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Flow characteristics analysis of purge gas in unitary pebble beds by CFD simulation coupled with DEM geometry model for fusion blanket

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HIGHLIGHTS

- A unitary pebble bed was built to analyze the flow characteristics of purge gas based on DEM-CFD method.
- Flow characteristics between particles were clearly displayed.
- Porosity distribution, velocity field distribution, pressure field distribution, pressure drop and the wall effects on velocity distribution were studied.

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ABSTRACT

Helium is used as the purge gas to sweep tritium out when it flows through the lithium ceramic and beryllium pebble beds in solid breeder blanket for fusion reactor. The flow characteristics of the purge gas will dominate the tritium sweep capability and tritium recovery system design. In this paper, a computational model for the unitary pebble bed was conducted using DEM-CFD method to study the purge gas flow characteristics in the bed, which include porosity distribution between pebbles, velocity field distribution, pressure field distribution, pressure drop as well as the wall effects on velocity distribution. Pebble bed porosity and velocity distribution with great fluctuations were found in the near-wall region and detailed flow characteristics between pebbles were displayed clearly. The results show that the numerical simulation model has an error with about 11% for estimating pressure drop when compared with the Ergun equation.

1. Introduction

The solid breeder blanket is considered to be one of the most promising fusion blankets for DEMO and first generation fusion power plant. The neutron multiplier and the tritium breeder materials are made into millimeter-sized pebbles and arranged in the blanket. Low pressure heliumis used as the purge gas to sweep tritium out when it flows through the lithium ceramic and beryllium pebble beds. The flow characteristics of the purge gas will dominate the tritium sweep capability and tritium recovery system design. In order to study the purge gas flow characteristics, it is necessary to carry out experimental investigation and numerical simulation. But the literatures on numerical simulation or experimental researches for the purge gas flow characteristics of fusion blanket pebble beds seems to be limited up to now. Thermal-hydraulic calculations based on 2-D non-Darcian momentum equations were performed by Ying et al. [1]. DEM software was used to set up the packed bed and small fluid domain contained only several pebbles was extracted for simulation by Song et al. [2], velocity probability distribution and pressure drop in the small fluid domain were given while the detailed flow characteristics between pebbles and in the whole bed was not studied. Van Lew et al. coupled discrete element models of ceramic breeder pebble beds with volume-averaged navier-stokes and the lattice-boltzmann method to resolve pebble-scale interactions with bed-scale conjugate heat transfer with flowing gas [3]. The various factors affecting pressure drop, such as the particle diameter and packing factor and so on, were studied through experiments by Abou-Sena et al. [4,5]. However, the detailed flow characteristics in the bed were not fully studied or it is not convenient for direct measurement in those papers. The work objective of this paper is to set up a numerical simulation model for detailed flow characteristics studying.

Regarding to the flow numerical analyses of the pebble beds, they can be divided into two main approaches depending on

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Nomenclature

d	Particle diameter (m)
D	Tube diameter (m)
L	Length of the packed bed (m)
Re	Reynolds number ($dU\rho/\mu$), dimensionless
U	Fluid velocity (m/s)
U_0	Inlet velocity (m/s)
U'	Cross-sectional average velocity (m/s)
A_0	Cross-sectional area of the bed (m^2)
Greek letters	
ρ	Density of fluid (kg/m^3)
μ	Dynamic viscosity (Pa·s)
ε	Porosity, dimensionless

the pebble bed is modeled as fictitious continuum or as actual geometry. In the first approach, the packed bed is regarded as a continuous and pseudo-homogeneous porous medium, where modified Navier–Stokes equations are applied in conjunction with the Ergun pressure drop correlation to account for the fluid–solid interaction [6,7]. However, it is difficult to reflect the packing structure in the bed, especially the near-wall region, as well as the details of the flow characteristics in the gap between pebbles. The other approach is numerical simulation based on the actual bed geometry, the fluid flow in packed beds with non-uniform voidage is simulated by solving the complete set of Navier-Stokes equations without any additional simplifying assumption [8–13]. Therefore, the later reflects more detailed local flow characteristics in the void space between pebbles.

