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Design optimization of rib-roughened channel to enhance turbulent heat transfer

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Abstract

This work presents a numerical procedure to optimize the shape of two-dimensional channel with periodic ribs mounted on both of the walls to enhance turbulent heat transfer. The response surface method is used as an optimization technique with Reynolds-averaged Navier–Stokes analysis of flow and heat transfer. Standard k–ε turbulence model is used as a turbulence closure. Computational results for overall heat transfer rate show good agreements with experimental data. The width-to-height ratio of the rib, rib height-to-channel height ratio, pitch-to-rib height ratio and distance between opposite ribs to rib pitch ratio are chosen as design variables. The objective function is defined as a linear combination of heat-transfer and friction-loss related terms with weighting factor. D-optimal design is used to reduce the data points, and, with only 36 points, reliable response surface is obtained. Optimum shapes of the channel have been obtained in the range from 0.0 to 0.1 of weighting factor. In the weighting factor range where designer's goal is shifted to reduction of pressure loss, both of pitch-to-rib height ratio and distance between opposite ribs to rib pitch ratio reach almost constant values.

1. Introduction

Ribs mounted on solid surface prevent development of thermal boundary layer, and increase production of turbulent kinetic energy, and thus enhance turbulent heat transfer. Attachment of rib turbulators to flow passages, therefore, 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 application in industrial fields. 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, inevitably. To optimize the shape of rib-roughened surface, thus, it is indispensable to compromise between enhancement of heat transfer and reduction of friction drag.

Convective heat transfer of the surface roughened by square ribs is affected significantly by the flow properties, such as reattachment length of separated streamline and turbulence intensities, as well as Reynolds number. Therefore, shape optimization of rib-roughened surface for enhancement of turbulent heat transfer should be based on precise analysis of the flow structure. Recently, with the aid of rapid developments of computer capacity and numerical algorithms, RANS (Reynolds-averaged Navier–Stokes equations) analysis has become a

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Nomenclature

c_p	specific heat
D	channel height
D_h	channel hydraulic diameter
F	objective function
f	friction factor
H	rib height
k	turbulent kinetic energy
L	length of the channel
Nu	Nusselt number
Nu_a	average Nusselt number
PH	pitch-to-height ratio divided by 7.0, Pi/7.0H
Pi	rib pitch
Pr, Pr_t	Prandtl number and turbulent Prandtl number, respectively
p, Δp	pressure and pressure drop in a channel, respectively
q_0	wall heat flux
Re	Reynolds number
R^2_{adj}	adjusted R square
s, s_0	coordinates along surface and of reference point, respectively
T	local mean temperature
$\widehat{T}$	transformed mean temperature
U, V	mean velocity components in axial and transverse directions, respectively
$\overline{U}$	averaged axial velocity
x, y	axial and transverse coordinates, respectively

Greek symbols

α	coefficient of the polynomial
β	weighting factor in objective function
ε	dissipation rate of turbulent kinetic energy
ν, ν_t	molecular and turbulent viscosities, respectively
ρ	fluid density
σ	increasing rate of bulk temperature in axial direction

practical method for the analysis of complicated turbulent flows and heat transfer. Therefore, optimization of the geometric configuration based on this analysis tool is expected to be an efficient and also economic design method for the rib-roughened surface.

Design optimization techniques have been developed rapidly for the last decade with the aid of high-performance computers. The numerical optimization methods [1] are regarded as general design tools with the advantages, such as automated design capability, varieties of constraints, and multi-disciplinary applications. However, due to large computing time, coupling with RANS analysis has become practical very recently. Among the methods of numerical optimization, response surface method [2], as a global optimization method, has many advantages over the gradient-based methods [3,4]. Local sensitivity analysis is not required. The information is collected from various sources and by different tools. Multiple criterion as well as multiple design point optimizations can be handled. Parallel computations can be easily performed. And, it smooths out the high frequency noise of the objective function, and is thus expected to find a solution near the global optimum. Recently, with these advantages, the response surface methods are being applied to many single- and multi-disciplinary optimization problems [5,6].

