



On contact point modifications for forced convective heat transfer analysis in a structured packed bed of spheres



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HIGHLIGHTS

- A systematical study on contact modifications is performed for structured packed beds.
- The bridges modification is found to give the most reasonable macroscopic results.
- The overlaps and bridges methods are suitable for predicting local heat transfer.
- Reasonable bridge diameter is found in a range from 16% d_p to 20% d_p .

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ABSTRACT

The present paper systematically investigated the appropriateness of different contact point modification approaches for forced convective heat transfer analysis in structured packed beds of spheres. The three-dimensional Navier–Stokes equations and RNG $k-\varepsilon$ turbulence model with scalable wall function are adopted to model the turbulent flow inside the pores. Both macroscopic and local flow and heat transfer characteristics for different packing forms (simple cubic, body center cubic and face center cubic packing forms) and contact treatments (gaps, overlaps, bridges and caps modifications) are carefully examined. In particular, the effects caused by the bridge size for the bridges treatment are discussed, and the numerical results are compared with available experiments in literature. It is found that the effects of contact treatments on the pressure drops are remarkable for different structured packing forms, especially when the porosity is relatively low, while such effects on the Nusselt numbers are relatively small. Among the four different contact modifications, the bridges method would give the most reasonable pressure drops for all the structured packing forms studied and this method is also proved to be suitable for predicting the Nusselt numbers. The local flow and heat transfer characteristics in the structured packed bed are sensitive to the methodology of contact modifications. The gaps and caps treatments would distort the local flow and temperature distributions in the packed bed, especially near the contact zones. While the local flow and temperature distributions from the overlaps and bridges treatments would be more reasonable and close to those in the original packing with points contact. Based on both the macroscopic and local flow and heat transfer analyses, the bridges treatment is recommended. The effects caused by the bridge size in the bridges treatment are also remarkable. It is noted that too small or too large bridge size would lead to unreasonable results for both the macroscopic and local flow and heat transfer analyses. A reasonable range of bridge diameter is found to be from 16% d_p to 20% d_p .

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1. Introduction

Nowadays, packed beds are used in a wide variety of nuclear energy and chemical process industries, such as high temperature gas-cooled nuclear reactors, packed bed regenerators, absorption towers, catalytic reactors and chromatographic reactors (van Antwerpen et al., 2012; Yang et al., 2012), to name a few.

Due to the rapid development of computer technology, computational fluid dynamics (CFD) becomes quite popular in the simulation of fluid flow and heat transfer in the packed beds. With the aid of CFD, detailed transport characteristics in the small pores of packed bed would be obtained. For example, in the recent studies of Shams et al. (2012, 2013a,b), three-dimensional turbulent flow and heat transfer in a pebble bed were numerically investigated with the quasi direct simulations method, which may serve as a benchmark for the validation of different turbulence modeling approaches. The obtained results showed a good prediction of the flow and heat transport in the pebble bed core and this would be

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Nomenclature

A	area [m ²]
c_p	specific heat [J/(kg K)]
$c_{\varepsilon 1}, c_{\varepsilon 2}$	model constants in turbulent kinetic energy equation
c_μ	model constant in turbulent viscosity correlation
d_p	particle diameter [m]
d_h	pore scale hydraulic diameter [m]
f_η	RNG k – ε turbulence model coefficient
h_{sf}	area heat transfer coefficient of particle to fluid [W/(m ² K)]
H	height of packed cell [m]
k	turbulent kinetic energy [m ² /s ²]
k_f	thermal conductivity of fluid [W/(m K)]
L	length of packed cell [m]
n	normal vector
Nu_{sf}	Nusselt number of particle to fluid
p	pressure [Pa]
P_k	shear production of turbulence [kg/(m s ³)]
q_p	heat flux on the particle surface [W/m ²]
Re_p	pore Reynolds number
T	temperature [K]
u	velocity in x direction [m/s]
u_D	Darcy velocity in x direction [m/s]
v	velocity in y direction [m/s]
V	volume [m ³]
$\vec{V}$	velocity vector [m/s]
$\vec{V}_D$	Darcy velocity vector [m/s]
w	velocity in z direction [m/s]
W	width of packed cell [m]
x, y, z	coordinate directions [m]
y^+	dimensionless wall distance

