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Interfacial shear stress in wavy stratified gas–liquid flow in horizontal pipes

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ABSTRACT

The scope of this study was to improve the Andritsos-Hanratty model for estimating interfacial friction factor and pressure drop in horizontal stratified gas–liquid two-phase flow. New experimental results (focusing on the effects of gas density and surface tension), combined with experimental data available in the literature, permit the development of semi-theoretical correlations for the transition from smooth stratified to 2-D wave region and from the latter to large-amplitude wave region and of different empirical relations for the interfacial friction factor in the two wave regions. The transition correlations agree reasonably well with existing and new data obtained in this work and the modified relations give improved predictions for both liquid holdup and pressure drop during gas–liquid stratified flow in horizontal and slightly downward pipelines as deduced from a statistical analysis of the results.

1. Introduction

Gas–liquid flow in horizontal or near horizontal pipelines has gained considerable importance over the past 50 years because of its widespread applications in oil, gas and geothermal industry and in the operation of nuclear and chemical reactors, evaporators and other types of process equipment. When gas and liquid flow concurrently in a horizontal or near horizontal pipe various flow patterns form, depending on flow conditions and pipe characteristics. At low gas and liquid rates the stratified flow pattern occurs, whereby the liquid flows along the bottom of the pipe and the gas flows above, while the interface may be smooth or covered by waves.

The stratified pattern can be considered as a rather "simple" one, especially when one compares this pattern with the more complex annular or slug flow patterns, since the two phases are completely separated. Despite this apparent simplicity, the flow characteristics of stratified flow (e.g. pressure drop, liquid holdup, interface shape) cannot be always predicted to a satisfactory degree, especially at high pressures or when fluids with much different properties than those of air–water are handled. Furthermore, a better understanding of the stratified regime may also help to better comprehend and model adjacent flow patterns, such as slug flow and annular flow. Indeed, stratified flow has been considered as a starting flow regime in a plethora of works dealing with stratified-to-slug flow transition (see e.g. Taitel and Dukler, 1976a; Lin and Hanratty, 1986).

According to Andritsos and Hanratty (1987b) and Tzotzi et al. (2011), the following subregimes of the stratified gas–liquid flow in horizontal and slightly downward pipes can be recognized, while similar subregimes of stratified flow were also identified by other investigators (e.g. Chen et al., 1997; Fernandino and Ytrehus, 2006).

(1) A smooth region, occurring at very low gas and liquid velocities, where the gas–liquid interface is smooth.
(2) A two-dimensional (2-D) wave region, where the interface is covered by small amplitude, short wavelength regular disturbances. It is rather well accepted that these first waves receive energy from pressure perturbations in phase with the wave slope (e.g. Miles, 1957; Hanratty, 1983), justifying in some way the "sheltering" hypothesis suggested by Jeffreys (1925). The 2-D waves are rather periodic and uniform and maintain their identity for several wave periods (Andritsos, 1992). A characteristic of these waves is that their amplitude and wavelength increase with the distance of the pipe. Liquid viscosity affects considerably the initiation of these waves by shifting the transition toward higher gas velocities. In fact, for liquid viscosities higher than about 20 mPa s this kind of waves does not appear at all, in accordance with a linear stability analysis presented by Andritsos and Hanratty (1987b).
(3) A wavy region with large amplitude, irregular waves, with a steep front and a gradually sloping back, also found in the literature as roll waves. These waves are characterized by

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strong wave–wave interactions and by the tendency to change their shape as they travel along the pipeline (Andritsos, 1992). Consequently, the auto-correlation function does not exhibit any periodicity. The transition to these waves is weakly influenced by both liquid viscosity and pipe diameter. It is quite probable that when older flow regime maps (e.g. Baker, 1954; Mandhane et al., 1974) refer to the transition to wavy region they mean transition to large-amplitude waves. In this paper, these waves are also called Kelvin–Helmholtz (K–H) waves, since their inception can be associated with pressure variations in phase with the wave height (Andritsos and Hanratty, 1987b).

(4) An atomization region, where droplets or liquid filaments are torn off from the crests of the large-amplitude waves and deposited on the pipe wall. Specifically, the transition to this region is defined to be the flow conditions at which droplets are first observed on the top of the pipe. Obviously, with the above definition the transition to atomization depends on the pipe size. Statistical analysis of wave traces in this subregime did not reveal any difference with the large-amplitude waves. In addition, the liquid starts climbing up the walls of the pipe and the shape of the interface is no longer approximated by a flat horizontal plane, at least for small pipe diameters (e.g. less than 0.05 m) and low viscosity liquids. It is noteworthy, however, that the behavior in this region is very similar to annular flow for large pipe diameters and high viscosity liquids, where most of the liquid flows at the bottom of the pipe.

As it is true for almost all the flow transitions, the transitions between the various subregimes of stratified flow do not occur instantly, but transitional zones appear between the various subregimes.

