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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF STRATIFIED GAS-LIQUID FLOW IN INCLINED CIRCULAR PIPES

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Abstract. *In this paper, a stratified gas-liquid flow is experimentally and numerically investigated. Two measurement techniques, namely an ultrasonic technique and a visualization technique, are applied on an inclined circular test section using a fast single transducer pulse-echo technique and a high-speed camera. A numerical model is employed to simulate the stratified gas-liquid flow, formed by a system of non-linear differential equations consisting of the Reynolds averaged Navier-Stokes equations with the κ-ω turbulence model. The test section used in this work is comprised mainly of a transparent circular pipe with inner diameter 1 inch, and inclination angles varying from -2.5 to -10.0 degrees. Numerical solutions are obtained for the liquid height as a function of inclination angles, and compared with our own experimental data.*

Keywords: *stratified flow; ultrasonic technique; numerical model*

1. INTRODUCTION

Two-phase stratified flow in pipes is frequently encountered in practical applications such as the flow of oil and natural gas in pipelines, and the steam generation and refrigeration equipment. In the main cooling lines of pressurized water reactors (PWR) nuclear power plants, the flow of steam and water during a hypothetical loss-of-coolant accident (LOCA) can occur as a two-phase stratified flow regime. In such scenario the two-phase flow generates instabilities which inhibit the emergency cooling of the reactor core.

The mechanistic model due to Taitel and Dukler (1976) has been widely used, which is a one-dimensional two-fluid model with closure relations for the wall and interfacial shear stresses calculated with single-phase flow correlations. Shoham and Taitel (1984) presented one of the earliest two-dimensional numerical solutions of fully developed turbulent-turbulent gas-liquid flow in horizontal and inclined pipes. The gas phase was treated as bulk flow, while the liquid phase momentum equation in the bipolar coordinate system with an algebraic turbulent model was solved by using a finite difference method. Also using the bipolar coordinate system, Issa (1988) modeled stratified flow, with a smooth interface, but solved the axial momentum equation in both gas and liquid phases with the standard *κ-ε* model. Stratified two-phase flow in inclined pipes has also been studied numerically and experimentally, Ottens et al. (2001), Ghajar and Tang (2007), Biberg (2007), Berthelsen and Ytrehus (2007). The influence of the liquid flow field on interfacial structure of two-phase stratified pipe flow was studied experimentally by Lioumbas et al. (2005), through local axial velocity measurements in the liquid phase in conjunction with other liquid layer characterization experiments. The results revealed the influence of the liquid flow field development on the interfacial structure, suggesting that the onset of the interfacial waves is strongly affected by the liquid flow structure. Banerjee and Isaac (2006) performed a numerical study to determine the rate of evaporation of gasoline while flowing through an inclined two-dimensional channel. More recently, Matsubara and Naito (2011) have investigated experimentally the effect of liquid viscosity on flow patterns of gas–liquid horizontal flow. Bartosiewicz et al. (2010) benchmarked different CFD codes results for stratified two-phase flow experiments performed in a horizontal air/water channel. Strubelj and Tiselj (2011) have proposed an improved two-fluid model for stratified flow, and Salhi et al. (2010) have investigated the modeling of gas–liquid interface in a two-phase stratified flow through a horizontal or nearly-horizontal circular duct.

In this work we have applied two measurement techniques, namely an ultrasonic technique and a visualization technique, on an inclined stratified gas-liquid flow test section using a fast single transducer pulse-echo technique and a high-speed camera. Experimental results of liquid height and void fraction measurements in the inclined pipe test section are presented. In addition, we solved the Reynolds averaged Navier–Stokes equations (RANS) with the *κ-ω* model for a fully developed stratified gas–liquid two-phase flow using the finite element method. The numerical results are then compared with our own experimental data.

2. STRATIFIED TWO-PHASE FLOW NUMERICAL MODEL

Considering the domains showed In Fig. 1 let us suppose a fully developed air-water stratified flow with the interface between the phases as a horizontal plane. Thus, the Reynolds averaged Navier-Stokes equations with the *κ-ω* turbulence model can describe the flow in both phases:

$$\nabla \cdot \left(A_i \nabla u\right) - \frac{dp}{dz} = 0 \tag{1}$$

$$\nabla \cdot \left(B_i \nabla \kappa\right) - \beta_2 \rho_i \kappa \omega + S_i = 0 \tag{2}$$

$$\nabla \cdot \left(C_i \nabla \omega\right) - \beta_1 \rho_i \omega^2 + \frac{\alpha_1 \omega}{\kappa} S_i = 0 \tag{3}$$

