Study on Pebble-Fluid Interaction Effect in Pebble Bed Reactors

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INTRODUCTION

In pebble bed reactors (PBRs), fuel pebbles containing TRISO particles continuously circulate within the core during operation, while the coolant fluid, either helium gas (in Pebble Bed Gas-cooled Reactors) or molten flibe salt (in Pebble Bed-Advanced High Temperature Reactors), continuously passes through the pebbles to transfer the heat generated by fission reactions out of the core. Such a design has many advantages in fuel efficiency and reactor safety. To accurately predict its neutronic and thermal-hydraulic behavior, high fidelity simulations are needed to obtain accurate pebble distributions and coolant fluid porosity distributions [1].

In PBRs, both pebble flow and coolant flow exist. They are not independent from each other but coupled through pebble-fluid interactions such as the fluid drag force and the pressure gradient force. In previous work [2, 3], coupled pebble and coolant flow were simulated using a high fidelity coupled Discrete Element Method-Computational Fluid Dynamics (DEM-CFD) model. However, the significance of the coupling was not addressed. This becomes the motivation for this summary, which is to quantitatively investigate the impact of the pebble-fluid interactions (coupling) on both the pebble flow and the coolant flow.

Two scenarios with different fidelities are investigated: 1) Simulation of the pebble flow and the coolant flow without coupling. The spatial distribution of steady-state pebble flow is first calculated by DEM, and then the coolant field is calculated by CFD approach based on this static pebble distribution. 2) Fully coupled pebble flow and fluid flow simulation via DEM-CFD approach, in which the dynamic interactions between both flows are considered at each simulation step.

By comparing the pebble/coolant behaviors under these two scenarios, the effects of pebble-fluid interactions on both flows are quantitatively analyzed. For pebble flow, the interaction impact on the average pebble speed and axial distributions is studied. For coolant flow, the influence on the axial/radial profile of velocity and pressure drop is investigated.

SIMULATION METHODOLOGY

In the first scenario (uncoupled situation), a DEM simulation is first performed to obtain the pebble distribution, then this distribution is used by the finite-volume based CFD solver to solve the fluid field, the pebble-to-fluid force $\boldsymbol{f}_P$ is calculated based on the sum of fluid-to-pebble forces within a fluid cell [4, 5], as shown in Eqs. (1)-(3):

$$\boldsymbol{F}_D = \frac{1}{2}\rho(\boldsymbol{u}-\boldsymbol{u}_P)\left\|\boldsymbol{u}-\boldsymbol{u}_P\right\|C_d\pi r^2\alpha(\varepsilon), \tag{1}$$

$$\boldsymbol{F}_P = -\int_{V_P}\nabla p dV, \tag{2}$$

$$\boldsymbol{f}_P = -\sum_i^{N_c}(\beta_i\sum(\boldsymbol{F}_D+\boldsymbol{F}_P))/V_c, \tag{3}$$

where $\boldsymbol{F}_D$ is the De Felice drag force [4], $\boldsymbol{F}_P$ is the pressure gradient force, $\boldsymbol{u}$ is the fluid velocity, p is the pressure, ρ is the coolant density, $\boldsymbol{u}_P$ is the pebble velocity, V_P is the volume of a pebble, V_c is the volume of a fluid cell, ε is the local porosity, C_d is the drag coefficient, $\alpha(\varepsilon)$ is an empirical function determined by ε and the Reynolds number Re [4-6], N_c is the number of pebbles within a fluid cell, and β_i is the volume fraction of i^{th} pebble that falls into a fluid cell.

In the second scenario, a tightly-coupled DEM-CFD approach is employed to solve the pebble-fluid interactions. Based on current pebble position $\boldsymbol{X}$ and velocity $\boldsymbol{u}_P$, the pebble-to-pebble and wall-to-pebble contact forces $\boldsymbol{F}_c$ are obtained [7] and the spatial distribution of the porosity ε is calculated. From Eqs. (1)-(2), the fluid-to-pebble forces $\boldsymbol{F}_D$, $\boldsymbol{F}_P$ are solved and these fluid forces as well as the contact forces will be imported into the DEM solver to solve the next step pebble position $\boldsymbol{X}'$ and velocity $\boldsymbol{u}_P'$ by using Newton's 2nd Law of Motion. Meanwhile, the pebble-to-fluid force $\boldsymbol{f}_P$ will be calculated in each fluid cell according to Eq. (3), and by introducing $\boldsymbol{f}_P$ into the equations of mass and momentum conservation (Navier-Stokes equations), the new fluid velocity $\boldsymbol{u}'$ and pressure p' in all the fluid cells are calculated and these new fluid and pebble status quantities are passed to the next computation step. From the description of the DEM-CFD approach it can be seen that there is two-way data exchange between the DEM solver and the CFD solver, as illustrated in Fig. 1.

RESULTS

A pebble-bed gas cooled reactor case is studied in this work. The reactor geometry is shown in Fig. 2a, which follows the HTR-10 core dimension.