The above categorization of waves is primarily phenomenological, but is supported by ample experimental evidence that clearly differentiates between them. More recent attempts to delineate the linear stability problem, by rigorous solution of the Orr–Sommerfeld equation reveal a more complex picture (e.g. Kuru et al., 1995; Boomkamp and Miesen, 1996), but are questioned by the difficulty to account fully for the turbulent dynamics of the gas phase.

In stratified flows, momentum balance equations are normally used to predict pressure drop and liquid film height. However, the presence of waves at the interface can cause the interfacial shear stress to be much greater than that which would be observed if the interface were smooth. As a result, larger pressure drops and lower liquid holdups are measured, not simply due to the interface roughening. Obviously, the correlation of the interfacial shear stress has a crucial role on the whole modeling effort and, despite over half a century of intensive research efforts, there is ample room for relation improvements. The situation is further complicated from the existence of more than one wave patterns (certainly originating from different mechanisms), and from the fact that at low gas velocities the flow is usually not well developed (Taitel and Dukler, 1987). The deviation from not well developed flow becomes more pronounced with decreasing the pipe length and increasing the pipe diameter. In addition, at high gas rates the liquid starts to climb up the pipe walls, especially in small diameter pipes, as previously discussed. The different wave types exert an influence not only on the pressure drop of the system, but also on the mass and heat transfer rates both at the interface and at the pipe walls.

More than 25 years ago, Andritsos and Hanratty (1987a) proposed a semi-empirical correlation for the estimation of the interfacial friction factor in horizontal stratified two-phase flow and a semi-theoretical approach for modeling the liquid wall shear stress. Although their model predicts rather satisfactorily the friction factor at the interface and, consequently, the liquid holdup and the pressure loss along the pipeline, the proposed correlation for the interfacial friction factor has two major drawbacks. First, this model assumes that the interfacial friction factor increases dramatically with the onset of large-amplitude waves, which for the air–water system takes place at a constant "critical" superficial gas velocity of 5 m/s at atmospheric conditions. This assumption obviously results in the overestimation of friction factor at low liquid rates and in its underestimation at large liquid velocities. Second, the attempt to make dimensionless the correlation by dividing the superficial gas velocity with the critical gas velocity at the transition to large-amplitude waves (which scales as ${\rho_G}^{-0.5}$, where ρ_G is the gas phase density) leads to unrealistically high values of friction factor for high density gases or high pressure systems.

The main objective of the present work is to improve the Andritsos–Hanratty model with a better description of the transitions to the various subregimes of stratified flow and to ameliorate the correlation for the interfacial friction factor. A secondary objective is to demonstrate that the modified model can be also used to sufficiently predict pressure drop and holdup in slightly downward flows. In order to clarify the effects of gas density and of surface tension on stratified subregimes, since only a very limited number of works have dealt so far with these physical properties, experiments were conducted in a 24-mm, i.d. horizontal pipeline using air, carbon dioxide and helium as gas phase and water and butanol–water solution as liquid phase.

2. Background literature

Almost all predictive methods for modeling stratified flow available in the literature are essentially one-dimensional models based on momentum balances of both phases. In the present approach the interface is assumed to be flat, as shown in Fig 1. This assumption is rather valid for most cases involving large diameter pipes, high liquid viscosity and density and liquid holdup higher than about 0.05.

For fully developed flow in a pipe the one-dimensional momentum equations for the two phases are written as:

$$-A_G\left(\frac{dp}{dL}\right)_G - \tau_{WG}S_G - \tau_i S_i - \rho_G A_G g\sin\theta = 0 \tag{1}$$

$$-A_L\left(\frac{dp}{dL}\right)_L - \tau_{WL}S_L + \tau_i S_i - \rho_L A_L g\sin\theta = 0 \tag{2}$$

where ρ_L and ρ_G are the densities of the liquid and gas phase, respectively. The geometrical parameters A_G, A_L, S_L, S_G, S_i and θ are defined in Fig. 1. As shown in the same figure, Eq. (1) represents a balance between the pressure forces on the gas space and the resisting stresses at the gas–solid boundary, τ_{WG}, and at the gas–liquid interface, τ_i. Eq. (2) is a balance between the pressure forces, the drag of the gas on the liquid at the interface and the resisting stress at the liquid–solid boundary, τ_{WL}.

By eliminating the pressure gradient between Eqs. (1) and (2), under the assumption that the pressure drops in both phases are equal, a relation for the liquid holdup, $\varepsilon_L = A_L/(A_L + A_G)$, or for the dimensionless height of the liquid layer, h/D, can be obtained:

$$\frac{\tau_{WG}S_G}{A_G} - \frac{\tau_{WL}S_L}{A_L} + \tau_i S_i\left(\frac{1}{A_L} + \frac{1}{A_G}\right) - (\rho_L - \rho_G)g\sin\theta = 0 \tag{3}$$

On the other hand, by eliminating the interfacial shear stress term in Eqs. (1) and (2) one may get the relation for the pressure drop of the system: