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Numerical simulation of two-phase gas–liquid flow through gradual expansions/contractions

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ABSTRACT

In the present work, turbulent two-phase flows of air and water are numerically simulated through a smooth area expansion/restriction with a constant opening angle. To model the multiphase flow, a two-fluid approach is adopted in which two sets of governing equations are solved simultaneously for continuous and dispersed phases and the coupling between these phases is forced by proper source terms. An extended version of two-equation k–ε turbulence model is used and the numerical result was validated in comparison to previously published experimental data. The effect of volumetric void fraction, Reynolds number and the opening angle is examined on the pressure distribution across the flow domain.

1. Introduction

Two-phase gas–liquid flows are encountered in numerous industrial systems including boilers and condensers utilized in power generation or refrigeration, oil/gas extraction wells and refineries, flame stabilizers and so on. Meanwhile, Sudden or gradual expansions/contractions are one of the most frequent geometrical singularities that gas–liquid mixtures undergo as a part of their flow paths through industrial systems such as in piping connections in chemical reactors, power generation units, oil wells and petrochemical plants . Therefore, the experimental and theoretical study of two-phase flows across expansions/contractions (aiming to examine or predict the two-phase flow characteristics including pressure loss, heat and mass transfer rate, flow pattern and void fraction distribution) can provide us with an effective designing tool for these systems together with a treasured insight into a complex physical phenomenon.

Due to its practical importance, the two-phase gas–liquid flows across area expansions have been exhaustively examined with numerous experiments. As an early example, the flow visualization of Aloui and Souhar (1996a, 1996b) in a flat sudden expansion captured a shift from dissymmetry in flow pattern toward symmetry by any increase in the void fraction value. Rinne and Loth (1996) focused on developing a new measuring technique for quantifying the local surface areas of the bubbles in a vertical bubbly flow across pipe expansion. More detailed experimental data on the wall shear stress, the void fraction profile and the local bubble velocities and sizes downstream of a sudden expansion was provided by Aloui et al. (1999). Additionally, they developed a theoretical model with satisfactory results based on multiple simplifying assumptions for predicting the pressure drop across sudden expansions.

Koichi and Kenji (2002) studied the vertical gas–liquid flow in a round tube with an axisymmetric sudden expansion. Bubble deformation and slug break up were reported due to a strong shear layer generated just above the expansion. Another interesting observation was a noticeable pick in void fraction distribution near pipe walls downstream of the expansion for various operational conditions. Ahmed et al. (2007), based on a series of experiment on oil–air flow through horizontal sudden expansions, developed a general formulation for pressure recovery across the sudden expansion accounting for wall shear stress, the losses in recirculation zone and void fraction (flow pattern) changes. Ahmed et al. (2008) extended their previous work by providing detail measurements on local characteristic of the two-phase flow. Particularly, it was concluded that the liquid turbulence intensity is higher in the immediate vicinity of the sudden expansion and reduces with axial distance.

Chen et al. (2007) examined the evolution of two-phase flow pattern with the mixture quality downstream of a sudden expansion in a small rectangular channel. A new liquid-jet flow pattern was observed for low values of the quality which reduces the pressure difference across the area expansion. This work was complemented by Wang et al. (2010) who presented a comprehensive evaluation of available pressure correlations for the aforementioned two-phase flow. Gas–liquid flows through smooth expansions (a divergent

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section with a constant slop) were studied thoroughly by Kourakos et al. (2009). In addition to presenting axial pressure profiles for various area ratios, the effect of volumetric void fraction on the pressure changes across the singularity was quantified and a modified correlation was provided for ΔP. More recently, Anupiya and Jayanti (2014) investigated gas–liquids flow through a diverging section. It was understood that pressure recovery immediately after expansion is affected by the smoothness of the expansion and the interfacial friction.

One the most comprehensive sets of pressure drop measurements for gas–liquid flows across sudden contractions was carried out by Schmidt and Friedel (1997). Pressure profiles were provided accompanied by a reliable yet practical pressure drop model. For sudden area restrictions in small channels, the corresponding pressure drop values, the two-phase flow pattern and accurate empirical correlations were reported by Abdelall et al. (2005) and Chen et al. (2008). Moreover, limited experimental data for air and water flows through a smooth contraction can be found in the work of Kourakos et al. (2009).

In contrast to the case of experimental studies, numerical simulations of gas–liquid flows through area changes are somehow limited and hard to find. One of the first attempted to numerically simulate a dilute bubbly flow through an area expansion was made by Brankovic and Currie (1996) utilizing an Eulerian description for liquid flow and a Lagrangian formulation for the gas bubble movements. For bubbly flows with high void fractions, Behzadi et al. (2004) modified the standard Eulerian approach in two-phase flow modeling to account for inter-phase forces in dense gas–liquid mixtures. They also proposed a modified version of k–ε turbulence model which was able to predict gas bubbles interaction with the liquid eddies more efficiently and they successfully simulated the bubbly flow through a sudden expansion. Sakr et al. (2012) extended the work of Behzadi et al. (2004) by considering various turbulence models. It was concluded that SST (k–ω) turbulence model produces the most accurate results for the two-phase flow across sudden expansions.