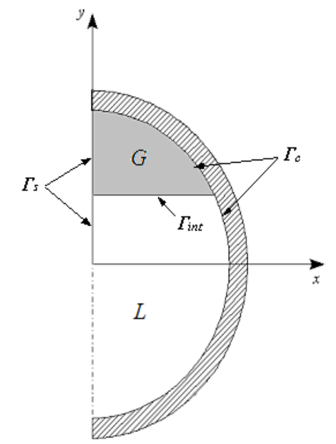

Figure 1. Domains for a stratified two-phase flow numerical model.

The terms in Eqs. (1) – (3) are $A_i = \mu_i + \mu_{ti}$, $B_i = \mu_i + \sigma_2 \mu_{ti}$, $C_i = \mu_i + \sigma_1 \mu_{ti}$, $S_i = A_i \nabla u \cdot \nabla u$, and $\mu_{ti} = \alpha_2 \rho_i \kappa / \omega$ where *κ* is the kinetic energy, *ω* is the energy dissipation, μ_{ti} is the eddy viscosity and $\alpha_1, \alpha_2, \beta_1, \beta_2, \sigma_1, \sigma_2$ are the *κ-ω* model parameters. dp/dz is the pressure loss along the co-ordinate *z* (perpendicular to the paper sheet), and u is the flow velocity. The subscripts *1* and *2* define, respectively, the liquid and gas phases. The boundary and interfacial conditions are defined on the symmetry boundary Γ_s where $\nabla u \cdot \boldsymbol{n} = 0$, $\nabla \kappa \cdot \boldsymbol{n} = 0$ and $\nabla \omega \cdot \boldsymbol{n} = 0$. On the pipe boundary Γ_c $u = 0$, $\kappa = 0$ and $\omega = \overline{\omega}_{ci}$ with $\overline{\omega}_{ci} = \dfrac{2\mu_i}{\beta_0 \rho_i Y_p^2}$, where $\beta_0 = 0.072$ is a model constant and Y_p is the distance of the closest grid point to the pipe wall. At the interface Γ_{int} the conditions were set up by $\sum_{i=1,2} A_i \nabla u \cdot \boldsymbol{n}_i = 0$, $\kappa = 0$ and $\omega = 10^6 u_0 / d$, where *d* is the inner pipe diameter, $u_0 = Q_L \Big/ \left(\dfrac{\pi d^2}{4}\right)$ and Q_L is the liquid flow rate. The solutions for the velocity profile, kinetic energy and energy dissipation are obtained in both phases, by using an iterative process combining two numerical techniques. More detailed information about the model's solution can be found in De Sampaio et al. (2008).

3. EXPERIMENTAL FACILITY

3.1 Two-Phase Flow Test Section

The inclined two-phase flow test section consists of a water flow loop, a feeding compressed air system, an air-water mixer, an inclined pipe test section and a separation air-water atmospheric tank. A schematic diagram of the experimental test section is shown in Fig. 2. The inclined pipe is a 6 m long stainless steel AISI 316 with inner diameter of 25.2 mm, connected by flanges in a transparent acrylic pipe of 1.8 m long with the same inner diameter. Distilled water is circulated through the mixer, coming from the single-phase water loop which is equipped with a centrifugal pump and a metering rig. Air is injected in the radial direction into the mixer by a compressor through a flow line equipped with appropriated air instrumentation. The air-water mixture goes out from the mixer and flows through the stainless steel tube along its length until the transparent acrylic pipe where it can be observed visually. The two-phase flow section is operated at pressures and temperatures close to atmospheric conditions. Measurements were carried out in the acrylic pipe.

