Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

Effect of Hybrid-Overlap Contact Modeling on Porosity and Pressure Drop in Pebble Bed Reactor CFD Analysis

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Keywords : Pebble Bed Reactor, TRISO, KP-FHR, CFD, Point Contact Model, Near Miss Model

1. Introduction

The Pebble Bed Reactor (PBR) is a nuclear reactor concept in which a large number of spherical fuel elements are packed to form a porous core. It offers several advantages, including inherent passive safety, excellent thermal shielding capability, and the possibility of continuous on-line refueling, which make it a promising candidate for next-generation nuclear systems. These characteristics necessitate a precise understanding of the thermal–hydraulic behavior within the reactor core, and a broad range of experimental and computational investigations have been conducted to address this need.

Because PBR core is formed by packed spheres, its irregular flow distribution and the accompanying localized hot spots are not reliably captured by bulk correlations or by simplified analyses based on one-dimensional or porous-media assumptions. By contrast, experiments at high temperature with helium coolant are costly, difficult to instrument, and provide only limited access to local fields. Accordingly, high-fidelity computational fluid dynamics (CFD) is an appropriate and indispensable tool for resolving pebble or pore scale transport and for accurately characterizing PBR thermal hydraulics. In practice, many researchers now employ CFD to analyze detailed flow and heat-transfer behavior within PBR core.

Despite these efforts, CFD analysis of PBR core remains challenging due to their geometrical complexity, particularly the random or quasi-regular packing structure and the presence of pebble–pebble and pebble–wall contact points. In the vicinity of these contacts, the interstitial gaps tend to degenerate into slender or pinched regions, leading to frequent failures in mesh generation, excessive cell counts, or the creation of poor-quality cells characterized by low orthogonality and high skewness. Such issues often compromise numerical stability and reduce the reliability of global parameters such as pressure drop predictions.

To mitigate these difficulties, several idealization strategies for contact regions have been proposed in the literature. Representative approaches include the Gap (Near-miss) [1], Cap [2], Bridge [3,4], and Overlap [5] models, each with distinct advantages and limitations in terms of mesh generation efficiency, porosity preservation, and convergence characteristics.

In this study, we adopt a Hybrid-Overlap model. Starting from the conventional Overlap treatment, where neighboring pebbles interpenetrate by an overlap ratio, we additionally insert a slender cylindrical bridge with minimal axial height at every pebble–pebble and pebble-wall contact. The bridge diameter is designed to be nearly equal to the contact circle but slightly larger to accommodate the minimal axial height. It is chosen such that the added solid volume remains negligible, meaning the porosity is effectively unchanged within numerical tolerance, while the extremely acute dihedral wedges responsible for sliver/pinch elements are eliminated and grid robustness is improved.

This construction retains the principal advantage of the Overlap model: it does not blunt the inter-pebble passages and thus preserves the point-contact–like pore geometry. Conversely, a pure Bridge model increasingly distorts the pore space as the bridge diameter grows, complicating validation against canonical pressure drop correlations.

At the same time, the auxiliary bridge provides just enough geometric regularization to enable reliable polyhedral/boundary layer meshing at contacts without materially altering porosity or hydraulic aperture.

Using this Hybrid-Overlap geometry, we perform a parametric sensitivity analysis varying the overlap ratio to quantify its effect on porosity deviation and pressure drop, and to establish a meshing and geometry recipe replicable in a refractive-index-matched PIV test section for subsequent CFD–experiment comparison.

2. Methods

2.1 Geometry Condition

The pebble diameter (D_p) was fixed at 30 mm, and an Face Centered Cubic (FCC) 5×5 in-plane arrangement was adopted. In theory, among all pebble arrangements of equal spheres, FCC exhibits the highest packing fraction and thus the lowest porosity. This narrows the flow paths and typically produces the largest pressure drop. FCC is therefore the most conservative choice for thermal-hydraulic analysis. To ensure fully developed turbulence, nine pebble layers were stacked vertically. For the development and stability of the flow velocity at the inlet and outlet, a buffer area of about $4D_p$ was added before and after the pebble bed region.

