FLOW DISTRIBUTION OF PEBBLE BED HIGH TEMPERATURE OF PEBBLE BED HIGH TEMPERATURE GAS COOLED REACTORS USING LARGE EDDY SIMULATION

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ABSTRACT

The simulation of complex three-dimensional gas flow through the gaps of the spherical fuel elements (fuel pebbles) of Pebble Bed Modulator Reactor is performed. This will help in understanding the highly three-dimensional, complex flow phenomena in pebble bed caused by flow curvature. The flow of this type has distinctive features, which strongly affect the boundary layer behavior. The transition from a laminar to turbulent flow around this curved flow occurs at different Reynolds (Re) numbers. Noncircular curved flows as in the pebble-bed situation need to be investigated. In this study, Large Eddy Simulation (LES) is used in modeling the turbulence to overcome the shortcoming of the Reynolds Average Navier-Stokes approach.

1. Introduction

The High Temperature Gas-cooled Reactor (HTGR) is one of the renewed reactor designs to play a role in nuclear power generation. The high temperature helium gas-cooled nuclear reactor, Pebble Bed Modular Reactor (PBMR) offers inherent safety with high thermal efficiency features as well as flexible fuel cycle with capability to achieve high burnup levels. The combination of coated particle fuel, inert helium gas as coolant and graphite moderated reactor makes it possible to operate at high temperature yielding a high efficiency. Under these conditions, heat transfer in both laminar and turbulent flows varies noticeably around curved surfaces. Curved flows would be present in the presence of contiguous curved surfaces. In the case of an appreciable effect of thermogravitational forces, the Nusselt (Nu) number depends significantly on the curvature shape of the surface. It could change with order of 10 times. The flow passages through the gap between the fuel balls have concave and convex configurations. Here the action of the centrifugal forces manifests itself differently on convex and concave parts of the flow path (suppression or stimulation of turbulence). The flow of this type has distinctive features. In such flow there is a pressure gradient, which strongly affects the boundary layer behavior. The transition from a laminar to turbulent flow around this curved flow occurs at different Reynolds (Re) numbers. Consequently, noncircular curved flows as in the pebble-bed situation, in detailed local sense need to be investigated. To the authors’ knowledge there is no detailed complete calculations for this kind of reactor to address this local phenomena. This work is an attempt to simulate the flow behavior within the gaps.
The simulation of these local phenomena cannot be computed with existing conventional computational tools. Not all Computational Fluid Dynamic (CFD) methods are applicable to solve turbulence problems, in complex geometries. As in pebble bed reactor core, a compromise is needed between accuracy of results and time/cost of effort in acquiring the results. Resolving all the scales of a turbulent flow is too costly, while employing highly empirical turbulence models to complex problems could give inaccurate simulation results. In this study, the compromise is achieved by utilizing the large eddy simulation (LES) method. Here, the large scales in the flow are solved and the small scales are modeled. A schematic of the core region used in the LES calculations is presented in Fig. 1. It should be noted that the pattern of the pebble arrangement has several other orientations of the spheres. Figure 1 represents the first attempt to model a core region with this regular pebble arrangement.

2. Computational Modeling Approach

Accurate predictions of the flow and temperature distributions using computational fluid dynamic (CFD) programs depend on several factors as accurate modeling of the geometry, number of cells within the flow domain, mesh quality, selection of the solution technique and the selection of the appropriate turbulence models. In this investigation, the calculations are performed using the CFD code Trio_U [2]. It is a thermo hydraulic calculation modular software package. It includes several turbulence models as k-ε (averaged Navier-Stokes (RANS) type models) and large eddy simulation (LES) models with various subgrid models as Smagorinsky and structure function. This technique was first applied to applications in field of meteorology in the early 1970s. LES seeks to use a combination of direct numerical simulation (DNS) for large scale eddies and models for smaller eddies. It is a suitable compromise between the RANS-type methods and DNS.

Helium gas is passed into the reactor from the top and flows over the fuel pebbles in which a fission reaction is taking place. The helium is heated to a temperature of about 900-Celsius degree and pressure of 7 Mpa inside the reactor. The fuel sphere is 6 cm in diameter. Figure 1 presents the first pattern of 27 spheres with 36 contact points with zero spacing. The peak temperature that can be reached in the reactor core is 1600 Celsius. This is below the temperature of 2000 degrees Celsius that may damage the fuel. The flow parameters are summarized in Table 1. To generate the nodalization scheme an external mesh generator was utilized. This is due to Trio U has a simple mesh generator which was not capable to create the complex geometry of the pebble bed. Periodic boundary conditions were imposed at the inlet and outlet boundary conditions. The center of the coordinate system is chosen as the center of inner sphere.

