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Design Optimization of Inlet Plenum of PBMR Using Kriging Modeling Technique

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1. Introduction

In pebble-bed modular reactor (PBMR), 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. In cooling system of PBMR shown in Fig. 1 [1], Helium gas as the coolant enters the reactor through inlet plenum, i.e., ring channel at the bottom of the reactor, goes up through several rising channels to upper plenum, enters the core at a temperature of about 540°C and at a pressure of about 7 MPa, and then leaves the reactor through lower plenum at a temperature of about 900°C under normal operating conditions. Ahmad et al. [2] performed a parametric study on inlet plenum geometry of PBMR with Reynolds-averaged Navier-Stokes (RANS) analysis, and suggested that the flow uniformity in rising channels as well as the pressure drop is found to increase as the channel diameter is decreased. The flow distribution in the rising channels is independent of Reynolds number. Increase in the angle between the inlet ports and aspect ratio is found to increase the uniformity in flow distribution. However, there has not been a trial to introduce systematic optimization techniques in the design of cooling passages of HTGR to find the geometry which maximizes the performance. In this work, shape optimization of inlet plenum and rising channels in PBMR has been performed based on three-dimensional RANS analysis. Kriging model [3] is used as a surrogate model for optimization. The objectives of the design are to maximize the uniformity in the flow distribution in rising channels and to minimize the pressure drop.

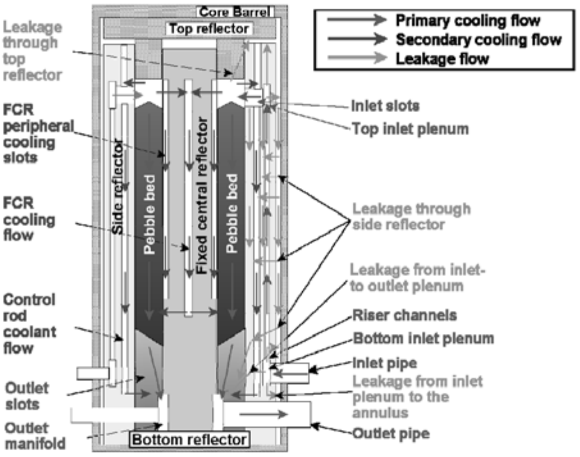


Fig. 1 Schematic Mass Flow Diagram of PBMR [1]

2. Flow Analysis and Optimization Methods

A commercial CFD code, ANSYS CFX-11.0 [4] has been used to solve continuity and Reynolds-averaged Navier-Stokes equations for three-dimensional incompressible steady flow in the inlet plenum and rising channels of PBMR shown in Fig. 2. In this work, Shear Stress Transport (SST) model [5] with automatic wall treatment is used to improve the accuracy of predictions. Only a half of the geometry is included since the geometry of inlet plenum is symmetric about x-z plane.

For the first step of the optimization procedure, the objective function and design variables are selected. The design space is then decided for improved system performance. Using Latin Hypercube Sampling (LHS) [6] as the mean of DOE (design of experiment), the design points are then obtained. At these design points, the objective function is calculated using a flow solver. Finally, the surrogate, i.e. the Kriging model, is constructed, and then optimal points are searched by the optimal point search algorithm.

The objective function (F) is defined as a linear combination of two different functions representing pressure loss in the inlet plenum (F_p) and uniformity of mass flow distribution in rising channels (F_f) with a weighing factor, β as follows:

$$\boldsymbol{F} = \boldsymbol{F}_p + \boldsymbol{\beta F}_f \tag{1}$$

Ratio of rising channel diameter to height of inlet plenum, ratio of width to height of inlet plenum, and angle between two inlet ports are employed as design variables.

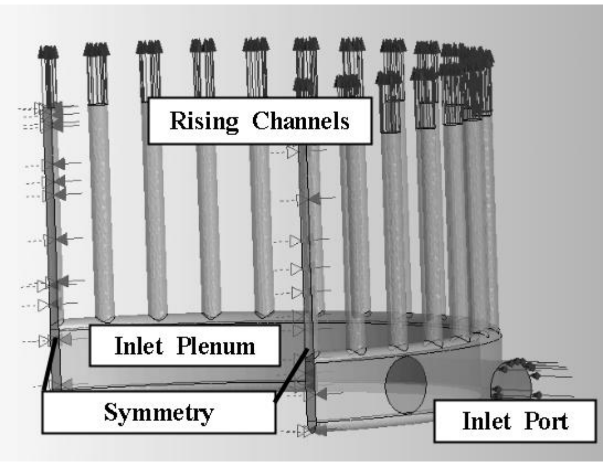
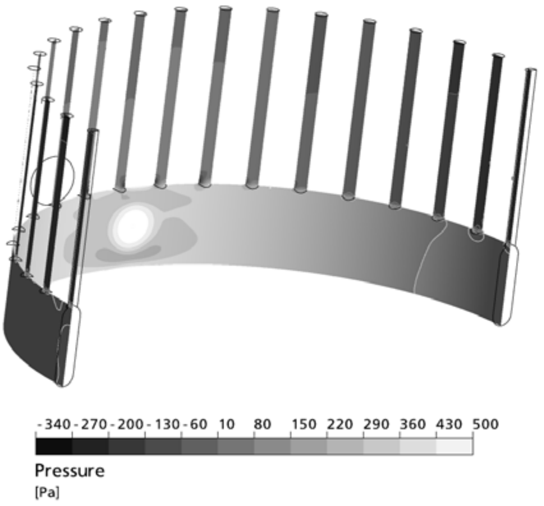


Fig. 2 Geometry of Ring-type Inlet Plenum

Table I: Results of Optimization

	Reference	Optimum
Objective Function	57.6	5.85

(a) Reference shape



(b) Optimum shape

Fig. 3 Static Pressure Distributions of the Inlet Plenum

3. Results

For the optimization, the Kriging model has been constructed based on the evaluations of the objective function by RANS analysis at 20 experimental points obtained by LHS. As results of the optimization, values of the objective function for the optimum geometry are compared with that for the reference geometry in Table I. The objective function is reduced by 89.8 % by the optimization.

Fig. 3 shows static pressure distributions of the inlet plenum and rising channels. In the reference geometry, the pressure decreases rapidly at the exit of the inlet plenum in the direction opposite to the other inlet port, and recovers gradually downstream. The similar behavior of the pressure is found in the optimum geometry, but the overall pressure difference in the inlet plenum is quite less than that in reference geometry.

4. Conclusions

Shape optimization of the inlet plenum has been performed to improve the uniformity of flow distribution in the rising channels and also to decrease the pressure drop. Kriging model as a surrogate model has been used to optimize the geometry with three geometric design variables, which required twenty evaluations of the objective function by Reynolds-Averaged Navier-Stokes analysis in the design space. As the results of the optimization, the uniformity has been improved by 92.9 %, and the pressure drop reduced by 1.55% in comparison with the reference geometry. It is confirmed by RANS analysis that the prediction by Kriging model at the optimum point is quite accurate. Therefore, the optimization procedure presented in this work is proved to be very efficient and also economic for the design of cooling passages of PBMR.

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