GAS-LIQUID INTERFACIAL DISTRIBUTION IN INCLINED DOWNWARD PIPE FLOW

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Summary. Two-phase air-water flow experiments for a wide range of pipe inclinations and flow rates are reported. Digital video camera connected to a boroscope is used to visualize phase distribution in the pipe cross-section illuminated by a laser light sheet. Advantages and limitations of the boroscope technique applied for two-phase flow are discussed. Simultaneously, wave gauges are used to measure the instantaneous surface changes. The main goal of this work is to investigate the transition from stratified to annular and to slug flow. Simultaneous video images and wave gauge records provide extensive information on the instantaneous and statistical properties of the phase distributions in the pipe.

Introduction

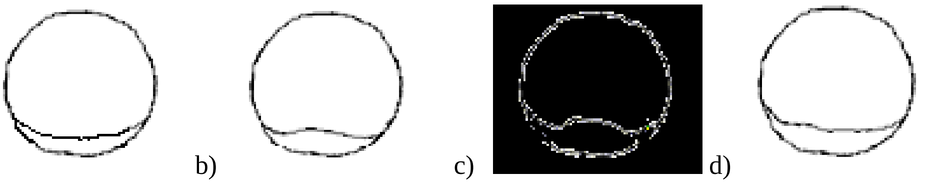
Two-phase (gas-liquid) flow in horizontal or downward inclined pipes is often stratified with the liquid film occupying the bottom part of the pipe. This flow regime is usually observed when gas and liquid flow rates are sufficiently low. One of the most intriguing problems in two-phase stratified flow is the distribution of the liquid film around the circumference in horizontal and inclined pipes. Transition from stratified flow to non-stratified slug or annular flow depends strongly on the film thickness and on the film shape. Experimental measurements of these parameters, especially near the transition zone, are quite rare. Calculations of the film thickness distribution in the pipe cross-section are usually complicated and require application of phenomenological models. For horizontal and slightly downward inclined flow, stratified – slug transition takes place at relatively high liquid flow rates, whereas stratified – annular transition occurs at high gas flow rates. At downward steep inclinations, stratified – annular transition is observed even at very low gas flow rates. The knowledge of the gradual variation of the average and the instantaneous film thickness and of the interfacial shape up to the transition to annular or slug flow is of utmost importance for understanding the mechanism of the flow pattern transition. In addition, the knowledge of the film shape for various operational conditions is required for pressure drop and heat and mass transfer calculations. The purpose of this study is to perform quantitative measurements of the distribution of the liquid and gas phases in the pipe cross-section in downward flow. Measurements are carried out for pipe inclination angles ranging from horizontal to nearly vertical (80^0).

Experimental facility and methods

Experimental investigation of the instantaneous cross-sectional distribution of the void fraction within a downward inclined pipe is carried out. The experimental facility consists of a 10 m long pipe with an internal diameter of 2.4 cm, built of 2 m long sections, that is placed on a steel frame and can be fixed at any desired angle of inclination. Water and air are used as the working fluids. The gas and the liquid superficial velocities are measured by a set of rotameters. In the current research we attempt to apply a novel and seemingly attractive approach to perform instantaneous void fraction measurements in the whole cross-section under various operational conditions. Two independent measuring techniques are employed. The first method uses a combination of a borescope based on fiber optic technology and a light-sheet illumination by a laser. This is a non-intrusive technique that practically does not interfere with the flow. The boroscope is inserted into the upper part of the pipe at an angle of about 20^0 relative to the pipe axis. To this end, a special module has been constructed. The boroscope is connected to a digital video camera using a special adapter. Calibration of the image is necessary to account for the optical distortions that arise from the slant angle at which the boroscope is introduced. The images recorded by the camera provide the necessary input to obtain the instantaneous cross-sectional void fraction distribution. Digital image processing of sequences of continuously recorded boroscope images makes it possible to calculate the appropriate statistical parameters.
Selection of the boroscope location and geometry is based on preliminary experiments that were carried out in our laboratory. These experiments demonstrated that when dispersed liquid drops or gas bubbles exist in the flow, the boroscope images become distorted. Moreover, in these cases optical distortions may be induced by liquid drops or gas bubbles that settle at the boroscope itself. Effective use of the boroscope technique seems to be limited to the cases where a single phase (either gas or liquid) exists at the boroscope lens. This limitation allows to study in detail separated gas-liquid flow, such as stratified flow (either smooth or wavy), annular flow, or the shape of elongated bubbles in slug flow.
Since the boroscope technique is quite new in two-phase flow studies, it is important to validate the results by more conventional methods. Measurements were therefore simultaneously performed using an alternative experimental method: capacitance wave gauges that are routinely used for studies of gravity-capillary waves on the water surface were applied to validate of the boroscope results. Up to four gauges can be used simultaneously. Here again, construction of a special module to introduce wave gauges into the pipe and to enable the gauge calibration is required. The probes are made of 0.6 mm tantalum wire which underwent an anodizing procedure to uniform coat it with a thin dielectric tantalum oxide layer. The probes are introduced into the measuring module at various angles relative to the vertical. The instantaneous wetted length measured by the probes allows capturing data at different points along the pipe.
Each measuring module is built of 20 cm long sections of 2.4 cm ID pipe. The modules can be placed at any connection between the 2 m long pipe sections. Most measurements in this study were carried out when the measuring modules were located at adjacent positions close to the exit from pipe (at about 8 m from the pipe inlet).

