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A review of recent study on the characteristics and applications of pebble flows in nuclear engineering

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Abstract

This paper reviews the recent three-year progress on the investigations of pebble bed flows in nuclear engineering. Both the application of pebble beds in the fission reactors and the fusion reactors are included. The fundamental characteristics of packing, flows, conduction, convection, radiation, and the effective thermal conductivity of pebble beds are reviewed. The important issues on the design of the pebble beds as well as that related to the reactor safety are also introduced. In addition, the advances in measurement techniques and numerical coupled methods for exploring the pebble flow characteristics are categorized and summarized too.

Keywords

pebble bed
pebble flow
high-temperature gas-cooled reactor (HTGR)
fluoride-salt-cooled
high-temperature reactor
lithium ceramic pebble bed
effective thermal conductivity

Article History

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Review Article

1 General introduction

Pebble bed has been widely used in nuclear engineering, such as the pebble bed reactor core used in the high-temperature gas-cooled reactor (HTGR), the pebble bed fluoride-salt-cooled high-temperature reactor (Shi et al., 2021), the thorium molten salt reactors, and the lithium ceramic pebble bed used for solid blankets in fusion reactors. In the HTGR, the reactor core is composed of a pebble bed with a helium coolant flow through it to remove heat and many recirculating fuel pebbles which are reloaded into the pebble bed from the top once they are drained from the bottom. The solid type breeding blanket contains breeder materials to produce tritium, which is transferred to the fuel cycle system by a helium purge gas and is used as a fuel for nuclear fusion reactions. Therefore, the pebble bed is of paramount importance in these kinds of nuclear facilities.

Herein the recent research on the pebble bed is reviewed. Some key issues are of common interest among these applications. For example, effective thermal conductivity is one of the vitally important factors for the HTGR because it determines directly the capability of the reactor to maintain its safety. Also, it is a key thermal property for the lithium ceramic pebble bed which has a significant impact on the design and analysis of the fusion blanket. Herein, the most important issues are generally divided into four parts, the methods and techniques, the fundamental issues, the design-related issues, and the safety-related issues, which are reviewed separately in the following sections.

2 Methods and techniques

2.1 Experimental techniques

In the experimental measurement techniques, a digital

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image processing (DIP) method was proposed to capture the particle motions (Wang et al., 2020b). The DIP method uses mathematical morphology and threshold segmentation to extract the particle position and binarize the particle image. The centroids and velocities of particles at a given time interval can be obtained by the DIP algorithm with an accuracy of recognition larger than 90%. A pilot experimental study was conducted to get quantitative data generated by particle-tracking-velocimetry (PTV) to show its capability in predicting residence time distribution, which was used to confirm the accuracy of neural network predictions (Liu et al., 2022b). The long-term tracking of multiple particles using PTV will eventually lead to lower accuracy with increasing time. Therefore, a full-field high-accuracy PTV algorithm for pebble flow measurement was developed by improving the matching algorithms for pebble flow (Liu et al., 2021) (Fig. 1). Two kinds of errors in the experimental data—unidentified centroids and misidentified centroids, and two amending methods were developed. The original PTV algorithm for pebble flow reached an average accuracy of 90% under 5 different flow rates. After adopting the three-point co-circular amending method, the accuracy is increased to 98%. Finally, this value exceeds 99% when the polygonal amending method is applied. The adaptability and stability of the algorithm have also been tested.

To show if hot spots possibly appear, Zhang et al. (2021) presented an on-line temperature measurement of HTR

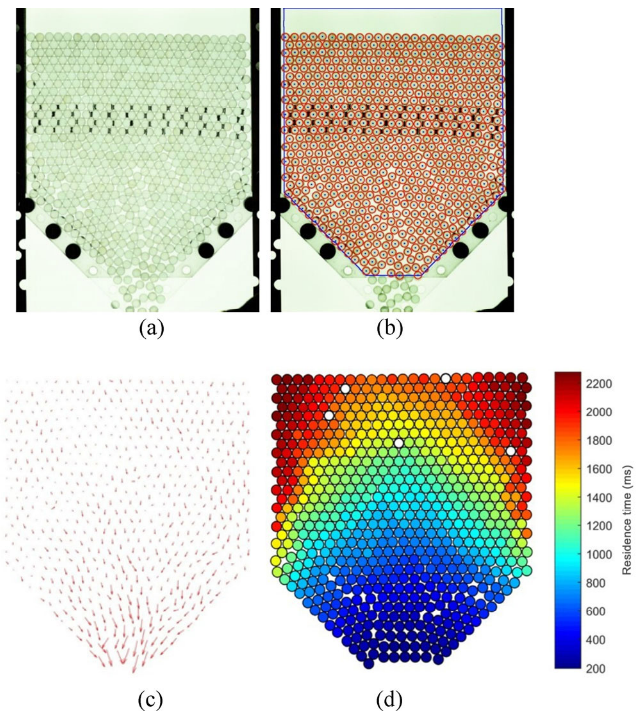

Fig. 1 Resident time distribution (RTD) of pebbles in PTV: (a) original image, (b) recognized image, (c) velocity fields, (d) RTD distribution.

