Effect of the Retention of Crushed Particle on Thermal Hydraulic Behavior in Local Region of Packed Bed in Fusion Tritium-Breeding Blanket

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Abstract

The fusion reactor blanket is critical for efficient energy utilization. However, the ceramic breeder pebbles within are susceptible to crushing under extreme operating conditions. The retention of crushed particle can influence helium purge and heat-transfer characteristics, leading to localized overheating and posing safety risks to the blanket’ s operation. This study focuses on investigating the influence of particle shape and helium purge velocity on the thermal field and heat-transfer characteristics within a local region of packed bed with face-centered-cubic structure. The results revealed that particle shape plays a significant role in determining retention positions. Near the contact point on the left side, the velocity approaches 0zero, increasing the possibility of potential hot-spot. The flow velocity on the right side increase with the increase of the sphericity. The temperature difference peak between the left and right sides occurs at the left contact point. Higher sphericity in particle improve the possibility of hot-spot generation and the hot-spot influence range.The middle layer exhibits the most significant average temperature difference variation, while the bottom layer sees a decrease in average temperature difference with increasing sphericity, with the top layer being the least affected. Increasing sphericity results in a higher average temperature difference between particle with and without retention, a decrease in average local heat transfer coefficien. The safety risk correlated with retented spherical particle is the most pronounced.Raising the purge velocity enhances the heat exchange capacity. However, retented particle will hinder improvements in the heat exchange capacity.

Full Text

Preamble

Effect of the Retention of Crushed Particle on Thermal Hydraulic Behavior in Local Region of Packed Bed in Fusion Tritium-Breeding Blanket Wang Jiana, b, c, Wang Haoxia, Deng Haishuna, b, Tang Zhengquana, Huang Junweia a School of Mechanical Engineering, Anhui University of Science and Technology, Huainan, 232001, China b Anhui Intelligent Mine Technology and Equipment Engineering Research Center, Huainan, 232001, China c Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, 230031, China Corresponding author: Wang Jian; wjfttt@mail.ustc.edu.cn Abstract: The fusion reactor blanket is critical for efficient energy utilization. However, the ceramic breeder pebbles within are susceptible to crushing under extreme operating conditions.

The retention of crushed particle can influence helium purge and heat-transfer characteristics, leading to localized overheating and posing safety risks to the blanket's operation. This study focuses on investigating the influence of particle shape and helium purge velocity on the thermal field and heat-transfer characteristics within a local region of packed bed with face-centered-cubic structure. The results revealed that particle shape plays a significant role in determining retention positions. Near the contact point on the left side, the velocity approaches zero, increasing the possibility of potential hot-spot. The flow velocity on the right side increase with the increase of the sphericity. The temperature difference peak between the left and right sides occurs at the left contact point. Higher sphericity in particle improve the possibility of hot-spot generation and the hot-spot influence range. The middle layer exhibits the most significant average temperature difference variation, while the bottom layer sees a decrease in average temperature difference with increasing sphericity, with the top layer being the least affected. Increasing sphericity results in a higher average temperature difference between particle with and without retention, a decrease in average local heat transfer coefficien. The safety risk correlated with retented spherical particle is the most pronounced. Raising the purge velocity enhances the heat exchange capacity. However, retented particle will hinder improvements in the heat exchange capacity.

Keywords: Face-centered-cubic structure ; Crushed particle; Local region of packed bed; Sphericity; Heat-transfer characteristics

1. Introduction

删除 [老实人小汪-金色大厅]: Fusion reactors represent a crucial future direction for clean energy development.

Their blanket systems constitute a key technological component for achieving efficient fusion energy utilization, playing a vital role in tritium self-sustaining, heat conversion, and neutron shielding [1]. To achieve tritium self-sustaining, solid-state blanket is typically filled with ceramic particles (such as) in a packed bed configuration as tritium breeding materials [2]. However, the particles in the packed bed for tritium breeding are subjected to prolonged exposure to severe conditions, including neutral irradiation, high thermal loads, and intense magnetic fields. Consequently, particles crushing and powder generation are inevitable under 4SiOLi 2TiOLi extreme conditions [3]. The fragments resulting from crush tend to migrate and deposit with the purge gas, with some potentially getting retented within gas channels.

