Shape Optimization of Wire-Wrapped Fuel Assembly of LMR

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1. Introduction

A wire wrapped fuel assembly of a Liquid Metal Reactor (LMR) consists of fuel rods arranged on a triangular array and housed in hexagonal ducts. To maintain a proper spacing between the fuel rods and enhance convective heat transfer by virtue of increased turbulent kinetic energy, helical type wire-spacers are wounded around each rod.

A lot of experimental as well as numerical analysis such as sub-channel analysis and porous body model analysis [1] has been performed for flow field and heat transfer analysis in a wire wrapped fuel assembly. Ahmad and Kim [2] performed the flow and heat transfer analysis based on the three-dimensional RANS analysis. But numerical optimization has not been applied to the design of wire-wrapped fuel assembly, yet.

The present work aims to enhance the turbulent heat transfer and reduce friction loss by optimization of 7-pin wire-wrapped fuel assembly using the response surface method (RSM) [3] for optimization technique coupling with three-dimensional Reynolds-averaged Navier-Stokes (RANS) analysis. Two geometric design variables and a objective function which is a combination of heat transfer and friction loss is considered for this problem.

2. Numerical Analysis and Problem Formulation

The numerical analysis is performed for one period of the wire spacer using periodic boundary condition. To adopt the periodic boundary conditions, modification of source terms in streamwise momentum and energy equations have been made to calibrate the gradual decrease and increase of pressure and temperature, respectively. Finally, for three-dimensional steady incompressible flows, mass, momentum and energy conservation equations in tensor form can be written as follows:

$$\frac{\partial U_i}{\partial x_i}=0 \tag{1}$$

$$U_j\frac{\partial U_i}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\nu\frac{\partial U_i}{\partial x_j}\right)-\frac{1}{\rho}\frac{\partial \hat{p}}{\partial x_i}+\gamma\delta_{1i} \tag{2}$$

$$\frac{\partial}{\partial x_j}(\rho c_p U_j\hat{T})=\frac{\partial}{\partial x_j}\left(k\frac{\partial \hat{T}}{\partial x_j}\right)-\sigma U_j\delta_{1j} \tag{3}$$

where $\hat{p}(x,y,z)$ and $\hat{T}(x,y,z)$ are the pressure and temperature transformed as follows in order to use the periodic boundary conditions in streamwise direction, *x*.

$$\hat{p}(x,y,z)=p(x,y,z)+\gamma x \tag{4}$$

$$\hat{T}(x,y,z)=T(x,y,z)-\sigma x \tag{5}$$

Here γ is the pressure gradient along streamwise direction and σ is the rate of bulk temperature increase

A commercial CFD code, ANSYS CFX [4], which employs unstructured grid, has been used for numerical analysis. Blending between fuel rod and wire spacer has been used to get a good quality of volume mesh. Shear Stress Transport (SST) turbulence model is used as a turbulence closure.

Periodic boundary condition is applied at the inlet and outlet of calculation domain. Constant heat flux condition is used at the surfaces of fuel rod while adiabatic condition is used at the hexagonal duct wall. Liquid sodium (Na) is used as coolant. After grid dependency test for the numerical analysis the optimum number of grid points was found to be approximately 8.62 X 10^5.

Design variables and computational domain are represented in Fig. 1. Computational domain is composed of one pitch of wire spacer (H). The fuel rod diameter, D (=8mm) was kept constant. Also fuel rod pitch (P) and distance from duct wall (W) were equal and the pitch was assumed to be equal to $P=D+D_W+C_0$, where, D_W is wire spacer diameter and C_0 is the gap between wire spacer and neighboring fuel rods. The dimensionless design variables and their ranges are shown in table 1. Latin Hypercube Sampling (LHS), which provides evenly spaced training points in the design space, was used to get design points.

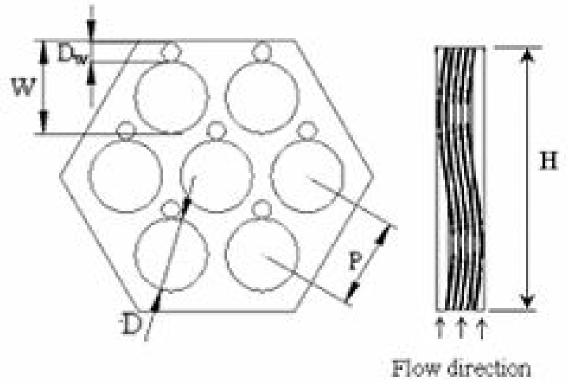

Figure 1. Design variables and computational domain

Table 1. Design variables and ranges

Design variable	Lower bound	Upper bound
D_W/D	0.16	0 .31
H/D	8	24

3. Optimization Technique

In the present work, response surface method (RSM), which is, simply a regression analysis, is used as optimization technique. A second-order polynomial is represented for RSM is written as follows:

$$F = \beta_o + \sum_{j=1}^{n} \beta_j x_j + \sum_{j=1}^{n} \beta_{jj} x_j^2 + \sum\sum_{i \neq j} \beta_{ij} x_i x_j \qquad (6)$$

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

Objective function values obtained from RANS analysis are used to formulate function for RSM and this function is used to find optimal point by Sequential Quadratic Programming (SQP).

The wire wrapped fuel assembly is shown in Fig. 1. Due to numerous geometric constraints for a wire wrapped fuel assembly of a LMR; there are not many choices of design variables. Therefore two design variables such as D_W/D and H/D are selected.

To maximize the performance of wire spacer, the optimal shape should be determined by a compromise between the enhancement of heat transfer and reduction in the friction loss. Therefore the objective function (F) is defined as a linear combination of two different functions representing the heat transfer (F_N) and the inverse of the friction loss (F_f), respectively with a weighing factor (ω) of 1 as follows:

$$F = F_N + \omega(1/F_f) \qquad (7)$$

The current optimization is done considering ω=1.0

4. Result and Discussion

The reference and predicted optimal values are shown in the table 2. Here, it is seen that large improvement in objective function value, which indicates the visible improvement in heat transfer compromising with friction loss.

The resulting 3-dimensional mesh plot of response surface is shown in Fig. 2. The axes (Dw/D and H/D) representing design variables are normalized in range [0 1]. The optimum point located at (0.531, 0.574) on the surface is shown in this figure. The corresponding values of D_W/D, H/D are 0.239 and 17.187 respectively in their original range. The predicted value of objective function at the optimal point is 1.362.

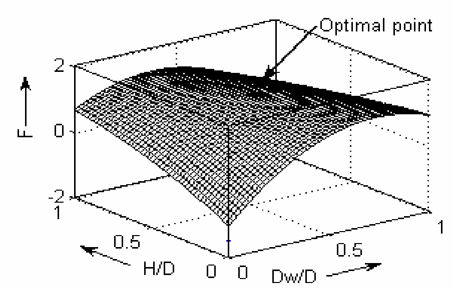

Figure 2. 3-D plot of response surface function

Table 2 result of optimization

Shape	Design variables		Objective function
	Dw/D	H/D	
Reference	0 .250	25.000	0.866
Optimal	0.239	17.187	1.362

5. Conclusion

Geometric parameters of the wire wrapped fuel assembly have been optimized by response surface based optimization method coupled with RANS analysis. The objective function is maximized to enhance the performance of wire spacers by compromising between heat transfer enhancement and friction loss reduction. The value of objective function is increased by 57.4 % and hence rate of heat transfer increased.

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