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Technical Note

Two-phase wavy-annular flow in small tubes

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ABSTRACT

Base liquid film thickness distribution, wave behavior, and pressure loss measurements have been obtained for 237 horizontal two-phase (air–water) flow conditions in 8.8 and 15.1 mm I.D. tubes in the wavy and annular regimes. The behaviors measured indicate the presence of a transitional wavy-annular regime at flow rates traditionally labeled as annular in these small diameter tubes. Data for a 26.3 mm I.D. tube do not show these same trends.

1. Introduction

The first step in most analyses of two-phase systems is to determine the flow regime present, as models and correlations pertain to specific regimes. Considerable work has been performed to investigate flow regime transitions. These efforts often result in flow regime maps that allow for graphical regime identification using flow rates, fluid properties, and/or tube size. For horizontal flow, the two most often cited maps are those of Mandhane et al. [1] and Taitel and Dukler [2]. The former, constructed from experimental data and observations, predicts flow regime transitions based on gas and liquid superficial velocities and does not include an explicit diameter effect. The latter is based on a mechanistic approach and includes a diameter effect for the transition of present interest, that between wavy (stratified-wavy) and annular (annular dispersed liquid) flow.

With the flow regime identified, models can be applied to predict specific flow behaviors, including pressure loss, film thickness, and wave behavior. The present work uses this process in reverse, employing measurements of these phenomena to investigate the transition between the wavy and annular flow regimes. A qualitative, diameter-dependent difference in transition behavior is seen.

2. Experimental setup

Additional details regarding the experimental facilities are available in previous work by the authors [3,4]. Schematics of the flow loop and the optical sensors for disturbance waves and base film thickness are shown in [3].

2.1. Flow loop

Laboratory compressed air was delivered to the test section inlet via a bank of variable-area volumetric flow meters. A pressure gauge near the flow meters allowed for the correction of flow meter readings to compensate for variations in air density and for the calculation of the gas mass flow rate. The water flow was measured using a bank of variable-area rotameters and entered the loop through a series of 1.5 or 3 mm holes drilled in the test section wall about 150 mm from the air entrance. The two-phase mixture passed through a development length of more than 200 diameters before any measurements were obtained. (See Okada and Fujita [5] for a discussion of required development length and method of liquid introduction).

2.2. Pressure measurements

A bourdon-tube gauge was placed near the test section to estimate local air density. In the 15.1 and 26.3 mm I.D. tubes, this gauge was placed at the beginning of the test section, while it was placed 0.5 m upstream for the 8.8 mm I.D. tube. Two-strain gauge based differential pressure sensors were used to measure

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Nomenclature

D	tube diameter [m]
$\frac{dP}{dz}$	axial pressure gradient [Pa m^{-1}]
f_{TP}	two-phase friction factor [–]
f_{wave}	wave frequency [s^{-1}]
KE_{sg}	superficial gas kinetic energy [J m^{-3}]
U_{sg}	superficial gas velocity [m s^{-1}]
U_{sl}	superficial liquid velocity [m s^{-1}]
x	flow quality [–]

Greek symbols

δ	film thickness [m]

Subscripts

b	measured at the bottom of the tube
s	measured at the side of the tube
t	measured at the top of the tube

pressure drop at the test section over 0.5 m for the 8.8 mm tube and 1 m for the 15.1 and 26.3 mm tubes. Uncertainty in the pressure loss is estimated at 2%.

2.3. Data range

For each diameter, an array of meter readings was selected to provide a large bank of data. Superficial gas velocities of between 10 and 86 m s^{-1} were considered, with superficial liquid velocities between 0.03 and 0.30 m s^{-1}. Estimated flow rate uncertainties are of order 5%. Based on the map of Mandhane et al. [1], flow conditions within the wavy and annular regimes are considered.

2.4. Film thickness measurement

Using a technique outlined by Shedd and Newell [6] and verified by Rodríguez and Shedd [7], base film thickness measurements were made at the top, bottom, and side of the tube for each flow condition. These measurements capture the film thickness between large disturbance waves (termed base film thickness). This non-intrusive method uses the pattern of diffuse light reflected from the gas–liquid interface. Uncertainties are estimated at 5–20% (highest for lowest gas flow rates). A calibration (bias) uncertainty of 5% is included in this estimate. This calibration will affect each measurement for a specific diameter and location (top, side, or bottom). Average base film thickness was estimated by

$$\delta = \frac{\delta_b + 2\delta_s + \delta_t}{4} \quad (1)$$

2.5. Wave measurements

An optical method, similar to that reported by Hawkes et al. [8], was used to study wave frequency. Two LED/phototransistor pairs were mounted on the outside of the tube, 0.115 m apart. Light from an LED passed through the transparent tube wall, through the air/water mixture, and on to the phototransistor. Digital video imaging, simultaneous with the LED/phototransistor measurement, confirmed that the phototransistor signal was very well correlated with liquid waves, which scattered LED light prior to the phototransistor. A mean wave frequency, f_{wave}, was derived using the Fast Fourier Transform (FFT) algorithm. A 10% uncertainty is estimated.