This not only reduces the effective flow area for the purge gas and increases overall flow resistance within the packed bed also disrupts the heat transfer balance of the packed bed, leading to degradation in heat exchange and localized overheating. Such issues not only affect tritium extraction efficiency also pose significant risks to the safe operation of the blanket system [4]. It is great importance to study the effects of crushed particle retented within the local region of packed bed on heat transfer within blanket systems. fusion engineering, Due to the multi-scale and multi physical processes involved in particle fragmentation failure in the field of research on particle fragmentation simulation is currently scarce. GanYX et al.[5] proposed a probability analysis model for analyzing the particle fragmentation energy of a fusion reactor proliferation ceramic ball bed under mechanical compression load. The model sets fragmentation criteria by assigning a statistically consistent fragmentation energy distribution to the particles. VanLew et al.[6] coupled the volume averaged Lattice Boltzmann method with DEM to calculate the flow characteristics of the purge gas in the cross-sectional gap of the ball bed. Subsequently, small particle size spheres were used to simulate the flow trend of particle fragmentation powder.Wang et al. [7]found that broken particles with a sphericity greater than 0.96 are more likely to flow through the packed bed and leave.)KmW × thermal DEM-CFD coupling program to predict Thermal conductivity plays a crucial role in the analysis of heat transfer within packed beds. Chen et al. [8] utilized a coupled CFD-DEM method to simulate heat transfer in packed bed, revealing that the effective thermal conductivity ranges from across temperatures ranging from 100 to 900°C. approximately 2.0 to 4.0 M. Moscardini et al. [9] conducted heat transfer calculations in packed bed under varying temperature gradients. By conducting parametric studies, they explored the impact of solid and gas materials, temperature, pressure, and compression state on the effective thermal conductivity of packed bed. T.Tsory et al. [10] developed a the effective three-dimensional transfer thermal conductivity of compressed fluidized bed, examining heat phenomena particles-wall interactions. Their study highlighted the significant contribution of heat conduction through bed voids, even when the thermal conductivity of particles surpasses that of air. Additionally, the size and structure of packed beds were shown to notably affect heat transfer. Ahn et al. [11] explored the influence of particles diameter and bed height on natural convective heat transfer in packed be, observing a decrease in average heat transfer with increasing bed height, which could be partially mitigated by reducing the bed diameter. Chen and Lee [12] investigated the impact of particles diameter on convective heat transfer in face-centered-cubic (FCC) structure packed spheres exhibited a total heat transfer bed, demonstrating that bed packed with spheres. Wu et al. [13] found that for rate 10.4% higher than those packed with particles-particles, particles-fluid, involving a given porosity, a bed of spheres with multiple particle sizes exhibits higher effective thermal conductivity than a bed of spheres with a single particle size. An even greater effective thermal conductivity is achieved as the particle size difference decreases.

Current research on heat transfer in packed beds primarily focuses on overall models, with limited attention given to localized heat transfer within them. Studies examining the impact of localized retented crushed particle on heat transfer are particularly scarce. Chen and Lee et al. conducted numerical simulations to analyze surface temperatures and heat-transfer characteristics in FCC structure packed bed, identifying potential hotspot locations [14]. These simulations also explored the influence of inserted spheres on thermal fields and heat transfer properties in FCC structure packed bed [15]. The shape of particle plays a crucial role in heat transfer within local region of packed bed. Therefore, this study applies simulation analysis methods inspired by previous work. By employing computational fluid dynamics and heat transfer techniques, a comprehensive mathematical and physical model of a local FCC structure packed bed is developed. Commercial CFD software is utilized for computations in this model. Studying the effects of particle shape on velocity field, thermal field, and heat-transfer characteristics of the local region of packed bed, this study examines 5 helium purge velocities and 7 different particle shapes as influencing factors. This research fills a gap in the existing literature concerning heat transfer in local region of packed beds containing fragmented components.

