European Journal of Mechanics B/Fluids 49 (2015) 250–263

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

journal homepage: www.elsevier.com/locate/ejmflu

Numerical investigation of turbulent-drag reduction induced by active control of streamwise travelling waves of wall-normal velocity

H. Ahmad, M.F. Baig *, P.A. Fuaad

Department of Mechanical Engineering, Aligarh Muslim University, Aligarh-202002, India

ARTICLE INFO

Article history:
Received 9 November 2013
Received in revised form
25 June 2014
Accepted 29 September 2014
Available online 18 October 2014

Keywords:
Turbulent channel flow
Streamwise travelling waves of wall normal velocity
Cross-flow fluctuating velocities
Near-wall streaks
Turbulent-bursting events
Power-budget

ABSTRACT

Direct Numerical Simulations studies in a fully-developed turbulent channel flow were performed to analyse the efficacy of the active control of streamwise travelling waves of wall-normal velocity on turbulent drag-reduction. A key result of application of control was reduction in cross-flow velocity fluctuations in the buffer layer zone ($10 < z^+ \leq 40$). This leads to the generation of more stable near-wall streaks of weaker magnitude which results in suppression of bursting events in the buffer layer. This eventually caused significant reduction in turbulent kinetic energy which further lead to reduction of turbulent skin-friction drag at the controlled wall (generally around 10%–11%). Upstream travelling waves of wall-normal velocity were most effective in bringing about considerable drag-reduction. For the case of downstream travelling waves, low phase-speed waves produced drag-reduction while waves with phase-speeds approaching $c^+ \simeq 10$ showed a significant increase in turbulent drag. The considerations of power-budget show the practical efficacy of upstream travelling waves and low phase-speed downstream travelling waves in producing net-power savings.

1. Introduction

Turbulence is a ubiquitous phenomenon in majority of industrial as well as terrestrial flows. A well known characteristic of turbulence is the enhanced dispersion of mass, momentum and energy which takes place due to the presence of coherent-structures. Hence, to obtain a better understanding of the phenomenon of turbulence, we need to carefully investigate the dynamics of these coherent-structures. The coherent-structure dynamics also holds a great relevance to skin-friction drag reduction for internal and external fluid flows. In the field of turbulence research, a large thrust has been on devising effective methodologies for controlling turbulent skin-friction. Several investigative studies, both experimental and numerical, have been performed which involve the application of active control in the form of streamwise travelling waves. These streamwise travelling waves have been categorised into two primary ways:

1. Streamwise travelling waves of spanwise-wall velocity (*STWSV*).
2. Streamwise travelling waves of wall-normal velocity (*STWNV*).

These travelling waves (of both types) are generated either by oscillations given to the walls confining the flow or by inducing suction and blowing on these confining walls. The *STWSV*, generally generated by spanwise oscillations of solid surfaces, are usually a cosine or sine function of space and time and are expressed as $v_{\text{wall}} = V_0 \text{Cos}(\kappa x - \omega t)$ where κ is streamwise wavenumber, ω is oscillation frequency and V_0 is the wave-amplitude. Such type of boundary condition on the bottom wall or on both the walls of the channel, will generate travelling waves that oscillate back and forth in spanwise direction while travelling in streamwise direction. A significant work in this regard has been done by application of *STWSV* on the walls of a planar channel. Jung et al. [1] conducted DNS for a channel flow subjected to spanwise oscillatory motion of the channel wall and found that for a certain range of time-period of oscillations, there was a suppression in turbulent-bursting phenomenon which led to a sustained reduction of up to 40% in turbulent skin-friction drag. Baron and Quadrio [2] confirmed these finding by DNS studies and also showed that net power gained (computed by taking in account power spent to produce oscillations of the wall) will be positive. Quadrio and Sibilla [3], performed DNS study for turbulent flow in a horizontal pipe oscillating around its longitudinal axis and compared it with turbulent flow in a stationary pipe. They reported that for certain appropriate parameters of wall-oscillations, there was around 40% drag reduction and that the results were comparable to those in planar flow-domains. Quadrio and Ricco [4] performed a series of DNS for a turbulent channel flow at $\text{Re}_\tau = 200$, with lateral sinusoidal oscillations and produced a database of numerically computed

* Corresponding author.
E-mail address: mfbaig.me@amu.ac.in (M.F. Baig).

http://dx.doi.org/10.1016/j.euromechflu.2014.09.004
0997-7546/

turbulent skin-friction reductions. They computed maximum drag-reduction of 44.7% and maximum net energy saving of 7.3%.

Motivated by the active control studies of *STWSV* in turbulent flows, some researchers started exploration of *STWNV* as an open-loop control strategy for drag-reduction. The use of *STWNV* as a control strategy stems from the works of Aamo et al. [5] who performed simulations on an incompressible unsteady two-dimensional channel flow employing a simple pressure-based feedback control strategy for wall-transpiration in order to obtain turbulent skin-friction reduction. Their results reported a presence of an instantaneous drag in the flow far lower than that of the corresponding laminar flow. Min et al. [6] performed DNS of a fully developed turbulent channel flow with *STWNV* (generated by suction and blowing of zero net mass-flux at the surface) and found that skin-friction drag could be sustained below that corresponding to laminar profile when flow is subjected to an upstream-travelling wave. Inspired by these findings, Lee et al. [7] performed the stability of flow subject to suction and blowing induced travelling waves by means of Floquet, DNS and SVD analyses. Their results show that stability of such flows depends largely on phase speed of the travelling waves and most disturbances become highly unstable when the phase speed is around 40% of the centreline velocity (i.e. $c \approx 0.4U_c$). Further increase of phase-speed of travelling waves ($c > U_c$) leads to three-dimensional disturbances becoming stabilised and suppression of transient growth for both the subcritical and supercritical Reynolds numbers. Lieu et al. [8] performed DNS studies in a three-dimensional planar channel flow in transition regimes, applying suction and blowing along both the walls of the channel and demonstrated the efficacy of *STWNV* in controlling the onset of turbulence in the channel. By computing the dynamics of fluctuating field and net power balance, they highlighted the effects of control strategy in modifying the base flow. They reported that the upstream travelling waves promote turbulence even when the uncontrolled flow stays laminar while the downstream travelling waves are capable of reducing the fluctuating flow-field and hence are more effective in delaying the onset of turbulence.

