Chemical Engineering Science 71 (2012) 300–309

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

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

Analysis of flow through an orifice meter: CFD simulation

Manish S. Shah [a,c], Jyeshtharaj B. Joshi [1,a,b,*], Avtar S. Kalsi [c], C.S.R. Prasad [c], Daya S. Shukla [c]

[a] Department of Chemical Engineering, Institute of Chemical Technology, Matunga, Mumbai 400019, India
[b] Homi Bhabha National Institute, Trombay, Mumbai 400094, India
[c] Chemical Technology Division, Bhabha Atomic Research Center, Trombay, Mumbai 400085, India

ARTICLE INFO

Article history:
Received 29 July 2011
Received in revised form
11 November 2011
Accepted 14 November 2011
Available online 1 December 2011

Keywords:
Chemical processes
Instrumentation
Simulation
Turbulence
Openfoam
Vena-contracta

ABSTRACT

Orifice meters are the most common instruments used for fluid flow measurement because of its ruggedness, simple mechanical construction and other known advantages. Orifice coefficients are empirical because of difficulty in accurately predicting the effects of geometrical complicacy and flow separation from the wall on the flow. In the present paper, Computational Fluid Dynamics (CFD) simulation has been used to predict the orifice flow with better accuracy. CFD simulations have been performed using OpenFOAM-1.6 solver and validated with the published experimental data of Nail (1991) and Morrison et al. (1993). CFD simulations have been validated with pressure drop and energy balance of our experimental data of water as fluid. The outcomes of the CFD simulations in terms of profiles of velocity, pressure, etc. are discussed in detail. A new scheme has been proposed to track vena-contracta with the help of CFD and with a suitable provision in the hardware of orifice meter. The new scheme maintains the existing advantages of orifice meters and provides better accuracy and sensitivity.

1. Introduction

It is very important to have information on flow rates of various chemical process streams with adequate accuracy in the plants, especially when it has a direct influence on efficiency and productivity of a given process. Although orifice meters have higher pressure losses and correspondingly higher pumping cost, they are still the most common meters used for fluid flow measurement because these are rugged, simple in construction and installation/replacement, without having any moving parts, economic, measurement flexibility with high rangeability, can be used for liquids, gases or slurries, well suited for use under extreme weather conditions, etc. (Husain, 2010 and McCabe et al. 1993). It works on simple principle of using effects of velocity and pressure variation caused by reduction of the available area for flow. Orifice meters are well known and have been studied by a number of investigators over a considerable range of Reynolds numbers and Beta ratio (Nail (1991); Morrison et al. (1993); Smith et al. (2008), Naveenji et al. (2010); Oliveira et al. (2010)). In international trade, it is implemented in accordance with international standards such as ISO 5167-1. The orifice meter is supplied with discharge coefficient (C_D) and installation procedure. The discharge coefficient is defined as the ratio of actual flow to the theoretical flow. It is obtained from experimental measurements after regression, wherein experiments are conducted in controlled conditions of undisturbed, symmetrical, swirl-free velocity profile in the upstream of orifice (Erdal and Andersson (1997)). Definite straight length of pipe is also kept downstream of the orifice to avoid the effects of outlet conditions on the flow profile close to downstream of orifice. With the above distinct advantages of a flow meter of high industrial importance, authors felt necessary to understand the flow pattern of orifice meter to further improve its performance in terms of flow measurement with better accuracy and sensitivity.

2. Previous work

The summary of published literature is given in Table 1. Very few attempts have been made to simulate the flow pattern for orifice with the help of Computational Fluid Dynamics (CFD). Durst and Wang, 1989 found good agreement between calculations using k–ε turbulence model and measurements, but pressure drop was not reported by them. Smith et al. (2008) have studied the effect of beta ratios from 0.5 to 0.8 on the flow field. Naveenji et al. (2010) have studied variation in discharge coefficient for non-Newtonian fluid flow at beta ratios from 0.4 to 0.8. Oliveira et al. (2010) have presented numerical methodology

* Corresponding author at: Institute of Chemical Technology, Department of Chemical Engineering, Matunga, Mumbai, Maharastra 400019, India.
Tel.: +91 22 3361 2106, fax: +91 22 3361 1020.
E-mail address: jbjsohi@gmail.com (J.B. Joshi).
[1] Tel.:+91 22 2559 7625.

0009-2509/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2011.11.022

Table 1
Summary of previous works.

