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• Letter to the Editor •

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Effect of uniform blowing or suction on hypersonic spatially developing turbulent boundary layers

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Dear Editors,

Over the past decades, the reduction of drag has attracted considerable attention for its potential applications in engineering [1-3]. Direct numerical simulations (DNSs) provide accurate data that can be used to study the underlying physics of drag reduction. In a recent DNS [4] of an incompressible spatially developing turbulent boundary layer with uniform blowing or suction applied on the wall, the drag reduction mechanism was quantitatively explained by the Fukagata, Iwamoto and Kasagi (FIK) identity [5]. Compared with incompressible flows, far fewer studies have been reported for high-speed (hypersonic) flows. Therefore, the purpose of this study is to investigate the effects of uniform blowing and uniform suction on the skin-friction in hypersonic turbulent boundary layers.

The DNS of hypersonic spatially developing boundary layers with a free-stream Mach number of 6 and uniform blowing or uniform suction is performed. A parallel high-order finite difference code OpenCFD developed by the authors [6] is used. The free-stream temperature is $T_\infty = 223.38$. The wall temperatures normalized by the free stream temperature are $T_w/T_\infty = 6.98$. The velocity components in the streamwise (x), wall-normal (y), and spanwise (z) directions are u, v and w, respectively. The compressible Navier-Stokes equations are solved by a seventh-order weighted essentially non-oscillatory scheme [7] for the convective terms and an eighth-order central difference scheme for the viscous terms. The temporal integration is performed using a third-order Runge-Kutta algorithm. A two dimensional (2D) laminar flat-plate boundary layer including a leading edge was simulated in our previous work and the computed 2D results at x=4.0 are used as the inflow conditions. Non-reflective boundary conditions are employed at the upper boundary and outflow boundary. Periodic conditions are used in the spanwise direction to exploit the homogeneity [6].

The computational domain is $L_x \times L_y \times L_z = 12.96\times0.54\times0.2$ and the number of grids is $N_x \times N_y \times N_z = 4700\times116\times256$ for all cases. Table 1 presents the flow parameters in the fully developed turbulent region (x=12.5). A constant wall-normal velocity is applied on the wall in the fully developed turbulent region. The velocity amplitude on the wall is in the range of $-0.03U_\infty \leqslant v_w \leqslant 0.003U_\infty$.

The local skin friction coefficient $C_f(x)$ is plotted as a function of x. This figure shows that the skin friction is reduced with uniform blowing control, and enhanced with uniform suction control. At x=12.5, the drag reduction rate are approximately 42% and −50% for blowing and suction, respectively. Furthermore, the relationship between the drag reduc-

Table 1 Flow conditions and grid parameters

Case	Re_τ	Re_θ	δ	$\Delta x^+ \times \Delta y^+_{min} \times \Delta z^+$
Unmanipulated	531	17701	0.1211	5.48×0.44×3.43
0.3% blowing	485	25863	0.1407	4.31×0.35×2.70
0.3% suction	552	11596	0.1042	6.62×0.53×4.14

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tion rate and the velocity amplitude on the wall is nearly linear, and a large blowing or suction velocity amplitude leads to a large drag reduction or augmentation. In a compressible spatially developing turbulent boundary layer with a mean streamwise pressure gradient of zero, the modified FIK identity [8] reveals that the skin friction can be split into six contributing terms, as follows:

$$\begin{aligned}
C_f(x) &= C_l(x) + C_t(x) + C_m(x) + C_c(x) + C_{ct}(x) + C_d(x) \\
&= \frac{4}{Re_\delta}(1-\delta_d) + 4\int_0^1 (1-y)(-\overline{\rho u''v''})\mathrm{d}y \\
&+ 4\int_0^1 (1-y)(-\bar{\rho}\,\tilde{u}\tilde{v})\mathrm{d}y + \frac{4}{Re_\delta}\int_0^1 (1-y)\left(\mu^*\frac{\partial \bar{u}}{\partial y}\right)\mathrm{d}y \\
&+ \frac{4}{Re_\delta}\int_0^1 (1-y)\left(\overline{\mu'\left(\frac{\partial u'}{\partial y}+\frac{\partial v'}{\partial y}\right)}\right)\mathrm{d}y \\
&- 2\int_0^1 (1-y)^2\left(\frac{\partial\overline{(\rho uu)}}{\partial x} - \frac{1}{Re\delta}\frac{\partial \bar{\tau}_{xx}}{\partial x} - \frac{1}{Re_\delta}\frac{\partial}{\partial y}\left(\bar{\mu}\frac{\partial \bar{v}}{\partial x}\right)\right)\mathrm{d}y, \quad (1)
\end{aligned}$$