DEM-CFD method has become an effective tool for analyzing the mass and heat transfer in packed bed [12,14,15], in which CFD numerical simulation is performed based on the packed bed structure established by DEM. The advantages of this method are that detailed local flow characteristics can be reflected and mass or heat transfer can be analyzed for the actual packed pebble beds. But taking into account the huge consumption of computer resources, the number of particles in the simulation is limited. In the current work, the known physical geometry of the pebble bed packed by DEM was recreated and the flow characteristics of purge gas in the bed were analyzed. In Section 2, numerical methodology is illustrated. The results and discussions are presented in Section 3. Finally, conclusions are summarized in Section 4.

2. Numerical methodology

The simulation procedure is illustrated in Fig. 1. Firstly, the pebble bed parameters, such as the bed dimensions, particle size and material properties, are determined in the beginning and then used as the input data for the DEM model. Second, the random packed pebble bed is directly simulated by DEM method. As a result, a scaled close packed pebble bed can be obtained so as to provide the particle information for the fluid domain reconstruction. After building mesh and defining boundary conditions on the DEM-based fluid domain, the flow characteristics can be analyzed by the CFD simulation.

2.1. Packing by DEM

In the DEM method, each particle is regarded as a discrete element, and the contact state of each individual particle is directly simulated using basic interaction laws [16–18]. In this paper, DEM method was used to achieve the prototypical pebble bed. Similar with the previous work [19], particles fall freely by gravity from

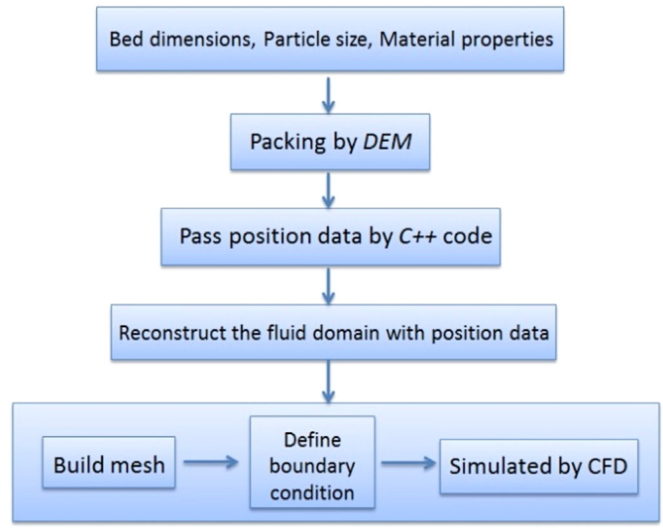

Fig. 1. Simulation procedure.

Table 1
Parameters for the DEM simulation.

	Symbol	Value
Particle diameter	d [mm]	2
Packing size	Lx, Ly, Lz [mm]	20, 10, 30
Young's modulus	E [GPa]	90
Poisson's rate	ν	0.24

the top of the container and finally a close packed pebble bed was built at the bottom. 859 particles were included in the current geometry model of the pebble bed, and the global packing factor ($V_{particles}/V_{container}$) is 0.60, which is close to the experimental value [20,21]. Parameters of material properties [22] for DEM simulation are shown in Table 1.

2.2. Geometry and mesh in the fluid domain

Particles' information (position and size) of the concerned pebble bed can be obtained according to the packing structure simulated by DEM. As the next step, the pebble bed geometry will be reconstructed based on the particles' detailed information and the fluid domain will be acquired by a series of geometry boolean operations in the CFD pre-processing software. To minimize the influence of the inlet and outlet boundary, the channel was extended at the inlet and outlet, as shown in Fig. 2.

