International Journal of Heat and Fluid Flow xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Large eddy simulation of turbulent channel flow with transverse roughness elements on one wall

C.D. Dritselis *

Mechanical Engineering Department, University of Thessaly, Pedion Areos, 38334 Volos, Greece

ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form 4 August 2014
Accepted 18 August 2014
Available online xxxx

Keywords:
LES
Subgrid-scale model
Immersed boundary method
Roughness elements
Ribs

ABSTRACT

This study examines the feasibility of large eddy simulation for predicting turbulent channel flows with two-dimensional roughness elements of square, circular and triangular shapes transversely placed on the bottom wall. Results are obtained for several values of the cavity width to the roughness height ratio using various subgrid-scale turbulence models. The present large eddy simulation predictions of mean streamwise velocity, root-mean-square velocity fluctuations, and skin frictional and form drags agree reasonably well with previously published results of direct numerical simulations at a low Reynolds number. All the subgrid-scale models examined here are capable of reproducing the relevant physics associated with the effect of the rough surface on the turbulent flow, exhibiting similar performances. Moreover, the use of the turbulence models leads to an improvement in the predictions of several turbulence statistics as compared with the case when no model is considered. Large eddy simulation can be combined easily with an immersed boundary method yielding satisfactory results based on a coarser grid resolution than in direct numerical simulation and, thus, it is suitable for the investigation of turbulent channel flows with riblets of various shapes.

1. Introduction

Roughness elements are often incorporated on the walls of a duct in order to promote turbulence and to enhance heat transfer (see, for example, Nagano et al., 2004; Saha and Acharya, 2004; Luo et al., 2005; Saidi and Sunden, 2000; Kim et al., 2004; Yucek and Dinler, 2006). These elements may have random shape and structure or well-defined dimensions and ordered pattern. Recently, several studies of direct numerical simulation (DNS) considered the turbulent flow over riblets with square, circular, or triangular cross-sections (Leonardi et al., 2003a,b, 2004, 2007; Ashrafian et al., 2004; Orlandi et al., 2006; Burattini et al., 2008; Leonardi and Castro, 2010). While restricted to flows with small Reynolds number, the use of DNS has shown itself to be a very suitable tool in obtaining detailed information of the relevant physics in turbulent flows with rough walls. Larger Reynolds numbers can be achieved potentially by using large eddy simulation (LES). Based on the standard and the dynamic Smagorinsky subgrid-scale turbulence models, flows with or without heat transfer in ribbed channels or pipes have also been investigated numerically (Ciofalo and Collins, 1992; Cui et al., 2003; Iacono et al., 2005; Leonardi et al., 2006; Vijiapuparu and Cui, 2007; Khan et al., 2010).

In the standard Smagorinsky model (Smagorinsky, 1963), the value of the model parameter is determined a priori and it changes depending on the flow. A wall function is always necessary to damp the eddy viscosity at the walls of the turbulent flow. Germano et al. (1991) proposed a dynamic procedure to calculate the model parameter during the numerical simulation. The subgrid-scale eddy viscosity of the initial version may acquire negative values causing subsequently numerical instabilities. Thus, averaging of the model coefficient in homogeneous directions is usually performed in order to overcome this difficulty. Some other alternatives include averaging locally over a stencil of three or more grid points in each direction (Zang et al., 1993; Gullbrand, 2004), averaging based on the dynamic localization model of Ghosal et al. (1995), time averaging of Meneveau et al. (1996) and ensemble averaging over many simultaneous computations proposed by Carati et al. (1996). Several others models suitable for engineering applications have also been proposed and used frequently (see, for example, Shimomura, 1994; Nicoud and Ducros, 1999; Yoshizawa et al., 2000; Vreman, 2004). In these models, the turbulent eddy viscosity is locally determined with some fixed values of the model parameters.

Kobayashi (2005) proposed a local subgrid-scale model based on the coherent structures of the turbulent flow field. The model

* Tel.: +30 24210 74337; fax: +30 24210 74085.
E-mail address: dritseli@mie.uth.gr

http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.08.008
0142-727X/© 2014 Elsevier Inc. All rights reserved.

parameter is composed of a predefined, fixed value and a function describing the coherent structures that plays the role of wall-damping. The coherent structure model has been tested in a series of canonical turbulent flows, such as rotating and non-rotating channel flows (Kobayashi, 2005) and magnetohydrodynamic (MHD) flows in channels (Kobayashi, 2006) and in ducts (Kobayashi, 2008). The results based on the coherent structure model were in good agreement with DNS and/or experimental data, exhibiting a level of accuracy at least similar to that obtained by using the standard dynamic model. The applicability of the coherent structure model was also assessed in large eddy simulations of a flow over a backward-facing step, a flow in an asymmetric plane diffuser, and staggered jets in cross-flow (Kobayashi et al., 2008). For all configurations, it gave almost the same performance as the dynamic localization model and the dynamic Smagorinsky model with averaging in homogeneous directions. However, the coherent structure model was inexpensive relative to the dynamic model and it was numerically stable without requiring averaging.

