Assessment of Local Blowing and Suction in a Turbulent Boundary Layer

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Abstract

Effects of local blowing or suction from a spanwise slot on a turbulent boundary layer flow are investigated using the direct numerical simulation technique. Three different blowing or suction velocities are imposed on the slot keeping blowing or suction flow rate constant. The recoveries of mean wall pressure for different blowing velocities collapse well on the same recovery line. However, each wall pressure recovers just after the slot for suction. In the blowing case, the relaxation of rms wall pressure fluctuations and pressure gradient after the slot is seen and the relaxation distance from the slot center is nearly constant for three different blowing velocities. In the suction case, the flow recovers from the immediate rear of the slot. These features are also observed in three-dimensional views of the near-wall vortices.

Introduction

Wall blowing or suction through a spanwise slot in a turbulent boundary layer has been frequently employed due to its potential possibility for turbulence control. A literature survey reveals that many experimental studies have been made on turbulent boundary layers subjected to a concentrated wall suction \cite{1} and blowing \cite{4}. Direct numerical simulations were performed for testing the wall blowing/suction in a turbulent channel \cite{2} and boundary layer \cite{6}. It was found that when wall blowing is applied through a spanwise slot, turbulent motions are enhanced with increasing turbulent shear stress, while suction diminishes turbulent fluctuations.

In order to assess the effect of blowing/suction on the downstream development of the flow, a measure of the local blowing/suction rate is generally used,

$$\sigma \equiv \frac{\nu_w b}{U_{\infty} \theta_{slot}} \quad (1)$$

where $\nu_w$ is the blowing/suction velocity, $b$ is the streamwise width of the spanwise slot and $\theta_{slot}$ is the momentum thickness of the unperturbed flow at the slot location \cite{1,6}. This quantity $\sigma$ represents the ratio of momentum flux gain/loss due to the blowing/suction to momentum flux of the incoming boundary layer \cite{1}. A perusal of the relevant literature indicates that $\sigma$ has been employed as a principal parameter to define the local blowing/suction \cite{1,7}. For example, Antonia et al. \cite{1} reported that the minimum value of skin friction decreases linearly with increasing $|\sigma|$ when the suction rate is sufficiently high ($|\sigma| \leq 2.6$). Sano and Hirayama \cite{7} demonstrated that the slot width hardly affects the turbulence characteristics as well as the velocity profiles when $\sigma$ is fixed at a constant value.

Although $\sigma$ has been employed as a representative parameter, it is necessary to further investigate the effect of $\nu_w$ on the perturbed flow. From the definition of $\sigma \equiv \nu_w b / U_{\infty} \theta_{slot}$, the role of $\nu_w$ is significant even though $\sigma$ is constant. This can be easily detected from the momentum integral equation

$$\frac{d\theta}{dx} = \frac{c_f}{2} + \frac{\nu_w}{U_{\infty}} + \frac{1}{\rho U_{\infty}} \int_0^\infty \frac{\partial P}{\partial x} dy. \quad (2)$$

where $\nu_w$ is closely related with the pressure gradient $(\partial P / \partial x)$, the skin friction ($c_f$) and the momentum thickness ($\theta$) of the perturbed flow. The purpose of the present study is to evaluate the role of $\nu_w$ at a fixed value of $\sigma$. Emphasis is placed on the relaxation of the perturbed flow. An understanding of the relaxation is of prime importance in analyzing the effect of blowing/suction through a spanwise slot, where the blowing/suction is applied only over a limited spatial extent. Three different blowing/suction velocities are applied at the slot. Toward this end, a direct numerical simulation of turbulent boundary layer is performed. The recovery process of the perturbed flow is examined in terms of the mean flow characteristics and the wall pressure fluctuations.

