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Effects of bed dimension, friction coefficient and pebble size distribution on the packing structures of the pebble bed for solid tritium breeder blanket

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A B S T R A C T

In solid tritium breeder blanket, the packing structures of the tritium breeder pebble bed and the neutron multiplier pebble bed are very important to analyze the tritium breeder ratio and the heat and mass transfer process in the pebble bed. In this study, the numerous simulations were conducted to investigated the effects of bed dimension, friction coefficient between pebbles, pebble size distribution and pebble density on the packing structures of the ceramic tritium breeder (Li_4SiO_4, Li_2TiO_3) pebble beds and the neutron multiplier (Be, $Be_{12}Ti$) pebble bed by discrete element method (DEM), respectively. The simulation results reveal that the pebble bed dimension, friction coefficient and pebble size distribution have a significant impact on the pebble bed packing fraction. As the width of the pebble bed container increases, the average packing fraction of the pebble bed gradually increases, meanwhile the influence of volume fraction of the wall effect gradually decreases. In addition, a lower friction coefficient between pebbles (smoother surface of the tritium breeder and the neutron multiplier pebbles) and wider pebble size distribution will result in a higher packing fraction of the pebble bed. However, the material density of the ceramic tritium breeder (Li_4SiO_4, Li_2TiO_3) pebbles and the neutron multiplier (Be, $Be_{12}Ti$) pebble seems to have no obvious effect on the packing fraction of the wider pebble bed for the solid tritium breeder blanket.

1. Introduction

Tritium breeding blanket system is a key component in fusion rector, which play a crucial role on the tritium self-sufficiency. In order to achieve the tritium breeding, a large amount of tritium breeder and neutron multiplier are utilized in the tritium breeding blanket [1–6]. The Lithium orthosilicate (Li_4SiO_4) and the lithium metatitanate (Li_2TiO_3) are the most potential tritium multiplier candidate materials. Pure Beryllium and Titanium beryllide ($Be_{12}Ti$) are the most promising neutron multiplier materials. Both of them are all packed in the tritium breeding zone and neutron multiplying region [2–5]. The packing behaviors of the pebble beds of tritium breeder and neutron multiplier affect the tritium breeding ratio of blanket [7–9], the thermal mechanical behavior and the effective thermal conductivity of pebble bed, the flow characteristic of the purge gas flowing through the pebble bed, and so forth. Therefore, a comprehensively understanding and accurately predicting the packing behaviors of tritium breeder pebble bed and neutron multiplier pebble bed and its influencing factors have important meaning and significance on the optimization and improvement of the solid tritium breeder blanket.

In the conceptual design of several solid tritium breeder blankets, The U-shaped or prismatic pebble beds are mostly utilized. For instance, the U-shaped tritium breeder pebble bed was employed in the Helium Cooled Ceramic Breeder Test Blanket Module (HCCB TBM) [2,3] and the China Fusion Engineering Test Reactor (CFETR) Helium Cooled Solid Breeder (HCSB) blanket [5]. A parallel prismatic pebble bed was adopted in the updated preliminary design of the CFETR HCCB blanket [4]. Taken together, the tritium breeder pebble bed and neutron multiplier pebble bed can be simplified as several prismatic pebble bed with rectangular container. The length and height of these pebble bed are very larger than the pebble size, while the width of pebble bed is relatively smaller. On this account, the width effect of pebble bed on packing behaviors should be considered in the design of the tritium breeding blanket.

In addition, numerous experiments and numerical simulations were conducted to investigate the packing behavior of the tritium breeder pebble bed. Reimann et al. [10–12] investigated the effect of bed dimension and filling factor on the mechanical properties and packing

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structures of pebble bed. The porosity distribution and packing fraction were obtained by the x-ray tomography. Abou-Sena et al. [13] explored the possible techniques of pebble packing process for the Helium Cooled Pebble Bed Test Blanket Module (HCPB TBM) and summarized the impact of the packing process on the HCPB TBM design. Hirose et al. [14] reported an experiment in which the Li_2TiO_3 pebbles were packed into a full-scale tritium breeder container for a water cooled solid breeder test blanket module for the ITER. Gong et al. [15,16] investigated the mono-sized and binary-sized pebble bed experimentally by optimizing the filling strategy and analyzed the effect of pebble size on the effective thermal conductivity of granular bed. Kim et al. [17] and Nakamichi et al. [18] investigated the packing structure of beryllium pebble bed and analyzed the effect of surface roughness on packing density. Pottbacker et al. [19] studied the effect of pebble material and filling method on the average porosity of pebble bed. In addition, due to the existence of void space in pebble bed, the thermal conductivity of the pebble bed is much lower than that of the solid pebble material. Mandal et al. [20–24] and Kulkarni et al. [25] investigated the relationship between the void fraction and the effective thermal conductivity of a packed fluidized bed with binary-sized pebbles, in which the small pebbles of solid tritium breeder will be filled in the void space formed between large pebbles. The results show that the effective thermal conductivity of pebble bed increase as the increase of the packing fraction and the pebble size. Pupeschi et al. [26,27] investigated the effect of the pebble bed height, pebble size and material on the mechanical response of the breeder pebble bed subjected to the cyclic mechanical loading by the uniaxial compression test (UCT) experiments and the discrete element method simulations. The results show that the pebble size distribution and bed height have significant influence on the strain-stress performance of the breeder pebble assemblies.

What's more, with the rapid development of the high efficiency numerical simulation method and high performance computing technology. The discrete element method (DEM) was employed to investigate the packing behaviors and thermal mechanical properties of tritium breeder pebble bed for fusion blanket. Gan et al. [28] analyzed the packing fraction distribution close to wall and coordination number of pebble bed based on a random close packing algorithm. Chen et al. [29] investigated the packing fraction of a mixed pebble bed with different pebble materials for the CFETR Water Cooled Ceramic Breeder (WCCB) blanket. Gong et al. [30–32] numerically analyzed the packing structure of the U-shaped tritium breeder pebble bed, which provided a reference for the design and optimization of the HCCB TBM. Wang et al. [33] explored the thickness effect and the friction coefficient on packing behavior of Li_4SiO_4 pebble bed. Lee et al. [34] investigated the mechanical characteristics of binary-sized pebble bed by DEM. Sohn et al. [35] and Choi et al. [36] investigated the effects of pebble size distribution and friction coefficient on the packing behaviors and purge gas flow in Li_2TiO_3 pebble bed. In further, Desu et al. [37] and Li et al. [38] investigated the effect of vibration process on packing structures of pebble bed by DEM simulation. Dai et al. [39] systematically investigated the evolution of the packing structure of mono-sized pebble bed confined in cylindrical container during vibration. The results of the numerical simulation show that the mechanical vibration brings a transition of packing structure from random packing to ordered packing especially in the near-wall region.

The above investigation shows that the packing behavior of pebble bed is affected by lots of factors. Such as the pebble material, pebble size distribution, bed dimension and container material, filling method and packing strategy, compression state, and so forth. In actual situation, due to the fabrication process and the pebble material, the pebbles were always manufactured with various surface roughness and pebble density. The pebble size always distributed in a certain range. Thus, more investigation should be conducted to thoroughly understand the packing behaviors of tritium breeder and neutron multiplier pebble bed for fusion blanket. In this paper, therefore, the packing structures of the tritium breeder (Li_4SiO_4, Li_2TiO_3) pebbles and neutron multiplier (Be, $Be_{12}Ti$) pebbles were investigated by DEM simulation. The effects of the ratio of bed width to pebble diameter, container shape, friction coefficient between pebbles, pebble size distribution and pebble density on packing fraction were analyzed comprehensively. The achievement of this paper will support the optimization and improvement of the solid tritium breeder blanket.

2. Modeling method and condition

2.1. Discrete element method

The discrete element method (DEM) is an effective numerical modelling method used to simulate the motion behaviors of particles in granular materials or discrete medium [40]. The DEM has been successfully applied to investigate the packing behaviors and thermal mechanical properties of lithium-based ceramic breeder and neutron multiplier pebble bed for fusion blanket [19–30]. The basic principles of the DEM are simple but effective. The finite displacements of each pebble are calculated based on the force interactions, such as the contact force with neighbor pebbles, the gravity, the van der Waals force, the cohesive force and so forth. Due to the relative larger pebble adapted in this work, the van der Waals force and the cohesive force can be negligible. Thus, only gravity and contact force due to sliding and collision were considered. The move of a pebble is governed by the Newton's second law of motion. The resultant acceleration of each pebbles is calculated from the gravity and the contact force. The contact force is calculated based on the contact overlap and the contact law. In the present investigation, the contact force of contact pairs was determined by the Hertz-Mindlin contact theory [34]. The Coulomb Friction Law was adapted to determine the friction interaction of inter-pebbles and pebble-wall. The DEM simulation in this work were carried out using the LIGGGHTS [41] based on DEM. The detailed theory of the DEM adopted in this work can be obtained in Refs. [30,40,41].

2.2. Packing process and condition

Tritium breeding blanket (TBB) is one of the key components in the CFETR with the important roles of tritium breeding, heat extraction, etc. As the primary option, the HCCB blanket concept has been investigated widely due to the good compatibility of helium coolant with other materials and no MHD effects as liquid breeder material, etc. SWIP has proposed a design scheme of the HCCB blanket module by considering manufacturability [4], as shown in Fig.1. The HCCB blanket is divided into 4 zones, including the manifold zone, the shielding zone, the distribution zone and the tritium breeding zone, as Fig. 1a illustrated. In tritium breeding zone, there are several layers of the Be pebble bed and the Li_4SiO_4 pebble bed separated by straight cooling plates. These pebbles are packed in a thin rectangular container with widths of 13~40 mm for breeder pebble bed and 21~133 mm for neutron multiplier pebble bed. The size of the cavity in other direction is much larger than the pebble size.

Thus, in this work, in order to investigate both the wall and the bed dimension effects on the packing structure, the container widths are selected as 5 mm, 10 mm, 15 mm, 20 mm, 30 mm, 40 mm, 50 mm, 60 mm in radial direction (X-axis) respectively. While in poloidal direction (Y-axis), the periodic boundary is accepted. The height of the pebble bed is set to 60 mm along the Z-axis, as shown in Fig. 1c. During the simulation, the pebbles were inserted from top region of container and then packed inside the cavity under the gravity. Firstly, the simulations began with a very loose packing in top region of container. Then, with an initial velocity, the pebbles fell down under gravity. Colliding and sliding appeared continuously and circularly during the packing process. Finally, all the pebbles packed in the cavity randomly with an almost balanced static state. The pebble position and the packing structures of pebble beds were no longer changing. We can further investigate the detailed packing structures of pebble beds.

