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Numerical investigation of the pebble bed structures for HCCB TBM

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ABSTRACT

The packing structures of tritium breeder and neutron multiplier pebble beds are important to estimate the thermal mechanical properties and the flow characteristics of purge gas in solid tritium breeding blanket. In this study, the pebble packing structures were numerical studied based on DEM simulation. The packing structures of cylinder pebble beds were further analyzed. The results show that the aspect ratio has a great influence on packing structure of pebble bed. Increasing the aspect ratio, a higher average packing factor can be obtained. Further, the U-shaped Li_4SiO_4 pebble beds were investigated. The results show that when the width of the U-shaped channel, the height of the bed and the diameter of the pebbles are given, the dimensions of the U-shaped container have little effect on the pebble bed packing structures. In addition, the influences of pebble size on packing structures of U-shaped pebble bed were analyzed and discussed. By decreasing the pebble size, the average packing factor can be increased, the wall effect region of the U-shaped pebble bed can be also reduced relatively and a more uniform pebble bed can be obtained.

1. Introduction

The tritium breeder (Li_4SiO_4, Li_2TiO_3, and Li_2O, etc, Lithium based ceramic) and the neutron multiplier (Be, BeO, and $Be_{12}Ti$) in solid tritium breeder blanket are all used in form of pebbles [1]. These individual pebbles are packed in the tritium breeding region and the neutron multiplying region to form the tritium breeder pebble beds and the neutron multiplier pebble beds. The Helium-Cooled Ceramic Breeder Test Blanket Module (HCCB TBM) is the primary choice for Chinese TBM program. The conceptual design of HCCB TBM has been completed in July 2014 [1]. In HCCB TBM, the Li_4SiO_4 ceramic pebbles with the diameter of ~1 mm and beryllium pebbles with the diameter of ~0.2 and 2 mm are selected as the tritium breeder and the neutron multiplier respectively [2]. Due to the discrete characterization of these pebbles, the pebble beds can be treated as granular materials. Their packing behaviors and packing structures need to be fully investigated before they can be applied. In solid tritium breeder blanket, the packing structures of pebble beds affect the thermal properties of pebble bed [3,4], the thermal mechanical of pebble bed [5,6], the flow characteristics of purge gas [7,8] and the tritium breeding ratio [1].Thus, to obtain an reasonable and feasible pebble bed for HCCB TBM, the packing structures of Li-based ceramic pebble beds and beryllium pebble beds should be investigated detailedly.

Lots of investigations about the packing structures of pebble beds have been reported in literature. Reimann et al. [9] studied the macro packing structures of the pebble bed in Plexiglas containers by packing experiments with different sized glass, beryllium, steel and lithium orthosilicate pebbles. Abou-Sena et al. [10] studied the possible technologies of pebble packing procedure for TBM by packing experiment. These experimental results reveal that the vibrating and tilting the pebble bed are necessarily to obtained dense packing. Besides, the filling hole of pebble packing should be located at the corner of the mock-up. Furthermore, the x-ray tomography was applied to study the macro and micro packing structures of pebble bed. After analyzing the experimental data, the detailed micro topological qualities and macro packing parameters can be obtained, such as pebble position, contact surface area between pebbles and between pebble and wall, coordination number, local packing factor distribution and 3D view of pebble bed. By using 3D X-ray computed tomography, Pieritz [11] studied the inner structure of the pebbles and pebble beds which packed with mono-sized pebbles. Reimann [12–14] analyzed the compressed and uncompressed pebble bed, the coordination number and the void fraction profiles were determined. Scaffidi-Argentina [15] analyzed the structure of a binary-sized beryllium pebble bed. Suzuki [16] studied the wall effect on pebble packing structure and proposed an empirical equation to predict the void fraction distribution in cylinder pebble bed.

Discrete element method (DEM) has been applied to investigate the packing structures and the thermo-mechanical behaviors of pebble bed

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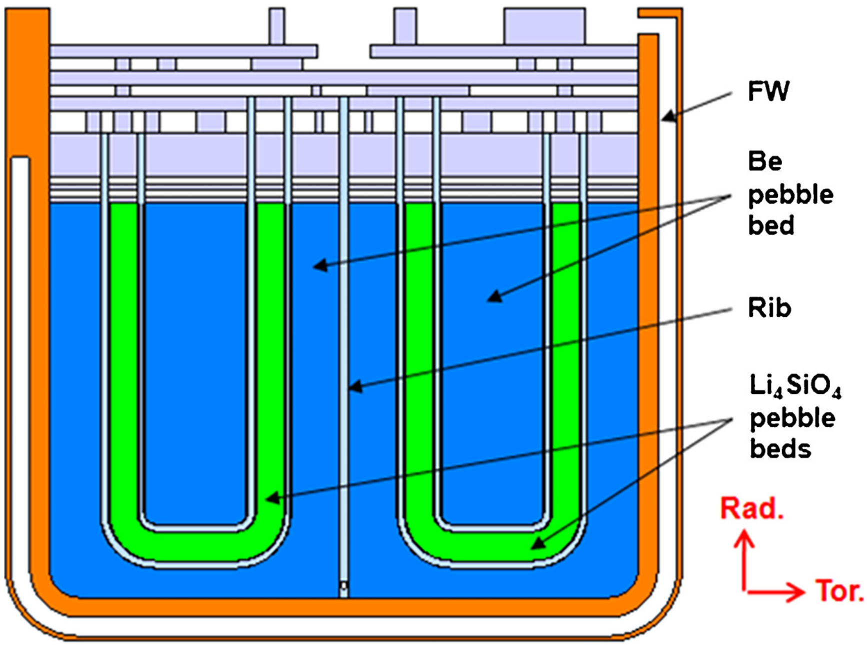

