STUDIES OF STRATIFIED/ATOMISATION GAS-LIQUID FLOW IN HORIZONTAL PIPES

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ABSTRACT

A synthesis of the work undertaken in our laboratory to systematically study stratified/atomisation flow is presented here. The main flow characteristics are outlined, based on detailed data on liquid film thickness, wave characteristics, pressure drop, axial liquid and gas velocity and liquid-to-wall shear stress obtained in horizontal pipelines with diameters of 50.8 and 24 mm. The gas/liquid interface is found to deviate (with increasing gas velocity) from the usually assumed flat profile. The liquid-to-wall shear stress tends to vary in the lateral direction. From the measured velocity profiles inside the gas phase, a secondary flow pattern is inferred with an upward motion at the pipe wall. By means of momentum balances, the average gas/liquid interfacial friction factor is determined. An equivalent gas/liquid interface roughness is expressed in terms of wave characteristics. For the purpose of examining the above findings and of improving our predictive capabilities, a simplified stratified flow problem was tackled by implementing a commercial CFD code (CFX®). The computed flow parameters are in qualitative (and in some cases quantitative) agreement with the ones obtained experimentally.

1. INTRODUCTION

Wavy stratified flow is readily established in the pipeline transportation of gas-rich two-phase mixtures. By increasing the gas flow rate (at a fixed liquid rate), the interaction between the fast moving gas and the liquid layer at the bottom causes droplet entrainment. Further increasing gas velocity leads to annular flow. Consequently, *stratified/atomisation* flow is an intermediate regime, between a separated and a dispersed/annular flow pattern, sharing some features with both of them. It is, therefore, considered advantageous to study stratified/atomisation flow as it may facilitate modelling over a rather broad range of conditions, aside from the fact that results of direct practical usefulness can be obtained. Experimental work in that direction has been carried out in this Laboratory in recent years; Paras and Karabelas [1] have reported local velocity data inside the liquid layer; Paras et al. [2] have presented detailed measurements of liquid layer thickness, including its wave characteristics; Vlachos et al. [3] have measured the liquid/wall shear stress distribution; Paras et al. [4] have reported local velocity profiles inside the gas phase. Similar measurements and observations in the gas phase have recently been presented by Dykhno et al. [5] and Flores et al. [6].

The rather detailed data obtained in these and in other related studies have provided considerable insight into the flow structure, and have helped develop improved, though relatively simple, computational procedures for making predictions of practical interest; e.g. [7, 8]. In the following, a brief overview of the detailed data is provided and the most interesting experimental findings are outlined. It is noted, however, that the complexity of the problem has not permitted so far verification of these findings, either by comparison of specific data with predictions from fundamentally sound flow calculations or through comprehensive simulations covering the entire flow field. A modest attempt in this direction is described in this paper by using a commercial Computational Fluid Dynamics code (CFX® 4.2). A model problem is solved by *a priori* specifying (from available data) the liquid layer thickness, the gas/liquid interface roughness and the pressure drop. All other flow properties are computed and compared with measurements. In the following sections experimental techniques and results are outlined.

2. MEASUREMENT TECHNIQUES

Measurements of time varying liquid film thickness, pressure drop, axial velocity, liquid-to-wall shear stress as well as visual observations have been carried out in horizontal pipelines with diameters 50.8 and 24 mm. Attention was paid to the lateral variation of liquid film properties, aiming at obtaining *local* values of the above hydrodynamic parameters. For this purpose, the measuring techniques included parallel-wire conductance probes, pressure transducers, Laser Doppler Anemometry (LDA), flush-mounted hot-film probes, and an electro-diffusion method, for measuring liquid-to-wall shear stress at various positions around the pipe circumference. The 50.8 mm i.d. flow loop was initially employed in the tests. In order to obtain information concerning the flow structure of the turbulently flowing liquid, Paras & Karabelas [1] made local (non-intrusive) LDA velocity measurements inside the *liquid layer* at the pipe bottom. Similar (LDA) techniques were recently used by Paras et al. [4] to measure the local velocity distribution in the *gas phase*. In another study, Paras et al. [2] obtained fairly complete sets of film thickness data and offered an improved picture of liquid layer characteristics, including the gas/liquid interface shape and friction factor. Limited shear stress measurements were also reported, using hot-film probes flush mounted at $\Theta=0^{o}$ and 45^{o} from the pipe bottom. Vlachos et al. [3] used a well-known electrochemical (or electro-diffusion) technique, with circular electrodes (0.5 mm dia) embedded in the pipe wall, for measuring liquid-to-wall shear stress at various positions around the circumference of a 24.0 mm i.d. pipe. For these measurements specially designed test sections were constructed to accommodate the measuring probes. For all the above experiments, pressure drop data were collected using sensitive differential pressure transducers, whereas visual observations were made with the aid of an angle gauge, for the determination of angle $\boldsymbol{\theta}$ over which the pipe walls are wetted by the continuous liquid phase.