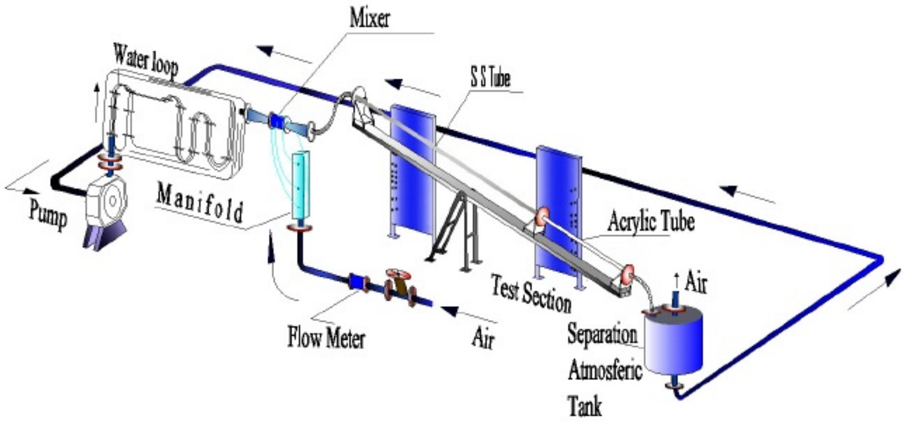

Figure 2. Schematic of two-phase flow test section.

3.2 High Speed Ultrasonic and Visualization System

The high speed ultrasonic system was developed to work with multiple ultrasonic transducers (up to four) in pulse-echo or transmission modes. This system consists of three physical parts: transducers, a generator/multiplexer board and a computer (PC) with software based on LabView® developed to control the measurement system. Two ultrasonic transducers of 10 MHz and 6.35 mm diameter (Panametrics model A555S), were mounted in the bottom of the acrylic pipe. Figure 3 shows the assembly of the high speed ultrasonic system. The generator/multiplexer board controlled by the software provides signal generation, multiplexing and data acquisition of the ultrasonic signals. The board generated an excitation frequency equal to 187 KHz and so the time pulse generated on each transducer was 4.4 ms. The ultrasonic signals were digitalized in the board, from each transducer, in time intervals of 10 ns. The buffer memory was settled to plot 8000 points.

The visualization system is formed by a monochrome digital high-speed camera equipped with a CCD sensor (maximum resolution 480 x 420 pixels), zoom lenses, a PCI controller board of 12 bits, an acquisition and image analysis program, and a computer. The lightning system includes a light projector placed in front of and above the transparent horizontal pipe. The frequency range from 125 to 250 frames per second was found to be sufficient for the measurements and was used in all experiments reported in this work. The sequence of images displayed on the computer monitor could be stored in a computer file, retrieved and replayed to analyze the flow motion sequence in detail. The set of discrete pictures were saved as a series of 512 greyscale avi images with a spatial resolution of 480×420 pixels.

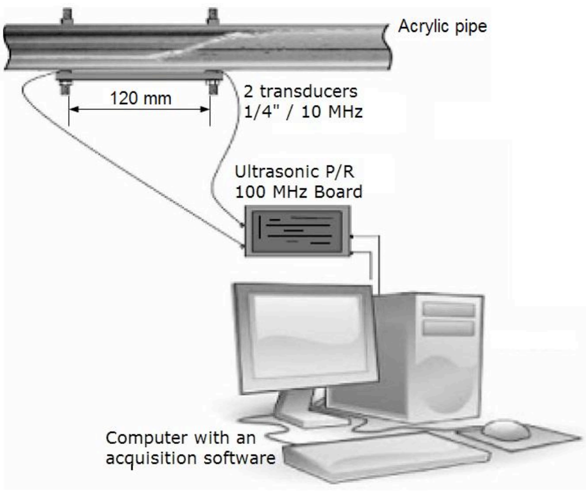

Figure 3. High speed ultrasonic system.

3.3 Experimental Technique and Results

In order to obtain liquid layer height measurements at various flow conditions, comparing the numerical and our own experimental data, two ultrasonic transducers were employed, separated by a distance of 120 mm as described previously. An ultrasound pulse discharged from both transducers is transmitted through the water and then reflected back to the same transducer from the air–water or tube wall–water interfaces. The transit time between the ultrasonic pulse and echo signals provides an accurate measurement of the liquid layer height. This technique was employed successful by Chang and Morala (1990) and Masala et al. (2007). The uncertainty of the measurements was estimated to be around ± 0.03 mm according to the previous calibration procedure. Figure 4 shows a series of typical ultrasonic signals reflected from gas-liquid interfaces. The ultrasonic transit time corresponds to the total time of the ultrasonic wave traveling through the liquid layer, reflected back from the air-water interface and returning to the ultrasonic transducer along the same way. The black line plot represents the ultrasonic signals of the two transducers when the test section was inclined -2.5 degrees, while the blue line plot represents the ultrasonic signals for an inclination angle

