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Prediction of the liquid film distribution in stratified-dispersed gas–liquid flow

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HIGHLIGHTS

- A model for liquid film distribution in gas–liquid stratified dispersed flows has been derived.
- The model allows the numerical calculation of the local axial liquid film height and velocity profiles.
- Droplet deposition, gravitational drainage and wave spreading are relevant.
- The strength of each mechanism depends on the underlying flow conditions.
- The wave spreading affect is modelled as function of a modified Froude number.

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ABSTRACT

A mathematical model for predicting the circumferential liquid film distribution in stratified-dispersed flow is presented. Objective of the model is to describe the typical flow conditions of wet gas transportation in long, near-horizontal pipelines. In these applications, depending on the gas velocity and pipe diameter, a large asymmetry of the liquid film distribution may arise. The model is based on the assumption that in stratified-dispersed flow, liquid droplets can only be entrained by the gas from the thick liquid layer flowing at pipe bottom. It is also assumed that the deposition of smaller droplets is related to an eddy diffusivity mechanism and regards the entire pipe circumference, while larger droplets deposit by gravitational settling on the pipe bottom. These assumptions explain the formation of a thin, non-atomizing film in the upper part of the pipe. The presence and flow structure of this film appreciably affect the pressure gradient and the liquid hold-up in the pipe and are of great importance in flow assurance studies. The model has been validated against i) the experimental observations recently published by Pitton et al. (2014), the data collected by ii) Laurinat (1982), iii) Dallman (1978), and iv) the predictions of three-dimensional CFD simulations conducted by Verdin et al. (2014). It is shown that the relevant mechanisms which are responsible for the liquid film distribution are the gravitational film drainage, droplet entrainment/deposition and wave spreading. In particular, at high gas velocities and/or small pipe diameters, the asymmetry of the liquid film diminishes owing to the wetting mechanism of wave spreading which makes the distribution of the film more uniform in the circumferential direction. As the gas velocity diminishes and/or for larger pipe diameters, wave spreading is less effective and for these flow conditions only gravitational drainage and droplet entrainment/deposition are responsible for the more asymmetric shape of the liquid film.

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1. Introduction

Pipeline transportation over long distances of natural gas or saturated steam in presence of a liquid phase is a common practice in the oil and the geothermal industry and can be extremely challenging when major flow assurance issues, such as corrosion or solid formation and deposition on pipe wall arise. In near-horizontal pipes, stratified flow conditions are encountered at moderate phase velocities. At increasing the gas velocity, only part of the liquid flows at the pipe wall, while the remaining liquid is entrained by the gas in the form of droplets which tend to deposit back onto the wall layer. The competing phenomena of droplet entrainment and deposition determine the liquid hold-up in the pipe and appreciably affect the pressure gradient. In large pipes

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the resulting flow pattern is usually classified as stratified-dispersed flow, while in smaller pipes as horizontal annular flow.

The critical flow parameter to be measured in stratified-dispersed flow is the flow rate and thickness distribution of the liquid layer flowing at pipe wall. This is because the split of the liquid phase determines the overall liquid hold-up in the pipe and the value of the frictional pressure losses. Besides to the fluid-dynamic issue, a better knowledge of the flow behavior of the wall layer has many implications in flow assurance studies. In particular, the effectiveness of the inhibitors usually adopted to prevent pipe corrosion depends on the formation of a liquid film around the pipe wall.

In stratified-dispersed flow, the flow field presents strong 3-D features. This makes difficult to describe this flow pattern in transient 1-D flow simulators, such as the model proposed by Bonizzi et al. (2009). In industrial applications, these simulators are widely adopted for flow assurance studies, but often their predictions are poor. The main objective of the present work is to develop a detailed model of stratified-dispersed flow. This model can then be coupled with a 1-D flow simulator and provide a complete picture of this flow pattern.

Stratified-dispersed or horizontal annular flow is more complicated than annular flow in a vertical pipe, due to the gravity force, which typically causes an asymmetrical liquid film distribution around the pipe circumference. For instance, Paras and Karabelas (1991) and Williams et al. (1996) observed significant gradients of the liquid film height in the circumferential direction and large vertical gradients of the droplet concentration. These authors used a sampling probe to measure droplet concentration and a conductance technique to measure the local film heights.

One of the pioneering investigations on horizontal annular flow has been carried out by Butterworth (1969), who measured the film thickness distribution of air/water flow in a 3.18 cm horizontal pipe with a conductance method. This author argued that five mechanisms may contribute to the asymmetrical film distribution:

- Gravitational drainage.
- Spreading of the film by wave motion.
- Liquid transfer because of atomization and deposition effects.
- Interfacial stresses due to the gas secondary flow.
- Surface tension effects.

