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Heat and fluid flow characteristics of a rectangular channel with a small diameter circular cylinder as vortex generator

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ABSTRACT

The flow characteristics and heat transfer performance of a rectangular channel with a small-scale circular cylinder vortex generator are numerically investigated with Large Eddy Simulation (LES). The circular cylinder is located in fully-developed turbulent boundary layer. The ratio of the gap between the circular cylinder and the channel bottom to the diameter of the circular cylinder G/D, varies from 0 to 6.0. The Reynolds number, based on the bulk velocity u_m and channel half-height H, is 3745. The influence of the circular cylinder wake on the wall boundary layer is probed. In addition, the effects of the presence of the small-scale vortex generator on the flow and heat transfer characteristics are investigated as well. The synthesis efficiency of heat transfer enhancement is characterized by the synthesis performance coefficient, which including Nusselt number and friction coefficient. The result shows that the interaction between the cylinder wake and the wall boundary layer can dramatically alter the flow structure of the turbulent boundary layer. The thermal performance of rectangular channel with small-scale vortex generator is improved prominently.

1. Introduction

The flow and heat transfer characteristics of turbulent channel flow have always been a research focus due to its extensive engineering applications background, such as chemistry industry, aerospace engineering and cooing of electrical devices, etc. In order to reduce the energy consumption, it is necessary to improve the heat transfer performance and reduce the flow drag. It is well known that the heat and momentum transport are associated with the disturbance of boundary layer. In the 1960's, Kline and Praturi et al. [1,2] studied the flow structures of near-wall region and found a series of structures such as high and low speed streaks, streamwise vortices and transverse vortices etc. In addition, some special events of turbulent coherent structures such as burst, ejection and sweep were observed. The impact of turbulent coherent structure on flow and heat transfer characteristics has attracted more and more attentions since then. It has been found that the near-wall streamwise vortices have a remarkable effect on heat transfer performance.

In wall bounded turbulent flow, the streamwise vortices induced with artificial methods can enhance the sweep event to some degree, which result in the augmentation of heat transfer. On the contrary, the vortices inhibited with artificial methods can realize drag reduction. In general, the heat transfer enhancement and the drag reduction are conflicting. Therefore, the synthesis performance of flow and heat transfer should be considered both in heat transfer enhancement. In general, the control methods can be divided into passive and active one. The active method generally requires complex mechanical devices. Compared with the active method, no additional power input, easily controlled, and less cost are obvious advantage of passive one. The wavy wall, vortex generator, rib, baffle and helically coiled tube are some typical examples of passive control method, which can be used for heat transfer enhancement. Choi and Suzuki [3] investigated turbulent flow in a channel with one wavy wall by LES. Their results indicated that the heat transfer performance of the wavy wall was enhanced notably with the increase of the wall wave amplitude. Furthermore, near-wall streamwise vortex and the separated shear layer played an important role in heat transfer enhancement. Ramgadiia and Saha [4] found that the heat transfer improvement can be achieved by using the wavy-wall duct, particularly at higher Reynolds number. Mohammed et al. [5] performed numerical simulations on heat transfer and flow characteristics in wavy micro-channel heat

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Nomenclature

D	the diameter of the cylinder, m
f	friction coefficient
G	the distance between the lower side of the cylinder and the channel bottom, m
H	channel half-height, m
h	heat transfer coefficient, W/(m^2 K)
L	channel length, m
Nu	Nusselt number
p	pressure, N/m^2
Pr	Prandtl number
q_j	subgrid-scale heat flux
Q	a vortex identification method
Re$_m$	mainstream Reynolds number

Greek symbol

α	thermal diffusion, m^2/s
η	synthesis performance coefficient
λ	thermal conductivity, W/m K
ν	kinematic viscosity of fluid, m^2/s
ρ	density of fluid, kg/m^3
τ_w	shear stress, N/m^2
Re$_\tau$	turbulent Reynolds number
S_{ij}	the strain rate tensor
T	temperature, K
u_m	mainstream average velocity, m/s
u_τ	frictional velocity, m/s
u, v, w	x, y, z velocity components, m/s
W	channel width, m
x, y, z	coordinate direction, m