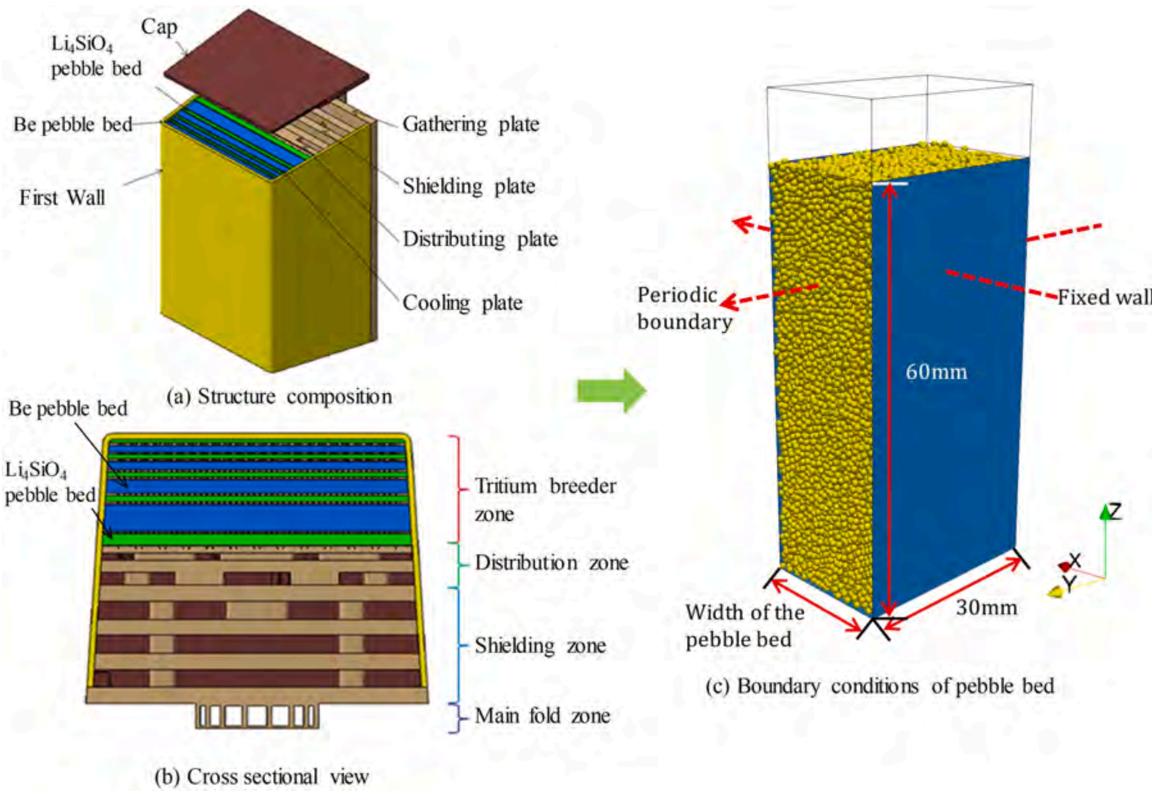

Fig. 1. Optimized preliminary design of CFETR HCCB blanket and boundary conditions of simplified pebble bed.

For the CFETR HCCB blanket, the Li_4SiO_4 pebble is selected as tritium breeder and Be pebble is adopted as neutron multiplier. Thus, in this work, the Li_4SiO_4 and Be pebble packing behaviors were investigated. In addition, other candidate tritium breeder and neutron multiplier pebble, Li_2TiO_3 and $Be_{12}Ti$, were also investigated. The reduced activation ferritic/martensitic (RAFM) steel of CLF-1 developed by the SWIP [42] is employed as container wall. The sphericity of the pebbles will also affect the packing structure of pebble bed [43–45]. Due to the high sphericity of the tritium breeder pebbles and the neutron multiplier pebbles for solid tritium breeder blanket, the pebbles were assumed to be the exact spherical pebbles in this work. The material parameters used in the simulation are listed in Table 1. These material properties are referenced and cited from the Refs. [28,30,46–48].

Due to lack of experiment results, the friction coefficient inter-pebbles and between pebbles and walls are always set to 0.1 artificially for breeder pebble bed. However, the friction coefficient between pebbles will significantly affect the packing behaviors. A low friction coefficient inter-pebbles increases pebble instability and causes the pebbles to move more easily. As a result, it may increase the packing fraction and reduces overall loads of pebble bed. In addition, due to the different surface roughness of pebbles produced by different fabrication process, the friction coefficient between pebbles will also be different. There is, at present, no experimental results reported on the friction coefficient between tritium breeder pebbles and between neutron multiplier pebbles. Therefore, in this work, the effects of friction coefficient on the pebble packing behavior were investigated by DEM simulation. The friction coefficient was set as 0.0, 0.1, 0.2, 0.3, 0.5, 0.7, 0.9.

Table 1
Material parameters used in simulation.

Property	Symbol	Value				
		Li_4SiO_4	Li_2TiO_3	Be	$Be_{12}Ti$	RAFM (CLF-1)
Density (g/cm^3)	ρ	2.323	3.189	1.82	3.15	7.847
Young's modulus (GPa)	E	90	200.6	238	277.8	225
Poisson ratio	σ	0.25	0.27	0.032	0.12	0.33

Although the mono-sized pebbles with diameter of ~1 mm were adopted in solid breeder blanket, there is a certain distribution of the pebble size for fabricated tritium breeder pebbles and neutron multiplier pebbles, it is difficult to achieve accurate 1 mm. Thus, in this work, we investigated the effect of pebble size distribution on the packing structure of pebble bed for fusion blanket. In practice, there are two kinds of methods to represent the pebble size distribution according to their physical meaning, namely, the number distribution, N(d), and volume distribution, V(d), or mass distribution, M(d). They have the relationship as following: $V(d) = \frac{\pi d^3}{6}N(d)$. The mass distribution also can be calculated by the density of pebbles as following: $M(d) = \rho V(d) = \rho\frac{\pi d^3}{6}N(d)$. Because of the difference of the density of pebble materials, and the pebble size distribution expressed by different methods can be transformed into each other, the number distribution was selected to represent the pebble size distribution of different pebble materials in this work. The mono-sized, normal distribution and uniform distribution of pebble size in number distribution, N(d), were chosen in the simulation.

In further, since the different densities appeared for the tritium breeder pebbles prepared by various fabrication process. For instance, the density of Li_4SiO_4 pebbles prepared by wet method is about 80 % ~85 %T.D. The density of pebbles fabricated by the melt spray method can be greater than 95 %T.D. The density and other properties of the same kind of pebbles prepared by the same process are fixed in generally. Therefore, it is difficult to investigate the alone effect of density on the packing behaviors of pebble bed experimentally. However, the numerical simulation can easily achieve a single property change in density. Thus, the densities of each kind of pebbles were set to 80 %T.D., 85 %T.D., 90 %T.D., 95 %T.D., 100 %T.D. in the simulation respectively.

2.3. Calculation of packing fraction

The packing fraction, or packing factor, is an important parameter describing the packing density. In tritium breeding blanket of fusion reactor, the packing fraction is an important input parameter for the design and optimization of solid tritium breeder blanket, which significantly affect the tritium breeder ratio of the breeding blanket. Therefore, the average packing fraction, axial packing fraction and local packing fraction were calculated in this work. The detailed definitions and calculation methods are as follow:

The average packing factor based on volume-averaged method is defined as the ratio of the summed volume of pebbles to the total volume of container they occupied, as follows:

$$\gamma_{avg} = \frac{\sum_{i=1}^{n} V_i}{V_{bed}}, \tag{1}$$

where V_i and V_{bed} are the volumes of the pebble *i* and the pebble bed. n is the number of pebbles.

The axial packing fractions based on area-averaged method was calculated in order to investigate the effect of boundary wall on packing fraction. As illustrated in Fig. 2, numerous parallel cut planes are created along the direction (*x*-axis) perpendicular to the fixed wall with the position x ranged from one fixed wall to another and with steps of 0.05d. The ratio of the summation of all the intersection areas to the cutting plane areas at position *x* is the axial packing factor. So the axial packing factor at the position *x* is defined as:

$$\gamma_{axial}(x) = \frac{\sum_{i=1}^{n_{cut}} S_i^{cut}}{S_{cutplane}}, \tag{2}$$

The intersection areas, S_i^{cut}, formed between the cutting plane and the pebbles as illustrated in Fig. 2, are calculated by:

$$S_i^{cut} = \pi r_{cut}^2 = \pi\left(r_i^2 - L_{cut}^2\right), \tag{3}$$

where r_i is the radius of the pebble which is cut by cutting plane, L_{cut}, is the distance of the pebble center to cutting plane, $0<L_{cut} < r_i$.

The Local packing fraction based on the line-average method is calculated to reveal the packing fraction distribution. Firstly, the pebble bed is meshed in the cross section plane (x–y plane) with grid size of 0.05d as shown in Fig. 3a. Secondly, the local packing friction, which is defined as the ratio of the summation of all the intersection line segment to the length of grid line, at grid point is calculated as illustrated in Fig. 3b and Fig. 3c.

$$\gamma_{line}(x,y) = \frac{\sum_1^{n_l} l_i(x,y)}{h(x,y)} V(d) = \frac{\pi d^3}{6} N(d), \tag{4}$$

where h is the length of grid line at the grid point (x,y). l_i is the intersection line segment intersected between the grid line and the pebbles (see Fig. 3b), which is determined by:

$$\begin{aligned} l_i(x,y) &= 2\sqrt{r_i^2 - L_{line}^2} \\ &= 2\sqrt{r_i^2 - \left[(x-x_i)^2 + (y-y_i)^2\right]}, \end{aligned} \tag{5}$$

where L_{line} is the distance of pebble center to the grid line. (x_i, y_i, z_i) is the center of the pebble intersected with grid line.

3. Results and discussions

The pebble packing structures of the tritium breeder (Li_4SiO_4, Li_2TiO_3) and the neutron multiplier (Be, $Be_{12}Ti$) in rectangular container with different width are studied through DEM simulations. The variation of the average packing fraction and the axial packing fraction in the pebble bed is obtained by slicing the bed in the direction perpendicular to the fixed wall and calculating the area-averaged packing fraction of each slice. The effects of the bed dimension, inter-pebbles friction coefficient, pebble size distribution and material density on packing structures has been analyzed.

3.1. Effect of bed dimension on packing structure

Fig. 4 show the average packing fraction variation of pebble beds packed with ceramic tritium breeder (Li_4SiO_4 and Li_2TiO_3) and neutron multiplier (Be and $Be_{12}Ti$) pebbles with different inter-pebbles friction coefficient in long and narrow prismatic container with different width. The results show that there has been a gradual rise in the average packing fraction as the increase of the width of pebble bed. A relatively low average packing fraction occurs in the pebble beds with lower width. For instance, when the pebble bed width is about 5d (5 times of the pebble diameter d), the average packing fraction is mostly lower than 0.6 except for the extreme case then the friction coefficient is zero. With the increase of pebble bed width, the average packing fraction increases rapidly and gradually stabilizes when the pebble bed width is greater than 40d. The effect of inter-pebbles friction coefficient will be discussed in section 3.2.

