Effect of Fluid Properties on Flow Patterns in Two-Phase Gas−Liquid Flow in Horizontal and Downward Pipes†

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This paper investigates the effect of gas density and surface tension on flow pattern transitions in horizontal and near-horizontal pipes. Experiments were conducted at atmospheric conditions in a 12.75-m long pipe with a diameter of 0.024 m and downwardly pipe inclinations of 0°, 0.25°, and 1°. The effect of gas density was examined using CO_2 and He gases and the effect of surface tension was examined using aqueous solutions of normal butanol. The various transitions were identified visually and by statistical analysis of film height measurements. Gas density strongly affects the transition to 2-D and K−H waves, whereas the transition from stratified to slug flow remains rather unchanged. Both wave transitions can be described satisfactorily by existing models in the literature with some modifications. A reduction in surface tension causes the transitions to 2-D waves to be shifted to much lower gas rates. For downward flows, as previously reported in the literature, even a small inclination can cause an expansion of the stratified flow regime. In this regime two different types of waves can be identified, which retain the 2-D and K−H wave characteristics observed in horizontal flow.

1. Introduction

The prediction of flow characteristics (e.g., pressure drop and liquid holdup) in two-phase gas−liquid flow in pipes is of particular interest to the petroleum, chemical, and nuclear industries. These flow characteristics are strongly dependent on the flow pattern that prevails in the pipe. The occurrence of a specific flow pattern depends upon many parameters, such as the flow rates, the physical properties of the two phases, and the geometrical characteristics of the pipe (shape, equivalent diameter, inclination angle, etc.). In general, the transition from one flow pattern to another is not abrupt, except for the transition to intermittent from stratified flow at low gas velocities.

Flow regimes in horizontal or near-horizontal pipes are usually more complicated than those encountered in vertical flow as a result of the influence of gravity. In this study, the following flow regimes (or subregimes) are recognized:[1−5]

- A stratified smooth region, occurring at very low gas and liquid velocities where the interface is smooth. It is only observed in horizontal and very slightly downward flows.
- A two-dimensional (2-D) wave region, where the interface is covered by regular, small amplitude waves. In horizontal flows they result from pressure variations in phase with the wave slope. These waves increase in amplitude and in wavelength as they propagate downstream. Liquid viscosity considerably affects the initiation of these waves by shifting the transition toward higher gas velocities.[1]
- A Kelvin−Helmholtz (K−H) wave region with large-amplitude irregular waves, also known as roll wave or as large-amplitude wave region. These waves are associated with pressure variations in phase with the wave height (K−H instability). The same mechanism is also considered responsible for the formation of slugs in medium and high viscosity liquids.[6,7] A summary of the theoretical tools used to explain the initiation of various types of waves in horizontal flow is given by Hanratty.[8]
- An atomization region, where droplets or liquid filaments are torn off from the crests of the K−H waves and deposited on the pipe wall. In addition, the liquid starts to climb up the wall of the pipe and the average shape 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. All the above subregimes are usually termed as stratified flow.
- An annular flow regime, in which the gas flows in the center of the pipe, and the liquid flows as a thin film that covers the entire circumference of the pipe. Annular flow is generated at extremely high gas velocities.
- A slug flow regime, which forms at high liquid rates and is characterized by the intermittent appearance of packets of liquid which bridge the entire pipe-section and move almost at the gas velocity. No distinction is made in this paper between slug and plug flow.
- A pseudoslug region, also called slug-froth regime, which visually looks like slug flow. A liquid film covers the top of the pipe, while most of the liquid, in the form of liquid frothy surges, moves at the bottom of the pipe.

The effect of fluid properties on two-phase flow phenomena has been studied by a number of investigators over the past 50 years. Probably the fluid property that has been most systematically examined is liquid viscosity. One of the first works on the effect of fluid properties on two-phase flow in horizontal pipes was carried out by Hoogerdorn,[9] who used air−water and air−oil mixtures in horizontal pipes with diameters ranging from 0.024 to 0.140 m. He concluded that liquid viscosity and pipe diameter did not significantly affect the transitions between

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† This paper is dedicated to Professors Tassos Karabelas and Stavros Nychas, on the occasion of their retirement from the University, to honor their many contributions to the chemical engineering community in Greece. We wish Tassos and Stavros many more productive and enjoyable years.

10.1021/ie100239v

flow regimes. The effect of gas density was studied in a subsequent work,[10] using superheated Freon-11 as gas phase. It was found that an increase in gas density does not affect the transition to slug or plug flow, but decreases significantly the onset of atomization. Hanratty and Hershman[11] investigated the effect of physical properties on the initiation of roll waves in a horizontal channel. An increase in liquid viscosity decreases slightly the gas velocity required for transition to roll waves, whereas the addition of a surfactant (sodium lauryl sulfate) dampened surface disturbances.

The effect of physical properties in horizontal pipelines was also examined by Weisman et al.[12] The flow maps with glycerol−water solutions showed little change from the maps obtained with the air−water system. The same trend was observed with the use of a surface active agent (Aliquat 221), with the only difference being that the smooth−wavy transition was reported to occur at much higher gas rates. The gas density was varied in experiments with boiling Freon-113 at pressures 1 and 4 bar, but the effect of the density itself is obscure, as liquid viscosity and surface tension were simultaneously drastically reduced with respect to the air−water case.

A systematic experimental investigation of the effect of liquid viscosity (in the range 1−80 mPa s) on flow characteristics was carried out by Andritsos and Hanratty[1] and Andritsos et al.[6] It was found that with increasing liquid viscosity a lower liquid throughput is required for the slug transition at low gas velocities. In addition, the region with two-dimensional waves shrinks with increasing viscosity, whereas the transition to roll (or Kelvin−Helmholtz waves) is only slightly affected.

The effect of a surface active agent on flow characteristics was further investigated by Hart et al.[13] and Hand et al.[14] who provided conflicting evidence. More specifically, the former investigators concentrated at small liquid holdups and found no effect on the holdup of the surface active agent Tween 80, but a slight increase in pressure drop. They attributed the latter to an expected increase in waviness due to lower surface tension. On the contrary, Hand et al.[14] used a 0.1% (w/w) aqueous solution of Chemtreat 271 to reduce the surface tension of the system and found a weak decreasing effect on pressure drop and an increase in liquid holdup. Also, the transition from smooth to wavy stratified flow occurred at greater air velocities, an observation attributed to the dampening effect of surfactants, while the transition to roll waves was unaffected by the addition of the surfactant.

Gas−liquid flow in inclined pipes has been studied by a number of investigators. Begs and Brill[15] observed that inclination angle significantly affects liquid holdup and pressure drop. Barnea et al.[3] reported that in downflow the stratified region is considerably expanded as the angle of inclination increases and higher liquid flow rates are required for the transition to intermittent flow. Conversely, upward inclination results in the expansion of intermittent flow region and stratified flow shrinks in a small bell-shaped region. Moreover, stratified flow is not observed at angles larger than 10°. Experimental investigations with downward inclinations were also carried out by Kokal and Stanislav[4] and Grolman et al.[16] Woods et al.[17] investigated experimentally the transition to intermittent flow in downward inclined pipes. They observed that the large amplitude small wavelength waves, which appear in horizontal flows at the transition to slug flow, are damped in pipelines that are inclined slightly downward. Recently, Paras and co-workers[18−20] systematically investigated the influence of surfactants on the interfacial structure and on the transition from the smooth to the wavy stratified flow regime in slightly inclined pipes. First, it has been suggested that the transition from a smooth to a wavy interface in a downflow can be related to the transition from laminar to turbulent flow inside the liquid layer. Second, the addition of small amounts of a nonionic surfactant strongly influences both the interfacial characteristics (e.g., damping of the small-amplitude waves) and the flow field within the liquid layer, resulting in a significantly lower pressure drop. Furthermore, the presence of surfactants affects almost all the transitions to the various flow regimes; i.e., the pseudoslug region appears to be shifted to higher liquid flow rates than those observed for tap water, whereas the atomization flow regime becomes narrower.

