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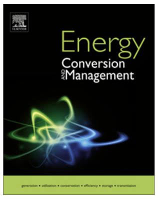

Heat transfer enhancement through control of added perturbation velocity in flow field

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ABSTRACT

The characteristics of heat transfer and flow, through an added perturbation velocity, in a rectangle channel, are investigated by Large Eddy Simulation (LES). The downstream, vertical, and upstream control strategy, which can suppress the lift of low speed streaks in the process of improving the performance of heat transfer, are adopted in numerical investigation. Taking both heat transfer and flow properties into consideration, the synthesis performance of heat transfer and flow of three control strategies are evaluated. The numerical results show that the flow structure in boundary layer has been varied obviously for the effect of perturbation velocity and induced quasi-streamwise vortices emerging around the controlled zone. The results indicate that the vertical control strategy has the best synthesis performance of the three control strategies, which also has the least skin frication coefficient. The upstream and downstream strategies can improve the heat transfer performance, but the skin frication coefficient is higher than that with vertical control strategy.

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1. Introduction

The control of turbulent flow with artificial methods is one of the most challenging recent topics in fluid engineering. The discovery of turbulent coherent structure indicated the possibility of controlling turbulence is existent [1,2]. The investigations on turbulent coherent structure show that the vortices near wall region are connected to the trailing legs of hairpin vortices, which can be found in the outer layer of the boundary layer. The vortices are in average inclined at an averaged of 45° to the wall. For the wall bounded turbulence, it is believed that the turbulent kinetic energy is mainly produced in the small scales very close to the wall [3]. The near-wall region containing the smallest scales is a net source of turbulent kinetic energy [4]. The near wall region of a channel flow is dominated by quasi-streamwise vortices or rolls with the downstream end slightly further from the wall and streamwise velocity streaks [5]. The flow structure of near-wall is associated with the performance of heat transfer and fluid flow. The performance of heat transfer and flow of fluid can be improved effectively by applying various control strategies. Passive control method, such as curved surface, obstacle and vortex generator can be used for heat transfer enhancement. The numerical simulation results show that the significant heat transfer enhancements are obtained when the asymmetric wavy channel is operated in the appropriate transitional Reynolds number range [6]. The obstacles mounted alternatively on the upper and lower walls in a channel can improve the performance of heat transfer and changer the flow structure. It is found that a traveling wave generated by the vortex shedding contributes mainly to heat transfer enhancement [7]. The obstacles mounted periodically with on the lower wall and oblique plates as vortex generators at the upper one in a horizontal channel have the effect *t* on heat transfer enhancement. The presence of vortex generators at the upper surface is a powerful mean to enhance the heat transfer [8]. The vortex generators attached to a surface of a heated cube can disturb the boundary layer around the cubes than the flow around the smooth cube. More complex structures are generated close to the surface of the cube with vortex generator, resulting in a considerable increase in the heat transfer coefficient [9]. Kumar et al. [10] investigated the performance of discrete W-shaped ribs applied in solar air heater. It is found that the values of Nusselt number and friction factor are substantially higher as compared to those obtained for smooth absorber plates. The performance of the heat sink pertaining to the influence of EHD is related to the electric field strength, the electrode arrangement, the electrode height, the fin structure, and the fluid flow characteristics [11]. Tavakoli and Hosseini [12] investigated the 3D axial flow between sinusoidal corrugated parallel plates. They found scale of vortices grows with increase in Reynolds number, and also their cores tend to shift toward the flow direction and away from the walls. Pressure drop in flows between corrugated plates is greatly affected by the vortices in various geometries. The optimal spacing between isothermal laminar natural convection plates cooled by air is investigated. It is found that

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Nomenclature

D_h	hydraulic diameter
f	skin friction factor
H	channel height
k_f	fluid conductivity
L	channel length
Nu	time mean local Nusselt number
Pr	Prandtl number
W	channel width
Re_b	Reynolds number $Re_b = (U_b D_h)/\upsilon$
p	mean pressure
t	time
U_b	bulk mean velocity
$\hat{u}_i$	filtered velocity
$\hat{p}$	filtered pressure
$\hat{h}_j$	subgrid-scale heat flux
y^+	nondimensional distance to wall
y_d^+	nondimensional distance from detection plane to wall
t^+	nondimensional time $t^+ = tU_b/L$
$\hat{\tau}_{ij}$	filtered subgrid-scale stress tensor
τ_w	shear stress at bottom of channel
u'	streamwise fluctuation velocity
v'	normal fluctuation velocity