Fig. 1. Cross-section view of HCCB TBM (color online).

in solid breeding blanket. With the help of DEM, Gan [5] and Wang [17] investigated the mechanical properties of pebble bed under mechanical cycling load. Ying [18] studied the thermal creep behavior of ceramic breeder pebble bed by discrete element method. Lew [19] analyzed the thermo-mechanical behaviors of the breeder pebble bed. Gan [20] studied the random close packing structure in pebble bed. Chen [21] explored the packing structure of a prototypical blanket pebble bed for CFETR WCCB. The above literature shows that the discrete element method can be well used to numerically investigate the packing behavior of tritium breeder pebble bed in solid blanket. In addition, An et al. [22–24], Baranau [25] and Reimann [14] experimentally and numerically investigated the influences of vibration and compaction on the densification procedure of mono-sized pebble bed, respectively. Such as, the effect of vibration amplitude and frequency, feeding method and compression rate on the packing factor were systematically investigated. The results revealed that, the average packing factor for random close packing of ~0.64 is an upper limit in mono-sized pebbles. After vibrating the mono-sized pebble bed, the more dens packing can be obtained by proper control of vibration amplitude and frequency. And a higher packing factor, significantly larger than 0.64, can be obtained in total bed for D/d (D is diameter of cylinder container, d is diameter of pebbles) larger than 20. The increase of the packing factor by using appropriate vibration parameters is caused by the grouth of ordered packing in wall region [14].These occur as a result of the crystallization of mono-sized pebbles convection under mechanical vibration.

The packing structure of pebble bed depends on lots of factors, such as pebble size, pebble shape, container dimension, pebble bed height, packing procedure and so on. Different packing structure can be obtained under different conditions. However, little works on U-shaped pebble bed is available. Thus, the packing structures of U-shaped pebble bed still needs to be fully exploited before they can be applied in HCCB TBM. In this paper, we focus on the packing structures of the U-shaped pebble bed. On the basis of previous studies of the pebble bed packing structures for HCCB TBM [26], we have further studied the effects of container structures and pebble size on the packing structures of U-shaped pebble bed.

2. Simulation method

2.1. Discrete element method

The discrete element method (DEM), originally introduced and applied by Cundall [27], is an effective and reliable numerical tool to characterize the packing behaviors of granular materials. For solid tritium breeder blankets, the DEM simulations have been successfully used to investigate the thermal mechanical behaviors and packing structures of lithium-based ceramic breeder pebble bed [6,17,19,28–30]. The basic principles of the DEM are simple but effective. By the Hertz-Mindlin [31] contact theory, the normal contact force and tangential contact force with its neighbor pebbles are calculated. After applying the contact force and the gravity on pebbles, the motion of each pebbles can be computed according to the Newton's second law of motion.

In this simulation, some assumptions are made for simplifying the calculation. a) all the breeder pebbles are absolute spherical and are separate particles without considering the cohesion force and so on, b) the properties of pebbles are uniform; c) the overlaps of contact pairs are very small, so it can be considered point contact. d) the contact force of contact pairs is determined by Hertz-Mindlin contact theory, and e) the Coulomb Friction Law is used to determine the friction function of pebble-pebble and pebble-wall. The detailed theory of DEM can be found in Refs [26,27,31].

2.2. Packing of pebble bed

According to the design of HCCB TBM [1,2], as shown in Fig. 1, the Li_4SiO_4 ceramic pebbles were selected as tritium breeder which packed in U-shaped container. So, in the view of Li_4SiO_4 pebbles application in solid tritium breeder blanket, the physical properties of Li_4SiO_4 pebble materials were chosen in this work, which were listed in Table 1. The pebbles density is selected to 2323 kg/m3 (96.8%TD) which was obtained by experimental measurement of Li_4SiO_4 pebbles fabricated by melt spraying method. The Young's modulus and the Poisson ratio of Li_4SiO_4 pebbles is set to 90 GPa and 0.24 at room temperature [26,30,32]. Due to the lack of experiment results of friction coefficient of Li_4SiO_4 materials, and reference to the literature [17,30,33–37], in which Li_4SiO_4 pebble bed properties were investigated by DEM

Table 1
Properties of Li_4SiO_4 materials.

Property	Value
Density (kg/m^3)	2323
Young's modulus(GPa)	90
Poisson ratio	0.24
Friction coefficient for pebble-pebble	0.1
Friction coefficient for pebble-wall	0.1

simulation, the friction coefficients for pebble-wall and for inter-pebbles are set to 0.1. These physical properties are referenced comprehensively from the Refs. [17,19,26,30,32–37]

In the simulation, the pebbles were inserted and packed in the container under the gravity. Firstly, a certain number of Li_4SiO_4 pebbles were inserted in the container with a very loose packing. Secondly, these pebbles were free-falling under gravity. At the same time, a variable number of pebbles were fed to the container every specified time steps. The total numbers of pebbles in the beds increased as the time goes on. When the height of pebble beds reached a certain values, few pebbles were inserted into the container any more. From then on, the packing process changed from the inserting and packing stages to the rearrangement and equilibrium stage. Finally, all pebbles randomly packed in the container with an almost balanced static state. The packing structures of pebble beds were no longer changing. We can further analyze the packing structures of pebble beds in detail.