With increasing emphasis on energy savings, many experimental and numerical works have been conducted to develop high-performance heat transfer surfaces for various heat exchanging devices. Taslim and Wadsworth [7] carried out experimental work on heat transfer performance for the case that ribs are mounted on both side of the walls in two-dimensional channel, where the ribs are staggered. In the experimental work of Sato et al. [8], they measured and compared heat transfer coefficients for three different types of rib location on the opposite walls. In this experiment, it is found that the heat transfer coefficients with the staggered (half pitch) ribs have larger values than those of the other two kinds of rib geometry. Han et al. [9] tested experimentally the effects of rib shape, angle of attack and pitch-to-rib height ratio on friction factor and heat transfer coefficient.

As well as the experimental works, plenty of numerical works were also implemented. By calculating two-dimensional laminar flows over the ribs which are mounted on both walls with staggered manner, Webb and Ramadhyani [10] estimated the effects of Reynolds number, rib height-to-channel height ratio, pitch-to-channel height ratio and Prandtl number on heat transfer rate and friction drag coefficient. Lopez et al. [11] performed a numerical investigation on laminar convective heat transfer in a three-dimensional channel with baffles. Kelkar and Patankar [12] conducted the similar numerical work for laminar flows as well, but Habib et al. [13] did the work for turbulent flows. Watanabe and Takahashi [14] calculated turbulent flows using large eddy simulation in rectangular straight channel with transverse ribs heated from a single wall in order to clarify the detailed characteristics of the heat transfer.

Experimental and numerical works mentioned above analyzed the effects of chosen parameters on heat transfer rate and friction drag coefficient, but with only a few selected values. Thus, the optimal shape of rib-roughened channel, considering wide ranges of all geometric variables, was not suggested. But, Kim and Kim [3] 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 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 geometric design variables.

2. Methods of analysis

For two-dimensional steady incompressible flows, Reynolds-averaged equations for mass, momentum and energy conservations in rectangular coordinates, using Boussinesq eddy viscosity hypothesis, can be written as follows.

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{1}$$

$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = \frac{\partial}{\partial x}\left[(\nu + \nu_t)\frac{\partial U}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\nu + \nu_t)\frac{\partial U}{\partial y}\right] - \frac{1}{\rho}\frac{\partial p}{\partial x} \tag{2}$$

$$U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = \frac{\partial}{\partial x}\left[(\nu + \nu_t)\frac{\partial V}{\partial x}\right] + \frac{\partial}{\partial y}\left[(\nu + \nu_t)\frac{\partial V}{\partial y}\right] - \frac{1}{\rho}\frac{\partial p}{\partial y} \tag{3}$$

$$U\frac{\partial \widehat{T}}{\partial x} + V\frac{\partial \widehat{T}}{\partial y} = \frac{\partial}{\partial x}\left[\left(\frac{\nu}{Pr} + \frac{\nu_t}{Pr_t}\right)\frac{\partial \widehat{T}}{\partial x}\right] + \frac{\partial}{\partial y}\left[\left(\frac{\nu}{Pr} + \frac{\nu_t}{Pr_t}\right)\frac{\partial \widehat{T}}{\partial y}\right] - \sigma U \tag{4}$$

where $\widehat{T}(x,y)$ is the temperature transformed as follows in order to use the periodic boundary condition [10].

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

Here, σ is the rate of bulk temperature increase due to wall heat flux.

$$\sigma = \frac{2q_0}{\rho \overline{U} c_p D} \tag{6}$$

In the latest work of Jia and Sunden [15], they analyzed the various numerical results for the flows in ducts roughened by ribs, and concluded that there is no generally consistent superiority of the Reynolds stress model over the other turbulence models including two-equation model in predicting the flow and heat transfer. Even though there is some superiority of Reynolds stress model in predicting local values of Nusselt number, average level of Nusselt number is not expected to show a considerable difference. Based on their result, the turbulent viscosity is determined in this work by the standard k–ε model [16] to reduce the computing time.

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 [17].

The computational domain of which length is one pitch has been selected as shown in Fig. 1. At the inlet and outlet of the domain, the following periodic conditions are adopted; for each dependent variable except pressure, the inlet value is same as the outlet value at the corresponding transverse location. In case of pressure, pressure drop is taken into account. Uniform turbulent kinetic energy and its dissipation rate are assumed at the inlet as initial boundary conditions. The uniform values are calculated as in the previous work [3]. However, these uniform inlet conditions are used only at the initial stage of calculation, and are not activated from the second iteration. At the all wall boundaries, the wall function [18] based on empirical wall law for near-wall turbulence is adopted for mean axial velocity.

Constant heat flux condition is imposed on 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 previous calculation of Webb and Ramadhyani [10]. Even though heat flux distribution on the rib surfaces is different from case to case, it is difficult to get the information on the heat flux distribution for all considered cases. In this respect, comment of Hwang [19] gave a good inspiration for the present work. He suggested that the rib thermal boundary condition alters negligibly the average heat transfer coefficient in the inter-rib region that massively affects the magnitude of average Nusselt number. Therefore, it is thought to be acceptable to give the variable heat flux condition on rib surfaces. On the rib surfaces, the wall temperatures are obtained from the wall function [18].

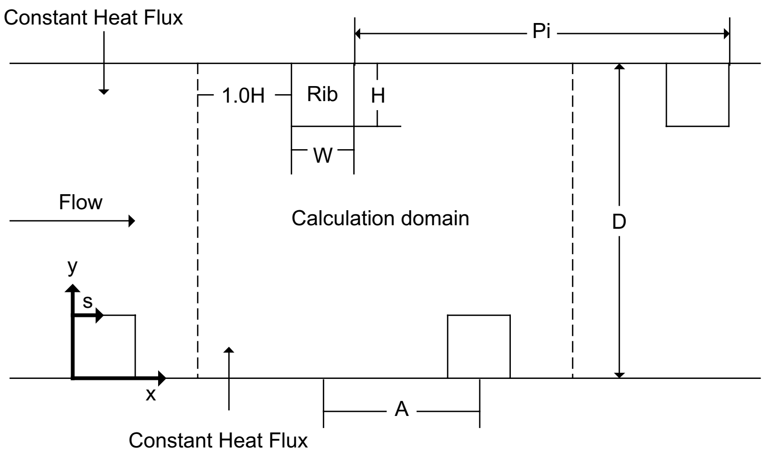

Fig. 1. Coordinate system, design variables and calculation domain.

3. Optimization techniques

In order to obtain an optimum shape of the rib-roughened two-dimensional channel, a numerical optimization is performed in this work. The optimization problem is defined as minimization of an objective function $F(\boldsymbol{x})$ with $x_i^{\mathrm{l}} \leqslant x_i \leqslant x_i^{\mathrm{u}}$, where $\boldsymbol{x}$ is a vector of design variables, and x_i^{l} and x_i^{u} are lower and upper bounds of each design variable.

Response surface method (RSM) [2] 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. When the second-order polynomial is used, the response surface is expressed as follows.

$$\eta = \alpha_0 + \sum_{j=1}^{n} \alpha_j x_j + \sum_{j=1}^{n} \alpha_{jj} x_j^2 + \sum\sum_{i \neq j} \alpha_{ij} x_i x_j \tag{7}$$

where η is the response function, x_i and x_j are the design variables, and α's are the unknown polynomial coefficients which are determined by least square method. The efficiency of response surface method is verified by Shyy et al. [20], Papila and Shyy [21], Madsen et al. [22], and Vaidyanathan et al. [23] in their works of designing rocket engine injector, supersonic turbines, diffuser, and rocket engine component, respectively. Prescribed set of design points, so called training points, is selected by D-optimal design [2]. D-optimal design is a useful and reliable way of constructing response surface with a small number of design points which is only 1.5–2.5 times the number of polynomial coefficients. Unal et al. [24] showed that D-optimal design provides an efficient approach for response surface model building and multi-disciplinary optimization.

The two-dimensional channel with rib-roughened walls, as shown in Fig. 1, has 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 $A/$Pi. 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.

$$F = F_{Nu} + \beta F_{\mathrm{f}} \tag{8}$$

where weighting factor, β is adjusted to the purpose of the designer.

The heat-transfer related term on the right-hand side is defined as an inverse of Nusselt number.

$$F_{Nu} = \frac{1}{Nu_{\mathrm{a}}} \tag{9}$$

where

$$Nu_{\mathrm{a}} = \frac{\int_{s_0}^{s_0+\mathrm{Pi}+2H} \frac{Nu}{Nu_{\mathrm{s}}}\,\mathrm{d}s}{\mathrm{Pi}+2H}$$

$$Nu_{\mathrm{s}} = 0.023 Re^{0.8} Pr^{0.4}$$

Nu_{s} is the Nusselt number obtained from the Dittus–Boelter correlation, which is for the fully developed turbulent flows in a smooth pipe.

The friction-loss related term in Eq. (8) is defined as follows.

$$F_{\mathrm{f}} = \left(\frac{f}{f_0}\right)^{1/3} \tag{10}$$

where

$$f = \frac{\Delta p D_h}{2\rho \overline{U}^2 L}$$

$$f_0 = 2(2.236 \ln Re - 4.639)^{-2}$$

f_0 is a friction factor for fully developed flow in a smooth pipe, and is obtained from Petukhov empirical correlation [25] which is modified from the Karman–Nikuradse correlation for the best fit in the range, $10^4 < Re < 10^6$.

After the definition propose by Gee and Webb [26], average Nusselt number and 1/3 power of friction factor became indexes of representing the thermal performance of ribbed surface, as used by Taslim and Wadsworth [7], Han et al. [27], and Cho et al. [28].

4. Results and discussion

4.1. Analysis of heat transfer

For the validation of present numerical solution, the results for the distribution of local Nusselt number are validated based on the measurement of Sato et al. [8] at Reynolds number, 20,000, where heights of the channel (D) and the rib (H) are 0.05 and 0.01 m, respectively, with $W/H = 1.0$ and $\mathrm{Pi}/H = 7.0$. And, the average Nusselt numbers for the wide range of Reynolds number are compared with the experimental data of Taslim and Wadsworth [7], where $W/H = 1.0$, $\mathrm{Pi}/H = 8.5$ and $H/D_h = 0.133$.

For grid dependency tests, five different numbers of grids, as shown in Fig. 2, are tested in the case of symmetric array of ribs with $Re = 20{,}000$. From the results, 82×81 grid is selected as an optimum one.

The distributions of local Nusselt number normalized by local Nusselt number obtained from empirical relation for the fully developed turbulent flow in a smooth pipe are compared with the measurements of Sato et al. [8] in Fig. 3. 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, i.e., the use of variable heat flux distribution on the rib surfaces calculated by Webb and Ramadhyani [10] for different rib geometry. 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. Although the agreement with experimental data is not excellent, especially, on the surfaces of the rib, it is not so bad for the purpose of present optimization. Since only the average level of Nusselt number is concerned in the present optimization problem, the discrepancies in the local Nusselt number distribution, not in the average level, are expected not to have a large influence on the optimization results. In this respect, Fig. 4 gives a good inspiration for the present optimization. For the wide range of Reynolds numbers, rib-averaged Nusselt numbers, i.e., Nusselt number averaged on rib surfaces, agree well with the experimental data [7,8].

Before optimizing the problem, it is instructive to know how the objective function depends on each design variable. Increase of Pi/H enhances the heat transfer by reducing the separation region, but, also reduces the turbulent intensity that promotes turbulent heat transfer. Therefore, as shown in Fig. 5, there is an optimum value

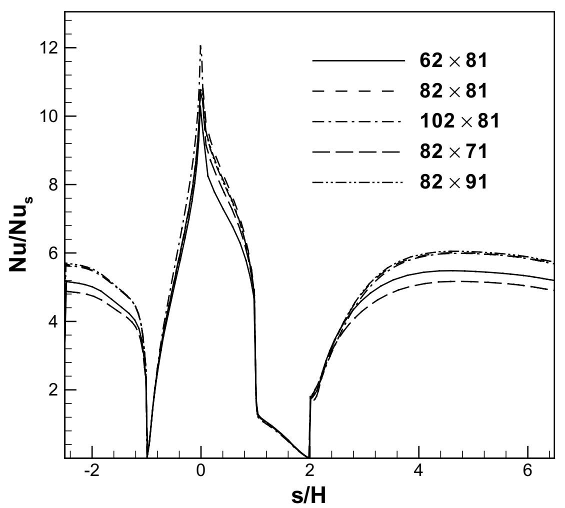

Fig. 2. Grid dependency test (PH = 1.0, $A/\mathrm{Pi} = 0.0$, $H/D = 0.2$, $W/H = 1.0$ and $Re = 20{,}000$).

