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Hydro dynamic modeling of stratified smooth two-phase turbulent flow with curved interface through circular pipe

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ABSTRACT

This study is motivated by the need to develop a model for numerical calculations of fully developed, stratified smooth gas–liquid pipe flow. A configuration of a curved interface is considered. The curved gas–liquid interface is modeled by invoking the principle of minimal total system energy (sum of potential and surface energies). The two-dimensional, steady-state axial momentum equation is solved together with a low Reynolds k–ε turbulence model for a variable interface curvature. The continuity of the shear stress and the velocity across the interface are enforced. The computations are performed in the bipolar coordinate system for convenient describing the curved interface and mapping of the physical domain. The numerical method compares well with experimental data of pressure gradient, liquid holdup, vertical and horizontal profile of the longitudinal velocity. In addition, the result indicates that the interfacial configuration effects on the liquid holdup and pressure gradient are significant.

1. Introduction

Stratified two-phase flow, which is considered to be among the simple and fundamental flow configuration in two-phase systems of a finite density differential, is frequently encountered in practical applications and theoretical points, such as the transport segment in the petroleum industry. The accurate prediction of pressure gradient and liquid holdup (i.e. liquid phase fraction) is of considerable research interest [1].

Due to the complex flow geometry of stratified flow in circular conduits, most common models for industrial application are based on greatly simplified representation of flow structure. Empirical approaches and mechanistic models are applied with common assuming that both phases are treated as one-dimensional flow [2]. The mechanical model due to Taitel and Dukler [3], Spedding et al. [4], and recently Zhang et al. [5], Which are two-fluid model with closure relationships for wall and interfacial shear stresses based on the average velocity using empirical correlations, such as the well-known Blasius formula for single-phase flow [1]. However, the Zhang et al. model [5] neglects the detailed velocity profile structure and angular distributions of the interfacial and wall shear stress. Unfortunately, with so little known about the distribution of wall and interface shear in gas–liquid flows, the predictive capabilities of these correlations are generally restricted to the flow conditions on which they are based, loss in calculation accuracy exceeding the range.

The computational fluid dynamics (CFD) techniques obtained a growing interest in the simulation of the stratified gas–liquid two-phase pipe flow behavior. In many practical stratified gas–liquid two-phase flows, the gas phase may be turbulent and may occur at high velocities. At the same time, the liquid phase is laminar or turbulent. For turbulent–turbulent two-phase flow regimes in the circular pipe, several researchers have obtained numerical solutions to such problems to determine the local and integral flow properties.

Shoham and Taitle [6] used two-dimensional momentum equation with an algebraic turbulence model for liquid phase to calculate the shear stress on the pipe wall and gas–liquid interface. The gas phase is treated as bubble flow simply and an empirical correlation was used to couple the two phases through the interfacial shear stress. The results showed reasonable agreement with the mechanistic model of Taitel and Dukler [3]. However, the momentum equation did not include first-order viscosity gradient terms, casting some doubt over the validity of the results.

Issa [7] coupled the axial momentum equation and the standard k–ε two-equation model with wall functions for both gas and liquid phase in circle and rectangular pipe. Newton and Behnia [8,9] extended the work of Issa [7], for smooth stratified flow in

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a 50 mm diameter pipe and used a low Reynolds number k–ε model for turbulent flow. The numerical results are shown that the minor tuning of the wall damping functions performed has little effect on the result.

Sampaio et al. [1] solve the Reynolds average Navier–Stokes equations with k–ε turbulence model using the finite element method. A smooth interface surface is assumed without considering the effects of the interfacial waves.

All the previous research cited above efforts on the stratified gas–liquid two-phase flows assumed that the interface is planar between the two phases, thus the influence of interface shape was ignored. The interfacial curvature has been found to have a significant effect on the local and integral flow characteristics and transition between different flow pattern [10,11]. Thus accuracy is poor when the interface is assumed as planar under some condition.

Most of previous works on stratified two-phase flow considering the prescription of the characteristic interfacial curvature is confined to laminar–laminar stratified flow, including those of Yu et al. [12], Joseph [13], Brauner et al. [14], Ng et al. [15]. The latter provided analytical solution for the pressure gradient, liquid holdup, the interface and wall shear stresses and the velocity profiles on the interface and through the cross-section of the pipe. The interface was considered to be cured determined by the Young–Laplace equation with various contact angles. They found that the circular arc approximation provides a very good model for all values of the dimensionless parameters.

Berthelsen and Ytrehus [10] used the immersed interface method to represent the interface sharp and the additional level set function is introduced into the numerical calculation, coupling the governing equation. The advantage of this technique is interface independence of the grid structure, to avoid complicated grid generation algorithms.

Hernandez-Perez et al. [16] discussed the grid generation issues of two-phase flow in pipe and the effect of the element type and structure of the mesh to the numerical simulation using the commercial software package. There were 4 different mesh structures employed in the computational domain, such as polar cylindrical mesh, butterfly grid, rectangular H-grid, unstructured pave grid. The butterfly type of grid is highly recommended for the simulation of two-phase flow in a pipe.