The objective of the present study is to assess the applicability and the predictive performance of LES in turbulent channel flows with roughness elements placed on one wall. For this reason, the LES results produced for several cases with square, circular and triangular bars on the bottom wall of the channel based on the standard dynamic Smagorinsky model, the Lagrangian dynamic Smagorinsky model, and the coherent structure model are compared with those obtained by using DNS at a relatively low Reynolds number (see, for example, Leonardi et al., 2003a,b, 2004, 2007; Orlandi et al., 2006), which has not been done previously. The main interest here is to stably apply the aforementioned subgrid-scale turbulence models to the present flows with complex geometries and to obtain reasonable results with respect to the aforementioned DNS studies, and not to conclude which model is better. An immersed boundary technique is adopted to treat the two-dimensional (2d) wall disturbances of various cross sections, which allows the numerical solution of flows over complex geometries without the need of computationally intensive body-fitted grids (see, for example, Fadlun et al., 2000; Iaccarino and Verzicco, 2003; Mittal and Iaccarino, 2005; Orlandi and Leonardi, 2006).

2. Simulations overview

2.1. Flow governing equations

The governing equations of the present flow are the three-dimensional (3d), unsteady, incompressible filtered continuity and Navier–Stokes equations

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho_f}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau^r_{ij}}{\partial x_j} + \Pi \delta_{i1}, \tag{2}$$

where $\bar{u}_i$ is the component of the large-scale fluid velocity in the i-direction, $\bar{p}$ is the fluid pressure, ρ_f and ν are the fluid density and kinematic viscosity, respectively, Π is the extra pressure gradient in order to keep the fluid mass flow rate constant, and δ_{ij} is the Kronecker delta. Note that $\bar{u}_x$, $\bar{u}_y$, and $\bar{u}_z$ are the fluid velocity components at the grid-scale in the streamwise (x), wall-normal (y), and spanwise (z) directions, respectively, and the indices i,j denote x, y, or z. The term τ^r_{ij} represents the effect of the subgrid-scale motions on the resolved grid-scale velocities of the fluid. It is the traceless part of the subgrid-scale stress tensor, defined as

$$\tau^r_{ij} = \tau_{ij} - \frac{1}{3}\tau_{mm}\delta_{ij} \text{ with } \tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j. \tag{3}$$

A schematic of the flow configuration is shown in Fig. 1. The velocity satisfies periodic boundary conditions in the x- and z-directions, and no-slip conditions at the walls. The 2d roughness elements are numerically treated by an immersed boundary method, which consists of imposing zero values to all fluid velocity components on the stationary boundary surface that does not necessarily coincide with the computational grid (see, for details, Fadlun et al., 2000; Orlandi and Leonardi, 2006). In accordance with the aforementioned studies, zero velocities are imposed in the grid points within the roughness elements. At the first grid point outside each roughness element, all the viscous derivates and the terms of the extra subgrid-scale stress tensor in the filtered flow equations are discretized by using the distance between the grid point and the boundary of the wall disturbance and not the actual mesh size. This is done in order to avoid describing the geometry in a stepwise way and to perform numerical simulations by maintaining a constant fluid mass flow rate in the channel.

2.2. Subgrid-scale turbulence models

In the present study, the extra subgrid-scale stress tensor τ^r_{ij} appearing in the LES equations due to the filtering procedure is modeled by the standard and Lagrangian dynamic Smagorinsky models and the coherent structure model.

2.2.1. Standard dynamic Smagorinsky model

In the standard dynamic Smagorinsky model, the subgrid-scale stress τ^r_{ij} is modeled as

$$\tau^r_{ij} = -2c\bar{\Delta}^2|\bar{s}|\bar{s}_{ij}, \tag{4}$$

where $\bar{s}_{ij}$ is the resolved strain-rate tensor and $|\bar{s}|=(2\bar{s}_{ij}\bar{s}_{ij})^{1/2}$ is its magnitude. The characteristic length is $\bar{\Delta} = (\Delta x \Delta y \Delta z)^{1/3}$, where Δx, Δy, and Δz are the grid spacings in the x-, y-, and z-directions, respectively. The model parameter c is determined by the dynamic procedure proposed by Germano et al. (1991) based on Lilly's (1992) modification

$$c = \frac{\langle l_{ij} m_{ij}\rangle_{x_i,hom}}{\langle m_{kl} m_{kl}\rangle_{x_i,hom}}, \tag{5}$$

with l_{ij} and m_{ij} given as

$$l_{ij} = \widehat{\bar{u}_i \bar{u}_j} - \hat{\bar{u}}_i \hat{\bar{u}}_j, \tag{6}$$

$$m_{ij} = 2\widehat{\bar{\Delta}^2 |\bar{s}| \bar{s}_{ij}} - 2\hat{\bar{\Delta}}^2 |\hat{\bar{s}}|\, \hat{\bar{s}}_{ij}, \tag{7}$$

where ($\hat{}$) denotes variables calculated on the test filter and $\langle\,\rangle_{x_i,hom}$ averaging over homogeneous directions. The present large eddy simulations of the turbulent channel flow with roughness elements on the bottom wall are performed by using a box filter in the physical space based on the trapezoidal rule. No filtering is applied in the wall-normal direction, while the width of the test filter is twice the size of the uniform grid spacing in the x- and z-directions. A cut-off is set to ensure positive values of the total viscosity in order to prevent any numerical instability.

2.2.2. Lagrangian dynamic Smagorinsky model

The model parameter c in Eq. (4) is also calculated based on the approach developed by Meneveau et al. (1996) as

$$c = \frac{i_{LM}}{i_{MM}}. \tag{8}$$

In principle, the quantities i_{LM} and i_{MM} are obtained from the solution of separate transport equations. However, the numerator and denominator of Eq. (8) are calculated by using a simple time discretization resulting in