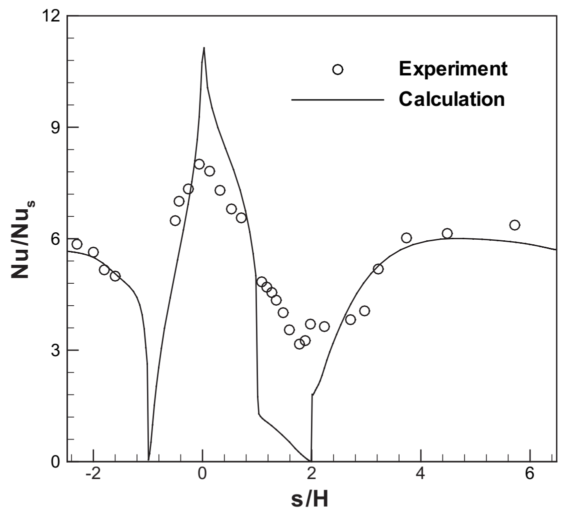

Fig. 3. Comparison of predicted and measured local Nusselt number distributions (PH = 1.0, $A/\mathrm{Pi} = 0.0$, $H/D = 0.2$, $W/H = 1.0$ and $Re = 20{,}000$).

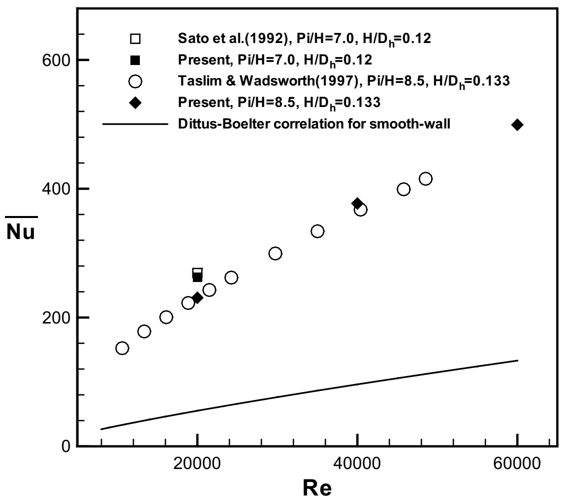

Fig. 4. Rib-averaged Nusselt number compared with experimental data.

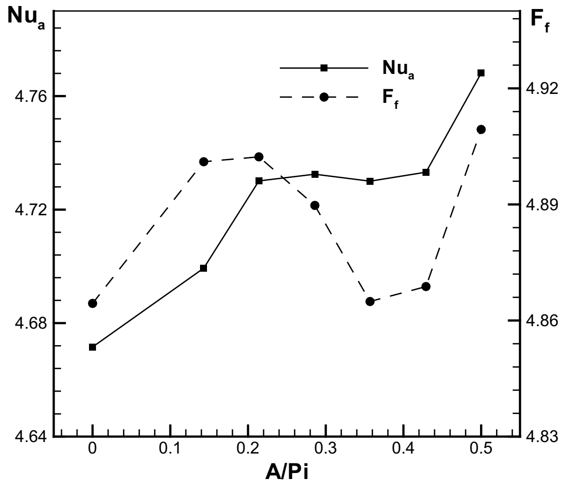

Fig. 6. Effects of A/Pi on Nusselt number and friction factor (PH = 1.0, H/D = 0.2, W/H = 1.0 and Re = 20,000).

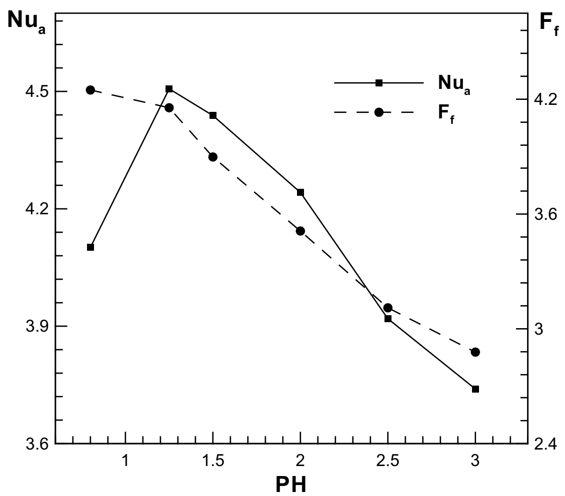

Fig. 5. Effects of PH on Nusselt number and friction factor (A/Pi = 0.5, H/D = 0.2, W/H = 1.0 and Re = 20,000).