The study is structured as follows: Section 1 introduces the background, current research status, and research methodology. Section 2 outlines the methodology, encompassing geometric modeling, mesh independence verification, numerical model validation, governing equations, material properties, boundary conditions, and measurement location setup. Section 3 analyzes simulation results, emphasizing the impact of particle shape and gas velocity on the thermal field and heat-transfer characteristics within the local region of packed bed. Lastly, Section 4 summarizes the research findings and suggests future research directions. 2、Methodology 4SiOLi In the tritium multiplication blanket packed bed of a fusion reactor, 1-2 mm particles serve as tritium proliferators [16]. Fig 1 [Figure 1: see original paper] shows the spherical cross-sectional face centered cubic structure of a randomly packed ball bed, which is the most important dense packing unit in the random packed ball bed. Its pore characteristics and particle contact modes are representative of random packing. In this study, a simulation model with local face centered cubic (FCC) particle packed bed arrangement characteristics was used to accurately reproduce the operating conditions. Subsequently, the crushed particles are inserted into the gaps in the local area of the packed bed to simulate the retention scenario, where both the crushed particles and the packed particles are composed of the same material.

Fig.1 Cross section of Random Stacked Ball Bed

2.1 Geometric Modeling

In the FCC structure packed beds, the contact points between particles are considered as geometric entities with 0 thickness , these contact points can lead to computational divergence in fluid flow and heat transfer simulations within the model, necessitating appropriate treatment [17]. Common methods for treatment include diameter reduction, expansion, cutting, and bridging. Among these methods, diameter reduction stands out as a relatively effective and easily implementable approach, although the reduction ratio must be carefully chosen. Excessive reduction in particles leading to deviations in flow and diameter can significantly increase porosity, heat-transfer characteristics from real-world conditions [18] thus impacting computational accuracy of the results. Research by Reddy et al. [19] focused on the diameter reduction method and demonstrated that reducing particles diameter by less than 2% results in near 0 flow velocity at the particles gaps, preserving the original flow pattern. Building on this insight, the current study adopts the diameter reduction method to address contact points by decreasing the diameter of the local packed particles by 0.5% (to), while ensuring consistent gaps between retented and packed particles. mm99.1 Fig 2 [Figure 2: see original paper] shows a local FCC structure packed bed model with reduced ball diameter.

The inlet and outlet sections are located above and below the packed bed, respectively, with a length of 1.6mm for each section. The model includes the fluid domain (helium channel) shown in Fig 2 (a) and the solid domain (particles) shown in Fig 2 (b). The solid domain consists of 14 stacked spherical particles: 2 complete particles, 8 quarter particles forming the top and bottom layers, and 4 half particles forming the middle layer. In addition, there are 14 embedded heating balls with a diameter of 1 millimeter located at the center of the filled particles. These heating balls are made of the same material as the filling particles and are used as a heat source. In addition, the model includes a broken particle whose position is based on the actual situation, that is, the broken particle must be in contact with at least three surrounding stacked particles to ensure stable retention. This contact form precisely satisfies the geometric constraint of "three-point determination of stable plane" and achieves force balance. The impact of fragmented particles being too small on the local heat transfer characteristics of the packed bed will make the analysis insignificant. This study considered 7 different sphericity non spherical particles and spherical particles with a radius equal one-third of the filling particle radius. All six non spherical particles have the same external sphere radius as the spherical particles. In order to remove the complex interference of particle motion, the actual process is simplified, assuming that the broken particles are already in a fixed position.

Most real fragments can be classified into near regular polyhedra or near spherical statistical rules. In order to explore the influence of particle shape on local heat transfer characteristics, seven ideal geometric configurations were selected as shape basis functions to characterize real fragments. Specific choices include regular tetrahedra, regular hexahedrons, regular octahedra, regular dodecahedron, regular icosahedron, quantitatively describe the shape of these particles can quantitatively analyze the influence of key shape parameters on heat transfer. spheres. Using rhombohedral icosahedron, sphericity Fig.2 Geometric modeling (a) fluid domain (b) solid domain

