Numerical Study on Powder Migration and Clogging Mechanism in Pebble Beds with Purge Gas

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Abstract

Objective: As the primary functional component of a fusion reactor, the fusion blanket pebble bed, composed of numerous particles, is crucial for tritium breeding, neutron multiplication, and radiation shielding. Particles within tritium-breeding pebble beds are subjected to prolonged neutron irradiation, high thermal loads, and strong magnetic fields in fusion environments. Such conditions render them susceptible to pulverization and fragmentation. The resulting fragments and powders migrate and are deposited into the gas channel, driven by the purge gas. The reduction in the effective flow area of the gas increases the flow resistance, resulting in tritium retention, degraded heat transfer, and other adverse effects. These conditions impair the thermodynamic properties of the pebble beds and hinder tritium self-sufficiency. Limited information exists on powder migration and clogging mechanisms in fusion blanket pebble beds, particularly under diverse physical conditions.

Methods: The aim of this study was to use a computational fluid dynamics model coupled with the discrete element method (CFD-DEM) to numerically explore powder migration and clogging in pebble beds.

Results: We propose two migration and clogging mechanisms. One involves powder with a large particle size, and the other does not. The results indicate that the powder migration velocity progresses through three stages: rapid decay, linear decay, and stability. Pebble-bed clogging manifests in two forms: extensive superficial clogging and uniform internal clogging. Two fitted curves were used to depict the migration and clogging tendencies. The powder size distribution significantly influenced the powder migration. The breeder orientation, powder size, and friction coefficient affected the distribution of the clogging powders. However, the impact of the purge velocity on powder migration and clogging in pebble beds was limited, and this effect varied significantly with

different particle size ratios. Based on the analysis, a formula is proposed to characterize the behavior of the powder in the pebble beds.

Limitations: For simplicity, all powders were modeled as spheres in this study, although real-world powder particles are irregularly shaped.

Full Text

Preamble

Numerical Study on Pebble Bed Powder Migration and Clogging Mechanism with Purge Gas

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Limited information exists on powder migration and clogging mechanisms in fusion blanket pebble beds, particularly under diverse physical conditions.

Methods: This study employed a computational fluid dynamics model coupled with the discrete element method (CFD-DEM) to numerically investigate powder migration and clogging in pebble beds.

Results: We propose two migration and clogging mechanisms—one involving powder with large particle sizes and one without. Results indicate that powder migration velocity progresses through three stages: rapid decay, linear decay, and stability. Pebble bed clogging manifests in two forms: extensive superficial clogging and uniform internal clogging. Two fitted curves depict the migration and clogging tendencies. Powder size distribution significantly influences powder migration, while breeder orientation, powder size, and friction coefficient affect the distribution of clogging powders. However, purge velocity has limited impact on powder migration and clogging, with this effect varying significantly across different particle size ratios. Based on our analysis, we propose a formula to characterize powder behavior in pebble beds.

Limitations: For simplicity, all powders were modeled as spheres, although real-world powder particles are irregularly shaped.

Conclusions: The results of this study can aid in analyzing and predicting powder dynamics in pebble beds.

Keywords: Coupled CFD-DEM; Pebble beds; Purge gas; Powder flow; Migration and clogging mechanism

Introduction

As the primary functional component of a fusion reactor, the fusion blanket is responsible for radiation shielding and tritium self-sufficiency [1-3]. Based on tritium breeder morphology, fusion blankets can be classified as solid- or liquid-breeder blankets, with solid breeder blankets viewed as leading candidates for fusion blanket design [4,5]. Both water-cooled ceramic breeding (WCCB) and helium-cooled ceramic breeding (HCCB) blanket designs utilize solid ceramic pebble beds with numerous particles. For WCCB blankets, Li TiO and Be Ti act as breeder and multiplier materials, respectively, whereas HCCB blankets employ Li SiO and Be. Numerous experimental [6–8] and numerical [9–12] studies have explored the thermohydraulic behavior of pebble beds. However, much of this research has focused on quasi-static conditions. The effects of neutron irradiation, high thermal loads, and strong magnetic fields [13] on pebble beds—which lead to pulverization and fragmentation—remain only partially understood. Breeder particle fragments and powders migrate to, deposit in, and accumulate within gas channels, driven by purging action. This accumulation diminishes the effective flow area of purge gas, increasing flow resistance and deteriorating gas flow distribution. These issues, including tritium retention and heat transfer degradation, seriously impair pebble bed thermodynamic properties and obstruct tritium self-sustainability [14,15]. Therefore, predicting and controlling particle powder migration and clogging are essential for reliable tritium extraction and energy conversion efficiency in fusion reactor ceramic pebble beds.

