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Multiple Surrogate Modeling for Wire-Wrapped Fuel Assembly Optimization

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1. Introduction

In this work, shape optimization of seven pin wire-wrapped fuel assembly has been carried out in conjunction with RANS analysis in order to evaluate the performances of surrogate models. Previously, Ahmad and Kim [1] 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. Surrogate models are being widely used in multidisciplinary optimization. Queipo et al. [2] reviewed various surrogates based models used in aerospace applications. Goel et al. [3] developed weighted average surrogate model based on response surface approximation (RSA), radial basis neural network (RBNN) and Krigging (KRG) models. In addition to the three basic models, RSA, RBNN and KRG, the multiple surrogate model, PBA also has been employed. Two geometric design variables and a multi-objective function with a weighting factor have been considered for this problem.

2. Numerical Analysis and Problem Formulation

A commercial CFD code, ANSYS CFX 5.7 [4], which employs unstructured grid, has been used for numerical analysis. The numerical analysis has been performed for one period of the wire spacer using periodic boundary condition at inlet and outlet of the calculation domain. Shear Stress Transport (SST) model with automatic wall treatment is used as a turbulence closure 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.

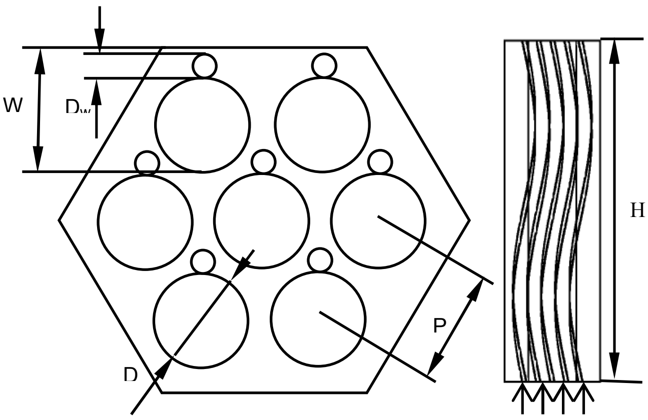


Figure 1. Design variables and computational domain

Design variables and computational domain are represented in Fig. 1. Computational domain is composed of one pitch of wire spacer (H).

To maximize the performance of fuel assembly, the objective function is defined as linear combination of two different functions representing the heat transfer and the inverse of friction loss with a weighing factor. Latin Hypercube Sampling (LHS) is used to get design points. Design variables and their ranges are shown in table 1.

3. Optimization Techniques

The three basic surrogate models and the weighted average model PBA are explained here.

Response surface approximation (RSA) method is collective use of design of experiment techniques, regression analysis, and analysis of variance (ANOVA). The second order polynomial function is fitted to get the response surface approximation. Radial basis neural network (RBNN) is two layer networks which consist of a hidden layer of radial basis function and a linear output layer. Kriging model is a deterministic technique for optimization. Linear polynomial function with Gauss correlation function is used for model construction. A weighted average model proposed by Goel et al.[3] is adopted in the present investigation. It is based on the PRESS-based-averaging (PBA) model (termed WTA3 by Goel et al.[3]). Evaluations of the objective functions at the design points are carried out by three-dimensional RANS analysis. At the next step, RSA, Kriging and RBNN models are constructed using objective function values at design points. To construct the weighted average model, cross validation errors are calculated using these design points and objective function values obtained as above. The constructed surrogates are used to search for optimal points.

4. Result and Discussion

Tables 2-3 show results of the optimizations obtained by different surrogate models. Table 2 show the comparison between the optimal objective function values predicted by different surrogate models with those obtained by RANS calculation at corresponding optimal design points for weighting factor, ω=1.0.

Table 1. Design variables and ranges

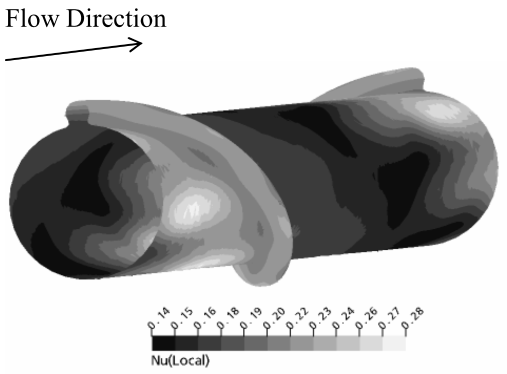
Design variable	Lower bound	Upper bound
D_W/D	0.16	0 .31
H/D	8	24

Table 2 Optimal points and respective predicted and calculated values of objective function for ω=1.0

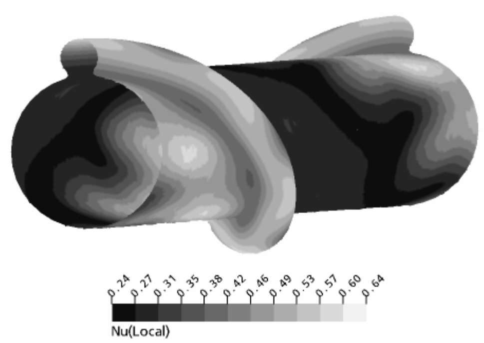
Model	Dw/D	H/D	$F_{surrogate}$	F_{RANS}	$F_{surrogate} - F_{RANS}$
PBA	0.247	14.3	1.429	1.458	0.029
RBNN	0.253	13.4	1.468	1.402	0.066
RSA	0.240	17.2	1.362	1.431	0.069
KRG	0.246	13.6	1.487	1.449	0.038
Reference	0.160	16.0		0.994	

Table 3.Weights for different models to construct weighted average model

MODEL	PRESS	Weight (PBA)
RBNN	0.180	0.351
RSA	0.187	0.337
KRG	0.203	0.312



(a) Reference shape



(b) Optimal shape (PBA)

Fig. 2 Nusselt number contours on reference and optimal (PBA) fuel rod

It is found that at the optimum point predicted by weighted average model, PBA, the highest RANS calculation (F_{RANS}) as well as the highest surrogate prediction ($F_{surrogate}$) for the objective function are obtained. And, among the individual surrogates, KRG shows the best performance. In comparison with the reference assembly which was selected arbitrarily in the design space, considerable increase in the objective function value, for example 46.7% by PBA, is achieved by the optimizations. Table 3 shows the cross validation errors and calculated weights for the weighted average model, PBA. RBNN shows the lowest cross validation error,and thus gives the highest weight. Without additional computational cost as these models uses the same computational data base, multiple optima which helps in getting substantial improvement in surrogate models performance have been obtained.

Fig. 2 shows the local Nusselt number contour on the central fuel rod in optimized and reference cases. In both cases, high heat transfer rate region appears just upstream of wire due to the strong vortex generated by the wire blockage .Downstream of the wire, the heat transfer rate increases rapidly beyond the line of flow reattachment. The overall level of Nusselt number on optimal fuel rod is larger than that on reference rod.

5. Conclusion

The performances of three basic models, RSA, KRG and RBNN as well as weighted average model, PBA in the optimization of wire wrapped fuel assembly are evaluated. It is found that the weighted average model, PBA predicts the highest objective function value as well as gives the most reliable surrogate. Among the basic models, KRG shows the best performance. From the results, it may be concluded that the weighted average model protects the designer from selecting a poor surrogate, and provides the most reliable optimization.

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