Pebble Flow Simulation Based on a Multi-Physics Model

Yanheng Li, Wei Ji

Department of Mechanical, Aerospace, and Nuclear Engineering

Rensselaer Polytechnic Institute, Troy, NY 12180-3590, liy19@rpi.edu, jiw2@rpi.edu

INTRODUCTION

Pebble bed gas-cooled reactor is a potential candidate for Gen IV reactor designs. Tens of thousands of fuel pebbles circulate within the pressure vessel in a typical reactor, providing better fuel performance and online refueling capability. Accurate modeling of pebble flow in reactor core is essential to reactor safety analysis and fuel performance evaluation [1].

Normally, pebble circulation in reactors is modeled as a dense granular flow through a high speed coolant (gas or liquid) field. A realistic model should simultaneously model the pebble flow and high-speed coolant flow, as well as account for the interaction (feedback) between two flows, which presents a multi-physics simulation effort. Discrete element method (DEM) and computational fluid dynamics (CFD) method are the most widely used methods in simulating pebble dynamics [1, 2, 9], and in computing the fluid force and thermal effect [3, 4], respectively. Coupling of two methods can provide more advanced capability in handling essential physics in pebble flow simulation. However, current methodologies used in existing codes, are either lacking of multi-physics capability, such as open source codes ESys-Particle [5], LAMMPS [1, 6], YADE [7], and specialized code PEBBLES [10] by Idaho National Laboratory, or limited in accounting for more precise physics, such as commercial codes PFC3D [8] and EDEM [9].

In this paper, a methodology based on a multi-physics model, coupling pebble flow dynamics and coolant fluid dynamics, is developed to provide a realistic model of pebble distribution in a scaled pebble bed reactor core. The new model combines DEM and CFD methods and provides a feedback mechanism between pebble flow and coolant flow, i.e. the change in pebble flow affects the fluid velocity distribution and the change in fluid velocity also affects the pebble flow distribution. Also, in speeding up the simulation, a novel initialization approach is developed to closely pack the pebbles before dynamic simulation in the computation model. This approach is advantageous over the trial algorithm that is widely adopted by other existing codes in effectively closely packing pebbles.

METHODOLOGY DESCRIPTION

Typical DEM-based pebble flow simulation consists of three steps: 1) static close packing for pebble initialization, 2) pebble contact detection, and 3) force/motion calculation.

In step 1, a geometry-based insert-and-fail approach is normally used for initialization [2, 10], which leads to a long initial loading time and is not capable in achieving high packing in pebble bed reactors where pebbles are mono-sized and space is confined. In order to effectively reach high packing and reduce the initial loading time, a novel quasi dynamic method is proposed. The method starts with generating fixed amount of pebbles randomly, allowing overlap. Then, an iterative pebble position adjustment is performed to eliminate the overlapping while keeping pebbles closely packed.

In order to determine the adjustment direction, two artificial forces are introduced. One is a large normal contact force F_n which ensures no overlapping. The other is a small attracting force F_a between neighboring pebbles which densifies the packing. These forces are updated step by step and indicate the search direction as Eq. (1):

$$
\begin{aligned}
F_{n,ij} &= \alpha_1 \delta_{ij} \frac{(X_i - X_j)}{\left\| X_i - X_j \right\|} \\
F_{a,ij} &= \alpha_2 \frac{1}{d_{ij}^{\,2}} \frac{(X_j - X_i)}{\left\| X_i - X_j \right\|}, \; d_{ij} \le d_{max} \\
\Delta X_i &= \alpha_3 \sum_j (F_{n,ij} + F_{a,ij}) \\
X_i^{new} &= X_i^{old} + \Delta X_i
\end{aligned}
\tag{1}
$$

where X_i is the position of the ith pebble, d_{ij} is the distance between the ith and jth pebble, d_{max} is the effective range of the attracting force, δ_{ij} is the overlapping depth, ΔX_i is the search direction, and α_k (k=1, 2, 3) are user defined coefficients. These two forces act simultaneously to drive the randomly generated pebbles toward a close packing configuration with no overlapping.

After initialization, dynamic simulation is performed by the contact detector (step 2) and force/motion solver (step 3). In order to speed up the detection, a nearest neighbor search is employed by checking only adjacent pebbles [2]. In this way, the contact information is evaluated much faster than the full core search. After the detection, contact forces, including normal force and shear force, are calculated pebble by pebble based on the contact information，spring-damper contact model (for normal direction) and stick-slip model (for tangential direction) [1]. Drag force are also calculated by the CFD solver. The gross force for each pebble can be acquired and the motion can be simulated over discrete time steps based on Newton's Laws of Motion.

