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Investigating effects of sphere blockage ratio on the characteristics of flow and heat transfer in a sphere array

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ABSTRACT

With advantage of higher heat transfer area per unit mass, a pebble bed is usually adopted as an essential component for design of energy production systems and thermal energy storage (TES) systems. The majority of this paper investigates the sphere blockage ratio (β) on the thermal–hydraulic characteristics of a pebble with 14 spheres using a three-dimensional (3-D) computational fluid dynamics (CFD) model with the $\overline{v^2}-f$ turbulence model. In a previous work, this model has been validated against measured distributions of the heat transfer coefficient on the selected spheres. The measured data are obtained using the transient liquid–crystal technique. According to the simulation results, the thermal–hydraulic characteristics in the sphere array can be captured reasonably with the present CFD model, including flow stagnation, flow separation, vortex formation and anisotropic characteristics of the heat transfer on the sphere surface. Comparisons of the simulation results for the sphere arrays with different blockage ratios show that the flow and turbulent intensity distributions are similar in most regions of a sphere array, except the portions between the pebbles. The heat transfer coefficient for the upstream spheres increases slightly as the blockage ratio decreases. However, a lower heat transfer coefficient is predicted for the downstream sphere if β is less than 0.75. In addition, the heat transfer coefficient around the front of a downstream sphere would not be influenced by the upstream spheres until $\beta \leqslant 0.75$. Similar results are also revealed in the dependence of the heat transfer coefficient on the zenith angle of the spheres for the different blockage ratios.

1. Introduction

Pebble beds are often adopted in the industry because they offer a higher transfer area per unit mass. The flow and heat transfer of sphere arrays are the most important parameters for the design of energy production systems [1–8] and thermal energy storage (TES) systems [9–15]. Although the geometry of a sphere array is simple, its flow characteristics, including boundary layer separation and vortex shedding in the wakes, are complicated. This puts much challenge for the researches to investigate sphere arrays [16–19].

Computational fluid dynamics (CFD) related to the pebbles had been performed in the previous investigations. Logtenberg and Dixon [20] investigated the flow and heat transfer in a fixed bed through CFD modeling for an arrangement of 8 spheres. Calis et al. [16] used a CFD code to predict the pressure drop characteristics for a packed bed of 8–16 spheres for Reynolds (Re) numbers between 0.01 and 5000. Nijemeisland and Dixon [21] compared the temperature predictions with the measured data for a geometry of 44 spheres arranged in a tube. Romkes et al. [22] assessed the CFD software in predicting the mass and heat transfer rates from the catalyst particles to the fluid for different values of the channel-to-particle-diameter ratio. This CFD model was validated using a single sphere. Constantinescu et al. [23] studied the skin friction coefficients, vorticity, and turbulence kinetic energy for a sphere. They found that the k–ω and $\overline{v^2}-f$ turbulence models are comparable with large-eddy simulation (LES) and detached-eddy simulation (DES) with unsteady Reynolds-averaged Navier–Stokes (URANS) equations. Schouveiler et al. [24] numerically and experimentally studied the wake interactions of two spheres placed side by side for the Re numbers between 200 and 350. Maheshwari et al. [25] investigated the influence of the blockage ratio on the flow and heat transfer phenomena for a sphere and an in-line array of three spheres. Hassan [17] used the LES approach to simulate the complex flow characteristics in a pebble bed with 24 spheres.

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Nomenclature

C_p	specific heat (kJ/kg K)
D	diameter of test tube (m)
D_p	sphere diameter (m)
dX	horizontal distance between two spheres (m)
dY	vertical distance between two spheres (m)
dZ	axial distance between two spheres (m)
h	heat transfer coefficient (w/m^2 K)
k	turbulent kinetic energy (m^2/s^2)
p	pressure (N/m^2)
Re_{in}	inlet Reynolds number = $\rho U_{in} D/\mu$
T	temperature (K)
u	velocity (m/s)
U_{in}	inlet velocity (m/s)
x	x coordinate (m)

Subscript

acry	acrylic
i	coordinate index
in	inlet value
ini	initial value
r	reference value
TCL	thermochromic liquid crystal
w	wall

Greek symbol

α	thermal diffusivity (m^2/s)
β	sphere blockage ratio = dZ/D_p
ε	energy dissipation rate (m^2/s^3)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
μ	viscosity (N s/m^2)
τ_{ij}	shear stress tensor (N/m^2)

Adopted a packed 4-row bed of spheres to model a sintered bed, Jang and Chiu [26] numerically and experimentally studied the transient fluid flow and heat transfer over a sintered bed during a cooling process. Augier et al. [27] investigated the transport and transfer properties within packed beds of spherical particles using CFD simulation. Their model can be applied to hundreds of particles. Baker and Tabor [28] compared computational simulations of the airflow through a packed column containing 160 spherical particles with experimental results of the pressure drop across the column. Dehbia and Martin [29] used the fluent code to simulate the flow characteristics around linear arrays of 8 spheres and compared the deposition rates against the experimental data. To develop and validate a mesh for CFD simulation in fixed beds, Dixon et al. [30] presented results for the drag coefficient and the Nu number for the flow past a sphere. Dixon et al. [19] simulated the heat transfer in the fixed beds of spheres for various ranges of particle Re numbers and two different ratios of tube-to-particle diameter. Shamsa et al. [31] adopted the LES to model a single face cubic centered pebble bed. Their results for the velocity and temperature fields were compared with the available quasi-DNS database. Ferng and Lin [32] proposed a CFD model to study the effects of the pebble arrangements for a pebble-bed core. Pavlidis and Lathouwers [33] used a CFD model with anisotropic mesh adaptivity to investigate the coolant flow and heat transfer in a very high-temperature reactor. According to the literature survey, Table 1 summarizes the previous studies related to the heat transfer phenomena for a sphere or a sphere array.

For CFD modeling in the engineering applications, it is common to investigate an entire pebble bed through a simple sphere-array geometry with periodic boundary conditions. In this paper, a three-dimensional (3-D) CFD model is developed to investigate the effects of the sphere blockage ratio on the flow and heat transfer characteristics. Based on the paper review in Table 1, 2–7 sphere layers are often adopted as the study layout for investigating the thermal–hydraulic characteristics in the pebble. A three-line array with 14 spheres is chosen in our simulations and experiments. In addition, the thermal–hydraulic characteristics around the pebbles have rarely been investigated in the high-Re number flows ($Re > 10^4$). Two inlet Re numbers of 10,000 and 20,000 are considered. This study thus set out to close this gap in the research. The sphere blockage ratio used herein is defined as dZ/D_p, where dZ is the axial distance between two spheres [20,21,24,34]. The blockage ratio is varied between 1.5 and 0.55 by changing the distance between adjacent spheres. Based on the comparison results with different turbulence models from Constantinescu et al. [23] and Kao et al. [35], the $\overline{v^2}-f$ model [36,37] is adopted as the turbulence model for the current simulations. Constantinescu et al. [23] first employed the $\overline{v^2}-f$ model to simulate the flow field in the pebbles. However, heat transfer is not considered in their work. The current model is also validated through the experiments [35] that were conducted by passing heated air across an array of 14 spheres inside a flow channel. It is notable that the current study is an extension of a previous work [35] that essentially set up the experiments and established an appropriated CFD methodology. Based on the validated model, the majority of current work can investigate the blockage effects for a sphere array and provide a greater degree of understanding about the complicated interactions between the pebbles.

Table 1
Comparison of previous researches related to the heat transfer phenomena for a sphere or a sphere array.

	Re number	Sphere number/arrangement	Turbulence model	Assessment data
Logtenberg and Dixon [20]	9–1450	1/2 Layers	k–ε	Experiment
Nijemeisland and Dixon [21]	373, 968, 1922	44/Line arrays	k–ε, RNG k–ε, RSM	Experiment
Romkes et al. [22]	0.1-10^5	1–40/Line arrays	k–ε, RNG k–ε, RSM	Experiment and correlation
Maheshwari et al. [25]	1–100	1 and 3/line array	Laminar flow	Experimental correlation
Jang and Chiu [26]	1300–11,000	14/4 Layers	Extended $k-\varepsilon$	Experiment
Augier et al. [27]	1–80	1 and ∼100/random	Laminar flow	Correlation
Dixon et al. [30]	40–20,000	1	SST $k-\omega$	Correlation
Dixon et al. [19]	2000–20,000	1000, 1250/random	Realizable $k-\varepsilon$	Experiment
Shamsa et al. [31]	3088	1 + 4 * 1/4 spheres/3 layers	LES	Quasi-DNS database
Ferng and Lin [32]	3716.8 4887.8	4 + 16 * 1/4 spheres/7 layers	RSM	Correlation
Pavlidis and Lathouwers [33]	1000–5000	12/3 Layers	LES	Experiment
Present work	$10^4,\ 2\times10^4,\ 2.6\times10^4$	14/3 Layers	$\overline{v^2}-f$	Experiment