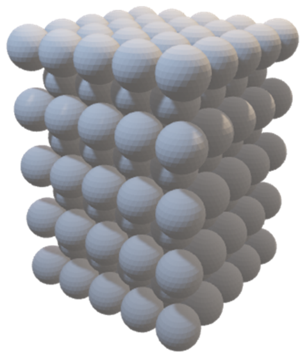

Fig. 1. Schematic of the FCC pebble packing (5×5 in-plane, nine layers)

For numerical robustness, pebble–pebble and pebble–wall contacts were treated with a Hybrid-Overlap scheme: in addition to the conventional overlap ratio (δ), a slender cylindrical bridge of radius (R_d) and axial height (h) was inserted along the line of centers at each contact. The bridge radius was chosen so that the axial height satisfies:

$$h = R_p(1-\delta) - \sqrt{R_p^2 - R_d^2} \qquad (1)$$

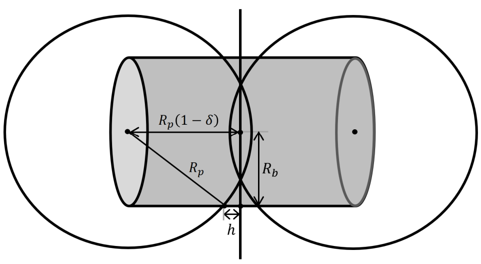

Fig. 2. Geometric Construction of the Cylindrical Bridge in the Hybrid-Overlap Model.

In this study, h values for all overlap ratios were set to 0.2 mm to optimize mesh generation while minimizing the influence and geometric deformation of porosity. At this time, in order to check the degree of pressure drop and the porosity change of the actual pebble bed according to the overlap ratio, a sensitivity analysis was performed within the range of 0.5% to 3% based on the pebble diameter.

2.2 Boundary and Flow Condition

The flow regime was characterized using the pebble-diameter–based Reynolds number (Re_p). Prior studies indicates that transition to turbulence in pebble beds typically occurs for $Re_p \geq 300$ (Hassan, 2008 [6]; Guardo et al., 2006 [5], and turbulent features have been observed even at $Re_p \approx 159$ and clearly at $Re_p \approx 1710$(Almathami et al., 2023 [7]). Turbulent behavior was also confirmed at $Re_p = 1600$ in KP-FHR [4], a PBR that uses molten salt rather than helium as a reactor coolant.

On this basis, Re_p=1600 was selected to lie safely within the turbulent regime across the cited criteria. In addition, for later PIV experiments, the physical properties of the refractive index matching solution were applied to the fluid of PBR. The specific boundary and flow conditions are as follows.

- $Re_p = 1600$
- $U = 0.3879\ m/s$
- $\rho = 1{,}064.4\ kg/m^3$
- $\mu = 7.743 \times 10^{-3}\ kg/m^3$

2.3 Meshing and Numerical Techniques

The mesh was made based on polyhedron. The turbulence model for analysis used the k-ω SST model. For accurate turbulence model simulation, five boundary (prism) layers were created on all solid surfaces, and the thickness of the first layer was set to be $y^+ \approx 1$ and $y^+ \leq 5$ across the domain. For the sensitivity analysis, the final grids contained approximately 5×10^6 to 6×10^6 cells, depending on the overlap ratio. CFD analysis was performed using Fluent Solver (2025R1).

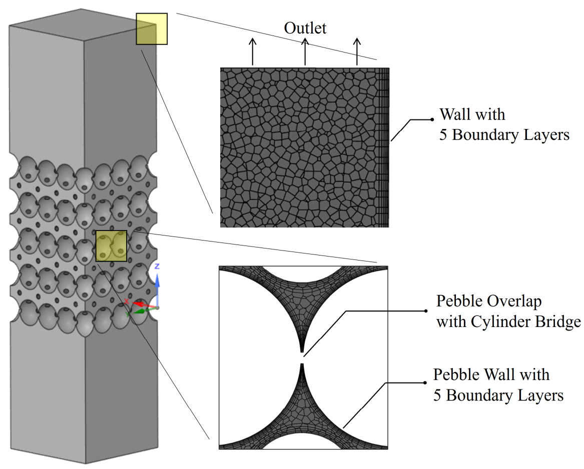

Fig. 3. Computational domain and local mesh details (wall and pebble–contact regions).

