Applied Mathematical Modelling 39 (2015) 6711–6724

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Turbulent models of oil flow in a circular pipe with sudden enlargement

Héctor Zambrano [a], Leonardo Di G. Sigalotti [b,c,*], Franklin Peña-Polo [c], Leonardo Trujillo [c]

[a] Instituto Venezolano Tecnológico del Petróleo, PDVSA-Intevep, Urbanización El Tambor, Los Teques 1201, Estado Miranda, Venezuela
[b] Área de Física de Procesos Irreversibles, Departamento de Ciencias Básicas, Universidad Autónoma Metropolitana-Azcapotzalco (UAM-A), Av. San Pablo 180, 02200 México D.F., Mexico
[c] Centro de Física, Instituto Venezolano de Investigaciones Científicas, IVIC, Apartado Postal 20632, Caracas 1020-A, Venezuela

ARTICLE INFO

Article history:
Received 30 June 2014
Received in revised form 20 January 2015
Accepted 5 February 2015
Available online 4 March 2015

Keywords:
Computational fluid dynamics
k–ϵ model
Sudden-expansion flow
Turbulent flow

ABSTRACT

We describe three-dimensional calculations of oil flow in a circular pipe with an abrupt expansion, using the commercial code *Fluent 6.3*, to evaluate the performance of three turbulence closures: the standard k–ϵ, the Realizable k–ϵ, and the RNG-based k–ϵ models. The effect of near-wall modelling in any of these closures is also investigated using the Standard Wall Functions (SWF) and the Enhanced Wall Treatment (EWT) approaches. The axial mean velocity, the turbulence kinetic energy, and the reattachment length are compared among the different models and with experimental measurements of oil flow through a 90° diffuser. Based on the standard deviation of the numerical profiles from the experimental data, we find that on average the RNG k–ϵ model gives slightly better results regardless of the near-wall treatment. However, the Realizable k–ϵ closure gives standard deviations comparable to the RNG k–ϵ model when the EWT approach is implemented. Concerning the reattachment length, the standard k–ϵ and the RNG k–ϵ models match very well the experimental value when used in combination with the SWF approach, while the best prediction with the EWT method is provided by the RNG k–ϵ closure.

1. Introduction

The turbulent flow that develops when a liquid (or gas) passes through an abrupt enlargement in a piping system is a common occurrence in numerous engineering and industrial applications. This geometry is typical of piping junctions and expansion joints. However, it also appears in many other practical settings and devices, ranging from air-conditioning ducts [1] to dump combustors [2,3]. In biomedical applications, it is relevant as a model of flow through arterial stenoses [4–6]. At a more fundamental level, this primitive geometry has served as a prototype for understanding the dynamics of flow separation. As the fluid flows through the expansion, it gives rise to an increase in static pressure at the expense of a drop in the flow kinetic energy. At the expanded section, a core forms with a relatively flat velocity profile, which spreads out behind the expansion and separates from the remaining fluid by a surface of separation. At moderate to high Reynolds numbers (Re), the surface of separation becomes unstable and generates turbulent eddies in a recirculation or free-mixing stall region, with

* Corresponding author at: Área de Física de Procesos Irreversibles, Departamento de Ciencias Básicas, Universidad Autónoma Metropolitana-Azcapotzalco (UAM-A), Av. San Pablo 180, 02200 México D.F., Mexico.

E-mail addresses: hectorj.zambranom@gmail.com (H. Zambrano), leonardo.sigalotti@gmail.com (L.D.G. Sigalotti), franklin.pena@gmail.com (F. Peña-Polo), leonardo.trujillo@gmail.com (L. Trujillo).

http://dx.doi.org/10.1016/j.apm.2015.02.028

the eddies developing and gradually disappearing. This essentially occurs because the fluid flows against an adverse pressure gradient, which constrains the fluid particles to follow a reverse path near the wall of the larger pipe just ahead of the step height. Therefore, immediately downstream of the expansion, the flow can be considered as a jet within an annular recirculation region, which expands radially over the larger pipe section until reattachment to the pipe wall occurs. In particular, for incompressible, fully developed turbulent flow in circular pipes, flow reattachment takes place at lengths from the enlargement of 6 to 9 times its step height [7], from which turbulent pipe flow is recovered [8].