Computational Details

As mentioned earlier, a direct numerical simulation of turbulent boundary layer is performed to test the flow. A schematic diagram of the computational domain is displayed in figure 1. The domain size is 200$\theta_{in}$ $\times$ 30$\theta_{in}$ $\times$ 40$\theta_{in}$ in the streamwise, wall-normal and spanwise directions, where $\theta_{in}$ is the momentum thickness at the inlet. Realistic velocity fluctuations at the inlet are provided by using the method of Lund et al. \cite{5}. The convective outflow boundary condition $\partial u_i / \partial t + c \partial u_i / \partial x = 0$ is used at the exit, where $c$ is the mean exit velocity. A no-slip boundary condition is imposed at the solid wall. At the free-stream, $u = U_{\infty}$ and $\partial v / \partial y = \partial w / \partial y = 0$ are applied. The periodic boundary conditions are used in the spanwise direction.

The governing Navier-Stokes and continuity equations are integrated in time by using a fully-implicit decoupling method, which has been proposed by Kim et al. \cite{3}. All terms are advanced with the Crank-Nicolson...
method in time and they are resolved with a second-order central difference scheme in space. Based on a block LU decomposition, both velocity-pressure decoupling and additional decoupling of the intermediate velocity components are achieved in conjunction with the approximate factorization [3]. The overall accuracy in time is second-order without any modification of boundary conditions. Since the decoupled momentum equations are solved without iteration, the computational time is reduced significantly.

The Reynolds number based on \( \theta_m \) and \( U_\infty \) in \( Re = 300 \) and the mesh contains \( 257 \times 65 \times 129 \) points. The mesh is uniform in the streamwise and spanwise directions, while a hyperbolic tangent stretching is used in the normal direction to cluster points near the wall. In wall units, the mesh resolution is \( \Delta x^+ \approx 12.40, \Delta y_{\text{min}}^+ \approx 0.17, \Delta y_{\text{max}}^+ \approx 23.86, \) and \( \Delta z^+ \approx 4.96 \), based on the friction velocity at the inlet. The computational time step \( \Delta t U_\infty/\theta_m \) is 0.3 (\( \Delta t^+ \approx 0.25 \)), and the statistical quantities are sampled at every 5th time step and averaged for \( 3000 \theta_m/U_\infty \approx 2517 \nu/\nu^2 \).

### Results and Discussion

For a fixed \( |\sigma|=0.322 \), three different blowing/suction velocities are imposed through the slot, \( |v_{wo} U_\infty|=0.01242 \), 0.02425 and 0.04630. Since \( \sigma \) is fixed, the streamwise width of the slot is inversely proportional to \( v_w \), i.e., \( v_w b = \text{const} \). The center of the slot for all cases is located at \( x/\theta_m = 83.2 \). The detailed blowing/suction conditions are listed in table 1. To examine the effect of local blowing/suction, streamwise variations of the mean wall pressure are displayed in figure 2. For blowing, the adverse pressure gradient appears before and after the slot while the favorable pressure gradient occurs above the slot. For suction, the opposite is observed. This feature is consistent with the result of Park and Choi[6]. A closer inspection of the wall pressure recovery after the slot discloses that the recoveries for blowing collapse well on the same recovery line. However, the recovery processes for suction are different, i.e., each wall pressure recovers just after the slot.

To characterize different recovery processes, the behaviors of each term in equation (2) are plotted in figure 3. At the inlet ahead of the slot, a canonical relation of turbulent boundary layer is satisfied, i.e., \( c_f/2 = d\theta/dx \). Near the slot, however, the variations of \( \int(\partial P/\partial x)dx \) and \( -d\theta/dx \) are significant due to the blowing/suction. For blowing, a local maximum of \( \int(\partial P/\partial x)dx \) appears after the slot. The maximum value increases with increasing \( v_w \). It is remarkable to find that the maximum points are located at the same position \( x/\theta_m \approx 104 \). However, the behaviors of \( \int(\partial P/\partial x)dx \) for suction in figure 3(b) show that the pressure gradients recover to zero just after the slot. Note that the behaviors of \( \int(\partial P/\partial x)dx \) are similar to those of the mean wall pressure in figure 2. The streamwise variation of \( c_f/2 \) for blowing is much smaller than for suction.