From the previous brief literature review it becomes clear that, despite the amount of data accumulated in the last decades, important questions still remain open about the effects of specific fluid properties on the flow regimes. First, the effect of gas density appears to have received very little attention. Second, the effect of surface tension has been examined mainly by the addition of a variety of surfactants. However, apart from reducing surface tension, surfactants modify the surface properties by introducing surface elasticity and surface viscosity, expressed respectively as the real and imaginary component of a complex surface dilational modulus (e.g., Lucassen−Reynders and Lucassen[21] and Lucassen[22]). The two modifications, i.e., reduction in surface tension and introduction of surface elasticity are expected to have a competing effect on interfacial disturbances, the former aggravating and the latter damping them.

This study aims at investigating the effect of gas density and surface tension on flow pattern transitions in horizontal and near-horizontal downward pipes. The fluids chosen for the experiments were selected in such a way as to allow changes in one property without considerably affecting other properties. The effect of gas density is examined using CO_2 and He gases. The effect of surface tension is systematically investigated using an aqueous solution of normal butanol (σ = 35 mN/m) as liquid phase.

2. Experimental Facility and Techniques

Experiments were carried out in a smooth, transparent Plexiglas pipe with an internal diameter of 24 mm and a total length of 12.35 m. A schematic of the experimental setup is shown in Figure 1. The carefully leveled pipe is placed on a steel frame that can be inclined slightly, up to ±3°.

Tap water and an aqueous solution of *n*-butanol (with a surface tension of 35 mN/m) were used as working liquid phases, whereas air, helium, and carbon dioxide were used as working gas phases. The main physical properties of the fluids at 20 °C and 1 atm are presented in Table 1. The Wilhelmy plate technique was used to measure the surface tension of the working liquids. The density of the butanol solution was measured with a buoyancy-type densitometer and its viscosity was measured with a glass capillary viscometer. The properties of the gases were taken from the literature. The liquid and gas phases were introduced into the pipe with a Y-shaped section, with liquid flowing in the lower branch. The two-phase mixture was emptied in a plastic separator open to the atmosphere. Liquid phase was usually circulated through the system in a closed loop using a centrifugal pump. Filtered air was supplied from a building service reciprocating compressor (AIRCO M529, 4 hp). Commercial-type carbon dioxide was supplied by a bank of CO_2 cylinders linked together in a group of 9 (Air Liquide), which then emptied in the flow system as if they were a single container. The inlet temperature was controlled by a resistance heater to compensate for expansion cooling. Com-

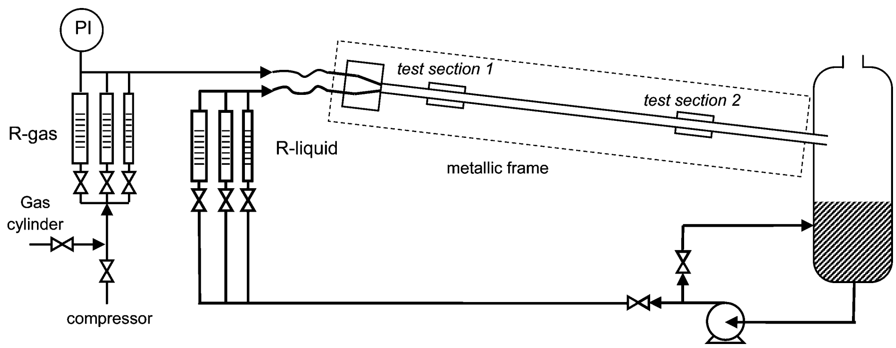

Figure 1. Schematic of the experimental apparatus.

Table 1. Physical Properties of Fluids Used in This Work at 20 °C and 1 atm

system	ρ_L (kg/m^3)	μ_L (mP·s)	ρ_G (kg/m^3)	μ_G (mP·s)	σ (mN/m)
air−water	998	1.002	1.204	0.0183	72
aqueous solution of *n*-butanol (∼3.5% w/w)−air	995	1.230	1.204	0.0183	35
water−CO_2	998	1.002	1.842	0.0148	70(23)[a]
water−He	998	1.002	0.167	0.0194	72(23)[a]

[a] At 25 °C.

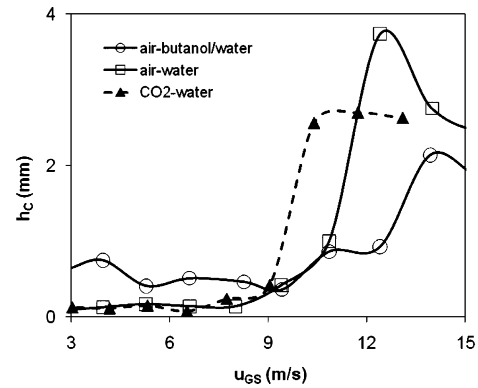

Figure 2. Wave amplitude with increasing superficial gas velocity at $\varphi = 1°$ ($u_{LS} = 0.01$ m/s).

mercial He was supplied from individual cylinders (Air Liquide). The volumetric flow rates of both phases were measured with a bank of three rotamerers for each phase, with an accuracy better than ±3%. The gas rotameters were calibrated using a Ritter BG 40 gas meter (minimum flow rate 0.4 m^3/h and maximum flow rate 65 m^3/h) for the three gas phases examined. The liquid rotameters were calibrated volumetrically.

The liquid height and the wave velocity were measured at two locations in the pipeline (at 88 and 336 pipe diameters from the inlet) using pairs of parallel wire conductance probes that extended in the vertical direction over the entire cross section of the pipe. The wires were 0.4 mm diameter chromel and their separation was 3 mm. An oscillating signal was sent to the probes and an analyzer converted the response to an analogue signal. A HAMEG HM 8030 5-MHz function generator was used to provide the input sine signal at a frequency of 25 kHz. A demodulation circuit provided the peaks of the output signal synchronously using the square wave output of the function generator as a reference. The output voltage was found to vary linearly with the conductance only at very high resistances ($R > 50,000$ Ohm). The electrical conductivity of the liquid phase was often measured during a run day to account for minor changes of the liquid temperature. The accuracy of the liquid height measurements is estimated to be ±3% or better. The film thickness data were usually collected for 60 s with a sampling frequency of 200 Hz.

3. Effect of Fluid Properties in Horizontal Flow

3.1. Effect of Gas Density. It has long been known that the primary parameters affecting the occurrence of a flow pattern in two-phase flow (at a certain pipe inclination) are the flow rates, although fluid properties and pipe diameter play also an important role. The present study investigates the effect of gas density and surface tension in horizontal and slightly inclined pipes. Emphasis is placed on the transitions within the stratified flow regime, and on the interpretation of the observations in terms of destabilization and restoring mechanisms.

