Wall and Interfacial Shear Stress in Stratified Flow in a Horizontal Pipe

Experimental values are presented for the wall and interfacial shear stresses in stratified gas-liquid flow in a pipe. The wall and Reynolds shear stresses were measured using a hot-film anemometry technique. The interfacial shear stress was determined using two methods: from a momentum balance, using the wall shear stresses and void fraction measurements, and from an extrapolation of the Reynolds shear profile at the gas-liquid interface. The predicted interfacial shear stress data were approximated by the formula relating the interfacial friction factor with the void fraction and gas and liquid Reynolds numbers, and were compared with other reported data.

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Introduction

Stratified two-phase flow in pipes may occur in various chemical and industrial processes. Examples include the flow of oil and natural gas in pipelines and the flow of steam and water in horizontal pipe networks during certain postulated loss-of-coolant accidents. Knowledge of the wall and interfacial shear stresses is required for modeling the flow in these applications.

Experimental studies of the interfacial shear stress have been presented in a number of papers (Davis, 1969; Hanratty and Engen, 1957; Fabre et al., 1984). However, all of the investigations reported to date have involved rectangular conduits at atmospheric pressure. At the present time no methods exist to measure the interfacial shear directly; however, this quantity may be deduced indirectly from:

- Gas velocity profile measurements (Hanratty and Engen, 1957; Ellis and Gay, 1959)
- Turbulent kinetic energy profiles (Fabre et al., 1984)
- The momentum balance using the wall-to-gas shear stress, liquid level, and pressure drop measurements (Davis, 1969)
- The extrapolation of the shear stress profiles at the gas-liquid interface (Besfamiliny et al., 1982; Fabre et al., 1984)

The objective of this study was to measure the wall and Reynolds shear for stratified flow in a circular, 50.8 mm dia. horizontal pipe. The shear stresses were measured using a hot-film anemometry technique. Tests were carried out with air-water flows at a pressure of 225 kPa, and Freon gas-water flows at pressures of 225 and 420 kPa. The interfacial shear stress was determined in two ways:

1. From a flow momentum balance using wall shear stresses and void fraction measurements
2. From Reynolds shear stress measurements

Wall-to-gas shear results were consistent with correlations given in the literature, but the liquid-to-wall shear data disagreed substantially with the prediction of Agrawal et al. (1973).

The Reynolds shear profile deviated from linearity close to the gas-liquid interface at high gas velocities. Our measurements also showed that the zero shear plane did not coincide with the maximum in the velocity profile.

Previously proposed criteria for predicting the interfacial shear stress did not represent the present experimental data satisfactorily, especially at higher gas densities. Hence, the improved criteria have been developed to calculate the interfacial shear factor. The empirical correlations agreed well with the experimental data for the rectangular and circular geometries of the channel at pressures of 100 to 420 kPa.

Theoretical Basis of the Experimental Techniques

Determination of interfacial shear stress from wall shear stress measurements

Russell et al. (1974) developed a mathematical model to calculate void fraction and pressure drop in stratified flows. This procedure may also be used to calculate the interfacial shear stress for laminar-liquid/turbulent-gas flows. A more general relationship can be used to evaluate the interfacial shear stress. It can be derived by considering momentum balances for the equilibrium stratified flow, Figure 1, for the liquid phase,

$$-(1 - \alpha) A \frac{dP}{dx} - \tau_{w\ell} S_\ell + \tau_i S_i = 0 \qquad (1)$$

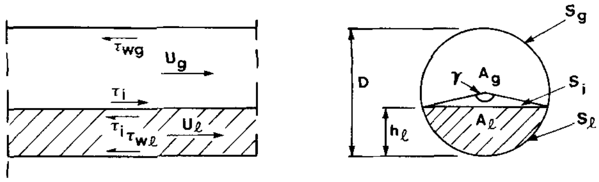

Figure 1. Stratified cocurrent flow.

and for the gas phase,

$$-\alpha A \frac{dP}{dx} - \tau_{wg} S_g - \tau_i S_i = 0. \tag{2}$$

By eliminating the pressure drop from Eqs. 1 and 2, we find

$$\tau_i = \tau_{w\ell} \frac{S_\ell}{S_i} \alpha - \tau_{wg} \frac{S_g}{S_i} (1 - \alpha). \tag{3}$$