Some studies have focused on particle clogging in porous media. Liu et al. [16] investigated particle clogging mechanisms through microfluidic chip tests, classifying them as dependent (involving one or more adjacent pores) or independent (without adjacent channel involvement). During seepage tests with river sand-filled columns, Ye et al. [17] identified three types of particle clogging: surface interception, internal clogging, and adhesion. Research has often focused on the median particle size ratio of fillers to fine particles as a key clogging factor [18-20]. Tan et al. [21] developed an empirical formula based on the Kozeny–Carmen equation to theoretically predict permeability reduction in permeable bases. Sun et al. [22] reviewed research on graphite dust generation, distribution, radioactivity, deposition, resuspension, and coagulation in pebble-bed high-temperature reactors. Numerical simulation methods have been utilized to explore hydraulic behavior and water quality performance of pervious pavements. An advanced computational fluid dynamics model coupled with the discrete element method (CFD-DEM) was developed and validated to assess pervious concrete permeability [23–26]. The CFD-DEM coupled method was first proposed by Tsuji et al. [27] and has since been adopted in many packed bed investigations [28-33]. These results proved that CFD-DEM is a valid method for simulating and observing two-phase packed-bed systems.

However, few studies have addressed powder flow under purge gas in fusion blanket pebble beds. Numerous factors can affect powder flow characteristics, and more parameters must be studied to obtain thorough understanding. Existing models fall short and offer limited predictive insights into powder transport, clogging, and interstitial purge gas dynamics. Consequently, the influence of purge gas on particle migration and clogging within pebble beds remains poorly understood. Furthermore, a theoretical basis for understanding the transition from particle migration to clogging in porous media is lacking. Therefore, this study employed coupled CFD-DEM for numerical investigation of powder migration and clogging, considering factors such as breeder orientation, purge velocity, powder size distribution, and friction coefficient. The primary aim was to elucidate the mechanism of powder migration and clogging within fusion blanket pebble beds.

From these numerical findings, a preliminary model for migration and clogging was formulated. The results can aid in analyzing and predicting powder dynamics and pebble-bed reactor behavior. The remainder of this paper is organized as follows: Section II outlines numerical methodologies, covering governing equations, coupling procedures, validation, DEM pebble-bed model construction, and CFD reconstruction. Section III presents and discusses simulation results, including effects of breeder orientation, purge velocity, powder size distribution, and friction coefficient on migration and clogging, as well as mechanism characterization and numerical modeling of these processes.

2.1 Numerical Methodology in CFD-DEM Model

In the CFD-DEM model, flow throughout the domain is calculated using continuity and Navier–Stokes equations with a porosity term and additional body force term to account for particle presence in the fluid. These are given by [34,35]:

$$+ \quad + \quad =- \quad + \quad + - \rightarrow$$

where are the volume fraction of the gas phase (porosity), density, velocity, pressure, and viscosity, respectively; is the interphase force exerted by pebble beds on helium, with drag force being the primary consideration. For gas-particle interactions, the buoyancy-to-gravity ratio is on the order of 10^{3}, so buoyancy can usually be ignored. are apparent volume and total particle volume. The porosity and body force of fluid mesh elements are determined through DEM.

The equations of motion for particles include an additional force term to account for fluid interaction. The equations [36,37] are given as:

where are particle mass, velocity, and angular velocity, respectively; is the fluid-particle interaction force; are contact force and moment between particles; is the particle' s moment of inertia; and is the body force, including gravity and drag force.