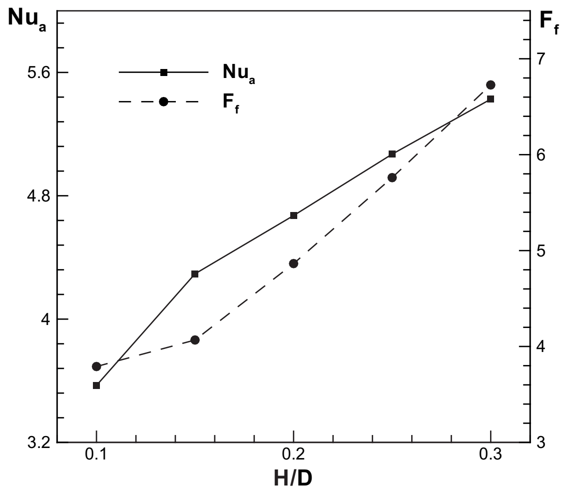

Fig. 7. Effects of H/D on Nusselt number and friction factor (PH = 1.0, A/Pi = 0.0, W/H = 1.0 and Re = 20,000).

of PH (=Pi/7.0H), which gives the maximum average Nusselt number (Nu_a). Taslim and Wadsworth [7] concluded, from their experimental results with staggered ribs, that heat transfer rate has a maximum value when the pitch-to-height ratio of the rib is approximately 8.5. This is consistent with the fact that the optimum value of PH is about 1.25 in Fig. 5, even though the cases are not exactly the same. Fig. 6 shows the effects of A/Pi on heat transfer rate and friction factor. Heat transfer rate has a maximum value when A/Pi is 0.5, which corresponds to staggered array of the ribs. The same result is also obtained in the experimental work of Sato et al. [8]. Fig. 7 shows that increase of H/D increases both of heat transfer and friction-loss. On the other hand, as shown in Fig. 8, increase of W/H decreases both of them.

4.2. Numerical optimization

As flow conditions for the present optimization, Reynolds number based on channel height is 20,000, and uniform heat flux is imposed on both walls. 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 listed in Table 1. Lower and upper

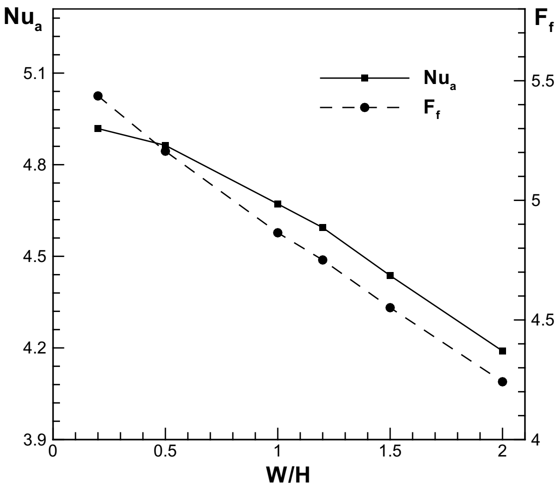

Fig. 8. Effects of W/H on Nusselt number and friction factor (PH = 1.0, A/Pi = 0.0, H/D = 0.2 and Re = 20,000).

Table 1
Design variables and design spaces

Design variable	Lower limit	Upper limit
PH	1.0	3.0
A/Pi	0.0	0.5
H/D	0.1	0.3
W/H	0.2	2.0

limits of PH are selected as 1.0 and 3.0, respectively, because maximum heat transfer rates were obtained within this range in the experimental works of Taslim and Wadsworth [7], Berger and Hau [29], and also in the numerical work of Habib et al. [13]. Design variable for asymmetry, A/Pi ranges from 0.0 to 0.5 that correspond to symmetric and staggered arrangements of the ribs, respectively. For H/D, its design space is set from 0.1 to 0.3. Below the lower limit, computational accuracy is not guaranteed since grids cannot be located very adjacent to the wall with the high-Reynolds number turbulence model as used in this work. Over the upper limit, pressure drop increases abruptly as was indicated by Lopez et al. [11], and this situation is never desirable. The minimum value of W/H is set to be 0.2 since computational failure may occur below this value due to the bad aspect ratio of the grid. And, the maximum value is fixed at 2.0 not to develop thermal boundary layer on top of the rib that prevents heat transfer.

Numerical optimization is performed in the range from 0.0 to 0.1 of weighting factor. To measure the uncertainty in the set of coefficients in a polynomial, ANOVA and regression analysis provided by t-statistic [2] is used and the results are shown in Table 2. Guinta [30] suggested that the typical values of R^2_{adj} are in the range, $0.9 \leqslant R^2_{adj} \leqslant 1.0$, when the observed response values are accurately predicted by the response surface model. In this respect, the present response surface is quite reliable.