The intention of this work is to investigate the possibilities of developing a theoretical model to predict stratified gas–liquid two-phase fully developed pipe flow with curved interface. In this approach, the two-dimensional time-averaged steady-state axial momentum equation and a low Reynolds number k–ε turbulence model for the eddy viscosity in turbulent flow. A configuration of a curved interface is considered and described by a closure relation obtained by invoking the principle of minimal total system energy (i.e. sum of potential and surface energy).

2. Mathematical model

We consider a fully developed stratified gas–liquid two-phase flow in a horizontal or slightly inclined circular pipe. The stratified flow is schematically shown in Fig. 1.

2.1. Interface configuration

A good prediction of interface shape is important when performing stratified gas–liquid two-phase flow calculations [17]. Consider the stratified flow of gas–liquid two-phase flow in horizontal or slightly inclined pipe. The flow configuration is irregular and the interface may be planar or curved concave configuration depending on the liquid holdup, liquid–solid (pipe wall) wet ability (i.e. surface tension) and the physical properties of the liquid fluid, as shown in Fig. 1. The effect of surface tension and gravity are characterized by the Bond number, B_O, defined as

$$B_O = \frac{\Delta\rho g R^2}{\sigma} \tag{1}$$

where $\Delta\rho$ is the density difference between two fluids, R is the radius of the pipe, σ is the interfacial tension, and g is the gravitation. In general, when Bond number decreases, the interface configuration tends to attain a convex or concave configuration and the larger the Bond number, the more closely the interface approaches a planar surface.

The interface of gas–liquid two-phase flow in pipe can be assumed as arc shape that suggested by Li et al. [11], as shown in Fig. 1. The arbitrary point, F, on the gas phase of the cross-section pipe is represented by the view angle, θ. The pipe perimeter and the interface between the two fluids are iso-line of θ. So the upper section of the pipe wall, which bounds the gas phase, is represented by $\theta = \theta_0$. The bottom of the pipe wall, which bounds the liquid phase, is represented by $\theta = \theta_0 + \pi$.

The interface considered to be of cylindrical shape, is represented by $\theta = \theta^*$. The contact angle, $\theta_0 + \pi - \theta^*$, is the angle between the two phase and the pipe wall. It is convex interface for $\theta^* < \pi$ and concave interface for $\theta^* > \pi$. In particular, when the interface is planar, it will be $\theta^* = \pi$. It is noticed that θ^* is bounded in the range of $\theta_0 \leqslant \theta^* \leqslant \theta_0 + \pi$. The prescriptions of the θ_0 and θ^* are required for solving the hydrodynamic problem.

In order to handle the problem of deriving the interface configuration, global energy considerations are introduced, as similar with the method of Brauner ea al. [18] The change of the total energy which is sum of the variations of potential energy and surface energy terms with respect to a planar interface (taken as a configuration of reference), for a unit length of a pipe is given by:

$$\frac{\Delta E}{L} = \frac{1}{L}\Delta(E_P + E_S) = R^3\rho_L g\left(1 - \frac{\rho_G}{\rho_L}\right) \left(\begin{pmatrix} \frac{\sin^3\theta_0}{\sin^2\theta^*}(\arctan\theta^* - \arctan\theta_0)(\pi - \theta^* + 0.5\sin(2\theta^*)) \\ +\frac{2}{3}\sin^3\theta_0^P \end{pmatrix} + \frac{2}{B_O}\left(\sin\theta_0\frac{\pi-\theta^*}{\sin\theta^*} - \sin\theta_0^P + \cos\alpha(\theta_0^P - \theta_0)\right) \right) \tag{2}$$

where ΔE, E_P and E_S are the change in total energy, potential energy and surface energy, respectively. L is the length of pipe. ρ_L and ρ_G are the density of the liquid and gas fluid, respectively. θ_0^P denotes the corresponding for plane interface. The changes in the potential and surface energy are relative to a planar interface, i.e. taken as a configuration of reference. The steady interface configuration determined by the minimum of total change system energy $\Delta E/L$.

According to the geometric relationship, the corresponding for plane interface θ_0^P is given as:

$$\theta_0^P = \cos^{-1}\left(1 - \frac{2h_L}{R}\right) \tag{3}$$

$$H_L = \frac{\theta_0^P - \sin\theta_0^P}{2\pi} \tag{4}$$

where h_L is the liquid level in the pipe, as shown in Fig. 1. H_L is the local liquid holdup $H_L = A_G/(A_G + A_L)$.

When the view angle θ_0 is determined, the θ^* can be calculated according to Eq. (2); and the interface shape is determined using Eq. (2). According to the geometric relationship, the relationship of the view angle θ_0 and the local liquid holdup H_L is given by:

$$\theta_0 - \sin\theta_0\cos\theta_0 = H_L\pi \tag{5}$$

Given the liquid holdup H_L, the interface represented by θ^* can be calculated using the above method.