Data on flow patterns and especially on stratified-flow subregions are obtained from visual observations, with the help of a high-speed camera and coupled by statistical analysis of film thickness recordings. The criterion to discriminate between slugs and pseudoslugs is that the velocity of the frothy liquid "packets" (pseudoslugs) is less than 75% of the actual gas velocity based on an average liquid thickness. The initiation of atomization region is defined as the gas velocity at which droplets first hit the top of the pipe, although the process of atomization is usually initiated at much lower gas rates.

Discrimination between the two types of waves observed in stratified flow, i.e., 2-D and K−H waves, is also done visually, based on a clear difference in shape, height, and regularity. To further document these differences, Figure 2 presents measured wave amplitudes in the stratified flow regime as a function of superficial gas velocity at an inclination angle of 1°. The abrupt increase in wave amplitude over a small range of gas velocities provides an objective criterion to discriminate between 2-D and K−H waves. Also, as suggested by Andritsos,[2] autocorrelation and cross-correlation functions can serve to discriminate between the periodic and mostly uniform 2-D waves and the K−H waves characterized by randomness, as shown in Figure 3 for the CO_2−water system.

The effect of gas density on the flow pattern in horizontal flow in a 0.024-m pipe is depicted in Figure 4a and b, which present the flow maps for the systems CO_2−water and He−water, respectively. For comparison, the transitions observed for the air−water system are also shown in the maps. A decrease of the gas density results in a considerable increase of the gas velocity required for transition to 2-D and K−H waves, at a constant liquid velocity. Obviously, due to the much greater difference between the densities of helium and air, the deviations of the transitions in Figure 4b are more distinct that those in Figure 4a. Since the process of atomization and the onset of annular flow are directly related to the evolution of large-amplitude waves, the transitions to atomization flow and to

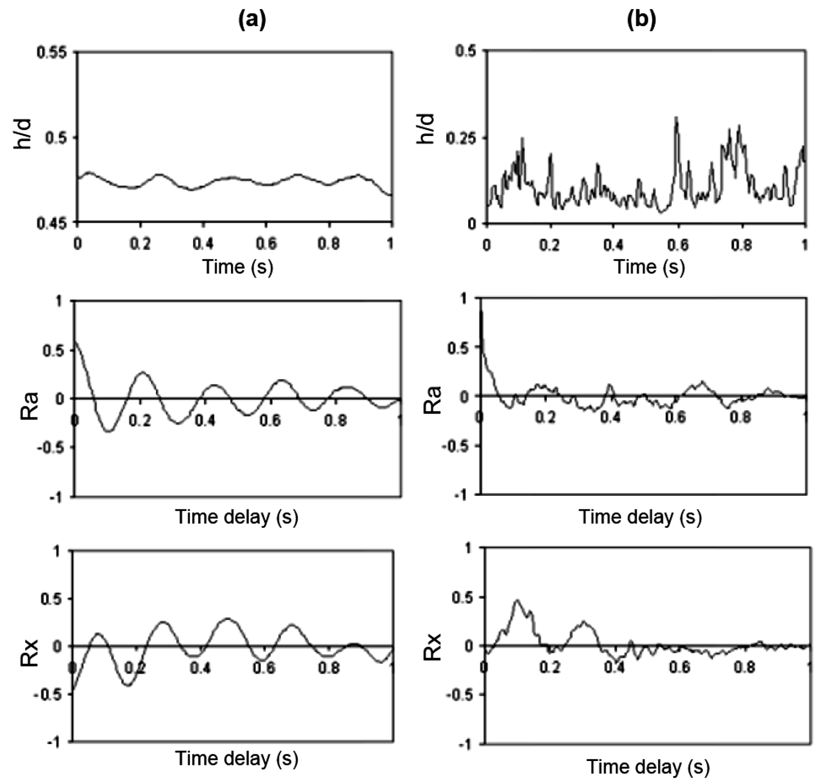

Figure 3. Film thickness tracings, autocorrelation and cross-correlation functions for the CO_2−water system and for and u_{LS} = 0.05 m/s. (a) Typical 2-D wave, u_{GS} = 1.7 m/s. (b) Typical K−H wave, u_{GS} = 9.12 m/s.

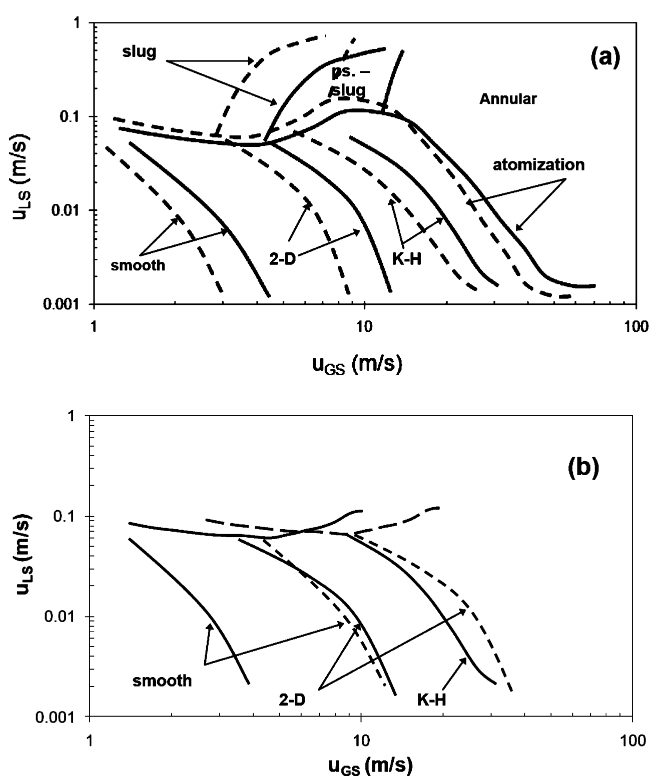

Figure 4. Comparison between air−water (continuous lines) and (a) CO_2−water flow maps (dashed lines) and (b) He−water flow maps (dashed lines).

annular flow are also affected significantly. A similar conclusion can be reached for the transition between slug and pseudoslug. It is reminded that the pseudoslug regime is encountered mostly in small diameter pipes and for low viscosity liquids.[1,6]

The observed strong dependence of the above transitions on gas density is interpreted as a confirmation that gas momentum, fed to the liquid phase, constitutes in all cases the main destabilization mechanism. In this respect, it is interesting to note in Figure 4a that the transition from stratified to slug flow appears to be rather insensitive to changes in gas density at low gas superficial velocities. This behavior agrees with an interpretation of the stratified-slug transition by the viscous Kelvin−Helmholtz analysis,[24−26,7] which predicts a significant destabilizing effect of liquid inertia. Thus, it is argued that the stratified-slug transition in Figure 4a is dominated by the destabilizing effect of liquid inertia at low gas rates and by the destabilizing effect of gas inertia at high gas rates.