Since the random arrangement of pebbles in the bed leads to a highly irregular fluid domain, mesh process will be very difficult, especially in the point-contacted region between pebbles. An appropriate contraction ratio is necessary for numerical simulation. Nijemeisland and Dixon created the models with 95, 97, 99, 99.5% of the original diameter, it has been indicated that when the gaps were larger (the 95 and 97% sphere sizes), the velocity distribution tended to move to higher velocities, while the 99.5 and 99% sphere size models showed good agreement with the touching model's velocity distribution [11]. And in the work by Calis et al., it has been introduced that the resulting friction factors differed less than 0.5% between 0.98d and 0.99d model [8]. Also, in the work by Reddy et al., it has been pointed that fluid velocity in the gap between the spheres is practically zero in both cases of diameter reduced to 99% and 98% of the original size [10]. From what has been discussed in the previous studies of others, we thought it is an appropriate choice to reduce the diameter to 98%–99%. So in order to avoid meshing problem, each particle in the pebble bed was shrinked by

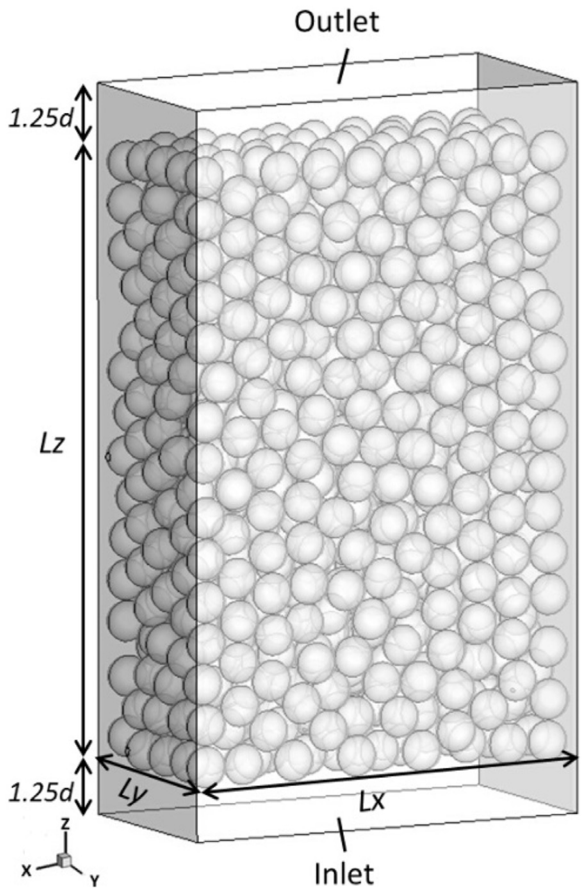

Fig. 2. Computational model overview.

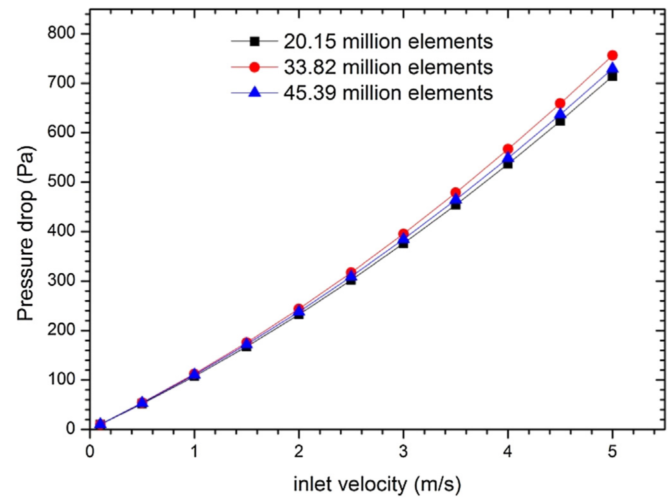

Fig. 3. Pressure drop for different numbers of mesh elements.

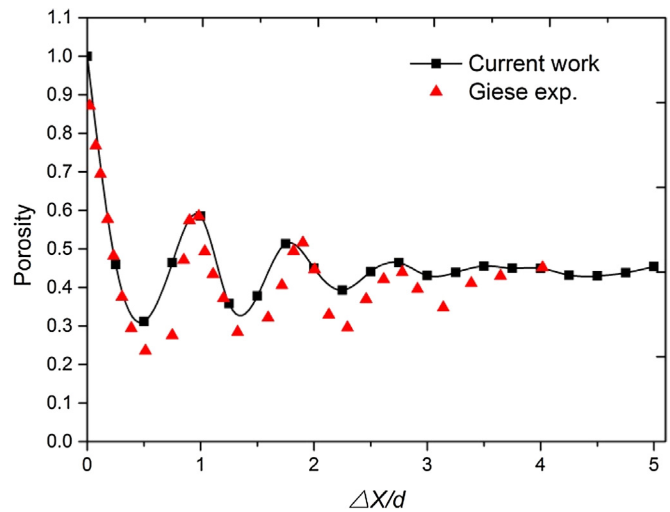

Fig. 4. Porosity distribution along X direction.