The force during particle-fluid interaction can be characterized by a combination of drag, pressure gradient, viscous tensor gradient, and various other forces. In gas-particle systems, the predominant factor influencing fluid-pebble bed interaction is drag force, which significantly impacts coupled CFD-DEM model precision. Consequently, accurate representation of interphase forces experienced by particles and fluid is essential for CFD-DEM simulations. The interphase force, denoted as , can be mathematically described as [38]:

where is grid volume, represents the number of particles in pebble beds, is the projected area of the particle along helium flow direction, and is the drag force coefficient. In this study, the Gidaspow model [39] was used to describe the drag coefficient, which combines the Wen-Yu model [40] and Ergun equation [41]. The Gidaspow drag model has wide application and high calculation accuracy, especially for dense-phase gas–solid pebble beds. Cd takes the following form:

R $1 + 0.15$ 200 $1 -$, 0.8 , > 0.8

Two-way coupling between DEM and CFD is numerically achieved by solving Eqs. (1)–(3) using the CFD code and Eqs. (4)–(9) using the DEM code. DEM determines porosity and interaction force, which are then normalized by volume obtained from CFD. CFD calculates fluid velocity and pressure for each element and subsequently shares these data with DEM during each exchange. The computational time steps used for fluid and powders are 6.0×10 s and 6.0×10 s, respectively.

For the particle phase, Li et al. [42] suggested a critical time step based on Rayleigh wave propagation time along the smallest particle:

ΔDEM $<$

where is the DEM time step; are particle Young' s modulus and Poisson' s ratio. In general, the critical DEM time step is much smaller than that in CFD, so total stability is dominated by DEM simulation. In the present model, information exchange between DEM and CFD is performed at each CFD calculation step.

Figure 1 [Figure 1: see original paper] shows the coupling procedures adopted in CFD-DEM simulations. The detailed calculation procedure was as follows: First, DEM data including positions and velocities were transferred to the CFD solver; then, translation from Lagrangian to Eulerian field was performed by the CFD solver, and porosity and interphase force between fluid and particles were updated according to exchanged DEM data. Second, fluid velocity and pressure p were calculated using continuity and Navier–Stokes equations, modified by considering particle influence on fluid. Finally, drag force applied to particle bodies was calculated using all updated parameters, and the CFD working step was temporarily paused, awaiting DEM calculation and data exchange. The drag force obtained in CFD was transferred to DEM, and the resultant particle force was updated to calculate new particle position and velocity. CFD-DEM coupling was achieved using commercial software Fluent for CFD and EDEM for DEM [43].

2.2 Simulation Study Setup

Tritium breeder type and size significantly affect solid blanket performance (e.g., porosity) in fusion reactors. Most solid blanket designs use 1 mm diameter Li SiO particles as tritium breeders. A numerical Li SiO pebble bed sample was prepared using DEM code. Table 1 lists the physical properties of Li SiO particles and key simulation parameters [44]. Boundary conditions [45] and powder numbers are listed in Table 2 .

Following material parameter determination, pebble-bed particles were generated using EDEM software. Slight compaction by plates ensured close interactions between breeding particles. As shown in Fig. 2 [Figure 2: see original paper], the CFD-DEM model measured 12 mm in length, 12 mm in width, and 15 mm in height. The velocity inlet was set 5 mm above the pebble bed surface to simulate purge gas. A particle factory or broken particle source was incorporated within an 8 mm × 8 mm × 1 mm area at the top of the pebble beds. In the CFD-DEM model, powders attempt to percolate through a fixed, non-deformable pebble bed under purge gas influence.

Powder sizes produced by crushing Li SiO pebbles cannot be uniformly distributed, and powder flowability may change with particle size (dp) distribution. Table 3 lists powder gradations and properties obtained from previous experimental and numerical studies [46]. In this study, three powder distributions were identified: fine, coarse, and well-graded particles. The powder grading table shows mass percentages of various powder sizes. All powders were spherical, and simulation settings and boundary conditions were consistent with those used for breeding particles. In EDEM software, each particle size gradation is depicted in four colors representing different sizes. For example, fine powder sizes ranging from 0.08 mm to 0.16 mm are color-coded as green, yellow, pink, or red. Powders smaller than 0.08 mm were excluded from simulation due to their small size and extensive generation time required.

Table 4 outlines various cases and parameters: Cases 1–3 and 6 examined purge velocity; Cases 1, 4, and 5 focused on powder size distribution; Cases 1, 7, and 8 investigated friction coefficient; and Cases 1 and 9 compared two breeder orientations. This study considered two ITER-relevant volumes, as shown in Fig. 3 [Figure 3: see original paper]. These volumes differed in configuration according to gravity direction. Due to their similarity, we employed generic coordinate systems (,). The configuration represents the EU TBM orientation [47], whereas the configuration aligns with several current ITER TBM designs [48,49].

