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Optimization of a Wire-Spacer Fuel Assembly of Liquid Metal reactor

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Abstract-- This study deals with the shape optimization of a wire spacer fuel assembly of Liquid Metal Reactors (LMRs). The Response Surface based optimization Method is used as an optimization technique with the Reynolds-averaged Navier-Stokes analysis of fluid flow and heat transfer using Shear Stress Transport (SST) turbulence model as a turbulence closure. Two design variables namely, pitch to fuel rod diameter ratio and lead length to fuel rod diameter ratio are selected. The objective function is defined as a combination of the heat transfer rate and the inverse of friction loss with a weighting factor. Three level full-factorial method is used to determine the training points. In total, nine experiments have been performed numerically and the resulting datas have been analysed for optimization study. Also, a comparison has been made between the optimized surface and the reference one in this study.

Key Words : Optimization, Response Surface Method (RSM), Wire-Spacer Fuel Assembly, Liquid Metal Reacto (LMR), Computational Fluid Dynamics

1.Introduction

A wire-spacer fuel assembly for Liquid Metal Reactors (LMRs) generally consists of fuel rods spaced on a triangular pitch and contained within a hexagonal duct. To minimize the hot spots and permit adequate cooling, the rods are separated by spacer wires wounded helically around each rod. The presence of wire-wraps increases the pressure drop and thus the pumping power required, but it has the virtue of enhancing flow mixing in the bundle and thereby reducing the hot spots and temperature gradients if they exist.

In an LMR, the fuel and blanket assemblies are subject to severe radial gradients in the rate of heat generation and have a wide range of flow conditions. This necessitates the basic understanding of these phenomena to achieve the optimum design performance.

Many experimental works as well as numerical analysis using simplified methods such as subchannel analysis method [1] and Porous body model analysis [1] have been performed for fluid flow and heat transfer analysis in a wire spacer fuel assembly. An account of the experimental and numerical works can be found in the work of Ahmad and Kim [2], where they performed the flow and heat transfer analysis based on the three-dimensional RANS analysis for the first time.

Inspite of the usefulness of wire-spacers inside the LMRs fuel assembly, shape optimization of the wire-spacers have not been performed, yet because of its complicated structure. The purpose of this work is to optimize the shape of wire-spacers using numerical optimization technique coupled with RANS analysis of fluid flow and heat transfer. The response surface method [3] as a global optimization method has been selected because of its obvious advantage over gradient based methods. Two design variables namely, pitch to fuel rod diameter ratio (P/D) and lead length to fuel rod diameter ratio(H/D) are selected for optimization purpose. The objective function [4] is defined as a combination of the heat transfer rate and the inverse of friction loss with a weigthing factor.

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2. Numerical Analysis

The analysis is performed for a single period of the wire spacer using periodic boundary conditions at inlet and outlet of the calculation domain. The pressure $p(x,y,z)$ in periodically fully developed flow can be expressed as;

$$p(x,y,z) = -\beta z + p_p(x,y,z) \qquad (1)$$

where, β is the mean pressure gradient, $p_p(x,y,z)$ is the periodic part of the pressure and βz is the pressure drop.

Similarly, the temperature, $T(x,y,z)$ can be expressed as;

$$T(x,y,z) = \gamma z + T_p(x,y,z) \qquad (2)$$

where, γ is the mean temperature gradient, $T_p(x,y,z)$ is the periodic part of the temperature, and γz is the rate of temperature rise in the flow direction.

Thus, the governing equations can be written as;

Continuity:

$$\frac{\partial \rho U_i}{\partial x_i} = 0 \qquad (3)$$

Momentum:(4)

$$U_j \frac{\partial U_i}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\nu \frac{\partial U_i}{\partial x_j}\right] - \frac{1}{\rho}\frac{\partial p_p}{\partial x_i} + \beta \delta_{ij} \qquad (4)$$

Energy:

$$\frac{\partial}{\partial x_i}(\rho c U_j T_p) = \frac{\partial}{\partial x_j}\left[K \frac{\partial T_p}{\partial x_j}\right] - \gamma U_j \delta_{ij} \qquad (5)$$

Where, U_i indicates the mean velocity component, c, the specific heat and δ_{ij} is the kronecker delta.

The definition of geometric parameters of a wire-spacer fuel assembly is shown in Fig. 1. The wire-wrap is mounted on the fuel rods in counter clock wise direction starting from 12-o'clock position as shown in the figure.

A commercial CFD code, CFX 5.7.1 [5] which employs unstructured grid has been used for numerical analysis. SST model [6] is used as a turbulence closure. To get a good quality volume mesh, blending between wire-spacers and fuel rods is used as shown in Fig. 2. In all the cases, fuel rod diameter, D (=8mm) was kept constant. Also, W/D and P/D ratios were equal and the pitch was assumed to be equal to P = D + d + c_0, where, d is wire-spacer diameter and c_0(=0.10mm) is a constant. The training points and the dimensionless design variables are shown in table 1.