At the end of his analysis, Butterworth concluded that the film thickness distribution was determined by a balance between the film drainage due to gravitational effects and the upward liquid movement associated with the lateral spreading of large disturbance waves.

A similar investigation was carried out by Lin et al. (1985) who analyzed the film distribution in a 2.69 cm I.D. pipe using a needle probe approach and performed a modelling analysis based on the fundamental conservation equations of mass and momentum written for the liquid film. These authors suggest a relevant effect of the term associated with the gas secondary flow.

Laurinat (1982) conducted an experimental study of air–water horizontal annular flow in a 5.08 cm I.D. pipe. In these experiments the liquid film height was measured at 7 different circumferential locations using conductivity probes. Laurinat et al. (1985) developed a 2-D model of liquid flow based on momentum conservation equations, where both normal and tangential stresses were considered. These authors found that a good agreement with the experimental data could be obtained by acting on the normal shear stress along the circumferential coordinate, while in their model the effect of gas secondary flow was negligible.

In both afore mentioned models, the direction of the gas secondary flows was modelled to be upwards, namely with flow directed downward along the vertical pipe diameter and upward at the walls. Nonetheless, it should be remarked that some controversy exists on the role of secondary gas flows in horizontal two-phase flows. For instance, Fisher and Pearce (1993) determined the liquid film distributions for horizontal annular flow in a 5 cm I.D. pipe and developed a model that neglected the secondary flow effect; yet they report a fair agreement between model predictions and the corresponding experimental measurements.

Secondary flows have been extensively investigated in the literature, and contradictory findings were published. The first detailed observations of turbulent secondary flows were made by Nikuradse (1930) and Prandtl (1927). The first used both flow visualization with a red dye and Pitot tube measurements to map the gas velocity profiles. The second suggested that the shape of the measured velocity contours implied the existence of secondary motion. According to Prandtl, turbulent velocity fluctuations exist tangent to the curved contours of constant mean axial velocity (i.e. isotach) surfaces, and these fluctuations increase with increased curvature of the isotachs. Hence, the resulting Reynolds stresses will generate forces on the convex side of the isotachs, which give rise to the secondary flows. According to this observation, considering the case of a gas–liquid flow in a circular pipe, a circumferential disturbance such as the asymmetric distribution of the liquid film (which would then lead to an asymmetrical interfacial roughness) might be sufficient in order to get secondary flows initiated under turbulent gas flow conditions.

As mentioned above, in a circular duct the gas secondary flow may be directed downwards along the vertical diameter or upwards. Darling and McManus (1969) conducted an experiment using a pipe with an eccentric thread, being deeper at the bottom than the top. In this way they could simulate the conditions of a non-uniform liquid film. Using hot-wire velocity measurements, they found that the gas velocity profile was skewed toward the bottom of the pipe. This indicates the presence of secondary flows directed downwards along the vertical diameter.

Similar observations were reported by Andreussi and Persen (1987) and by Vlachos et al. (2003). The latter authors adopted a Laser Doppler method to measure the time-averaged gas flow field in 5 cm and 2.4 cm pipes for gas–liquid stratified flow and confirmed the presence of secondary flows, directed downwards along the vertical diameter. It has to be remarked that the range of gas superficial velocities investigated by Vlachos et al. (2003) was below 12 m/s.

Dykhno et al. (1994) took detailed velocity measurements in air–water stratified/annular horizontal flows for a 9.5 cm pipe. Using Prandtl's interpretation of curved isotachs, they confirmed the existence of secondary flows. These authors were the first to identify conditions under which the direction of the secondary flows changed: while at lower gas velocities (typically <20 m/s) the motion of secondary flows was directed downward at the center, at higher gas velocities the secondary flows appeared to be directed upwards. Dykhno et al. (1994) argued that the atomization of the liquid film was responsible for the change in direction of the gas secondary flows.

Dallman (1978) investigated air–water annular flows in a 2.3 cm inner diameter pipe, and, from his measurements of local liquid film thickness, proposed to correlate the film height with a modified Martinelli flow parameter. Hurlburt and Newell (1997) proposed a simplified model for estimating the liquid film distribution, based on the Laurinat et al. (1985) derivation. These authors analyzed available experimental measurements of the liquid film heights for gas–liquid stratified/dispersed flows gathered by different researchers for horizontal pipes, and proposed a correlation for predicting the degree of asymmetry of the liquid film, based on a modified Froude number, which represents the square root of the ratio between the gas kinetic energy and the work required to pump the liquid from the bottom to the top of

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