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Comparative computational study of turbulent flow in a 90° pipe elbow

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A B S T R A C T

Turbulent flow through a 90° pipe elbow in a range of moderately high Reynolds numbers between 14,000 and 34,000 is studied computationally using wall-resolved large-eddy simulation (LES) as well as various RANS (Reynolds-averaged Navier–Stokes) models aiming at a comparative assessment to illustrate benefits and drawbacks of different computational approaches for the considered case. The RANS models applied in the framework of this study include both the basic low Reynolds number k–ε-model, see Launder and Sharma (1974), as well as a near-wall second moment closure model as proposed by Jakirlić and Maduta (2015). Accordingly, the respective results for the mean flow fields being subjected to strong pressure variations – thus causing locally alternating flow acceleration and deceleration which are correspondingly reflected in a distinct Reynolds stress anisotropy variability – are analyzed in detail along with experimental data by Kalpakli and Örlü (2013). Furthermore, characteristic secondary motions resembling the axially oriented counter-rotating Dean vortices, see Bradshaw (1987), are further investigated and their predictability using LES is assessed.

1. Introduction

Fully turbulent flow through curved conduits and channels have been studied intensively in the past by applying theoretical and experimental approaches. Berger et al. (1983) and the earlier publication by Smith (1976) provide a broad range of theoretical investigations regarding curved pipe flow. However, with the scenario of curved flows being considerably more complex and resource-demanding than flows through straight domains, only recently, in the past few decades numerical investigations have been added to the range of scientific tools assessing curved pipe flows, see e.g. Rütten et al. (2005). With increasing computing capacities, the applicable methods to predict curved pipe flows are now shifting from simpler, steady-state approaches to more elaborate, temporally resolving techniques.

The flow configuration of a 90° pipe bend exhibits numerous key features which are of significance to turbulence modeling of various kind. The features include – amongst others – geometry-induced favorable and adverse pressure gradients, longitudinal streamline curvature, velocity profile inhomogeneity on planes of constant radius and developing secondary motions being linked to transverse streamline curvature effects. Additionally, the flow is of particular interest since it is not known a priori whether the flow is separating from the smoothly curved surface inside the bend or if it remains attached, nonetheless developing a strong unsteady shear layer and a region of severe momentum deficit.

In the absence of a comprehensive set of experimental data, wall-resolved LES is used to generate reference data for turbulence closure calibration and validation. Despite the undisputed deficiency in accuracy as compared with direct numerical simulation (DNS), the latter method is at present assumed to be merely feasible due to excessive resolution requirements. However, even the performance of physically correct large-eddy simulations develops into a challenging task when viscous near-wall processes exert major influences on the primary flow properties, as it is the case for the present configuration. This circumstance is well recognized and emphasized in the work of Fröhlich et al. (2005) which underlines that separation from curved surfaces essentially demands greater care with respect to resolution and modeling than flows separating from sharp edges.

Essentially, the simulations performed within this framework represent preliminary investigations concerning specific inlet conditions for the erosion process of a helium stratification as motivated by the TH26 campaign of the Reactor Safety Research Project 150 1455 (Freitag et al., 2014). Within this test configuration, the stratification is eroded by means of an air jet issuing from a 90° elbow within a model test containment of a nuclear reactor,

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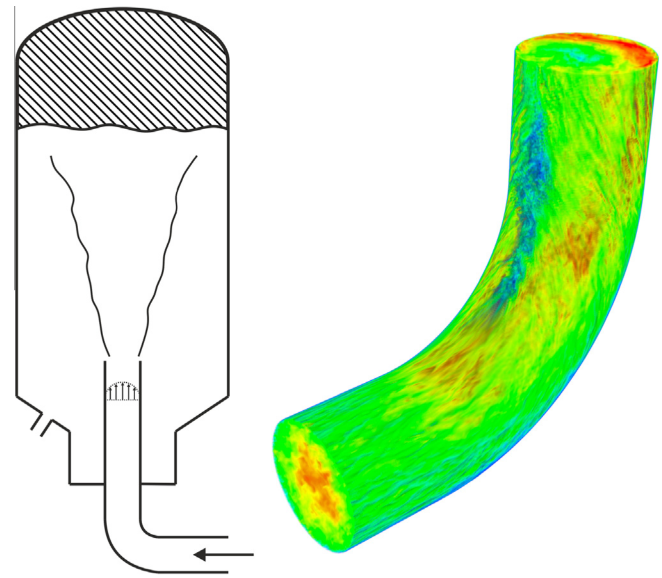

Fig. 1. (Left) Schematic overview of the TH26 setup: a helium stratification (shaded) inside a containment is dissolved by an entraining air jet developing from a 90° elbow. (Right) Instantaneous velocity magnitude for a flow through an elbow pipe as obtained by the present LES with the color scale intentionally omitted for illustrative purposes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

see Fig. 1. The eventual goal is to demonstrate LES' uprising capabilities for handling relevant engineering applications with significant streamline curvature such as flows through bends, manifolds or helically coiled pipes, as they appear in e.g. oil pipelines, automotive air intakes or heat exchangers, respectively.