2.3.1 Pebble Bed Model Verification

Pebble bed specificity mainly depends on wall effect influence [30]. The classic Klerk model [50] was adopted to verify porosity distribution validity along the x-axis for pebble beds in this study. Local porosity is expressed as:

b + 0.29e − 2.53 + 1 0.637 cos 2.3 − 0.16 + 0.15e > 0.637

where represents dimensionless wall distance and is porosity at pebble bed center. Figure 4 [Figure 4: see original paper] shows porosity along the x-axis direction of DEM static pebble beds, calculated and compared using Eq. (11). Results demonstrate distinct oscillation characteristics of porosity within pebble beds near the wall, with oscillation amplitude decreasing along the radial direction and agreeing closely with experimental results. Therefore, the pebble-bed model obtained using DEM was considered valid for this study.

2.3.2 CFD-DEM Model Verification

The Ergun equation [51] has been extensively employed to predict pressure drop within pebble beds, describing the relationship between pressure drop and averaged velocity for flow in pebble beds as:

where is pressure drop from inlet to outlet; is pebble bed height; is inlet gas velocity; and (1 −) = 150 + 1.75 in.

To verify the CFD-DEM model constructed above, calculated results were compared with the Ergun equation, as presented in Fig. 5 [Figure 5: see original paper]. The comparison shows excellent agreement, indicating that the proposed CFD-DEM model can accurately capture particle and fluid flow behavior.

3.1 Powder Transport and Clogging Behavior in Pebble Beds

Figure 6 [Figure 6: see original paper] illustrates powder migration and clogging processes for varying particle size distributions within pebble beds. As shown in Fig. 6(a), for Case 1, surface-accumulated powders moved downward under purging gas drive, with their number gradually decreasing. Numerous particles accumulated in the upper pore structure after running for 2 s. However, powder distribution in the pore structure decreased rapidly with decreasing pebble bed height, showing a wide distribution range. Figure 6(b) shows that in Case 4, smaller surface-accumulated particles gradually migrated inward under purge gas drive, but their migration distance was significantly shorter than in Case 1, with most powder deposited in the upper pebble bed region and a smaller spread range. Figure 6(c) indicates that in Case 5, negligible vertical migration of surface-accumulated particles occurred due to purge gas, leading to significant accumulation in the upper pore structure.

Gerber et al. [52] observed that decreasing particle size ratio (dp/d) resulted in particle clogging closer to the filler surface. A smaller ratio accelerated surface deposition and increased accumulation. With a smaller particle size ratio, particles encounter similar-sized pores more frequently during transport, leading to earlier deposition and shallower clog depths. Continuous accumulation at these sites causes clogging at shallower depths. The small particle size ratio caused fine particles to clog only a thin layer of gravel pores near the pebble bed surface, hindering further permeation. The pebble-bed model features pores composed of larger pore bodies and smaller pore throats. Powders are captured in pores larger than or equal to their volume, irrespective of particle size. Clogging can be distinguished by the presence of larger powder particles, which divide clogged areas into Zones A and B, as shown in Fig. 6(a). Zone A contains large powder particles, whereas Zone B does not. The clogging mechanism of Zone A was: red or pink particles initially settled within the pebble bed, predominantly in a shallow 5 mm layer. After forming a pore skeleton in shallow pores, particles could not easily migrate again. This channel narrowing in the shallow layer facilitated rapid accumulation of smaller-sized deposits. The clogging mechanism of Zone B was: smaller powder particles, such as green particles, migrated and permeated inward through voids under sweeping gas and gravity, eventually forming local deposits alongside larger particles.

Based on two-dimensional images, Fig. 7 [Figure 7: see original paper] analyzes powder retention rate within pebble beds. Considering the pebble bed surface as the zero horizontal plane (H = 0), the distribution of accumulated powder retention rate above depth H is defined as:

where is powder content (g) in the part above depth H, and is initial total powder mass (g). Figure 7(a) shows accumulated retention rate distribution for different running times. Within 1 s, the vertical accumulation retention rate in the surface layer (1 mm to 5 mm) decreased, signifying gradual powder migration into the porous medium due to purging. Beyond 1 s, powder retention rate in the surface layer remained constant, indicating stabilization of powder deposition in this area. From 1–2 s, a noticeable retention rate difference occurred in the middle layer (6 mm to 12 mm), but beyond 2 s, only minor changes were observed in the lower layer (12 mm to 15 mm), with retention rate largely unchanged elsewhere. This indicates that powder deposition stabilized within pebble beds, with clogging development progressing from top to bottom. Initially, powder stabilized at the pebble bed top, followed by stable deposition in middle and bottom regions.