As is evident from the existing literature, most of the investigations, employing travelling waves as control strategy have been carried out for turbulent flows in channels and pipes subject to *STWSV*. There are comparatively fewer investigations on active control of turbulent flows subject to *STWNV* generated by suction and blowing, on one or both the walls of the channel. This DNS study aims to perform a series of simulations of turbulent channel flow at a fixed friction Reynolds number $\mathrm{Re}_\tau = 180$, subject to upstream, downstream, oscillating, almost standing-travelling waves of wall-normal velocity, in order to investigate their effect on turbulent skin-friction drag. Further, we aim to study the effect of varying phase-speeds of these travelling waves on mitigation/augmentation of near-wall turbulence. Moreover, we wish to analyse the flow-dynamics on the basis of statistics of modified turbulent-fluctuations, instantaneous visualisation of near-wall coherent-structures and burst-event detection of the coherent structures using *VITA* conditional-sampling technique. Finally, we aim to explore the practical efficacy of this control strategy by computing the net-power savings.

2. Mathematical-formulation and Numerical-scheme

2.1. Governing equations

The evolution of an incompressible, isothermal turbulent flow with constant thermo-physical properties is governed by the Navier–Stokes equations expressed in indicial form as:

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\mu\left(\frac{\partial^2 u_i}{\partial x_j\partial x_j}\right)+F_i \tag{1}$$

$$\frac{\partial u_i}{\partial x_i}=0. \tag{2}$$

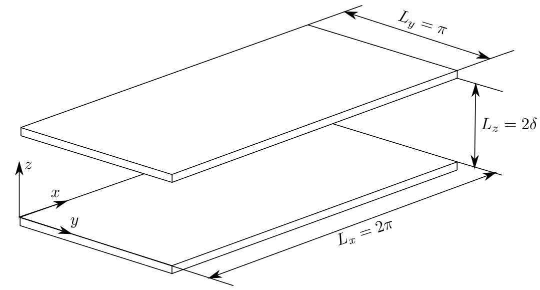

Fig. 1. Physical domain of the channel flow.

In order to generalise the results of the solver from the view point of dynamic-similarity, we non-dimensionalise the governing equations using suitable scales for velocity, length and time as u_τ, δ and $\frac{\delta}{u_\tau}$. The constant mean-pressure gradient term F in Eq. (1) is non-dimensionalised as $\frac{d\bar{P}}{dx}$ which can be related to the friction velocity u_τ using the balance of mean forces in streamwise direction. The non-dimensional value of mean pressure gradient turns out to be -1. The final non-dimensionalised equations in indicial form are expressed as:

$$\frac{\partial u_i^*}{\partial x_i^*}=0 \tag{3}$$

$$\frac{\partial u_i^*}{\partial t^*}+u_j^*\frac{\partial u_i^*}{\partial x_j^*}=-\frac{\partial p^*}{\partial x_i^*}+\frac{1}{\mathrm{Re}_\tau}\left(\frac{\partial^2 u_i^*}{\partial x_j^*\partial x_j^*}\right)+F_i^*. \tag{4}$$

These governing equations are subject to no-slip condition on both the walls, previous boundary-condition on the control wall and translational periodicity in both streamwise and spanwise directions, respectively. The initial condition for all simulations was a fully-developed uncontrolled turbulent flow that has reached statistical stationarity. All the variables represented in this paper will be in non-dimensionalised form and will not carry overhead $*$ sign (see Fig. 1).

A channel of streamwise length $2\pi\delta$, spanwise length $\pi\delta$ and wall normal height 2δ in Cartesian system of coordinates was chosen as the physical flow domain and δ was numerically equal to 1. The code employs a non-staggered mesh of $130 \times 130 \times 106$ points in x, y and z directions, respectively with about 17 points in $z^+ < 10$ and 4 points in $z^+ < 1$ in order to faithfully capture the viscous sublayer. The mesh employed in this study is four times more finer than the mesh employed in DNS study of Min et al. [6], Lieu et al. [8].

2.2. Numerical-scheme

We employ a semi-implicit pressure-correction based scheme on a collocated Cartesian mesh in which semi-implicit time integration methodology is obtained by treating the viscous-terms implicitly. The two-step predictor–corrector scheme is essentially a modified version of Simplified Marker and Cell (SMAC) method for unsteady flows as given by Cheng and Armfield [9]. The implementation of the scheme in the computer-code is done using Euler's first-order accurate scheme for time-integration with diffusion terms treated implicitly in order to get a provisional estimate of velocity field at intermediate time-level.

$$\widetilde{u}-\frac{\delta t}{\mathrm{Re}_\tau}\nabla^2\widetilde{u}=u^n-\delta t(\nabla p^n+(u^n\cdot\nabla)u^n+F^n). \tag{5}$$

These predicted velocities are then further corrected in a vorticity preserving manner as shown in Eq. (6) by using a corrected-pressure field to get a corrected velocity-field whose divergence