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Influence of Arrangement for Elements of Bed to Flow and Heat Transfer

E. Szymanek[a,*] and P. Szymanek

Czestochowa University of Technology, 42-201 Czestochowa, Poland

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*e-mail: ewa.szymanek@pcz.pl

The article presents numerical simulations of the flow and heat transfer for beds with an ordered and shifted arrangement of elements. The numerical model applied is based on the unsteady equation of heat conduction (3D) and the Navier–Stokes equations. A high-order compact method in combination with the weighted essentially non-oscillatory scheme and predictor–corrector method is applied for the spatio-temporal discretisation. The flows of air and heat in the bed are modelled using the immersed boundary technique, which allows the use of Cartesian meshes for objects with very complex geometric shapes. The influence of the shift of elements in the bed on the temperature and velocity field was analysed. For two of the selected beds, the influence of arrangements of elements on the flow and heat exchange was analysed, which can lead, for example, to an improvement in the heating properties and to eliminating defects in the construction of reactor fillings.

topics: computational fluid dynamics (CFD) modelling, granular material, heat transfer

1. Introduction

Analysing the distribution of granulates in the beds, it can be concluded that numerical simulations of the flow in granular layers are carried out for configurations with both deterministic and random arrangements of elements. An example can be work [1], where pressure drops in a fixed bed of spheres in different arrangements are examined. In [2], the authors analysed the flow in a catalytic reactor with different types of arrangement of granular elements. In this case, a thorough understanding of flow dynamics is important, especially regarding the voids between bed elements. The aim of this work is to analyse heat flows through packed beds of granular materials using advanced numerical simulations and investigate to what extent changed arrangement elements can influence flow. The applied numerical model provides the temperature distributions and their variability over time inside the solid objects and around them. It is based on the unsteady equation of heat conduction (3D) and the Navier–Stokes equations for modelling the fluid flow between the layers made of solid objects. Complex structures of the beds are modelled using the immersed boundary technique (IB). The results of the analyses show that the structure of the layer and the size of the elements have a decisive influence on the flow parameters (pressure drop, mixing intensity, velocity). An innovative computational algorithm was used, which combined the IB method with a computational algorithm dedicated to the analysis of flows with a low Mach number. The use of the IB method allowed for simulations to be performed on Cartesian grids, which eliminated the need to generate computational grids adjusted to solid surfaces.

2. Mathematical model

Variable density, variable temperature, and low Mach number flows are described by the continuity equation, the Navier–Stokes equations, and the energy equation defined as

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0, \tag{1}$$

$$\rho\Big(\partial_t \boldsymbol{u} + (\boldsymbol{u}\cdot\nabla)\,\boldsymbol{u}\Big) + \nabla p = \nabla \tau + f^{\mathrm{IB}}, \tag{2}$$

$$\rho C_p\Big(\partial_t T + (\boldsymbol{u}\cdot\nabla)\,T\Big) = \nabla\cdot(\kappa\nabla T) + f_T^{\mathrm{IB}}, \tag{3}$$

where ρ stands for the density, T — temperature, p — hydrodynamic pressure, $\boldsymbol{u}$ — velocity vector, C_p — heat capacity, and κ — heat conductivity. The set of three equations is complemented with the equation of state $p_0 = \rho R T$, where p_0 denotes the thermodynamic pressure, and R is the specific gas constant. In open flows with inlet/outlet boundaries, p_0 is constant in space and time [3], and in this work, it is assumed to be 101325 Pa. The molecular viscosity (μ) within the viscous stress tensor τ is computed from the Sutherland law.

2.1. IB-VP source term

The source terms f^{IB} and f_T^{IB} originate from the immersed boundary volume penalization approach (IB-VP). Their role is to penalize a difference between the actual and assumed velocity and temperature of the solid body. They act on a fluid in such a way as if there were solid objects immersed in the flow domain, and they are defined as

$$f^{\text{IB}} = -\frac{\rho}{\eta}\,\Gamma(x)\big(\boldsymbol{u} - \boldsymbol{u}_s\big), \tag{4}$$

$$f_T^{\text{IB}} = -\frac{\rho C_p}{\eta}\,\Gamma(x)\big(T - T_s\big), \tag{5}$$

where $\boldsymbol{u}_s$ and T_s are the velocity and temperature of the solid body, the parameter $\eta \ll 1$ is the so-called penalization parameter with a dimension of time unit, and Γ — the phase indicator defined as

$$\Gamma\,(x) = \begin{cases} 0, & \text{for } \ x \in \Omega_f, \\ 1, & \text{for } \ x \in \Omega_s, \end{cases} \tag{6}$$

where Ω_f and Ω_s are the regions of fluid and solid part of the computational domain. For $\Gamma(x) = 1$, discrete forms of (2) and (3) with the time step Δt reduce to $\boldsymbol{u}^* \approx \nabla(t\boldsymbol{u}_s)/(\eta + \Delta t)$ and $T^* \approx \nabla(tT_s)/(\eta + \Delta t^n)$, which for $\eta \ll \Delta t$ leads to $\boldsymbol{u}^* \approx \boldsymbol{u}_s$ and $T^* \approx \nabla(tT_s)$ Thus, the forcing terms enforce the no-slip boundary conditions and set the required temperature of the solid objects. The simplicity of the IB-VP method has, however, direct consequences in lowering solution accuracy. Similarly as in the classical IB method with a stepwise approach (i.e., without the interpolation [4]), the formal order of the IB-VP method is at most equal to one [5].