3. SUMMARY OF EXPERIMENTAL RESULTS

3.1 The liquid layer

Statistical analysis of liquid film time records leads to the determination of local time-averaged thickness, RMS values as well as of other wave characteristics (wave characteristic frequency, height, amplitude and intermittency) useful in computing gas/liquid interface friction (e.g. [2], [3]). Visual studies of the gas/liquid interface confirm that its profile is concave. The area of the interface tends to increase with increasing gas velocity, and to deviate significantly from the flat (time-averaged) shape.

Another notable feature of the stratified/atomisation regime is the appearance of *disturbance waves*, travelling on the liquid surface, with a characteristic frequency (greater than 1 Hz) strongly dependent on U_G. Interpretation of film thickness data taken at $\Theta=0^{o}$ and 45^{o} suggests that these dominant waves may spread in the lateral direction, and that their celerity is almost linearly increasing with U_G. It is possible that such wave spreading may promote the concave (time-averaged) profile of the gas/liquid interface.

Using Laser Doppler Anemometry, measurements were made of the axial velocity component within the liquid layer [2]. Statistical analysis of such data provided useful information (i.e. time-averaged local velocity, RMS, distribution of turbulence intensity, power spectra) concerning the flow field. It is evident from this information that the flow in the layer is **turbulent**. Furthermore, the data show that only in the vicinity of the pipe surface (sublayer) does the liquid motion resemble the well-known behaviour of single-phase flow. Beyond that, the flow field is strongly influenced by the wavy gas/liquid interface and by the apparently intensive energy transfer from the fast moving gas to the liquid layer.

Measurements of local, instantaneous liquid-to-wall shear stress ([2], [3]) provide significant information for checking the consistency of other types of data and for facilitating modelling. An interesting result obtained here is that the time-averaged shear stress tends to decrease in the lateral direction (i.e. away from the pipe bottom, $\Theta=0^{o}$) along which the liquid film gradually becomes thinner. Only for relatively thick liquid layers, the mean shear stress is almost constant up to $\Theta\approx45^{o}$. Beyond that lateral position, shear stress tends to decrease as the film thickness decreases to reach, at the angle $\boldsymbol{\theta}$ of the triple-point (solid/gas/liquid), a value typical of the gas-to-wall shear stress. To aid design computations and modelling, a generalised expression was proposed for predicting the shear stress lateral distribution [3]:

$$\frac{\tau_{wL}(\Theta)}{\tau_{wG}} = 1 + \left(\frac{\tau_{wL0}}{\tau_{wG}} - 1\right)\left\{1 - \exp\left(-m\frac{\theta - \Theta}{\Theta}\right)\right\} \qquad (1)$$

where τ_{wL0} is the liquid-to-wall shear stress at the pipe bottom ($\Theta=0^{o}$); $\boldsymbol{\theta}$ is defined in Figure 1; m is a dimensionless parameter. The stress τ_{wG} is considered to be constant, over the tube perimeter in contact with the gas phase (P_G), and equal to the liquid-to-wall shear stress value at the angle $\boldsymbol{\theta}$. The parameter m in Eq. (1) was determined by usual regression methods and found to be strongly influenced by both gas and liquid superficial velocities, U_{GS} and U_{LS}.

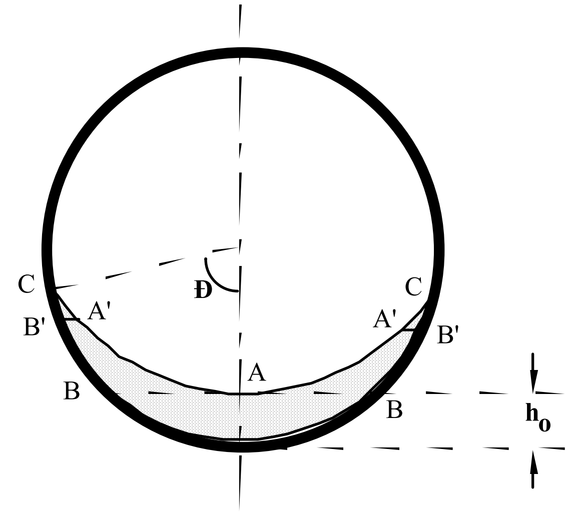

Figure 1. Schematic representation of horizontal gas/liquid stratified/atomisation flow.