Results of optimization for $\beta = 0.02$ are shown in Table 3. For example, compared with a reference case of symmetric arrangement (PH = 1.0, A/Pi = 0.0, H/D = 0.1, W/H = 2.0), average Nusselt number is improved by 31%. But, friction-loss related term increases by 22%. Finally, the objective function is improved by 16%. Fig. 9 shows the streamlines in the optimized rib-roughened channel, where the arrangement of ribs is asymmetric. This arrangement induces flow interference between upper and lower ribs. The flow refracted by the upper rib goes downward and vice versa, resulting in the deflection of streamlines, which seems to increase the heat transfer. Fig. 10 shows the comparison of optimized Nusselt number distribution with that of reference case. Even though there is slight decrease in maximum Nusselt number at top of the rib, considerable increases are observed at the surface between the ribs. Hence, the overall average Nusselt number is increased.

Figs. 11 and 12 show the variance of optimum values of design variables with the weighting factor in the range from 0.0 to 0.1. In Fig. 11, optimum values of PH and A/Pi are shown. In case with zero weighting factor, the optimum A/Pi is 0.5, i.e., the case of staggered array. This is same as the empirical result obtained by Sato et al. [8], which suggests that the staggered array of ribs gives the maximum heat transfer rate. When weighting

Table 2
Results of ANOVA and regression analysis

β	R	R^2	R^2_{adj}	Standard error of the estimate
0.02	0.989	0.977	0.962	1.149E−2

Table 3
Results of optimization for $\beta = 0.02$

	Design variable				Nu_a	F_f	Objective function
	PH	A/Pi	H/D	W/H			
Ref.	1.000	0.000	0.100	2.000	3.4015	3.0390	0.35476
Final	2.007	0.43	0.158	0.200	4.4523	3.7091	0.29745

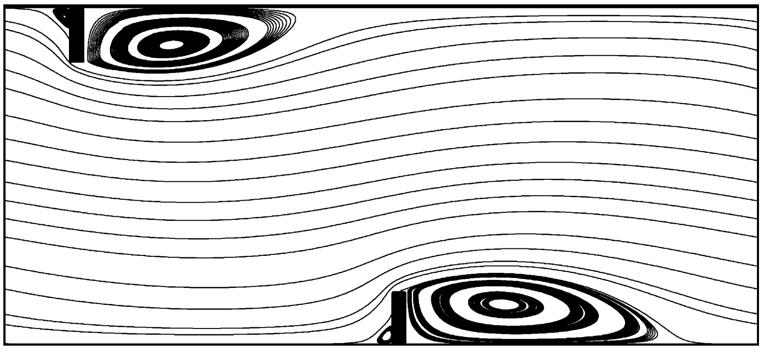

Fig. 9. Streamlines in optimized channel for $\beta = 0.02$.

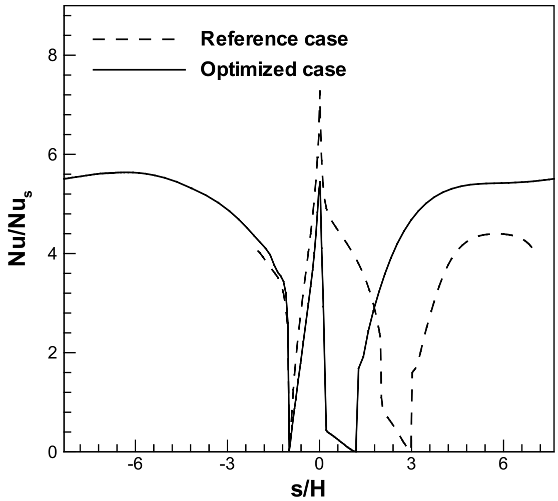

Fig. 10. Optimized Nusselt number distribution for $\beta = 0.02$.

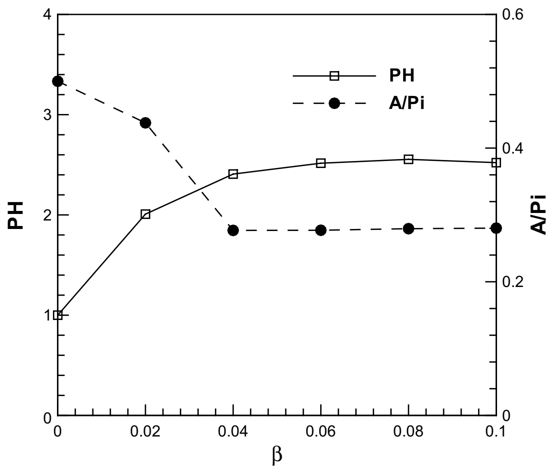

Fig. 11. Optimal values of PH and A/Pi with weighting factor.