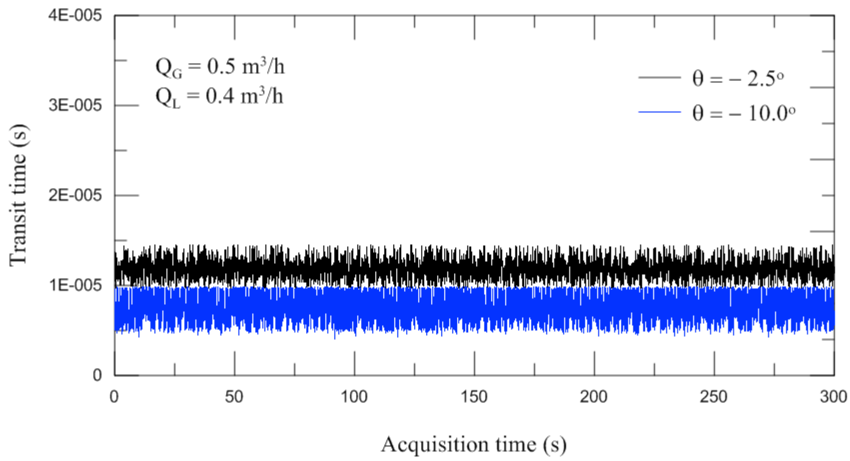

Figure 4. Typical ultrasonic signals reflected from gas-liquid interfaces.

of -10 degrees. It has been noted that there is a "matching" between the ultrasonic signals profile and the interface profile: less "oscillations" in the amplitude of the ultrasonic signals means a flatten interface, while more "oscillations" in the amplitude means a wavy interface. Measuring the transit time of the ultrasonic signals and knowing the sound velocity, the calculation of liquid layer height in the stratified flow can be obtained by:

$$h_L = c\left(\frac{\Delta t}{2}\right) \tag{4}$$

where h_L is the liquid height, c is the sound velocity in the water and Δt is the transit time of the ultrasonic signals in the water. In this work the sound velocity was estimated by means of a correlation proposed by Lubbers and Graaf (1998) with a maximum error of 0.18 m/s, for a temperature range of 15 °C to 35 °C. The transit time Δt could be measured by the high speed ultrasonic system. Then a local time-averaged h_L was calculated using all the instantaneous transit time measurements in the water averaged over the acquisition time period as given by the Eq. (4). Typical frames of the stratified flow taken with the visualization system are presented in Fig. 5, where the gas-liquid interface, tube centreline and wall have been arrow marked. In these frames the flow is moving from the right to the left into the inclined pipe.

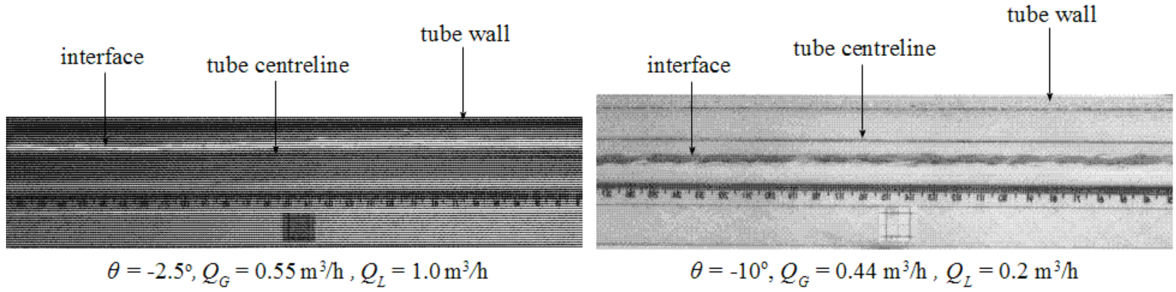

Figure 5. Frames of the stratified flow taken with the visualization system.

The Fig. 6(a) and 6(b) show the normalized h_L / d as a function of β for two inclination angles -2.5 and -10 degrees, respectively, where d is the inner diameter of the test section and β is the gas volumetric fraction defined as $\beta = Q_G / Q_G + Q_L$ where Q_G is the air volumetric flow and Q_L is the water volumetric flow. In these figures is presented a comparison between the experimental results given by the ultrasonic and visualization systems, and the present simulation. The vertical bars represent the largest and the smallest values as given by the ultrasonic system measurements.