The prediction of the transitions to 2-D and K−H wave regions is important in modeling stratified flow, since the interfacial shear stress is greatly affected by the presence of waves. The transition from smooth stratified to wavy stratified region is often modeled in the literature as the appearance of the first disturbances on the interface.[27,28,1] Obviously, this corresponds to the initiation of the so-called "two-dimensional waves" (2-D), because of their appearance. All the theoretical efforts provide a physical interpretation of the initiation of waves, but it is rather difficult from these works to derive a design correlation. For the smooth to 2-D wave transition the approach of Taitel and Dukler[29] was adopted here, which was based on the postulate—originally due to Jeffreys[30]—that the air flow separates above wave crests, resulting in pressure variation in phase with the wave slope that does work on the liquid. It was later proven by Miles[31] that flow separation is not necessary to produce the above effect. In fact, the perturbation introduced in the gas flow by an inifinitesimal deformation of the interface results in a distribution of mean Reynolds stress along the wave that varies in phase with the wave slope, and thus provides the needed mechanism for energy input from the gas to the liquid. However, the original expression of Jeffreys is still useful as a simple, empirical model of the pressure variation caused by interfacial disturbances. The Taitel and Dukler correlation for this transition is written as

$$u_G \geq \sqrt{\frac{4\mu_L(\rho_L - \rho_G)g}{s\rho_G u_L}} \quad (1)$$

where u_G and u_L are the actual gas and liquid velocities in the pipe, respectively, ρ_G and ρ_L are the gas and liquid densities, μ_L is the viscosity of the liquid phase, and g is the gravitational acceleration constant. Taitel and Dukler suggest a value for the sheltering coefficient, s, 0.01. However, other investigators suggested a larger value of 0.06.[1,32]

In this study, as well as in the work of Andritsos and Hanratty,[1] an effect of the liquid film thickness was evident when applying eq 1 to describe the initiation of waves in a pipe. As the liquid rate decreases, the deviation between experimental observations and eq 1 increases. One explanation may be the damping effect of pipe wall, the other being the "deep water" assumption in the original paper by Jeffreys, which does not stand for small film thicknesses. Accordingly, in the present work eq 1 is modified by considering that the sheltering coefficient depends on the dimensionless film thickness, to better describe the experimental transition to 2-D wave region:

$$u_G \geq \sqrt{\frac{4\mu_L(\rho_L - \rho_G)g}{s\left(\frac{h}{D}\right)^{0.5}\rho_G u_L}} \quad (2)$$

where h is the height of the liquid film at the vertical centerline and D is the pipe diameter. It is obvious from eq 2 that both liquid viscosity and liquid density have a stabilizing effect on the transition.

For the correlation describing the K−H wave transition, the theoretical approach of Lin and Hanratty,[24] as modified by Andritsos et al.,[6] was adopted. This approach is based on the fundamental notion of gas pressure variation in phase with the wave height, which constitutes the basic ingredient of classical Kelvin−Helmholtz theory, supplemented by viscous correction terms. The significance of the latter is to introduce a destabilizing effect of liquid inertia. As with the classical Kelvin−Helmholtz theory, the modified approach of Lin and Hanratty predicts that the gas velocity needed for the transition from 2-D to roll waves scales with $\rho_G^{1/2}$. This theoretical dependency is very close to an empirical one, $\rho_G^{\sim 0.4}$, implied by Benard and Spedding.[33]

Figure 5a shows flow-regime data for the air−water and He−water systems and predictions based on the aforementioned correlations. It is observed that the transitions to 2-D and to K−H waves are described very satisfactorily. We note in particular that both correlations predict a dependence of u_{GS} inversely proportional to the square root of the gas density, which agrees reasonably well with the experimental data. Finally, the characteristics of 2-D and K−H waves (as determined by the analysis of time-series of interfacial elevation) are very similar for the three different gases used in the present study, and thus are not further discussed. As we will see later, this is not the case when surface tension is reduced.

3.2. Effect of Surface Tension. Next, we perform experiments with an aqueous solution of normal butanol. The addition of *n*-butanol in water is expected to reduce surface tension without introducing significant surface elasticity or viscosity, and the solution practically behaves as a pure liquid with lower surface tension. As has been argued by Lucassen−Reynders and Lucassen,[21] this behavior is a result of the considerable solubility of *n*-butanol in water, which—in combination with the low viscosity, i.e. high diffusivity, of the aqueous solution—permits fast diffusional interchange between the surface and the bulk. Thus, surface tension gradients that would attribute visco-elastic properties to the surface are completely shortcircuited for all the wave frequencies observed in the present work.

The effect of decreasing surface tension on the flow pattern is illustrated in Figure 6. With a decrease in surface tension from 72 to 35 mN/m, the transitions to 2-D waves, K−H waves, pseudoslugs, atomization, and annular flow are shifted to lower gas velocities. On the other hand, the transition to slug flow is not affected by the change of this physical property. Preliminary observations with aqueous solutions of *n*-butanol and isopropyl-alcohol with a surface tension of 50 mN/m have shown similar quantitative trends.

It is evident from Figure 6 that the effect of surface tension is stronger for 2-D waves. This behavior points to an important stabilizing role of surface tension for the primary waves, which is physically reasonable, but appears not to have been documented in the literature. The correlation based on the approach of Taitel and Dukler[29] obviously fails to describe the transition to 2-D waves for the low surface tension system, since the Jeffreys' sheltering analysis neglects surface tension. Moreover, even more rigorous stability analyses (e.g., that developed by Craik[28] and Andritsos and Hanratty[1]) do not disclose any noticeable effect of surface tension in the initiation of 2-D waves. Thus, the observed strong effect of surface tension on the initiation of 2-D waves reveals a need for re-examining the presently available models. Although certainly this issue needs to be further addressed with the examination of other low surface tension systems, a tentative suggestion is to multiply the transition correlation by $(\sigma_{water}/\sigma_L)^{\sim 0.6}$, where σ_L is the surface tension of the system and σ_{water} is the surface tension of the air−water system.

Unlike the disagreement in the prediction of the 2-D waves, the transition to K−H waves can be described reasonably well by the correlation based on the modified theoretical approach of Lin and Hanratty[24] that was previously used for the air−water system (see Figure 5b). This theoretical approach also shows that the critical gas velocity for the transition to K−H waves scales with $\sim\sigma_L^{-1/3}$. A comparison of experimental data with predictions from the previously discussed approaches is depicted in Figure 5b.

As it has been already stated, the transition to slug flow is not strongly affected by changing surface tension. This behavior is in line with the modeling of slug transition as a long-wave instability, and is predicted reasonably well by the modified Lin−Hanratty approach. Figure 7 compares the experimental film thicknesses just prior to the transition either to slug flow or to K−H waves with theoretical predictions. The critical dimensionless film height above which any disturbance will cause slugging is about 0.30. This value appears to increase with increasing liquid viscosity,[6] but it is rather unaffected by the physical properties examined in this work.

It is also noted that the characteristics of K−H waves (irregularity, large amplitude compared to the mean film thickness, steep fronts, etc.) are common in the low and high surface tension systems. However, the approach to the K−H transition is qualitatively different in the low surface tension system, and this is described in more detail next.

