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Inlet Plenum Analysis for a Pebble Bed Modular Reactor

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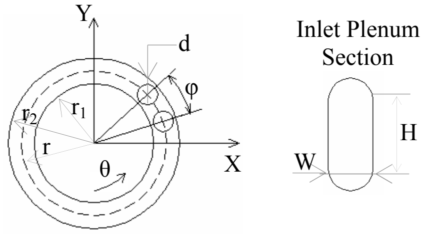
1. Introduction

A High Temperature Gas Cooled Reactor (HTGR) [1] is one of the renewed reactor designs to play a vital role in nuclear power generation. This reactor design concept is currently under consideration and development worldwide including Korea. Since the HTGR concept offers inherent safety, has a very flexible fuel cycle with capability to achieve high burn up levels, and provides good thermal efficiency of power plant, it can be considered a further development and improvement as a reactor concept of generation IV. 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.

The current Pebble-Bed Modular Reactor (PBMR) [2] design under development by Korea Atomic Energy Research Institute (KAERI) [3] belongs to the class of generation IV reactors satisfying the goal of HTGR. Its power conversion unit is based on the thermodynamic Brayton cycle. The Helium gas traverses through inlet plenum, rising channels and outlet plenums also called riser plenums before entering into the core from the top of the reactor at a temperature of about 540^0C and at a pressure of about 7 MPa. The coolant exit temperature of the PBMR is 900^0C under normal operating condition.

For optimum performance of the core, uniform cooling is required as non-uniformity may cause severe temperature gradients inside the pebble core. Also, there is a limit to the maximum temperature rise inside the core as the higher temperature inside the core increases the probability of neutron absorption by U-238 atoms thereby, reducing the number of neutrons available for U-235 fission which in turn, will result in reduced power output. These entail the requirement of uniform coolant flow distribution in rising channels. Another important phenomenon of concern is the pressure drop inside the inlet plenum, rising channels and outlet plenums since higher losses will result in decrease in overall efficiency of the power plant. Thus, good knowledge of the flow details in the inlet and outlet plenums as well as rising channels are necessary for optimum design.

This study deals with the flow analysis inside the inlet plenum and rising channels using Computation Fluid Dynamics (CFD). CFD has extensively been used in different engineering applications including nuclear science. A ring type inlet plenum, as shown in Fig. 1, is proposed for use as Inlet Plenum for Korean Pebble Bed Modular Reactor. In this work, three-dimensional flow distributions and pressure drop in the inlet plenum and rising channels of a PBMR are predicted. Resulting flow distributions for the reference case have been studied and subsequently, parametric studies have been performed to assess the effect of different parameters on the flow distribution in the rising channels and pressure drops.



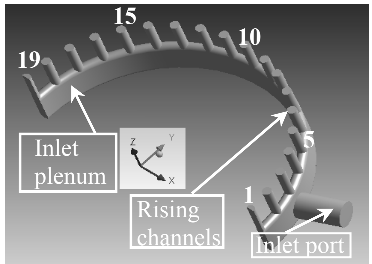


Fig. 1 Ring-type Inlet plenum

2. Governing Equations and Numerical Conditions

The present calculation is based on CFD simulations. The 3-dimensional Reynolds Averaged Navier-Stokes (RANS) equations are solved in conjunction with the k-ε model as a turbulence closure. A commercial CFD code, CFX 5.7.1 [4] is used for the calculations. Taking advantage of symmetry about x-z plane as shown in Fig. 1, calculations are performed for only half of the geometry to reduce the computational load. The reference case dimensions are as follows: W = 0.22m, H = 0.60m, d = 0.20m, $\varphi = 10^0$, r_1 = 3.0m, and r_2 = 3.22m. The angle between inlet ports, α in this case is 40^0. Reynolds number, Re of the calculation based on inlet diameter was 75600, and the fluid used in the calculation was He (Ideal gas) at 500°K. All the calculations were performed under isothermal condition.

The following boundary conditions were adopted:

- Normal velocity specified as the mean flow velocity at the inlet.
- Constant pressure at the outlet.
- No-slip and adiabatic conditions are used at all the wall boundaries.

- Symmetry condition (zero normal gradients) is specified on the symmetry plane.

A systematic study of grid independence for the reference case was carried out to verify the grid independency of the numerical solution. From the results, grid having 331,500 nodes is selected as an optimum grid. All the simulations were conducted by means of a segregated method using the SIMPLE scheme [5] for pressure-velocity decoupling. Nominally second order-accurate schemes were selected for the discretization of the governing equations. A residual reduction factor of 10^{-6} for the mass conservation equation was used to monitor the convergence of the iterative solution.

