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Numerical investigation of gravitational effects in horizontal annular liquid–gas flow

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ABSTRACT

In this work, exploratory numerical simulations of liquid–gas flows in horizontal pipes are conducted for three different sets of conditions in the annular and stratified-annular flow regimes. Careful dimensional analysis is used to choose governing parameters in a way that yields flows that are relevant to realistic engineering applications, while remaining computationally tractable. Statistics of the velocity field and height of the liquid film are computed as a function of circumferential location in the pipe, demonstrating the existence of a viscous sublayer within the liquid film, as well as a viscous layer near the interface and a log law region within the gas core. The probability of dry-out conditions at the wall in upper regions of the pipe is shown to increase as gravitational effects increase. Circumferential motion of the liquid and gas phases within the pipe cross section are analyzed, informing possible mechanisms for sustainment of the liquid film. A simple model is developed that helps to characterize the dynamics of the liquid annulus and aids in understanding the effect of secondary gas flow on the circumferential motion of the film. Void fraction, film height, and film asymmetry are compared with experimental correlations available in the literature.

Introduction

The concurrent flow of liquid and gas inside circular pipes occurs in a vast range of engineering devices, such as chemical and nuclear reactors, pipelines, oil wells, and the receiver tubes of direct steam generation, among others. Depending on the relevant governing dimensionless parameters, the distribution of the phase interface can take many different forms. The way in which the phases are distributed will significantly impact hydrodynamic and thermal properties of these flows, which will in turn affect the optimized operation conditions and economical design of such systems. In horizontal systems, gravitational effects lead to stratification, i.e., the buoyancy of the gas phase causes it to migrate to upper regions of the domain. This tendency can be diminished, depending on the relative importance of inertial and gravitational effects, as well as the gas volume fraction (also known as the void fraction). Within horizontal circular pipes, common flow regimes include bubbly flow, plug flow, slug flow, stratified and stratified-wavy flow, and annular and disperse–annular flow (Carey, 2008).

Details regarding global flow characteristics that lead to different multiphase flow regimes are provided by Carey (2008) and are briefly conveyed here. At small void fractions, bubbly flow is characteristically observed. Small bubbles coalesce as the void fraction increases, forming larger bubbles. Larger bubbles intermittently flow in the upper region of the pipe, characteristic of plug flow. If the void fraction is high and inertial effects are small, the gas and liquid fully separate and stratified flow occurs. Kelvin–Helmholtz type instabilities can occur in the stratified regime if the inertia of the gas is high enough, causing the interface between the phases to become wavy. The waves may reach the top of the pipe if their amplitude becomes large enough, taking a “slug-like” appearance, thus referred to as slug flow. When the void fraction is large and inertial effects dominate in the gas phase, an annular flow can occur in which the liquid assumes the form of a thin annular film around the interior surface of the pipe, while a gas core flows through the center. Buoyancy effects cause the film to be thinner near the top of the pipe than the bottom, leading to interfacial corrugations that vary in the circumferential direction due to waves that protrude further into the gas core near lower regions of the pipe. Shear caused by the high-inertia gas also has a tendency to entrain liquid droplets into the gas core. The aforementioned flow regimes for horizontal gas–liquid flows can be difficult to distinguish from one another, as transitional forms of these regimes are common. In the past half-century, much work has gone into developing flow pattern maps in order to predict

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flow regimes based on important flow parameters (Alves, 1954; Baker, 1953; Ghajar et al., 2007; Hoogendoorn, 1959; Kosterin, 1949; Krasiakova, 1957; Mandhane et al., 1974; Taitel and Dukler, 1976). These maps aim to categorize the two-phase flow into the discussed regimes based on characteristics of the phases, such as superficial velocities and Reynolds numbers. Some maps have had more success than others, but it is difficult for any two parameters to contain enough information about the two-phase flow to determine the resulting interfacial distribution.

Annular flows are especially common under conditions relevant to a plethora of thermo-fluid transport systems, and have therefore received much attention from experiments. A common goal of many experiments has been to extract the liquid film thickness, measured through planar laser-induced fluorescence (Schubring et al., 2010a,b; Farias et al., 2011), conductance probes (Hagiwara et al., 1989; Paras and Karabelas, 1991a), fast response X-ray tomography (Hu et al., 2013), and other techniques (Laurinat et al., 1985; Hewitt et al., 1990; Hurlburt and Newell, 1996, 2000; Shedd and Newell, 2004; Schubring and Shedd, 2008). Other workers have measured mean circumferential velocity through photochromic dye activation (Sutharshan et al., 1995). A range of other quantities relevant for practical applications have also been measured extensively, such as wall shear (Hagiwara et al., 1989; Schubring and Shedd, 2009a) and pressure drop (Shedd and Newell, 2004; Schubring and Shedd, 2008). Multiphase dynamics that pertain to film sustainment mechanisms have been measured, such as characteristics of droplet entrainment and deposition (Paras and Karabelas, 1991b; Azzopardi, 1999; Al-Sarkhi and Hanratty, 2002; Rodriguez et al., 2004; Alekseenko et al., 2013), induced secondary gas circulation (Flores et al., 1995), and surface wave characteristics (Jayanti et al., 1990a; Hurlburt and Newell, 1996; Schubring and Shedd, 2008). Despite efforts to formulate theories and models to predict flow regime characteristics and regime transitions (Jacowitz et al., 1964; Anderson and Russel, 1970; Taitel and Dukler, 1976; Kadambi, 1982; Ooms et al., 1983; Fukano and Ousaka, 1989; Serdar Kaya et al., 2000; Ooms and Poesio, 2003; Adechy, 2004; Moreno Quibén and Thome, 2007; Schubring et al., 2011; Al-Sarkhi et al., 2012; Öztürk et al., 2013), there is a lack of theoretical understanding that would allow for a description of the interface distribution from first principles.