2.2 Mesh Independence Verification

Polyhedral meshes are commonly utilized for constructing finite element models to analyze temperature distributions in fluidized beds due to their ability to decrease computational burden and enhance convergence [20]. As shown in Fig.3, polyhedral meshing is utilized to generation the fluid and solid components of the geometric model, with specific focus on refining the mesh in the contact area. To ensure mesh independence, a series of high-quality meshes comprising elements ranging from 225,000 to 2,215,000 are generated for the geometric model without crushed particle Conditions at an inlet flow velocity of 0.2 m/s and a pressure of 101 kPa [21], calculations are conducted for the inlet-outlet pressure drop and the average surface temperature of the particles in the local packed bed. The results presented in Table 1 , indicate that deviations in pressure drop and average temperature below 1% when the mesh number surpasses 1,090,000 elements. This suggests that schemes exceeding 1,090,000 elements can effectively replicate the surface temperature of the local packed bed. To optimize computational efficiency, the grid generation approach employing 1,090,000 elements is adopted in this study. The same grid generation strategy is used in the remaining 7 geometric models containing crushed particle, with variations only in the number of elements allocated to the crushed particle.

Fig.3 Mesh generation results and mesh details. In order to avoid steep temperature gradients caused by sharp corners and high bending gaps of fragmented particles, exclusive grid independence verification was conducted on seven particle models. The results are shown in Fig 3 [Figure 3: see original paper]. When the number of grids exceeds 1,110,000, the calculation deviation of the average temperature is less than 1%. This indicates that the scheme with more than 1,110,000 grids can also ensure the reliability of the simulation results of the surface temperature of the local ball bed with broken particles.

Table 1 Mesh independence verification The number of mesh Average temperature(K) Pressure drop(Pa/m) Table 2 Verification of Independence of Crushed Particle Grid Average temperature(K) number of mesh regular tetrahedron regular hexahedron Regular octahedron regular dodecahedron regular icosahedron rhombic triacontahedron

2.3 Numerical Model Validation

A fuel packed bed heat transfer experimental apparatus utilizing FCC structure was assembled. Experiments were conducted to get the relationship between the maximum temperature differenc maxTD of the fuel pebbles surface and the Reynolds number at 5 distinct air flow rates[22]. The generated mesh model is imported into the CFD software solver for simulation, employing parameters consistent with those outlined in the aforementioned experiment. The simulation results were then compared with both the experimental data and the numerical calculations [23]. The comparative analysis is presented in Fig.3and Fig.4, indicates a strong agreement between the simulation results in this study and both the experimental data and the numerical calculations. The discrepancies observed remained within acceptable margins. The comparison results explained the reliability of the numerical model developed herein, proving its suitability for future investigations into heat transfer within local packed beds.

Fig.3 Maximum temperature difference of the fuel pebbles surface at different Reynolds numbers Fig.4 Temperature comparison of detection points and particles

2.4 Governing Equations

The substantial momentum and heat transfer interactions at the interface between behavior. helium gas Eulerian-Lagrangian method Consequently, the governing equations are formulated according to this method [24]: fluidized bed support effectively model in the the use of coupled their Eq.(1) and (2) represent the continuity equation and momentum equation for the fluid[25], where Ñ represents the Hamiltonian operator, r is the fluid density, v is the fluid velocity, P is the fluid pressure,tis the viscous stress tensor of the fluid, g is the gravitational acceleration, pfR is the momentum exchange between fluid and particles. mrepresents the dynamic viscosity in Eq.(3). In the Eq.(4), brepresents the interphase momentum exchange coefficient, sv is the particle velocity, which is set to 0 in this calculation to simplify momentum exchange computations.

Eq.(5) represents the energy equation for the fluid, where E is the total energy of the fluid, comprising internal energy, kinetic energy, and potential energy, k and pc are the thermal conductivity and specific heat capacity of the fluid, respectively, vS is the internal heat source term. T is the fluid temperature in Eq.(6). z and vq are the height of potential energy and the volumetric heat source in Eq.(7).

2.5 Material Properties and Boundary Conditions

The packed bed comprises 4SiOLi particles. Helium purging at the inlet takes away heat from the top layer to the bottom layer. Due to notable variations in thermal conductivity and specific heat capacity of these particles at different temperatures, inappropriate. Consequently, calculations using temperature-dependent equations are employed for accurate computations[26] [27]. constant values where sk represents the thermal conductivity of the particles)KmW × ST is the surface temperature of the particles (,jis the porosity of the local packed bed, sc represent the specific heat capacity of the particles The density of 4SiOLi particles is taken as [28].

