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Investigation of flow through multi-stage restricting orifices

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ABSTRACT

In this study, the characteristics of flow through a serial arrangement of two similar bevel-edged orifice plates fitted in a horizontal pipe of 25.4 mm internal diameter has been investigated. Computational fluid dynamics calculations were performed using the realizable k-ε eddy viscosity model to predict the flow features. The effects of various parameters such as pipe flow velocity in the range 1–4 m/s, orifice spacing of 1D and 2D, and orifice plate diameter ratios of 0.5, 0.63 and 0.77 on axial velocity and pressure distributions were obtained. The flow is always turbulent with Reynolds number ranging from $R_e = 2.54 \times 10^4$ to 1.02×10^5. The location of vena contracta associated with the first orifice was found to be independent of addition of second orifice but varies with orifice diameter ratios while the presence of vena contracta downstream of the second orifice was found to depend on the orifice spacing. Also, the flow features downstream the second orifice is qualitatively similar to single orifice flow in terms of presence of recirculation, reattachment and shear layer regions but the flow features in the spacing between the two orifices are quite different having a donut-shaped vortex near the wall and jet-like flow in the core region. Not only the flow structure between the two orifices and downstream the second orifice was found to depend on the orifice spacing but also the total pressure drop and hydraulic losses. Orifice spacing of 1 and 2 pipe diameters gave the highest and lowest pressure recovery respectively compared to single orifice arrangement. The current study provides an insight into methods of pressure control without redesigning the complete flow system.

1. Introduction

Many engineering applications involving piping systems utilize flow passage restrictions such as control valves and orifices to achieve control of flow rates and pressures. Accurate determination of flow characteristics through these restrictions especially orifices is important for industrial operations such as control measures in HVAC, quality control in food processing industry, metering of high viscous liquids and calibrating tools in metrology of liquid and gas flows (Gronych et al., May 2012). Single orifices are also used to enhance uniformity of flow distribution and exchange of heat and mass as applicable in pre-mixed combustion (Roul and Dash, 2012). Orifice meters are the most widely used type of differential flowmeters for measurements of single-phase and multiphase flows due to their design simplicity, ruggedness and reliability. Orifices are also used as flow restriction devices for the sake of pressure control, flowrate control or both. However, the use of restricting orifices may result in high hydraulic losses, severe erosion in the presence of solid particles; cavitation in liquid flows, choking is gas flows in addition to noise and vibration. Engineering applications of restricting orifices (RO) are numerous as for example their use in the downstream side of a blowdown valve to ensure controlled flow rate in blowdown piping or blowdown header (such as gas flare header). They are also carefully designed and used in pump recirculation lines for the sake of preventing cavitation/pump starvation. The restricting orifice may have one-hole or multiple-holes geometry where the multiple-holes orifice is designed for achieving lower pressure drop while having high discharge coefficients (Haimin et al., 2013; Rani et al., 2013).

In some applications, the required pressure drop is too high to be achieved by a single orifice without problems such as liquid flashing, flow-choking (in gas flows) or severe erosion resulting from high flow velocities. In such cases, a multistage restricting orifice (MRO) can be used to achieve the required pressure drop through the effective arrangement of the orifices and optimum geometry design as applicable in the pipe letdown line in cooling systems of power plants and other process controls (Haimin et al., 2013). Like a single stage RO, the MRO can be of single-hole or multi-hole design or combination of both. The restricting

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Nomenclature

$\bar{\boldsymbol{a}}$	flow acceleration
d	orifice diameter
D	pipe diameter
D_r	diameter ratio
k	turbulence kinetic energy
P	static pressure
Re	Reynolds number based on inlet velocity
t	time
$\bar{\boldsymbol{u}}_{\boldsymbol{i}}$	fluctuating velocity component
$\bar{\boldsymbol{U}}_{\boldsymbol{i}}$	component of average velocity
U_{max}	flow maximum velocity
V_i	inlet flow velocity

Greek symbols

ε	turbulence kinetic energy dissipation rate
δ_{ij}	kronecker delta
ρ	density
σ_k	effective prandtl number for kinetic energy
σ_k	effective prandtl number for dissipation
μ	dynamic viscosity
μ_t	turbulence viscosity
μ_{eff}	effective viscosity

orifices may have concentric holes assembled in an MRO tube and sometimes eccentric holes that are arranged diametrically opposite to each other in the tube. It is well known that the flow field characteristics downstream of a single restricting orifice depend on the upstream conditions as well as the orifice shape, diameter ratio, flow velocity and fluid properties. Due to the change in flow passage geometry across the orifice plate, the flow structure experience the greatest sudden change in flow turbulence parameters (Rani et al., 2013). The complex nature of the flow through an orifice is further aggravated when passing through multiple orifices located close to each other. The aggressive nature of the flow in such combined geometries causes failures in many energy and oil & gas transportation systems due to variety of degradation mechanisms such as cavitation erosion, erosion-corrosion (Hwang et al., 2014), thermal fatigue, flow-accelerated corrosion (FAC) Ahmed et al., 2012; Xiong et al., Jan. 2014, liquid droplet impingement erosion (LDIE) Hwang et al., 2014 and internal flow fluctuations causing noise and vibration which may excite the confining surface (Bull and Agarwal, 1983). This severely affects both safety and reliability of these systems and sometime lead to fatalities and huge economic loss (Bull and Agarwal, 1983). All of these failure modes strongly depend on the flow characteristics downstream of the orifices and the flow instabilities generated within the complex geometry of the flow passage.