2% [10,12,13] and an unstructured tetrahedral grid was used for the following CFD simulation. The effects of size contraction and the appropriate choice of contraction ratio will be discussed in the following Section 3.3.

2.3. CFD simulation

The numerical model was performed by the commercial CFD software FLUENT14.5. Energy equation was not considered in the current CFD model, the purge gas property was defined as helium at a typical pebble bed temperature of 500 °C(ρ = 0.063 kg/m^3, μ = 3.8 × 10^{-5} Pa s). The velocity-inlet and pressure-outlet boundary conditions were employed. Because the sweeping velocity is very low for fusion blanket design, so only the velocities range 0.01 m/s to 0.2 m/s were analyzed in the results and discussion. Since the Reynolds number ($dU\rho/\mu$) was less than 100, the laminar flow model was applied[23]. The SIMPLE algorithm was employed for the pressure-velocity coupling and all terms of the governing equations for steady state were discretized using the second-order upwind differencing scheme. The simulations were performed using a high performance windows server with a configuration of 24 cores and 256GB memory. In order to verify the accuracy of the calculation model and obtain grid independence results, the fluid domain was meshed into 20.15 million, 36.85 million and 45.39 million grids. As shown in Fig. 3, it can be found that the differences between the three results of pressure drop were very small, and the results of 45.39 million grids will be discussed in next section.

3. Results and discussions

3.1. Porosity distribution

The cross-sectional porosity can reflect the packing density in local region, it was defined as the ratio of flow area to the total area on each cross section. The average porosity distribution from the two parallel walls to the zone center of X direction (porosity distribution along Y direction was similar with X direction, not shown in this paper) and Z direction were shown in Figs. 4 and 5. ΔX and ΔZ were the distance from the wall to the zone center along X and Z direction. As shown in the figures, the porosity profiles along X direction were close to experimental measurements done by Giese et al. [24] while the porosity distributions along Z direction were less close to the experiment results, it may be caused by the different packing size along Z direction because a larger packing size will weaken the wall effects. Damped oscillatory porosity variation was observed in the near wall region within 2.5 times the diameter of particle, while there was small fluctuation in the bulk zone. The first porosity peak appears at a distance of one particle diameter from the wall and the first porosity minimum is at about a half particle diameter from the wall. This is because the first layer of packing in contact with the wall is very structured due to the squeeze of the inner particles, but subsequent layers don't retain this level of

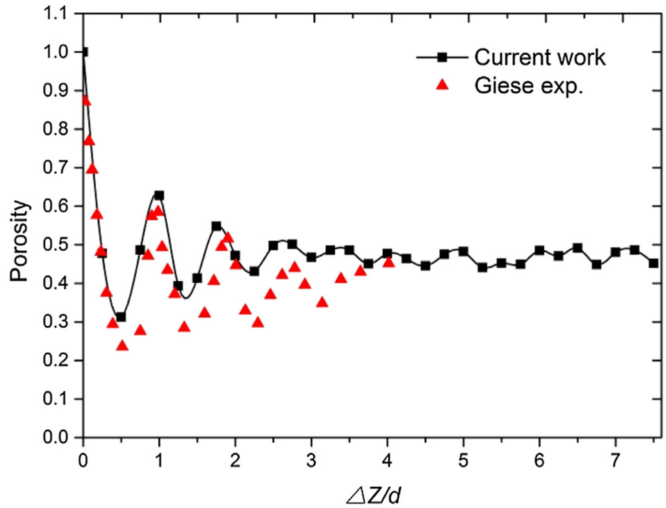

Fig. 5. Porosity distribution along Z direction.