Tetrahedral mesh type is used to achieve the complex geometry nodalization and to capture the details of the curved surfaces with sufficient number of nodes. Most of the commercial grid generation tools have the difficulty to handle the points where the curved surfaces are touching as in this model shown in Figure 1. Therefore, artificial spacing is usually applied due to limitations in mesh generation for this kind of three-dimensional complex model. This approach may cause convergence problems. In this study, zero spacing between the pebbles are achieved adjusting the quality of the isotropic nodes over the flow domain using a three-dimensional finite element mesh generator called Gmsh. Mesh description is summarized in Table 2. The maximum time step achieved for 43496 tetrahedral is 0.98 msec due to the CFL condition. One-second simulation took approximately 80 hours CPU time with a 4 processor (400MHz each) Ultra Spark 2 Sun System.

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3. Turbulence model

Selection of the turbulence model has a great influence on the accuracy of the prediction. To achieve accurate solutions under the complex flow conditions of pebble bed, the large eddy simulation (LES) technique is adopted. In LES the large-scale motions are explicitly resolved while small-scale motions, taking place below the limits of numerical resolution, are represented by a subgrid mode [3]. The underling premise is that the largest eddies are directly affected by the geometry and boundary conditions and can be computed. By contrast, the small-scale turbulence is nearly isotropic and has universal characteristics; consequently, it is more amenable to modeling.

Large-scale field is obtained by applying filtering. A filter provides a formal definition of the averaging process and separates the resolvable scales from the subgrid scales. Filtering is used to derive the resolvable-scale equations. With a generalized filter, the quantity $u_i$, resolvable-scale filtered velocity, is defined as follows:

$$ u_i (\mathbf{x}, t) = \iiint G(\mathbf{x} - \xi_i \Delta) u_i (\xi_i, t) \, d^3 \xi_i $$

(1)

The filter function, $G$, is normalized by requiring that

$$ \iiint G(\mathbf{x} - \xi_i \Delta) u_i (\xi_i, t) \, d^3 \xi_i = 1 $$

(2)
Among the many filter functions, the most popular one used in LES research is Gaussian filter and is defined by

\[ G(x - \xi; \Delta) = \left( \frac{6}{\pi \Delta^2} \right)^{1/2} \exp \left( -6 \frac{(x - \xi)^2}{\Delta^2} \right) \]  

(3)

where the filter width \( \Delta \) is defined by

\[ \Delta = (\Delta x \Delta y \Delta z)^{1/3}. \]  

(4)

In Trio, a homogeneous filter is utilized which is based on the selected numerical method (Barrè et al., 2000) [1]. For incompressible flow, the continuity and Navier-Stokes equations after applying filtering will have the following forms:

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0
\]  

(5)

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nabla \left( \bar{u}_i \frac{\partial \bar{u}_i}{\partial x_j} + \tau_{ij} \right)
\]  

(6)

Smagorinsky model assumes the SGS stress tensor, \( \tau_{ij} \), follow a gradient-diffusion process, similar to molecular motion. More detailed of subgrid modeling can be obtained from reference 2.

4. Results and Discussion

Figure 2 presents the location of several studied points. Regions close to the central pebble have been studied in details. Parameters such as velocity and pressure are analyzed. L1-L1’, L2-L2’, L3-L3’ and L4-L4’ are lines drawn along the y - direction from inlet to outlet.

- L1-L1’ => X = 0.03 m  Z = 0.00 m
- L2-L2’ => X = 0.03 m  Z = 0.015 m
- L3-L3’ => X = 0.03 m  Z = 0.03 m
- L4-L4’ => X = 0.0212 m  Z = 0.0212 m

Flow parameters have 1/8 symmetry along the x-z plane. As seen in Figure 2, the triangle is one of the 8 symmetric portions of the square surrounding the central pebble at the inlet. P1-P1’, P2-P2’, P3-P4’ and P4-P4’ are lines perpendicular to the y - direction as illustrated in Figure 3.

- P1-P1’ => Y = 0.00 m  Z = 0.03 m
- P2-P2’ => Y = -0.03 m  Z = 0.03 m
- P3-P3’ => Y = -0.06 m  Z = 0.03 m
- P4-P4’ => Y = -0.09 m  Z = 0.03 m

Pressure drop along the y-axis at different locations in x-z plane is shown in Figure 4. Total pressure drop along the flow direction is 204 Pa. The pressure difference along the X direction between L1-L1’ and L3-L3’ is approximately 50 Pa causing cross flow. Pressure drop along the x-axis at different locations on y-z plane is illustrated in Figure 5. The pressure distribution along the x-axis is symmetric. The maximum pressure change is about 75 Pa causing cross flows. Vector velocity plot for velocity within the pebble gaps is presented in Fig. 6. Various ranges of velocity scales are observed. In addition, flow circulation and stagnation are predicted.
5. Conclusion

A flow distribution calculation is performed using the state-of-the-art large eddy simulation technique. The complex highly three-dimensional flow in the gaps between the pebble beds is predicted.

6. References

Fig 4. Pressure distribution along y-axis at different locations

Fig 5. Pressure distribution along X-axis at different locations

Fig 6. Velocity vector distribution along X-Y plane at Z= 0.085 m