As pebbles move and rotate, the concentration and speeds of pebbles is changing, thus affecting the fluid flow speed around pebbles. The change in fluid speed reversely

affects the fluid force acted on the pebbles. Therefore the CFD solver needs to account for this interaction to better predict the long term pebble motion. An Eulerian method based on finite difference approach is used. The full space is first discretized by large fluid cells, which usually consist of tens of pebbles. Then for every 100 DEM steps, information about local porosity and pebble motion are recorded and sent to the CFD solver. And the averaged coolant velocity $\boldsymbol{U}$ is calculated once within each fluid cell based on two-phase Navier-Stokes equations:

$$\frac{\partial \varepsilon \rho_f}{\partial t} + \nabla \bullet (\varepsilon \rho_f \boldsymbol{U}) = 0$$
$$\frac{\partial \varepsilon \rho_f \boldsymbol{U}}{\partial t} + \nabla \bullet (\varepsilon \rho_f \boldsymbol{U}) = -\varepsilon \nabla p + \rho_f \nabla \bullet \nu \nabla \boldsymbol{U} + \boldsymbol{f}_p + \varepsilon \rho_f \boldsymbol{g} \quad (2)$$

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 $\boldsymbol{g}$ is the gravitational acceleration.

Through an iterative finite difference version of Eqs. (2), p and $\boldsymbol{U}$ are calculated within each fluid cell. Then the drag force $\boldsymbol{F}_d$ is calculated by [12]:

$$\boldsymbol{F}_d = \frac{1}{2}\rho_f (\boldsymbol{U} - \boldsymbol{V}) \|\boldsymbol{U} - \boldsymbol{V}\| C_d \pi r^2 (1-\varepsilon)^{1-\beta} \quad (3)$$

where ρ_f is the coolant density, $\boldsymbol{V}$ is the pebble speed averaged within each fluid cell, C_d is the drag coefficient, and β is decided by the pebble's Reynolds number Re_p [12].

There also exist other fluid forces, such as buoyancy and Magnus force due to pebble rotation. However, for typical helium coolant, these two forces can be negligible. The drag force is then output to the DEM solver for gross pebble force calculation.

As a summary, the flow chart of the whole methodology is shown in Figure 1:

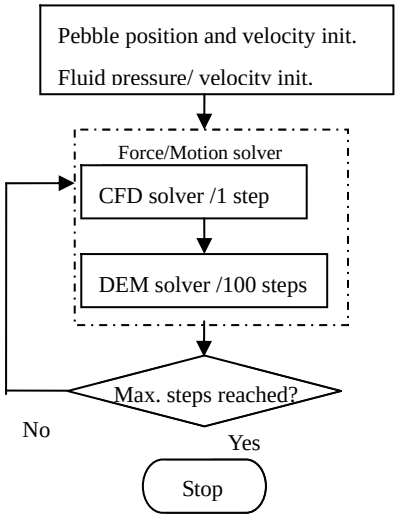
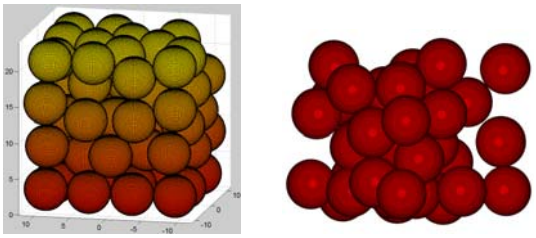


Figure 1 Flow chart of pebble flow simulation

RESULTS

First, the comparison of newly developed quasi dynamic method with the insert-and-fail method used in ESys-Particle is made and shown in Figure 2. The cube is 8r in side length. The new method generates highly dense packing of 66 pebbles with the packing ratio of 0.54, while ESys-Particle only generates 36 pebbles with the packing ratio of 0.29.



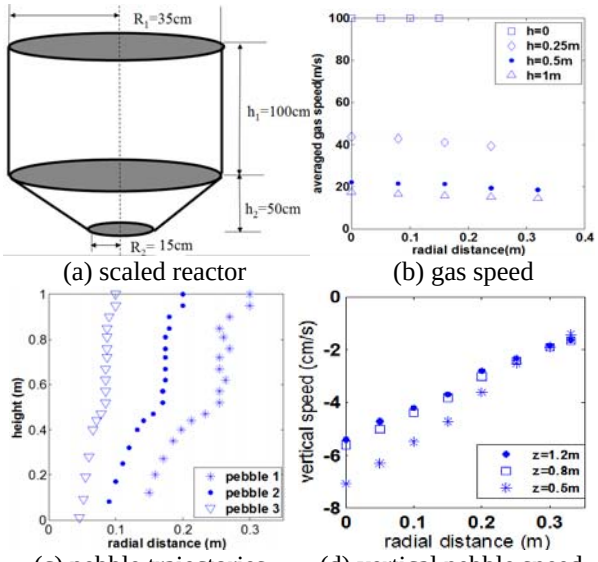
(a) Quasi dynamic method (b) ESys-Particle

Figure 2 Initialization comparison

Although the new method takes longer time than other codes, the overall simulation time is reduced due to much less time spent in successive steps to closely pack the pebbles. Besides, since few pebbles are removed, the resultant pebble quantity can be well controlled, which is significant for a pebble bed reactor's criticality.