core temperature. The temperature monitors, with built-in metal fuse wires and the same shape as normal graphite pebbles, were employed to participate in the circulation of pebbles in the core. The core temperature was measured and recorded when the monitors flow through the hot spots. Based on the proposed core temperature measurement technique, the temperature and distribution in the HTR-10 core were measured effectively and the technique was verified by practical application

2.2 Numerical methods

IBM: Wongkham et al. (2020) developed a fluid–solid coupling strategy, p-IBM, which combines the porosity-based mesh adaption and the immersed boundary method (IBM) to model the helium cooled pebble bed (HCPB) system. A small pebble bed consisting of 158 particles was simulated and agreed with the traditional particle-resolved simulation using body-fitted grids. The p-IBM method was also applied to simulate a larger pebble bed containing 3190 particles.

LB–IB–DEM: For numerical methods dealing with interactions in two-phase flow, a lattice Boltzmann (LB) method–immersed boundary (IB) method–discrete element method (DEM) coupled approach is utilized to study the gas–pebble flow characteristics under the recirculation mode of operation. The coupled model was validated by sedimentation of a sphere, and the flow fields (Fig. 2) and characteristics of recirculating gas–pebble flows were explored (Gui et al., 2019).

CFD–DEM: This framework was employed for pebble bed simulation considering the heat transfer behavior (Sharma et al., 2020). It captured the detailed and localized flow behavior in the presence of pebble aided by the porous medium approach to predict the average flow characteristics. The pebble–pebble, pebble–wall, and pebble–fluid momentum exchanges, as well as the characteristic fluid flow structures, are investigated by utilizing the coupled computational fluid dynamics–discrete element method (Mardus-Hall et al.,

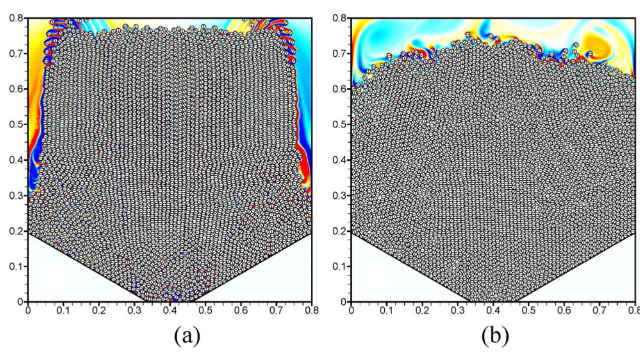

Fig. 2 Pebbles' motion with helium in a pebble bed: (a) t = 2 s, (b) t = 4 s (Gui et al., 2019; reproduced with permission © Elsevier Ltd. 2018).

2020) (Fig. 3). The geometry is the pebble recirculation experiment (PREX) conducted at the University of California, Berkeley (UCB) to simulate a pebble-bed fluoride high-temperature reactor's (PB-FHR) core. Also, Lee et al. (2020) also implemented CFD–DEM to simulate the purge gas flow through binary-sized pebble beds. The pebble geometries are modified by smoothing the sharp circular edges at the contact points of pebbles to construct proper meshes for CFD simulations. Similar work on this kind of method can also be seen in the dense dispersed phase model–discrete element method (Sedani et al., 2021).

OpenFOAM and ANSYS software: The OpenMC/OpenFOAM code was used for a neutronic analysis of a very high-temperature gas-cooled reactor (VHTR) (Wang et al., 2022a). The OpenMC code is used to generate few-group cross-sections, and the OpenFOAM code is used to perform core neutron diffusion kinetics analyses. In Kumar et al.'s (2021) work, considering the radiation effect, the effects of different heat generation rates, mass flow rates, and packing arrangements on the flow-field and temperature profile were explored by OpenFOAM. In the numerical model, the local thermal non-equilibrium (LTNE) was assumed to exist between the pebbles and the purging gas, and a local porosity distribution was considered. The BCC and FCC packing arrangements have better purging behavior than random packing. Gámez Rodríguez et al. (2021) evaluated the thermohydraulic behavior of the steady-state of the HTR-10 gas-cooled pebble-bed high-temperature test reactor using real-scale three-dimensional computational thermohydraulic modeling. The ANSYS CFX's full porous media approach was used to model the pebble-bed reactor core. A variable porosity model was implemented in the pebble bed simulation to consider the closeness of the walls. The k–ε turbulence model was also applied for convective heat transfer with helium coolant in the reactor core zone (Avramenko et al., 2021).

