Shape Optimization of A Surface Roughened by Staggered Ribs To Enhance Turbulent Heat Transfer

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Abstract

The present study investigates on design optimization of rib-roughened two-dimensional channel to enhance turbulent heat transfer. Response surface method with Reynolds-averaged Navier-Stokes analysis is used as an optimization technique. Standard k-ε model with wall functions is adopted as a turbulence closure. The objective function is defined as a linear combination of heat transfer and friction drag coefficients with weighting factor. Computational results for overall heat transfer rate show good agreements with experimental data. Four design variables are optimized for weighting factor of 0.02.

Keyword: *Numerical Optimization, Response surface method, Turbulent heat transfer, Reynolds-averaged Navier-Stokes analysis, Staggered ribs*

1. Introduction

Attachment of rib turbulators to flow passages becomes one of the widely used means of heat transfer enhancement, and has received extensive interest over the years due to the wide range of its applications. Typical use of rib-roughened surface can be found, for example, in the internal cooling of turbine blades, electronic cooling devices and heat exchangers. However, artificial ribs attached on the surface cause extra flow resistances, unavoidably. To optimize the shape of rib-roughened surface, thus, it is indispensable to compromise between enhancement of heat transfer and reduction of friction drag.

Recently, with the aid of rapid developments of computer capacity and numerical algorithms, numerical optimization with RANS(Reynolds-averaged Navier-Stokes equations) analysis has become a practical method for the design of aerodynamic shapes. Among the methods of numerical optimization, response surface method, as a global optimization method, has many advantages over the gradient-based methods. Recently, the response surface methods are being applied to many single- and multi-disciplinary optimization problems.

Kim and Kim [1] presented an investigation on numerical optimization technique coupled with Reynolds-averaged Navier-Stokes analysis of turbulent flow and heat transfer for the design of rib-roughened surface in case of single surface roughened in two-dimensional channel. They suggested the optimal values of W/H and Pi/H with the objective function defined as linear function of heat transfer coefficient and friction drag coefficient, and showed that the numerical optimization method is quite effective and reliable way of designing heat transfer surface. However, they optimized only two design variables among three geometric variables of the rib-roughened surface, and used a gradient-based optimization method that is less effective for the optimization.

In this work, a numerical optimization is carried out for the design of heat transfer surfaces of two-dimensional channel with both walls roughened by ribs. Turbulent convective heat transfer is analyzed with Reynolds-averaged Navier-Stokes analysis. Response surface method is employed as an optimization technique to optimize four design variables, i.e., Pi/H, A/H, H/D and W/H in Fig. 1.

2. Numerical analysis

For two-dimensional steady incompressible flows, Reynolds-averaged equations for mass, momentum and energy conservations in rectangular coordinates, using Boussinesq eddy viscosity hypothesis, are calculated as Kim and Kim [1]. Standard k-ε turbulence model is used as a turbulence closures. To discretize the governing differential equations, finite volume method is used with power-law scheme. Staggered grids are used. And, the solution procedure is based on SIMPLE algorithm.

Fig. 1 shows the computational domain of which length is one pitch. At the inlet and outlet of the domain, periodic conditions are adopted for each dependent variable except pressure. Uniform turbulent kinetic energy and its dissipation rate are assumed at the inlet as an initial boundary condition. At the all wall boundaries, the wall function based on empirical wall law is adopted. Constant heat flux condition is imposed at rib-roughened surfaces. At the base of the rib, heat flux is constant. At the variable heat flux boundaries on rib surfaces, the heat flux distribution is deduced from the empirical data. On the rib surfaces, the wall temperatures are obtained from the wall function.

