity is an important parameter that is representative of the overall heat transfer in a packed bed of spheres. It includes the effects of conduction through the solid material and contact areas between spheres, conduction through the stagnant gas phase as well as thermal radiation between the surfaces of the spheres. An accurate prediction of the effective thermal conductivity is necessary for the design and analysis of packed pebble bed gas-cooled and solid fuel molten salt-cooled generation IV reactors, especially when considering the safety case. This includes the near-wall region where the packing structure is altered significantly. The well-known ZBS correlation is widely applied to predict the effective thermal conductivity and it is often implicitly assumed that it is equally applicable in the near-wall region. This paper presents an analysis of the validity of the ZBS correlation in this regard. In addition to this, an up-to-date review of methods used to predict the effective thermal conductivity is presented and methods that specifically account for the near-wall region are identified. It is noted that the contributions of the various heat transfer mechanisms are not yet fully understood and therefore the ability to separate the different mechanisms can be useful for understanding the characteristics in the near-wall region.

1. Introduction

Energy transfer through randomly packed beds is important for various thermal-fluid industrial applications, including catalytic reactors, drying processes, thermal insulation, heat storage systems, hydrogen production and gas-cooled nuclear reactors (Asakuma et al., 2016; Ren et al., 2017; Van Antwerpen et al., 2010; Zhou et al., 2007). A thorough understanding of the thermal properties and the heat transfer phenomena in packed beds is essential to achieve an optimal design (Zhou et al., 2007; Zhou et al., 2010).

Pebble bed gas-cooled reactors (PBRs) are generation IV type reactors that are favoured because of the inherent safety characteristics of the reactor design (Wu et al., 2016). The effective thermal conductivity is an important parameter that is representative of the overall heat transfer through a packed pebble bed. In order to achieve a PBR design with the desired safety characteristics one must be able to accurately predict the effective thermal conductivity (Van Antwerpen et al., 2010; Zhou et al., 2007; Zhou et al., 2010). This is also true for another generation IV type reactor namely the fluoride salt-cooled high-temperature reactor (FHR). It is a variant of a molten salt reactor (MSR) that has solid fuel with a core structure similar to the PBR, but instead of helium gas it has molten liquid FLiBe salt as the coolant (World Nuclear Association, 2017).

When considering the safety case of a PBR during a depressurized loss of forced coolant incident, the effective thermal conductivity consists of three components: (1) conduction through the pebble material itself and through the stagnant fluid, k_e^g, (2) conduction through physical contact points and contact surfaces of the solid materials, k_e^c, and (3) thermal radiation between solid surfaces, k_e^r (Van Antwerpen et al., 2010). Thus, the total effective thermal conductivity of the packed bed can be given by the super-positioning of the three components as shown in Eq. (1):

$$k_{eff} = k_e^g + k_e^c + k_e^r \quad (1)$$

The geometry of a randomly packed bed consists of three main regions namely the bulk, wall and near-wall regions (Van Antwerpen,

Abbreviations: BCC, Body Centred Cubic; BEM, Boundary Element Method; CFD, Computational Fluid Dynamics; DEM, Discrete Element Method; DPS, Discrete Particle Simulation; FCC, Face Centred Cubic; FEA, Finite Element Analysis; FHR, Fluoride Salt-Cooled High-temperature Reactor; HTTU, High Temperature Test Unit; IAEA, International Atomic Energy Agency; MSR, Molten Salt Reactor; MSUC, Multi Sphere Unit Cell; NWTCTF, Near-wall Thermal Conductivity Test Facility; PBR, Pebble Bed Gas-cooled Reactor; RTC, Radiative Transfer Coefficient; RTE, Radiative Transfer Equation; SC, Simple Cubic; ZBS, Zehner, Bauer & Schlünder; ZS, Zehner & Schlünder