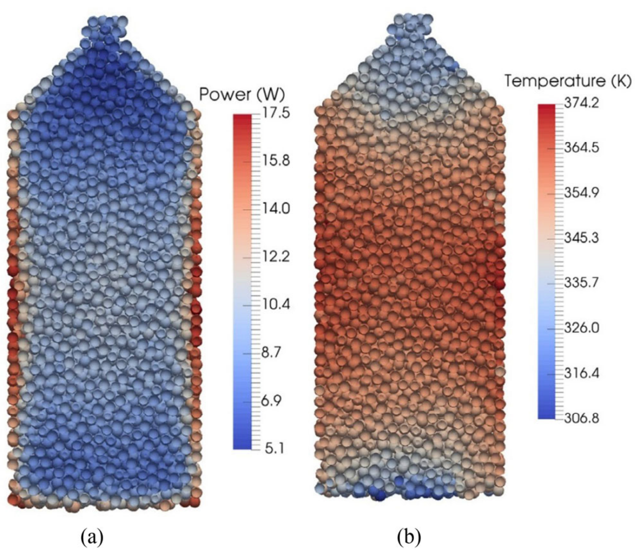

Fig. 3 (a) Realistic power distribution and (b) resultant steady state pebble temperatures (Mardus-Hall et al., 2020; reproduced with permission © Elsevier Ltd. 2019).

Combination methods: A high-fidelity whole-core model of the annular core pebble-bed HTR was studied by a two-step whole-core modeling (TSWCM) scheme with flexibility (Yang et al., 2022). This TSWCM scheme was based on the Monte Carlo method, and verified by the HTR-10 experiment results (Fig. 4). Based on the simulation, the effect of the central graphite column dimension and the pebble size upon the nuclear heating power density distribution in annular core pebble-bed HTR were investigated. Moreover, the neutronics, thermal-hydraulics, and multi-physics benchmark models were developed (Fig. 5) for a generic pebble-bed fluoride-salt-cooled high-temperature reactor using the Kairos Power, which is an extensive toolbox that includes commercial and inhouse-codes (Satvat et al., 2021). This toolbox coupled the Monte Carlo codes, porous

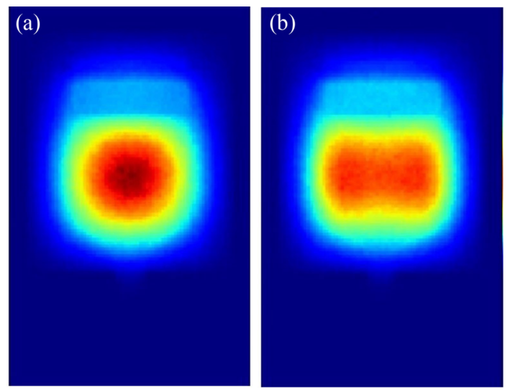

Fig. 4 Contour plots of the neutron flux in the annular core at (a) 0% and (b) 100% of the inner-core graphite pebbles (Yang et al., 2022; reproduced with permission © John Wiley & Sons Ltd. 2022).

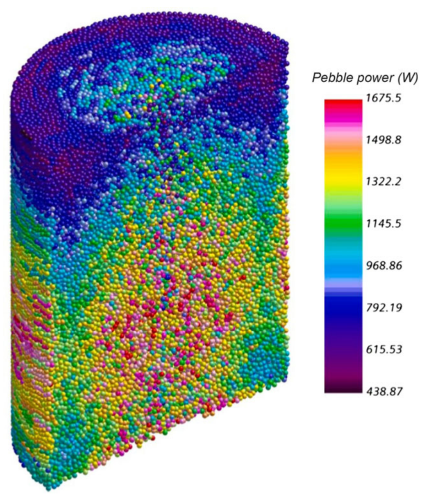

Fig. 5 Pebble power distribution in the reactor core at the equilibrium state (Satvat et al., 2021; reproduced with permission © Elsevier B.V. 2021).

media models, discrete element modeling, nodal diffusion, and tailored wrappers.

Other methods: A multiscale model as a simulation tool was applied in the Pronghorn pebble bed reactor to carry out a steady-state analysis of the Mark-1 pebble bed fluoride-salt-cooled high-temperature reactor (PB-FHR) (Novak et al., 2021). Material-wise pebble temperatures were predicted to be within 10 °C over a wide range in thermal conditions. For computing the radiative heat transfer, the multiscale model includes an explicit pebble-temperature model nested in the porous-media model for the pebble-bed reactor (Zou et al., 2022). The multiscale solid-phase energy balance model includes the pebble surface energy balance equation and explicit modeling of pebble temperature to predict the temperature distributions. The multiscale model was solved in a fully coupled manner using the Newton–Krylov method (Zou et al., 2022).

Accelerating-running-speed technique: Wu et al. (2022a) and Zou et al. (2021) utilized the deep residual neural network for view factor prediction, where the swish activation function avoids vanishing gradients and model degradation problems during training. It had proven to be 7.3×10^5 times faster than the traditional numerical method in view-factor calculations. This makes it feasible to explore the local and macroscopic thermal radiation behaviors in large-scale pebble beds filled with up to 1.0×10^7 spheres.