Author	Pipe diameter (mm)	β	Working fluid	Range of *Re*	Remarks
Ho and Leung (1985)	25.4	0.247, 0.36, 0.448	water	100–1000	Low *Re* (laminar flow) experiments. Variation in C_D vs. *Re* presented.
Nail (1991)	25.4	0.5	air	18,400	Experiments using 3 Dimensional LDA technique.
Morrison et al. (1993)	50.8	0.5	air	91,100	Experiments using 3 Dimensional LDA technique. Measured mean velocity and wall pressure. Turbulence quantities calculated and discussed in detail.
Smith et al. (2008)	25.4	0.5, 0.6, 0.8	air	18,400	Effect of turbulence models (k–ε and RSM) on mean axial velocity and wall pressure studied using CFD simulation and compared with experimental data of Nail.
Naveenji et al. (2010)	50, 100, 200	0.4–0.8	Non-Newtonian fluids (prepared with varying concentration of salt)	100–10,000	C_D vs. *Re* predicted using CFD simulation.
Oliveira et al. (2010)	100	0.1–0.6	water	4000–10^6	Predicted pressure drop vs. flow rate with various values of β, C_D vs. *Re* and wall pressure using CFD simulation.

for calibrating orifice meter. CFD technique requires reliable experimental data on flow profiles to validate its outcome. In all the above literature, limited part of CFD simulations have been compared with experimental data. Nail (1991) has presented experimental measurements of centerline axial velocities, wall-static pressure, Renoylds' stresses and wall shear stresses measured using Laser Doppler Anemometer (LDA) in his PhD Dissertation. Morrison et al. (1993) have measured flow field using a three-color, 3D LDA and reported the mean velocity and turbulence field inside orifice flow meter with a beta ratio of 0.5. Centerline axial velocity and wall pressure profiles were also presented. To summarise, though reliable experimental data are available, comprehensive information is not available in the published literature on the predicted flow structure downstream of orifice explaining the flow features using CFD simulations. Moreover, advancement in the CFD, availability of high speed computing machines and robust solvers have encouraged us to make an attempt for predicting orifice flows with better accuracy. It was also thought desirable to propose a cost effective tool towards replacement of experiments required for estimating the discharge coefficient. In the present paper, efforts are made to combine experimental and CFD modeling to achieve better explanation for the flow phenomena in the upstream and downstream of orifice. Experiments are conducted with water as fluid with various flow rates. Pressure drop across the orifice meter was measured with the help of manometer mounted on flange taps of the meter. CFD simulations have been carried out and compared with experimental data using water (up to 3 ms^{-1} pipe velocity) and published experimental data of Nail (1991) and Morrison et al. (1993). Energy balance is also established for the simulated cases. Sensitivity analysis of turbulence model parameters has also been reported in the present work. Typical geometry of orifice meter considered for all the simulations is given in Fig. 1.

It is also known that the actual locations of vena-contracta change with flow rates and may not match the vena-contracta tapping. It is shown that in the CFD simulation, it is possible to locate the vena-contracta. Using this capability of CFD, a suitable modification in the hardware has been proposed to position the pressure tap at vena-contracta for flow measurement with better accuracy and sensitivity without compromising the existing advantages of orifice meter.

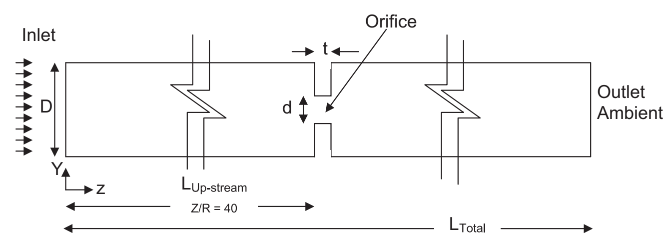

Fig. 1. Typical orifice geometry considered for simulation (orifice is at z/R=40 from inlet).

3. Numerical procedure

3.1. Governing equations

In order to simulate the steady state flow through an orifice meter, the governing equations (continuity and momentum) with the appropriate Reynolds stress closure need to be solved. In the present work, standard $k-\varepsilon$ turbulence model by Launder and Spalding (1972) has been used. The k–ε turbulence model is simple to use, most widely validated and has excellent performance for many industrially relevant flows (Versteeg and Malalasekera (1995); Thakre and Joshi (2002)). It also requires less computational power compared to more general Reynolds Stress Model. All the governing equations are given in Table 2.

3.2. Grid independence

A grid independence study was performed to find the mesh size that was sufficiently fine so that solution does not change by further refining the mesh. The velocity profiles and pressure profiles for 351,360 hexahedral cells and 10,47,360 hexahedral cells are given in Fig. 2. No appreciable change has been found in velocity and pressure profiles for coarse and fine meshes. However, there has been improvement in the energy balance with an error reduction of predicted pressure drop from 13.34% to 5.59%.

3D simulations have been carried out for water and air with different values of β, inlet velocity and pipe diameter. The geometrical parameters and grid details are given in Table 3. Adequate length at the upstream and downstream of the orifice plate is provided to avoid the effect of patched boundary