For different materials pebble packing, similar increase trends can be observed, that is, the average packing fraction of the pebble bed increases with the increase of the pebble bed width. The influence of the

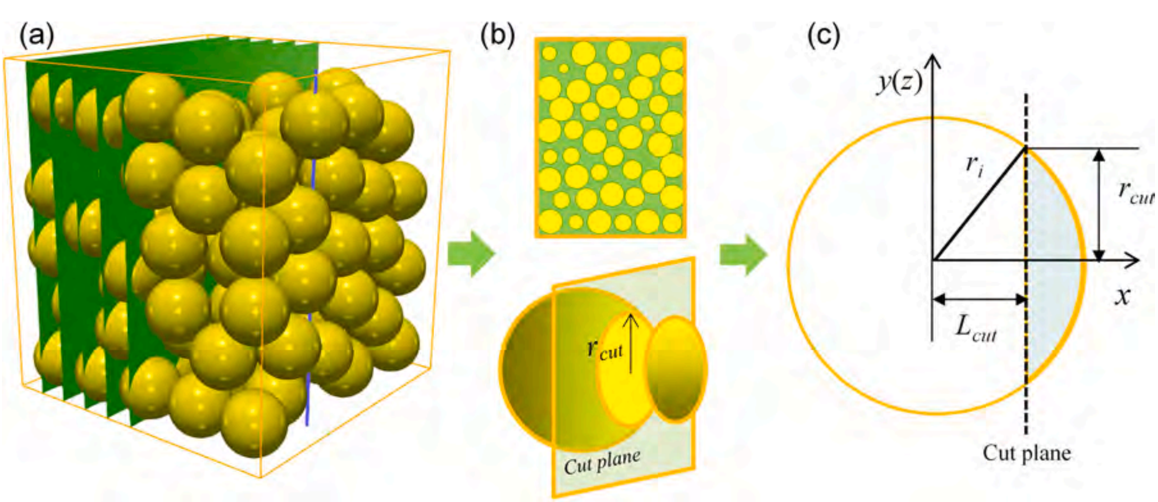

Fig. 2. Simplified calculation method of axial packing fraction.

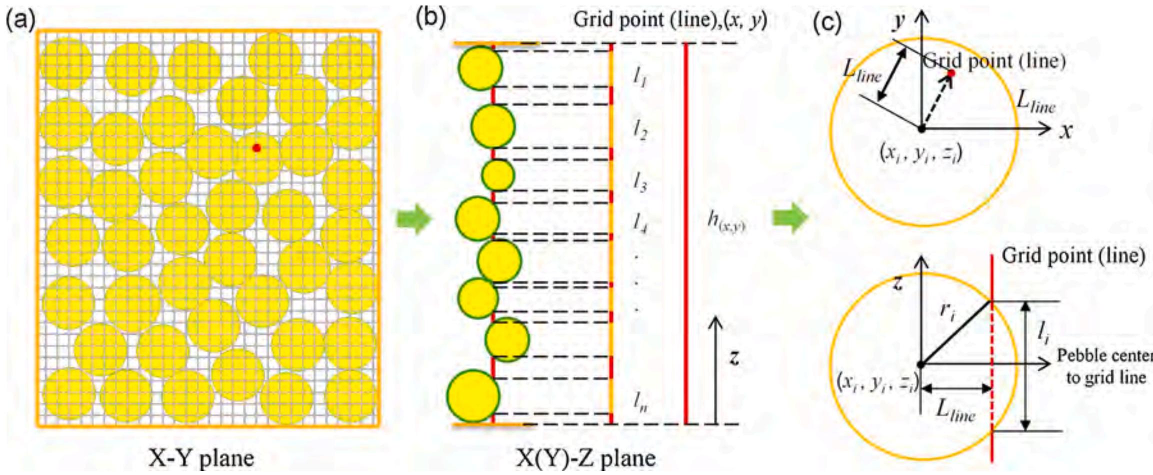

Fig. 3. Schematic of the intersection line between grid point (line) and pebbles.

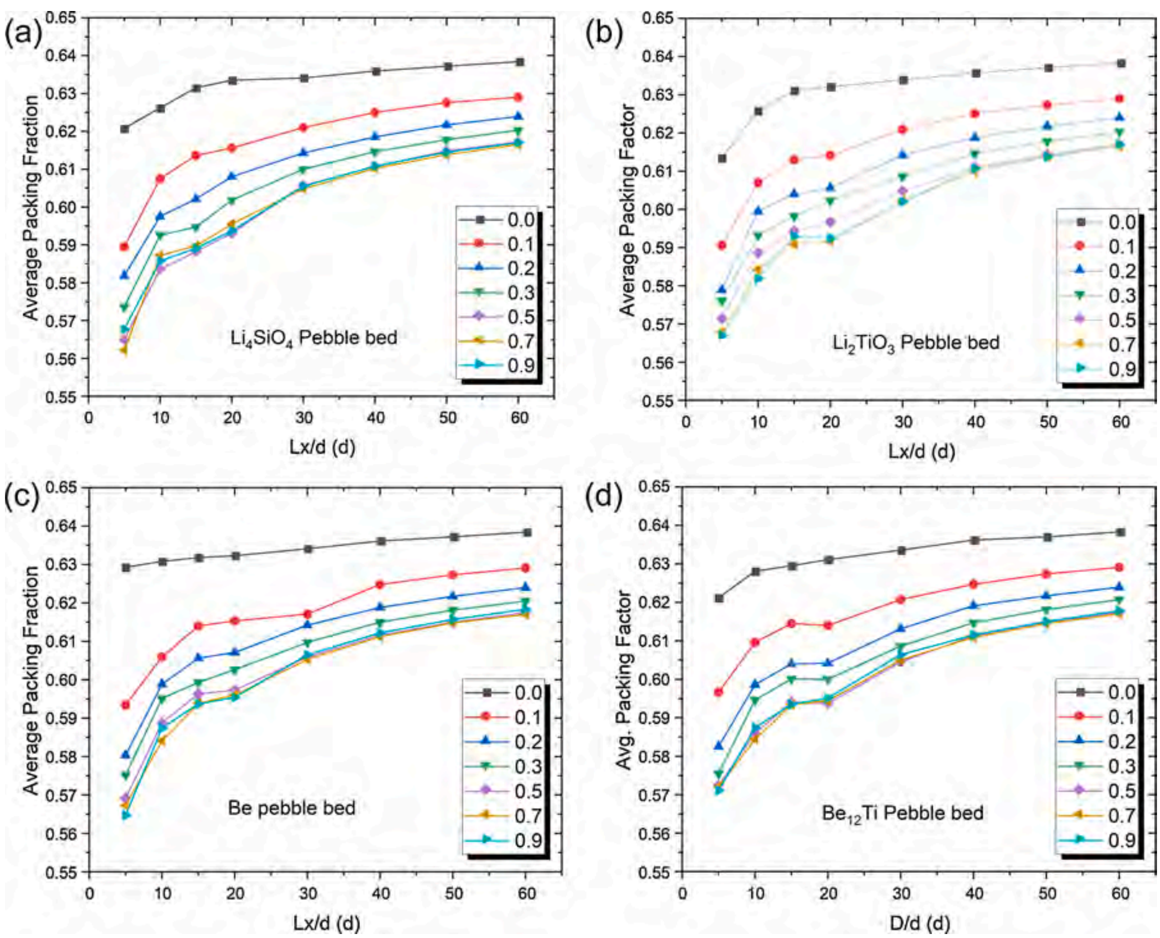

Fig. 4. Average packing fraction of mono-sized pebble bed as a function of the bed width to pebble diameter ratio (W/d) with different friction coefficient.

pebble material on the average packing friction can be observed only for the pebble beds with relatively small width. When the bed width is equal to 5d, there is a relatively obvious difference in packing fraction of the pebble bed packed with difference materials and with difference friction coefficient, which might be caused by the integrative effect of the material properties (such as, pebble density, Young's modulus and Poisson ratio) and the friction interaction between the pebble and the wall. With the increase of bed width, the effect of material properties on packing fraction gradually reduce. When the width of the pebble bed is greater than 30d, the average packing fractions of both the tritium breeder (Li_4SiO_4 and Li_2TiO_3) pebble beds and neutron multiplier (Be and $Be_{12}Ti$) pebble beds are all greater than 0.60 regardless of the value of friction coefficient between pebbles. An average packing factor of larger than 0.61 can be obtained when the width of pebble bed is larger than 40d, similarly. That is to say, no additional densification technique (such as vibration, knocking the container wall, etc.) is required to achieve an average packing factor of greater than 0.60 with $L/d > 30d$ and greater than 0.61 with $L/d > 40d$ even if the pebbles have a relatively rough surface. The difference of packing fraction of pebble bed with different friction coefficient gradually reduced with the increase of the bed width, which will be discussed in detail in section 3.2.

In addition, the average packing fraction of the Li_4SiO_4 pebble bed with rectangular shaped container are compared with the results of the pebble bed with cylinder and square container, referred to literature [30,33] and shown in Fig. 5. Here, the aspect ratio is determined as the size ratio of cylinder diameter to pebble diameter for cylindrical pebble bed. For square and rectangular pebble bed, the aspect ratios are defined as the size ratios of the side length of square container and the width of rectangular container to the pebble diameter respectively. It is clearly show that the average packing fraction also increase with the increase of the aspect ratio in all pebble beds. The container shape has the influence on the average packing fraction. In contrast the pebble bed in cylinder and square container, a higher average packing fraction of the pebble bed can be obtained in rectangular container when the aspect ratio is relatively small, which is mainly attributed to the effects of container walls, namely, a larger porosity occurs in the area close to the container wall.

Fig. 6 show the axial packing fraction variation along the direction perpendicular to the fixed lateral wall. The axial packing fraction presents a drastic damped oscillation as the distance to the fixed wall increase. When the pebbles touch the container wall, the axial packing fraction is almost zero owing to the point contact between pebble and wall. In the range of adjacent walls, 0~0.5d, the axial packing fraction increase rapidly. A maximum axial packing fraction can be observed at the distance of 0.5d. When the distance is greater than 0.5d, the axial packing fraction of pebble bed gradually oscillates and decays as the distance increases. The axial packing fraction gradually tends to constant value in the inner region of pebble bed.

In further, the axial packing fraction does not always reach a constant value in the inner region of pebble bed. For instance, when the width of pebble bed is 5d, the axial packing fraction oscillates throughout the pebble bed. When the width is increased to 10d, the axial packing fraction seems to reach a constant value only close to the midplane. As the width of pebble bed further increase, the proportion of the stable region of the axial packing friction also increase gradually. However, one can find that the oscillations of the axial packing fraction are always restricted to the space close to the wall at a distance about 5d for the pebble bed with a width greater than 10d. In other words, only the width of bed is greater than 10d, the axial packing fraction will achieve a stable region in the inner region of pebble bed.

