International Journal of Heat and Mass Transfer 78 (2014) 707–720

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Large eddy simulation of smooth–rough–smooth transitions in turbulent channel flows

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ARTICLE INFO

Article history:
Received 12 December 2013
Received in revised form 28 June 2014
Accepted 29 June 2014
Available online 6 August 2014

Keywords:
Turbulent
High Reynolds number
LES
Roughness
Wall model

ABSTRACT

We describe a high Reynolds number large-eddy-simulation (LES) study of turbulent flow in a long channel of length 128 channel half heights, δ, with the walls consisting of roughness strips where the long stream-wise extent invites a full relaxation of the mean velocities within each strip. The channel is stream-wise periodic and strips are oriented transverse to the flow resulting in repeated transitions between smooth and rough surfaces along the stream-wise direction. The present LES uses a wall model that contains Colebrook's empirical formula as a roughness correction to both the local and dynamic calculation of the friction velocity and also the LES wall boundary condition. This operates point-wise across wall surfaces, and hence changes in the outer flow can be viewed as a response to the temporally and/or spatially variant roughness distribution. At the wall surface, dynamically calculated levels of time- and span-wise-averaged friction velocity $\overline{u_\tau}(x)$ over/undershoot and then fully recover towards their smooth or rough state over a stream-wise distance of order 10–30 δ depending on both roughness and Reynolds number. Also, the initial response rate in $\overline{u_\tau}$ shows Reynolds number and roughness dependence over both transitions. The growth rate of the internal boundary layer (IBL), defined by the abrupt change in stream-wise turbulent intensity, is found to grow as $x^{0.70}$ on average over multiple simulation conditions for the case of a smooth-to-rough transition, which agrees with the experimental results of Antonia and Luxton (1971) [1] and Efros and Krogstad (2011) [2]. IBL profiles demonstrate a good collapse on $\delta/\log(Re_\tau^*)$, where Re_τ^* is the local Reynolds number based on $\overline{u_\tau}$ at the point of full recovery.

1. Introduction

Two conditions that abound in environmental and engineering flows are high Reynolds number turbulence [3] and wall boundaries with surface roughness (see [4]). The effect of surface roughness on drag and heat transfer has garnered much attention within the naval, aerospace and industrial communities [5] and it is an essential variable in meteorological prediction [6,7]. What constitutes high Reynolds number depends on the flow in question (see [8] for discussion). Typically it represents a sufficient separation of eddy scales, and, for canonical wall-bounded flows, this amounts to an appreciable length of logarithmic behavior in the mean velocity profile.

Recent experimental evidence of roughness effects appearing in high-Reynolds number, canonical wall-bounded turbulent flow has prompted Saito et al. [9] to conclude that roughness effects become significant to large eddy simulations (LES) operating at sufficiently high Reynolds number. Therefore they have incorporated a semi-empirical roughness model into their wall-modeled channel flow LES, which allowed simulations up to $Re_b = \mathcal{O}(10^{10})$, where $Re_b = u_b\delta/\nu, u_b$ is the bulk velocity, δ is the half channel height and ν is the kinematic viscosity. The present work builds on Saito et al. [9], who have studied the roughness and Reynolds number dependence of the friction factor and thus produced a Moody-like diagram for channel flow, by exploring step transitions from smooth-to-rough ($S \to R$) followed by rough-to-smooth ($R \to S$) surfaces in a fully developed turbulent channel flow. These geometries are important in areas of micro-meteorology [10,11], in spoiling of heat exchangers, and in turbine blades with surface degradation or deposits [12–14]. We refer to these alternating transverse step changes in roughness as roughness "strips" and take advantage of the high Reynolds number capability of our numerical method in a channel flow in order to examine flow responses and trends when various levels of Reynolds number and roughness are encountered by the flow.

The treatment of a single step change in roughness has traditionally relied on a thermally neutral zero-pressure-gradient turbulent boundary layer (ZPTBL), rather than a channel flow, to

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.06.088
0017-9310/

elucidate the structure and response rates of the perturbed flow. Boundary layer field experiments [21,41] and wind tunnel work [1,15–17] under steady-state conditions reveal the formation of an internal boundary layer (IBL) that grows from the location of the step change in roughness. The height of the IBL δ_i can be determined either through the stream-wise mean velocity [1,18,17], stress [19] or through stream-wise turbulent intensities [2]. Detailed findings from several of these studies, including modeled equations for the IBL growth rate, are given in Section 4.4. For the case of a ZPGTBL, at any given wall-normal height above the IBL, the flow appears statistically as it would for the upstream wall condition alone except for a slight upward shift of streamlines [15]. Within the IBL, two further layers are observable: a transition layer and an equilibrium layer. The transition layer immediately below δ_i is where flow is affected by both upstream and downstream wall surfaces and where turbulent conditions are transitioning gradually from one equilibrium flow to another. The equilibrium layer is adjacent to the wall up to the height δ_{eq}, wherein the flow is fully adjusted to the new wall state.

Quantitatively, the rate at which the flow adjusts to the new surface can be examined in a number of direct flow variables such as wall shear stress, mean velocity and turbulent statistics, or indirect quantities such as δ_i, δ_{eq}, or log-law constants/parameters. When enough of the direct variables reach a state that no longer has any memory of the upstream step change, a flow can be considered to be fully relaxed. Indeed one must quantitatively but subjectively select how many variables to consider and what constitutes the signature of transition to this relaxed state in each variable. Relaxation rates and distances may be quite sensitive to the selection of the threshold made, as discussed by Cheng and Castro [17]. The present study reaches consistent trends when exploring each of the following variables separately: inner- and outer- scaled mean velocity (Section 4.1), friction velocity (Section 4.2) and internal boundary layer growth (Sections 4.3, 4.4).

Several observations in the literature have demonstrated firstly that flow after a step and very near the wall is seen to relax towards equilibrium almost immediately (e.g. [1,15,17,2] and secondly, that $S \rightarrow R$ transitions result in flows that relax more rapidly than $R \rightarrow S$ flows. A possible exception is [44] who has recorded Reynolds shear stress in both cases as having not relaxed after a distance of 20δ in a channel flow [20,21]. Antonia and Luxton [1,15] have found that boundary layer flows encountering a step from $R \rightarrow S$ adjust towards equilibrium less rapidly than $S \rightarrow R$ at $U_\infty \delta/\nu = 1.9 \times 10^4$ and 3.1×10^4, where U_∞ is the free stream velocity. Their $S \rightarrow R$ case has required less than 20δ for equilibrium and self-similarity to be restored in mean flow integral parameters and turbulent intensities. For their $R \rightarrow S$ case at $U_\infty \delta/\nu = 2.6 \times 10^4$ and 4.8×10^4, within the extent of their test section of length 16δ, the flow never fully re-establishes equilibrium or similarity. They have suggested that a possible reason for this long "memory" is that in the rough wall flow, a greater proportion of the turbulent energy resides in the larger scale turbulence in the outer layer that is then advected into the flow above the smooth wall. Away from the wall, Jacobs [22] has found that shear stress distributions obtained in the outer part of a channel flow adjust more slowly than those near the wall. This observation is indicative of the slower growth of the equilibrium layer in the outer parts of the flow.

Rather few authors have considered more than one roughness step change. Weng et al. [23] have numerically modeled 2-D flow over multiple short strips of roughness. Andreopoulos and Wood and Jacobi and McKeon introduced both $S \rightarrow R$ and $R \rightarrow S$ transitions by the addition of a short/impulsive roughness strip [10,24,25]. In between the two corresponding IBLs, a "stress bore" is formed wherein the influence of the rough strip on the Reynolds shear and normal stresses can be detected and where the flow is in non-equilibrium [26,10,24,25]. Jacobi and McKeon [24], through their study of static impulsive roughness, have noted that impulsive roughness affects the spectral energy of only smaller wavelengths, which they suggest is a potential tool for flow control. Further studies have then included dynamic impulsive roughness, where the role of the temporal frequency of the impulse has been shown to be significant [25].

In contrast, the present channel LES utilizes a roughness strip of considerably longer extent (64δ) than the aforementioned studies. This long domain length invites a relaxation towards equilibrium. The majority of workers have examined relaxation rates at only one or two relatively low Reynolds numbers, with many of them being concerned with the non-equilibrium zone immediately after a step and close to the wall. In the present LES we consider a wider range of considerably larger Reynolds numbers and focus on flow responses over the entire domain. The present numerical approach implements spectral techniques that rely on the span-wise periodicity of the channel, and therefore, for given computational resources, the simulation receives a computational benefit such that it allows for a longer stream-wise computational domain to be used. The overall channel flow geometry is advantageous because, far enough downstream from any change in surface roughness, the flow plateaus towards a state that is statistically independent of downstream distance (except close to a downstream transition), making for a more straightforward identification of the relaxed state. We also note that due to the particular numerical wall treatment in our LES, the value of the local wall shear stress is directly available and no further uncertainty is introduced by sampling location or through any indirect calculation.

This paper is organized into three main portions. First, the present LES method is expounded briefly in Section 2 and model validation and simulation conditions are presented in Section 3. This is followed by results and discussion of the mean flow velocity in Section 4.1 and friction velocity in Section 4.2. The stream-wise turbulent intensities and IBL growth rate are discussed in Sections 4.3 and 4.4. We finally present the conclusions in Section 5.

2. Stretched vortex SGS model and wall model with roughness

The present LES of a strip-roughness channel uses a stretched vortex subgrid scale (SGS) model to calculate flow dynamics away from the wall, a region henceforth called the "outer" LES. This is distinct from flow dynamics near the wall that are captured by a wall model and an embedded roughness correction. This SGS model and wall model are described in Saito et al. [9] for uniformly-smooth- and uniformly-rough-wall channel flows. Inclusion of surface roughness modifies only the present wall model, which is responsible for the effect of near-wall fine scales and sets the boundary conditions for the outer LES. Therefore, the flow behaviors observed in the outer LES under rough surface conditions are the result solely of the change in the boundary conditions, which is consistent with the physical picture of flow over rough surfaces. In what follows, the stretched-vortex model as well as the wall model with roughness are briefly reviewed.

2.1. Stretched-vortex SGS model

The stretched-vortex approach is a structural SGS model and represents the statistical effects of subgrid motion by using information from resolved scale quantities [27]. It is assumed that the subgrid vorticity in each cell comprises a superposition of vortices that may be stretched by the resolved-scale rate of strain tensor, and each of which is unidirectional and of cylindrical type. Upon coordinate transformation from the vortex-fixed frame to the lab-fixed frame, the distribution of orientations of the vortex