Figure 7(b) shows size grade effects. The disparity between well-graded and coarse powders was minimal, both exhibiting substantial surface layer deposition with retention rates rapidly reaching 100%. In contrast, fine powders demonstrated notable differences, characterized by deeper penetration. This minimal difference occurred because both well-graded and coarse powders contain particles larger than 0.16 mm. At equilibrium, these large particles clogged surface pores, hindering smaller particles in well-graded powders from penetrating the surface and limiting further retention rate increase. This result further confirms the two different clogging mechanisms mentioned: one involving powder with large particle size and one without.

3.2.1 Influence of Powder Size Grading

Figure 8 [Figure 8: see original paper] illustrates powder transport speed variation with size grading, representing the average speed of all powders. Results indicate a gradual decrease in powder transport speed over time, with powders ultimately becoming static in pebble beds. Fine powders took longer to settle than well-graded and coarse powders. Furthermore, powder transport speed increased with decreasing particle size because smaller powders are more easily mobilized by fluid forces. The average speed of fine powders was 80% higher than that of well-graded and coarse powders, highlighting the significant impact of large powders on powder flow velocity in pebble beds. Dynamic migration and static clogging results were similar: the presence or absence of large particle sizes significantly influenced the dynamic migration process.

3.2.2 Influence of Powder Friction Coefficient

Figure 9 [Figure 9: see original paper] shows the relationship between fine powder average vertical velocity and friction coefficient changes. Average vertical velocity and transport speed changes were similar. As friction coefficient increased, fine powder average vertical velocity decreased significantly. According to friction coefficient values ranging from low to high, average vertical speeds were 1.09 mm/s, 0.43 mm/s, and 0.32 mm/s for the three cases. For powders with varying friction coefficients, migration velocity followed a consistent pattern over time: it first decreased rapidly and then gradually approached a static state.

Influence of Purge Velocity
Figure 10 [Figure 10: see original paper] illustrates how powder vertical velocity changed with purge velocity, adjusted by controlling outlet velocity. Figure 10(a) shows that average vertical migration velocity tended to increase with increasing purge velocity. This effect is less pronounced than that of size grading or friction coefficient because purge velocity impact range is limited to 0.07 mm/s to 0.2 mm/s—a factor of 4 smaller in magnitude. Furthermore, Fig. 10(b) demonstrates that coarse powder migration was less affected by purge velocity

than fine powder. Despite higher purge velocities, mobilizing large particles that cause clogging remains challenging, indicating clogging stability. In summary, purge velocity impact on powder migration in pebble beds was limited, with this effect varying significantly across different particle size ratios.

3.3.1 Distribution Frequency of Clogging Powders in Pebble Beds

Powder clogging data from the final stability state were selected for analysis. Different colors, each corresponding to a unique powder size distribution, were extracted. Depth was segmented into 1 mm layers for statistical analysis. The ratio of clogging powder in each layer to total clogging powder was calculated. Figure 11 [Figure 11: see original paper] shows the dimensionless ratio N/N normalized by N , illustrating distribution of powders with specific size grading, where N is total clogging powder number and N represents clogging particles in each layer.

Powders of different sizes within the same layer were stacked. Figure 11(a) illustrates how fine powder distribution frequency changed across layers during clogging. Red powder with dp = 0.14 mm to 0.16 mm distributed within the 0 mm to 4 mm range. Pink powder (dp = 0.12 mm to 0.14 mm) exhibited peak frequencies in the 0 mm to 3 mm range, with most powders concentrated within 5 mm. The surface layer void structure was blocked by large particles, and green and yellow powders (dp = 0.08 mm to 0.12 mm) primarily distributed in the 0 mm to 5 mm range. However, green and yellow powders still penetrated the interior and even the bottom of pebble beds. Smaller particle size powder was more widely distributed.

As shown in Figs. 11(a), 11(b), and 11(c), coarse powder seldom invaded middle pebble-bed layers, whereas fine powder penetrated to the bottom. Fine powder distributed more evenly at depth because coarse powder prevents downward clogging. However, comparison between well-graded and coarse powders revealed no significant differences in concentration or invasion depth. Comparison between Figs. 11(a) and (d) shows that under varying purge velocities, larger powder particles (> 0.14 mm) primarily settled in the surface layer, whereas smaller particles (< 0.12 mm) distributed more evenly throughout middle and lower sections.