The density, thermal conductivity, and dynamic viscosity of helium vary significantly with changes in temperature and pressure. As a result, constant value calculations are equally inappropriate, and nonlinear fitting equations are necessary for accurate computations [29].

The specific heat capacity pc of helium is taken as The computational model comprises a velocity inlet at the top and a pressure outlet at the bottom, with inhibition backflow promoting helium outflow. Initially filled with helium, the model incorporates non-slip walls and adiabatic boundaries on particles and side walls. Internal heat sources uniformly heat, with specific boundary conditions outlined in Table 3 . Radiation effects on surfaces are disregarded due to low surface temperatures. Helium purge velocity in boundary conditions ranges [30], the Reynolds number is well below than 2,300, warranting the use of a laminar flow model. To enhance convergence and reduce computational burden, steady-state calculations are employed, leveraging the stability of laminar flow fields in computational models. All other parameters are maintained at default settings.

Table 3 Computational model boundary conditions [31] sm0.2 sm1.0 Boundary conditions Numerical value Inlet velocity v (0.1~2.0 Initial temperature T (Velocity inlet pressure P (Pressure outlet pressure P (Heat source)3mMW

2.6 Measurement Location

This study refers to the numerical simulation conducted by Chen and Lee [15], due to the significant data volume generated by numerous surface meshes per particle.

To examine local heat transfer conditions, temperature measurement points were designated on particle surfaces within a selected representative physical plane mm). Fig.5 illustrates the position of measurement points (the XZ plane at 1~6, 7~17, and 18~23 on the particle surfaces at the top, middle, and bottom layers, respectively. Each particle surface features measurement points separated by an angular distance of 9°. The presence of crushed particle retented within gaps in the local region of packed bed results in an asymmetrical structure, impacting heat transfer differentially on particle surfaces located on opposite sides of the XZ plane.

To study and analyze this asymmetry, an additional 21 measurement points were added symmetrically to points 2–22, resulting in a total of 44 measurement points.

The trigonometric calculations were employed to determine the precise positions of all measurement points.

Fig.5 44 measurement points on the middle segment of the XZ plane We also set temperature measurement points 0.08 mm inside each surface transfer measurement point on the particle in order to calculate the local heat coefficient (HTC). The equation for the local HTC [15] is as follows:

Where nTD represents the temperature difference between the measurement point N , where N is an integer) and the point M (mm08.0 inward from point N) , r is the radius of the packed particle, nr and mr are the distances from the measurement point N and measurement point M to the particle center, h is the local HTC, nST is the surface temperature at the measurement point, 0T is the inlet temperature .

3. Results and Discussion

The study examined the effects of the different conditions on thermal behavior using simulations.These conditions included 6 non-spherical particles with varying degrees of sphericity and spherical particle, as well as different inlet velocities under conditions where spherical particle is retented. We analyzed the fluid velocity field and thermal field, temperature difference and local HTC on particle surfaces for each operational condition.

3.1 Particle shape and retention position

The 7 particle shapes include the regular tetrahedron, hexahedron, octahedron, icosahedron, rhombic-triacontahedron, and sphere, with sphericity dodecahedron, values ranging from 0.671 to 1.0 [32]. The formula for calculating sphericity as follows: where F , PV and PS are the sphericity , volume and surface area of the crushed particle.

Table 4 presents specific geometric parameters of these shapes. where a is the side length of non-spherical particle and R is the radius of spherical particle. The radius of the circumscribed spheres for all six non-spherical particles are consistent with the radius of the spherical particle.