Results

A typical sequence snapshots recorded by the camera in stratified flow regime is presented in Fig. 1. According to the flow pattern map (Barnea et al. 1982), stratified flow in downward pipe flow is wavy. The unsteady character of the flow is indeed clearly visible in variation of the instantaneous shape of the interface in the illuminated by the laser sheet pipe cross-section.



a) b) c) d)

Figure 1: Sequence of instantaneous interface shapes. Pipe inclination 10°, U_{LS} =0.1m/sec, U_{GS} =0.1 m/sec.

Increase of the inclination angle strongly affects the interface shape which varies from a smooth for zero inclination to wavy-stratified at higher inclinations and to nearly axially-symmetric annular flow for inclination angles approaching the vertical. The variation of the mean interface shape with the inclination angle is studied for various flow conditions. The transition between from stratified to non-stratified flow patterns is compared with the model predictions given in Barnea et al (1982). It is observed that the temporal variation of the instantaneous film thickness depends strongly on the pipe inclination angle. This is demonstrated in Fig. 2. A comparison is carried out between the instantaneous water depth measured at the vertical diameter of the pipe cross-section by the wave gauge, and that derived from a sequence of the video images. Good agreement is obtained between the two measuring techniques. The mean film thickness for given flow rates decreases with increasing inclination angle. The wave amplitudes and frequencies dependence on pipe inclination and on the gas and liquid flow rates is studied in detail.

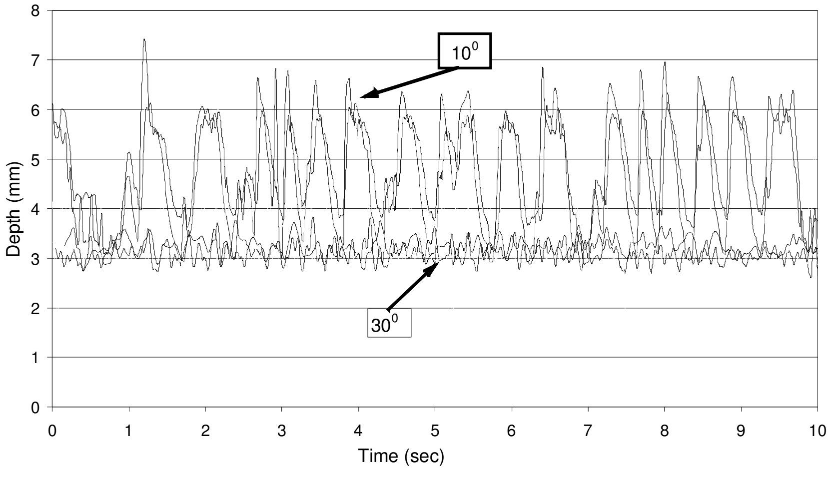


Figure 2: Instantaneous liquid film depth at the vertical diameter in the pipe cross-section derived from the recorded boroscope images (thin line) and measured by a capacitance probe (thick line). Flow rates as in Fig. 1.

Measurements were also performed in the slug flow regime, which is obtained for higher gas and liquid flow rates. Results of the shape of the elongated bubbles, as well as slug unit propagation velocities and the mean lengths of the liquid slugs and elongated bubbles, are obtained for various flow conditions. Transitions between the flow patterns observed in the present study are compared with those reported before. The present results demonstrate the potential of the experimental approach adopted in this study for two-phase flow measurements.

Acknowledgement

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Reference

Barnea D., Shoham O. and Taitel Y. (1982) Flow pattern transition for downward inclined two phase flow; horizontal to vertical. Chem. Eng. Sci. 37, 735-740.