Typical film thickness tracings are displayed in Figure 8a and b for the air−aqueous butanol solution system (Figure 8b actually shows three tracings presented in 8a in greater detail)

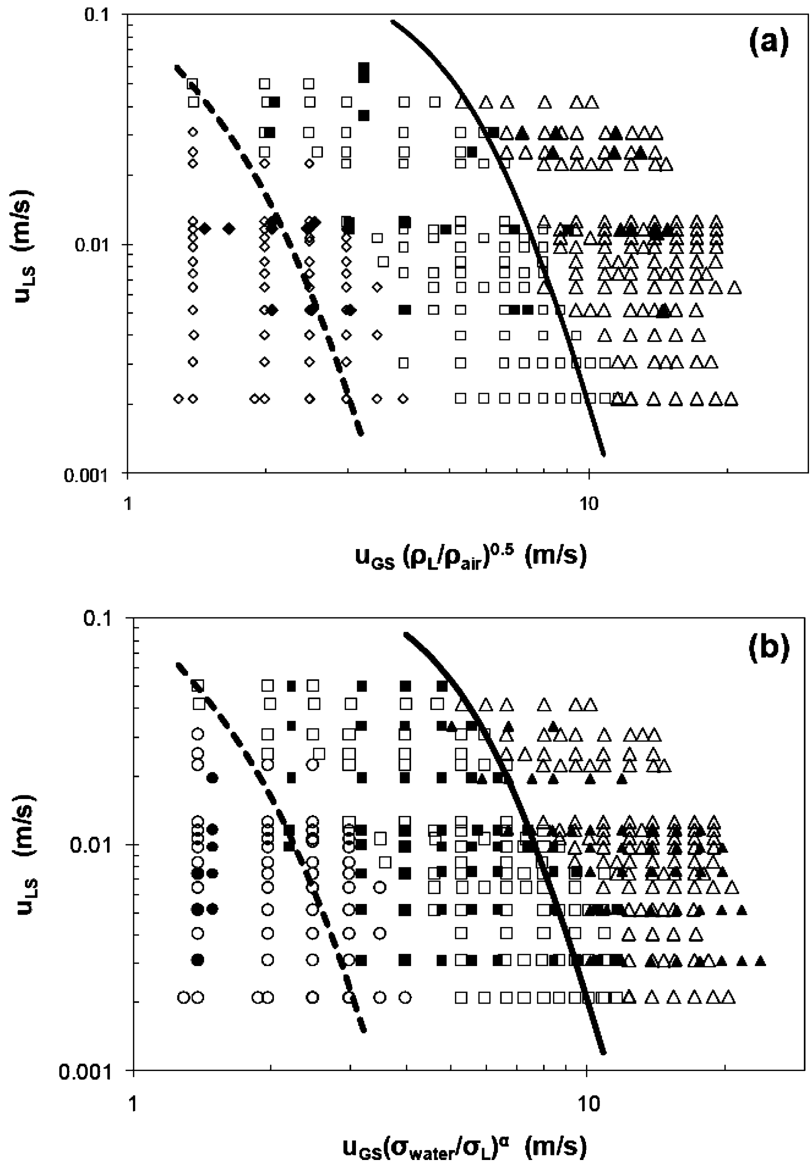

Figure 5. Comparison of experimental data with predictions for the transitions to 2-D and K−H wave regions. (a) He−water and air−water and (b) air−aqueous butanol solution and air−water. Open symbols: air−water; filled symbols: He−water or air−aqueous butanol solution. Circles: smooth; squares: 2-D waves; triangles: K−H waves. Dashed line: predicted transition to 2-D waves. Continuous line: predicted transition to K−H waves. The value of exponent α is 0.6 for the transition to 2-D wave region and 0.33 for the K−H one.

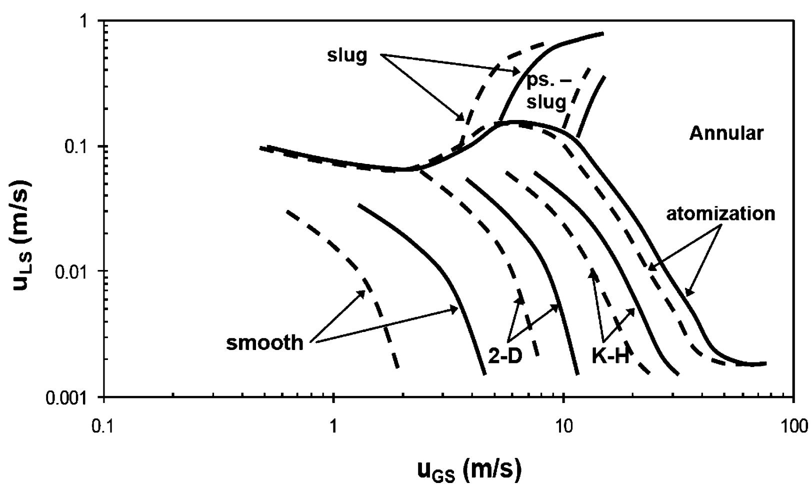

Figure 6. Comparison between air−water (continuous lines) and air−aqueous butanol solution flow map (dashed lines).

and 8c for the air−water system for a liquid superficial velocity of 0.0116 m/s. The latter tracings correspond to a transitional zone between 2-D and K−H waves, since as it is stated in the introduction, transition from one regime or subregime to another

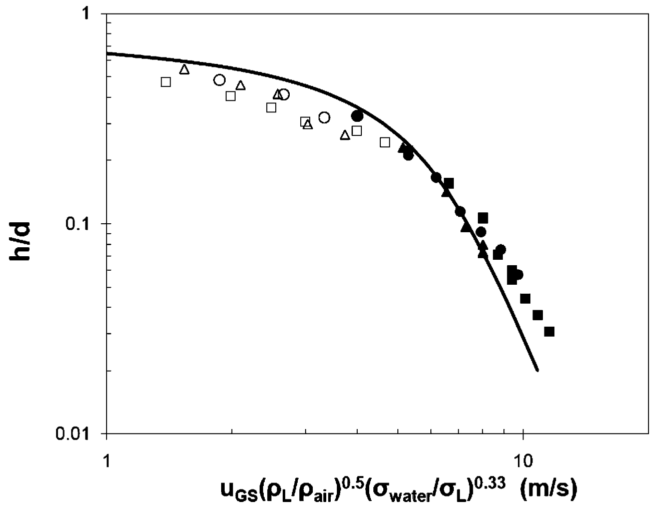

Figure 7. Comparison between experimental values of dimensionless film-thickness at the transition to slug flow and K−H waves with theoretical predictions. Open symbols: transition to slug flow. Filled symbols: transition to K−H waves. Circles: air−aqueous butanol solution; squares: air−water; and triangles: CO_2−water. Continuous line: predicted transition to slug flow or K−H waves.

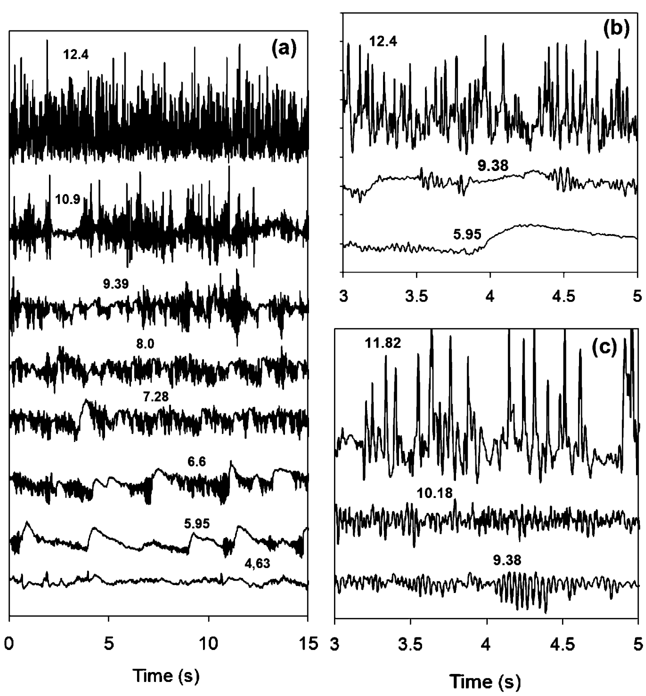

Figure 8. Typical film thickness tracings for a constant liquid velocity, u_{LS} = 0.0116 m/s, and increasing gas velocity. (a) and (b) air−aqueous butanol solution, and (c) air−water.

does not take place abruptly. It is observed that the transitional zone in the butanol solution system is broader than that of air−water and CO_2−water systems. Moreover, wave characteristics in this transitional zone are quite different for butanol solution compared to those for water.

The 2-D wave region in the air−water and CO_2−water systems is dominated by low-amplitude, regular waves (e.g., film tracing in Figure 3a). The picture is quite different in the low surface tension system. Initially, the first disturbances formed in this system have very low amplitude (of the order of 10−20 μm), they can be observed only through light reflection from the liquid interface and cannot be recorded properly due to signal noise. Well within the 2-D region, low-frequency “solitary” waves are formed with numerous capillary ripples in

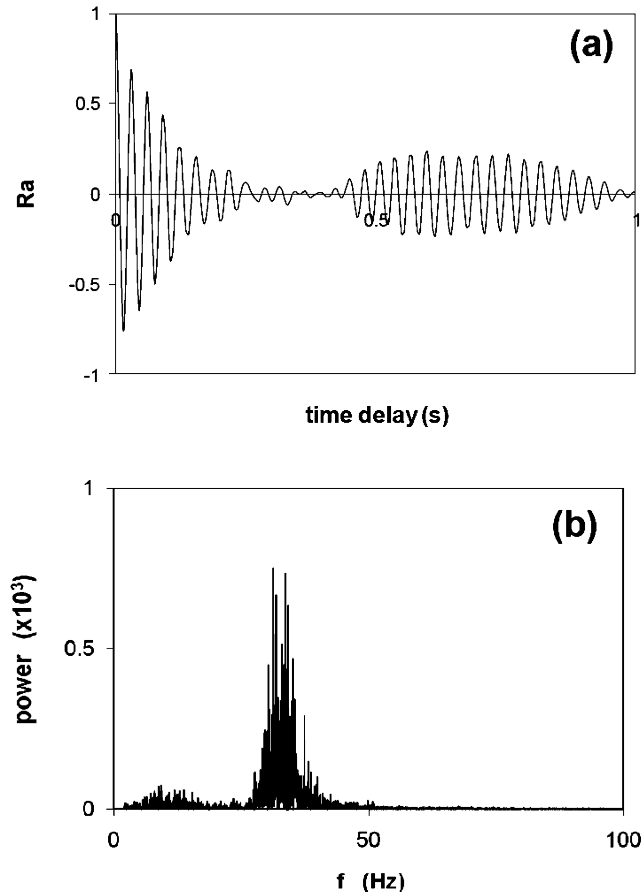

Figure 9. (a) Autocorrelation function and (b) wave spectrum of a film thickness tracing just before the transition to K−H waves for the air−water system in a horizontal pipe (u_{LS} = 0.005 m/s and u_{GS} = 9.4 m/s).

front of the waves (Figure 8a). These waves resemble solitary waves in gravity-driven flows, as reviewed by Chang.[34] The frequency of these waves increases with increasing gas velocity, whereas their amplitude remains constant or even decreases. With further increase of gas rate no solitary waves are evident, and the waves progressively acquire the characteristics of K−H waves. The above series of events is interesting and novel. A preliminary explanation is that the early appearance of 2-D waves permits extensive nonlinear interactions that result in solitary-like waves. Thus, this regime is probably determined by a balance between gas shear and capillary forces. With increasing gas velocity capillary forces become gradually less important, and the appearance of typical K−H waves marks the onset of a regime where gas shear is mainly balanced by viscous drag forces at the wall.

For the air−water system at the beginning of the transitional zone small wavelength 2-D waves are observed at the water interface as depicted in Figure 8c for u_{GS} = 9.4 m/s. With an increase in gas velocity (u_{GS} = 10.2 m/s) the waves start to acquire some K−H wave characteristics, as these waves become larger in amplitude and their crests are much steeper compared with the 2-D waves. Finally, at a little higher gas rate (u_{GS} = 11.8 m/s.) irregular K−H waves are clearly seen. The same picture also holds for the CO_2−water system. The frequency of the 2-D waves prior to transition remains rather constant (approximately at 30 Hz) for a considerable range of gas velocities. Figure 9 illustrates the autocorrelation and wave amplitude spectra of a run at a gas velocity just prior to the transition to K−H waves for the air−water system.

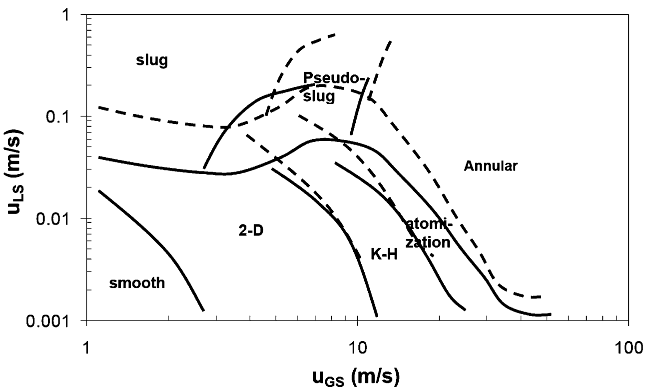

Figure 10. Comparison of air−water flow maps at $\varphi = 0.25°$ (continuous lines) and $\varphi = 1°$ (dashed lines).

4. Effect of Downward Inclination

In downward inclined pipes, the component of gravity in the direction of flow causes a decrease in liquid film height and an increase in liquid velocity. As a result, the stratified flow region expands considerably at the expense of the slug region. Figure 10 illustrates this shifting of the transition boundaries with an increase in inclination angle. It is also noted that for $\varphi = 1°$ the stratified smooth region was not observed for the liquid rates examined, i.e., the interface was wavy even for zero gas velocity.

The disappearance of the smooth region is attributed to the onset of gravity-driven instabilities, which proceeds independent of the existence of gas shear. This argument may be strengthened by an order-of-magnitude calculation, based on the classical result for the instability of inclined films $Re_{cr} = 5/6 \cot\varphi$. For $\varphi = 1°$, the above relation predicts $Re_{cr} = 48$. Recalling the minimum superficial liquid velocity used in the present experiments, $u_{LS} = 0.001$ m/s, and assuming a rectilinear film of width $w = 0.01$ m, we calculate a liquid Reynolds number $Re = q/\nu = (u_{LS} A/w)/\nu = 50$, where ν is the kinematic viscosity of the liquid. Thus, the flow may be unstable in the above sense even at the lowest liquid flow rate used.

Two different types of waves (2-D and K−H) can be again identified in the stratified region and it turns out that, although the transition to 2-D waves is shifted to lower superficial gas velocities, the transition to K−H wave region is not strongly affected by the inclination angle.

Figures 11 and 12 depict typical tracings of the types of waves encountered in the stratified region. In Figure 11, tracings are shown for the CO_2−water system at $\varphi = 1°$. At low superficial gas velocities (e.g., $u_{GS} = 4.17$ m/s), 2-D regular waves are initially observed, which with increasing gas velocity ($u_{GS} = 9.04$ m/s) grow in amplitude and become rougher. At a slightly higher gas velocity, $u_{GS} = 10$ m/s, the typical K−H wave characteristics are evident.

As in horizontal flow, lowering the surface tension alters the appearance of waves in the 2-D region. This is displayed in Figure 12, where solitary-like waves of significant amplitude are observed at low gas velocities. With increasing gas velocity, the interface becomes gradually more complex until the onset of K−H waves. It is noted once again that K−H waves sustain their characteristics irrespective of inclination angle, as was also observed for all the other parameters varied in the present study.

Figure 2 illustrates measured wave amplitudes in the stratified flow regime for roughly the same liquid rate for the three systems examined. It can be seen that wave amplitudes in the 2-D wave region are systematically larger for butanol solution system than that for air− and CO_2−water systems. However,

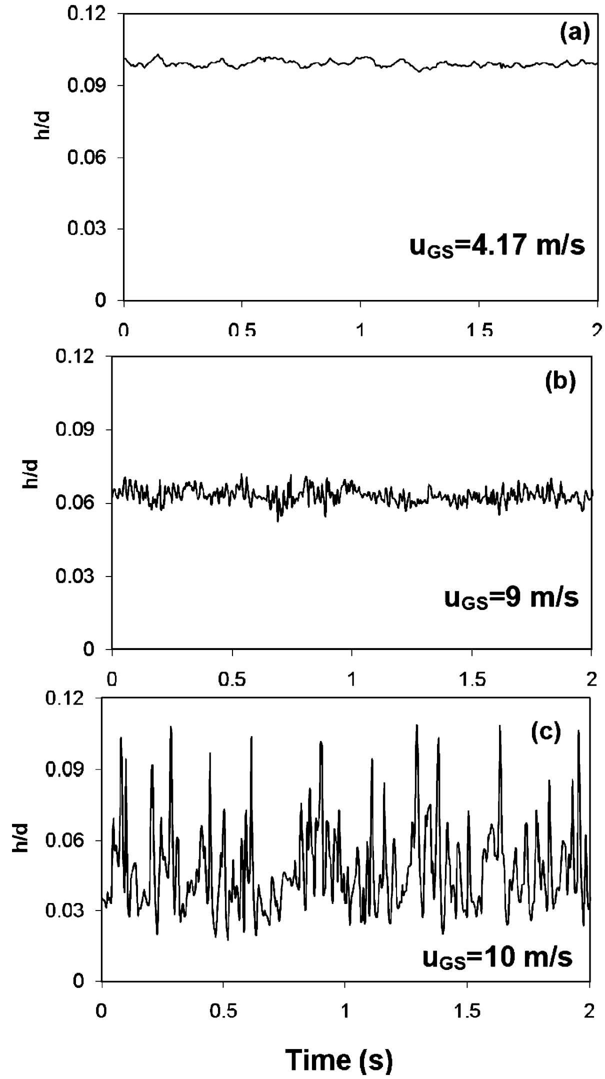

Figure 11. Typical film thickness tracings in the CO_2−water system at $\varphi = 1°$ and $u_{LS} = 0.0116$ m/s.

for the latter two systems at the transition to K−H waves an abrupt increase in wave amplitude is observed and wave amplitude remains at high levels.

Wave velocity in the stratified regime was calculated from the cross-correlation of two adjacent film traces at a distance of 336 pipe diameters. Some of these measurements are illustrated in Figure 13a and b for different flow systems. It is observed that in the 2-D wave region the actual wave velocity increases slightly with increasing inclination angle. However, as shown in Figure 13b, the relative 2-D wave velocity appears to decrease with inclination angle in the 2-D wave region and to remain constant in the K−H wave region. This behavior may be explained by considering that, at low gas velocities, the liquid film is accelerated mainly by gravity (which varies with inclination), whereas at high gas velocities it is accelerated mainly by gas shear.

Both the gas density and the surface tension affect the various transitions in downward inclined pipes in a manner similar to that found in horizontal flow. Again it is found that an increase in gas density and a decrease in surface tension destabilize the stratified region and shift the transitions to lower superficial gas velocities. Regarding the effect of surface tension, a similar trend has been also observed by Lioumbas et al.[19] with an aqueous solution of acetic acid with a surface tension of 43 mN/m. The transition to slug flow remains unaffected (for a fixed inclination

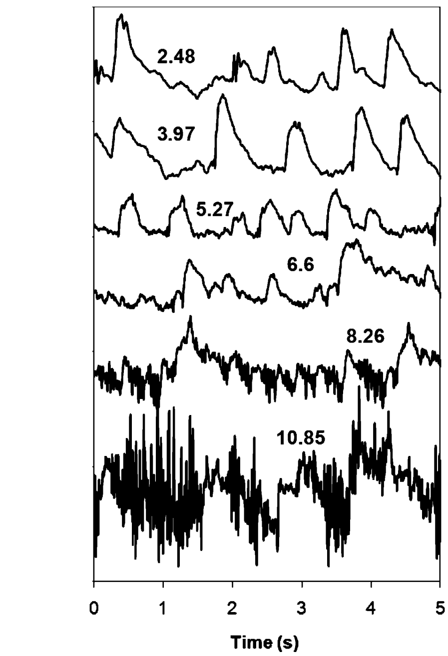

Figure 12. Typical film thickness tracings in the air−aqueous butanol solution system for a constant liquid velocity, u_{LS} = 0.0116 m/s, and increasing gas velocity.

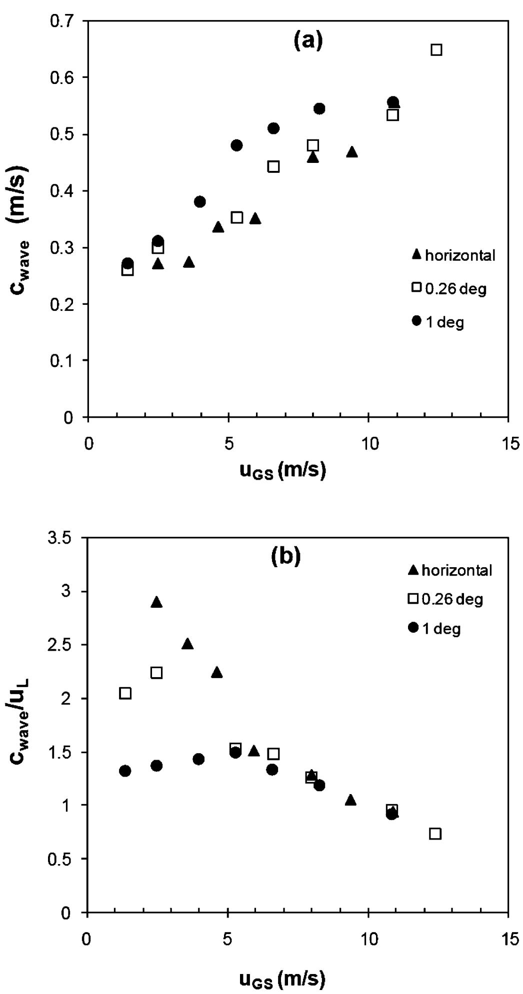

Figure 13. Values of measured wave velocity with increasing inclination and superficial gas velocity. (a) CO_2−water system and (b) air−aqueous butanol solution system for u_{LS} = 0.0116 m/s.

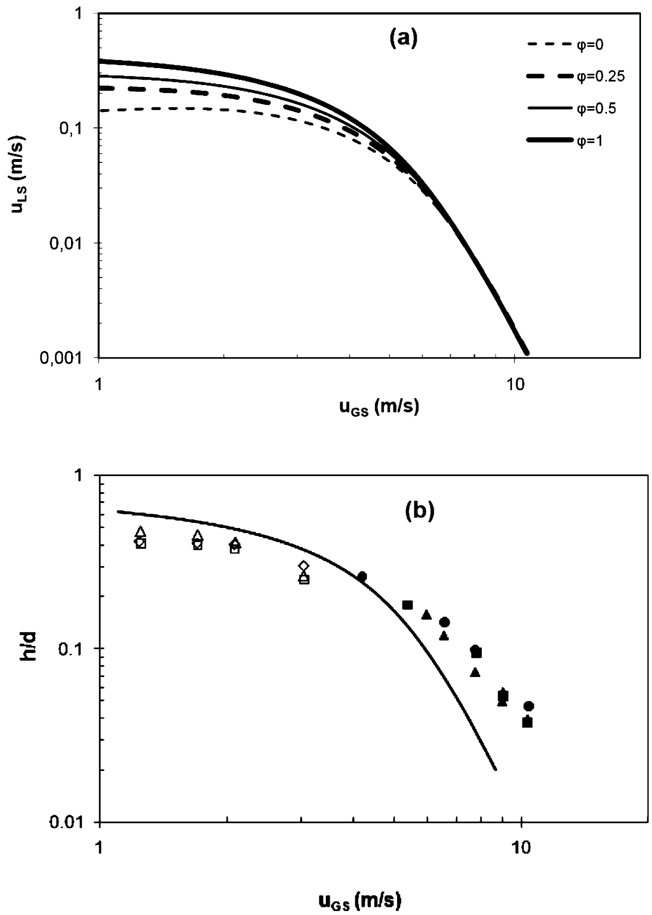

Figure 14. Theoretical prediction from the modified Lin−Hanratty model for transitions to slug flow and K−H waves for the air−water system. (b) Comparison between experimental data and predictions for the CO_2−water system. Open symbols: transition to slug flow; filled symbols: transition to K−H waves. Squares: 0°; triangles: 0.25°; circles: 1°; continuous line: predicted transition to slug flow or K−H waves.

angle), as in horizontal flow. As it has been discussed previously, no stratified smooth flow was observed, for all the systems and liquid rates (u_{LS} > 0.001 m/s) examined, for an inclination angle greater than about 1°. On the other hand, the transition to the K−H wave region (and consequently the transitions directly related to the onset of roll waves, i.e., atomization region and annular flow regime) is only weakly affected by pipe inclination. In fact, the gas velocity required for this transition increases slightly with increasing the inclination angle.

The modified Lin−Hanratty model can be extended to account for small inclination angles. Figure 14a presents theoretical transitions to slug flow (at low gas rates) and to K−H waves for three angles for the air−water system. The expansion of the stratified flow is predicted quantitatively, but the model is not capable of showing the small experimental shift of the transition to K−H waves toward higher gas rates with increasing angle. The latter behavior can be partly attributed to the fact that the model assumes that the critical gas velocity is much larger than the liquid velocity, whereas in downflow the film thickness becomes thinner and the liquid velocity increases considerably with increasing inclination angle. Measured values of liquid film thicknesses just prior to the onset of slugging and at the observed transition to K−H wave region are plotted against predictions from the modified Lin−Hanratty model in Figure 14b. It is noted that in such a plot, the predicted transition line is independent of pipe inclination. This is verified by the experimental results, although the agreement is not perfect. In

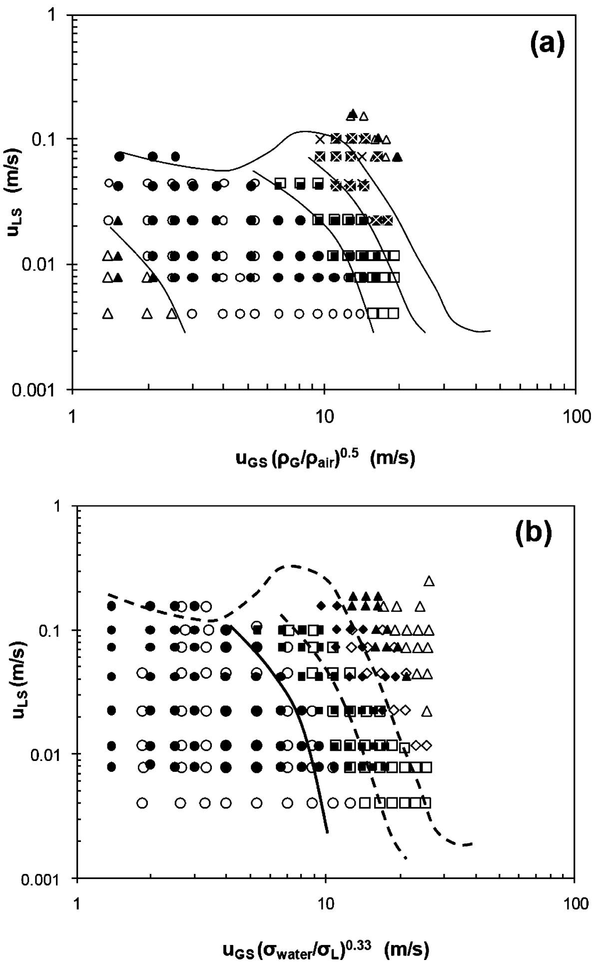

Figure 15. (a) Comparison of air−water (filled symbols) and CO_2−water (open symbols) flow maps at $\varphi = 0.25°$, and (b) of air−water (filled symbols) and air−aqueous butanol solution (open symbols) flow maps at $\varphi = 1°$.

addition, the critical dimensionless film thickness above which slugs are formed (instead of K−H waves) is again about 0.30 and unaffected by the inclination angle.

Finally, it can be also shown that with suitable modification to the coordinates, the transitions to the various subregimes of stratified flow for any inclination angle almost coincide for the different fluid properties, as depicted in Figure 15a and b, which illustrate the effects of gas density and surface tension, respectively.

5. Concluding Remarks

The effect of gas density and surface tension on flow characteristics in gas−liquid flow in horizontal and slightly downward pipes was investigated experimentally in this work. As it is anticipated, the gas density strongly affects both the transitions from smooth to 2-D waves and from the latter to K−H waves. More specifically, an increase in gas density "destabilizes" the flow and the transitions to 2-D and K−H waves take place at lower gas velocities. The same is true for the transitions to atomization region and to annular flow regime, which are directly connected to the onset of roll waves. Both transitions can be predicted rather adequately by modifying existing models in the literature.

A decrease of surface tension from 72 mN/m (water) to 35 mN/m (by using a butanol aqueous solution) results in a considerable decrease of the gas rate required for the onset of the first disturbances for the same liquid rate. Both the transitions to 2-D and to K−H waves are shifted to lower gas velocities, but the effect is more pronounced for the 2-D wave transition. The effect of surface tension on the transition to K−H waves can be predicted reasonably well by the modified Lin and Hanratty model. On the other hand, the correlation describing the onset of 2-D waves has to be corrected empirically. For both physical properties examined, the only transition that remains almost unaffected is the onset of slugging at low gas velocities.

Finally, even a slight inclination of the pipe downward causes considerable expansion of the stratified flow region. At angles higher than about 1° the smooth stratified flow ceases to exist. As in horizontal flow, two distinct types of waves can be observed (low amplitude waves reminiscent of 2-D waves in horizontal flow and K−H waves) for all the systems examined. In particular with the low surface tension system, "solitary" waves are formed instead of well-shaped 2-D waves.

Acknowledgment

The present work was partly supported by the EU under the Marie-Curie Initial Training Network "Multiflow" (GA 214919-2).

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Received for review February 1, 2010
Revised manuscript received May 11, 2010
Accepted May 19, 2010

IE100239V