It is important to examine the downstream turbulence quantities that arise due to the blowing/suction. The streamwise variations of \( \langle p' \rangle_{w_{rms}} \) for blowing/suction are exhibited in figure 4. Here, \( p_{\text{rms}} \) is the wall pressure fluctuations without blowing/suction. As shown in figure 4, the effect of the blowing/suction is significant. For blowing, \( \langle p' \rangle_{w_{rms}} \) increases after the slot, while it decreases for suction. An overall examination of the profiles in figure 4 indicates that all the data collapse well for a given \( \sigma \), except for the region of blowing/suction. This suggests that \( \sigma \) is a universal parameter to represent the blowing/suction. Near the slot, however, the profiles of \( \langle p' \rangle_{w_{rms}} \) are different depending on \( v_w \). As similar to that shown in figure 3(a), the distributions of \( \langle p' \rangle_{w_{rms}} \) have a local maximum after the slot for blowing. Note

<table>
<thead>
<tr>
<th>( v_{wo}/U_\infty )</th>
<th>slot span</th>
<th>( b/\theta_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01242</td>
<td>61.2\theta_m \approx 99.2\theta_m</td>
<td>32.0</td>
</tr>
<tr>
<td>0.02425</td>
<td>75.0\theta_m \approx 91.4\theta_m</td>
<td>16.4</td>
</tr>
<tr>
<td>0.04630</td>
<td>78.9\theta_m \approx 87.5\theta_m</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Table 1: Blowing/Suction conditions.
that the local maxima are located at the same position as that of $\int (\partial P/\partial x)dy$ for the three blowing cases.

Three-dimensional views of the streamwise vortices very near the wall are illustrated in figure 5 and 6. These instantaneous flow visualizations are helpful in capturing the global effect of $v_w$ on the flow. The contour values of $\omega_x$ are $|\omega_x| = 0.35U_\infty/\theta_m$. The width of the slot is denoted in gray. For blowing (figure 5), the vortical structures are lifted up above the slot and become much stronger downstream. An interesting finding is that the strengthened near-wall vortices are accumulated at $x/\theta_m \approx 104$, regardless of $v_w$. A ‘relaxation’ distance is observed for blowing, which is defined as the distance between the center of the slot ($x/\theta_m \approx 83.2$) and the position ($x/\theta_m \approx 104$). Note that the distance is constant when $\sigma$ is fixed. These are closely linked with the previous results that the maximum values of $\int (\partial P/\partial x)dy$ and $(p'_{w,rms} - p'_{w,o,rms})$ are located at the same position ($x/\theta_m \approx 104$) for different blowing velocities. For suction (figure 6), however, the vortical structures are drawn toward the wall above the slot and become weaker downstream. Due to the suction, the near-wall vortices are substantially weakened at the immediate rear of the slot. Just after the suction, they begin to recover without relaxation. This reflects that $\int (\partial P/\partial x)dy$ and $(p'_{w,rms} - p'_{w,o,rms})$ recover monotonically for suction as shown in figure 3(b) and 4(b).

Conclusions
Effects of blowing/suction with the same mass flux ($\sigma$) on a turbulent boundary layer were studied by carrying out direct numerical simulation. The Reynolds number based on the inlet momentum thickness was 300 and the local blowing/suction rate ($|\sigma|$) was fixed at 0.322. Above the slot, the pressure gradient was significantly influenced by the blowing/suction velocity. In the blowing case, a relaxation distance was observed in the recovery of both mean pressure gradient and wall pressure fluctuations, while the quantities were recovered at the immediate rear of the slot in the suction case. In the blowing case, the recovery curves had a local maximum which was located at the nearly same position for three different blowing velocities. These recovery patterns were also found in the iso-surface plot of streamwise vorticity.

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References