From frequency distribution superposition, with purge velocity of 0.1 m/s, clogging powder in the 0 mm to 3 mm region constituted 76% of total powder. At 0.2 m/s, clogging powder in the 0 mm to 3 mm area represented 81% of total powder, with pink powder (dp = 0.12 mm to 0.14 mm) present in middle pebble-bed regions. Results indicate that powder penetration depth and quantity into pores increased with purge velocity. Comparing Figs. 11(a) and (e) shows that as friction coefficient increased, peak distribution frequency of clogging powder also increased. In Case 1, 63% of powder clogged in the surface layer (0 mm to 2 mm), and in Case 7, this value increased to 69%. Larger particles predominantly clogged the surface layer, whereas smaller particles penetrated the bottom layer. This demonstrates that friction coefficient significantly affects powders with larger surface areas, with minimal effect on smaller powders.

3.3.2 Effect of Breeder Orientation on Powder Migration and Clogging

Figure 12 [Figure 12: see original paper] illustrates the impact of various breeder orientations on powder migration and clogging. Figure 12(b) reveals that in the configuration, powder near the upper wall (Y = −6 mm) moved downward away from the top wall, with significant deposits forming as powders from the middle rolled down to the lower wall area (Y = 6 mm). In contrast, pebble beds in the configuration exhibited distinct powder migration and sedimentation patterns. Figure 12(a) shows that powder near the wall settled in the same post-migration area, a trend observed in other pebble-bed regions. When breeder particles in pebble beds are crushed, they fall due to gravity and fluid force while maintaining their general direction. Comparing Figs. 11(f) and (a) shows that powder in the configuration predominantly settled in the 0 mm to 5 mm region in the upper part of pebble beds, with deposited powder quantity sharply decreasing with height.

Characterization and Developmental Stages of Migration and Clogging

Powder migration and clogging in pebble beds significantly impact the system, influenced by various factors. Complex powder behavior dynamics are observed, with different parameters affecting dynamic behavior differently. To characterize powder behavior including migration distance and velocity, we define this as migration efficiency. Based on prior analysis and with purge gas parameters in the fixed pebble bed established, the factors impacting migration efficiency, in descending order of significance, are: powder size distribution ( ), breeder orientation of pebble beds ( ), friction coefficient ( ), and average purge velocity ( ). Furthermore, parameters not studied in this paper, such as particle size and temperature, may also affect powder migration. These effects are uniformly classified as other factors ( ). Thus, migration efficiency was characterized as = , g , , , .

By analyzing average transport velocity at various times, we observed powder migration behavior within the 0.2 to 5.0 s range. Powder migration velocity in pebble beds between 0.2 and 5.0 s was normalized. Figure 13 Figure 13: see original paper illustrates that powder migration velocity can be categorized into three phases: rapid decay, linear decay, and stability. During the 0.2–5.0 s period, average powder velocity first decreased rapidly (rapid decay stage), followed by a linear decrease in rate of change (linear decay stage), culminating in stabilization. Stages 1, 2, and 3 were modeled using polynomial and linear analyses:

Stage 1:

Stage 2: $1 = 1 + 1 + 1$
Stage 3: $2 = d1x + e1$

In this paper, vn1 represents normalized migration velocity during Phase 1, vn2 during Phase 2, and vn3 during Phase 3. The parameters in Eqs. (16) and (17) vary according to boundary conditions. Taking Case 1 as an example, under conditions of purge velocity = 0.1 m/s, friction coefficient = 0.1, and fine-powder size distribution, the values of are respectively 1.1024, -2.2963, 1.3778, -0.0786, and 0.2935.

Following powder stabilization ($v \to 0$), we analyzed powder clogging trends at different pebble-bed locations. Figure 13(b) shows that the 0 mm to 4 mm depth was the predominant area for powder retention. Clogging can be classified into two categories: extensive superficial and uniform internal. Initially, retention rate in the 0 mm to 4 mm range increased quickly, indicating extensive surface deposition blockage. This was followed by gradual, consistent retention rate change, suggesting uniform internal deposition of fine-grained powder.