3. Results

Base film thickness distribution, wave frequency, and a two-phase friction factor are shown in Fig. 1 for the 8.8 and 15.1 mm tubes. Based on the results discussed in [3], a two-phase friction factor based on gas superficial kinetic energy and quality is proposed:

$$f_{TP} = \frac{\frac{dP}{dz} D x}{KE_{sg}} \quad (2)$$

At high gas flows (fully annular), f_{TP} varies over a narrow range for each diameter.

At gas superficial velocities above 30 m s^{-1}, the base liquid film is nearly symmetric, with the average thickness well-approximated by the side measurement. No significant effect of liquid superficial velocity on the distribution is observed. At lower superficial gas velocities, liquid pools at the bottom of the tube, leading to a significant increases in the maximum asymmetry (δ_b/δ_t) and the normalized deviation of the side measurement from the estimated average. At these lower gas flows, a stronger dependence of film thickness distribution on liquid flow rate is also present.

The third pair of graphs in Fig. 1 shows that at higher gas flow rates, wave frequency is an increasing function of liquid flow. This trend is not repeated at lower gas flow rates (wavy-annular), for which the observed, weakly inverse dependence on liquid flow rate is within experimental uncertainty. The bottom pair of graphs show that the non-dimensionalization of pressure drop (i.e., f_{TP}) found for annular flow does not extend well into wavy-annular flow.

Based on these data, there appears to be a weak diameter effect with respect to the critical gas superficial velocity for this wavy-annular to fully annular transition. In the 26.3 mm tube (Fig. 2), trends characteristic of wavy-annular flow (little liquid flow effect on wave frequency, increased liquid flow effect on film thickness distribution) extend to gas superficial velocities higher than 60 m s^{-1}. This is a qualitative difference with respect to a change in tube diameter, in contrast with the functional dependence seen between the 8.8 and 15.1 mm data.

These data indicate that flows visually identified as annular (continuous wetting of the top of the tube) or deemed so based on flow regime maps may in fact belong to two or more separate regimes that may need to be modeled differently. In these flows, two of the most significant modeling parameters are film thickness distribution and wave behavior. These behaviors do not show continuous trends across all flow conditions studied in this work that might be termed annular based on regime maps. Therefore, care should be taken in developing and using models obtained at significantly different tube diameter or gas superficial velocity, even if both databanks are considered annular based on regime maps.

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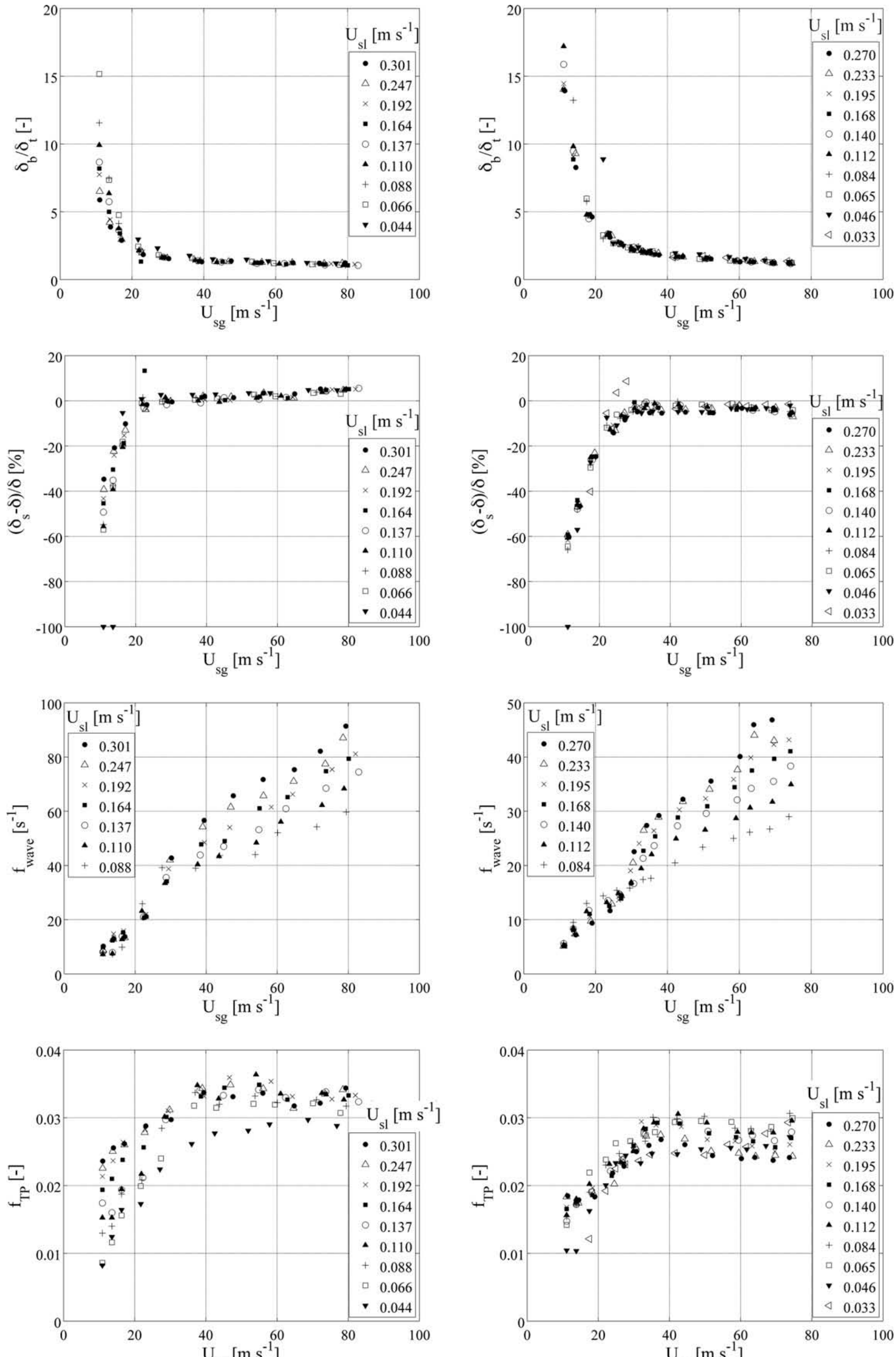