Fig. 7 show the local packing fraction distribution of the Li_4SiO_4 pebble bed with various width. It is clearly shown that the local packing

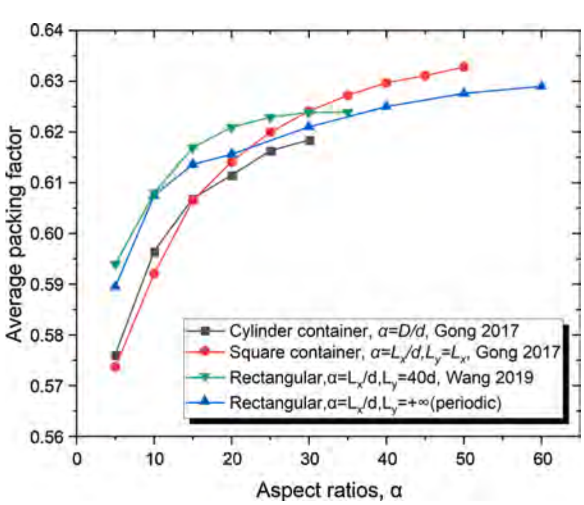

Fig. 5. Effects of the aspect ratios on average packing fraction of pebble bed with different container shape and size.

fraction also exhibits a significant wall effect. There are several layered high local packing fractions parallel to the fixed wall, which corresponds to the peak of the axial local packing fraction distribution in Fig. 6. As the distance to the fixed wall increases, a more uniform local packing fraction distribution can be observed. However, even though the local porosity distribution in the inner area of the pebble bed is relatively uniform, there is still a certain degree of fluctuation, which corresponds the low amplitude variation of axial packing fraction in the inner region of pebble bed in Fig. 6. In addition, to reveal the wall effect of packing fraction distribution, the pebble center is projected to the x–y plane as shown in Fig. 8. It can be seen that the two side walls of the pebble bed have a significant impact on the packing structure of pebbles close to the wall. The pebble center also showed a layered distribution, which indicate that the pebbles are arranged more regularly close to the wall. Increasing the distance to fixed wall, the pebbles packed from an orderly and regular arrangement transition to a random packing structure.

From the above discussion of the packing fraction and packing structure, it can be concluded that the layered distribution caused by the fixed wall effect is always restricted to the range of 5d close to the container wall. Therefore, the volume fraction of the wall effect region will decrease with the increase of the bed dimension including cylindrical pebble beds, square pebble beds, and rectangular pebble beds, as shown in Fig. 9, which is consistent with the results in Fig. 4~Fig. 8. For this reason, the average packing fraction of pebble bed gradually increases as the width increases. Additionally, the friction coefficient between pebbles has an obvious effect on packing fraction which will be discussed in the next section.

3.2. *Effect of inter-pebble friction coefficient on packing structures*

In tritium breeding blanket, the tritium breeder and neutron multiplier are all adopted as spherical pebbles generated by different fabrication process. Owning to the effect of fabrication process and material properties, the surface of the tritium breeder and neutron multiplier pebbles prepared by different process have different smoothness, which will result in a different inter-pebbles friction coefficient. Further, no experiment results about the friction coefficient of the tritium breeder and neutron multiplier pebbles were reported. Therefore, the effects of the friction coefficient of the Li_4SiO_4, Li_2TiO_3, Be, $Be_{12}Ti$ pebbles on packing structure were investigated numerical in a region of friction coefficient of 0~0.9. The results will also provide a reference for the research and development of the tritium breeder pebbles and the neutron multiplier pebbles.

Fig. 10 shows that the average packing fraction of all tritium breeder and neutron multiplier pebble bed declines significantly with the increase of the inter-pebble friction coefficient. When the friction coefficient is equal to 0, namely, the pebble has an absolutely and ideally smooth surface, a relatively high average packing fraction can be gained without taking any other densification measures. The average packing factor can reach 0.64 with a wider pebble bed. Even if the pebble bed width is 5d, the average packing fraction of can still be greater than 0.62. With the increase of the friction coefficient, however, the average packing fraction decrease rapidly. When the friction coefficient $\geq$0.5, the packing fraction no longer changes with the increase of friction coefficient. It is mainly because the friction can control the slid motion between pebbles. the contact force can easily satisfy the sliding condition of Coulomb Friction Law with a relative low friction coefficient. The sliding motion between pebbles causes the pebbles to continuously rearrange and promotes the densification process of the pebble bed. As the friction coefficient increases, the sliding between pebbles will be blocked and the rearrangement process will be terminated early, which result in a decrease of packing fraction.

For the relatively wider pebble bed, for example, the bed width is greater than 30d, there are almost same variation trend of the packing fraction of the pebble bed packed with different materials pebbles and with different friction coefficient. However, in the narrow pebble bed,

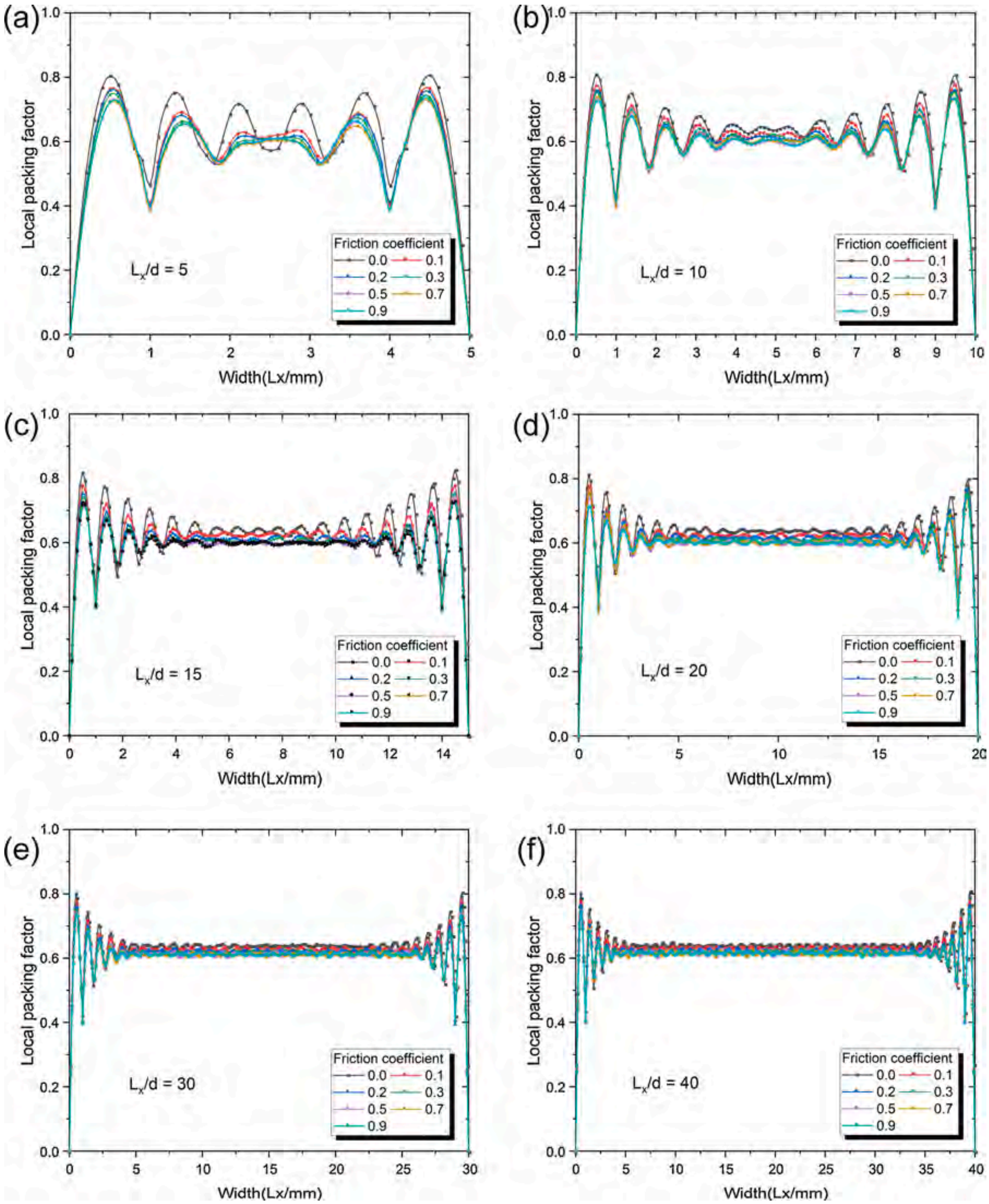

Fig. 6. Axial packing factor variation of mono-sized pebble bed with different widths and friction coefficient.

for instance, the width of pebble bed is 5d, the packing fraction of pebble bed packed with different material are relative difference. Compared with the Li_2TiO_3 pebble bed and the $Be_{12}Ti$ pebble bed, a relatively low packing fraction of the Li_4SiO_4 pebble bed and the Be pebble bed was obtained respectively when the friction coefficient is greater than 0.5. which may caused by the difference in material properties and the friction interaction between the pebbles and the fixed side wall. During the dynamic packing process and the rearrangement process, the motion and rearrangement of the pebbles close to the wall is affected not only by the gravity effect and the inertia, but also by the friction interaction between the pebbles and between the pebble and wall, which are all related to the material properties, such as, pebble density, Young's modulus and Poisson ratio. With the increase of the bed width, the proportion of the pebble-wall friction effect gradually decrease, which is consistent with the decrease of the wall effect as discussed in section 3.1. The motion and rearrangement of pebbles will be largely determined by the inter-pebbles friction, the inertia and the gravity effect in the packing process. Thus, for a narrow pebble bed, the material properties of pebble seems to have a relatively obvious influence on packing structures of the pebble bed packed under gravity falling and without taking additional densification technique (such as vibration, knocking the container wall, etc.). With the increase of the bed width and the friction coefficient, the effect of pebble materials and pebble-wall friction on the packing structure of pebble bed gradually reduce.