Greek symbols

α	thermal diffusivity
υ	kinematic molecular viscosity
$\hat{\theta}$	filtered temperature

Superscript

^	filtered parameter

Subscript

o	parameter of without control strategy

the optimal plate's allocation spacing is different from the conventional way, where the boundary layers of the plates merge early. It is the distinguishing feature of the outlet velocity that causes an enhancement of heat transfer [13]. Wua and Tao [14] studied the delta winglet pairs used as longitudinal vortex generator. Numerical simulation results show that delta winglet pairs can bring about a further heat transfer enhancement and pressure drop decrease through the careful arrangement of the location, size and attack angle of delta winglet pairs either in "common flow up" or "common flow down" configurations. Khaled [15] found that the distribution of heat flux over the boundary have remarkable effects on heat transfer enhancement. The exponential heat flux distributions produced the most favorable energy performance factors. The properly managing the heat flux distribution can transfer additional noticeable heat under same maximum temperatures. The heat transfer enhancement can be obtained with a reduction of pressure loss by the strategies of fin-tube surface with longitudinal vortex generator design and appropriate placement on the fin-tube surfaces [16].

As one of the control methods, active control has been paid more and more attention for its potential to manipulate turbulent flows effectively with a very small energy input [17,18]. Endo et al. [19] applied a control strategy by using wall information, and that 10% drag reduction was observed. Huppertz and Fernholz [20] found that the length of the three-dimensional separation region downstream of a swept surface-mounted fence can be reduced by time-periodic blowing and suction generated by loudspeakers. The vibration caused by flow can be used for heat transfer enhancement. A method to enhance the heat transfer by using the flow-induced vibration of a new designed heat transfer device has been proposed. It is found that the new designed heat exchanger can significantly increase the convective heat transfer coefficient and decrease the fouling resistance [21]. In theoretic analysis of heat transfer enhancement, the field synergy principle for heat transfer enhancement indicates that the characteristic of heat transfer enhancement is directly associated with synergy angles [22].

The micro-electromechanical systems have been used for the diagnosis and control of turbulent shear flows. It is possible to achieve effective reactive control targeting toward specific small-scale coherent structures in turbulent wall-bounded flow with micro-sensors and micro-actuators [23]. The DNS of a channel flow under coupled dynamical effects of buoyant and Coriolis forces show that the momentum and heat transfer with the quasi-coherent structures is strikingly altered [24]. Mouyon et al. [25] investigated the transition on a flat plate equipped with a porous zone which allows a suction of the boundary layer. Kim et al. [26] investigated the relationship between the flow behavior induced by ultrasonic vibration and the heat transfer enhancement in nature convection and pool boiling regimes. Choi et al. [27] found that the drag reduction can be achieved when the surface boundary condition was modified to suppress the coherent structures present in the wall region. Considering the minimization of a cost functional, which represents some balance of the drag integrated over the wall and the net control effort, Lee et al. [28] investigated the drag reduction in turbulent channel flow with a new adaptive controller based on a neural network. Their results show that the reduction in skin friction can be reached by as much as 20%.

Lee et al. [29] proposed a feedback control laws, which needs the information of pressure or shear-stress only at the wall, and obtained a 16–22% reduction in the skin-friction drag when applied it to a turbulent channel flow. Fukagata and Kasagi [30] adopted a control strategy, in which the control input was applied only partially over a limited length in streamwise, but not on the entire wall surface.

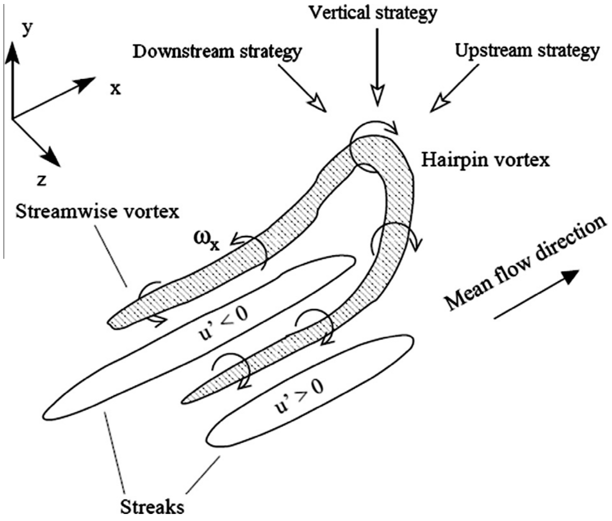

Fig. 1. Control principle of the near-wall coherent structures.

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