Fluid flows upward in the fuel assembly. Periodic conditions are set at the inlet and outlet sections. The calculated values of velocities and turbulence quantities at the outlet section were substituted as the inlet conditions for the next iterations. Constant heat flux is imposed on the fuel rod surfaces while at the hexagonal duct wall, adiabatic condition is used. At all the wall boundaries, the wall function based on empirical wall law for the near-wall turbulence is adopted for mean axial velocity.

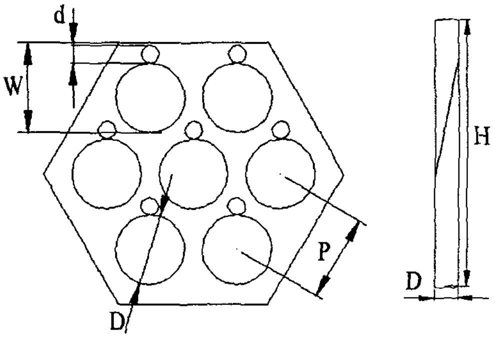

Fig. 1 A 7-pin wire-spacer Fuel Assembly

3. Numerical Optimization

To maximize the thermal performance of the wire-spacer fuel assembly, the following objective function is defined;

$$F = F_N + \omega(1/F_f) \tag{6}$$

where,

$$F_N = \frac{1}{H}\int_0^h \frac{\overline{Nu_h}}{\overline{Nu_o}}dh \tag{7}$$

and, $$F_f = \frac{1}{H}\int_0^H \left(\frac{f}{f_o}\right)^{1/3} dh \tag{8}$$

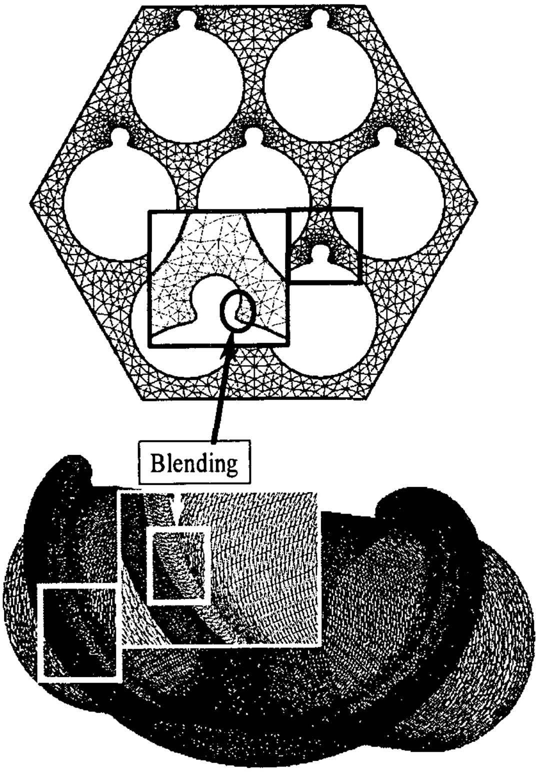

Fig. 2 Mesh structure on periodic surfaces and fuel rods (P/D = 1.178, H/D = 8, Number of Nodes = 976,000)

where, the subscript o indicates the sates without wire-spacers, h is the coordinate in the axial direction, H is the lead length, is f the friction factor obtained from Cheng and Todreas correlations [7]. $\overline{Nu_h}$ is the average local Nusselt number.

In this work, the objective function is approximated by a response surface based on numerical experiments. A polynomial based response surface is commonly employed in the RSM. Unknown coefficients of a polynomial are obtained from a regression process. The response model is usually assumed as a second-order polynomial, which can be written as follows:

$$F = \beta_0 + \sum_{j=1}^{n}\beta_j x_j + \sum_{j=1}^{n}\beta_{jj} x^2 + \sum \sum_{i \neq j}\beta_{ij} x_i x_j \tag{9}$$

where n is the number of design variables, and the number of regression coefficients (β_0, β_1, etc.) is $(n+1)(n+2)/2$.

Table 1 Dimensionless Design Variables

P/D	H/D		
	8	12	16
1.1780	(-1, -1)	(-1, 0)	(-1, 1)
1.2665	(0, -1)	(0, 0)	(0, 1)
1.3550	(1, -1)	(1, 0)	(1, 1)

4. Results and Discussion

Grid dependency for the numerical analysis is tested first and the resulting grid for the case is shown in Fig. 2. The numerical result has been validated with the bundle friction factor and the numerical analysis for design data's at training points is performed afterwards. A very complex flow and heat transfer phenomena is observed in the wire-spacer fuel assembly. A detailed discussion on the flow and heat transfer phenomena can be found in the work of Ahmad and Kim [2].

The variation of a component of objective function with H/D and P/D is shown in Fig 3 (a) and (b), respectively. It can be observed from this figure that the objective function is sensitive to both the design variables as expected. Also, as the P/D ratio and H/D ratio were increased, the average Nusselt number was found to increase. However, opposite phenomena was observed in case of P/D and H/D for friction factor.

In Fig. 4 (a) and (b), a comparison has been made for the reference case and for the optimized case. As can be seen in the figure, a very effective optimized surface can be found as a result of the response surface method optimization study.

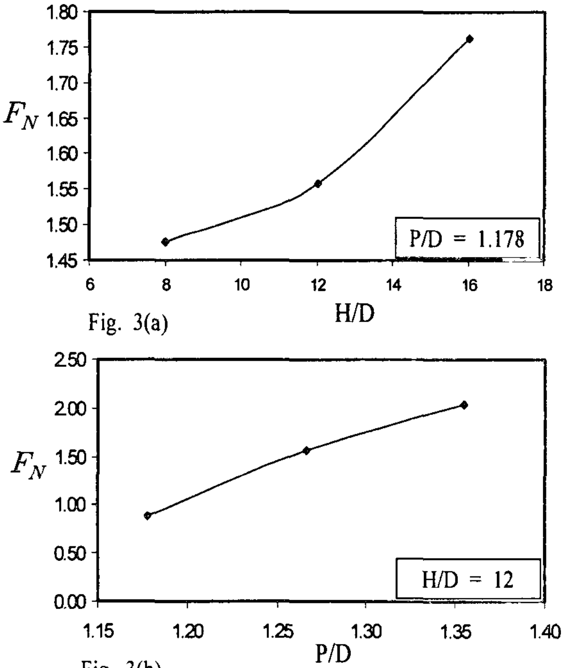

Fig. 3(a)

Fig. 3(b)

Fig. 3 Variation of F_N with (a) H/D ratio and (b) P/D ratio.

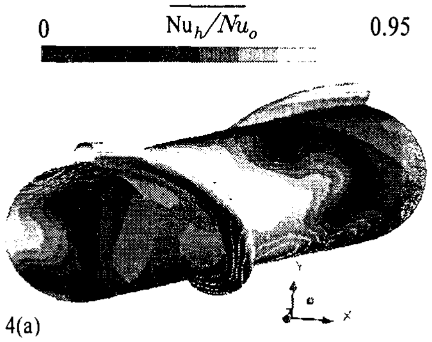

Fig. 4(a)

5. Conclusion

The flow and heat transfer analysis was performed using RANS analysis and the shape optimization was done using response surface method. The flow and heat transfer phenomena observed in the wire spacer fuel assembly is very complex . The objective function is found to be sensitive to the design variables and in this case, a very good optimized result is found with response surface optimization technique.

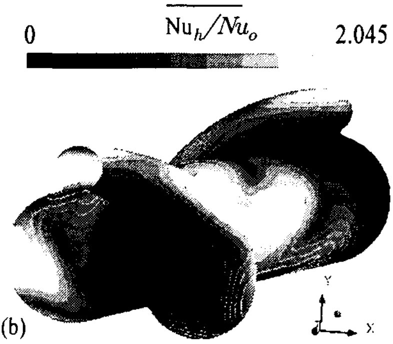

Fig. 4(b)

Fig. 4 Average Nusselt numver variation on the fuel rod and wire-spacer surfaces for (a) reference shape, and (b) optimized shape.

References

[1] William T.SHA, An overview on rod-bundle Thermal-Hydraulic analysis, Nuclear Engineering and Design 62 (1980), pp. 1-24.

[2] Imteyaz AHMAD and Kwang-Yong KIM, Three Dimensional Analysis of Flow and Heat Transfer in A Wire-Wrapped Fuel Assembly, Proceedings of the ICAPP 2005, Paper 5071

[3] R. H. MYERS and D. C. MONTGOMERY, Response Surface Methodology: Process and Product Optimiztion Using Designed Experiments, Jonh Wiley & Sons, New York (1995).

[4] J. W. SEO and K. Y. KIM, Numerical optimizationfor the design of spacer grids with a mixing vane, Nuclear Technology, Vol. 149, No. 1, Jan. 2005. pp. 62-70.

[5] CFX-5.7 Solver Theory, Ansys Inc.,2005.

[6] Menter, F., and Esch, T., 2001, "Elements of Industrial Heat Transfer Predictions," 16th Bazilian Congress of Mechanical Engineering (CPBEM). Uberlandia. Brazil.

[7] S.K. Cheng, N.E. Todreas, "Hydrodynamic Models and correlations for bare and wire-wrapped hexagonal rod bundles- bundle friction factors. subchannel friction factors and mixing parameters."Nuclear Engineering and Design 92. 227-251(1986).