Accordingly, the present study is dedicated to the investigation of turbulent flow through 90° pipe bends using state of the art computational models of different complexity, accuracy and computational cost. In what follows, Section 2 briefly outlines the numerical framework and discusses the turbulence models employed. Section 3 presents results for fully-developed flow through a straight pipe at different Reynolds numbers in order to validate the employed computational procedures, to approve the adopted mesh properties and to generate suitable inlet conditions for the elbow cases. Section 4 provides detailed information on the present flow configuration. Results for the case of a 90° elbow are subsequently arranged in Section 5 and compared against experimentally obtained data from Kalpakli and Örlü (2013), leading to the conclusions presented in Section 6.

2. Computational methodology

The equations governing the mass and momentum balance for a flow in a bent pipe are given by the Navier–Stokes equations for incompressible Newtonian fluid as shown in Eqs. (1) and (2), respectively. The common standard nomenclature for velocity, pressure, density and kinematic viscosity being U_i, p, ρ and ν, respectively, is employed.

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

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} \tag{2}$$

The presently applied computational framework implies solving the spatially-filtered Navier–Stokes equations pertinent to the large-eddy simulation (LES) method and their time-averaged counterpart underlying the Reynolds-averaged Navier–Stokes (RANS) approach.

2.1. LES

In order to reduce the computational effort in the sense of LES, i.e. to explicitly resolve the larger scales while modeling the fairly universal smaller ones by means of approximative assumptions, the Navier–Stokes equations are spatially filtered yielding

$$\frac{\partial \widetilde{U}_i}{\partial x_i} = 0 \tag{3}$$

$$\frac{\partial \widetilde{U}_i}{\partial t} + \frac{\partial (\widetilde{U}_j \widetilde{U}_i)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \widetilde{p}}{\partial x_i} + 2\nu \frac{\partial}{\partial x_j}(\widetilde{S}_{ij}) - \frac{\partial \tau_{ij}}{\partial x_j}. \tag{4}$$

In the above expressions the tilde-operator denotes a three-dimensional filter operation in space with a filter width of Δ, indicating a measure for the turbulence resolution length scale, where the terms arising from commutation are not explicitly accounted for. In Eq. (4), $\widetilde{S}_{ij}$ is the filtered strain rate tensor ($\widetilde{S}_{ij} = 0.5(\partial \widetilde{U}_i/\partial x_j + \partial \widetilde{U}_j/\partial x_i)$), whereas $\tau_{ij} = \widetilde{U_i U_j} - \widetilde{U}_i \widetilde{U}_j$ represents the part of the non-resolved (i.e. subgrid) motions in the governing equation for the resolved momentum, which needs to be modeled in order to close the equation.

In this study, the filtering operation is of implicit nature in terms of a finite cell size of $\Delta = (\Delta x \Delta y \Delta z)^{1/3}$, with Δx, Δy and Δz representing the cell face lengths in all three coordinate directions. Moreover, the well established approach according to *Boussinesq* is utilized, which assumes linearity between the anisotropic part of the subgrid-scale (SGS) tensor τ_{ij} and the mean strain rate tensor $\widetilde{S}_{ij}$ according to

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -2\nu_t \widetilde{S}_{ij}, \tag{5}$$

with δ_{ij} being Kronecker's delta. The isotropic subgrid-stress τ_{kk} is absorbed into a modified pressure. In Eq. (5), the SGS viscosity ν_t is approximated according to the assumptions stated by Smagorinsky (1963) as

$$\nu_t = (C_S \Delta)^2 |\widetilde{S}_{ij}|, \tag{6}$$

where the model parameter C_S is dynamically evaluated as a function of the smallest resolved scales as first proposed by Germano et al. (1991). However, to improve the stress–strain relationship the least-square minimization according to Lilly (1991) is employed throughout this study, thus yielding

$$\nu_t = C_D \Delta^2 |\widetilde{S}_{ij}|. \tag{7}$$

In Eq. (7), the dynamically determined coefficient C_D can locally become negative (backscattering). We refer to Fröhlich (2006) and Lilly (1991) regarding further details for the different dynamical Smagorinsky models as well as specific equations for C_D.

2.2. RANS

Complementary to the LES methodology, the flow in the elbow configuration is computationally investigated within a steady RANS framework. The unknown Reynolds stress tensor $\overline{u_i u_j}$ appearing in the RANS equations of motion

$$\frac{\partial (\overline{U}_j \overline{U}_i)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + 2\nu \frac{\partial}{\partial x_j}(\overline{S}_{ij}) + \frac{\partial}{\partial x_j}(-\overline{u_i u_j}) \tag{8}$$

solved in conjunction with the corresponding continuity equation $\partial \overline{U}_i / \partial x_i = 0$ is presently primarily determined by applying