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Numerical simulation of manipulated flow and heat transfer over surface-mounted rib

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ABSTRACT

A numerical study of the manipulated air flow and heat transfer over a surface-mounted rib is performed using Large-Eddy Simulation (LES). The Reynolds number is set as $Re = 3000$ (based on the rib height, h, and the inflow velocity, U_0) and the frequency of zero mass-flux jet is chosen as $St_r = fh/U_0 = 0.08$. The purpose of this study is to elucidate the effect of perturbation on the flow and thermal fields and the dissimilarity of transportation between momentum and heat transfer. Due to perturbation, the mean reattachment length shows a reduction of 13%, while the maximum mean Nusselt number on the heated wall has an augment of 10%. The effect of perturbation on heat transfer disappears after 10h, which is shorter than 15h for the friction coefficient. The Stanton number and the coefficient of friction are applied to study the dissimilarity of heat and momentum transport. Detailed instantaneous flow structures and spectral analysis suppose that spanwise vortices (large turbulent coherent structures) shed behind the rib contribute to the dissimilarity by transporting the hot fluid to the center flow and carrying the cold fluid to the bottom wall. The phase-averaged iso-surface of Q-criteria confirms above dissimilarity mechanism.

1. Introduction

The surface-mounted rib is widely used for heat transfer enhancement in engineering systems, such as heat exchangers, gas turbine engines and combustors et al. Due to the obstacle mounted on the wall, the flow, which is characterized by separation and reattachment, yields an augment in heat transfer and pressure drop.

For practical importance, previous studies generally focused on the situation of repeated ribs and the effect of rib size, arrangement, channel aspect ratio on the thermal/hydraulic performance was presented [1–8]. For example, Han [1], Han [2] performed experiments to study the effects of rib geometries on the heat transfer and friction factor, and predicted the average thermal/hydraulic performance in channels. Korichi and Oufer [9] numerically investigated the conjugate heat transfer with the effects of Reynolds number and rib configurations in a rectangular duct with wall-mounted obstacles. These works help to know the overall performance and can be useful for engineering design studies. However, the detailed information of transport dissimilarity between momentum and heat is unclear. Moreover, to predict both experimentally and numerically is so difficult in such flows due to complicated transport phenomena caused by complicated geometries in various types of machinery.

In fact, the investigation of a single obstacle means a lot scientifically. Most of the available studies on separated and reattaching flow over a single obstacle merely focused on the fluid dynamic [10–14]. The most interested parameter was the mean reattachment length (x_r), which was affected by Reynolds number, aspect ratio of the obstacle, condition of the incoming flow. Concerning the unsteady behavior of such flow, Liu, Ke and Sung [12] experimentally studied the spectra of surface pressure and velocity signals over the whole flow field, which showed that there were three instabilities: the K-H instability in the shear layer, a shedding mode in the reattaching region and a low-frequency mode referred to the flapping of the shear layer. As for the numerical study, a simulation of transitional flow with a lower Reynolds number was done by Abdalla, Cook and Yang [11,13]. They made a visualization study of the flow structures in the rib wake and revealed spanwise roll-up vortices shed from the rib. Besides, they also found three instabilities with the analysis of spectra, but the frequencies are different with Liu, Ke and Sung [12]. This discrepancy encourages us to figure out the exact turbulent coherent structures and their effects on heat transfer.

Involving with thermal fields, Acharya, Dutta and Myrum [15] investigated the heat transfer and flow structure in a duct with wall-mounted rib. They found that the heat transfer in recirculation bubble was weak and reached its maximum ahead of the mean reattachment point (x_r) by analyzing the local Nusselt number. This characteristic was

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Nomenclature

B	slot width (m)
C_f	wall friction coefficient
C_p	specific heat at constant pressure (J/kg K)
C_s	Smagorinsky constant
f	perturbation frequency (Hz)
h	rib height (m)
Nu	Nusselt number
p	static pressure (Pa)
Pr	Prandtl number
Pr_t	SGS turbulent Prandtl number
q_j	SGS heat flux
q_w	wall heat flux (W/m^2)
Re	Reynolds number, $Re = hU_0/\nu$
St_r	Strouhal number, $St_r = fh/U_0$
S_{ij}	strain rate tensor of the flow field
S_t	Stanton number, $Nu/PrRe$
T	temperature (K)
t	time (s)
U_0	inlet velocity (m/s)
u, v, w	velocity components (m/s)
x_r	reattachment length (m)
x, y, z	spatial coordinates (m)