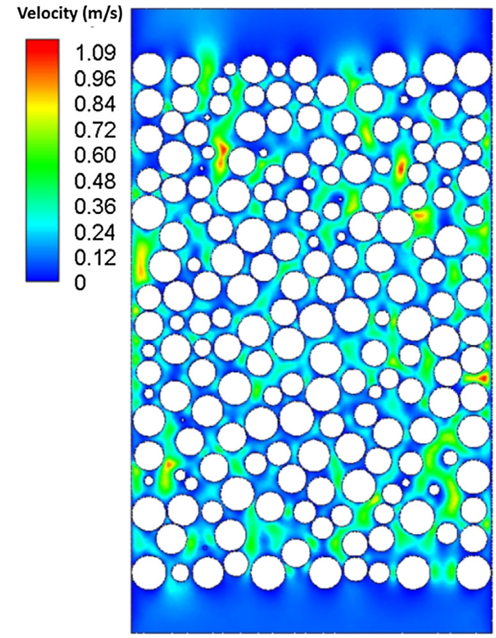

Fig. 6. Overview of velocity profiles on the Y = 0 plane (U_0 = 0.1 m/s).

order because of the degree of randomness increases with distance from the wall. This phenomenon can also be clearly observed in our previous work [19] by the gnomonic projection near the wall at the bottom of container of all particles.

3.2. Velocity field distribution

The velocity distribution of the whole packed bed especially in the gap between particles is an important flow characteristic. A global overview of velocity profiles on the Y = 0 plane was shown in Fig. 6, where we can find out that greater velocity appears in the higher porosity region, and the locally maximum velocity is about 10 times of the velocity of inlet.

Fig. 7 quantitatively explains the dimensionless velocity distribution on the line of X axis at different inlet velocities, the value of 0 corresponds to the existence of solid pebbles. As can be seen from Fig. 7(a), velocity gradient was big in the gaps between pebbles and