In this work, the pebble structures of the cylinder pebble bed were compared with the experimental results to validate the simulation results which were obtained in previous simulation [26]. The 3D views of cylinder pebble with various aspect ratios of cylinder diameter to pebble diameter are shown in Fig. 3. In the cylinder pebble bed, the diameters (d) of pebbles are given as 1 mm, the diameters (D) of cylinder container are given as 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 30 mm, respectively. The height (H) of pebble bed are about 2*D. Then the pebble packing in three U-shaped containers were simulated and analyzed as shown in Fig. 4a–c. And the height of U-shaped pebble beds are all equal 100 mm. The corresponding containers are shown in Fig. 2. Finally, the effects of pebble size on the packing structures of U-shaped pebble beds were analyzed. The 3D view of the U-shaped pebble beds are summarized and shown in Fig. 4.

3. Results and analyses

3.1. Packing structures in cylinder pebble bed

The cylinder bed is one of the most typical pebble bed structures, which is widely used in industry. Lots of researches paid attention to the cylinder pebble bed and obtained a lot of achievements. The cylinder pebble bed structures with various aspect ratios (cylinder diameter to pebble diameter ratio) were studied in previous simulation and

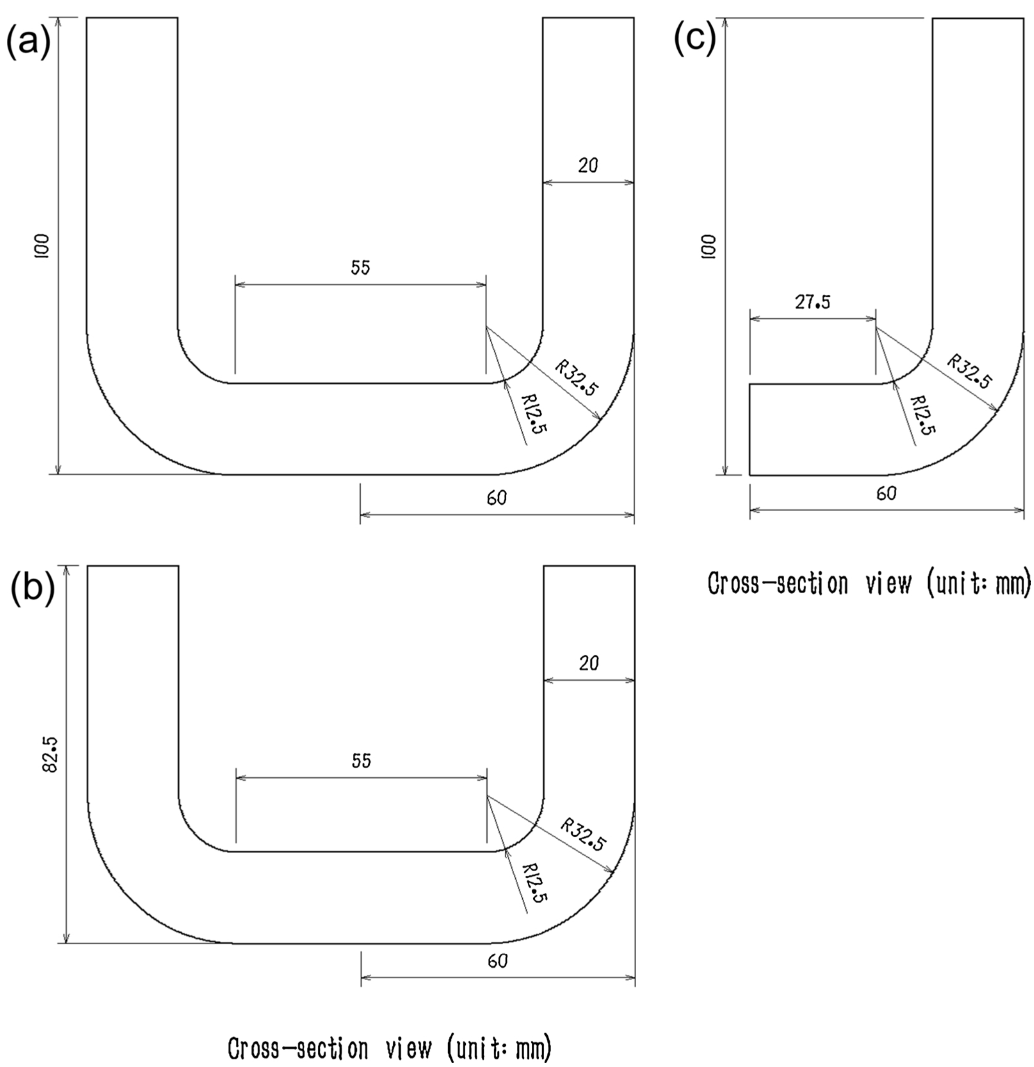

Fig. 2. Dimension of simplified U-shaped container.