3. Results and Discussion

3.1 Porosity

As shown in Fig. 4, the porosity decreases approximately linearly with increasing overlap ratio and is highly sensitive even to small overlaps (≤1%). Given the ideal FCC porosity (ε) of 0.2595, porosity decreases rapidly with modest increases in overlap ratio. Therefore, maintaining the overlap ratio as small as possible is recommended to preserve the ideal porous characteristics of the pebble bed.

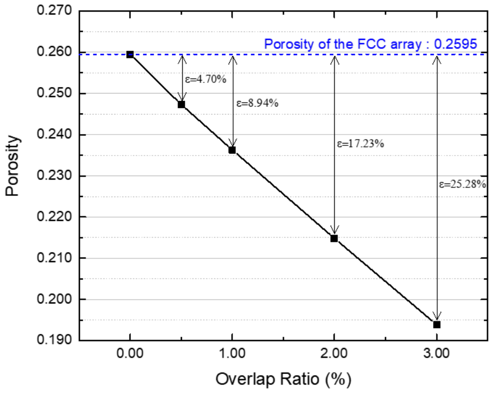

Fig. 4. Variation of Porosity with Overlap Ratio.

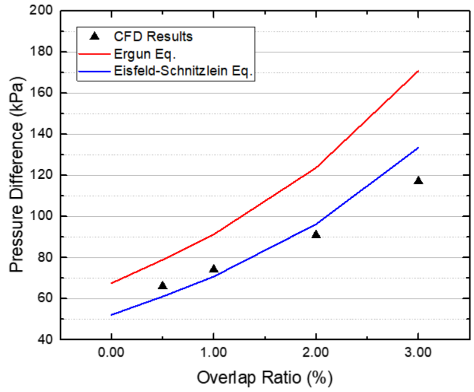

Fig. 5. Variation of Pressure Difference with Overlap Ratio.

3.2 Pressure Drop

To assess the predictive fidelity of the CFD model, the pressure drop across the pebble bed was benchmarked against canonical packed-bed correlations, namely the Ergun equation :

$$\frac{\Delta P}{L} = \frac{150(1-\varepsilon)^2 \mu U}{\varepsilon^3 D_p^2} + \frac{1.75(1-\varepsilon)\rho U^2}{\varepsilon^3 D_p} \qquad (2)$$

and the Eisfeld-Schnitzlein correlation [8]:

$$\Delta P = \left(154 \cdot A_w^2 \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{1}{Re_p} + \frac{A_w}{B_w} \cdot \frac{(1-\varepsilon)}{\varepsilon^3}\right) \cdot \frac{L}{D_p} \cdot \rho \cdot U^2 \quad (3)$$

with the coefficients A_w and B_w

$$A_w = 1 + \frac{2}{3 \cdot \frac{D_v}{D_p}} \cdot (1-\varepsilon) \qquad (4)$$

$$B_w = \left[1.15 \cdot \left(\frac{D_p}{D_v}\right)^2 + 0.87\right]^2 \qquad (5)$$

Although the Ergun equation is widely used in nuclear thermal-hydraulics, it is known to overpredict the pressure drop for randomly packed or structured beds of smooth spheres once the Reynolds number exceeds approximately $Re_p \approx 700$ [9]. By contrast, the Eisfeld-Schnitzlein correlation explicitly accounts for wall effects through coefficients formulated as functions of Re_p and the vessel-to-pebble diameter ratio D_v/D_p, and it has been reported to reproduce pebble bed pressure drop more accurately than Ergun equation.

As shown in Fig. 5, the present CFD predictions showed closer agreement with the Eisfeld–Schnitzlein correlation, whereas deviations from the Ergun equation were systematically larger across the conditions considered.