The characteristics of orifice flow were extensively studied by many researchers both numerically and experimentally taking into account various parameters such as inlet velocity, orifice size, orifice thickness, and pipe size. The important flow characteristics studied are velocity distribution, pressure distribution, void fraction, turbulence parameters, discharge coefficients and cavitation effects with the goal of establishing relationships with the orifice geometry. Amongst recent studies is the numerical investigation of orifice flow using ANSYS CFX-10 software (Singh and John Tharakan, 2015), MATLAB and OPEN-FOAM 1.6 (Shah et al., 2012) and most utilized ANSYS/FLUENT (Hollingshead et al., 2011; Arun et al., 2010; Shaaban, Jun. 2014). Hollingshead et al. (2011) carried out performance analysis of four differential pressure flowmeter types; namely Venturi tube, wedge, standard concentric orifice and V-cone based on experimental measurements and computational modeling. They established equations for correction factors of the discharge coefficient for the different flowmeter types at low Re. Different turbulence models were used by Eiamsa-ard et al. (2008) for simulating turbulent airflow through a circular concentric bevel-edged orifice. They focused on the effect of orifice diameter ratio (D_r = 0.5, 0.6 and 0.8) on the flow characteristics and the influence of turbulence model on results by comparing the standard k-ε model and the Reynolds stress model with experimental results. Dabiri et al. (2007) determined the cavitation sites for laminar and turbulent flow through the orifice of an atomizer using both pressure and total stress criteria. They submitted that the total stress criterion gives a better prediction of cavitation for laminar flows than the pressure criterion, a little difference in their predictions for turbulent flow, and that cavitation is less likely to happen at high Reynolds number. A model for the prediction of pressure drop and discharge coefficient over a wide range of Re for incompressible flow through orifice tube (orifice with a larger thickness to diameter ratio that is mostly used for creeping flows) was developed by Jankowski et al. (2008).

Previous studies by Ahmed et al. (2012) showed that separation of flow at the throat of an orifice produces a downstream field characterized by higher velocities, streamlines with large curvatures, formation of recirculation and reattachment zones. Nygard and Andersson (2013) carried out numerical simulation for an incompressible turbulent flow through a pipe with sudden axisymmetric constriction of 0.5D (D = pipe diameter) by solving 3-D Navier-Stokes equation in cylindrical coordinates using the 'direct forcing' scheme of IBM (Immersed Boundary Method) to embed the boundary conditions of the constriction in the equations. The results obtained were in good agreement with experimental data for fully developed flow although the simulated problem was for upstream developing flow. They also reported a reattachment length is 2.25 pipe diameters downstream the constriction and the absence of asymmetries in the mean flow field. A comprehensive study was also carried out on the efficient analysis of flows through a pipe fitted with an orifice by Nilsson et al. (2014) using CFD resources on Phoenics commercial code. Arun et al. Eiamsa-ard et al. (2008) studied the discharge coefficient of orifices using an aqueous solution of a non-Newtonian fluid SCMC (sodium salt of carboxymethyl cellulose) of four different concentrations; 0.2, 0.4, 0.6 and 0.8 kg/m^3, pipe diameter; 50, 100 and 200 mm, diameter ratio, Dr = 0.4, 0.6, and 0.8 and flow velocity resulting in Reynolds number in the range $100 < Re < 10^5$. They reported that for the fluid considered, the discharge coefficient increases with increasing Reynolds number and a constant value of 0.6 for Reynolds number above 100000. Also, Muñoz-Díaz et al. (2012) carried out a 3-D numerical study validated with experiments on the reduction of the effects of vortices and dead zones inherent in the downstream for newtonian and non-newtonian fluid flowing through an orifice meter. They suggested a semihyperbolic profile for the orifice geometry as an alternative to excess pressure requirement in minimizing these effects and reported a shear free axial flow.

Shah et al. (2012) employed a combination of experiment and Numerical methods using OPEN-FOAM 1.6 to carry out a comprehensive analysis of orifice flow. Dempster and Arebi (2001) performed experiments to study the effects of varying flow rates of neighboring orifices on the bubble characteristics in a parallel arrangement of three orifices of similar size with 1 mm and