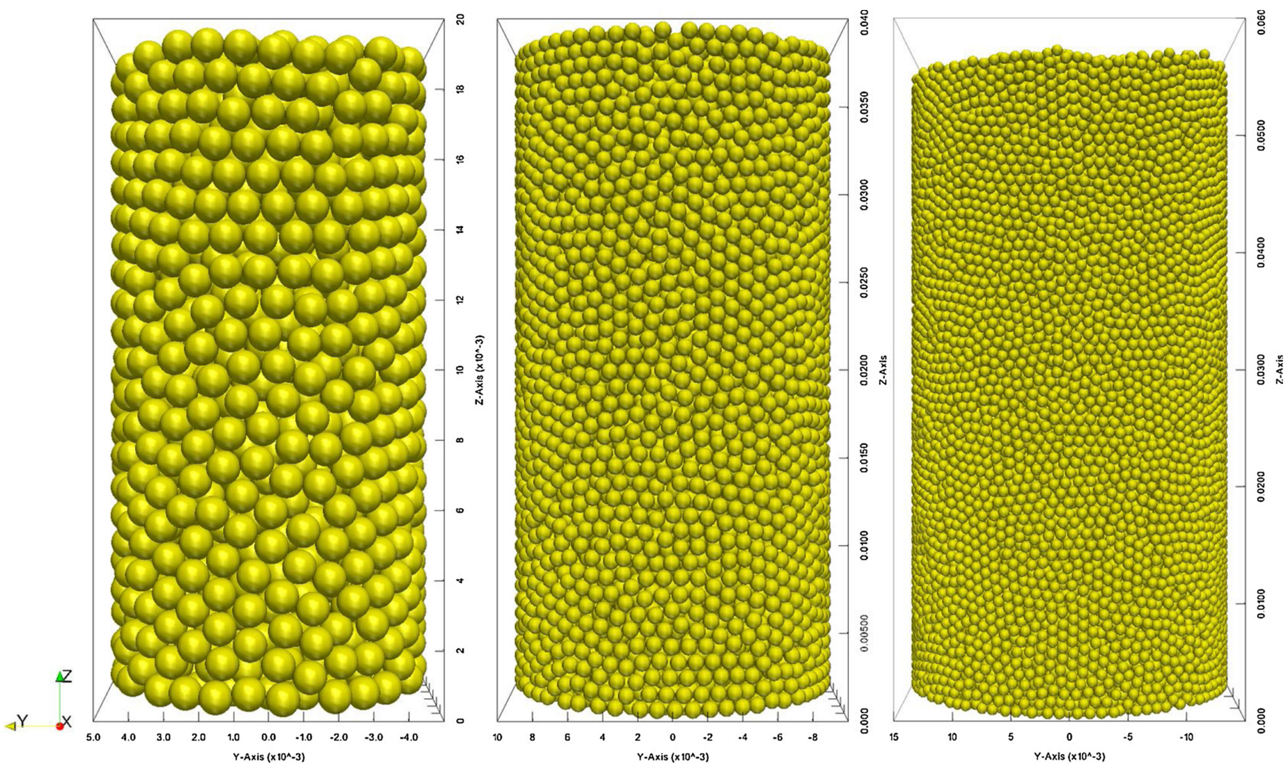

Fig. 3. 3D view of cylinder pebble bed with various aspect ratios: a) D/d = 10, b) D/d = 20, c) D/d = 30 (color online).

compared with the experiment and simulation results from literature [38–41] to validate the simulation results in this work.

The average packing factors of the cylinder pebble bed as a function of aspect ratios are shown in Fig. 5. When the aspect ratios are equal to 5 and 30, the average packing factors are equal to 0.5762 and 0.6184 respectively in this work. When aspect ratio is equal to 30, the average packing factor increases by 7.32% compared with aspect ratio of 5. it can be seen that these results have the same tendency, the average packing factor increases with the aspect ratios increases. The results in this work are agreement well with that in literature [38,39,41]. But when aspect ratio is less than 15, the packing factor in literature [40] are lower than in our simulation. The reason may come from the different materials properties and packing method. In further, the results show that the average packing factor can be significantly improved by means of vibrating pebble bed [41].

The average packing factor increasing with the augment of aspect ratios are partly attributed to the effects of container walls. Base on the previous simulation [26], we further analyze the local packing factor distribution of cylinder pebble bed with various aspect ratios, as shown in Fig. 6. The results show that, in the near wall region, the local packing factor show a damped oscillation curve. With the increase of the distance from the container wall, the local packing factors gradually approach to a constant value, namely average packing factor. When aspect ratio is equal to 10, the container wall almost affects the region through the entire bed (see Fig. 6a). When aspect ratio is equal to 30, the wall effect regions are limited in about 5 pebble diameters close to container wall (see Fig. 6f). In the whole pebble bed, the volume fraction of wall effect region gradually decreases with the increase of aspect ratios. Thus the packing factors increase with the growing of the aspect ratios.

In attention, the local packing factor distributions are compared with Klerk's empirical model [42], Suzuki's predictive model [16], and Lu's model [43] to further validate the simulation results in this work. The Klerk's empirical model are presented in the following:

$$\varepsilon(Z)=\begin{cases}2.14Z^2-2.53Z+1 \quad (\text{if } Z\le 0.637)\\ \varepsilon_b+0.29\exp(-0.6Z)\times\cos(2.3\pi(Z-0.16))\\ +0.15\exp(-0.9Z) \quad (\text{if } Z>0.637)\end{cases} \quad (1)$$

where ε(*Z*) is the local porosity of pebble bed, and packing factor γ(*Z*) = 1-ε(*Z*). *Z* is the non-dimensional wall distance and *Z* = (D/2-*l*)/d, where d is pebble diameter, D is cylinder diameter and *l* is the distance to the axis of the cylinder. ε_b is the average porosity in bulk region.

