Modeling of Interactions between Liquid Coolant and Pebble Flow in Advanced High Temperature Reactors

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INTRODUCTION

In pebble bed gas-cooled or fluoride salt-cooled high temperature nuclear reactors, pebbles are circulating in the core, while the high speed gas or liquid coolant flow is passing through pebbles. Pebble-to-pebble, pebble-to-fluid and pebble-to-reflector wall interactions are the major forces that govern the coupled pebble flow and coolant flow process. This process is dependent on the reactor power and temperature distributions, which have strong effect on pebble graphite friction coefficient and coolant viscosities [1]. A fully coupled neutronic-mechanical-fluid dynamic simulation is needed to address the complicated reactor core behavior due to these multi-physics couplings. Accurate and efficient modeling of interactions between coolant flow and pebble flow is one of the most important steps in addressing this multi-physics simulation effort.

In pebble bed gas-cooled reactors, one of Very High Temperature Gas-cooled Reactor (VHTR) designs [2], drag force is the major interaction force between pebble and helium coolant. In previous research [3], a multi-physics model has been developed to simulate the 3-D pebble flow in VHTR design accounting for the gas-pebble interaction. The method is implemented in a self-developed code PEBFD [3]. In this paper, in order to account for significant liquid buoyancy and viscosity, we extend previous work and incorporate new computational models to study the unique pebble recirculation feature in Pebble Bed Advanced High Temperature Reactors (PB-AHTR), a conceptual design proposed by researchers from UC Berkeley [4].

In PB-AHTR, molten fluoride salt serves as liquid coolant around pebbles. The coolant's density is higher than the fuel pebble, hence pebbles are floating upward due to buoyancy, which requires the fuel loading at the bottom and defueling at the top in the reactor core. This is quite different from PB-VHTR design. Several experiments have been performed to show the pebble injection loading, pebble upward landing and defueling process in a scaled facility [5, 6], such as the PREX(Pebble Recirculation Experiment). In this paper, modeling of liquid coolant and pebble flow interactions are developed and for the study of three physical phenomena in PB-AHTR: 1) pebble injection process; 2) lower plenum pebble landing dynamics process; and 3) pebble defueling process from the top of the core. The simulation results are compared with the experiment observation from UC Berkeley team.

SIMULATION METHODOLOGY

There are four major mechanical interactions existing within AHTR (or PREX experiment): 1) Contact force among pebbles and between a pebble and the boundary, including the normal and tangential contact force. 2) Pebble gravity. 3) Buoyancy. 4) Fluid drag force. Other forces such as the Magnus force due to slow pebble motion and rotation also exist but in limited quantity. Pebble flow and coolant flow are tightly coupled via these forces.

Discrete Element Method (DEM) is widely employed to simulate the first three forces [7, 8], and Finite Volume Method (FVM) in an Eulerian frame is used as the Computational Fluid Dynamics (CFD) approach for drag force calculation. In the simulation, the transient porosity distribution is retrieved from the DEM solver and provided to the fluid solver to obtain the fluid velocity and pressure profile and consequent fluid drag force. The whole core is meshed into control volumes (fluid cells) and the physical property of solid and fluid is averaged within each control volume. Then the averaged coolant velocity $\boldsymbol{U}$ is calculated within each fluid cell based on two-phase Navier-Stokes equations [8, 9]:

$$\frac{\partial \varepsilon \rho_f}{\partial t} + \nabla \bullet (\varepsilon \rho_f \boldsymbol{U}) = 0$$
$$\frac{\partial \varepsilon \rho_f \boldsymbol{U}}{\partial t} + \nabla \bullet (\varepsilon \rho_f \boldsymbol{U})\boldsymbol{U} = -\varepsilon \nabla p + \rho_f \nabla \bullet \nu \nabla \boldsymbol{U} + \boldsymbol{f}_p + \varepsilon \rho_f \boldsymbol{g} \quad , (1)$$

where ε is the local porosity, ρ_f is the coolant density, p is the coolant pressure, ν is the coolant viscosity, $\boldsymbol{f}_p$ is the force density that pebbles exert onto the coolant and g is the gravitational acceleration.

For a pebble with radius r and velocity $\boldsymbol{V}$, the drag force from the coolant can be calculated as:

$$\boldsymbol{F}_d = \frac{1}{2}\rho_f (\boldsymbol{U} - \boldsymbol{V}) \left\| \boldsymbol{U} - \boldsymbol{V} \right\| C_d \pi r^2 \varepsilon^{1-\beta} , \quad (2)$$

where ρ_f is the coolant density, $\boldsymbol{V}$ is the pebble velocity averaged within each fluid cell, C_d is the drag coefficient, and β is decided by the Reynolds number Re [9]. As seen in Eqs. (1) and (2), the pebble flow pattern, especially the local packing fraction will affect the flow pressure and velocity field, which will determine the local drag force and affect the pebble flow vice versa. With the coolant mass flow of 3.6 Liters/cm^3 in PREX 0 [4], the inlet coolant velocity is about 3cm/s, and the Reynolds number can be calculated Re$\approx$840 according to the equation:

$$Re = \rho_f \left\| \boldsymbol{U} - \boldsymbol{V} \right\| d / \nu \, . \quad (3)$$

With above Reynolds number it is reasonable to adopt the laminar flow assumption.

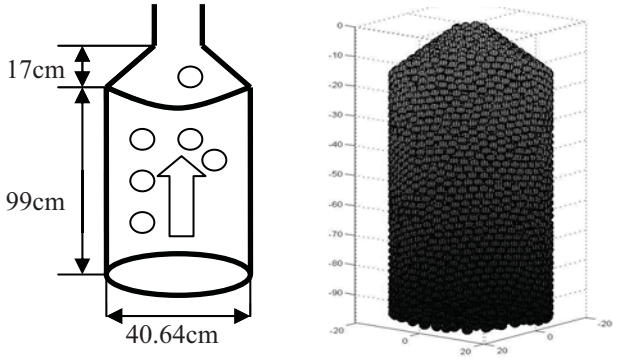
The geometry of PREX is shown in Fig. 1(a). The pebbles are injected from the bottom of the core, move upward due to the coolant buoyancy and discharged at the top outlet. The coolant also flows from bottom to top at a constant mass flow rate. For practical PB-AHTR core (2400 MW integral design), there are 1.2 million 6cm-diameter regular or annular fuel pebbles (10% and 20% TRISO packing fraction in the fuel zone respectively, but with the same amount of TRISO particles) within the active core, which is 6.4m in height and 6.8m in diameter [4]. This is a great challenge for either computational or experiment study. Hence scaled geometry is necessary to cut down the simulation or experiment time. In UC Berkeley's PREX 0 experiment, 8,300 2.54cm-diameter stimulant pebbles are injected into the core, which has the height of 99cm and radius of 20.32cm (16*d*). Water is chosen as the simulant coolant. Though water cannot reflect the temperature dependence of viscosity as the molten LiF salt does, its viscosity is close to that of LiF-based molten salt at operational temperatures. And since molten salt has the density of 1.94g/cm^3, and the fuel pebbles' density ranges from 1.68 g/cm^3 to 1.81g/cm^3 with the average around 1.7g/cm^3 [4], in order to preserve similar density ratio as in the practical AHTR, the PREX 0 experiment adopted uniform polypropylene spheres as the simulant fuel pebbles with the density of 0.843g/cm^3.

RESULTS: PREX 0 experiment validation

In the original PREX 0 experiment [4], 8,300 pebbles are injected one by one from the bottom of the reactor and settle in the core. At this point, the fluid is considered to be stagnant. This pebble landing process is simulated by our code, as shown in Fig. 1c. In both the PREX 0 experiment and our simulation, all pebbles have the same composition and density, though the variable density case in practice can also be solved by our algorithm without significant difficulty. According to PREX 0, the sequential landing pattern leads to a concave surface of the pebble assembly (Fig. 1d) which is observed in our result.

Another collective pebble packing process is simulated by first generating all the pebbles within the core allowing overlapping and rearranging them and then letting them settle down based on the algorithm recently developed [10]. The packing efficiency is greatly enhanced compared with the sequential landing. In our code, the sequential landing of 8,300 pebbles needs 14 hours while the collective packing can be achieved within 2 hours. However, the concave bottom surface is not as appreciable as the sequential packing, as shown in Fig.1b. It demonstrates that the fuel loading pattern can affect the pebble distribution at the bottom.

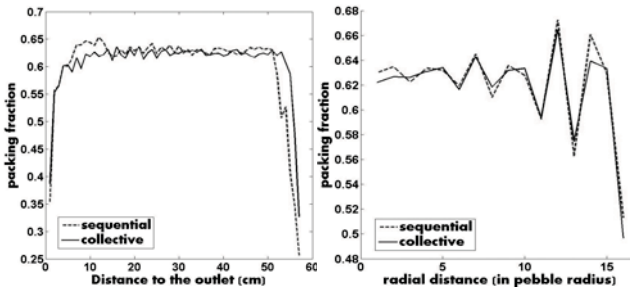
The pebble packing distribution function (PDF), either in the radial direction or in the axial (vertical) direction, is essential for coolant dynamics [8], thermal [11] and neutronic calculation [12]. For qualitative analysis, it is easy and sufficient to obtain the PDF by first dividing the core into thin radial or vertical layers and then summing up the pebble volume that falls into each layer. An assembly with 5,000 pebbles is analyzed using this approach. Although significant difference exists between the sequential and collective packing methods at the top and bottom of the pebble assembly, they have similar PDFs in the cylindrical middle core region, as shown in Fig. 2.



(a) core geometry (b) collective packing

(c) concave bottom surface for sequential landing (d)PREX 0 experiment (bottom) [4]

Figure 1 core geometry and pebble packing



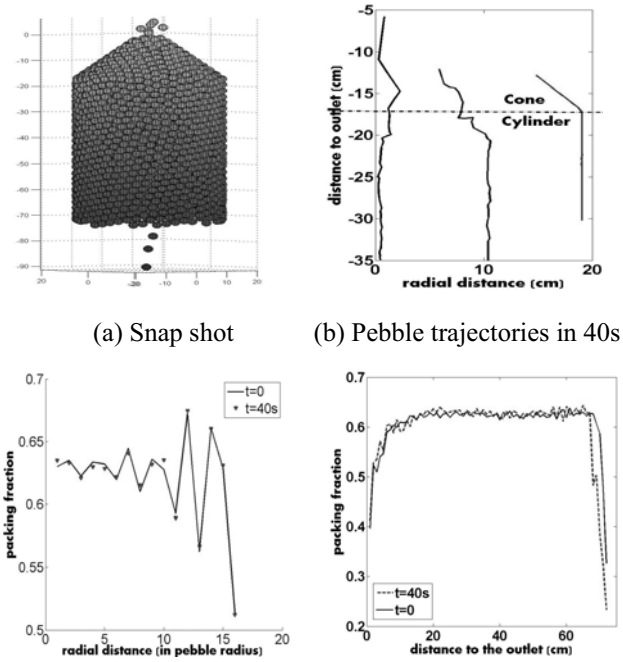
(a) axial distribution (b) radial distribution

Figure 2 packing fraction distribution comparison

From Fig. 2 it can be first seen that, the actual packing fraction in the cylindrical middle core region (62%) is slightly larger than the designed packing fraction of 60% owing to the densification effect of buoyancy. It also clearly shows that compared with collective initialization,

sequential landing leads to a higher packing fraction within the outlet conic area, while the concave bottom shape leads to the drop of local axial packing fraction. However, they share similar packing fraction distributions for most of the middle core region, which indicates that we can use collective initialization packing to expedite the overall simulation process.

After the initial packing, a combined pebble injection, landing and defueling process is simulated using the coupled method as mentioned in Refs. [3, 8]. Figure 3a shows a snap shot of fuel loading process at the bottom and defueling process at the top. Typical pebble trajectories starting with different radial distance is shown in Fig. 3b, which exhibits same streamline pattern as does in VHTR [3,7]. Figure 3b also shows that pebble starting with smaller radial distance travels faster due to less friction. The comparison of PDFs between t=0s and t=40s is shown in Fig. 3c and Fig. 3d. From the PDFs, it can be seen that the packing fraction profile basically remain unchanged during the recirculation process except for the axial PDF of the pebble assembly's bottom end.



(a) Snap shot (b) Pebble trajectories in 40s

(c) Radial PDF (t=0, 40s) (d) Axial PDF (t=0, 40s)

Figure 3 Injection-landing-defueling simulation

CONCLUSIONS

Based on the coupled DEM and CFD methodology in previous PB-VHTR simulation [3], the liquid buoyancy is accounted for and the pebble injection-landing-defueling feature is introduced to model the PB-AHTR which adopts molten salt as the coolant. Simulation results verified the principal phenomena of pebble landing in the scaled PREX experiment. The initialization packing fraction analysis shows that collective initial packing technique can be adopted to prepare the initial assembly, which can greatly enhance the packing efficiency while preserving the packing fraction profile in the middle core region. It is also observed that the packing statistics (PDF) does not change noticeably during the dynamic recirculation process.

Future improvements include the simulation of full core geometry with the realistic graphite pebble and molten flibe salt properties. Due to the temperature dependence of the flibe viscosity, the thermal effect also needs to be considered, which requires an extra energy conservation equation on the basis of Equations (1).

ACKNOWLEDGMENT

This work was performed under the auspices of the U.S. Nuclear Regulatory Commission Faculty Development Program under contract NRC-38-08-950.

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