Greek symbols

Ω	computational domain
Δ	grid filter width
ρ	density (kg/m^3)
λ	thermal conductivity (W/(m K))
ν	kinematic viscosity (m^2/s)
μ_t	SGS turbulent viscosity
τ_{ij}	SGS stress tensor
τ_w	wall shear stress
Δt	time increment
Δx, Δy, Δz	grid spacings in x, y, and z directions
Δx^+, Δy^+, Δz^+	dimensionless distance from the wall

Subscripts

max	maximum heat transfer
r	flow reattachment
ref	reference value

Superscripts

$'$	fluctuating component
$\bar{}$	spatial grid filter indication or ensemble average value

confirmed by Terukazu [16], who summarized the heat transfer in the separated and reattaching flow for various geometric configurations. Miura, Matsubara and Sakurai [17,18] numerically studied a single rib mounted channel to figure out the augment of the heat transfer comparing with the flat-plate case. The mechanisms of heat transfer augmentation were discussed by turbulent statistics of flow and thermal fields. However, none of them analyze the relationship between velocity and thermal fields until recent studies done by Hattori and Nagano [19] and Matsubara, Miura and Ohta [20]. They discussed the dissimilarity between momentum and heat transport that the reduction of friction and enhancement in heat transfer simultaneously occurred in a local spot.

This dissimilarity phenomenon was also observed within a plate turbulent boundary layer, which was disturbed by a cylinder set above the plate by Suzuki, Suzuki and Sato [21]. They made turbulent structure study of the flow with octant analysis and clarified that hot outward and cold wallward motions, which were related to the third and first quadrants in u'-v' plane, contributed to positive heat transfer and negative momentum transfer resulting in the generation of the dissimilarity. Yao, Nakatani and Suzuki [22]investigated channel flow obstructed by a square rod, and they argued about the Karmam vortex street shed from the obstacle may cause the local dissimilarity. Latterly, a numerical simulation with similar geometry was performed by Inaoka, Yamamoto and Suzuki [23], their unsteady two-dimensional analysis discussed the washing process caused by spanwise vortices and their effects on the dissimilarity, which coincided with the above results. These flow conditions are viewed as the interaction between boundary layer and the wake behind an obstacle. Avancha and Pletcher [24] investigated the heat transfer with flow over a backward-facing step and also observed the dissimilarity in the recirculation region, but they did not make any specific analysis. Matsubara, Miura and Ohta [20] made a conceptual vortex model and suggested that the transport dissimilarity was caused by spanwise vortices shed from the wake, which keep the Reynolds shear stress low and increase the turbulent heat flux. However, the detailed flow field was not clearly investigated as its complexity.

Besides, the employment of flow control, such as external forcing, is a popular way to improve the heat transfer by reducing the recirculation zone. This technique has been demonstrated in the literatures related to the separated and reattaching flow. The manipulated backward-facing step flow has been extensively investigated with different Reynolds number [25–27]. And the studies of manipulated flow on surface-mounted fence were reported lately [10,28–30]. The mechanism is explained that the forcing can be increased by the shear layer which promotes the growth of large-scale structures and the interaction with the wall earlier, thus accelerates reattaching. It can be summarized that the parameters affecting the flow are the location of perturbation, the forcing frequency and the amplitude, respectively. Recently, Cukurel, Selcan and Stratmann [31] experimentally investigated the aero-thermal condition of an excited flow over a rib with different forcing frequencies and amplitudes. It was found that the perturbation resulted in the reduction of reattachment length and enhancement of heat transfer, also there was an optimal one. In addition, the results of Orellano and Wengle [10] showed that the flow structures under perturbation were more organized, which suggested that this method can be used to investigate combined fluid dynamic and heat transfer more efficiently.

For the purpose of enhancing heat transfer, employment of flow control is proposed in separated and reattaching flow over a single rib. The flow structure and heat transfer over a surface-mounted rib are performed by LES. There are two objectives of this paper: first one is to figure out the effect of perturbation on such flow; second is to clarify the dissimilarity between heat and momentum transport.

2. Numerical method and flow configuration

2.1. Mathematical formulation

2.1.1. Governing equations

As is known, the method of LES computes the large eddies explicitly and models the smaller eddies, which are assumed to be universal and isotropic. In present work, the Navier-Stokes equations are processed with a low-pass filter that the small eddies are removed and their effects on the large scales are provided by subgrid-scale (SGS) models. Therefore, the LES equations (filtered continuity, Navier-Stokes and energy equations) for incompressible flow, neglecting the effects of buoyancy, are as below: