International Journal of Heat and Mass Transfer 127 (2018) 573–584

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Comparative evaluation of heat conduction and radiation models for CFD simulation of heat transfer in packed beds

Yanan Qian [a,b], Zhennan Han [c], Jin-Hui Zhan [a], Xiaoxing Liu [a,b,*], Guangwen Xu [a,c,*]

[a] State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Institute of Industrial Chemistry and Energy Technology, Shenyang University of Chemical Technology, Shenyang 110142, China

ARTICLE INFO

Article history:
Received 12 December 2017
Received in revised form 5 June 2018
Accepted 26 June 2018

Keywords:
Packed bed
Heat transfer
Conduction
Radiation
CFD modeling
Coal pyrolysis

ABSTRACT

The existing major heat conduction and radiation models for packed bed of particles are reviewed and evaluated by comparing the predicted results with experimental data. For low-temperature condition, it is found that the Zehner-Bauer-Schlünder (ZBS) model is less sensitive to the effect of contact area and is thus recommended for the calculation of effective thermal conductivity of packed bed. For high-temperature condition, although numbers of models can be used to calculate the radiative heat transfer behavior in packed bed, the Breitbach and Barthels (B-B) correlation is the optimal method applicable for different particle diameters, emissivities and voidages. The results of CFD simulations using the identified optimal heat transfer models agree well with the thermal measurements by thermocouple in four coal pyrolysis fixed-bed reactors mounted with or without particularly designed internals.

1. Introduction

Packed beds are widely used in energy conversion systems such as nuclear reactors [1], metal hydride installations [2], processes of fuel combustion, gasification and pyrolysis [3–5]. These systems are all associated with heat transfer. A proper knowledge of heat transfer in such packed beds is of importance in their designs and controls. However, the thermal conditions in energy conversion systems are complicated and require deep understanding. The computational fluid dynamics (CFD) approach provides an efficient way to explore flow and heat transfer behavior in chemical reactors. For the CFD approach, the adopted constitutive relations for heat transfer are critical to the final results. Concerning energy conversion, the packed granular beds are usually at high temperatures, and conduction and radiation offer the major path ways of heat transfer.

Yagi and Kunii [6] identified the heat transfer mechanism in a packed bed, as is shown in Fig. 1. For conductive heat transfer, it consists of conduction through ① solid particles, ② gas in voids, ③ contact area between adjacent particles and ④ fluid film near contact surface. Based on the mechanism, some correlations were proposed for the prediction of the effective thermal conductivity of packed beds. Table 1 summarizes some typical correlations. Deissler and Boegli [7] noted the maximum stagnant thermal conductivity through parallel layers of solid and fluid phases and the minimum by a series arrangement. Kunii and Smith (KS) [8] developed a correlation for a particle-packed bed by discretizing solid and fluid phases into separate modes arranged in series or parallel. Zehner and Schlünder (ZS) [9] considered a cylindrical unit cell to replace the pebble bed by assuming that heat conduction in the unit follows two parallel paths: fluid in the outer concentric cylinder and fluid through the inner cylinder consisting of both solid and fluid. Later, Bauer and Schlünder [10] improved the model developed by Zehner and Schlünder [9] by introducing a surface fraction parameter for heat transfer through contact area. This improved correlation is the commonly recognized Zehner-Bauer-Schlünder (ZBS) model. The KS and ZBS models have been widely used in the literature [11–13].

Radiative heat transfer becomes important for the bed packed with 1-mm particles at temperatures above 400 °C [14]. Many different methods were developed to simulate the radiative heat transfer in packed bed systems [15], which mainly involved two approaches. The first is the radiative transfer equation (RTE) approach [16] that solves a radiative energy balance equation for calculating the radiation intensity distribution in porous medium on basis of the optical properties of particles including emitting, absorbing and scattering [17]. Nevertheless, these optical

* Corresponding authors at: State Key Laboratory of Multiphase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China.
E-mail addresses: xxliu@ipe.ac.cn (X. Liu), gwxu@ipe.ac.cn (G. Xu).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.127
0017-9310/

Nomenclature

a	absorption coefficient, 1/m
B	empirical deformation parameter
B_r	radiation transmission number
d_p	particle diameter, m
F_E	radiation exchange factor
H_g	specific enthalpy of gas phase, J/kg
H_s	specific enthalpy of solid phase, J/kg
h_{gs}	heat transfer coefficient between gas and solid phases, W/(m^2·K)
h_p	heat transfer coefficient representing the heat transfer rate through the contact surface between particles, W/(m^2·K)
I	radiation intensity, W/(m^2·sr)
k_g	thermal conductivities of gas, W/(m·K)
k_e	total bed effective thermal conductivity, W/(m·K)
k_e^c	effective thermal conductivity due to thermal conduction, W/(m·K)
k_e^r	effective thermal conductivity due to thermal radiation (effective radiative conductivity), W/(m·K)
$k_{g,e}$	effective thermal conductivity of gas phase, W/(m·K)
k_s	thermal conductivities of solid, W/(m·K)
$k_{s,e}$	effective thermal conductivity of solid phase, W/(m·K)
n	refractive index
$q_{radi,s}$	radiative heat flux, W/m^2
S_r	scaling factor
$S_{radi,s}$	heat source due to solid phase radiation, W/m^3
s	radiation path length, m
T_g	temperature of gas phase, K
T_s	temperature of solid phase, K

