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Three-dimensional turbulent flow and heat transfer characteristics of longitudinal vortices embedded in turbulent boundary layer in bent channels

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ABSTRACT

The present study numerically investigated the three-dimensional turbulent flow and heat transfer characteristics of longitudinal vortices embedded in a turbulent boundary layer in a bent channel and examined the effects of a spanwise pressure gradient on the distortion of the turbulent boundary layer. The commercial code (ANSYS Fluent v17.0) was used for the simulation with the Reynolds stress model (RSM) to consider anisotropic effects. The simulation results showed that an asymmetric distortion of the turbulent boundary layers and a substantial change in the vortex shape were caused by the presence of an additional mean shear rate, originated from the spanwise pressure gradient. It was also found that an increase in the spanwise pressure gradient contributed to an enhancement of production of turbulent kinetic energy, resulting in stronger mixing flows. In particular, the Stanton number had an asymmetric distribution mainly in the bent region where the spanwise pressure gradient was dominant.

1. Introduction

Longitudinal vortices embedded in turbulent boundary layers in various flows such as those over swept wings of aircraft, those inside turbomachines, and pairs of horseshoe vortices generated by a blunt body mounted on the wall have received considerable research attention since a long time. These longitudinal vortices must be controlled precisely to prevent flow separation, enhance heat transfer, and ensure cooling effectiveness. During the past decades, considerable efforts [1–7] have been made toward understanding the detailed physics behind the interaction of a pair of longitudinal vortices with the turbulent boundary layer under conditions where the turbulent flow structure varies with the large-scale evolution of vortices and the heat transfer changes considerably. It must be such a crucial issue in controlling skin friction and boundary layer separation.

In fact, many studies have been conducted for investigating the interaction between longitudinal vortices and the turbulent boundary layer. Shabaka et al. [8] measured the circulation, streamwise velocity, eddy viscosity, and friction factor and demonstrated the formation of the complex flow structures distorted by longitudinal vortices. Further, Cutler and Bradshaw [9,10] reported that the velocity boundary layers around vortices thinned or thickened depending on the lateral divergence or convergence of fluid flow. They concluded that for common-flow-down and common-flow-up vortices, the growth of the velocity boundary layer differed with the rotation direction of the vortices and the effect of these two vortices on the friction factor was dissimilar. Meanwhile, Kim and Patel [11] performed a simulation of a pair of vortices mounted artificially in a two-dimensional turbulent boundary layer and showed that circulation around the primary vortex decreased on flat and convex surfaces but increased on a concave surface.

Also, the effects of the longitudinal vortex on heat transfer enhancement have also been extensively studied [12–14]. Gentry and Jacobi [12] examined the augmentation of heat transfer using delta wings placed on a flat plate, which resulted in substantial changes in the flow structure, a relatively low-pressure drop, and heat transfer enhancement. They also found that the maximum spatially averaged heat transfer increased by 35%–80% at low Reynolds numbers. Biswas et al. [13] also examined the augmentation of heat transfer by longitudinal vortices at high Reynolds numbers, and they reported that the promotion of mixing within the fluid layer and the disruption of the thermal boundary layer enhanced the heat transfer.

Indeed, the configuration of a vortex generator affects the vortex strength and also has directional effects on turbulent flows.

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Previous studies [15–20] have reported that some relevant parameters such as the attack angle and the configuration of a vortex generator are closely related to flow and heat transfer characteristics. Schubauer and Spangenberg [17] developed the mixing devices with various shapes to examine the influence of device configuration on the evolution of the boundary layer, and they showed that a variety of mixing devices had similar effects on fluid flow, except for flow variation caused by changes in displacement and momentum thickness. Also, Fiebig et al. [18] measured the drag and heat transfer coefficients in a laminar flow with various wing-type vortex generators and determined the appropriate attack angle and shape of the vortex generator for stabilizing longitudinal vortices and enhancing heat transfer. They also reported that triangular vortex generators with an attack angle between 45° and 70° were more effective than rectangular vortex generators. Schwarz and Bradshaw [21] showed that the crossflow generated in curved tunnels contributed to increasing the additional mean velocity gradient $\partial U_z/\partial y$, where U_z is the spanwise mean velocity, and y denotes the transverse direction.

As mentioned, the interaction of turbulent boundary layer with longitudinal vortices must be a significant research topic. From the literature, there is still the lack of knowledge on close interaction of spanwise pressure gradient with embedded longitudinal vortices in the turbulent boundary layer. It is necessary to examine the influence of the spanwise pressure gradient on the turbulent flow structure and heat transfer characteristics. Thus, the present study aims to numerically investigate the fluid flow behavior and heat transfer characteristics of turbulent flows with longitudinal vortices embedded in bent channels. This study also provides such quantitative fluidic and thermal assessment with the use of important parameters such as the velocity boundary layer, the direction of the velocity gradient vector (γ_g), the skin friction coefficient (C_f), and the Stanton number (St).