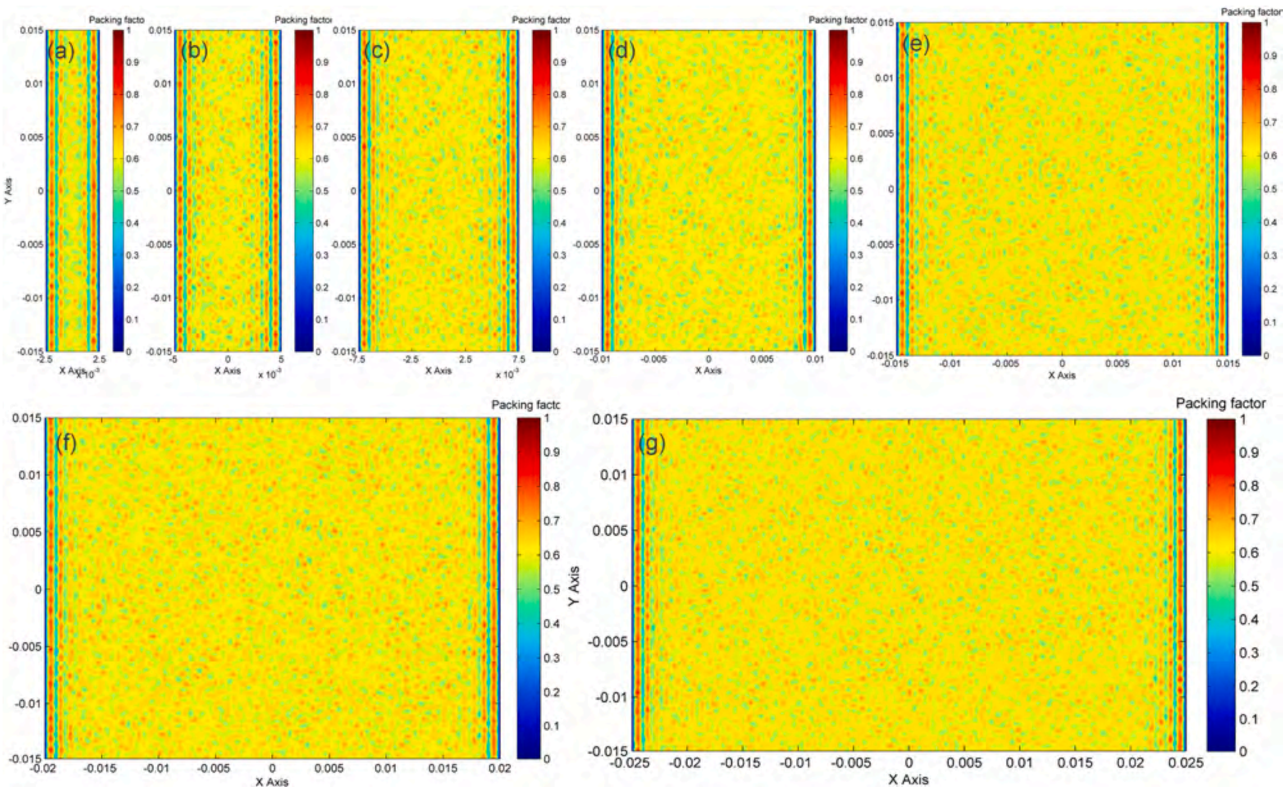

Fig. 7. Local packing factor distribution of pebble bed with different bed width and μ = 0.1. a) L = 5, b) L = 10, c) L = 15, d) L = 20, e) L = 30, f) L = 40, g) L = 50 (color online).

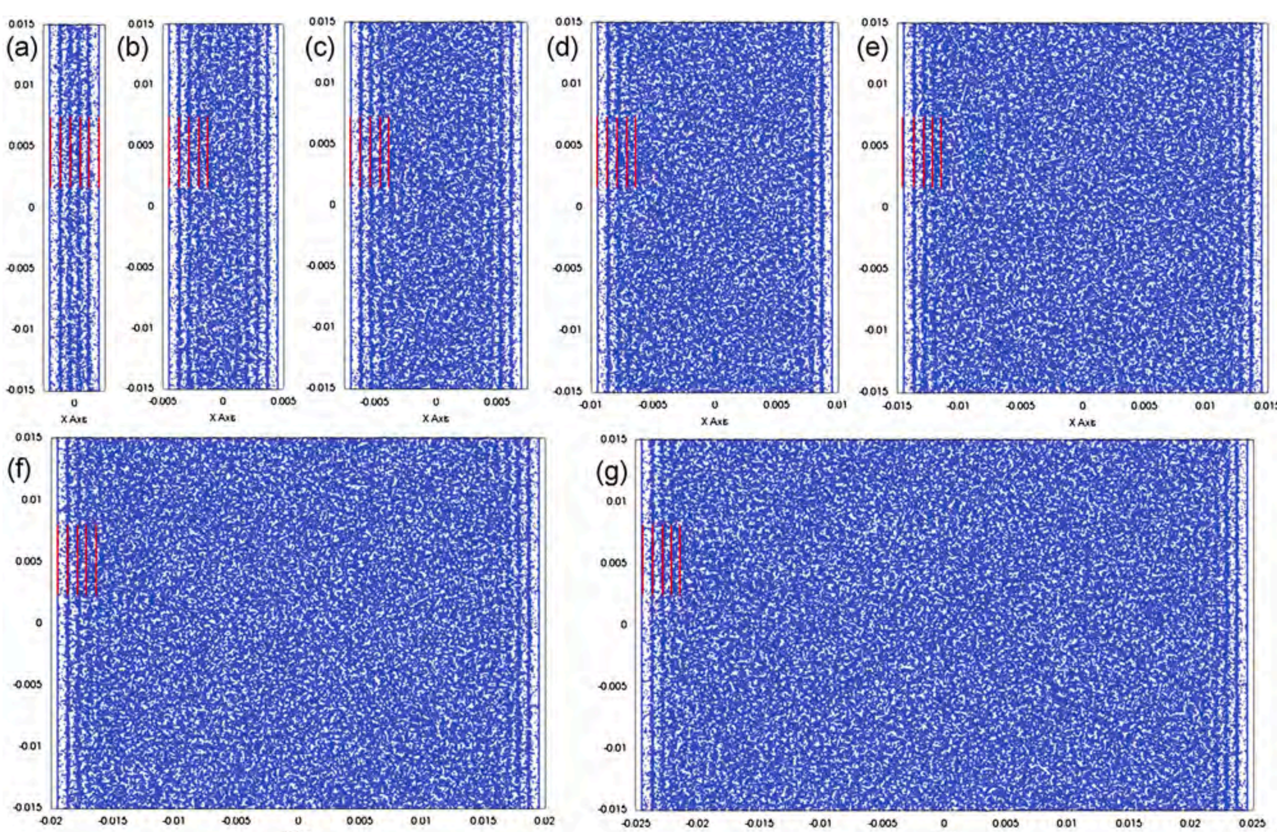

Fig. 8. Pebble center distribution inside the packed pebble beds with different bed width. (Pebble centers were projected to the bottom plane, namely X-Y plane) (color online).

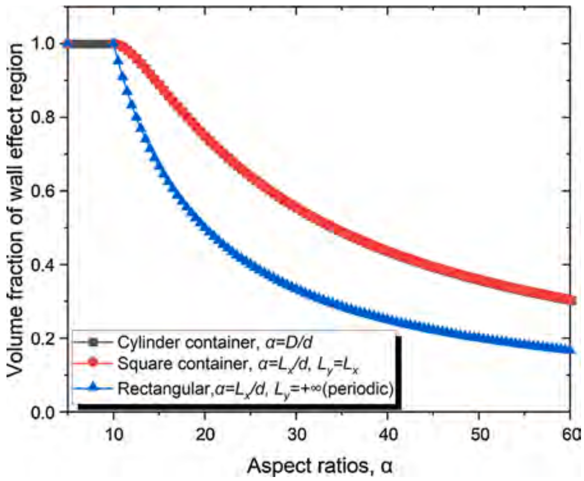

Fig. 9. Volume fraction of fixed wall effect region with different container shape and dimension.

The axial packing fraction distribution with various friction coefficient can be found in

Fig. 6. One can find that low friction coefficient can result in relatively larger amplitude fluctuation of axial packing fraction, but the damping and oscillation are still limited in ~5d close to fixed wall. Whereas, in the inner region of pebble bed, the packing fraction increase with the decrease of friction coefficient. Fig. 11 and Fig. 12 show the local packing fraction distribution and pebble center distribution of the Li_4SiO_4 pebble bed only with different friction coefficient. The significant influence of friction coefficient on local packing fraction and packing structure can be observed. In the near wall region, the pebbles are arranged orderly due to the wall effect, resulting in a layered distribution of the local packing fraction and pebble center. The regularization gradually weakens with the increase of the friction coefficient, which consistent with the results shown in Fig. 10.

Therefore, to obtain a higher packing fraction in tritium breeder blanket, on the one hand, it is necessarily to prepare the tritium breeder and the neutron multiplier pebbled with smoother surface by optimizing the fabrication process, on the other hand, a relatively wider pebble bed should be used to reduce the wall effect. Otherwise, other more densification measures must be considered to increase the packing fraction.

3.3. Effect of pebble size distribution on packing structure

In the design of the solid tritium breeder blanket, the tritium breeder and neutron multiplier are generally mono-sized pebbles. As a matter of fact, the pebble sizes of the fabricated tritium breeder and neutron multiplier pebbles are always distributed in a certain range. Hence, the effect of pebble size distribution on packing structure of the Li_4SiO_4, Li_2TiO_3, Be, $Be_{12}Ti$ pebble beds were investigated respectively. The detailed size distribution of pebbles and the packing fraction of pebble beds were shown in Fig. 13 ~ Fig. 16.

Actually, the pebble size distribution can be represented by two kinds of methods, namely, the number distribution, N(d), and volume distribution, V(d), which refers to the proportion of the number of pebbles in a certain pebble size to the total number of the pebble assembly, or the percentage of the pebble mass of a certain pebble size in the total mass of the pebble bed, respectively. The pebble size distribution characterized by these two methods can be transformed into each other through a certain relationship. In this work, the number distribution was selected to characterize the size distribution of the tritium

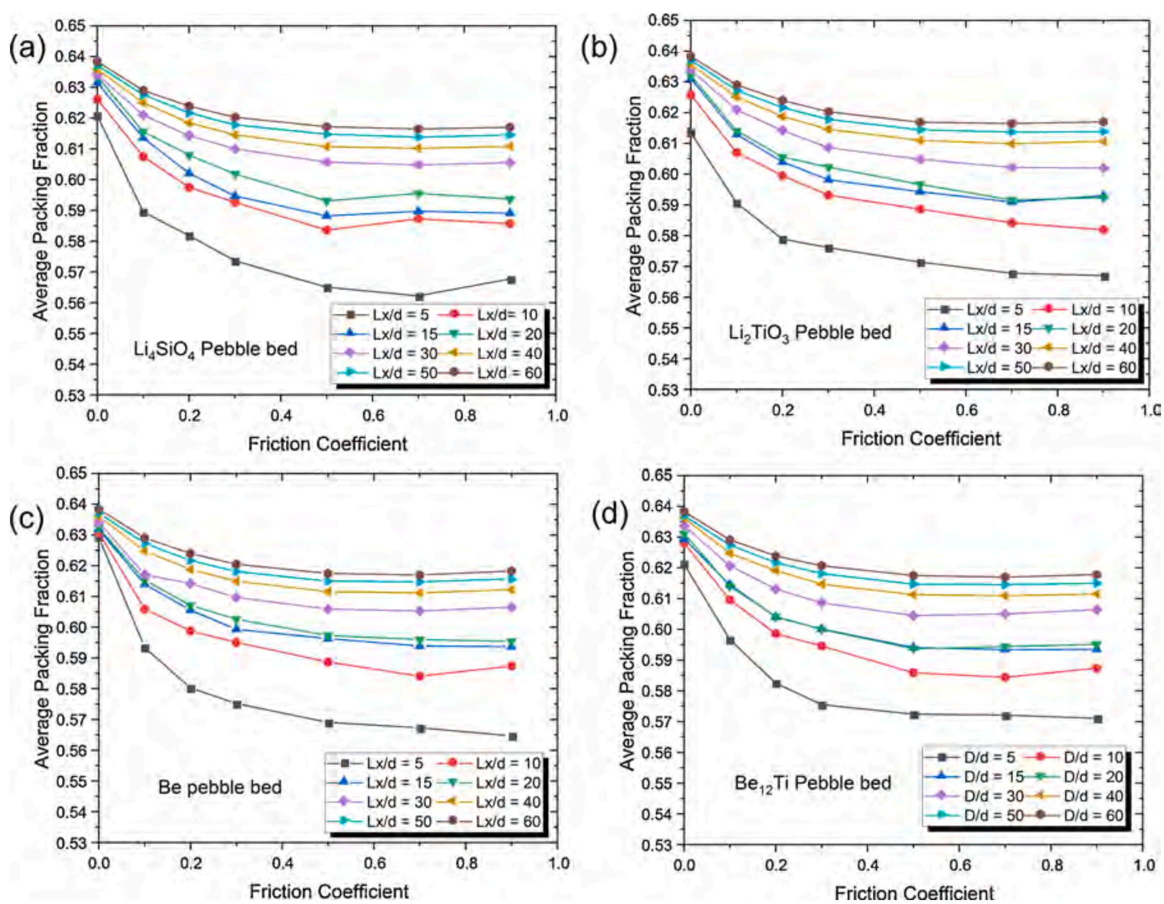

Fig. 10. Average packing factor as a function of the friction coefficient at different bed width.