where C_l is the laminar contribution term, C_t is the turbulent contribution term, C_m is the mean convection contribution term, C_c is the compressible contribution term, C_{ct} is the compressible-turbulent interaction term, and C_d is the spatial development contribution term. The mean convection and spatial development terms are zero in a fully developed channel and pipe flows, and the compressible contribution and compressible-turbulent interaction terms are zero in incompressible flows.

The results computed by eq. (1) agree well with the results obtained directly using the wall-shear stress. In the unmanipulated case (M6UM), the turbulent contribution term C_t, the spatial development contribution term C_d, the mean convection contribution term C_m, and the laminar contribution term C_l are the main terms for the skin friction, and the compressible effects on the skin friction i.e. the compressible contribution term C_c and the compressible-turbulent interaction term C_{ct} are quasi negligible compared with the turbulence action. In flows of uniform blowing, the mean convection term C_m contributes to the reduction of the skin friction, and the turbulent term C_t associated with the Reynolds stress and the spatial development term C_d have opposite effects. Figure 1(b) demonstrates that in hypersonic turbulent flows with uniform blowing or suction, the mean convection term C_m has the most important contribution to the reduction or augmentation of the total skin friction. Figure 1(c) plots the mean viscous shear stress (VSS) and Reynolds stress (RS) as functions of y^{um+} (normalized by the unmainpulated wall shear velocity). It clearly shows that in the flow with uniform suction, the VSS is enhanced and the RS is reduced, whereas in the flow with uniform blowing, the opposite is observed. Figure 1(d) shows one-dimensional profiles of the terms in the turbulent kinetic energy equation at $x = 12.5$ for three cases.

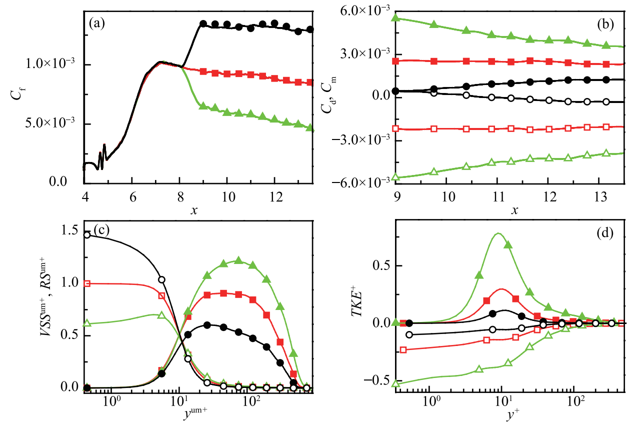

Figure 1 (Color online) Effect of uniform blowing/suction onhypersonic spatially developing turbulent boundary layers: square, unmanipulated; triangle, 0.3% uniform blowing; circle, 0.3% uniform suction. (a) Skin-friction as a function of x, computed using the wall shear stress (lines) and the FIK identity (symbols); (b) contributions to the skin-friction coefficient: open symbol, C_m, solid symbol, C_d; (c) shear stresses: solid symbol, (RS); open symbol, (VSS); (d) turbulent kinetic energy, solid symbol, production term; open symbol, dissipation term.

The peak value of the production is increased in the uniform blowing cases and reduced in the suction cases. This indicates that uniform blowing enhances the turbulence intensities, whereas uniform suction suppresses the turbulence intensities. These opposite effects are similar to those observed in incompressible flow [4]. In addition, uniform blowing reduces the mean density and increases the mean temperature, whereas uniform suction increases the mean density and reduces the mean temperature. The effect of uniform blowing or suction on the turbulent Mach number is small.

This research demonstrates that the mean convection term can be used for reducing the friction in hypersonic spatially developing boundary layers, even if it enhances the turbulence.

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