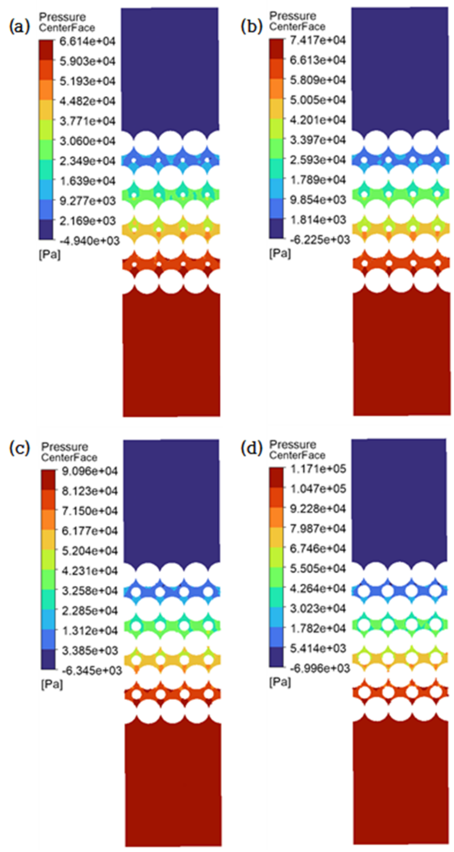

Fig. 6. Distribution of the Pressure Drop of the Pebble Bed according to the Overlap Ratio. (a) 0.5% (b) 1.0% (c) 2.0% (d) 3.0%

3.3 Flow Field

The Hybrid-Overlap model, being based on the overlap treatment, preserves the native inter-pebble flow passages with minimal geometric distortion. Accordingly, it is well suited for investigating the in-bed flow behavior of pebble bed cores. According to the CFD results, the flow was accelerated in a narrow flow path between adjacent pebbles to form a local maximum velocity, and a distinct vortex area was formed in the cavity among the flow paths.

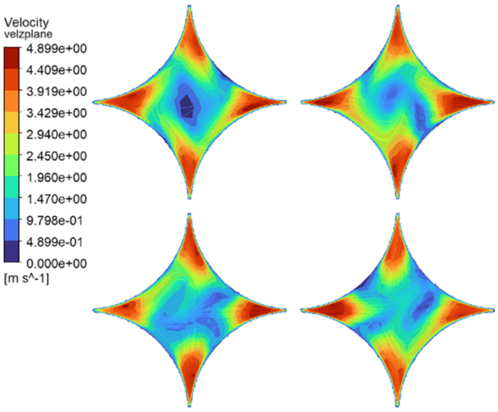

Fig. 7. Cross-sectional Velocity Field (z-plane) between Pebbles (Overlap Ratio 0.5%)

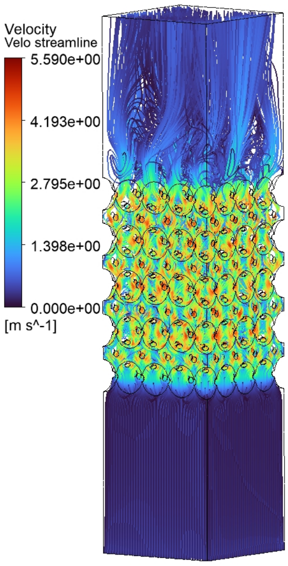

Fig. 8. Velocity Streamlines in the Full Computational Domain (Overlap Ratio 0.5%)

4. Conclusions

This study assesses contact overlap in an FCC 5×5, nine pebble layers and finds an almost linear—and highly sensitive—decrease in porosity with increasing overlap, which in turn produces a substantial increase in pressure drop relative to the ideal point-contact case. The computed pressure losses exhibit closer agreement with the Eisfeld–Schnitzlein correlation than with the Ergun equation. To numerically approximate point contact, an overlap ratio of $\leq$ 0.5% is recommended. Future work will employ refractive-index-matched PIV experiments to measure bed pressure drop and local flow fields for quantitative comparison and calibration of the CFD predictions.

ACKNOWLEDGEMENT

This work is financially supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Ministry of Trade, Industry and Energy (MOTIE) of Republic of Korea (No. RS-2024-00398867)

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