Table 4 Particle of different shapes and their geometric parameters[32] [33] Picture Volume Surface area Sphericity Circumscribing sphere radius tetrahedron hexahedron octahedron dodecahedron Continued Table 4 Picture Volume Surface area Sphericity icosahedron Circumscribing sphere radius rhombic-triacont ahedron 525 + sphere Fig.6 shows the retention positions of crushed particle within the local region of packed bed as their sphericity varies. With an increase in sphericity, the retention position of crushed particle gradually shifts from the entrances of gaps between three packed particles to the center of these particles. This shift occurs due to the thinner, longer edges of particle with low sphericity compared to those with high sphericity, increasing the possibility of particle with low sphericity getting lodged in the gaps between the three packed particles. When particle with low sphericity are retented at the gap entrances, their impact on the local packed bed is constrained by the surface resistance of the packed particles, resulting in a limited influence area. As particle sphericity increases, this resistance decreases gradually. Consequently, the retention position shifts towards the central region, significantly expanding the influence area on the velocity and thermal fields of the local region of packed bed. The specific effects of these changes will be discussed in detail in the following paragraph.

3.2 Effect of Particle Shape on Velocity Field and Thermal Field

Fig.7 illustrates the velocity distribution in the central region of the XZ plane with various shapes of crushed particle. Compared to the condition without retented particle (Fig.7 (a)), the presence of retented particle on the left side, deviates the original flow direction and velocity. This occurs because part of the flow channel is occupied the retented particle , increasing the flow resistance. Consequently , the flow from the left side forms a bypass flow above the retented particle and inflows the right side. As the sphericity increases, the gap between the retented particle and the top layer packed particle diminishes, further hindering the flow from the left and gradually decreasing the bypass flow velocity. For highly spherical particle (sphericity), a range of blunt-body bypass flows forms on the left side. Even near the contact point between the retented particle and the packed particle on the left side of the middle layer, the velocity approaches 0, increasing the possibility of potential hot-spot. 91.0^3 Fig.6 Retention positions of particle with different shapes in the local region of packed bed On the right side, the flow velocity rises with increasing sphericity (Fig.7 (b) - (g)) due to the reduced spacing between particles, leading to increased flow velocity.

The velocity peak in Fig.7 (h) is comparatively lower, due to the smoother surface of the spherical particle compared to polyhedral ones, resulting in milder streamline contraction and weaker flow disruption, thereby preventing sudden local velocity spikes.

Fig.7 Velocity field in the XZ plane under different particle shapes Fig.8 shows the temperature distribution in the central region of the XZ plane with various shapes of crushed particle. The helium inlet and outlet gaps present the highest and lowest temperatures in the field, respectively, lying beyond the primary influence zone of the retented particle. Consequently, the maximum and minimum temperatures remain relatively consistent across all conditions involving retented the condition without retented particle (Fig.8 (a)) show slightly lower particle, maximum and minimum temperatures compared to other conditions. However, within the region impacted by retented particle, temperature elevation correlates with increased sphericity. As showed in Fig.8 (b) - (h), the left side exhibits lower velocity, slower heat transfer, and quicker temperature escalation, while the right side dispalys higher velocity, thereby establishing a noticeable temperature gradient difference. transfer, and slower temperature increase, faster heat Fig.8 Thermal field in the XZ plane under different particle shapes

3.3 Effect of Particle Shape on Two-Surface Temperature Difference

The variation in surface temperature of the packed particles on both sides of the local region of packed bed is relatively small. This study defines TD as the surface temperature difference between symmetrical measurement points on both sides in the central region of the XZ plane. The TD variation is used to assess the impact of crushed particle shape on temperature variations across both sides of the local region of packed bed . Fig.9 (a) - (g) show the TD variations with measurement points indicating a location for different sphericity. Notably, all consistent lower heat transfer intensity on the left side compared to the right, aligning with findings from the velocity field analysis. The TD charts for the 7 different sphericity exhibit similarities: minimal changes in the top and bottom layers 5 pairs of measurement points, while significant fluctuations are observed in the middle layer 11 pairs, initially increasing and then decreasing. Fig.9 (h) illustrates a 1% rise in the TD are positive, surface temperature difference peak pTD as sphericity progresses from 0.671 to 0.961. pTD occurs the contact point between the retented particle and the packed particle on the left of the middle layer,the elevated pTD heighten the risk of potential hot-spot.