Fig. 1. (Top) Maximum film thickness asymmetry. (Next) Deviation of side film thickness from average. (Next) Wave frequency. (Bottom) Two-phase friction factor. (Left) 8.8 mm tube. (Right) 15.1 mm tube.

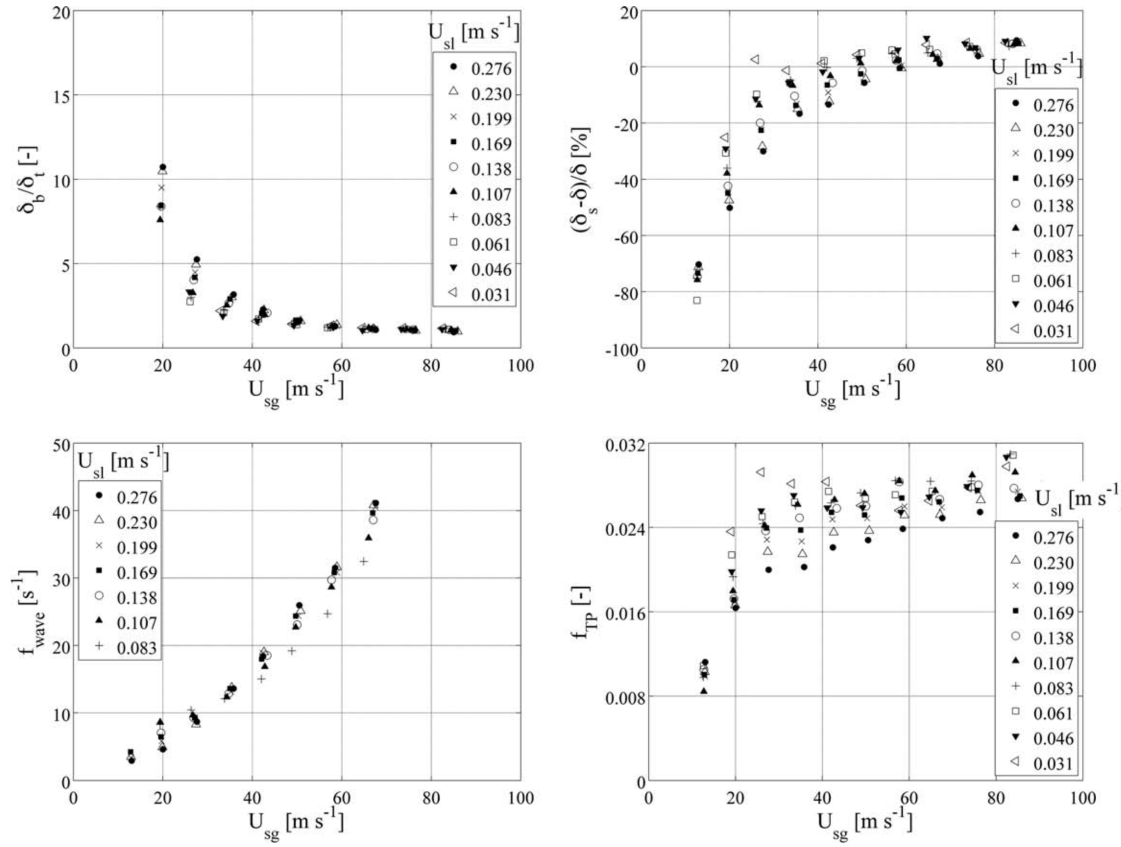

Fig. 2. Data for 26.3 mm tube. (Top left) Maximum film thickness asymmetry. (Top right) Deviation of side film thickness from average. (Bottom left) Wave frequency. (Bottom right) Two-phase friction factor.

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