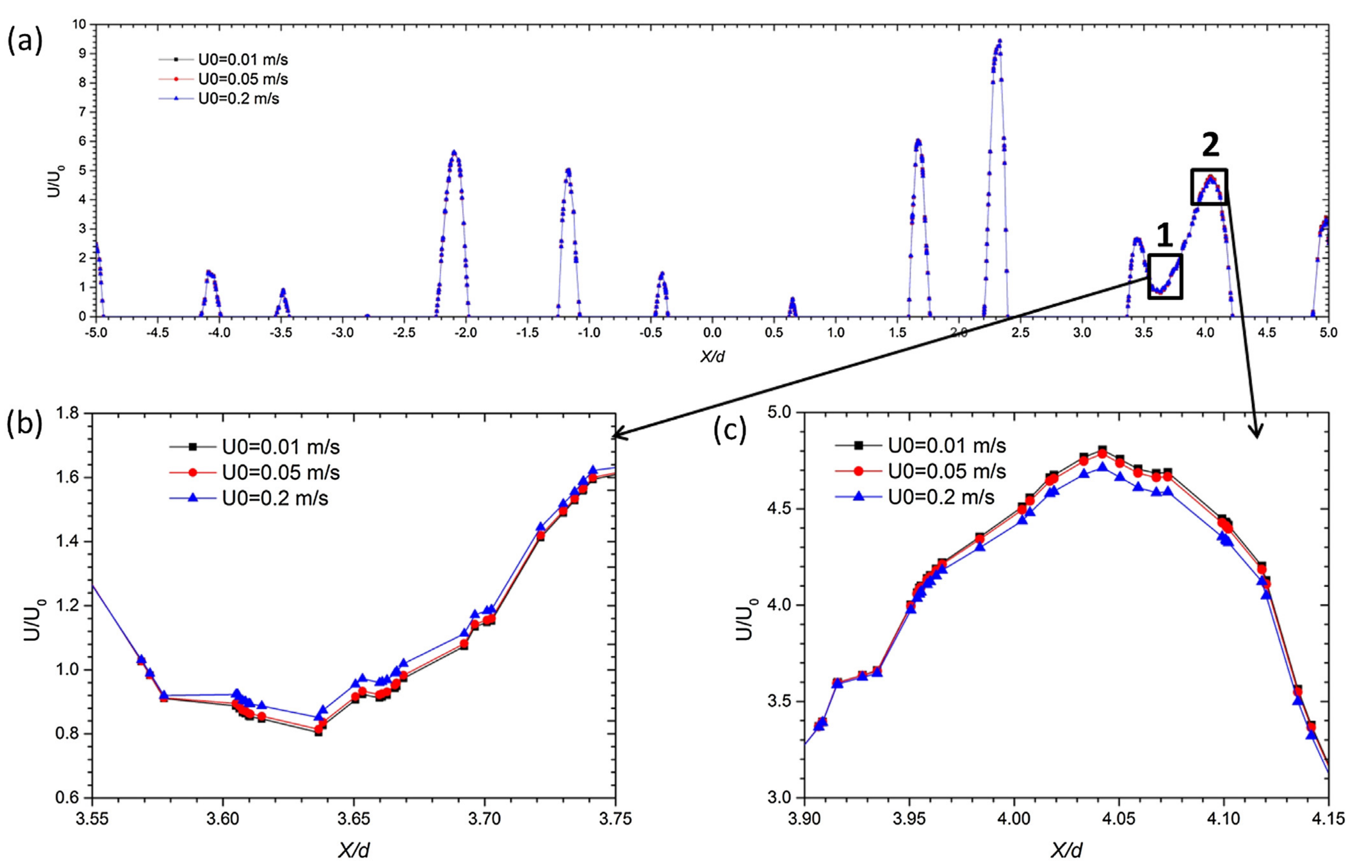

Fig. 7. Dimensionless velocity distribution on the line of X axis at different inlet velocities.

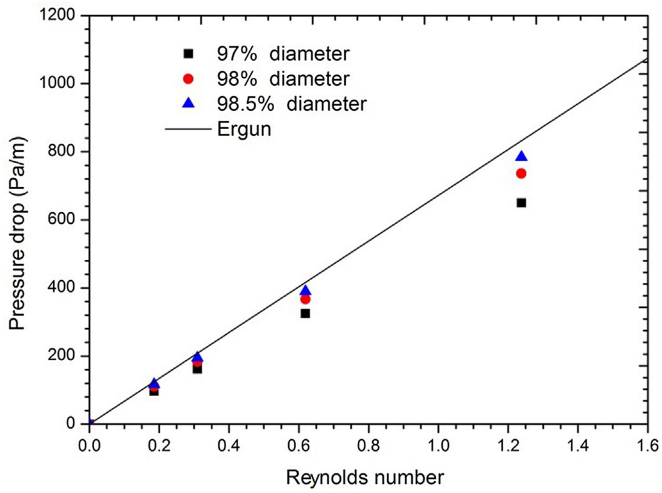

Fig. 8. Pressure drop for different Reynolds numbers.

velocity distribution trend at different inlet velocities were almost similar, but there were differences in local area with large porosity. Enlarged drawings for region 1 and region 2 were taken as examples, from Fig. 7(b) and (c) we can find that in some regions velocity gradient at low inlet velocity is larger than it at high inlet velocity, while in some other regions this phenomenon becomes the opposite. It seems indicate that the flow characteristics substantially similar in the whole bed but there may be slightly different in some local regions, it may be caused by the different local resistance in different regions.

3.3. Pressure drop and pressure field distribution

The pressure drop of the packed bed is an important property of flow characteristic for bed design. In order to evaluate the effect of diameter contraction on pressure drop, the CFD results of diameter reduced to 97%, 98% and 98.5% original size were compared with the well-known Ergun equation [25] using the original parameters of void fraction and diameter without contraction, as shown in Fig. 8. Although the mesh procedure was successful finally when the diameter was reduced to 99%, but the mesh quality was not so good because the narrow gap between pebbles and the convergence was unachievable. It can be seen that the errors of the models when diameter reduced to 98.5% and 98% original size were about 5% and 11% respectively, while the case of 97% diameter underestimated the pressure drop a little much with a deviation about 25%. In summary, diameter reduced to 98%–99% is an appropriate choice as described in section 2.2, but considering the difficulty of meshing, mesh quality, mesh number and computer resources, diameter with 2% contraction is a priority choice for simulation because it can guarantee a good convergence and an acceptable error.