Furthermore, the pTD location shifts from 14 to 11 with increasing sphericity. This shift signifies a gradual migration of the hot-spot location from the gap area towards the critical central region, amplifying its impact within the local region of packed bed and significantly compromising bed safety. The lower observed in spherical particle compared to other highly spherical particles may be due to reduced the fluid velocity peak on the right side.

Fig.9 The TD variations with measurement points location for different sphericity Fig.10 variation illustrates temperature difference TD among the top, middle, and bottom layers of the packed bed with increasing sphericity. The middle layer, including symmetrical measurement points 7-17, is most affected by particle shape, with the TD rising from 2.8% to 4.1% as sphericity increases. The TD decreases slightly when sphericity increases to 1, aligning average surface with the trend of the pTD variation depicted in Fig.9(h). Conversely, the impact on the bottom layer ,including symmetrical measurement points 18-22 , contrasts with that of the top and middle layers. The TD decreases from 2.9% to 2.0% as sphericity increases.

This phenomenon may be attributed to the increased sphericity enlarging the particle-covered area in the bottom layer, thereby diminishing the surface flow velocity and reducing the average heat transfer capacity. The top layer , including symmetrical measurement points 2-6,is minimally affected as the retented particle is situated farthest from it. The TD climbs from 0.2% to 1.7% as sphericity increases.

This increase is attributed to the rightward movement of the inflow on the left side as sphericity increases, leading to heightened flow velocity on the right side and an enhanced average heat transfer capacity.

Fig.10 The TD among the top, middle, and bottom layers with increasing sphericity

3.4 Effect of Particle Shape on Heat-transfer Characteristics

The surface heat-transfer characteristics of the local region of packed bed can be described by considering the temperature difference and the local HTC of the surface. *DT as the temperature difference between the left surface This study defines measurement point of particle with and without retention, indicating the temperature fluctuation within the packed bed. The local HTC for the 23 measurement points on the left side of each sphericity were calculated using Eq.(13). Fig.11 (a) - (g) show* DT variations and local HTC magnitude h based on measurement points location *DT variations for different sphericity. A strong negative correlation exists between the* DT exhibits 2 peaks and 2 valleys, aligning and HTC magnitude. Each sphericity *DT peaks are observed near precisely with the local HTC' s 2 valleys and peaks. The 2 the contact points between the middle and bottom packed particles and the retented particle, indicating lower heat transfer efficiency near these contact points, fostering* DT peak near the middle layer contact point the formation of potential hot-spots. The is higher than that in the bottom layer due to the shorter distance between packed particle in the the middle layer and the retented particle, resulting in a smaller *DT valleys occur at the corresponding valley in the local HTC. Conversely, the 2 helium inlet and outlet gaps, minimally influenced by particle shape, thus exhibiting* DT valley at the higher heat transfer efficiency compared to the central region. The bottom is slightly higher than at the top due to the closer proximity of the packed particle in the bottom layer to the retented particle.Increasing sphericity heightens the to more influence *DT escalates pronounced from 1.1% to 6%.

Similarly, leading *DT variations. Specifically, at measurement point 1, the* DT peak in the middle layer also increases with sphericity, expanding from 5.4% to 6.7%. This phenomenon indicates that elevated sphericity elevate local temperature and the probability of potential hot-spots. Fig.11 (h) shows *DT and the average local HTC with sphericity. As the variations of the average* DT rises from 2.6% to 4.1%, while the average local sphericity increases, the average HTC exhibits an inverse pattern. This observation implies that a higher sphericity of retented particle results in the temperature rise across the entire affected central region. *DT , spherical crushed Considering the particle exert the most significant impact in the local region of packed bed .* DT peak in the middle layer and the average retented particle layer, influence on the local region of packed bed. 5 distinct