Numerical studies of multiphase flows in transport systems are very limited in comparison with their experimental counterparts. The vast majority of relevant liquid–gas direct numerical simulations (DNS) have focused on bubbly flows (Esmaeeli and Tryggvason, 1998, 1999; Bunner and Tryggvason, 1999, 2002a,b; Nagrath et al., 2005), while significantly less computations of other regimes have been performed. Those that do exist often rely on a simplified models to account for relevant physical processes, such as two- and multi-fluid model-based simulations of slug flow (Issa and Kempf, 2003; Bonizzi and Issa, 2003a) and arising mechanisms for bubble entrainment (Bonizzi and Issa, 2003b). A number of numerical studies have been conducted that isolate a particular physical process that is relevant to a liquid–gas pipe flow, such as hydrodynamic counterbalancing of the buoyancy on the gas core (Ooms et al., 2007, 2012), DNS and large-eddy simulation (LES) of a sheared interface in turbulence (Fulgosi et al., 2003; Reboux et al., 2006), DNS of turbulent heat transfer across a sheared interface (Lakehal et al., 2003), LES and Reynolds-averaged Navier–Stokes (RANS) simulations of secondary flow effects on droplet deposition and turbophoresis (Jayanti et al., 1990b; van't Westende et al., 2007), two-dimensional simulation of wave entrainment in vertical pipes (Han and Gabriel, 2007), and simulation of liquid film formation through wave pumping (Fukano and Inatomi, 2003).

These types of numerical studies are very useful for gaining insight toward the important dynamics of liquid–gas pipe flows, yet computational limitations have prevented the formulation of a detailed, first principles-based study of a horizontal liquid–gas flow inside a pipe that combines a fully turbulent gas phase with the effects of a deformable interface and non-unity density and viscosity ratios. The present work is an exploratory investigation that seeks to combine all of these effects together, demonstrating that simulations of annular and stratified flows relevant to realistic engineering applications are computationally feasible if governing parameters are chosen carefully. The aim of the present study is to further understand the hydrodynamic conditions that delineate the annular and stratified flow regimes, and to test if the present numerical approach is capable of capturing the transition between these regimes.

The computational approach used in the current study is outlined in 'Computational approach', including a discussion of the governing equations and the methodology for interface capture. The system configuration is provided in 'System configuration', describing the simulation domain and the flow forcing mechanism, as well as validating the mesh resolution and immersed boundary method. Results of the simulations are discussed in 'Results', providing a wide range of computed statistics and comparison with experimental data and correlations. Mechanisms for film sustainment are discussed in 'Dynamics in the pipe cross section', followed by a simple model for the liquid film provided in 'A model for the liquid film' to further aid in understanding the interfacial dynamics as they pertain to film replenishment.

Computational approach

Mathematical formulation

The two-phase annular flows in this study are described by the continuity and Navier–Stokes equations. Assuming incompressibility of both phases, i.e., $\nabla \cdot \boldsymbol{u} = 0$, the continuity equation is written

$$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + \boldsymbol{u} \cdot \nabla \rho = 0, \tag{1}$$

where $\boldsymbol{u}$ is the velocity field and ρ is the fluid density. The Navier–Stokes equations are written as

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u}) = -\nabla p + \nabla \cdot \left(\mu \left[\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^{\mathsf{T}}\right]\right) + \rho \boldsymbol{g} + \boldsymbol{f}_b, \tag{2}$$

where p is the pressure, $\boldsymbol{g}$ is the gravitational acceleration, and μ is the dynamic viscosity. The body force $\boldsymbol{f}_b$ used for momentum forcing within the periodic computational domain will be discussed in 'Flow forcing'.

The material properties are taken to be constant within each phase, and the subscripts l and g are used to describe the density and the viscosity in the liquid and gas, respectively. These quantities are discontinuous across the interface Γ, and it is convenient to introduce their jump as $[\rho]_\Gamma = \rho_l - \rho_g$ and $[\mu]_\Gamma = \mu_l - \mu_g$. The velocity field is continuous across Γ in the absence of phase change, i.e., $[\boldsymbol{u}]_\Gamma = 0$. This is valid for the isothermal conditions simulated herein. The surface tension force will lead to a discontinuity in the normal stress at the gas–liquid interface, which translates into a pressure jump that can be written as

$$[p]_\Gamma = \sigma\kappa + 2[\mu]_\Gamma \boldsymbol{n}^{\mathsf{T}} \cdot \nabla \boldsymbol{u} \cdot \boldsymbol{n}, \tag{3}$$

where σ is the surface tension coefficient, κ is the curvature of the interface, and $\boldsymbol{n}$ is the normal vector at the interface. The discontinuous pressure is dealt with using the ghost fluid method (GFM) (Fedkiw et al., 1999), and information regarding numerical implementation of these equations is given by Desjardins et al. (2008a,b).