Parting from bubbly flow pattern, the most promising numerical simulation of a two-phase turbulent flow through sudden expansions/contraction was carried out Roul and Dash (2011) who relied on the two-phase Eulerian–Eulerian scheme with the k–ε model of turbulence. It was shown that the calculated value of pressure changes across sudden expansion/contraction by the numerical method was in a near perfect agreement with experimentally measured data. Moreover, it was concluded that the use of the mixture model instead of the homogenous model (which neglects the velocity slip at the gas–liquid interface) is a necessity to acquire an admissible numerical simulation of the multiphase flow. Eskin and Deniz (2012a, 2012b) presented a numerical simulation for gas–liquid flows with three different volumetric void fractions through a single smooth expansion with the area ratio of 0.64. They employed an Eulerian multiphase approach together with a RSM dispersed turbulent model which neglects the effects of air-bubbles interactions. No clear conclusion could have been made on the effect of void fraction on the pressure drop; moreover, the discrepancy between their numerically-predicted pressure changes and void fraction distribution and the corresponding experimental values increased with the elevation of void fraction.

To study the two-phase flow patterns across a narrow duct with a sudden expansion, Ueda et al. (2012) used a volume of fluid (VOF) formulation accounting for surface tension and wall adhesion effects. They predicted a bubble fragment pattern for low gas flow rate and annular pattern for higher values of void fractions which is in a qualitative agreement with the experiment. No discussion was provided on the quantity of pressure losses and the effect of gas flow rate on this important quantity.

Despite all the aforementioned numerical attempts to study the physics of the two-phase gas–liquid flows through area changes, especially in the case of smooth expansions/contractions, there are still needs for more detailed numerical simulation of the problem to complete our knowledge of the flow at first and subsequently improve our predictive tools. As a result, in this work a detailed numerical simulation of two-phase air and water flow through gradual expansions/contraction is presented and the effect of various geometric and flow parameters are investigated on the pressure changes across the area change. To achieve its goals, the manuscript is organized as: in Section 2, the governing equations are presented briefly together with their pertinent boundary conditions. The numerical method of solution will be described next in detail. Numerical results are then presented and validated addressing the flow of gas–liquid mixture across smooth expansions/contractions. The work is concluded by highlighting its major findings.

2. Mathematical formulation

In this work, the turbulent two-phase gas–liquid flow through a round tube with a smooth linear expansion/contraction is considered. The schematic diagram of the flow domain and is illustrated in Fig. 1 and its geometrical details are given in Table 1. Where the opening angle of the gradual expansion/contraction is denoted by θ and σ is the area ratio.

To obtain the governing equations of the problem (i.e. conservation of mass and momentum) following assumptions are undertaken,

- The flow is axisymmetric and isothermal.
- The orientation of the round tube is vertical and the flow direction is assumed to be upward. Moreover, the gravitational acceleration is on the opposite of flow direction.
- Mass transfer at the gas–liquid interface is negligible.
- Both phases are incompressible Newtonian fluids with a constant viscosity.
- By neglecting capillary effects a common pressure field (P) for gas and liquid phases is assumed.
- Mathematical modeling of the two-phase flow is carried out by employing Eulerian (two-fluid) approach in which ease phase is treated as a continuum and the distribution of phases throughout the flow domain is resolved with the introduction of volume fraction concept (Yeoh and Tu, 2010).
- To model the momentum transfer by turbulent eddies the Boussinesq approximation (Pope, 2000) is used.

By employing the two-fluid model for the turbulent gas–liquid mixture, the effective governing equation for the kth phase could be written as (Drew, 1983; Kataoka and Serizawa, 1989; Yeoh and Tu, 2010):

- Continuity equation:

$$\frac{\partial}{\partial t}(\alpha^k \rho^k) + \nabla.(\alpha^k \rho^k u^k) = 0 \tag{1}$$

where ρ^k is the density of kth phase, $\mathbf{u}^k$ is the velocity vector and α^k is the volume fraction of kth phase (i.e. the ratio of the fractional volume of the kth phase in an arbitrary small region over total volume of the region) which is considered to be a continuous function of time and space.

- Momentum equation:

$$\frac{\partial}{\partial t}(\alpha^k \rho^k u^k) + \nabla.(\alpha^k \rho^k u^k \otimes u^k) = -\alpha^k \nabla P + \nabla.\tau^k + \alpha^k \rho^k g + S^k \tag{2}$$

In Eq. (2), $\mathbf{g}$ is the gravitational acceleration vector and $\mathbf{S}^k$is the interphase momentum transfer term. Moreover, the extra stress tensor of the kth phase ($\boldsymbol{\tau}^k$) is given by Eq. (3) in which μ_T^k denotes the turbulent eddy viscosity:

$$\boldsymbol{\tau}^k = \alpha^k \left(\mu^k + \mu_T^k\right)\left[\nabla \mathbf{u}^k + (\nabla \mathbf{u}^k)^t\right] \tag{3}$$