To validate the newly developed multi-physics model, the pebble flow in a scaled pebble bed reactor is simulated. The reactor has a cylindrical vessel (R_1=35cm, h_1=100cm) with a conic bottom (R_2=15cm, h_2=50cm), where 1,500 pebbles are generated (Fig.3 (a)). The coolant enters the reactor from the bottom with an initial speed of 100m/s.

The trajectories of three pebbles, which enter the reactor core at different radial distances, are tracked (Fig.3(c)). And the vertical speeds of pebbles that pass through fixed locations are recorded and averaged, which have the radial distribution as shown in Fig.3 (d).



(a) scaled reactor (b) gas speed

(c) pebble trajectories (d) vertical pebble speed

Figure 3 Reactor geometry and results

Fig.3 (c) indicates a laminar pebble flow type in a typical pebble bed reactor. From Fig.3 (d), it can be seen that for a fixed height, the vertical pebble speed will decrease as the radial distance increases, due to the increase of friction. This is consistent with the results obtained by other researchers [1].

For fluid calculation, the fluid speed is obtained from the interpolation of cell-centered average values. The speed distribution along the radial direction at the height of h=0, 0.25m, 0.5m, and 1.0m is shown in Fig.3 (b).

From Fig.3 (b) we can see that, in the conic area (h<0.5m), the coolant speed decreases quickly as the cross section area increases. In cylindrical area, this decrease is not so obvious. And for a fixed height, the coolant speed decreases slightly as r increases. This is because the porosity in the periphery is larger than that in the center. For z=1.0m, the void fraction grows from 0.40 at r=0m to 0.44 at r=0.35m.

As a comparison, standard ESys-Particle and PFC3D can only simulate the drag force by introducing a uniform local viscous damping force term. This term is proportional to the pebble velocity and incapable of describing the coolant speed variation.

CONCLUSIONS

A methodology based on multi-physics model, coupling DEM and CFD, is developed and implemented to predict the pebble flow in a scaled pebble bed reactor core. Simulation results show that the methodology is robust and effective in simultaneously simulating pebble flow and high-speed coolant flow, as well as in obtaining both pebbles' dynamic behavior and coolant speed distribution, which are necessary for future neutronic and thermal-hydraulic analysis.

A new initialization approach is also developed using quasi dynamic method. The results show that it is an efficient way to generate higher concentration pebbles at the initialization stage, which reduces subsequent simulation workload in the realistic model. Not like the methods used in ESys-Particle or PFC3D, pebble quantities can be easily controlled in this approach.

As one of future research plans, thermal effect will be incorporated into current methodology to account for the non-uniform distribution of coolant temperature, which has strong effect on coolant pressure distribution. And for further speeding up, parallelization will be implemented for effectively simulating pebble flow in a real full core.

ACKNOWLEDGMENT

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

REFERENCES

1. C. H. Rycroft, et al. "Analysis of Granular Flow in A Pebble Bed Nuclear Reactor," Phys. Rev. 2006.
2. A. M. Ougouag, J. J. Cogliati, "Methods for Modeling the Packing of Fuel Elements in Pebble Bed Reactors," M&C and SNA, France, 2005.
3. J. J. Lee, et al., "Numerical Treatment of Pebble Contact in the Flow and Heat Transfer Analysis of A Core," Nuclear Engr. And Design, 237, 2007.
4. J. E. Hoffmann, "Verification and Validation of the CFD Model of the PBMR Reactor," 3rd Intl. Topical Meeting on High Temperature Reactor Tech., 2006.
5. S. Abe and K. Mair, "Effects of Gouge Fragment Shape on Fault Friction: New 3D Modeling Results," Geographical Research Letters, Vol. 36, L23302, 2009.
6. J. W. Landry, et al. "Discrete Element Simulations of Stress Distributions in Silos: Crossover from Two to Three Dimensions," Powder Technology, 139, 2004.
7. J. Kozicki, F. V. Donze, "YADE-OPEN DEM: An Open-Source Software Using A Discrete Element Method to Simulate Granular Material," J. of Engineering Computations, Vol.26, Iss.7, 2008.
8. N. Djordjevic, "Discrete Element Modeling of Power Draw of Tumbling Mills," Mineral Processing and Extractive Metallurgy, 2003.
9. S. Okawara, et al., "High-fidelity DEM-CFD Modeling of Packed Bed Reactors for Process Intensification," Proceedings of European Congress of Chemical Engineering (ECCE-6), Copenhagen, September 2007.
10. J. J. Cogliati, A. M.Ougouag, "PEBBLES: A Computer Code for Modeling Packing, Flow and Re-Circulation of Pebbles in A Pebble Bed Reactor," 3rd International Topical Meeting on High Temperature Reactor Technology, 2006, South Africa.
11. P.A. Cundall, O.D.L.Strack, "A Discrete Numerical Model for Granular Assembles," Geotechnique 29(1) 47-65, 1979.
12. R.D. Felice, "The Voidage Function for Fluid-Particle Interaction Systems," Int. J. Mult. Flow, 20, 1994.