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An inverse study to optimize the rib pitch in a two–dimensional channel flow problem for heat transfer enhancement

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ABSTRACT

An inverse convection heat transfer in a two–dimensional channel mounted with square ribs was concerned in the present work. A simplified conjugate gradient method was adopted for optimizing the convection heat transfer. The optimal pitch ratio of the ribs was searched under the maximum heat transfer rate. The sensitivity and adjoint problems were not considered but a constant search step size was applied. The results showed that the simplified conjugate gradient method can be used to search the optimal pitch ratio of the ribs at various initial values. But the constant search step size may result in the oscillation of the numerical results. The searched optimal pitch ratio with the inverse method at one Reynolds number can be spread to a large range of Reynolds numbers.

1. Introduction

The fluid flow and heat transfer characteristics over ribbed surfaces is of great importance for electronic devices, cooling passages, solar air heater et al. The ribbed surfaces enhance the heat transfer by breaking the thermal layer and/or creating turbulence since the flow separation and reattachment.

There have been many investigations of fluid flow and heat transfer over ribbed surfaces in public literatures. Several factors in terms of rib shape, geometrical parameters such as rib pitch, rib height, rib width and angle of attack have effects on the flow and heat transfer characteristics. For example, Korichi and Oufer [1] investigated the heat transfer of rectangular channel with mounted blocks on upper and lower walls. Karmare and Tikekar [2] investigated the fluid flow and heat transfer in a solar air heater roughened by small ribs with circular, square and triangular cross–section. The results showed that the absorber plate of square cross–section rib with 58° angle of attack has the maximum heat transfer. Yadav and Bhagoria [3] investigated the heat transfer and fluid flow in a rectangular duct with square sectioned rib roughness on the absorber plate. The effects of rib pitch and rib height on heat transfer and fluid flow were discussed and optimized. Seo et al. [4] conducted an optimization of a boot–shaped rib in a rectangular cooling channel. The effects of the tip width, rib width and rib height on heat transfer characteristics were analyzed. Chiang et al. [5] experimentally investigated the heat transfer in three side–open and bottom–sealed rectangular channels with two opposite walls roughened by 45° staggered ribs. The results showed that the channel roughened by 45° staggered ribs can further enhance heat transfer in comparison with that by 90° staggered ribs. Yemenici et al. [6] experimentally investigated the flow and heat transfer characteristics of a rectangular channel with a blocked surface. The effects of the size and number of the blocks on the heat transfer are measured. Ryu et al. [7,8] investigated the heat transfer and flow resistance of a turbulent flow in channels with ribs of square, triangular, semicircular and wavy cross–sections. Shen et al. [9] numerically investigated the fluid flow and heat transfer in a U–shaped channel with the combination of ribs, dimples and protrusions. The results showed that the rib–protrusion structure is the most effective structure while rib–dimple structure has only slight advantage than ribbed channel. Aghaie et al. [10] numerically investigated and optimized the fluid flow and heat transfer of a solar air heater channel by use of Taguchi method and the optimum configuration was obtained. Singh et al. [11] presented a numerical investigation to study the effects of non–uniform and uniform cross–section rib on heat transfer and friction characteristics of solar air heater duct. Sahu et al. [12] carried out an exergy efficiency analysis on solar air heater with arc–shaped wire rib roughened absorber plates. The results showed that the maximum enhancement of roughened solar air heater as compared to smooth absorber plate solar air heater was found as 56%. Singh et al. [13] carried out experimental and numerical study of flow and heat transfer in a two–pass channel featuring four rib geometries including 45° angled, V, W and M–shaped ribs. Yadav and Bhagoria [14] performed CFD based thermo–hydraulic perfor-

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Nomenclature

d	search direction
f	Darcy friction factor
H	channel height, mm
h	heat transfer coefficient, W m^{-2} K^{-1}
J	objective function
k	turbulence kinetic energy, m^2 s^{-2}
L	length of the main channel, mm
l	length of the upstream and/or downstream channels, mm
Nu	Nusselt number
n	number of ribs
p	pressure, Pa
Δp	pressure drop in flow direction, Pa
q	heat flux, W m^{-2}
Re	Reynolds number
s	distance between two successive ribs, mm
T	temperature, K
t	time, s
Δt	time step, s
u, v, w	x, y, z velocity components, m s^{-1}
w	rib width, mm
x, y, z	coordinate direction, m