3. Results and Discussions

The following parameters have been defined to express the results in physical terms:

$$S_i = \frac{m_i - m_{avg}}{m_{avg}} \qquad (1)$$

$$c_p = \frac{p - p_{in}}{1/2 \rho U^2} \qquad (2)$$

where, m_i is the mass-flow through a rising channels (i = 1, 2,..,19), m_{avg} is the average mass flow, S_i is the relative mal-distribution parameter, p is the static pressure, p_{in} is the inlet static pressure, ρ is the fluid density and U is the mean inlet velocity.

The relative flow mal-distribution parameter, shown in Fig. 2 for the reference case, shows the magnitude of difference between the flow-rate in different rising channels from the average value. As it is clear from this figure, the mass flow distribution is strongly non-uniform in this case. Figure 3 shows the distribution of pressure coefficient (c_p) at a distance just below the rising channels inlet (z = 0.4m). Fluctuating pressure variation is observed because the flow stagnates on the plenum wall as it turns into the rising channels.

The parametric studies have been performed using rising channels diameter, angle between inlet ports, and Reynolds number based on inlet diameter in the range 0.07m < d < 0.20m, $0^0 < \alpha < 180^0$ and 75600 < Re < 378000, respectively. Figure 4 shows the relative mal-distribution parameter variation for different rising channels diameter. As it is clear from the figure, as the rising channels diameter decreases, flow uniformity increases. For, d = 0.08m, the relative mal-distribution parameter was within 5 percent of the average mass-flow rate of all the rising channels and hence this value of d has been used in other parametric studies. Figure 5 shows the pressure drop variation for different rising channels diameter. The Reynolds number is found to have no effect on the flow distribution. However, it is found that as the Reynolds number increases, the pressure drop also increases. The angle between inlet ports, α is found to increase the flow uniformity with the increase in its value. The pressure drop in this case showed decreasing trend.

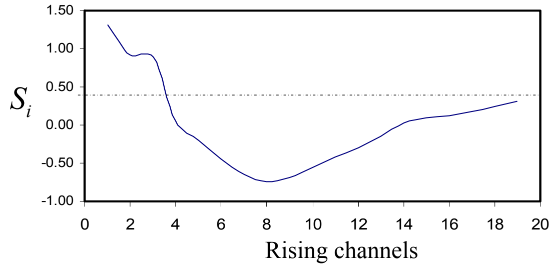


Fig. 2 The relative mal-distribution parameter variation

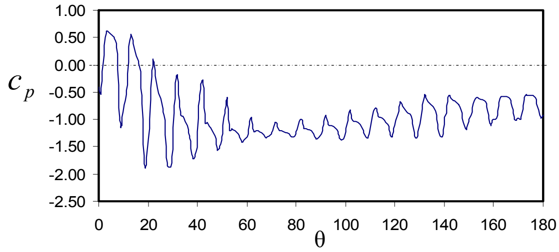


Fig. 3 Non-Dimensional Static Pressure Distribution inside the plenum

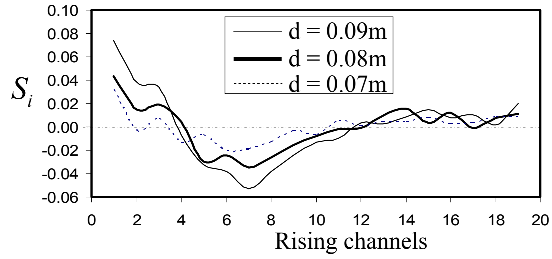


Fig. 4 The relative mal-distribution parameter variation for different rising channels diameter

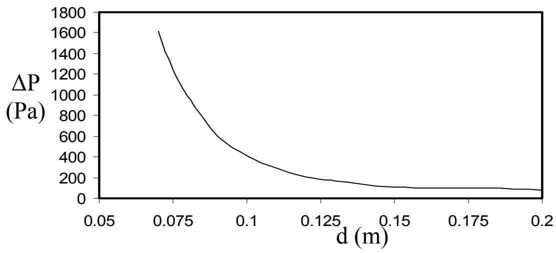


Fig. 5 Effect of d on the pressure drop inside the plenum

Conclusion

The mass-flow distribution in the reference case was strongly non-uniform which necessitated the need of parametric study. The rising channels diameter affects the flow distribution as well as pressure drop tremendously. However, the effect of angle between inlet ports was not much pronounced.

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