3 Fundamental issues

3.1 Pebble flow characteristics

Voidage and packing fraction: Concerning the characteristics of packed pebbles, the packing fraction of the pebble bed is affected by the pebble bed dimension, the friction coefficient (Feng et al., 2021a; Wu et al., 2022c), the coefficient of restitution (Wang et al., 2021b), the pebble size distribution, and the wall effects. As the width of the pebble bed increases, the average packing fraction of the pebble bed gradually increases. A lower friction coefficient between pebbles and a wider pebble size distribution result in a higher packing fraction (Feng et al., 2021a). The near-wall volume fraction gradually decreases. As the friction coefficient increases, the packing structure becomes looser and the average packing factor goes lower. Qi et al. (2020) also characterized the effect of the restitution coefficient on the flow of the pebbles in terms of the motion trajectory, the packing peaks, the apex angles, the velocity deviations, the residence time, and the residence ratios. A larger friction coefficient makes the pebble bed structure need more cycles to achieve a stable state (Wu et al., 2022c). Moreover, the coefficients of friction and restitution impose opposite effects on the packing heights and the global packing factor of a polydisperse pebble bed (Wang et al., 2021b). The effects of the fixed wall and the pebble size ratio on the evolution of the distributions of packing fraction and porosity, the radial distribution function, and the contact force were also analyzed by Feng et al. (2021b). The fixed wall results in a reduction of the average packing fraction and an obvious wall effect in the local porosity distribution. The pebble size ratios have a great influence on the radial distribution function and the contact force in binary-sized pebble beds at the maximum packing efficiency state. In a particular "J"-type pebble bed, both the radial and axial local packing factors exhibited oscillation behavior but a clear difference was observed in the cylindrical part and the torus part. Besides the effect of the pebble diameter on the global packing factor, the distributions of the contact force and the force chain, and the coordination number distribution were also important for pebble bed (Wang et al., 2021a). In addition, constant frequency vibrations of binary-sized pebbles were imposed by Kim et al. (2021) to enhance the connectivity of pebbles. The final packing fractions were analyzed focusing on the influences of the size, the volume ratios, and the vibration frequency and direction. In general, the pebble-size difference makes the packing fraction higher. The vibration frequency has no significant effect on the packing fractions but causes segregation of the binary-sized pebble beds. The vertical vibration reduces the segregation more effectively than the horizontal vibrations. In contrast, the packing of mono-sized pebbles is extremely sensitive to vibration frequency.

Voidages or porosities: Bester et al. (2021) dealt with the evaluation of the distribution of the porosity of a model of the HTR-10 packed bed reactor using semi-analytical methodologies. They suggested using the Hertz–Mindlin model for the contact force between the spheres and > 0.1 GPa for Young's modulus of the spheres. The overall porosity was found to be 0.382, whilst the average porosities of the pipe, conical and cylindrical sections were found to be 0.439, 0.378, and 0.381 respectively. Moreover, a fast region homogenization method based on an experimental silo discharging process was proposed to quickly calculate the homogenized voidage of particles in any local region. The Hough transform was applied to the image to obtain the centroid and radius (Liu et al., 2022a). The hash set is constructed in advance to quickly calculate the regional homogenization parameters. Compared with the traditional methods, the calculation speed is greatly accelerated on the premise of ensuring the calculation accuracy.

Flow pattern: Pebble flow characteristics can be significantly affected by the configuration of the pebble bed. How to achieve a desired uniform flow pattern without stagnation is the top priority for reactor design. Wu et al. (2019b) explored the effect of density difference on the spatial distribution and flow characteristics of particles

(Fig. 6). By premixed and discharged at fixed number rates, although the difference in density affects the local equivalent density, it influences little on the uniformity and compactness of the whole bed with an overall average voidage of about 0.39. Overall, the heavy particles push the light particles toward the wall side during the circulating process. The basic features of three-dimensional pebble flow in HTR-PM were simulated to explore the effects of the base angles, friction coefficients, and recirculation modes on the characteristics of pebble flows (Gui et al., 2020). By pebble stripes, the three-dimensional pebble spindles and pebble streamlines were quantified to show the pebble diffusion in the pebble spindle. The effect of the super-ellipsoid particle on the particle flow behavior in the HTR-10 reactor core was shown to have a more stable packing structure, and the particles with an aspect ratio between 1.5 and 2 show better discharge behavior than spherical pebbles (Cui et al., 2021a). The wet cohesive particles discharged in a three-dimensional packed bed were described by the liquid bridge model in terms of the Bond number *Bo* and the liquid content (Cui et al., 2021b). The discharge efficiency decreases with the increase of particle viscosity, but its influence would be neglected when $Bo \leq 0.1$ or $W \leq 6\%$. Additionally, the residence time distribution (RTD) is a key indicator to assess the inherent safety of pebble bed reactors. The RTD isolines in different regions were discovered by experimental measurement and the feasibility of applying neural network methods to RTD prediction was demonstrated (Liu et al., 2022b).