3.2 The gas flow field

Time-averaged local velocities, RMS values and other statistical information are obtained by analysing the instantaneous gas velocity records [4]. From the measured velocity profiles inside the gas core, a secondary flow pattern is inferred with an upward motion at the pipe wall and a downward motion at the vertical pipe centreline. The velocity measurements are assessed in connection with the aforementioned data of liquid layer characteristics and wall shear stress, obtained under the same flow conditions, and found to be consistent. According to Paras et al. [4], well-known forms of the turbulent velocity profile seem to be quite satisfactory for correlating the data, not only at the pipe top but also in the lower strata of gas phase if the equivalent roughness of the wavy interface, calculated from wave characteristics (outlined below), is properly taken into account. The basic features of single phase pipe flow seem to be preserved at the upper part of the pipe, as shown in typical PSD curves and distribution of velocity intensities in the radial direction.

The influence of large liquid waves is quite significant near the gas/liquid interface, as expected. An interesting finding of this work (obtained from the velocity spectra) is that the influence of large waves may extend up to the pipe top, probably through the secondary motion in the gas core.

3.3 The gas/liquid interface

Data on significant wave characteristics such as height, h_w, amplitude, dH, and intermittency, I, were utilised to compute the average gas/liquid interfacial friction factor, f_i. These data are expected to be useful in future modelling of f_i and of liquid atomisation. By means of momentum balances, Vlachos et al. [3] employed averaged liquid-to-wall shear stress data (obtained from measured local values around the wetted portion of the pipe circumference) and complemented them with data on liquid film thickness, wave properties and pressure drop measurements, to propose the following correlation for the interfacial friction factor:

$$f_i = 0.024 \varepsilon_L^{0.35} Re_L^{0.18} \qquad (2)$$

where ε_L is the liquid holdup and Re_L the liquid Reynolds number, based on the superficial velocity and pipe diameter.

For these calculations, the gas/liquid interface is considered to be concave, which is verified by visual studies and film thickness measurements. Additionally, an equivalent gas/liquid interface roughness (k_s) is expressed in terms of wave characteristics:

$$\frac{k_s}{D} = 2.85 \left(\frac{dH}{D}\right) I^{0.17} \qquad (3)$$

It is noted ([2], [3]) that the ratio of wave amplitude dH over mean thickness at the bottom is roughly $(dH/h_o) \approx 1.05$ and that the intermittency values from these tests vary in the range 0.05 to 0.35. To obtain rough estimates from Eq.(3) one may select an intermediate value $I^{0.17} = (0.2)^{0.17} \approx 0.75$ leading to

$$k_s \approx 2.3 h_o \qquad (4)$$

It will be pointed out that Hart et al. [7] propose a similar expression for estimating k_s i.e., $k_s = 2.3\delta$ where δ in their notation is an average liquid film thickness, not necessarily equal to the thickness h_o employed in Eq. (4). It is noted, that information on liquid surface roughness will be employed in the subsequent flow simulation.

4. THE USE OF A CFD CODE

Using CFD techniques, it is possible to simulate gas-liquid stratified flow in order to elucidate the effect of the interfacial waves on the flow field and to examine/verify, at least qualitatively, the main experimental findings already outlined. Ideally, in two-phase flow a CFD code would calculate the flow fields of both phases and the interfacial structure, starting only with the inlet flows and the geometry of the conduit. However, this seems to be beyond the capabilities of existing software. A procedure followed so far (e.g. [9]) is to construct two individual "conduits" using the observed time-averaged interfacial shape as the "separating wall" and to calculate the gas and liquid flow fields separately. At the interface continuity is assumed and therefore each local flow parameter must attain the same value along it. Furthermore, the grid of each phase must be constructed by making use of this assumption.