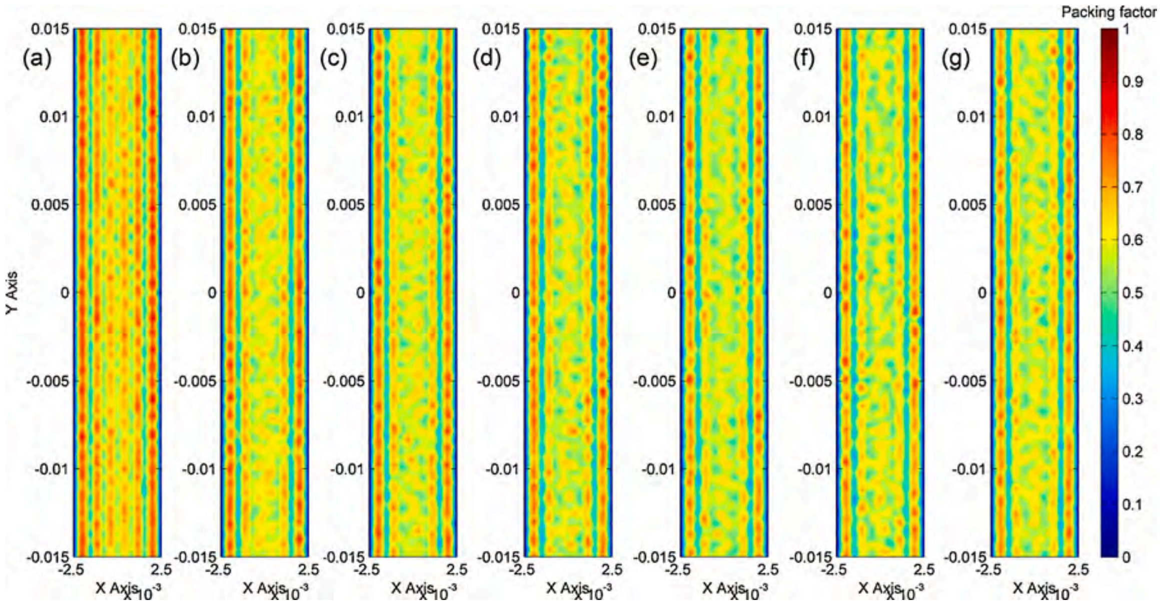

Fig. 11. Local packing factor distribution of pebble bed with different friction coefficient (color online).

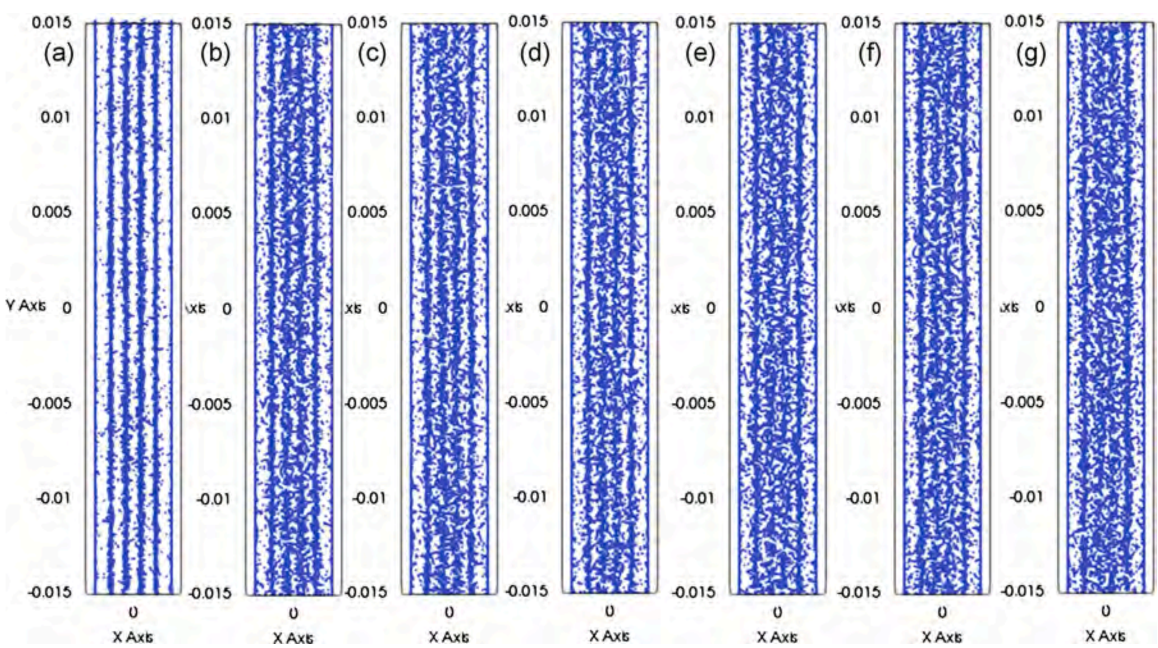

Fig. 12. Pebble center distribution of mono-sized pebble bed with different friction coefficient. (color online).

breeder pebbles and the neutron multiplier pebbles. In this section, The effect of the discrete normal distribution and the discrete uniform distribution of pebble size in number distribution, N(d), of the Li_4SiO_4, Li_2TiO_3, Be, $Be_{12}Ti$ pebbles on the packing fraction of pebble bed were investigated in the simulation. For both the discrete normal distribution and the discrete uniform distribution of pebble size, the average pebble diameter are all equal to 1 mm. The pebble size was discretized with a step of 0.05d.

Fig. 13 provides the final packing state of pebble bed and the corresponding discrete normal distribution of pebble size in detail. For discrete normal distribution of pebble size, the standard deviation σ is in the range of 0.02~0.16 mm with a step of 0.02 mm. The detailed distribution can refer to Fig. 13(*b*) - (*i*). With the increase of the standard deviation, relatively larger and smaller pebbles will be inserted into the pebble bed. Fig. 14 presents the average packing fraction of pebble bed with the discrete normal distribution of pebble size. In Fig. 14, there is a clear trend of increasing of the average packing fraction of pebble bed as the standard deviation increasing. The pebble size distribution has great influences on the pebble packing structures of the tritium breeder and the neutron multiplier pebble bed. For the pebble bed with the friction coefficient of zero, namely, the pebble has an absolutely smooth surface, a higher packing fraction of $\geq$0.635 can be obtained without additional densification measures. At the same time, the packing fraction also increase from about 0.637 to 0.645 with the increase of the standard deviation of pebble size. When the friction coefficient is 0.1, the average packing fraction increase from 0.618 to 0.626. When the friction coefficient increases to 0.5, the packing fraction of pebble bed further reduce to the range of 0.59~0.60. However, in general, compared to the mono-sized pebble bed, a higher packing fraction can be achieved in the packed pebble bed with the normal distribution of pebble size. In the

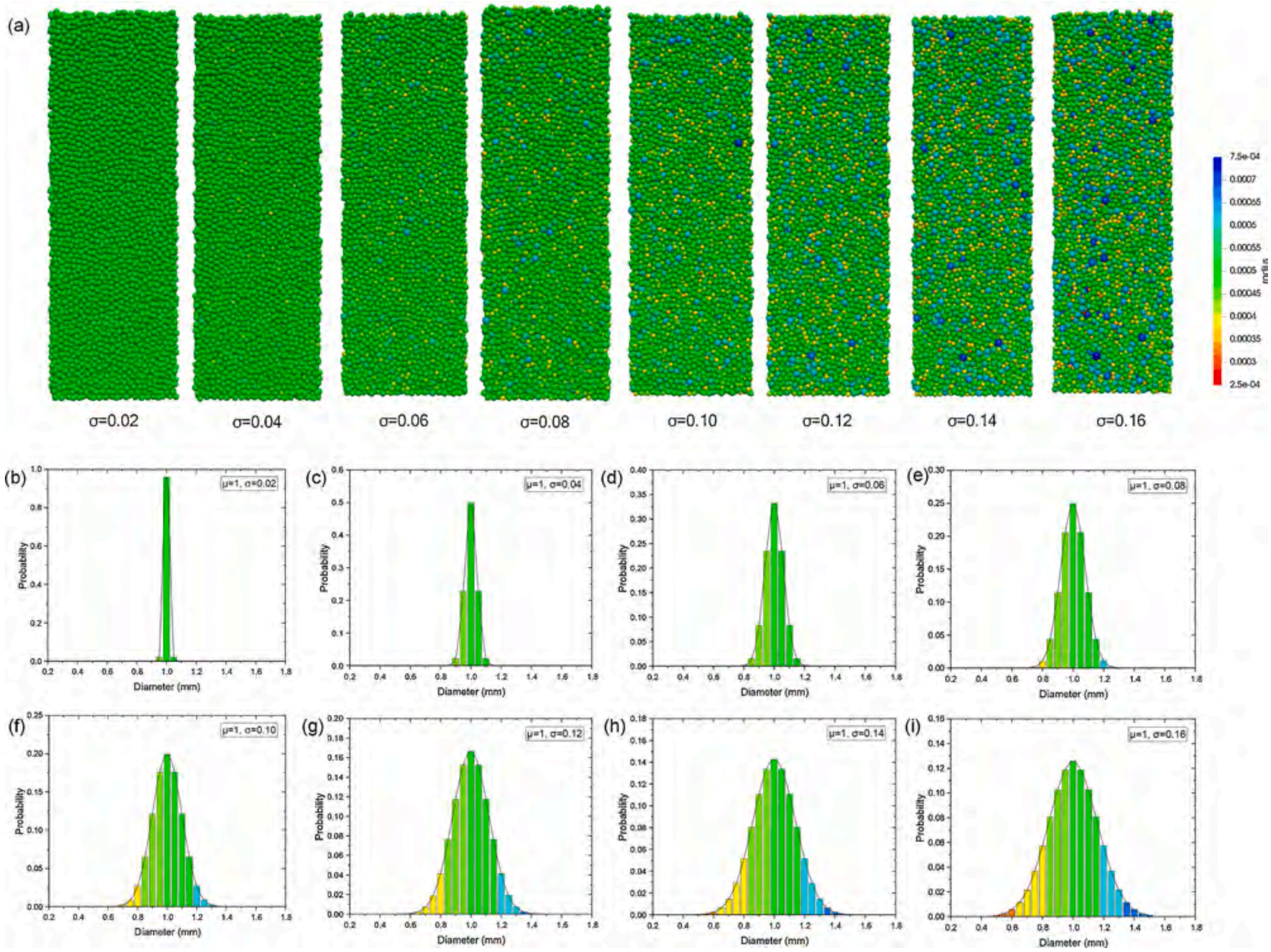

Fig. 13. Final packing configurations of pebble bed with normal distribution of pebble size: *a*, pebble bed structures, *b* ~ *i*, pebble size distributions. (color online).

pebble bed, because the small pebbles can fill the void between the relatively larger pebbles, a higher local packing fraction can be obtained. The proportion of the local structures with higher local packing fraction will raise with the increase of the standard deviation, which will result in a higher average packing fraction of pebble bed.

In addition, the final packing states of pebble beds with a discrete uniform distribution of pebble size are shown in Fig. 15. In the polydisperse pebble bed with the discrete uniform distribution of pebble size, the pebble size was also uniformly discretized with a step of 0.05d between the maximum pebble diameter, $d_{\max}$, and the minimum pebble diameter, $d_{\min}$. In each group of the discrete pebble size, the same number of pebbles were filled into the pebble bed. The average diameter d_{avg} is also 1 mm, which is equal to the average of $d_{\max}$ and the $d_{\min}$. If we define the $\Delta d=|d_{\max}\text{-}d_{avg}|$,or $|d_{\min}\text{-}d_{avg}|$, the pebble size will be uniformly distributed between the $d_{avg}+\Delta d$ and the d_{avg} - Δd. Thus, once the d_{avg} and the Δd were determined, the pebble size distribution in the form of the discrete uniform distribution in number can be determined. The Δd can also represent the dispersion of pebble size in the form of discrete uniform distribution. In this work, the average diameter d_{avg} is 1 mm. The Δd varies in the range of 0.05d ~ 0.50d. The detailed pebble size distribution can refer to Fig. 15(*b*) - (*i*). The variation of the average packing fraction of the tritium breeder and the neutron multiplier pebble bed with the discrete uniform distribution of pebble size as the Δd are displayed in Fig. 16, the corresponding pebble size distribution can be seen in Fig. 15. It can be seen from the results that the obviously increment of packing fraction can be gained in pebble bed with the discrete uniform distribution of pebble size for both the tritium breeder pebble bed and the neutron multiplier pebble bed. For the pebbles with absolutely smooth surfaces, namely, friction coefficient is 0, the average packing fraction is greater than 0.64 when Δd is larger than or equal to 0.15. For pebble bed with the $\Delta d \geq 0.4$, a packing fraction of larger than 0.65 can be observed. When the friction coefficient is 0.1, the packing faction are in the range of 0.62~0.63 and increase from 0.619 to the 0.635 as the Δd increasing. The Δd can also be used to characterize the dispersion of pebble size to some extent. The similar increase of packing fraction can also be observed for the packed pebble bed with normal distribution of pebble size. In other word, the packing of pebbles with a polydisperse pebble size will increase the average packing fraction of pebble bed compared with a mono-sized pebble bed. It is mainly because that the smaller pebble filled the gaps formed between larger pebbles, which can reduce the local porosity of the polydisperse pebble bed. so that the larger the pebble size dispersion, the higher average packing fraction of pebble bed with both the discrete normal distribution and the discrete uniform distribution of pebble size.

From the above results, it can be seen that both the pebble size distribution and the friction coefficient between pebbles have great influence on the packing fraction of pebble bed. A smooth surface of pebbles can achieve a higher packing fraction of pebble bed without any additional densification techniques. The pebble bed packed with polydisperse pebbles can increase the packing fraction of the pebble bed, which is beneficial to increase the tritium breeding rate of the blanket. However, it should be controlled within a narrow range in the actual situation of tritium breeder blanket. Otherwise, the pebble size that is too dispersed may affect the uniformity of the pebble bed packing structure owing to the segregation effect, which will be investigated in detail in the future.

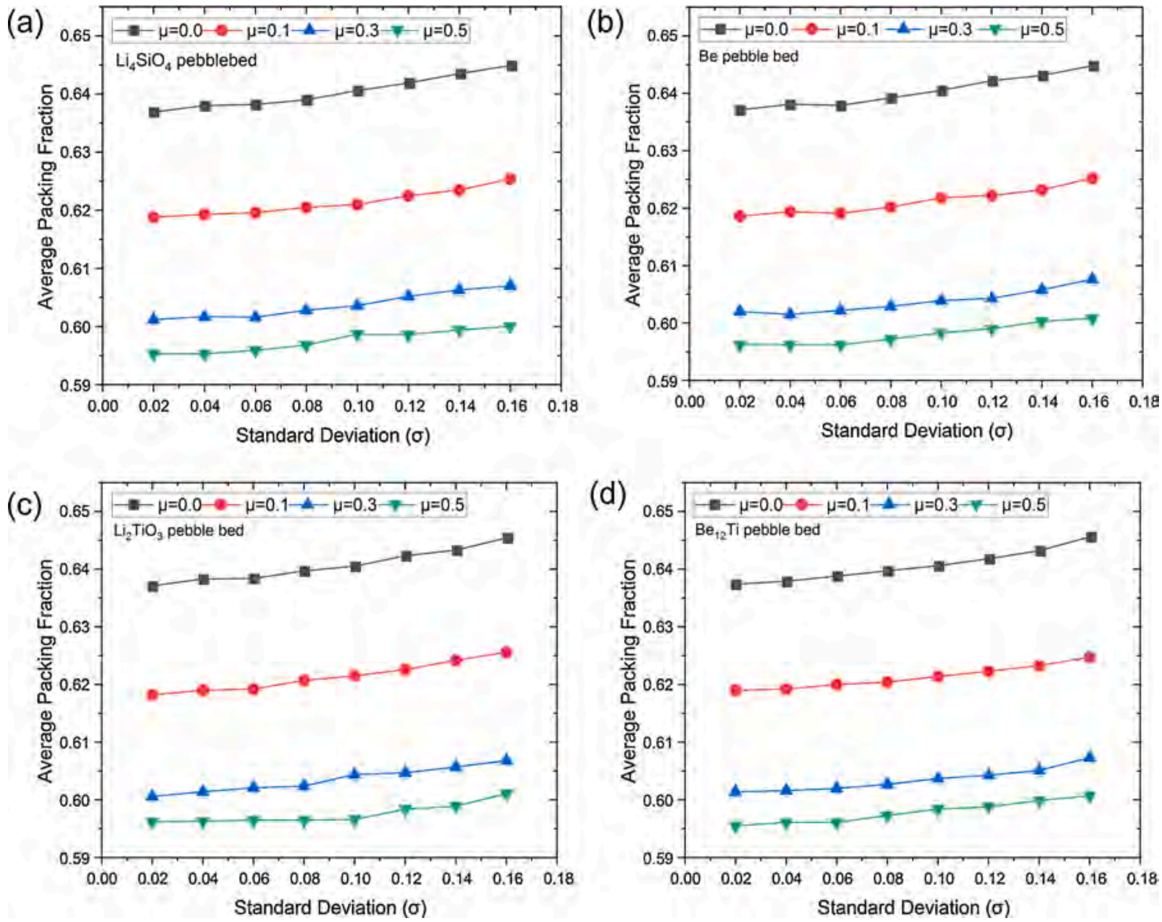

Fig. 14. Average packing fraction variation of pebble bed with normal distribution of pebble size.

3.4. *Effect of pebble density on packing structures*

The preparation methods and fabrication process affect the density of pebbles. For instance, the density of Li_4SiO_4 pebbles fabricated by the wed method is in the range of 80 %TD (theoretical density) ~ 90 %TD resulting from the sintered temperature, sintering time, and so forth, whereas that of the Li_4SiO_4 pebbles prepared by the melt spraying method can reach larger than 95 %T.D. In terms of the effect of pebble density on packing fraction of pebble bed, different results were obtained by different investigated. Pottbacker et al. [18] investigated the effect of filling method and pebble materials on the pebble packing experimentally. High pebble density having a tendency to result in a lower porosity was observed. However, Nakamichi et al. [17] investigated the pebble fraction by vibrated packing experiment by using the Be, $Be_{12}Ti$, SiO_2, Al_2O_3 and SS pebbles, respectively. The result reveals that the packing fraction dose not correlate with the pebble density. In their experiment, the pebbles of different materials were used for packing experiment. Not only the density, but also the surface roughness is different. It is difficult to vary the material parameter apart from each other in experiment owing to the material properties overlap. Whereas, the material parameters can be changed according to the expected value in numerical simulation. Thus, the effect of pebble density on packing structures of the Li_4SiO_4, Li_2TiO_3, Be, $Be_{12}Ti$ pebble beds were investigated respectively by DEM simulation in this work. The pebble density varied in the range of 80 %TD to 100 %TD. The pebble diameter is 1 mm. The friction coefficient was all set to 0.1. To excluded the influence of wall effect, the periodic boundary was selected in the direction of the X (Y) axes.

Fig. 17 shows the variation of the average packing fraction of the Li_4SiO_4, Li_2TiO_3, Be, $Be_{12}Ti$ pebble beds separately with the pebble density. The average packing fraction fluctuates around 0.62, no obvious tendency can be observed. The results in Fig. 17 reveals that the pebble density does not correlate with the average packing fraction of the tritium breeder pebble bed and neutron multiplier pebble bed with the excluding the wall effect, namely, for a relatively wide pebble bed. In addition, from the above results and discussion, it can be seen that the average packing fraction of the pebble bed of different tritium breeders (Li_4SiO_4 and Li_2TiO_3) and the pebble bed of neutron multipliers (Be and $Be_{12}Ti$) respectively has the almost same tendency. Thus, the difference of tritium breeder and neutron multiplier pebble materials effect on the packing fraction of pebble bed seems can be ignored for a relatively wider pebble bed in the application of the tritium breeding blanket. However, for a tall bed packed with high density pebbles, or for a narrow pebble bed, due to the effect of gravity and the pebble-wall friction interaction, the variation of high density may effect the packing fraction of pebble bed, which needs furthr investigation in detail for different material in both experimental and numerical.