3.2 Gas–pebble interactions and heat transfer

Gas–pebble interactions (friction factors and pressure drop): On the hydro-dynamic issue, the Ergun correlation was always compared (Fig. 7) to experimental measurement to show if the friction factors of the pebble by helium flow can be well predicted for the rectangular pebble bed channel randomly filled with spherical particles with SC-1, BCC-1, and FCC-1 arrangements of the packed bed reactors (Wu et al., 2019d). While helium purge gas flows through pebble beds, the flow characteristics of purge gas depend on the configuration of pebble beds (Choi et al., 2019). Various pebble bed models composed of discrete uniform distribution and normal distribution of pebble sizes were studied. In the laminar flow of helium purge gas through pebble beds, the pressure drop increases in proportion to the packing fraction and inverse proportion to the difference in pebble size. A smaller difference in the pebble size leads to a higher pressure drop due to a larger surface effect at the same volume of pebbles. The Ergun equation and the Kozeny–Carman equation were also used for model validation. Moreover, in Panchal et al.'s (2020a) experiments, the gas pressure drop across packed pebble beds was experimentally measured as a function of pebble sizes, shapes, materials, and gas velocity. Stainless steel spheres and alumina pebbles, and lithium meta-titanate pebbles were used. The static differential pressure across the pebble beds has been monitored by a differential pressure transducer. The pressure drop significantly increases with the decrease in the diameter of pebbles and the increase in the packing fraction of the bed. The material type does not affect the results. Their experimental results show that Ergun's correlation predicts the gas pressure drop well. In Ahmed et al.'s (2021) work, a pebble bed reactor with a modular model with a realistic approach and finite volume method (FVM) instead of porous media was used to predict the distribution of the critical thermal-hydraulics parameters like temperature, pressure, velocity, and heat transfer coefficient (HTC) over the pebbles as well as the reactor core. In the simulation, the boundary conditions such as coolant inlet and outlet temperatures, mass flow, and other thermal-hydraulics parameters, were validated by the IAEA benchmark document. The design safety limits like maximum fuel temperature and coolant flows distribution were demonstrated.

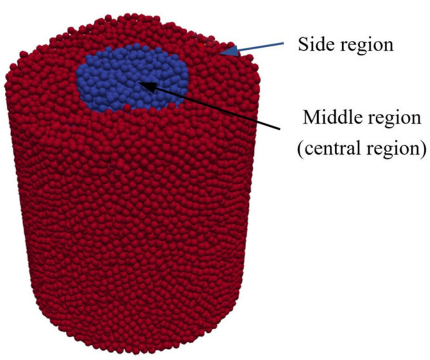

Fig. 6 Configuration of the two-region arrangement (Wu et al., 2019a; reproduced with permission © Elsevier Ltd. 2019).

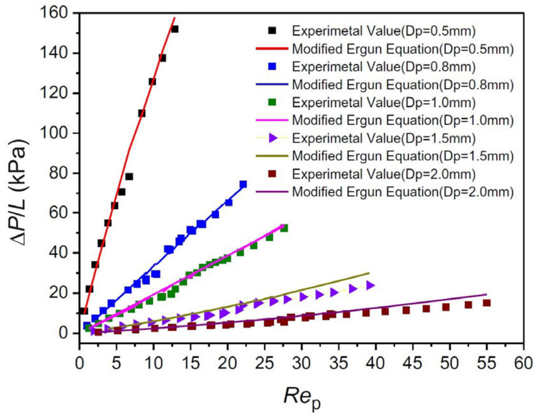

Fig. 7 Comparison of experimental values and the Ergun correlation predictions (Wu et al., 2019d; reproduced with permission © Elsevier Ltd. 2019).

Heat transfers (conduction, convection, and hot spots): For computing the effective thermal conductivity of pebble beds by using the 3D DEM–CFD one-way coupling method considering contact conduction, the contact conduction needs to be taken into account when the solid-to-fluid conductivity ratio $k_s/k_f > 20$ (Fig. 8) (Wang et al., 2019). Wang et al. (2022b) designed a pebble-bed experimental facility to study the convective heat transfer characteristics of molten salt in the pebble bed channels on the heat-transfer-salt (HTS) loop. A new correlation was proposed for predicting the convective heat transfer coefficients of molten salt. The results will provide an important reference for the core design of a thorium-based molten salt reactor. Chen and Lee (2020b) measured experimentally the locations of the hotspots in a face-centered-cubic-structured pebble bed for improving the heat-transfer performance of a pebble bed. A small sphere was placed in the gap of the bed to observe the flow and thermal fields around it and investigate the effect of sphere diameter on the heat-transfer characteristics. They found that the inserted sphere reduces the local surface temperature of adjacent pebbles and increases the local heat transfer coefficient (HTC). Moreover, the average HTC increases with the diameter of the inserted sphere, as well as the Reynolds number. The HTC increases by 28.8% at D = 0.05 m, and average HTC has a relation to the Reynolds number by $h = 0.045Re^{0.8}$. A new correlation was proposed $Nu = 0.238Re^{0.8}Pr^{0.4}$, which seems to be better than the KTA correlation. Furthermore, later work on convective heat transfer coefficient in FCC beds packed with pebbles of 3 different diameters (10 cm, 12 cm, and 14 cm) was performed (Chen and Lee, 2020a). The impact of pebble diameter on the heat transfer coefficient was shown: reducing the pebble diameter improves the heat transfer performance. The case of 10 cm in diameter shows an enhancement ratio of 10.4% more than the case of 12 cm pebbles. A correlation of the Nusselt number was given as $Nu = 0.1941Re^{0.8}Pr^{0.4} - 0.3226(L/D - 1.027)^2 Re^{0.8}Pr^{0.4}$. Liu et al. (2020) set up a randomly packed pebble bed test facility to study the flow and convective heat transfer in a water-cooled pebble-bed type nuclear reactor core. The correlations given by Wakao et al. (1979) and KTA agree well with the experimental convective heat transfer coefficients in the high-velocity and low-velocity conditions respectively. A new correlation was presented based on the trend similarity between the Colburn J factor and friction factor, to predict the pebble bed convective heat transfer characteristics, with a discrepancy of no more than 10%.