Superscript

"$-$"	the filtered spatial variable

Subscript

i, j,k	different direction
0	the rectangular empty channel
w	the channel bottom surface

sink with different wavy amplitudes. The results showed that the heat transfer performance of the wavy micro-channel was improved and dramatically superior to that of the straight micro-channel, and the remarkable drag reduction was obtained as well. Min and Qi et al. [6] conducted a numerical simulation of heat transfer and flow characteristics over the combined rectangular winglet pair (CRWP) in a rectangle channel. It was found that vortices induced by the accessory wings moving downward to the channel bottom and the growth of the boundary layer was effectively weakened. Consequently, the heat transfer was enhanced. Colleoni et al. [7] investigated the thermal performance of heat exchanger with a combination of delta winglet vortex generators (DWVG) and riblets by asymmetrical heating, the results showed that a half-channel height of DWVG or bigger and thinner riblets had the best thermal performance. Gholami et al. [8] found that the wavy rectangular winglet vortex generator can significantly enhance heat transfer performance of the fin-and-tube compact heat exchangers. Installing the obstacles in the flow field is an effective way to improve the heat transfer performance [9]. An impingement flow was induced on the sidewall by the P-vortex flows and the inter-baffle cavity leaded a drastic increase of the heat transfer in channel [10]. Ary et al. [11] studied the effect of inclined perforated baffles on the flow patterns and heat transfer in a rectangular channel. The results showed that the flow patterns near the holes depended on the numbers of holes and significantly affected the local heat transfer performance. Narrein et al. [12,13] found that the nanofluids in different tubes can significantly improve the thermal performance with a slight increase of pressure drop. In addition, they investigated the effects of some nanofluids with different geometrical parameters (helix radius, inner tube diameter) on heat transfer and flow characteristics in the helically coiled tube heat exchanger [14,15]. Fan et al. [16–18] revealed that the conical strip inserted in a circular tube had a very good thermo-hydraulic performance, and larger slant angle and small pitch were very beneficial for improving heat transfer performance. Contrarily, active control category is performed with the external energy, such as mechanical vibration, electromagnetic field, jet impingement, etc. Kim and Lee et al. [19] investigated the effects of mechanical vibrations on critical heat flux (CHF) in vertical annulus tube under electrically heated condition. The results showed that the reinforced turbulent mixing caused by the vibration can made CHF enhanced.

As mentioned above, the heat transfer enhancement can be obtained by imposing various disturbances in boundary layer near the wall. But the augment of flow drag occurs inevitably, which is derived from the enhanced disturbance in boundary layer. The suppression on drag augment is a key in heat transfer enhancement. In other words, the heat transfer enhancement is meaningful only if with less flow drag augment.

In the present work, a passive control method, which installing a small-scale circular cylinder vortex generator in the fully-developed turbulent boundary layer of a rectangular channel, is adopted. When fluid flows past a stationary circular cylinder, the boundary separation from the upper and the lower of the circular cylinder occurs under some special conditions. Then, recirculation vortices and the corresponding vortex-shedding appear regularly. The induced vortices perturb the boundary layer and strengthen mixing of fluid. Therefore, it can be predicted that the heat transfer performance would be improved effectively. However, until now, flow past a small scale circular cylinder which is in close proximity to a wall has been received less attention for its complexity, especially the cylinder geometric scale is equivalent to that of boundary layer thickness. In addition, the feature of boundary layer with an equivalent scale insertion is bound up with some factors such as the Reynolds number, the gap ratio, etc. Price et al. [20] performed flow visualization in the wake of a circular cylinder near to the wall. They found that the gap ratio was a major factor which affected the flow characteristics. Wang and Tan et al. [21] investigated the effects of the gap ratios ($G/D = 0.1-1.0$) on the near-wake flow patterns of a cylinder placed in the proximity of a fully developed turbulent boundary layer. It was observed that the flow feature strongly depended on gap ratios. Sarkar et al. [22] revealed that the gap ratios had a strong influence on shear layer instability and turbulent coherent structure of near-wall region. Park [23] numerically investigated the effects of an inserted square cylinder on wall heat transfer in laminar channel flows. They found that the cylinder wake altered significantly the thermal boundary layer, and wall heat transfer was increased when the temperature distributions became steeper. Mohesn et al. [24] studied the effect of the cylinder which is close to the wall on heat transfer enhancement in channel flow. The results showed that the velocity and temperature distributions gradually tended to steady, the heat transfer and pressure drop gradually decreased when the distance from the cylinder to the bottom wall gradually became small.