The Suzuki proposed the following relationship to predict radial porosity distribution:

$$\varepsilon(r)=\begin{cases}\varepsilon_r+A\cdot\exp(-b\cdot(r/d)^{\alpha})\cdot\cos(2\pi\cdot(r/d)^{\beta})\\ A=0.018\cdot\ln(D/d)+0.483,\\ b=0.312\cdot\ln(D/d)+0.580,\\ \alpha=0.2061\cdot\ln(D/d)+0.128,\\ \beta=-0.033\cdot\ln(D/d)+1.177.\end{cases} \quad (2)$$

where D and d are diameters of cylinder container and pebbles, respectively, r is the distance from the wall of cylinder container, and ε_r is the overall void fraction of pebble bed. The packing factor can be calculated by γ(r) = 1 − ε(r).

The Lu's Model are presented in the following:

$$\varepsilon(z)=\begin{cases}\varepsilon_{min}-(\varepsilon_{min}-\varepsilon_b)\cdot B\cdot z+(1-\varepsilon_{min})z^2\\ +(\varepsilon_{min}-\varepsilon_b)\cdot B\cdot z^3, \text{ For } -1\le z\le 0;\\ \varepsilon_b+(\varepsilon_{min}-\varepsilon_b)e^{-B\cdot z}\times\cos(C\cdot z), \text{ For } z\ge 0.\\ B=0.2+0.586/(D/d);\\ C=3.9-7.197/(D/d).\end{cases} \quad (3)$$

where the dimensionless distance is z = 2(y/d) − 1, y is the radial distance from the container wall, and ε_{min} is the minimum porosity at a distance of approximately half a sphere diameter away from the wall. And ε_b is bulk porosity. When z = 0, y = d/2 and $\varepsilon(0)=\varepsilon_{min}$. D is diameter of cylinder container, d is diameter of pebble.

The radial distributions of local packing factor in cylinder pebble

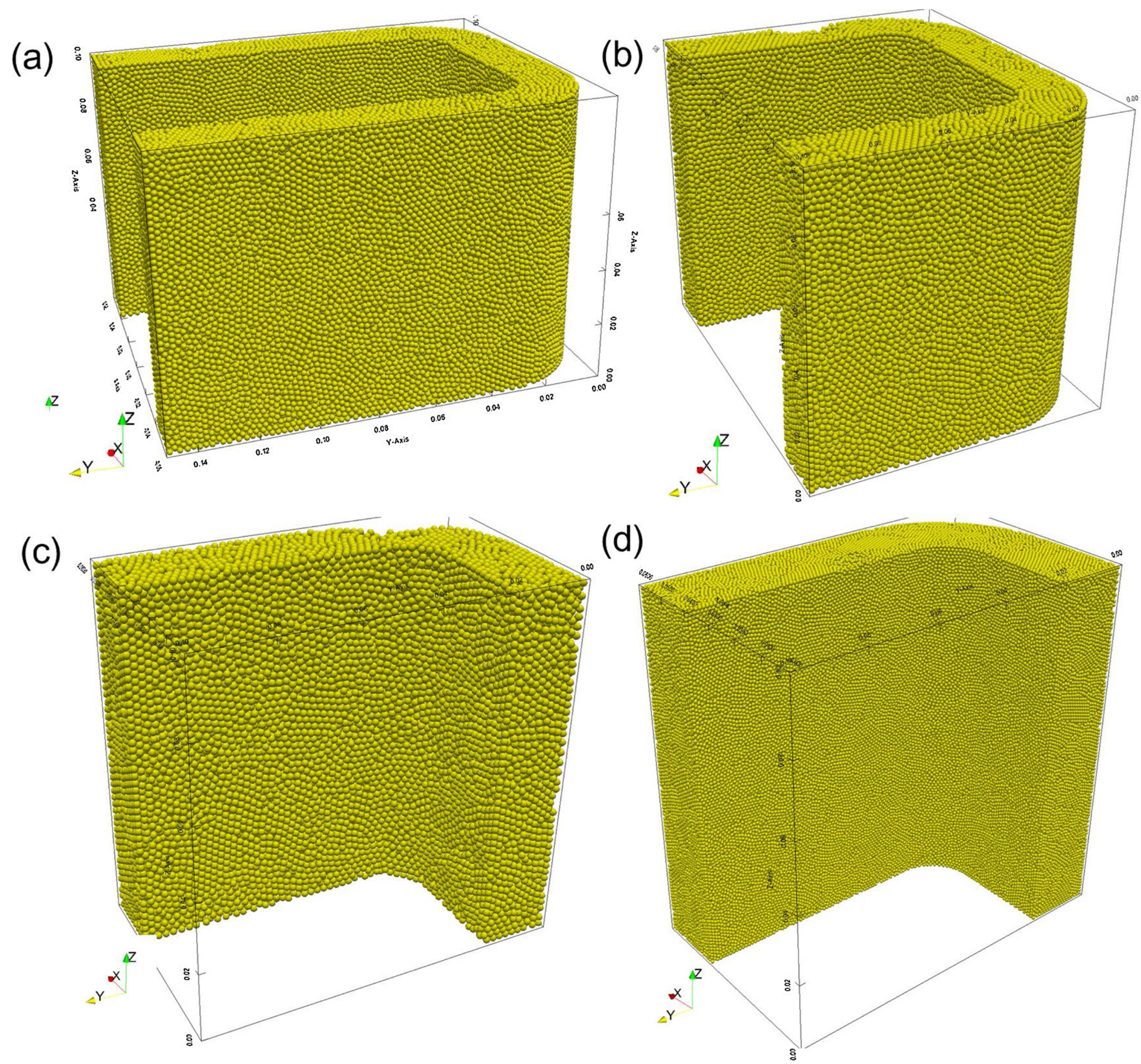

Fig. 4. 3D views of U-shaped pebble beds (color online).

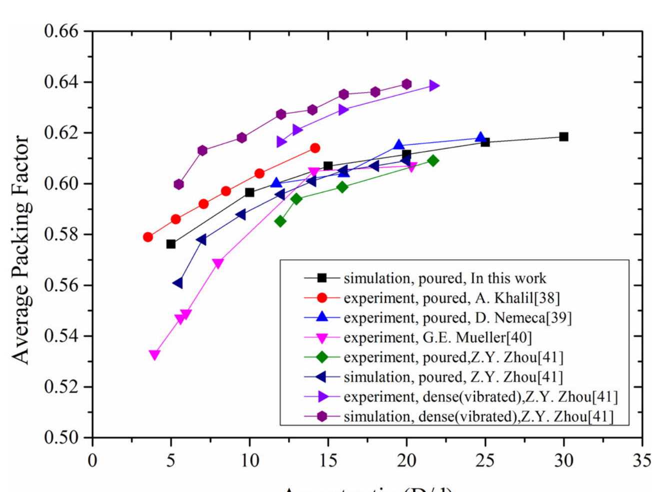

Fig. 5. Packing factor as a function of aspect ratio (D/d) (color online).

beds are shown in Fig. 6. and compared with three empirical prediction model. It can be seen that a oscillatory and damping characteristics of local packing factor distribution can be observed. And a good agreements are obtained when $D/d \geq 10$. However, when D/d is smaller than 10, the results in this work demonstrate some difference in comparison with the predictive results, which were evaluated by various empirical correlation. This could be attributed to the different types of prediction correlation and the experiment data used to fit them and the measurement and calculation error for the determination of the porosity in the bulk region of packed pebble bed.

3.2. Container dimension effects on U-shaped pebble bed

The majority region of the tritium breeding zone in HCCB TBM can be regarded as a U-shaped column container which can be cut into several long, tall, narrow cubic boxes and two bend columns (see Fig. 1). The full-sized pebble beds in blanket are very large compared with the typical Li_4SiO_4 pebble diameter (~ 1 mm). So simulating the full-scaled pebble bed requires very large computational time and computer resources. Thus, refer to the tritium breeder region of HCCB