The void fraction was determined simply by the geometric relation:

$$\alpha = 1 - \frac{1}{\pi}\left[\arccos\left(1 - \frac{2h_L}{d}\right) - \frac{\sin\gamma}{2}\right] \tag{5}$$

where $\gamma = 2\arccos\left(1 - \frac{2h_L}{d}\right)$, $\alpha = \frac{A_G}{A_G + A_L}$, A_G is the area occupied by the air and A_L is the area occupied by water inside the test section. Figure 7 presents similar results as Fig. 6, this time comparing the void fraction experimental results with the numerical simulation. Both the experimental ultrasonic technique and numerical simulation do not take into account any type of entrainment (by small bubbles or droplets). Figure 6 shows that the agreement, between the normalized liquid height determined by the numerical simulation with the time-averaged liquid height given by the ultrasonic technique, is acceptable. The discrepancies between the ultrasonic and visualization techniques as is shown in Fig. 6 (b) are accounted for by the difficulties with the image processing due to the undesirable effects such as shadows and light reflections.

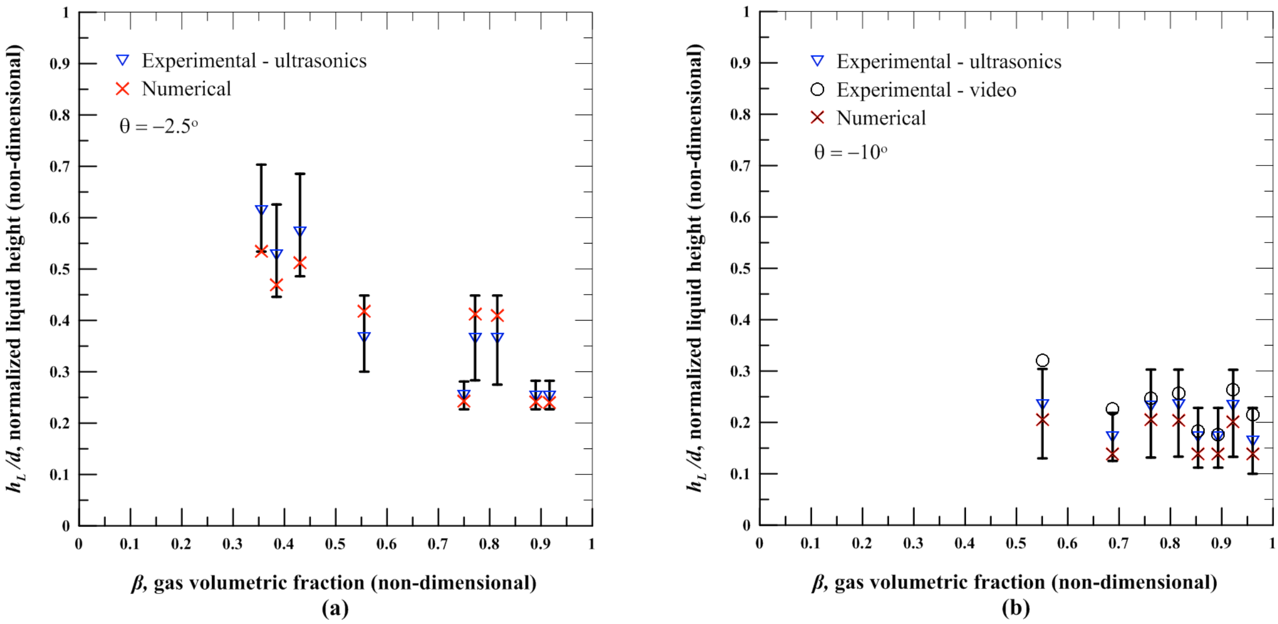

Figure 6. Normalized liquid height as a function of gas volumetric fraction. (a) θ = -2.5°, (b) θ = -10°.

In Fig. 7 the time-averaged void fraction was determined by averaging the liquid height showed in Fig. 6 using Eq. (5). In Tab. 1 is presented the relative differences between the void fraction numerical results and the time-averaged void fraction experimental results where the relative difference was estimated as

$$RelDif = \frac{\alpha(Num) - \alpha(US)}{\alpha(US)} \tag{6}$$

In Eq. (6) $\alpha(Num)$ is the void fraction given by numerical simulation and $\alpha(US)$ is the void fraction as measured by the ultrasonic technique.