Previous experimental and computational work on sudden-expansion flows have focused primarily on the steady, laminar flow regime and the determination of the separation and subsequent reattachment [9–14]. The main conclusion drawn from these studies is that the reattachment length is a linear function of Re in the steady regime, with the proportionality factor depending on whether the flow at the inlet corresponds to a flat or a fully developed parabolic velocity profile [15]. Flow separation and reattachment at high Re in the turbulent regime have also been investigated experimentally in a flow through an axisymmetric sudden expansion [16]. In addition, experimental measurements of the velocity field for moderate and relatively high Re have been carried out by a number of authors [10,17–22]. These measurements have shown that the separation region contains large velocity gradients and correspondingly high shear coupled with an adverse pressure gradient, while back flow velocities in the recirculation region are on the order of 10% of the mean velocity at the expanding section. The presence of the solid boundary inhibits entrainment of the fluid, so that an unsteady eddy structure is established further downstream. In general, it is difficult to obtain accurate quantitative turbulence measurements in this region because the mean velocities are usually small and the turbulence intensities are large.

It is well-known that plane sudden expansions of high aspect ratios ($\chi = W/H > 10$, with W being the external duct width and H being the step height) and expansion ratios, $D_2/D_1 > 1.5$ (with D_2 and D_1 being the inner outlet and inlet pipe diameters) produce asymmetric flows in which the pair of recirculating eddies are no longer symmetrically disposed about the central plane of the flow [23,24]. The midplane symmetry of the flow is known to be broken at a pitchfork bifurcation as Re is increased above a critical value [25,26]. Further experimental evidence indicates that steady-state breaking of the symmetry occurs at a critical Re $= 1139 \pm 10$ for flow through a 1:2 sudden axisymmetric expansion [27]. Recent numerical simulations of flow in open channels with sudden expansions show that the numerical model does not reproduce the experimentally observed asymmetry at supercritical Re unless the wall roughness coefficient in the inlet is set to 50% higher than in the outlet [28]. It has been suggested that the onset of asymmetry is likely to be driven by small imperfections in the experiments. This possibility has begun to be explored numerically by perturbing either the incoming flow or the geometry [29]. For example, a transient linear growth analysis of flow through a sudden expansion in a circular pipe has shown that the flow is sensitive to small perturbations in the range of Re covered in the experiments [30]. On the other hand, recent numerical bifurcation studies predict the onset of a steady symmetry-breaking bifurcation at Re ~ 5000, far beyond the experimental estimate of Re ~ 1139 [31].

Most recent numerical simulations of sudden-expansion flows have mainly focused on examining the accuracy of different turbulence-closure models to predict the experimental observations on the velocity field, the turbulence kinetic energy, the recirculation length, and the pressure variation [32–38]. Here we perform three-dimensional calculations of oil flow through an abrupt expansion in a circular pipe with the aid of the commercial CFD code *Fluent 6.3*. In order to offer a basis for the choice of a type of turbulence model for industrial and engineering purposes, we consider three different turbulence closures: the standard k–ϵ [39], the Realizable k–ϵ [40], and the RNG k–ϵ models [41] with two different near-wall treatments available in *Fluent*: the Standard Wall Functions (SWF) and the Enhanced Wall Treatment (EWT). The performance of these three turbulence models is investigated and their predictions for the axial mean velocity and the turbulence kinetic energy are compared among themselves and with experimental data of oil flow through a 90° diffuser [21]. The structure of the paper is as follows. The basic equations and flow geometry are given in Section 2. Section 3 describes the computational details and the validation of the calculations against a mesh-convergence test. The results are discussed in Section 4 and the conclusions are given in Section 5.

2. Governing equations and flow geometry

In this paper, we analyze numerically the three-dimensional, turbulent flow that is generated when an oily fluid passes through an abrupt pipe enlargement. We consider stationary turbulence and assume that the flow remains isothermal and incompressible. This type of flow can be described by the well-known Reynolds averaged Navier–Stokes (RANS) equations, which in tensor notation can be written as

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

$$\rho \bar{v}_j \frac{\partial \bar{v}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{v}_i}{\partial x_j} + \frac{\partial \bar{v}_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}\left(\rho \overline{v_i' v_j'}\right), \tag{2}$$

where $\bar{v}_i$ is the mean velocity component in the x_i-direction, $\bar{p}$ is the mean static pressure, ρ is the fluid density, g_i is the gravitational acceleration component in the x_i-direction, μ is the fluid dynamic viscosity, and the time-averaged product $\overline{v_i' v_j'}$ is the Reynolds stress, where v_i' denotes the fluctuating velocity in the x_i-direction. We solve the above equations in