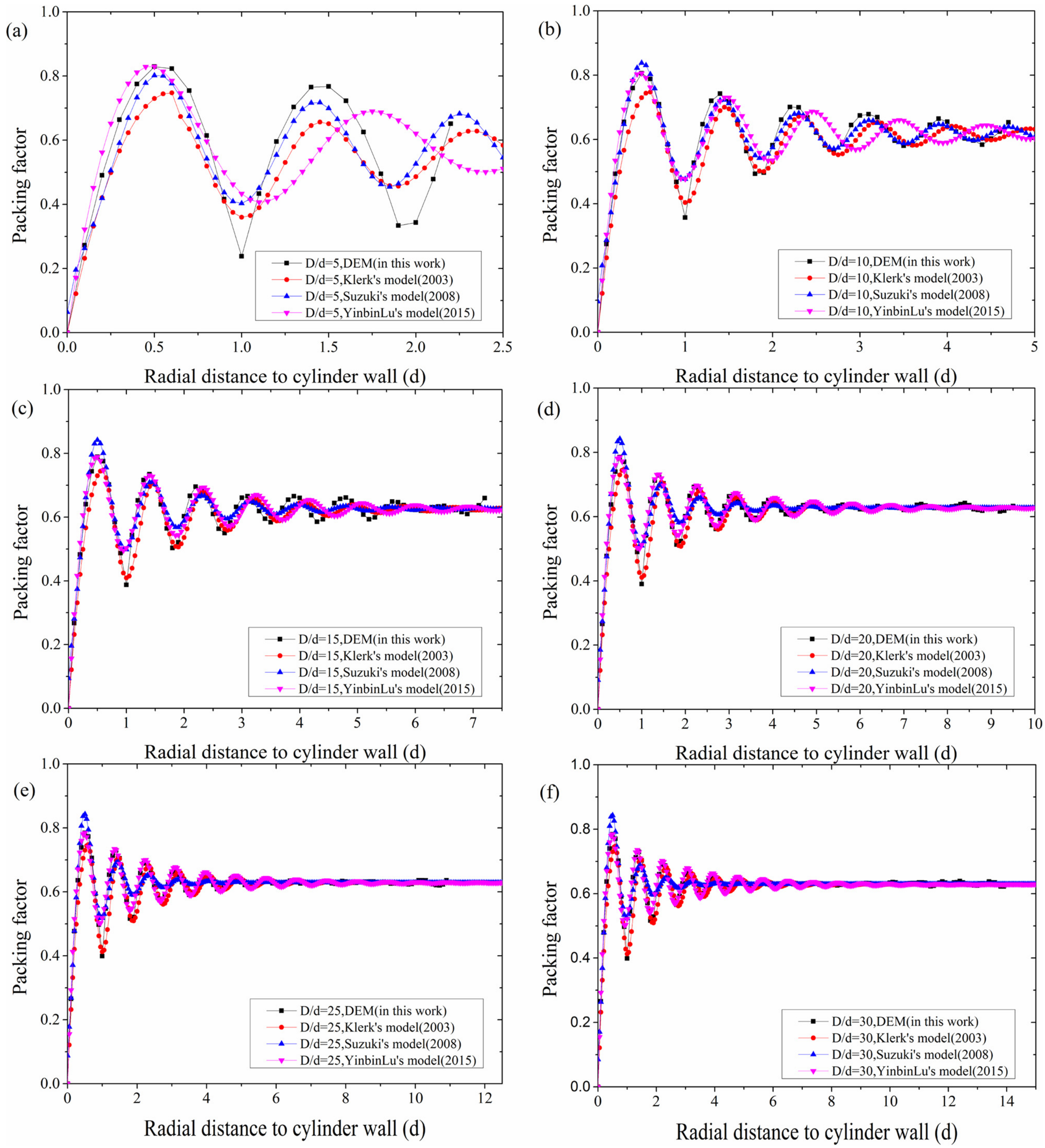

Fig. 6. Radial local packing factor distribution in cylinder pebble bed with various aspect ratios: a) D/d = 5, b) D/d = 10, c) D/d = 15. d) D/d = 20, e) D/d = 25, f) D/d = 20 [26] (color online).

Table 2
Average packing factor of U-shaped pebble bed.

Case	Dimensions of containers in Fig. 2	Pebble diameter/mm	Number of pebbles	Average Packing Factor
1	a	2	105358	0.6153
2	b	2	76193	0.6145
3	c	2	38128	0.6193
4	c	1	308083	0.6278

TBM, three kinds of simplified U-shaped containers were designed to simulate the Li_4SiO_4 pebble packing. The detailed dimensions of the three U-shaped containers are shown in Fig. 2. In the previous experiment research [10–13], the wall effect zones were about 4d. Therefore, the widths of the U-shaped channel were expected for L ≥ 10d. So the pebble diameter should be ≤2 mm (L = 20 mm). In this work, to illustrate the dimension effects on U-shaped pebble beds, the packing of Li_4SiO_4 pebbles with diameter of 2 mm were simulated and analyzed. The U-shaped pebble bed packed with 2 mm Li_4SiO_4 pebbles in these three kinds of container are shown in Fig. 4a–c. The average packing factors in these three pebble beds are listed in Table 2. From the result

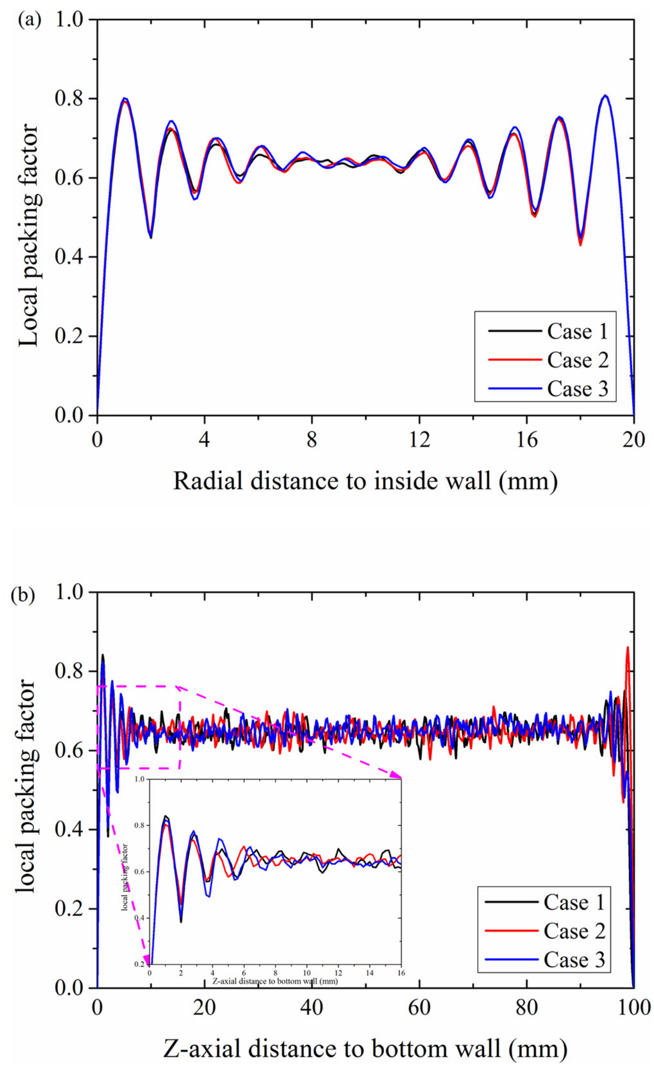

Fig. 7. local packing factor distribution in these three U-shaped pebble bed (color online).