4. Conclusions

In terms of packing fraction of pebble bed packed with tritium breeder (Li_4SiO_4, Li_2TiO_3) pebbles and neutron multiplier (Be, $Be_{12}Ti$) pebbles, numerous simulations were conducted to investigated the effects of friction coefficient, pebble size distribution and bed dimension on the packing structures of pebble bed. From the results obtained in this study, it is clearly that:

1) Bed dimension have a salient effect on the pebble packing structures owing to the existence of fixed wall. With the enlargement of the pebble bed width, the average packing fraction of pebble bed

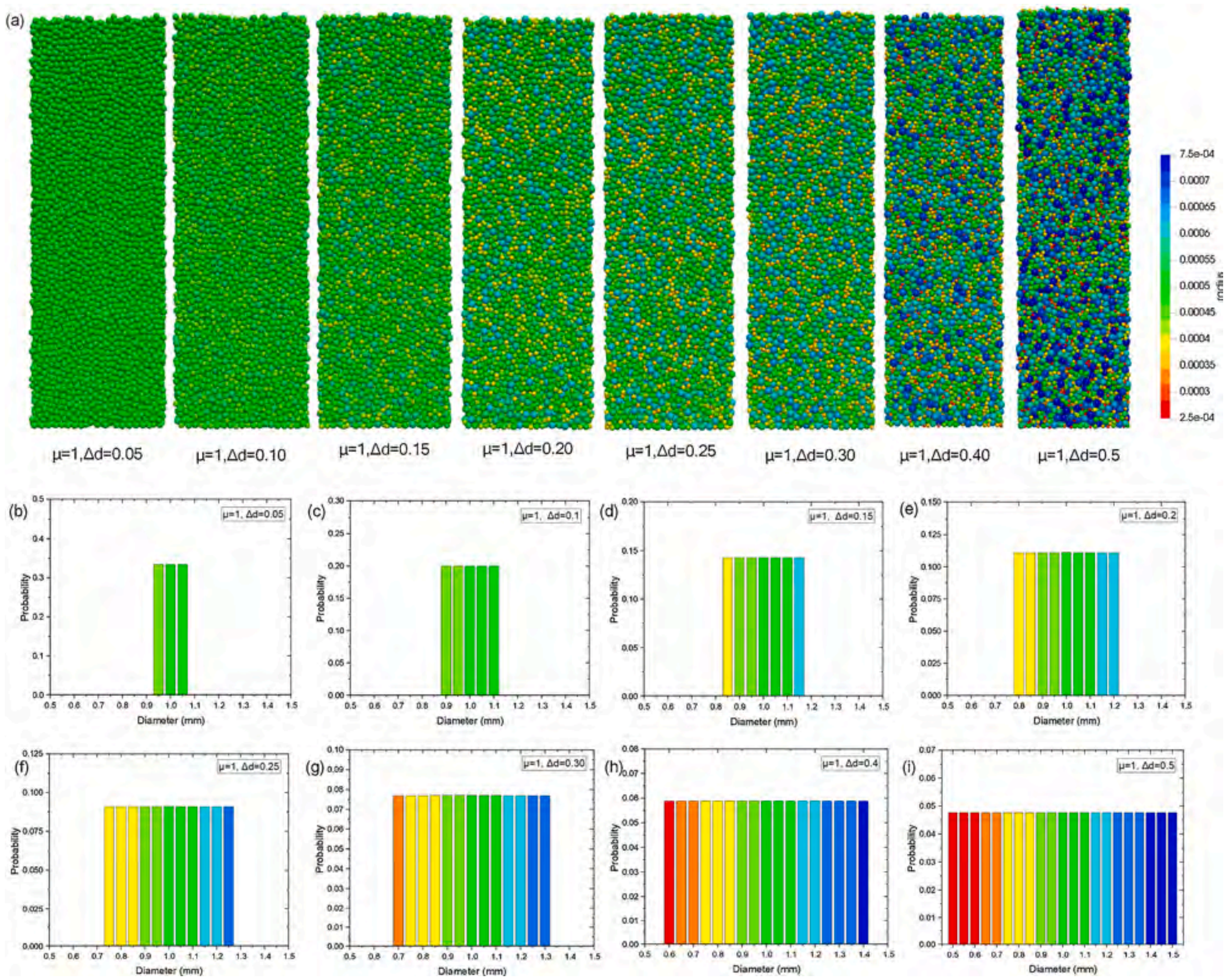

Fig. 15. Final packing configurations of pebble bed with uniform distribution of pebble size: *a*, pebble bed structures, *b* ~ *i*, pebble size distributions (color online).

gradually increase, which is mainly due to the gradually decrease in the influenced volume fraction of wall effect.

2) The friction coefficient between pebbles has a significant influence on the packing fraction of pebble bed, which is mainly attribute to the fact that the friction coefficient between pebbles affects the sliding motion between pebbles. Since the higher friction coefficient will lock the pebble sliding prematurely and terminate the rearrangement process of the pebble packing structure too early, the average packing fraction of the pebble bed decrease as the friction coefficient increases. Therefore, to obtain a higher packing fraction in tritium breeder blanket, it is necessarily to prepare the tritium breeder and the neutron multiplier pebbles with smoother surface by optimizing the fabrication process.
3) The packing fraction of pebble bed is remarkably affected by the pebble size distribution. A polydisperse pebble packing can increase the packing fraction of the pebble bed. However, in the tritium breeding blanket, the pebble size distribution should be controlled within a reasonable narrow range. Otherwise, the pebble size that is too dispersed may affect the uniformity of the pebble bed packing structure owing to the segregation effect.
4) No obvious tendency can be observed in pebble bed packed with different density pebbles for the ceramic tritium breeder (Li_4SiO_4, Li_2TiO_3) and the neutron multiplier (Be, $Be_{12}Ti$) under the condition of excluding wall effect or a more wider pebble bed. Thus, regarding the packing fraction of pebble bed, the effect of pebble density of tritium breeder (Li_4SiO_4, Li_2TiO_3) and the neutron multiplier (Be, $Be_{12}Ti$) seems can be ignored for a relatively wider pebble bed in the application of the tritium breeding blanket. For the tall and narrow pebble bed packed with high density pebbles, the variation of high density may effect the packing fraction of pebble bed owing to the gravity effect and the pebble-wall friction interaction, which needs to be furthr investigated.

In a word, from the above results obtained in this work, it is clearly show that the pebble size distribution, the friction coefficient between pebbles (related to the surface roughness of the pebble) and the pebble bed dimension have an obvious and significant influence on the packing fraction of pebble bed. The smooth surface of pebbles and the reasonable selection of pebble size distribution and the bed dimension will result in a higher packing fraction of pebble bed, which is beneficial to improve the tritium breeding performance of the pebble bed in solid tritium breeder blanket. The effect of pebble materials on the packing fraction can be ignored for the large dimensional pebble bed compared to the pebble size, but not for the narrow or smaller pebble bed.

CRediT authorship contribution statement

Yongjin Feng: Conceptualization, Funding acquisition, Methodology, Supervision, Writing - review & editing. **Baoping Gong:** Data curation, Formal analysis, Investigation, Funding acquisition, Methodology, Software, Validation, Writing - original draft, Writing - review & editing. **Hao Cheng:** Data curation, Methodology, Validation,

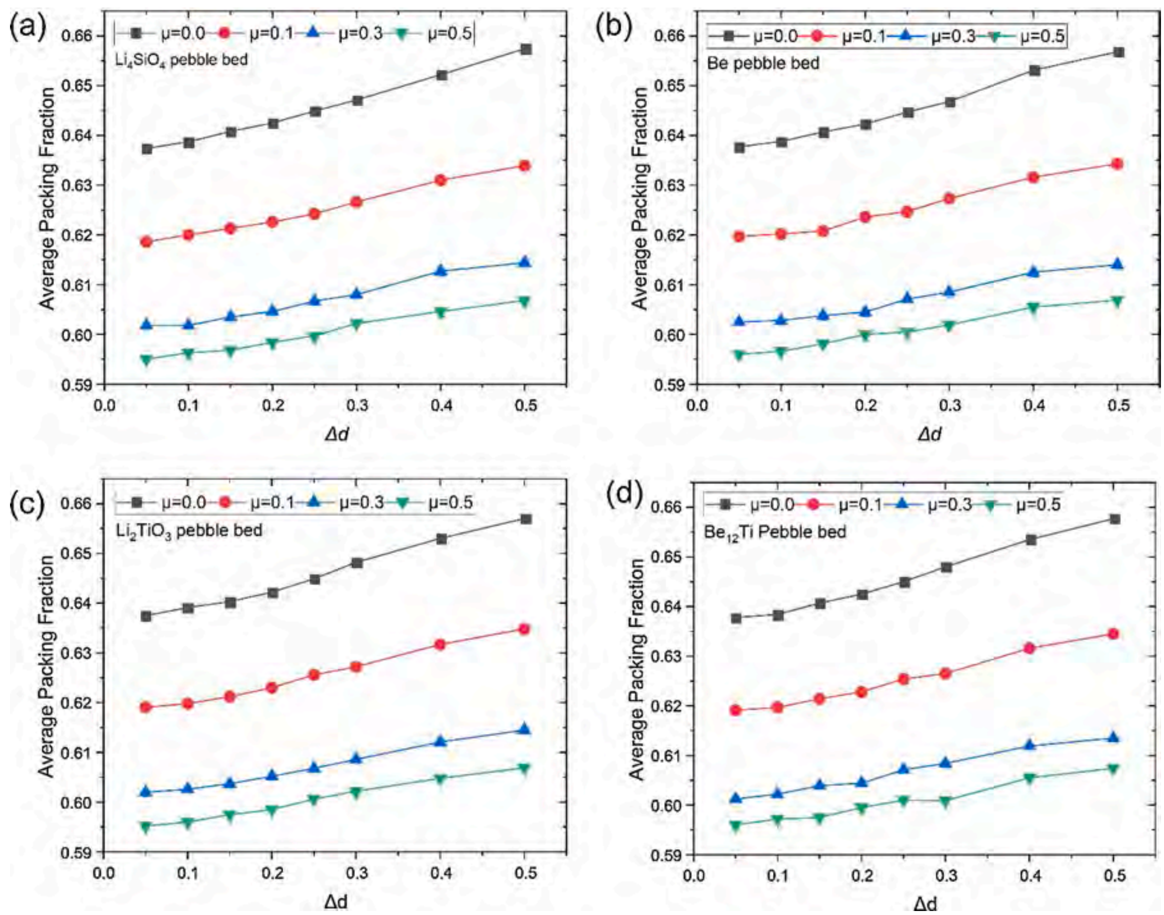

Fig. 16. Average packing fraction variation of pebble bed with uniform distribution of pebble size.

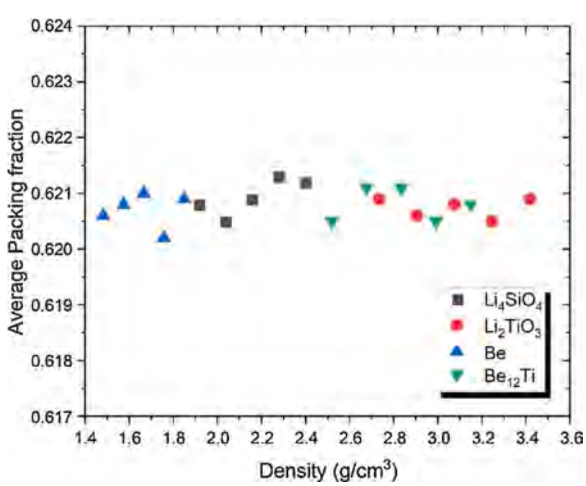

Fig. 17. Average packing fraction as a function of the pebble density.

Visualization. **Xiaofang Luo:** Conceptualization, Methodology. **Long Wang:** Conceptualization, Methodology. **Xiaoyu Wang:** Conceptualization, Funding acquisition, Resources, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fusengdes.2020.112156.

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