3.5 Effect of Inlet Velocity on Heat-transfer Characteristics

To examine the impact of inlet velocity on heat-transfer characteristics within the local region of packed bed, we opted for spherical crushed particle that exert the inlet velocity greatest conditions were selected from Table 3 to scrutinize variations in the average local *DT . Fig.12 illustrates the variation in the h concerning HTC magnitude h and the both spherical retented particle and non-retented particle in relation to the inlet velocity. Both conditions demonstrate a proportional rise in h as the inlet velocity escalates, indicating that improving the purging velocity can amplify the convective heat transfer capacity of the local region of packed bed. Nonetheless, the gap between retented particle impede further implying that enhancement of the heat transfer capacity. This phenomenon attributed to particle obstructing the flow channel, thereby diminishing the contact area between the helium gas and the surface of packed particle in the bottom layer, diminishing the efficacy of convective heat transfer. widens progressively, Fig.11 the* DT variations and local HTC magnitude h based on measurement points location for different sphericity Fig.12 The average local HTC magnitude h variation concerning both spherical particle and non-retented particle with the inlet velocity Fig.13 shows the variation of the average temperature difference DT and the temperature difference peak *D pT with elevated inlet velocity. The findings indicate a decrease in DT with rising velocity, supporting the notion that higher purging velocities augment heat transfer efficiency. Conversely, the* D pT exhibits an initial increase followed by a decrease as inlet velocity escalates. The *D pT is observed near the contact points between the packed particle in the bottom layer and rentented particle. Notably, a critical velocity of 0.8 m/s has been found: below this threshold, the intensified heat transfer near contact point is outweighed by the obstructive influence of the rentented particle. Above 0.8 m/s, the velocity-driven enhancement prevails, resulting in a subsequent decline in the* D pT .

Fig.13 The DT and *D pT with increasing inlet velocity

4. Conclusion

This study employs CFD methods to systematically examine the effects of a retented crushed particle within the interstitial space of a FCC structure local region of packed bed on the thermal field and heat transfer. The shape of the crushed particle is identified as a critical factor affecting heat transfer. Qualitative analysis of the velocity and thermal field variations in the central region of the XZ plane with varying shapes of the retented crushed particle. Quantitative evaluation of temperature difference and local HTC indicated changes in the thermal field and heat-transfer characteristics on both sides of the local region of packed bed. Furthermore, the impact of different purge velocities on the heat-transfer characteristics of the local region of packed bed was explored. The findings led to the following conclusions: (1) Sphericity dominated retention position: the thinner, longer edges of particle with low sphericity, increasing the possibility of particle with low sphericity getting lodged in the gaps between the three packed particles, resulting in a limited influence area. As particle sphericity increases, the retention position shifts towards the central region, significantly expanding the influence area on the velocity and thermal fields. (2) The velocity field and thermal field exhibit coupled variations: the flow from the left side forms a bypass flow above the retented particle. For highly spherical particle, a range of blunt-body bypass flows forms on the left side,the velocity approaches 0 near the contact point, increasing the possibility of potential hot-spot. The flow velocity rises with increasing sphericity on the right side. (3) The thermal field differences are concentrated in the middle layer: The temperature difference peak between the left and right sides occurs at the left contact point. As sphericity rises from 0.671 to 0.961, the peak increases by 1%, and the peak position shifts closer to the center. Higher sphericity in particle improve the possibility of hot-spot generation and the hot-spot influence range.

The middle layer exhibits the most significant average temperature difference variation, while the bottom layer sees a decrease in average temperature difference with increasing sphericity, with the top layer being the least affected. (4) The local HTC is inversely proportional to the temperature difference:

Increasing sphericity results in a higher average temperature difference between particle with and without retention, a decrease in average local HTC, and a 1.3% increase in temperature difference peak. (5) The effect of purge velocity is influenced by retented particle: Raising the purge velocity enhances the heat exchange capacity. However, retented particle will hinder improvements in the heat exchange capacity.

The findings presented in this paper provide insights into the mechanisms influencing heat transfer within packed beds. They provide theoretical support for optimising heat transfer and ensuring the safe design of the blanket packed bed in fusion reactors. Future studies should focus on investigating the dynamic evolution of crushed particle, from migration to retention.

Credit authorship contribution statement Wang Jian: Writing -original draft, Validation, Software, Resources, Investigation, Conceptualization.Wang Haoxi: Visualization, Validation, Data curation. Tang Zhengquan: Visualization, Software, Resources, Investigation. Deng Investigation, Conceptualization.

Haishun: Supervision, Project administration, Huang Junwei: Visualization, Software, Methodology, Project administration.

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