As already mentioned, the time-averaged profile of the gas-liquid interface was found experimentally to be concave rather than flat. However, this poses a great difficulty to the construction of the liquid phase grid in the narrow strip A'CB' (Figure 1). Consequently, in this study a flat interface is assumed and the liquid phase "conduit" is constructed using the experimentally obtained mean liquid film height at $\Theta=0^o$. The effect of the liquid waves on the gas phase is taken into account by applying throughout the interface a local equivalent roughness (2.3 times the corresponding liquid film thickness, as one can conclude from Eq. (4)). It should be pointed out that the liquid film climbing along the pipe side walls is intermittently immobile (with respect to air flow), very thin, and tends to diminish circumferentially. Nevertheless, its effect on the prediction of the gas flow field should be taken into consideration by assuming a small roughness on that wetted portion of the pipe wall.

In these calculations, the flow is considered to be fully developed. The gas phase is calculated with a no-slip boundary condition at the solid wall and a specified velocity at the interface. A no-slip boundary condition is also assumed for the liquid phase wall but a specified shear stress is applied at the interface. In the calculation of the liquid phase the turbulence is taken into account by using the low Reynolds Number k-ε model [10]. For the gas phase calculations (where a secondary flow is expected) the Reynolds stress model is considered more suitable, since the standard k-ε model does not predict any secondary flow [11].

In stratified flow the axial pressure gradient must be the same for both phases and consequently an experimentally obtained pressure drop is applied as a boundary condition. Hence, by first assuming a zero velocity at the gas-phase "interfacial wall" a shear stress is calculated, which is in turn fed as initial condition to the liquid phase in order to predict a new velocity. This procedure is continued until convergence is achieved with respect to the shear stress and velocity at the interface.

5. RESULTS OF CFD SIMULATION

The results obtained by employing the CFX® code were checked against experimental data. The simulation was carried out using as a basis the data from runs A1 and B1 ([2]). Experimental conditions and some flow parameters are summarised in Table 1. U_{LS} and U_{GS} are the superficial liquid and gas velocities, respectively.

Table 1. Summary of experimental conditions and results [2].

run	**U_{LS}** m/s	**U_{GS}** m/s	**h_o** 10^{-3}m	**q_L** Kg/s	**q_G** Kg/s	**dp/dx** N/m^3
A1	0.10	11.9	7.60	0.20	0.029	140
B1	0.08	11.9	6.50	0.16	0.029	125

The distribution of the axial **gas** velocity on the vertical symmetry plane is shown in Figures 2a and 2b, for runs A1 and B1, respectively. The computed maximum velocity is shifted slightly upwards, whereas the velocity gradient near the gas-liquid interface is found to be less steep than that near the smooth top wall. This is attributed to the larger equivalent roughness at the interface which causes a higher shear stress. Thus, the maximum velocity of the gas phase is located in a region further away from the wavy interface and closer to the top pipe wall. Figure 2 shows that these results are in fairly good agreement with the experimental data of Paras et al. [4].

Typical axial velocity profiles, at 90^o to the vertical (at various distances y from the top pipe wall), shown in Figure 3, clearly exhibit a "moustache" shape, with a local minimum at the pipe center and two (symmetrically spaced) maxima. A similar shape was obtained by Dykhno et al. [5] and Paras et al. [4] for velocity measurements at 90° to the vertical. The observed type of velocity profiles (both on the vertical symmetry plane and at 90° to the vertical) was attributed [4] to secondary flow, with downward motion at the vertical symmetry plane and an upward flow at the pipe wall. Such a secondary current is probably generated by the non-uniform liquid film roughness (e.g. [5], [11]). Additionally, from the distortion of the isotachs one can draw the conclusion that a secondary pattern exists inside the gas phase. It is noted, that the computed results of Figure 3 display only qualitative agreement with the measurements. In fact, in the simulation results, the distortion (due to secondary flow) is smaller than that displayed by the data.