The pressure distribution for $Re = 0.62$ ($U_0 = 0.1$ m/s) was analyzed as an example, the pressure distribution of the whole fluid field and pressure contour of Y = 0 mm plane were shown in Fig. 9(a) and (b). Cross sectional average pressure along the main flow direction were calculated, and the results were shown in Fig. 10. It can be seen that the cross sectional average pressure of the packed bed decreases linearly.

3.4. Wall effects on velocity distribution

In order to investigate the impact of wall effects on cross sectional average velocity distribution, the average dimensionless velocity distribution along X axis (perpendicular to the main flow direction) and Z axis (main flow direction) at different Reynolds numbers were plotted in Figs. 11 and 12, from which we can observe that the velocity distributions were almost similar at different low Reynolds number. The velocity shows great fluctuation within 2.5 times the particle diameter distance from the wall and the maximum velocity near the wall can reach more than 3 times the inlet velocity, but velocity distribution in bulk region is relatively uniform. Along the direction of X, the first velocity peak appeared at 1/8*d* (d is the particle diameter) away from the wall, and the second peak appeared at a distance of about 1 times the particle diameter away from the wall. From Fig. 5 and Fig. 12, it can be seen that along the main flow direction (Z direction) the velocity has an opposite fluctuation trend with porosity distribution, which can be explained by the continuity equation of constant incompressible fluid written as follows.

$$U_0 A_0 = U \varepsilon A_0 \text{ or } U/U_0 = 1/\varepsilon$$

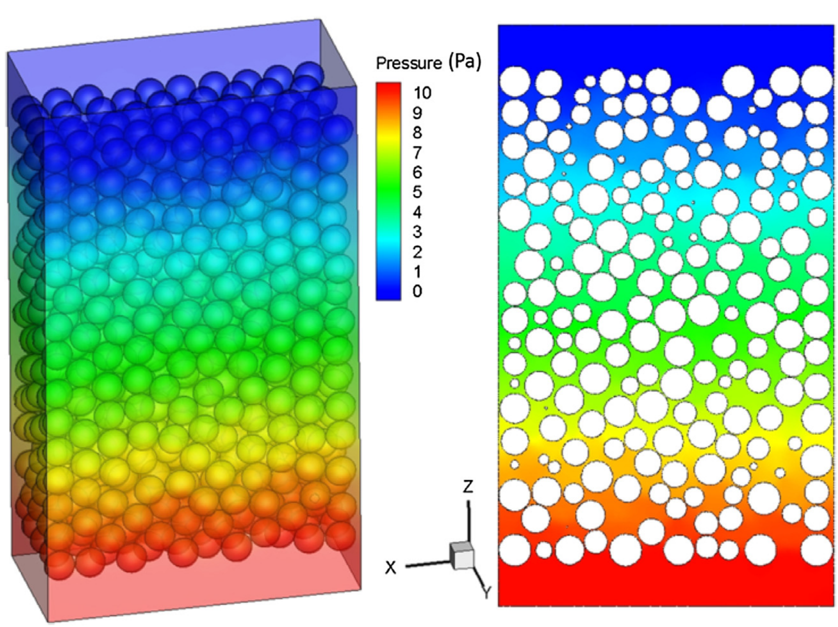

Fig. 9. Pressure contours.