Radiation: Concerning radiative heat transfer in pebble beds, some key parameters are of paramount importance in nuclear engineering, such as the effective thermal conductivity (k), effective thermal diffusivity (α), and effective specific heat (c_p) of a packed pebble bed (Patel et al., 2021). In this regard, a full-radius-scale heat test facility was developed to measure effective thermal conductivity (k) and effective thermal diffusivity (α) by the inverse method at high temperatures (Wu et al., 2019c). The experimental tests were performed in either vacuum and helium gas up to 1200 °C. Sensitivity and uncertainty analyses were also carried out in respective tests to give reasonable results. Wang et al. (2020a) designed an experimental platform including a test section and a helium loop to measure the effective thermal conductivity (Fig. 9). The hot wire method and the helium loop were designed to satisfy different experimental conditions. The pebble bed experiments of Li_2TiO_3 and Li_4SiO_4 were performed in the stagnant helium at atmospheric pressure, and the binary glass pebble-bed experiments with different diameter ratios were performed at room temperature in the stagnant helium and air. The effective thermal conductivity was found strongly dependent on the packing factor. Also, the effective thermal conductivity of Li_2TiO_3 pebble beds was measured by the transient hot-wire technique (Panchal et al., 2020b). The experiments was performed on 1±0.15 mm diameter Li_2TiO_3 pebble bed with a packing fraction of 63%. A reduction in effective thermal conductivity was found with a decrease in helium gas pressure while it is few in air

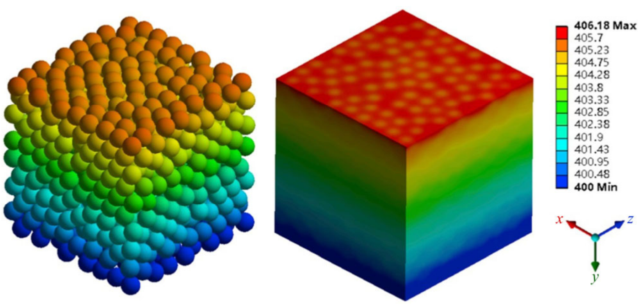

Fig. 8 CFD simulation in the steady-state thermal module (Li_2TiO_3/helium pebble bed) (Wang et al., 2019; reproduced with permission © Elsevier B.V. 2019).

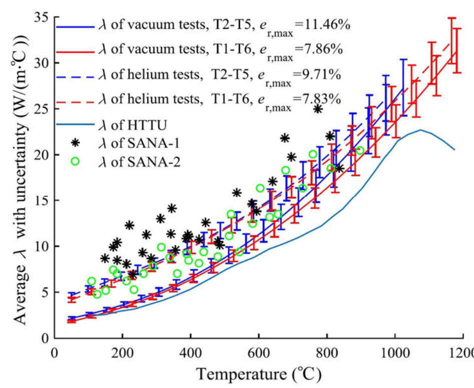

Fig. 9 Average effective thermal conductivities with the expanded uncertainty at a 95% level of confidence (Wu et al., 2019c; reproduced with permission © Elsevier Ltd. 2019).

pressure. Under vibration conditions (Kim et al., 2021), the effective thermal conductivity of binary-sized pebble beds decreases as the pebble size difference decreases and the vibration frequency increases. For mono-sized pebble beds, the effective thermal conductivity can be extremely high or low depending on the vibration.

Wu et al. (2022a) discussed the packing-property linkage for radiative heat transfer in the large-scale particle bed by using a large obstructed view factor dataset of thermal radiation. They used the optimized ray-tracing method (ORTM) with a Sobol quasi-random sequence to calculate the obstructed view factor between spheres by parallel CUDA computing for training a deep learning regression model. Moreover, radiative heat flux and effective thermal conductivity were obtained mathematically by a matrix model (Wu et al., 2020a) to present the thermal radiation between particles in pebble beds. For a structured packing, the transient radiative heat transfer is proven to be similar to thermal diffusion. A correlation to predict the radiation exchange factor under different porosity was proposed (Wu et al., 2020b, 2020c). For random pebble beds, a regression model of the multi-layer neural network was trained from large datasets to compute the view factor matrix efficiently. It provides a possible way to perform real-time simulations of full-range radiations inside large-scale pebble beds. Bu et al. (2020) used a numerical method combining conduction and radiation to study the stagnant effective thermal conductivity of a simple cubic packed bed with high solid to fluid thermal conductivity ratios. In their results, the effective thermal conductivity declines first until 690 K. The ZBS correlation with a proper empirical parameter φ predicts the stagnant effective thermal conductivity in the bulk region well. The solid–fluid conduction, contact conduction, and radiation are extracted from the total effective thermal conductivity. The contact conduction makes a major contribution to the effective thermal conductivity but gets weaker as the temperature rises. The radiation overtakes the contact conduction after 920 K. The solid–fluid conduction has little influence on the effective thermal conductivity. Later, Bu et al. (2021) carried out a numerical study of the stagnant effective thermal conductivities in the three types of ordered pebble beds to access the ZBS model's parameters, contact area fraction φ, which is related to the contact radius ratio γ and the coordination number N_c. Then the multiple linear regression was performed to get a semi-empirical formula $\varphi = 0.15N_c \cdot 1.1\gamma$. Compared to SANA and HTTU experiments, the ZBS model was proven be able to predict the effective thermal conductivity in the bulk region of pebble beds. The effective thermal conductivity of different thickness pebble beds in the three-dimensional directions was analyzed by the three-dimensional thermal network method (Wang et al., 2021c). It was observed that the thin pebble bed showed anisotropic effective thermal conductivity under the practical design size. Normally, the effective thermal conductivity along the bed's vertical direction is higher than the horizontal direction due to the gravity effect. As the thickness increases, the effective thermal conductivity of the pebble bed gradually increases.

