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Turbulent drag reduction using active control of buoyancy forces

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ABSTRACT

The present study involves Direct Numerical Simulations (*DNS*) of a turbulent channel flow subject to spatially modulated thermal forcing with a special interest to realize reduction of skin-friction drag. Thermal forcing has been employed using both streamwise and transverse arrays of heated strips on the bottom wall of the channel. The simulations have been carried out for a fixed friction Reynolds number $Re_\tau = 180$ with friction Richardson number Ri_τ varying from 15 to 30. The periodic transverse strips exhibited an increase in skin-friction drag with a decrease in the width of hot strips though wider hot strips exhibit a slight decrease in skin-friction drag. Streamwise periodic strips exhibited a reduction in skin-friction drag of the order of 8% with an increasing trend in reduction of friction drag with increasing Ri_τ. The mechanism responsible for turbulent skin-friction drag reduction due to streamwise thermal forcing affects two processes, namely: (a) advection of streamwise kinetic energy from the buffer-layer to outer layer by the wall-normal buoyancy forces leading to formation of broader low-speed streaks over the heated regions and (b) brings about suppression of cross-flow fluctuating velocities which in turn weakens the transient growth of the turbulent streaks.

1. Introduction

Reliable flow control to reduce turbulent skin friction is of principal importance in engineering applications for an increased energy efficiency and additional environmental benefits (Bushnell et al., 1989). The pioneering work by Kline et al. (1967) laid the foundations for classification and understanding of near-wall coherent structures. The structures which populate the near-wall region, such as low-speed organized streaks, quasi-streamwise and the hairpin-like vortices are responsible for most of turbulent kinetic energy production (Robinson, 1991). Several strategies have been employed for drag reduction under the assumption that the near-wall turbulence regeneration cycle can be favorably modified, weakened, or mitigated by the manipulation of the near-wall turbulence structures (Choi et al., 1994). For example, all drag reducing flows, regardless of the drag reduction methodology exhibit weakened near-wall streamwise vortices and weaker strength of streaks with larger spanwise spacing (Kravchenko et al., 1993). In a fully developed turbulent channel, Iuso et al. (2002) employed vortex generator jets distributed along the wall in the spanwise direction to investigate the modification of near-wall coherent structures by large-scale streamwise vortices. Large scale forcing was used for skin friction reduction by Schoppa and Hussain (1998). In their studies, colliding spanwise wall jets yielded about 50% frictional drag reduction while for imposed counter-rotating streamwise vortices they found approximately 20% drag reduction. They imposed a forcing flow with spanwise wavelength of 400 wall-units with a maximum effect at perturbation amplitude of 6% of the channel centerline velocity. The drag reduction was attributed to suppression of an underlying streak instability mechanism by the induced forcing. Active blowing has been studied (Choi et al., 1994; Sumitani and Kasagi, 1995) and found that uniform blowing from the wall leads to a decrease in skin friction drag. *DNS* studies were performed by Yoshida et al. (1999) to evaluate the response of coherent structures to blowing or suction below a low-speed streak. Turbulence suppression was reported for suction with an attenuation of near wall streaks.

El-Samni et al. (2005) investigated the effect of buoyancy on turbulent air flowing horizontally between two differentially heated vertical plates employing the Boussinesq approximation. They found that the buoyancy forces led to skewness in mean velocity profiles with non-zero anti-symmetric spanwise component and suppressed primary Reynolds stress in near-wall region. Turbulence intensities were found enhanced in the channel core by induced mean spanwise strain. Yoon et al. (2006) employed buoyancy forces to bring about turbulent drag-reduction in heated turbulent channel flow. They generated the buoyancy forces by applying large temperature difference between periodically arrayed heated strips aligned in the spanwise direction of a vertical channel, with streamwise mean flow perpendicular to the grav-

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ity vector. They obtained considerable drag reduction at higher Grashof numbers and they found that at the highest Grashof number, an optimum strip size of about 250 wall units gives drag reduction of about 35%. Mamori et al. (2009) utilized traveling wave-like surface heating to impart skin-friction reduction drag in a channel flow and studied the phenomena using linear analysis and *DNS*. Creation of negative Reynolds shear stresses was reported in the near-wall region due to non quadrature between the streamwise and the wall-normal velocity disturbances induced by the buoyancy force leading to skin-friction drag reduction. Reynolds stress and velocity fluctuations were found to be slightly attenuated in cases with traveling waves at high wavenumber. Though frictional drag was found increasing for larger magnitudes and lower wavenumbers of the traveling waves. In another related work, Mamori and Fukagata (2014), using *DNS* of fully developed turbulent channel, imposed a wave-like wall-normal body force to obtain a maximum drag reduction rate of about 40% in the case of a stationary control input. They attributed the reduction of friction drag to the spanwise roller like vortices which produce a negative Reynolds shear stress in near-wall area.

