Computers & Fluids 89 (2014) 111–123

Contents lists available at ScienceDirect

Computers & Fluids

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

# A comparative study of turbulence models in a transient channel flow

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ARTICLE INFO

*Article history:*
Received 19 January 2013
Received in revised form 21 October 2013
Accepted 28 October 2013
Available online 1 November 2013

*Keywords:*
Unsteady
Acceleration
Turbulent flow
Turbulence models
Channel flow
Wall shear stress

ABSTRACT

The performance of a number of low-Reynolds number turbulence models is evaluated against direct numerical simulations (DNS). All models are applied to an unsteady flow comprising a ramp-type excursion of flow rate inside a closed channel. The flow rate is increased linearly with time from an initial Reynolds number of 9308 (based on hydraulic diameter and bulk velocity) to a final Reynolds number of 29,650. The acceleration rate is varied to cover low, intermediate and high accelerations. It is shown that among the models investigated, the $k$–$\varepsilon$ models of Launder and Sharma (1974) and Chang et al. (1995) [28] and the $\gamma$–$Re_\theta$ transition model of Langtry and Menter (2009) [38] capture well the key flow features of these unsteady turbulent flows. For the cases of low and intermediate acceleration rates, these three models yield predictions of wall shear stress that agree well with the corresponding DNS data. For the case of high acceleration, the $\gamma$–$Re_\theta$ model of Langtry and Menter (2009) [38] and the $k$–$\varepsilon$ model of Launder and Sharma (1974) yield reasonable predictions of wall shear stress.

## 1. Introduction

Unsteady turbulent flows are of interest to turbulence researchers because of their wide range of occurrence across many engineering disciplines. A large amount of on-going research is leading to a better understanding of the complex turbulence mechanisms present in such flows. Studies of unsteady turbulent flows are mainly conducted through two main categories; periodic and non-periodic.

Numerical and experimental techniques have been employed to investigate the turbulent flow features associated with periodic changes of flow rate with time. Brereton and Mankbadi [1] and Gündoğdu and Çarpinlioğlu [2] present comprehensive reviews. The experimental studies of Gerrard [3], Mizushina et al. [4], Shemer et al. [5], Mao and Hanratty [6], Tardu et al. [7] and He and Jackson [8] and the numerical studies of Scotti and Piomelli [9,10] and Cotton et al. [11] are all examples of such research. The research includes study of the flow behaviour for a range of frequency, amplitude and mean flow rates in the case of pulsating flow. Efforts on correlating the data on such flows have led to non-dimensional parameters representing the extent to which shear waves generated attenuate in terms of wall units.

The experimental studies of Maruyama et al. [12], Lefebvre [13], He and Jackson [14], Greenblatt and Moss [15,16] and He et al. [17] are examples of research on non-periodic flows, while the numerical investigations of Chung [18], He et al. [19], Ariyaratne et al. [20], Seddighi et al. [21], Di Liberto and Ciofalo [22], Jung and Chung [23] and He and Seddighi [24] examined the effects of sudden changes in pressure gradient or of linear ramp up/down in flow rates.

He and Jackson [14] focused their research on linearly increasing and decreasing flow rate in fully developed pipe flows. They identified three delays associated with the response of turbulence. Delays in turbulence production, turbulence energy redistribution and turbulence radial propagation were found to be the key features of such unsteady turbulent flows. It was found that the first response of turbulence to the imposed flow rate initiates from a region close to the wall where turbulence production is highest (buffer layer). The axial component of the Reynolds stress is the first to respond to the excursion while the other two normal components experience a longer delay. Eventually response of turbulence to the excursion is propagated towards the pipe centre due to the action of turbulent diffusion.

He et al. [19] identified three stages in the development of wall shear stress in ramp-type flow rate excursions through numerical studies. The first stage corresponds to the period of delay in turbulence response (frozen turbulence), occurring when inertial forces are dominant. This stage covers the period when wall shear stress first overshoots and then undershoots the corresponding quasi-steady values. He et al. [19] showed that a non-dimensional parameter involving inner turbulence time scales associated with the turbulence production correlates very well with the unsteady wall shear stress. It was shown by He and Ariyaratne [25] that

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http://dx.doi.org/10.1016/j.compfluid.2013.10.037

during this first stage the unsteady component of the wall shear stress behaves in a laminar-like manner. The second stage begins with the generation of new turbulence which causes the wall shear stress to escalate. It is shown by He et al. [17] that a correlation exists between the outer turbulence time scales and the critical Reynolds number at which transition from stage one to two occurs. The third stage includes the period when the wall shear stress asymptotically approaches the corresponding quasi steady trend. He et al. [19] also investigated the effects of fluid properties on the unsteady wall shear stress behaviour. For this purpose, two flow cases with different working fluids (water and air) but identical Reynolds range and acceleration rate were examined. It was shown that the unsteady wall shear stress deviation from the corresponding quasi-steady values is much smaller for air than for water because of water's higher density.

The ability of Reynolds Averaged Navier–Stokes (RANS) models to predict the flow behaviour of steady/unsteady channel/pipe flows has been investigated by a number of researchers. The studies of Patel et al. [26], Myong and Kasagi [27] and Chang et al. [28] are some good examples of application of RANS models to steady pipe/channel flows. Sarkar and So [29] investigated the performance of different turbulence models for steady channel flows (along with Couette, boundary layer and back-step flows). They examined ten different low-Reynolds number turbulence models, comparing their results with available DNS and experimental data. They observed that models with asymptotically consistent near wall behaviour generally return better predictions of flow features. Asymptotic behaviour of the turbulent kinetic energy, its dissipation rate and the Reynolds shear stress near a wall is explained by Launder [30].