Types 1 and 2 were fitted with polynomial and logarithmic analyses, respectively:

Type 1:
Type 2:

The parameters in Eqs. (19) and (20) changed according to boundary conditions. For Case 1 with purge velocity = 0.1 m/s, friction coefficient = 0.1, and fine-powder size distribution, the values of are respectively -9.085, 66.267, -32.37, 0.5646, and 88.098.

4. Conclusion

This study employed a two-way coupled CFD-DEM calculation to analyze powder migration and clogging mechanisms within pebble beds. Governing equations, CFD-DEM model establishment, validation, and coupling process are detailed in this paper. Effects of breeder orientation, purge velocity, particle size grading, and friction coefficient on powder migration and clogging were assessed through numerical calculations. Powder migrated within pebble beds due to fluid force. With increasing purge velocity, fine powder penetrated deeper into pebble beds, while coarse powder showed less sensitivity to this effect. Increases in friction coefficient and powder size distribution led to increased powder accumulation in the top pebble-bed layer. Powder migration progressed from top to bottom, with upper-layer powder stabilizing first before developing downward. Two migration and clogging mechanisms were identified: one involving powder with large particle size and one without. The first mechanism is more common and develops rapidly.

Powder size distribution significantly influenced migration depth; coarser layers tended to block the surface, whereas finer particles reached lower pebble-bed regions. Breeder orientation significantly impacts migration clogging: in the - configuration, powder moves in the gravity direction, away from the upper wall, forming extensive deposits on the lower wall. Various parameters influence powder migration and clogging behavior differently. Excluding time, sensitivity ranks from highest to lowest as: powder size distribution ( ), breeder orientation of pebble beds ( ), friction coefficient ( ), and average purge velocity ( ). From this analysis, a formula is proposed to characterize powder behavior in pebble beds: = , g , , , .

Powder migration velocity development is categorized into three stages—rapid decay, linear decay, and stable—analyzed and fitted with normalization and formulas. Clogging in pebble beds is categorized into two types depending on distribution: extensive superficial clogging and uniform internal clogging, with the process modeled using formulas. The fitted curve was utilized to depict migration and clogging tendencies, culminating in a model depicting powder migration and clogging behaviors.

For simplicity, all powders were modeled as spheres, although real-world powder particles are irregularly shaped. Despite these simplifications, the findings offer valuable general conclusions, particularly because input parameters mirror those of actual pebble beds. Consequently, this study provides an effective reference for further research on powder dynamics and pebble bed properties in packed beds and offers ideas for fusion reactor blanket design.

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Figure Legends

Fig. 1 Scheme diagram of CFD-DEM coupling procedures.
Fig. 2 CFD-DEM model.
Fig. 3 Sketches of the two breeder orientations.
Fig. 4 Porosity distribution of particles along the x-axis.
Fig. 5 Comparison of the results of pressure drop in pebble beds.
Fig. 6 Migration and clogging process of powders of different grades in pebble beds.
Fig. 7 Distribution of accumulated powder retention rate.
Fig. 8 Transport speed of powders in different size grading.
Fig. 9 Vertical velocity of powders for different friction coefficients.
Fig. 10 Vertical velocity of powders for different purge velocities: (a) Fine powders, (b) coarse powders.
Fig. 11 Distribution frequency of clogging powders in pebble beds.
Fig. 12 Three-dimensional distribution of clogging powders with different breeder orientations.
Fig. 13 Normalized analysis of migration and clogging development.

Figures

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Tables

Table 1 Numerical parameters used in the simulation

Parameters	Value
DEM particle phase	
Particle diameter (ds/mm)	1
Particle number	12×12×15
Density (kg/m³)	
Young' s modulus (GPa)	
Poisson' s ratio	
Coefficient of friction	
Coefficient of restitution	
Domain size (mm³)	
CFD fluid phase	
Fluid density (kg/m³)	
Fluid viscosity (Pa·s)	1.99 e-5

Table 2 The boundary conditions

Boundary conditions	value
Velocity(m/s)	0.1, 0.2, 0.3
Outlet pressure (KPa)	
Powder number	
Powder size (dp/mm)	

Table 3 Particle size grading of powders

Size distributions	Fine powder (%)	Coarse powder (%)	Well-graded powder

Table 4 Cases of powders migration and clogging in pebble beds.

	Friction coefficient	Purge velocity(m/s)	Well-graded	Coarse	Coarse	Breeder orientations

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