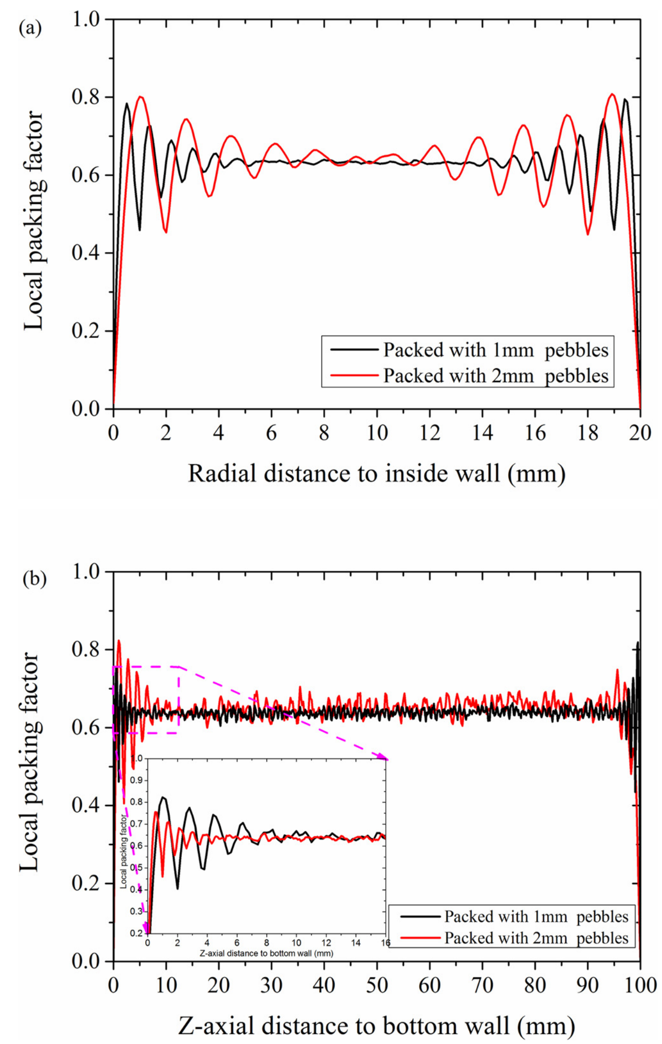

Fig. 8. Local packing factor distribution in U-shaped Li_4SiO_4 pebble bed with 1 mm and 2 mm pebbles (color online).

can be seen that the average packing factor in these three U-shaped pebble bed are all about 0.6164 ± 0.0026.

The local packing factor distributions of these three U-shaped pebble beds are shown in Fig. 7. It can be seen that the oscillatory and damping behaviors of local packing factor are observed in the near wall region. With the increase of the distance from side wall, the local packing factors gradually approach to a constant value, namely, packing factor in bulk region. In Fig. 7b, the local packing factor distributions along the Z-axial distance to the bottom wall are also plotted. It also can be treated as along the height of pebble bed. It can be seen that the similar local packing factor distributions are obtained. It should be noted that the regions close to the side wall were excluded when axial local packing factor were calculated. Although the side wall effect cannot be completely excluded because the side walls almost affect the entire pebble bed in the simulation (see Fig. 7a), and the fluctuation of local packing factor still can be observed in the bulk, a similar effect can be observed experimentally in [14], the following conclusion still can be drawn. Namely, when the width of U-shaped channel, the height of pebble beds and pebble diameters are constant, the dimensions of the U-shaped container have little effect on the pebble bed packing structures.

3.3. Pebble size effects on U-shaped pebble bed

From the results in the above we know that the dimensions of the U-shaped pebble bed have few influences on the packing structures when the width of U-shaped channel, height of the bed, pebble diameters were determined. Thus the pebble bed packed with Li_4SiO_4 pebbles of different pebble diameters, 1 mm and 2 mm, are simulated and analyzed in this work. The most simplified U-shaped container (see Fig. 2c) is chosen in the simulation. The width of U-shaped channel is equal to 20 mm. The ratios of L/d are equal to 10 and 20, respectively, when d = 2 mm and 1 mm. The height of pebble bed is 100 mm. The 3D views of the pebble beds packed with 2 mm and 1 mm Li_4SiO_4 pebbles are shown in Fig. 4c and d. In the final equilibrium states, there are 308083 and 38128 Li_4SiO_4 pebbles with a diameter of 1 mm and 2 mm packed in the U-shaped container, respectively. The average packing factor of U-shaped pebble bed is about 0.6278 when the bed packed with 1 mm Li_4SiO_4 pebbles. While 2 mm Li_4SiO_4 pebbles were used to pack the container, the average packing factor are reduced to 0.6193. Thus, it can be concluded that when dimension of pebble bed is determined, reducing pebble size can increase average packing factor of U-shaped Li_4SiO_4 pebble bed.

The local packing factor distributions of U-shaped Li_4SiO_4 pebble beds packed with 1 mm pebbles are compared with 2 mm pebbles. The results are shown in Fig. 8. It is clearly show that the oscillatory and damping behaviors of local packing factor are observed obviously close to the side wall. In the inner region, the packing factor also close to the packing factor in bulk region. When the pebble diameter is equal to 2 mm, the local packing factors vary almost throughout the pebble bed. But when the pebble diameter is equal to 1 mm, the wall effect region is rapidly decreasing. The axial local packing factor distributions along the distance from bottom wall are shown in Fig. 8b. The regions that were affected by side wall are also excluded. A similar variation of local packing factor is observed. The variation is limited in 5d region close to the container wall. A transition region of pebble packing is formed between inner bulk region and the region adjacent to container wall. Therefore, decreasing the pebble size can reduce the wall effect region of the pebble bed and a more uniform pebble bed can be obtained.

4. Conclusions

The U-shaped pebble bed packing structures was numerically investigated by DEM. The results demonstrated that the DEM code can well simulate the reasonably and realistically pebble packing process. The pebble packing structures of cylinder pebble beds are in good agreement with previous experimental results in literature. Further, The U-shaped pebble bed packing structures were also studied. The results show that the oscillating and damping characteristics of local packing factors are observed. When the width of the U-shaped channel, the height of the bed and the diameter of the pebbles are determined, the dimensions of the U-shaped container have little effect on the pebble bed packing structures. When the dimensions of the U-shaped containers were determined, decreasing pebble size can reduce the wall effect region of the pebble bed and a more uniform pebble bed can be obtained.

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