2. Numerical details

2.1. Mathematical representation

When the spanwise pressure gradient is spatially exerted to the embedded longitudinal vortices in the turbulent boundary layer, substantial flow distortion occurs in the bent region, making anisotropic flow structure and subsequently a rapid change in the convective heat transfer. For accurate prediction of the anisotropic and asymmetric behavior of mean and turbulent flow structures, we adopted the Reynolds stress model (RSM) based on the Reynolds-averaged Navier–Stokes (RANS) equations for steady and incompressible flow. The governing equations are expressed as follows [22]:

$$\frac{\partial U_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial U_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right), \tag{2}$$

$$\frac{\partial}{\partial x_k}\left(\rho U_k \overline{u_i' u_j'}\right) = P_{ij} + D_{ij} - \varepsilon_{ij} + \Pi_{ij} + \Omega_{ij}, \tag{3}$$

$$\frac{\partial}{\partial x_i}\left[U_i(\rho E + p)\right] = \frac{\partial}{\partial x_j}\left[\left(k + \frac{c_p \mu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_j}\right]. \tag{4}$$

In Eq. (3), P_{ij}, D_{ij}, ε_{ij}, Π_{ij}, and Ω_{ij} are the rate of production of Reynolds stress, the transport of Reynolds stress by diffusion, the rate of dissipation of Reynolds stress, the transport of Reynolds stress by pressure–strain interactions, and the transport of Reynolds stress by rotation, respectively. This study also uses the turbulent diffusion model proposed by Lien and Leschziner [23] and the pressure-strain correlation proposed by Gibson and Lauder [24]. The empirical constants used for RSM model are summarized in Table 1.

2.2. Computational domain and boundary conditions

Fig. 1 shows the entire computational domain and a constructed vortex generator with two half-delta winglets, based on a previous experiment of Pauley and Eaton [25], for forming a spanwise pressure gradient in the bent region. The curvilinear coordinate system is adopted here, where the X-axis represents the streamwise direction along the centerline of the channel, and the Y-axis and Z-axis represent the transverse directions normal to the bottom surface and the centerline, respectively. Given a channel with a 61 cm × 13 cm rectangular cross-section, the inlet surface is located at $X = -5$ cm and the vortex generator is mounted at $X = 0$ cm. Different bend angles of 0°, 30°, and 60° are considered in the present simulation to examine the effects of the spanwise pressure gradient for the fixed attack angle of 18° and the spacing (d) of 4 cm. The bent region is in the range of $X = 10$ cm–147 cm, and the bottom wall is heated from $X = 10$ cm to the end of the channel. A constant heat flux of 817 W/m^2 was used in the heated region. The grid sensitivity analysis was performed in the present study for a different number of grids ranging from 190,000 to 3,170,000. Based on the maximum relative errors of 1.29% in Stanton number, we determined the optimized grid system with approximately 2,100,000 cells in all simulations. Based on previous literature [25], the free-stream velocity was given as 16 m/s with a turbulence intensity of 0.3%, and the corresponding Reynolds number ($\equiv \rho_\infty U_\infty L/\mu$) based on the channel width was about 57,000. The power-law relationship was used for creating a fully developed turbulent boundary layer. This study also used Neumann condition and the no-slip boundary condition to the outlet surface and the walls. The non-equilibrium wall functions [26] to consider the pressure gradient effect with the modification of the turbulent kinetic energy was used to account for the near-wall anisotropic characteristics induced by the pressure gradient near the wall. This simple near-wall treatment to reduce computational cost shows that substantial improvement can predict the complex turbulent flows including separation, recirculation, and reattachment accurately.

3. Results and discussion

Unfortunately, it turns out that there are no available experimental data reported previously on the interaction of spanwise pressure gradient with longitudinal vortices embedded in the turbulent boundary layer. For justifying our numerical results, therefore, we compared the numerical predictions of skin friction coefficient and Stanton number with the previous experimental data [25], obtained from the case without the spanwise pressure gradient. In the middle section at $X = 89$ cm, Fig. 2 shows the distributions of the skin friction coefficient and Stanton number, defined as follows:

$$St = \frac{Nu}{Re \cdot Pr} = \frac{h\left(=\frac{q}{(T_w - T_\infty)}\right)}{\rho_\infty \bar{u}_\infty c_p}, \tag{5}$$

$$C_f = \frac{2\tau_w}{\rho_\infty u_\infty^2}. \tag{6}$$

where ρ_∞ means the density of the free stream and $\bar{u}_\infty$ indicates the free-stream velocity. And, T_w and T_∞ are the wall temperature and the free stream temperature, respectively. As presented in Fig. 2, the