2.2. Solution algorithm

The solution algorithm for (1)–(3) is formulated in the framework of a projection method for pressure–velocity coupling. The time integration is based on a predictor–corrector approach (Adams–Bashforth/Adams–Moulton), and the spatial discretisation is performed using 6th/5th order compact difference and WENO (weighted essentially non-oscillatory) schemes on half-staggered meshes. The verification of the proposed model can be found, e.g., in work [6]. The validation of the method showed very good agreement of the results with exemplary data.

3. Numerical results and discussion

The main configuration is placed in the computational domain (box $0.05 \times 0.35 \times 0.05$ m^3) and consists of a layer of $10 \times 10 \times 10$ hot spheres with a temperature $T = 400$ K and diameter $D = 0.008$ m (Fig. 1). The spheres are separated by 0.0001 m. At the lower boundary, we assumed a uniform velocity of 0.1959 m/s and a temperature of

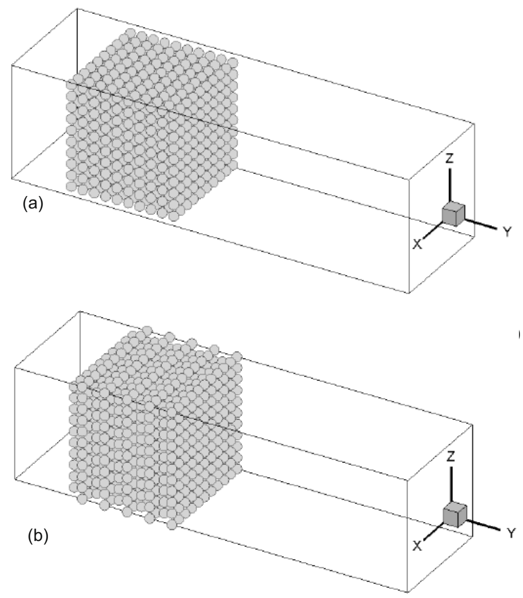

Fig. 1. Computational domain with: ordered bed — Config. 1 (a) and shifted bed — Config. 2 (b).

300 K (Re = UD/ν=100). The computations were performed with the use of a Cartesian mesh consisting of $137 \times 480 \times 137$ nodes.

Additionally, we consider configuration, which differs in distribution of the spheres. In the configuration denoted as Config. 2, there are $N = 10 \times 10 \times 10$ spheres, in which alternate layers are shifted towards the centres of the preceding layer.

Figure 2 shows contour plots showing temperature and velocity distributions in the central plane of the beds. It can be observed that the flow is clearly faster in the intergranular spaces for configuration denoted as Config. 1. Where air hits the spheres, the flow slows down. This creates recirculation zones that lead to more heat transfer. The situation is different in the case of Config. 2 with shifted spheres. In this case, no rapid increase in velocity is observed because there is no empty space for an undisturbed stream between the spheres. It turns out that the accelerating fluid in the intergranular space of one layer is inhibited by the spheres of the next layer. However, as a result, the mixing process is very intense, which favours rapid heat transfer. This can also be seen in Fig. 3, where the distributions of vectors for both configurations are presented. As the fluid gets hotter, its density decreases, and the forced fulfilment of the law of conservation of mass causes its velocity to increase. It can be seen that in the case of shifted layers, the velocity at the ends of the layers is much higher compared to their initial values. Nevertheless, the locally highest velocity values were recorded for the ordered configuration, where the medium could move with little disturbance.

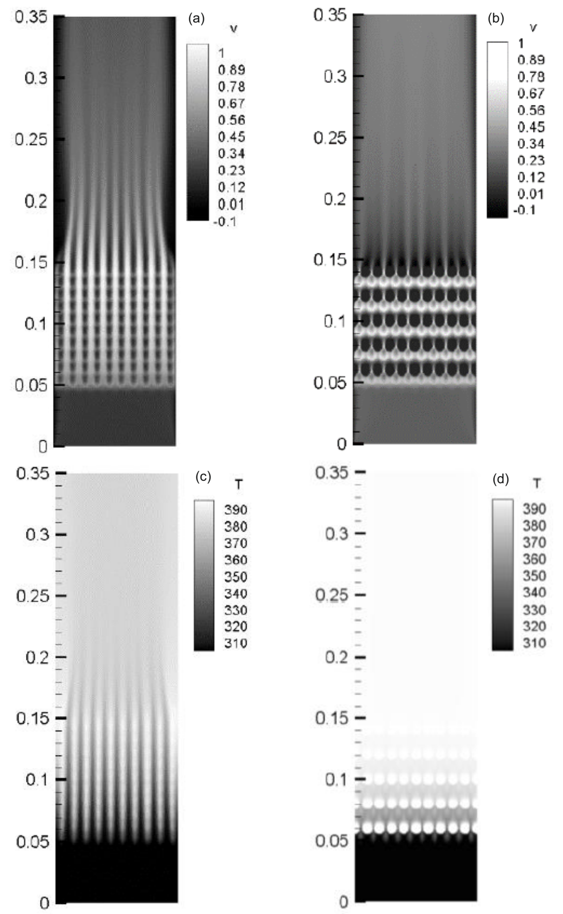

Fig. 2. (a, b) Velocity and (c, d) temperature distribution on the planes from the middle part of the bed: Config. 1 on the left and Config. 2 on the right, along y direction.

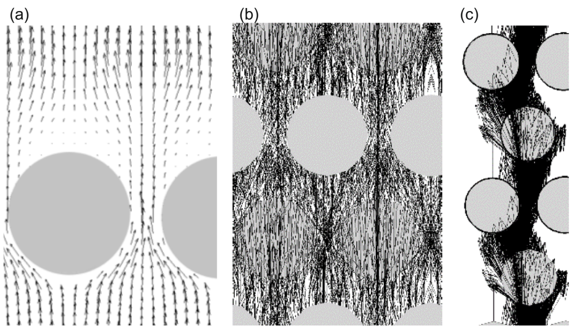

Fig. 3. Vector distribution around ordered (a) and shifted (b, c) bed spheres.

Figure 4 shows the velocity, temperature, pressure and vorticity profiles along the bed height (y direction). The values presented in the graphs have been averaged in the x–z planes and normalized by the input values. In both cases, there is a rapid rise in temperature. However, already in the first part of the bed, differences in temperature values can be seen, which persist until the end of the domain.

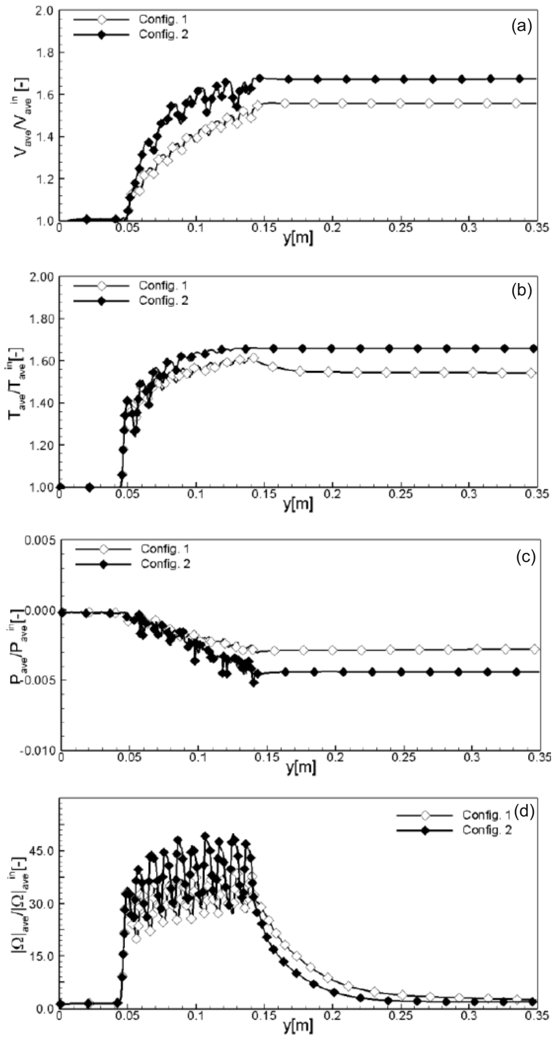

Fig. 4. (a) Spatially averaged velocity, (b) temperature, (c) pressure, and (d) vorticity profiles along the computational domain.

In the initial section of the layers, the fluid heats up with varying intensity, which is manifested by the wavy shape of the profiles. Significant differences can also be observed in the velocity profiles. The vorticity profiles show a very non-uniform flow field. In both cases, the vorticity between the individual layers changes rapidly and reaches significantly higher values in the "shifted" bed (Config. 2). Hence, it can be concluded that higher vorticity values mean areas with increased mixing intensity, and therefore the heat exchange taking place in such configurations is the most effective.

4. Conclusions

The paper presented numerical studies on the heat and flow transfer in the layers of spheres for ordered arrangement and shifted distributions. An advanced numerical method based on high-order discretisation combined with the immersed boundary (IB) method was applied. The applied model allowed for deep analysis of the flow and temperature distributions between the spheres and above the layers. It was shown that it characterises a very complex structure and that the configuration of the layer significantly affects the effectiveness of the mixing and heat transfer. It was found that even a small interference in the arrangement of the bed elements (shift) can result in an improvement in the heating properties.

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