Greek symbols

α	search step size
β	conjugate coefficient
λ	thermal conductivity, W (m K)$^{-1}$
μ	fluid viscosity, kg (m s)$^{-1}$
ε	turbulent energy dissipation rate, m^2 s^{-3} or a small positive number
ρ	density of the fluid, kg m^{-3}

Subscripts and superscripts

eff	effective value
in	channel inlet
init	initial value
k	iteration number
m	log–mean value
opt	optimal value
out	channel outlet
s	smooth channel
x	local position
w	wall

mance analysis of an artificially roughened solar air heater with 12 different configurations of equilateral triangular sectioned rib roughness on the absorber plate. They concluded that the maximum enhancement in Nu and f was 3.037 and 3.356 respectively than the smooth duct. Recently, Sharma and Kalamkar [15] reviewed the application of CFD in analysis of flow through ducts and solar air heaters with rib roughened walls.

The above references mainly focused on the analysis of the flow and heat transfer characteristics with the existence of the ribs. However the optimal design, more important in engineering applications, regarding the shapes, locations and arrangements are limited in the open literature. Here the optimal design does not denote experimental or numerical tests but some methods are used to search the optimal results. For instance, the Taguchi method [10] can generally obtain satisfactory optimal results. However, one must select the optimal one from plenty of results. Hence an effective method for heat transfer optimization is important and the inverse method is considered in the present work.

The inverse heat transfer problems have received much attention in recent years. Some methods such as the Levenberg–Marquardt method [16], the conjugate gradient method [17] and the Tikhonov regularization method [18] have proven to be useful algorithms in the optimal design of heat transfer. Some other methods such as the boundary element method [19], the simulated annealing method [20], the meshless local Petrov–Galerkin method [21] and the Gauss–Newton method [22] have been successfully studied in the inverse heat transfer. Earlier studies about the inverse heat transfer mainly focused on the inverse heat conduction problem (IHCP) for obtaining accurate thermal quantities such as heat sources, material's thermal properties and boundary conditions [23,24]. In addition, the inverse radiation problem [25] or conduction–radiation problem [26,27] also have been taken in account.

There have been many studies on the inverse conduction heat transfer and/or inverse radiation heat transfer, while there are relatively fewer studies on inverse convection heat transfer due to the complex nature of the latter. The inverse convection heat transfer has been received attention in recent years [28–30]. The conjugate gradient method has been widely used in inverse heat transfer. For instance, Huang and Chen [31] and Prud'homme and Nguyen [32] estimated the boundary heat flux in a duct and an enclosure, respectively, using the conjugate gradient method. Huang and Chaing [33] solved the shape identification problem using the conjugate gradient method. Lu et al. [34] estimated the transient fluid temperatures near the inner wall of a pipeline using the conjugate gradient method. In present work, the conjugate gradient method is adopted for optimizing the convection heat transfer.

The above review shows that the previous published studies rarely focused on the convection heat transfer optimization with the inverse method. It motivates the present work to develop an inverse method for optimizing the convection heat transfer. As an example, the optimal pitch of the two successive ribs in a two-dimensional duct mounted with ribs on the bottom will be determined. In Section 2, the direct problem is illustrated and used to find the optimal pitch ratio. The design problem of obtaining maximized objective function using the conjugate gradient method is addressed in Section 3. Some parameters are defined in Section 4. The grid independence test is implemented in Section 5. The optimal pitch ratio obtained by the inverse method is analyzed in Section 6.

2. Direct problem

A two-dimensional channel with periodic transverse square ribs is considered as the physical model and is shown in Fig. 1. As an example, three ribs are shown in the figure. The main channel length (L) is 250 mm and the channel height (H) is 20 mm. To avoid the backflow at the outlet region, the downstream domain is extended 5 times of the channel height, i.e., l = 100 mm. There

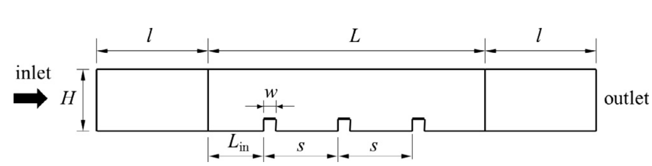

Fig. 1. Schematic diagram of the model.