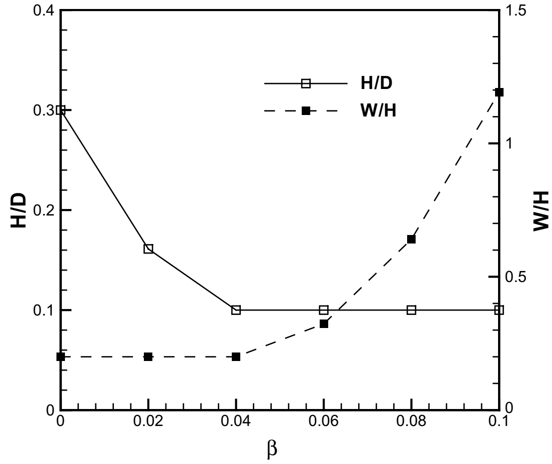

Fig. 12. Optimal values of H/D and W/H with weighting factor.

factor is less than 0.04, PH increases and A/Pi decreases as weighting factor increases. But, for weighting factor larger than 0.04, optimum values of PH and A/Pi reach almost constant values as the designer's goal is shifted to reduction of pressure loss. In case of A/Pi, the optimum value is approximately 0.286, which is consistent with the result of Sato et al. [8]. They reported that among three different arrangements of ribs (A/Pi = 0.0, 0.25, 0.5), the arrangement of quarter-pitch (A/Pi = 0.25) gives the smallest pressure loss. As for the optimum value of PH, the results show that increase of PH beyond about 2.5 is no more effective to reduce the objective function for the weighting factors larger than 0.05, where reduction of pressure loss is more important. Optimum values H/D and W/H are shown in Fig. 12. While H/D reaches its lower limit, 0.1 beyond $\beta = 0.04$ as weighting increases, W/H reaches its lower limit, 0.2 for $\beta \leqslant 0.04$ as weighting factor decreases. This indicates that if the designer's concern is to increase the heat transfer rate, optimum rib shape becomes similar to fin type heat exchanger. For the weighting factor larger than 0.04, *W*/*H* increases continuously since pressure is recovered fast with the large width of the rib.

In the previous work on shape optimization of rib-roughened surface performed by Kim and Kim [3], the gradient-based optimization technique with two design variables required a lot of flow analyses of which number varies from 100 to 1000 depending largely on weighting factor and initial conditions. However, in the present work, the response surface method reduces the computing time significantly with only 36 times of flow analyses to optimize four design variables.

The computations were carried out by personal computer with Intel Pentium IV CPU 2.4 GHz, using MS-Developer Studio Ver. 6.0 as program compiler. The computing time of single flow analysis is in the range of 15–25 min.

5. Conclusions

Rib-roughened two-dimensional channel has been geometrically optimized by response surface method coupled with RANS analysis of flow and heat transfer. In comparison with experimental data, it is found that the analysis gives generally good prediction of overall heat transfer and pressure loss for specific configuration of the channel, enough to be used in optimization process. The objective function is defined in order to maximize the performance of the ribs by compromising between enhancement of heat transfer and reduction of friction-loss with weighting factor. Four geometric variables are selected as design variables. Numerical optimizations are performed in the range of 0.0–0.1 of weighting factor. Thirty-six training points selected by D-optimal design construct reliable response surface. For the weighting factor less than 0.04, optimum *A*/Pi and *H*/*D* decrease, but optimum Pi/*H* increases as weighting factor increases, while *W*/*H* stays at the lower limit, 0.2. For the weighting factor larger than 0.04, optimum Pi/*H* and *A*/Pi reach almost constant values, approximately 17.5 and 2.0, respectively, and optimum *H*/*D* reaches the lower limit, 0.1, but only optimum *W*/*H* increases continuously. As the conclusion, the numerical optimization using response surface method with RANS analysis provides quite reliable and economic tool for the design of a heat-transfer channel with rib-roughened surfaces.

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