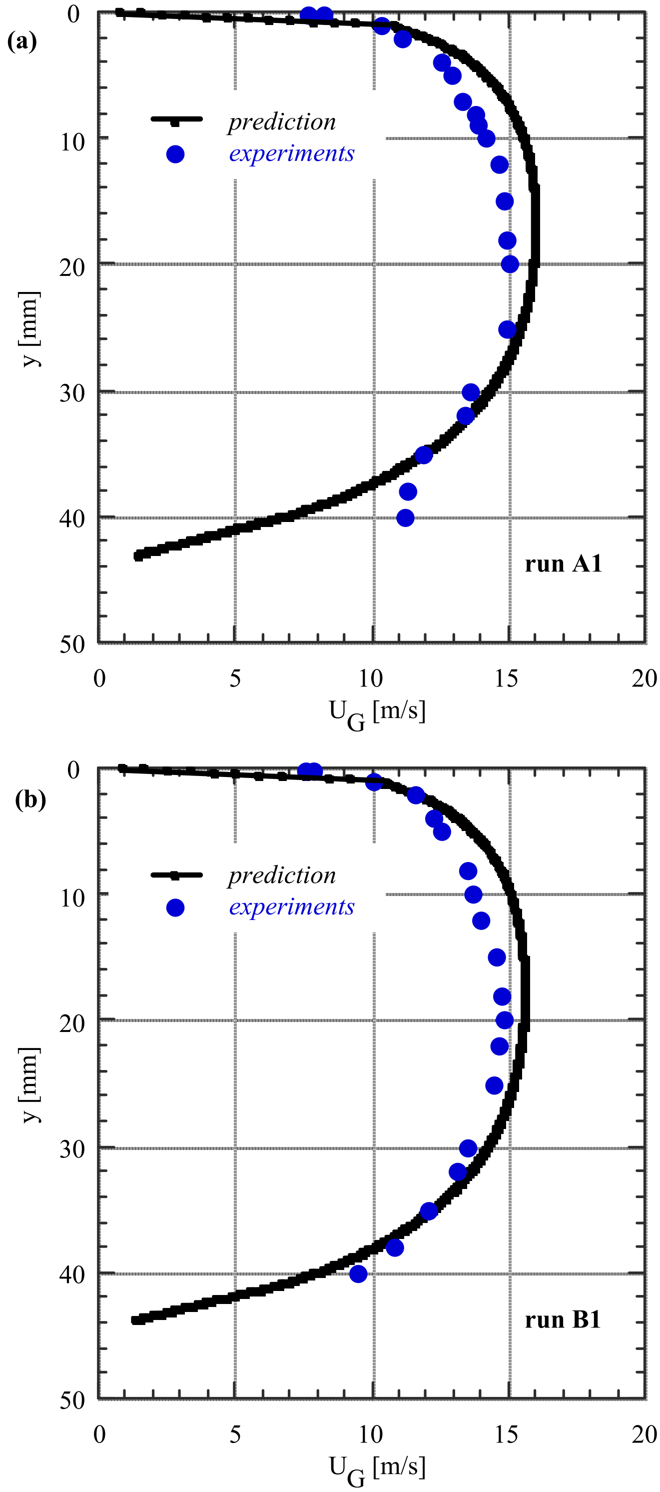

Figure 2. Gas axial velocity profile along the vertical diameter. Comparison of data [4] with results of simulation: (a) run A1 and (b) run B1 (coordinate y corresponds to the vertical distance from top pipe wall).

For the **liquid** phase, the maximum velocity is located at the gas/liquid interface. The computed axial velocity profiles, as shown in Figure 4, are S-shaped. Hewitt et al. [12], made observations of the velocity profile using a photochromic dye tracing technique. They reported two types of velocity profiles; i.e. the distorted S-shaped profile prevailing in film flows subjected to interfacial shear without waves and the parabolic type occurring during the passage of a wave. Since in our experiments the interface was wavy, one would expect that the time averaged axial velocity profile is apparently influenced by the presence of large waves at the gas/liquid interface. The results of the simulation compare favourably with experimental data obtained with LDA techniques by Paras and Karabelas [1]. It will be noted that it is not feasible to obtain LDA measurements close to the randomly varying (wavy) gas/liquid interface.