The reactor has a cylindrical core with the radius of 90cm and the height of 180cm. A conic bottom of 72cm in height and 18cm in outlet radius is adopted. There are 28342 equal-size pebbles circulating within the reactor, each of which has the standard 3cm radius. The helium gas coolant are infused from the top of the reactor and emitted at the bottom. The inlet coolant speed is 50m/s,

and the boundary conditions are constant pressure at the outlet and uniform constant velocity at the inlet.

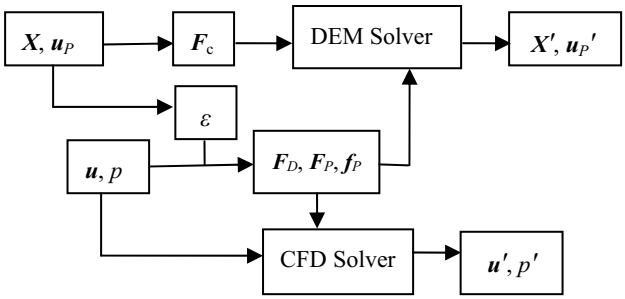
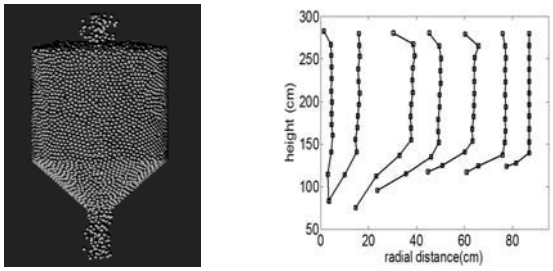


Fig. 1 DEM-CFD schematics



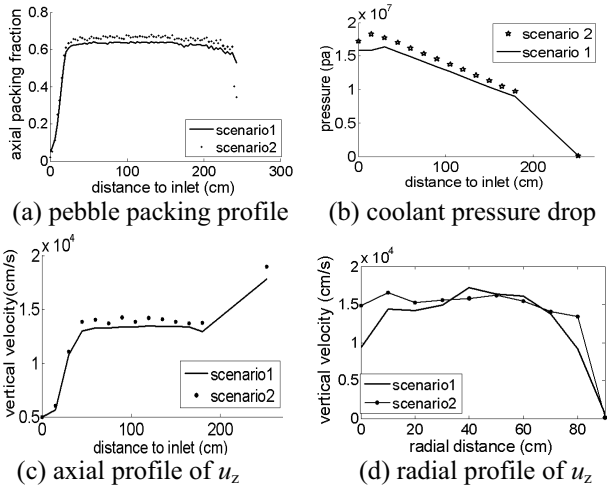
(a) simulation geometry (b) pebble trajectories

Fig. 2 Simulation geometry and pebble trajectories

The circulating process of the pebbles is realized through the adoption of periodic boundary condition. For every pebble, once its position is below the surface of the outlet, it will recur from the top of the core. This periodic boundary condition is close to the realistic operation case and can well preserve the total quantity and motion balance of the pebble flow. For both scenarios, typical pebble trajectories starting from the same height but different radial distance are shown in Fig. 2b. The axial profile of radially averaged pebble packing fraction distributions are shown in Fig. 3a. Considerable differences can be seen between two scenarios due to the strong densification effect of the coolant onto the pebble flow. As scenario 1 neglects the fluid-to-pebble forces, pebble packing fraction is lower than that of scenario 2 over the whole core. The neglected fluid force also has direct influence on pebbles' vertical speed: the average pebble traveling time from inlet to outlet in scenario 1 is 167s, while it is 145s in scenario 2. Based on Eqs. (1)-(3), we can also expect that the pebbles will also have noticeable counteraction onto the coolant. Figure 3b shows that the pressure drop difference between two scenarios can be as large as 10%, which is the direct result of pebble packing differences.

Figure 3c gives the axial profile of vertical coolant velocity u_z (radially averaged) in both scenarios. It is clear that scenario 1 underestimates u_z overally. It is interesting to find that a stable region for the u_z profile exists in the middle of the core. Figure 3d shows the radial profile of u_z in this stable region (z=100cm). It can be seen that scenario 2 has a more centered vertical velocity distribution compared with scenario 1.

Finally for the velocity along the radial direction u_r, there indeed are differences between two scenarios, but since u_r is much smaller than u_z in the HTR application (u_r / u_z~1/100), this difference is not significant.



(a) pebble packing profile (b) coolant pressure drop

(c) axial profile of u_z (d) radial profile of u_z

Fig. 3 Comparison between two scenarios

CONCLUSIONS

By comparing two PBR simulation scenarios with different fidelities, significant impacts of pebble-fluid interactions on pebble distribution and fluid velocity and pressure profiles are found. In tightly-coupled simulation, axial pebble packing is higher due to high speed coolant flow and the average pebble travel time is shortened by 13%. Coolant pressure drop is increased byas large as 10% and the vertical speed is increased over the whole core. These considerable changes in pebble and coolant behaviors suggest that a tightly-coupled pebble and coolant flow simulation is essential in assessing the design and operation safety of PBRs.

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