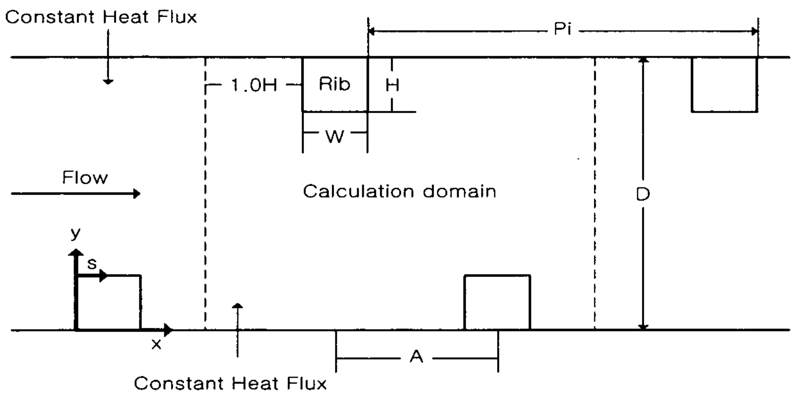

Fig. 1 Coordinate system, design variables and calculation domain

3. Optimization process

Response surface method (RSM) as an optimization technique is to perform a series of experiments or numerical analyses, for a prescribed set of design points, and to construct a response surface of the measured quantity over the design space.

The two-dimensional channel with rib-roughened walls, as shown in Fig. 1, have five geometric variables; height of the channel (D), height of the rib (H), width of the rib (W), pitch of the periodic ribs (Pi) and streamwise distance between upper and lower ribs (A). There are four dimensionless variables; H/D, W/H, Pi/H and A/H. In the present optimization, these four dimensionless geometric variables are selected as design variables.

To maximize the performance of the ribs, the optimum shape should be determined by compromising between the enhancement of heat transfer and reduction of friction loss. On this purpose, the objective function defined as follows is minimized in the optimization process.

$$F = F_{Nu} + \beta F_f \tag{1}$$

where weighting factor, β is adjusted to the designer's goal. The heat-transfer related term on the right-hand side is defined as an inverse of average Nusselt number. And, the second term is the friction-loss related term.

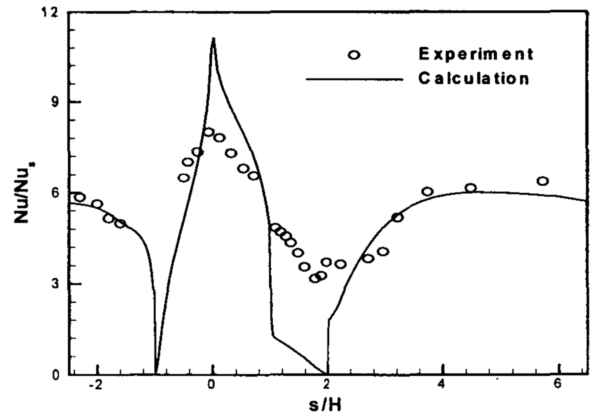

Fig. 2 Comparison of predicted and measured local Nusselt number distributions (Pi/H=7.0, A/H=0.0, H/D=0.2, W/H=1.0 and Re=20,000).

4. Results

The distributions of local Nusselt number normalized by local Nusselt number for the fully developed turbulent flows in a smooth pipe are compared with the measurements of Sato et al. [2] in Fig. 2. The maximum value on top of the rib is overestimated, but underestimated on sides of the rib, probably due to the approximation of heat flux distribution on the rib surfaces. However, the computed heat transfer rates are in good agreements with experimental data upstream and downstream of the rib, where uniform heat flux is imposed.

In the present optimization, Reynolds number based on channel height is 20,000, and uniform heat flux imposed on both walls is 600 W/m^2. For the optimization, response surface method is used. To construct the response surface, 36 training points are selected by D-optimal design, and the ranges of each design variable are as follows: 7.0≤Pi/H≤21.0, 0.0≤A/H≤3.5, 0.1≤H/D≤0.3 and 0.02≤W/H≤2.0. Numerical optimization is performed when weighting factor is 0.02. To measure the uncertainty in the set of coefficients in a polynomial, ANOVA and regression analysis provided by t-statistic is used.

Table 1 Results of optimization

	Design variable				Nu_a	F_f	Objective function
	Pi/H	A/H	H/D	W/H			
ref.	7.000	0.000	0.100	2.000	3.4015	3.0390	0.35476
final	14.05	3.003	0.158	0.200	4.4523	3.7091	0.29745

Results of optimization are shown in Table 1. For example, compared with a reference case of symmetric arrangement, average Nusselt number is improved by 31%. But, friction-loss related term increases by 22%. Finally, the objective function is improved by 16%.

The computing time of single flow analysis spends only 15 ~ 25 minutes using Intel Pentium IV 2.4 GHz with MS-Developer Studio Ver. 6.0 as a compiler.

References

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