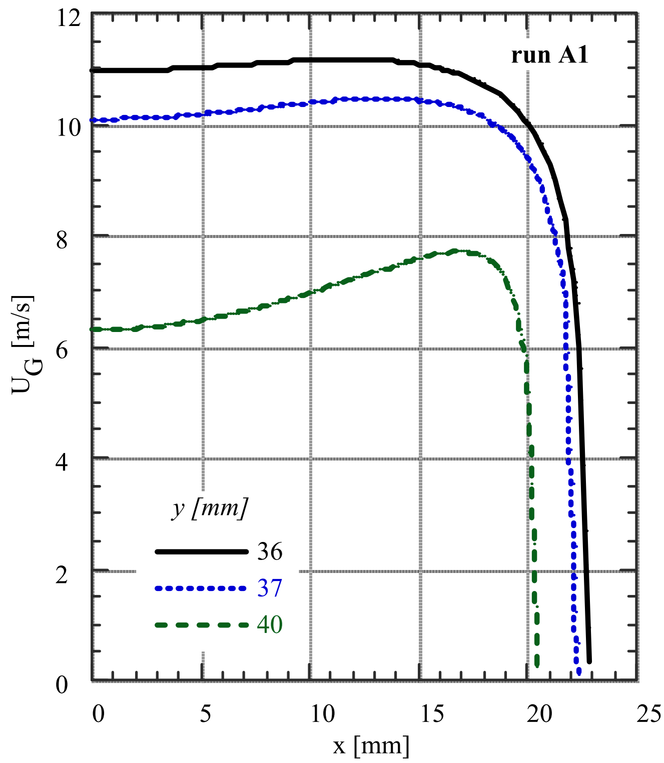

Figure 3. Gas axial velocity profile, at 90° to the vertical. Coordinate y corresponds to the vertical distance from the top pipe wall, whereas x corresponds to the horizontal distance from one side of the pipe inner wall.

The **liquid-to-wall shear stress** circumferential distribution calculated by CFX® (for both runs A1, B1) is depicted in Figure 5. This figure shows that the time-averaged shear stress is roughly constant in a flow region where there is a relatively thick liquid layer. Beyond that region, shear stress tends to decrease in the lateral direction along which the liquid film gradually becomes thinner. These simulation results tend to verify the measured stress distributions reported elsewhere (e.g. [2], [3]) and correlated with Eq. (1). A quite similar trend is shown in Figure 6 obtained by Paras et al. [2]. Unfortunately, a direct comparison between the results in Figures 5 and 6 cannot be made since in the computations

(Figure 5) the assumption of the flat gas/liquid interface was employed. The latter limits the liquid phase up to only 45° and ignores the proven fact that a continuous liquid film, though very thin, could climb up to 90° or more. With regard to the interfacial shear stress distribution (τ_i), as predicted by the CFX® code, it is observed that qualitatively it follows the corresponding τ_{wL} distribution. The lateral distribution of τ_i is shown in Figure 7. To the authors best knowledge there is no similar work reported in the literature for making direct comparisons.