Greek symbols

β	empirical parameter
Γ	combination parameter
γ	empirical parameter
ε_g	voidage
ε_r	particle emissivity
ε_s	solid fraction
κ	dimensionless parameter, κ_s/κ_g
Λ_f	dimensionless solid conductivity
ρ_g	density of gas phase, kg/m^3
ρ_s	density of solid phase, kg/m^3
σ	Stefan-Boltzmann constant, 5.67×10^{-8} W/(m^2·K^4)
σ_s	scattering coefficient, 1/m
Φ	phase function
ϕ	empirical parameter
ϕ_1	ϕ value corresponding to the loose packing of spheres
ϕ_2	ϕ value corresponding to the tight packing of spheres
Ω'	solid angle, sr
ω	surface fraction parameter

Subscripts

e	effective
g	gas phase
p	particle
radi	radiation
s	solid phase

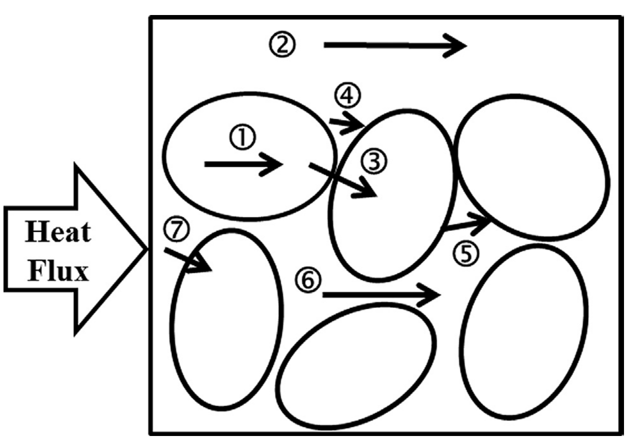

Fig. 1. Heat transfer mechanisms in a high temperature packed bed: ① Conduction through the solid particles; ② Conduction across the gas in the voids; ③ Conduction through the contact area between adjacent particles accounting for surface roughness; ④ Conduction across the fluid film near the contact surface between particles; ⑤ Radiation between adjacent particle surfaces; ⑥ Radiation between adjacent voids; ⑦ Heat transfer by convection, solid-fluid-solid.

properties are closely related to material properties and the microstructures of individual packing [18]. Some empirical correlations have been proposed to calculate the optical properties of solid phase in packed bed. The correlation proposed by Singh and Kaviany [19] formulate absorption (a) and scattering (σ_s) coefficients as a function of particle emissivity ε_r, particle diameter d_p, bed voidage ε_g and a scaling factor S_r. Shin and Choi [20] ignored the scattering effect ($\sigma_s = 0$) and expressed the absorption coefficient as a function of particle diameter and bed voidage. Both these two correlations have been widely adopted in literature to calculate radiative heat transfer [21–23].

The second approach is the effective radiative conductivity method, in which the energy distribution for the packed bed is formulated as a set of simple algebraic equations similar to the Fourier conduction law [15]. To solve these algebraic equations the effective radiative conductivity must be obtained first. Two types of model are commonly used in literature for the calculation of effective radiative conductivity. The first one is the so called the unit cell method. This method treats radiation as a local effect taking place between adjacent particle surfaces (mechanism ⑤ in Fig. 1) and adjacent voids (mechanism ⑥ in Fig. 1). Some models consider only the radiation exchange between adjacent particle surfaces, such as the correlations proposed by Argo and Smith [24], Laubitz [25] and Wakao and Kato [26]. Some models also take account of the radiation exchange between adjacent voids in a unit cell, such as those proposed by Yagi and Kunii [6], Schotte [27] and Zehner and Schlünder [28]. The model of Breitbach and Barthels [29] further accounts for the radiation exchange effect from the voids outside a unit cell. The second one treats the discrete particle assembly as a pseudo-homogeneous continuum, where radiation can penetrate freely and is modeled in terms of absorbing and scattering properties of the medium. By assuming the radiation intensity being the black-body intensity at gas temperature, Rosseland [30] proposed a relation between the radiative conductivity and general radiative properties of solids. Chen and Churchill [18] also derived an expression of the radiative conductivity in the interior of an optically thick bed based on the predetermined absorption and scattering coefficients. Vortmeyer [31] derived expressions for the radiative properties in terms of the particle emissivity