Greek letters

ε	turbulence dissipation rate [m ² /s ³]
η	RNG k – ε turbulence model coefficient
μ	dynamic viscosity [kg/(m s)]
μ_t	turbulent viscosity [kg/(m s)]
ρ	density [kg/m ³]
σ_k	Prandtl number in turbulent kinetic energy equation
σ_T	Prandtl number in energy equation
σ_ε	Prandtl number in turbulence dissipation rate equation
ϕ	Porosity

Subscripts

cell	packed cell
f	fluid
in	inlet
out	outlet
p	particle

meaningful for the design and safety consideration of high temperature reactors. Furthermore, in the studies of [Nijemeisland and Dixon \(2001, 2004\)](#), [Dixon and Nijemeisland \(2001\)](#) and [Dixon et al. \(2008, 2013\)](#), a series of numerical researches on the flow and heat transfer processes in the fixed-bed reactors were performed. The velocity and temperature distributions inside the pores were detailed and the corresponding hydrodynamic and heat transfer performances were carefully analyzed. Other relevant studies on packed beds were also reported by [Calis et al. \(2001\)](#), [Guardo et al. \(2004, 2006\)](#), [Gunjal et al. \(2005\)](#), [Bai et al. \(2009\)](#), [Xia et al. \(2010\)](#)

and [Li et al. \(2012\)](#). The CFD method was proved to be a reliable tool when modeling convective heat and mass transfer in the packed beds of particles.

However, it is difficult to generate high-quality computational grids near the particle–particle or particle–wall contact points. The grid cells near the contact points would be highly skewed which may lead to simulation convergence problems and affect the computational accuracy. In order to diminish this defect, several methods aimed at modifying the contact points were presented in the literature. For example, in the studies of [Nijemeisland and Dixon \(2001, 2004\)](#) and [Bai et al. \(2009\)](#), the particles were shrunk by a certain amount and the contact points were replaced by the small gaps between particles. On the other side, [Guardo et al. \(2004, 2006\)](#) suggested increase the particle diameters by a certain value and the contact points were replaced by the overlapping areas between particles. Furthermore, in the work by [Ookawara et al. \(2007\)](#) and [Kuroki et al. \(2007\)](#), the particles in or near contact points were cylindrically bridged to reduce the fine computational cells around the contact points. And [Eppinger et al. \(2011\)](#) presented another alternative way of flattening the particles locally in the proximity of the contact points if the distance between two particle surfaces fell below a predefined value. This method would be equivalent to the removal of spherical caps at the contact points between particles. In the above-mentioned studies, the contact point modification methods were in good agreement within the respective studies. But there is no general agreement so far. For example, the particle shrinking method would reduce the porosity and may cause underestimations of the pressure drop and heat transfer in packed beds. In a recent study of [Dixon et al. \(2013\)](#), a systematical study on the wall–sphere and sphere–sphere contact points were performed based on the two-particle model. Four different contact modification methods including gaps (particle shrinking), overlaps (particle enlarging), bridges (cylindrically bridging) and caps (sphere cap removing) were carefully compared to examine the modification effects on the flow and heat transfer performances. It was found that the global modifications (gaps or overlaps methods) would change the bed porosity and give erroneous results, while the local modifications (bridges or caps methods) would make little deviations in the porosity and give much better results, such as in the prediction of drag coefficient and pressure drops. Furthermore, between the local modifications, the bridges method was found to offer the best computational results for the particle–particle and particle–wall heat transfer. Meanwhile, in another recent study of [Dixon et al. \(2012\)](#), the numerical work on the treatment of contact points based on the two-particle model was extended to investigate the effects of contact points in a random fixed bed of spheres. The gaps (particle shrinking), bridges (cylindrically bridging) and caps (sphere cap removing) methods were compared in the simulations. It was found that the gaps method would give slightly poorer results; the bridges and caps methods would be better and indistinguishable from each other. The CFD results were also compared with available experimental data and reasonable agreements were obtained. These findings would be important and meaningful for reducing the modeling difficulties and errors in packed bed simulations.

In our previous numerical and experimental studies ([Yang et al., 2010, 2012](#)), it was found that the hydrodynamic and heat transfer performances in structured and random packed beds were quite different. With proper selection of packing form and particle shape, the pressure drops in the structured packed beds could be greatly reduced and the overall heat transfer performance would be improved. These findings would be of great help for the optimal design of packed bed reactors. In the numerical study of [Yang et al. \(2010\)](#), the gaps method was employed for the structured packed beds, where the particles were assumed to be stacked with small gaps (1% of particle diameter). And this manner was proved

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