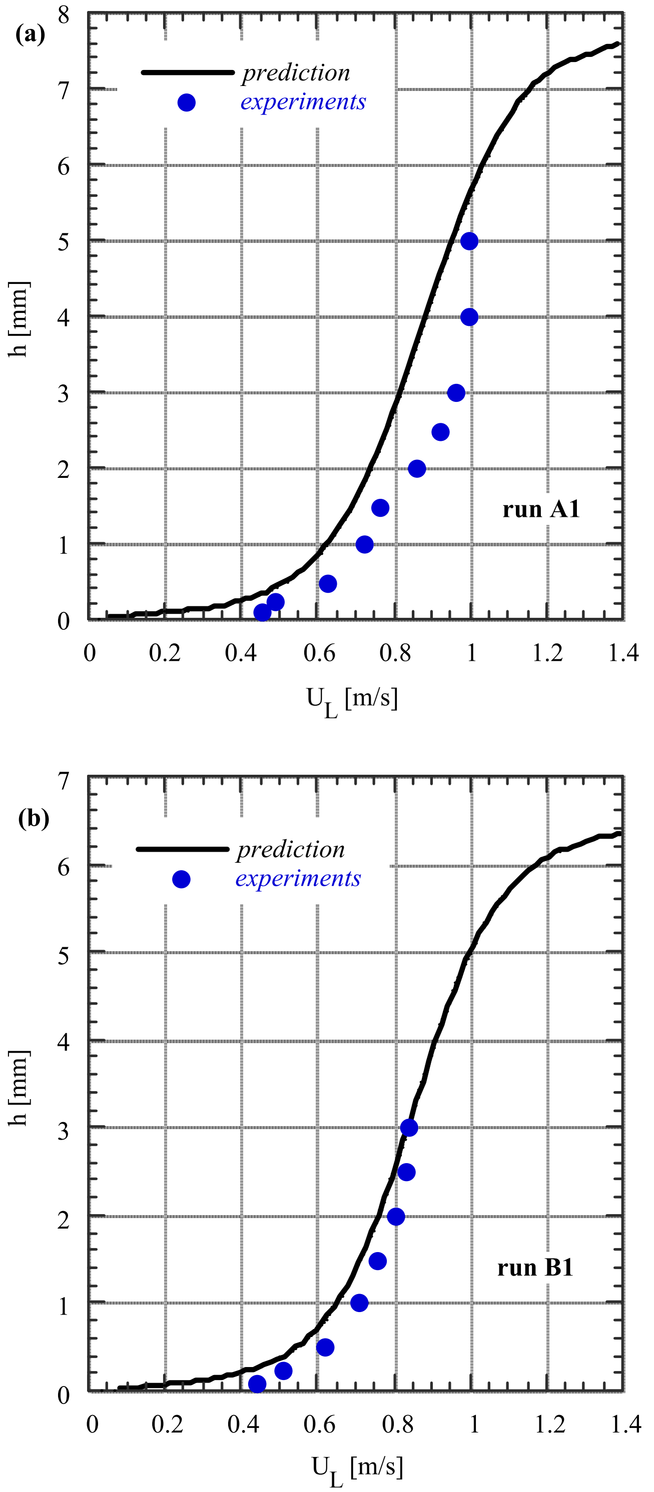

Figure 4. Liquid velocity profile along the vertical diameter. Comparison of data [1] with results of simulation: (a) run A1 and (b) run B1 (h corresponds to the vertical distance from the bottom pipe wall).

The assumption of a flat gas-liquid interface, by ignoring the areas ABC (shown in Figure 1) which were actually covered by the liquid, was estimated to reduce the real area occupied by the liquid phase by approx. 20%. This trend, combined with the fact that the liquid droplets (entrained in the gas phase) are not taken into consideration in the calculations, provides an explanation for the relatively large deviation (25%) between the calculated (by the CFD code) and the actual liquid mass flowrate. With regard to the gas flowrate, the observed deviation is negligible (less than 3%), since the void fraction is quite large and (in our case) attains values of 90% or greater of the total pipe cross-section. Therefore, the overprediction of the gas space due to the assumption that the areas ABC are covered by the gas and not by the liquid film (as it actually happens) is relatively small.

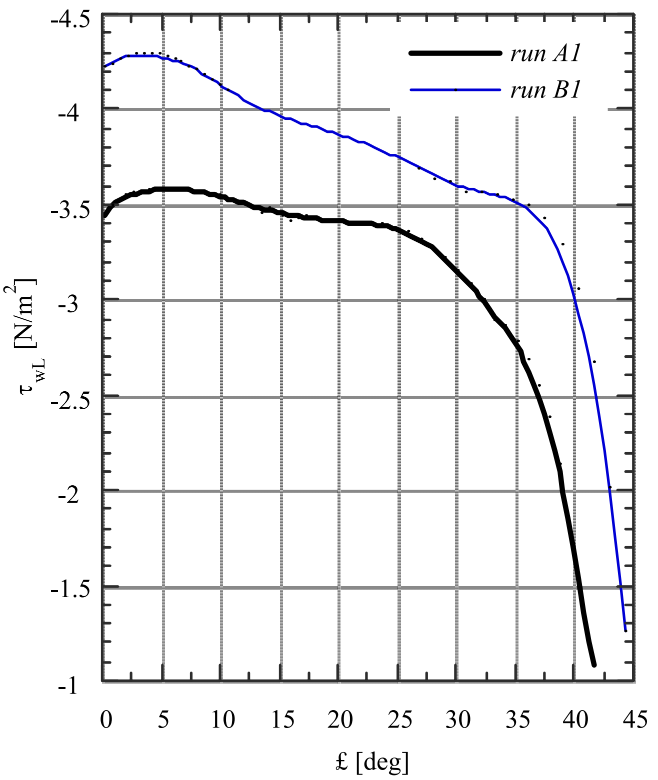

Figure 5. Predictions of liquid-to-wall shear stress circumferential distribution.