In the experiments where the inclination was -2.5 degrees the averaged relative difference was 0.153 while for an inclination angle of -10 degrees this value was reduced to 0.036. Although the more significant presence of interfacial waves in the -10 degrees than in the -2.5 degrees inclination flows, the time-averaged liquid height (or time-averaged void fraction) for -10 degrees could be better determined by numerical simulation remembering that actual κ-ω model supposes an interface gas-liquid as a horizontal plane. Similar results were obtained by Faccini et al. (2009) in relation to the experimental results of Lioumbas et al. (2005).

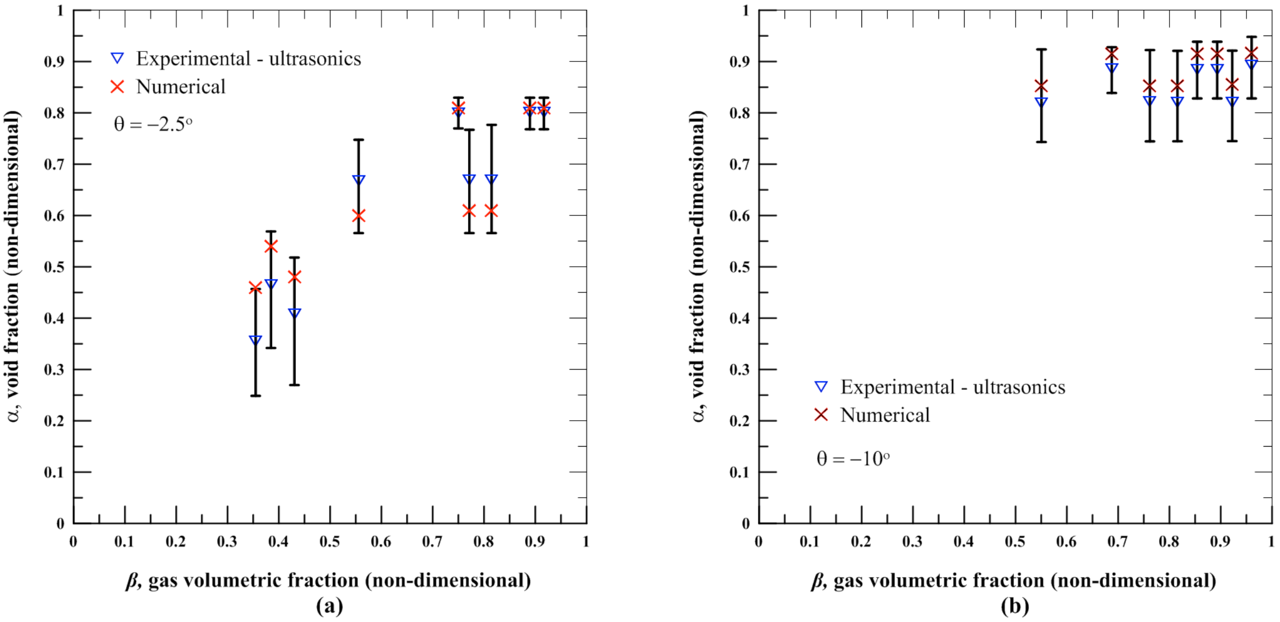

Figure 7. Averaged void fraction as a function of gas volumetric fraction. (a) θ = -2.5°, (b) θ = -10°.

Table 1. Relative differences in void fraction as calculated by Eq. (6).

Inclination angle (degrees)	*RelDif*		
	Min.	Aver.	Max.
-2.5	0.065	0.153	0.30
-10	0.027	0.036	0.042

4. CONCLUSIONS

This paper has presented experimental and numerical results for stratified two-phase flow in inclined pipes. The experimental results were obtained using two measurement techniques, namely an ultrasonic technique and a visualization technique. A high speed ultrasonic system was employed with two ultrasonic transducers in pulse-echo mode, a generator/multiplexer board and a computer with software to control the measurement system. The visualization system was formed by a digital high-speed camera, a PCI controller board and an acquisition and image analysis program. The numerical results were generated employing a κ-ω numerical model. The experimental results were compared with the numerical results, in terms of a normalized liquid height and void fraction as a function of gas volumetric fraction for inclination angles of -2.5 and -10 degrees. The comparison has been evaluated by means of a relative difference between the numerical and experimental values, resulting in an average difference of 0.153 for the inclination angle of -2.5 degrees while for -10 degrees the average difference was 0.036. Although the time-averaged liquid height (or time-averaged void fraction) for -10 degrees could be better determined by numerical simulation than for an inclination of -2.5 degrees, the numerical model can be considered suitable to simulate the present experiments.

5. ACKNOWLEDGEMENTS

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