4 Design concerns

Geometry-related concerns (wall issues): On the effect of different three-dimensional wall structures (Li et al., 2021), eight kinds of 3D wall structures were designed to show their different degrees of influence on impeding the pebble flow near the wall. The triangular and helicoidal structures perform better in accelerating the cycling speed and strengthening the mixing of the upper and lower pebbles, and the triangular is the optimal structure.

Boundry condition-related concerns (inlet–outlet): The effect of the location of the inlet and outlet on the uniformity of the fluid flow was studied by considering different combinations of inlet and outlet (Sharma et al., 2020). It is found that the pebble bed with a diagonally opposite inlet and outlet configuration has a higher tritium sweeping efficiency as compared to the existing design of the inlet and outlet at the same face.

Moreover, in the HTGR, the effects of outlet size on the flow characteristics in the pebble bed were studied with two ways of changing the outlet: fixed hopper angle ("FHA" case) and fixed hopper height ("FHH" case) (Wu et al., 2022b). The transitional region from mass flow to funnel flow occurs earlier when the opening is smaller, and the transitional height increases with the decrease of outlet size for the "FHH" case. By contrast, there is almost no difference in the transitional time and heights in the "FHA" case. This means that the hopper angle is a more important factor affecting the overall flow pattern rather than the hopper height. Changing the outlet by adjusting the hopper angle influences more significantly on the flow performance. When the opening is larger, less retention of pebbles near the wall was observed. Simply changing the hopper height to adjust the opening does not affect the flow of pebbles within a 1D range from the wall.

Configurations: On the contraction configuration, Wu et al. (2021) simulated the pebble flows inside some specially designed pebble beds with arc-shaped contraction configurations at the bottom, including both concave-inward and convex-outward shapes. Concerning flow pattern for reactor design, the traditionally designed pebble bed with the cone-shaped bottom is not the most preferred structure. By improving the contraction configuration, the flow performance can be significantly enhanced. The flow in the convex-shape configuration features uniformity, consistency, and less stagnation, which is much more desirable for pebble-bed design. In contrast, when the shape is from convex-forward to concave-inward, the flow shows more nonuniformity and stagnation in the corner although the average cross-section axial velocity is the largest due to the dominant middle pebbles.

Compared to the cylindrical core, the annular–core reactor (ACR) has a more edgy distribution of neutron flux and nuclear heating power density and a higher peak value (Yang et al., 2022). The ACR with a higher thermal power could realize a higher helium outlet temperature, and higher thermoelectric conversion efficiency. Using smaller pebbles reach the criticality more quickly. The pebbles' size affects less the neutron flux and nuclear heating power density distribution than the central graphite column's size. A one-to-one mapping technique was utilized in the running-in phase process, that sets the temperature of pebbles to their real value, varying from their locations. The heating power density gradually flattens in the running-in phase process. This shows a possibility to do further work on the neutronic/thermal-hydraulics analysis.

Concerning the configuration of the whole bed, the three-dimensional coolant velocity and pressure drop profiles were obtained based on a 3D CFD simulation of the whole HTR-10 (Fig.10) (Gámez Rodríguez et al., 2021), which are important to the design of the thermohydraulic behavior of the reactor. The temperature values obtained in the pebbles, the coolant, and the structural elements were confirmed to be under the normal operating limits. For a two-region-designed pebble-bed reactor core, Wu et al. (2019a) explored the influence of loading ratio and pebble density on flow patterns. After a period of recirculating flow,