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Nomenclature

A_j	joint conduction area [m^2]
A_r	radiation conduction area [m^2]
A_s	surface area of sphere [m^2]
C	fitting parameter [–]
d_p	particle diameter [m]
f_k	non-isothermal correction factor [–]
F	contact force [N]
F_{1-2}	diffuse view factor between two surfaces [–]
$F^L_{1-2,avg}$	average long-range diffuse view factor [–]
k_e^c	effective thermal conductivity through contact area [W/m-K]
k_e^g	effective thermal conductivity through fluid/gas and point contact [W/m-K]
$k_e^{g,c}$	effective thermal conductivity through fluid/gas, point contact and contact area [W/m-K]
k_e^r	effective thermal conductivity due to radiation [W/m-K]
$k_e^{r,L}$	effective thermal conductivity due to long-range radiation [W/m-K]
$k_e^{r,S}$	effective thermal conductivity due to short-range radiation [W/m-K]
k_{eff}	total effective thermal conductivity [W/m-K]
k_f	fluid thermal conductivity [W/m-K]
k_s	thermal conductivity of solid material [W/m-K]
ℓ_o	physical separation distance between particles [m]
L	height of particle column [m]
L_j	length between centres of two spheres [m]
n_e	effective number of contacts in solid core region [–]
$\bar{n}_{long}$	average coordination flux number for long-range radiation [–]
r	radial position in packed bed [m]
r_a	radius of the micro-contact area [m]
r_c	particle-particle contact radius [m]
r_c'	reduced particle-particle contact radius [m]
r_o	radius of contact area [m]
r_p	sphere radius [m]
r_λ	mean free path radius between two spheres [m]
R_{cont}	contact resistance [K/W]
R_g	resistance of the interstitial gas in the micro-gap [K/W]
R_i	inner radius [m]
$R_{in,1,2}$	inner solid material resistance [K/W]
R_j	thermal resistance of joint [K/W]
$R_{L,1,2}$	macro-contact constriction/spreading resistance [K/W]
R_m	resistance through middle region [K/W]
$R_{mid,1,2}$	middle solid material resistance [K/W]
R_o	initial radius [m]/outer radius [m]
R_{out}	resistance through outer region [K/W]
$R_{out,1,2}$	outer solid material resistance [K/W]
R_s	micro-contact constriction/spreading resistance [K/W]
T	temperature [K]
$\bar{T}$	average surface temperature of interacting spheres [K]
Q	heat flux [W]
z	sphere diameters from wall [–]
z_{depth}	Z coordinate in packed bed [m]
ε	bed porosity [–]
ε^*	porosity correction factor [–]
ε_c	average porosity of core region [–]
ε_r	emissivity [–]
ζ	correction factor [–]
θ	thermal parameter [–]
λ	mean free path of gas molecules [m]
$\lambda_{es,c}$	effective thermal conductivity of the solid core region [W/m-K]
$\lambda^0_{e,c}$	effective thermal conductivity of a stagnant bed [W/m-K]
ξ	compressive displacement [m]
σ	Stephan-Boltzmann constant [W/m^2-K^4]
ω_o	deformation depth at origin [m]

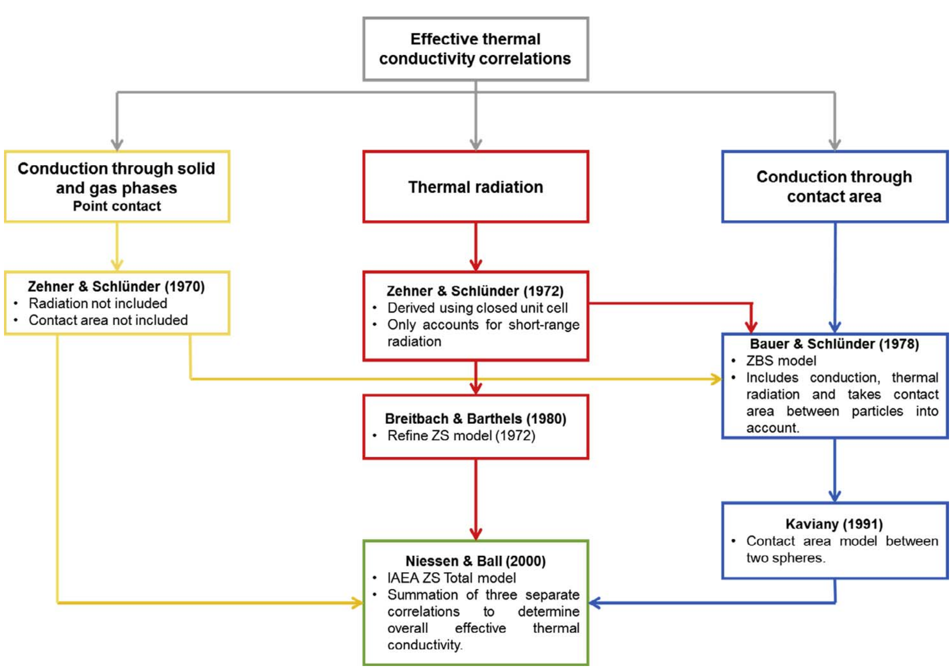

Fig. 1. Summary of the effective thermal conductivity correlations originating from the research of Schlünder and co-workers.