Few researchers have attempted to use buoyancy forces applied normal to mean-pressure gradient driven flows, in order to manipulate the near-wall organized structures for reducing skin-friction drag. We aim to conduct a series of *DNS* investigations with a periodic surface array of heated strips on the bottom wall at a fixed $Re_\tau = 180$ and Ri_τ varying from 15 to 30. The strips are arranged both in streamwise and transverse orientation and their effect on turbulence modification is analyzed. We also aim to change the ratio of heated strip to non-heated width (λ_h/λ_c) to accomplish a reduction in the cross-flow velocity fluctuations (v' and w') leading to a generation of weaker near-wall streaks thereby mitigating near-wall turbulence. In Section 2, we briefly touch upon the mathematical formulation and numerical scheme. In Section 3, we introduce the seven numerical experiments performed and analyze the results using spatio-temporal and statistical analysis. We have also computed the bursting frequency of the near-wall streaks using VITA conditional sampling and further instantaneous visualizations of the coherent structures has been performed. Based on the collective analysis of these result, we propose a phenomenological model to explain the key mechanism relating thermal forcing to observed reduction in wall shear stresses. Finally, we present conclusions based on our results and the observed trends of thermal forcing.

2. Mathematical formulation and numerical scheme

The numerical simulations are performed using our validated *DNS* code which employs a finite difference based discretization on a collocated Cartesian grid of 130 × 130 × 130. An incompressible, pressure-driven, fully-developed turbulent plane Poiseuille flow was considered for numerical experiments for a planar channel of height ($L_z = 2\delta$), streamwise length ($L_x = 2\pi\delta$) and spanwise width ($L_y = \pi\delta$). The fluid physically considered in this study was thermally stratified air of Prandtl number $Pr = 0.71$. The governing equations are a system of unsteady Navier-Stokes equations coupled with the energy equation taking into consideration Oberbeck-Boussinesq (OB) approximation. Together these equations govern the evolution of the velocity and temperature fields in a turbulent flow. The non-dimensionalization of the governing equations has been performed using half-channel height δ as length scale, friction velocity u_τ as velocity scale, $\frac{\delta}{u_\tau}$ as time-scale, $\rho_{ref} u_\tau^2$ as pressure-scale while temperature is non-dimensionalised as $\Theta = (T - T_{cold})/(T_{hot} - T_{cold})$. The relevant non-dimensional parameters are friction Reynolds number $Re_\tau = \frac{u_\tau \delta}{\nu}$ and friction Richardson number $Ri_\tau = \frac{g\beta\delta(T_{hot} - T_{cold})}{(u_\tau)^2}$, where ρ_{ref} is the reference density, $(T_{hot} - T_{cold})$ is the difference in temperature between hot and cold walls and g is the magnitude of gravitational acceleration. The non-dimensionalised governing equations in indicial form are given below:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{Re_\tau}\frac{\partial^2 u_i}{\partial x_j^2} + \frac{dP}{dx}\delta_{i1} + Ri_\tau \theta \delta_{i3} \tag{2}$$

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = \left(\frac{1}{Re_\tau Pr}\right)\frac{\partial^2 \theta}{\partial x_j} \tag{3}$$

A fully developed neutrally buoyant turbulent flow at isothermal conditions *i.e.* $\theta = 0$ is taken as initial condition. The flow has translational periodicity in the streamwise (x) and spanwise (y) directions while no-slip condition is applied at both the walls along with no-temperature jump condition. A non-dimensional temperature of $\theta = 0$ is applied at top wall of the channel while boundary conditions of alternate cold ($\theta = 0$) and hot surfaces ($\theta = 1$) are applied on the thermally controlled bottom wall as is evident from Fig. 1. Eqs. (1)–(3) have been solved using a pressure-correction based numerical scheme in which viscous terms have been solved implicitly. The scheme is essentially a modification of the SMAC method proposed by Cheng and Armfield (1995) and is a two step predictor-corrector algorithm. In the predictor step, Eqs. (2) and (3) are marched forward in time by treating the diffusion terms implicitly to yield provisional estimates of the velocity and temperature fields for an intermediate time level. In the corrector step, the non-solenoidal provisional estimate of the velocity field is corrected using a vorticity preserving pressure-correction field. Mathematically, this is illustrated as follows:

Predictor-step

$$u^* - \frac{\delta t}{Re_\tau}\nabla^2 u^* = u^n - \delta t\left(\nabla p^n + (u^n.\nabla)u^n - \frac{dP}{dx}\hat{i} - Ri_\tau \theta^n \hat{k}\right) \tag{4}$$

$$\theta^* - \frac{\delta t}{Re_\tau Pr}\nabla^2 \theta^* = \theta^n - \delta t((u^n.\nabla)\theta^n) \tag{5}$$

Corrector step

The divergence free velocity field at a new time level, u^{n+1} and the associated pressure fields p^{n+1}, is made to satisfy the momentum equation,

$$u^{n+1} - \frac{\delta t}{Re_\tau}\nabla^2 u^* = u^n - \delta t\left(\nabla p^{n+1} + (u^n.\nabla)u^n - \frac{dP}{dx}\hat{i} - Ri_\tau \theta^n \hat{k}\right) \tag{6}$$

Subtracting Eq. (4) from (6), we get:

$$u^{n+1} - u^* = -\delta t(\nabla p^{n+1} - \nabla p^n) \tag{7}$$

The difference of pressures at current time-level and previous time-level is defined as correction-pressure (p') and is expressed as:

$$p' = p^{n+1} - p^n \tag{8}$$

In light of this mathematical definition of correction-pressure, we can express Eq. (7) as:

$$u^{n+1} - u^* = -\delta t(\nabla p') \tag{9}$$

Defining the difference of u^{n+1} and u^* as correction-velocity (u'), we get:

$$u' = -\delta t\{\nabla p'\} \tag{10}$$

Expressing this correction-velocity as gradient of correction-pressure results in conservation of vorticity for both predictor and corrector steps. Now, taking the divergence of Eq. (9) assuming