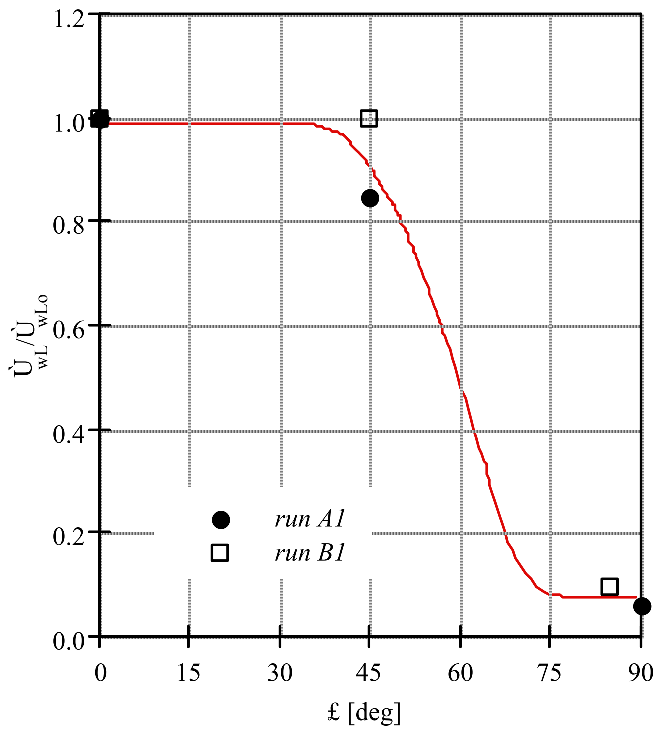

Figure 6. Circumferential distribution of τ_{wL} with respect to its value at Θ=0° [2].

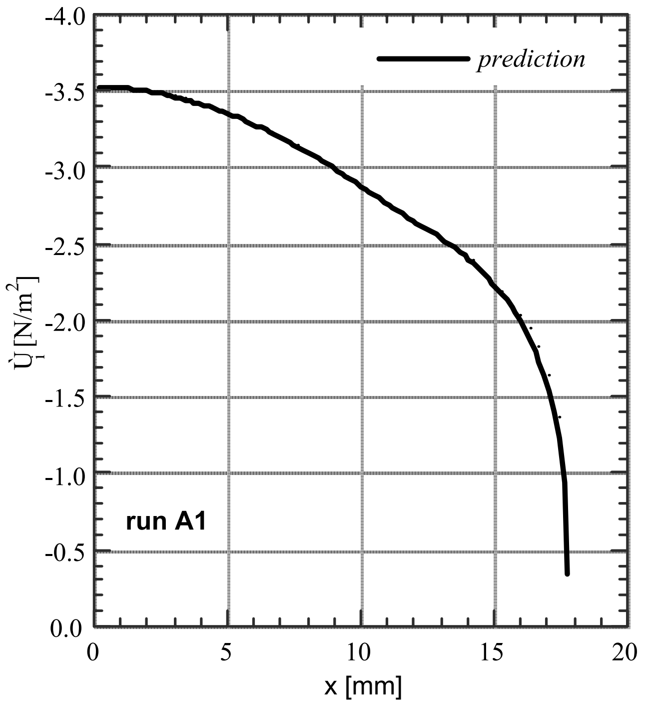

Figure 7. Prediction of interfacial shear stress distribution in the lateral direction. Coordinate x corresponds to the horizontal distance from one side of the pipe inner wall.

6. CONCLUDING REMARKS

The flow field in stratified/atomisation flow is asymmetric due to the liquid layer with a wavy surface. The results of flow simulations (using a ‘static’ liquid surface roughness) suggest that these purely geometric features may be responsible, to a large extend, for the gross flow development in both phases. Indeed, the (main) axial velocity distributions and wall shear stresses appear to be fairly well predicted if realistic estimates of the cross-sectional area of each phase and of gas liquid interface roughness are available. Even secondary motion in the gas phase (though fairly weak compared to measurements) is predicted under these conditions.

Although the simulation case treated here was by necessity simplified, it nevertheless allowed to confirm the validity of the main experimental results obtained so far. Furthermore, by gaining confidence in this type of flow simulation, and with additional development work, it may be possible to tackle the same type of problem (with a CFD code) for **large** diameter pipelines; that is, to use the simulation code as a scale up tool.

It should be stressed that the important issue of dynamic interaction between the two phases (along their interface), involving wave generation, and propagation, was essentially untouched here. This of course requires much more work.

7. NOMENCLATURE

D = pipe diameter
dH = wave amplitude
dp/dx = pressure drop
f = friction factor
h = film thickness or vertical distance from the bottom pipe wall
h_W = wave height
I = wave intermittency
k_s = equivalent gas/liquid interface roughness
m = dimensionless parameter in the Eq. (1)
q = mass flow rate
P_G = part of tube circumference in contact with the gas phase
Re = Reynolds number
U = velocity
y = vertical distance from the top pipe wall
x = horizontal distance from one side of the pipe inner wall

Greek Letters
δ = average liquid film thickness [7]
ε_L = liquid holdup
Θ = angle in the lateral direction
$\boldsymbol{\theta}$ = angle defined in Figure 1
τ = shear stress

Subscript
G = gas phase
i = gas/liquid interface
L = liquid phase
o = at the pipe bottom (Θ=0°)
S = superficial velocity
w = wall

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