Performance of RANS models in unsteady flows have been studied by Cotton et al. [11], Scotti and Piomelli [10], Tardu and Da Costa [31], Al-Sharif et al. [32], Khaleghi et al. [33] and Revell et al. [34]. The performance of turbulence models in predicting features of unsteady flows differ according to the turbulence model formulations. In most cases researchers compare the performance of different models against the available experimental or DNS data. Cotton et al. [11] examined the performance of the second-moment closure model of Shima [35] and the $k$–$\varepsilon$ model of Launder and Sharma [36] for both oscillatory flat-plate boundary layer and pulsatile pipe flow. It was found that the second-moment closure schemes generally performed better in comparison with the $k$–$\varepsilon$ model examined. Scotti and Piomelli [10] assessed the performance of five turbulence models against their own DNS data on pulsating flows (Scotti and Piomelli [9]), while Khaleghi et al. [33] investigated the performance of four turbulence models for a ramp-up pipe flow, comparing their results with the experimental data of He and Jackson [14]. In each of these two studies, the performance of an algebraic one-equation model, a $k$–$\varepsilon$ model, a $k$–$\omega$ model and a $k$–$\varepsilon$–$\overline{v^2}$ model were examined. It was concluded from both studies that $k$–$\varepsilon$–$\overline{v^2}$ model outperforms the rest. However, these conclusions were based on investigations of only a limited number of models among the various formulations. Furthermore, new turbulence models have recently been developed which were not considered by previous researchers.

The present paper reports on a systematic study of the performance of a wide range of low-Reynolds number turbulence models used to predict the detailed flow characteristics of ramp-up-type unsteady flows in a channel. Recent DNS results are used as benchmark data for the assessment.

## 2. Methodology

The study reported here involves the assessment of ten different turbulence models applied to three accelerating flow test cases. FLUENT 13.0 is used as the RANS solver for the numerical investigations.

The flow domain consists of a rectangular channel section with smooth wall boundaries and the working fluid is water ($\rho = 1000\ \mathrm{kg/m^3}$, $\nu = 1 \times 10^{-6}\ \mathrm{m^2/s}$). The channel is 8 m long and 0.05 m high, giving a length to height ratio of $L/H = 160$ as shown in Fig. 1. Because of symmetry, the computational domain covers half the channel height. In this study, only spatial fully developed flow is of interest; hence, the results presented are taken at 7.5 m from the inlet ($L/H = 150$, AB line in Fig. 1). Systematic mesh sensitivity tests were carried out for each group of turbulence models to obtain mesh-independent solutions. These tests were conducted by distributing 70, 100 and 180 control volumes in the wall normal direction ($y$ direction, shown in Fig. 1). It was concluded that distributing 100 control volumes non-uniformly along the wall normal direction is adequate to achieve mesh independent solutions. The number of control volumes used in the axial direction ($x$ direction, shown in Fig. 1) is 30 but this is of no significance since only axially developed flow is of interest. This also means that the level of turbulence intensity at the inlet is of no relevance as long as it is set to a sufficiently high level to initiate turbulence in the pipe. In this work, it is set to be 5% in all simulations. The non-dimensional distance of the first node from the wall is maintained within the range of $y^+ = 0.3$–$0.9$ ($y^+ = yu_\tau/\nu$, $u_\tau$ representing friction velocity) during the excursion to ensure the low-Reynolds criterion for the models is satisfied.

In all test cases the flow rate is increased linearly from an initial steady state Reynolds number ($Re_0 = U_{b0}D_h/\nu$, $U_{b0}$ representing the bulk velocity) of 9308 to a final Reynolds number ($Re_1$) of 29,650. The length scale of the Reynolds number is based on the hydraulic diameter, i.e. $D_h = 2H$, where $H$ is the full height of the channel. We consider three acceleration time periods ($T$): Case A, 8.16 s ("low" acceleration); Case B, 2.86 s ("intermediate" acceleration); Case C, 0.02 s ("high" acceleration). Table 1 summarises the initial and final flow conditions of examined flow cases along with non-dimensional time scale $\Delta t^* = T/(H/2)/U_{b1}$ and ramp rate ($dU/dt = (U_{b1}-U_{b0})/T$). Although these simulations are carried out for water, as long as the boundary conditions such as the initial and final Reynolds numbers and non-dimensional acceleration rate are consistent, the choice of fluid is of no significance to the outcome of the simulations.

The continuity and momentum transport equations along with the Reynolds stress closure equations are solved for the computational domain. The flow is assumed to be two-dimensional and Cartesian coordinates are employed for the governing equations.

Continuity:

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

Momentum:

$$\frac{DU_i}{Dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\nu\frac{\partial U_i}{\partial x_j} - \overline{u_i u_j}\right) \tag{2}$$

where linear eddy viscosity models employ a stress–strain relation as follows:

$$\overline{u_i u_j} = 2/3k\delta_{ij} - \nu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{3}$$

where $\nu_t$, the eddy viscosity, is obtained by solving a set of turbulence transport equations, the details of which are presented in the next sections.

Only low-Reynolds number turbulence models can potentially predict the features of unsteady flows. Here we consider ten low-Reynolds turbulence models, which can be categorised into four