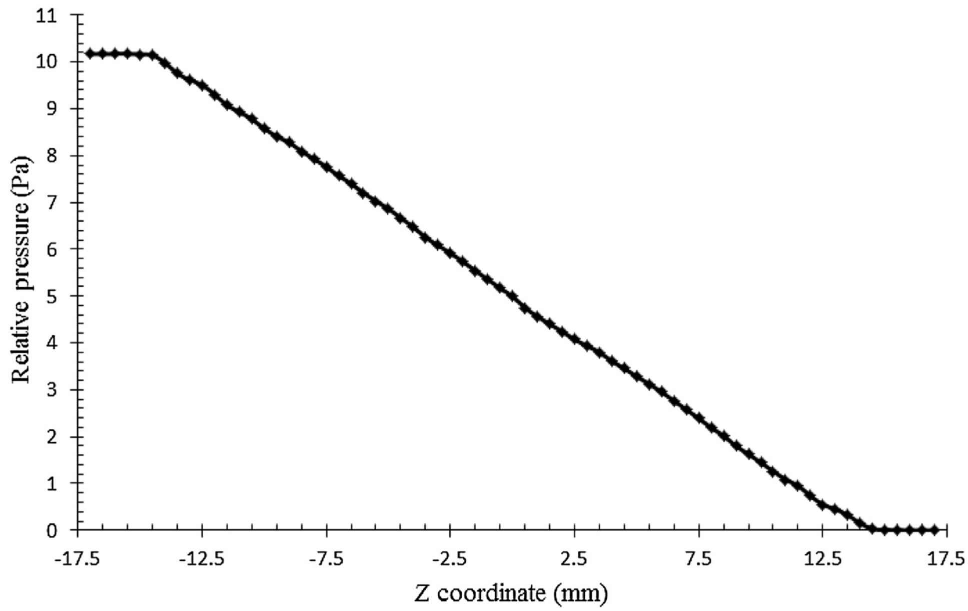

Fig. 10. Cross sectional average pressure.

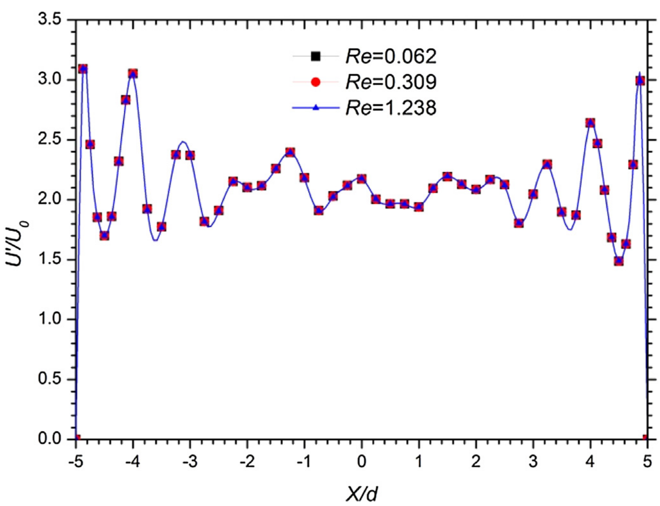

Fig. 11. Dimensionless velocity distribution along X direction.

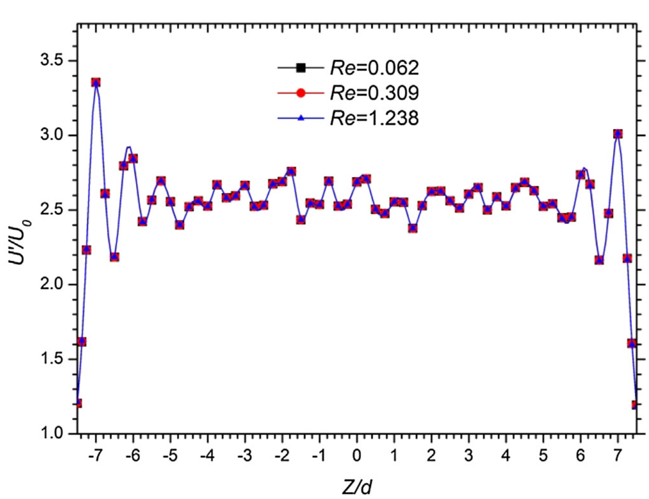

Fig. 12. Dimensionless velocity distribution along Z direction.

According to this equation, a large flow area will lead to a small velocity value due to the conservation of mass, so the velocity performed an opposite fluctuation trend with porosity along the main flow direction.

4. Conclusions

In this current work, the geometry of pebble bed for fusion blanket was directly created by DEM method and then the fluid domain was recreated using the known geometry for CFD simulation in which the fluid flow was simulated by solving the complete set of Navier-Stokes equations without any additional simplifying assumption. Flow characteristics were analyzed, including porosity distribution, velocity field distribution, pressure drop and the wall effects on velocity distribution. The results showed that porosity and velocity with great fluctuations occured in the near-wall region, and the numerical simulation model has an error about 11% for estimating pressure drop when compared with the Ergun equation.

However, some influencing factors, such as temperature effects, were not considered in this simulation. More works such as heat and mass transfer will be taken into account and this modeling method will be improved based on more experimental results in our future work before applying it to future tritium sweeping models.

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