EFFECT OF VISCOSITY AND DENSITY GRADIENTS ON TURBULENT CHANNEL FLOWS

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Abstract We perform Direct Numerical Simulations (DNS) of a turbulent channel flow with temperature dependent density and viscosity. The Navier-Stokes equations are solved using their low Mach number formulation. In the simulations performed, the fluid is internally heated and the temperature at the walls is fixed. The friction Reynolds number based on half channel height and wall friction velocity is $Re_\tau = 395$. The modulation of turbulence, which is caused by the density and viscosity gradients, is characterized using the semi-local scaling of Huang et al. [3].

INTRODUCTION

Variable thermophysical properties in wall bounded turbulence at low Mach number is a common occurrence both in nature and modern-day industry. The large thermo-physical property gradients alter the conventional behaviour of turbulence due to the strong coupling between the momentum and energy equations. Earlier studies with respect to variable property wall turbulence has been done mostly in the compressible framework for air [1, 3, 2, 4]. Coleman et al [1] studied a supersonic channel flow using DNS with cold isothermal walls and concluded that only mean property variations, but not thermodynamic fluctuations, are important at supersonic Mach numbers. They observed that the property variations lead to an enhanced streak coherence (longer streaks) when compared to incompressible cases. Morinishi et al. [5] performed DNS of compressible turbulent channel flows between adiabatic and isothermal walls and showed that the near-wall velocity streaks for compressible turbulent flows do not become more coherent and are independent of thermal wall boundary conditions if the semi-local scaling by Huang et al. [3] is used to compare with incompressible flows. We try to further investigate these effects by investigating turbulence behavior for a more general set of variable property conditions and we characterize these effects using the semi-local based scaling.

RESULTS

We study several cases with different functional relations for temperature dependent density ρ and viscosity μ. We show that turbulence statistics are a strong function of the semi-local Reynolds number Re_τ^* ($= \frac{\sqrt{\overline{\rho}/\rho_{wall}}}{\overline{\mu}/\mu_{wall}} Re_\tau$) only and that they do not depend on the individual density or viscosity profiles. In the performed simulations considerable variations in both ρ and μ are obtained, such that the Re_τ^* changes by almost a factor of 2 across the channel for a case with $Re_\tau^* < Re_\tau$ (395 at wall to 150 at centre) and a case with $Re_\tau^* > Re_\tau$ (395 at wall to 700 at centre). Re_τ^* profiles for the individual cases are indicated in figure 1. When compared with the constant property case $CP395$, we see an increase in anisotropy for the case $Re_\tau^* < Re_\tau$, while the reverse happens for the case $Re_\tau^* > Re_\tau$. A visual impression for this change in anisotropy can be gained from figure 2, which shows contour plot for the stream-wise velocity fluctuation u''/u_τ^* (with $u_\tau^* = u_\tau/\sqrt{\overline{\rho}/\rho_{wall}}$) in plane parallel to the wall at $y^* \approx 15$ for all cases. The contours are shown in semi-local

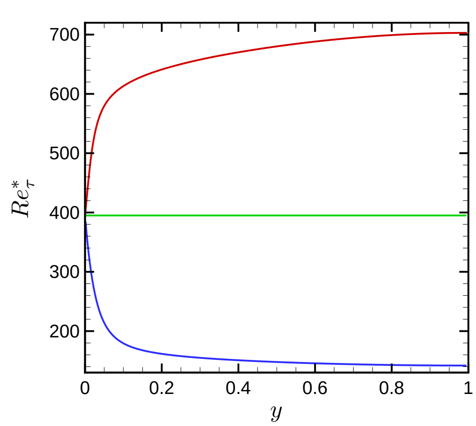

Figure 1. Local Reynolds number Re_τ^*. (green) CP395 ; (red) $Re_\tau^* > Re_\tau$; (blue) $Re_\tau^* < Re_\tau$.

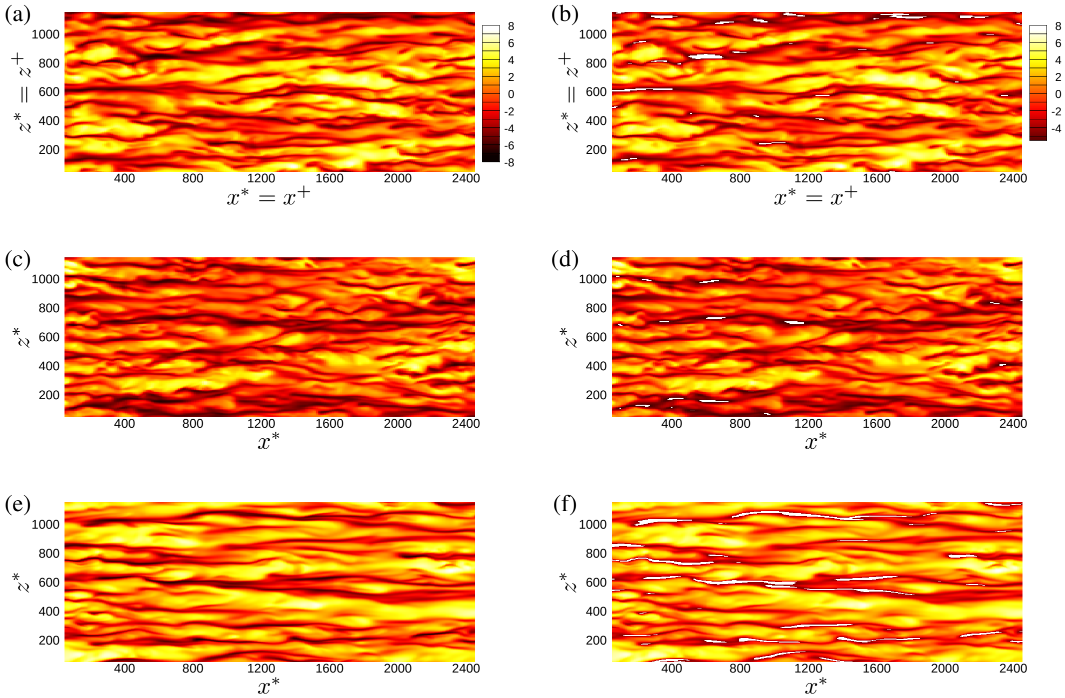

Figure 2. Instantaneous stream-wise velocity fluctuations u''/u_τ^* in a $x-z$ plane at $y^* \approx 15$ (a) and (b) CP395, (c) and (d) $Re_\tau^* > Re_\tau$, (e) and (f) $Re_\tau^* < Re_\tau$. In (b), (d) and (f) contour for $u''/u_\tau^* < -5.5$ are cut-off (seen as white).

($x^* - z^* = xRe_\tau^* - zRe_\tau^*$) wall units. The box size in all the visualisations is 2400×1100, based on non-dimensional co-ordinates. Scale separation, when compared with the constant property case (figure 2(a)), becomes more prominent for the case $Re_\tau^* > Re_\tau$ (figure 2(c)) and less prominent for the case $Re_\tau^* < Re_\tau$ (figure 2(e)). Comparison of semi-locally scaled variable property contours (figure 2(c) and 2(e)) with constant property contours (figure 2(a)) show similar mean span-wise spacing between the streaks for all cases. The change in anisotropy is assosiated with the strengthening (for the case $Re_\tau^* < Re_\tau$) and weakening (for the case $Re_\tau^* > Re_\tau$) of near-wall structures with respect to the constant property case as shown in figure 2(b), 2(d) and 2(f). The low-speed streaks in figure 2(b), 2(d) and 2(f) are cut-off below a threshold value of $u''/u_\tau^* = -5.5$ (seen as white), to highlight the energetic structures. It can be seen that for case $Re_\tau^* > Re_\tau$ (figure 2(d)) the energetic spots reduce in comparison to the constant property case (figure 2(b)). On the other hand, the energetic spots in the case of $Re_\tau^* < Re_\tau$ (figure 2(f)) become more prominent.

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