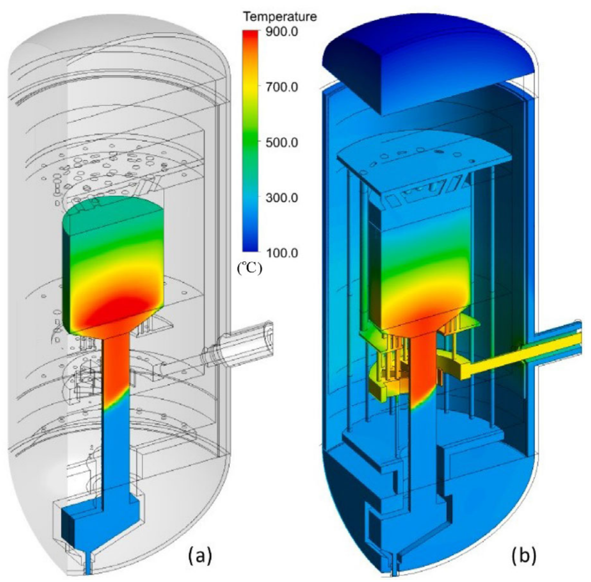

Fig. 10 10 MW steady-state temperature profiles (Gámez Rodríguez et al., 2021; reproduced with permission © Elsevier B.V. 2020).

the pebble bed reaches its equilibrium state with invariable boundaries between the zones and a stable discharging number ratio of pebbles in the zones consistent with the loading ratio. The loading ratio does not influence on the retention rate. But it could significantly affect the two-region configuration. The two zones could be affected by pebble density. Increasing the pebble density in the middle zone accelerates the pebble flow and reduces the size of the central region, enlarging the stagnant zone and enlengthening the total retention time. On the contrary, the reverse comes true by increasing the pebble density in the central region, and all pebbles flow out of the bed in a shorter time, with a smaller stagnant zone, and shorter total retention time.

Applications (thermal energy storage): Hu et al. (2022) evaluated the overall heat storage quantity, heat release quantity, average charging power, average discharging power, enthalpy efficiencies, and exergy efficiencies in the coupled packed-bed thermal energy storage (PBTES) system by the orthogonal design optimization. The most optimal capsule diameter, the phase change materials, the inlet flow rate of the high-temperature-fluid (HTF), and the inlet HTF temperature or initial PCMs temperature were also indicated.

5 Safety issues

As a demonstrative application for reactor safety evaluation, a thermal radiation computation of the decay heat removal of a real reactor was carried out aided by predicting the effective thermal conductivity with the matrix models. The demonstrative application showed that the highest temperature is still within the design limitation of the packed bed (Wu et al., 2020a).

Understanding the burnup profile of pebbles is essential for reactor safety, as well as for fuel economy. However, in pebble-bed reactors, each fuel pebble has a different amount of burnup depending on the precise trajectory it follows. Therefore, the pebble's motion trajectory provides the basis for evaluating the burnup profile via a burnup calculation in each pebble. Usually, the reactor geometry, neutron flux data, and thermal characteristics should be precisely provided and all used for burnup evaluation and the safety analysis, especially for the pebbles near the reactor wall (Tang et al., 2019).

As the pebbles are tightly packed inside the pebble bed reactor, they experience long time and high pressures. The integrity of fuel pebbles is an important issue of safety consideration. On the other hand, the spent fuel pebbles are also packed in the on-site storage system based on canisters. It is also an important issue to ensure the safe containment of the radioactive contents by accessing the interactions between spent fuel pebble bed and storage canister in the event of accidental drop (Lin and Li, 2020).

Concerning the threat of earthquakes to pebble flows, a scaled model based on TMSR-SF was built to conduct the measurement of vibration on pebble flows (Chen et al., 2020). The pebble bed keeps stable under weak vibrations and becomes denser under strong vibrations. Also, the packing factor increases rapidly by 5% in 5 min under strong vibration, accompanied by a variation of approximately 2500 PCM reactivity.

For safety evaluation in accidents, Kile et al. (2022) presented the application of SCALE and MELCOR models for a fluoride salt-cooled high-temperature reactor (FHR) based on publicly available specifications to calculate the thermal-hydraulic response of an assumed FHR primary system. The depletion of a core slice model and the blending of fuel compositions at different burnups were used to determine three-dimensional fuel composition in the equilibrium state. A comparison of entirely fresh fuels and the composition of equilibrium fuels shows that the equilibrium core leads to lower steady-state temperatures but slower cool-down during a loss of flow accident (LOFA). The transient response of the equilibrium core of our FHR system to variations in thermal-hydraulic parameters of the system was analyzed. Uncertainties in decay heat led to negligible impact on peak temperatures during the transient response, which is less than approximately 700 K below the anticipated failure limits for the LOFA.

6 Conclusions

This work provides a literature review on the very recent research progress of the pebble bed flow. Generally speaking, the pebble bed research is going into very detail especially on the pebble-scale characteristics, like the packing fraction and the relevant factors. Also, the pebble-scale gas–pebble flow has been shown with the aid of the state-of-the-art development of advanced measurement techniques, the image processing algorithms, as well as the coupled complex methods, and software that usually run by using parallel computing. For experimental studies, it is urgent and needed to perform high-temperature measurements of both the two-phase microscopic characteristics and the macroscopic performance of the whole pebble beds in terms of effective parameters. For numerical approaches, it is clear that the trend of integrating some kinds of advanced mathematical models to solve the neutron, the mechanics, the thermodynamics, and the fluid flow issues together after each of them has been rigorously verified. In application, we believe the pebble bed is not a limiting facility that can only be applied in the aforementioned cases. With necessary optimal designs, it is potentially suitable for much wider applications that are still waiting for us to explore.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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