Thus, by measuring the void fraction, α, and the wall-to-phase shear stresses $\tau_{w\ell}$ and τ_{wg}, the interfacial shear stress τ_i can be determined using Eq. 3. The values of S_ℓ, S_g, and S_i are obtained from the following geometrical relations (Agrawal et al., 1973):

$$S_\ell = \left[\pi - \cos^{-1}\left(2\frac{h_\ell}{D} - 1\right)\right] D \tag{4}$$

$$S_g = D \cos^{-1}\left(\frac{2h_\ell}{D} - 1\right) \tag{5}$$

$$S_i = \left[\sqrt{1 - \left(\frac{h_\ell}{D} - 1\right)^2}\right] D \tag{6}$$

$$h_\ell = \frac{D}{2}\left(1 - \cos\frac{\gamma}{2}\right) \tag{7}$$

$$(1 - \alpha) = \frac{1}{2\pi}(\gamma - \sin\gamma). \tag{8}$$

The method used for measurement of $\tau_{w\ell}$, τ_{wg}, and α is described below.

Determination of interfacial shear stress from Reynolds shear stress measurements

The accuracy of the interfacial shear stress obtained from Eq. 3 is influenced by changes in the gas-liquid interface area as a result of wave formation in wavy stratified flows. It is therefore desirable to have an independent, more direct measurement of the interfacial shear stress. Besfamiliny et al. (1982) and Fabre et al. (1984) proposed that the interfacial shear stress in wavy stratified flow be determined from the Reynolds shear stress distribution in the gas and liquid phases.

The tangential shear stress in the gas phase may be expressed as

$$\tau_g = \mu_g \frac{\partial U_g}{\partial Y} - \rho_g \overline{u'v'}. \tag{9}$$

According to the data of Gayral et al. (1979) and Yuen (1982), the Reynolds shear stress, $\rho_g \overline{u'v'}$, far outweighs the viscous component, even very close to the interface. Consequently, as a reasonable approximation, the viscous component may be omitted.

In the present work, following the technique suggested by Fabre et al. (1984), the Reynolds shear stress profile was extrapolated to the gas-liquid interface to give the interfacial shear stress.

Experimental

Apparatus

The experimental facility used is shown schematically in Figure 2. It consisted of two parallel circuits, one circulating air or Freon 12 gas and the other water. The two streams were brought together in a mixer and then passed through the test section. Two centrifugal pumps circulated the water; a liquid-ring compressor circulated the gas. Bypass lines allowed the gas and water flows to be adjusted by manual valving. The test section was a Lexan pipe, 3.67 m long and 50.8 mm ID.

Procedure

To generate the wall shear stress and Reynolds shear stress data, the loop was brought to the desired operating pressure. The volumetric flow rate of the water was adjusted to a preselected value and the flow rate of the gas was increased in steps.

The wall shear stress experiments were conducted with air-water at 225 kPa and Freon 12 gas-water at 225 and 420 kPa, corresponding to a range of liquid-to-gas density ratios from 46 to 392. The range of Reynolds numbers were Re_g = 22,600 to 430,600 for the gas and Re_ℓ = 8,800 to 47,800 for water.

The Reynolds shear stress tests were carried out in air-water flows at 225 kPa, with Re_g = 24,260 to 57,200 and Re_ℓ = 15,590 to 36,560.

Instrumentation

Measurements were made of the wall shear stresses, the gas Reynolds shear stress $\rho_g \overline{u'v'}$, the void fraction, and the gas and liquid volumetric flow rates. Details are given below.

Measurement of wall shear stress

To measure $\tau_{w\ell}$ and τ_{wg}, the anemometry technique proposed by Shiralkar (1970) was used. The method used two flush-mounted probes, one on the top and one on the bottom of the pipe. Each probe was operated by a linearized, constant-temperature anemometry system, Thermo-Systems Inc. (TSI) model 1054A. The probes used in the gas and the water were TSI models 1237 and 1237W, respectively. The sensors were oriented so that their length was normal to the principal direction of flow.

By considering the boundary layer problem associated with flow over a heated wall (Leveque problem), it can be shown that the bridge voltage, E, of the anemometer is related to the wall shear stress, τ_w, as

$$E^2 = A_1 + B_1 \tau_w^{1/3} \tag{10}$$

where A_1 and B_1 are calibration constants.

The flush probes were calibrated by measuring the pressure drop and phase velocity in single-phase flows of air, Freon gas, and water. The wall shear stress measurements agreed with cal-

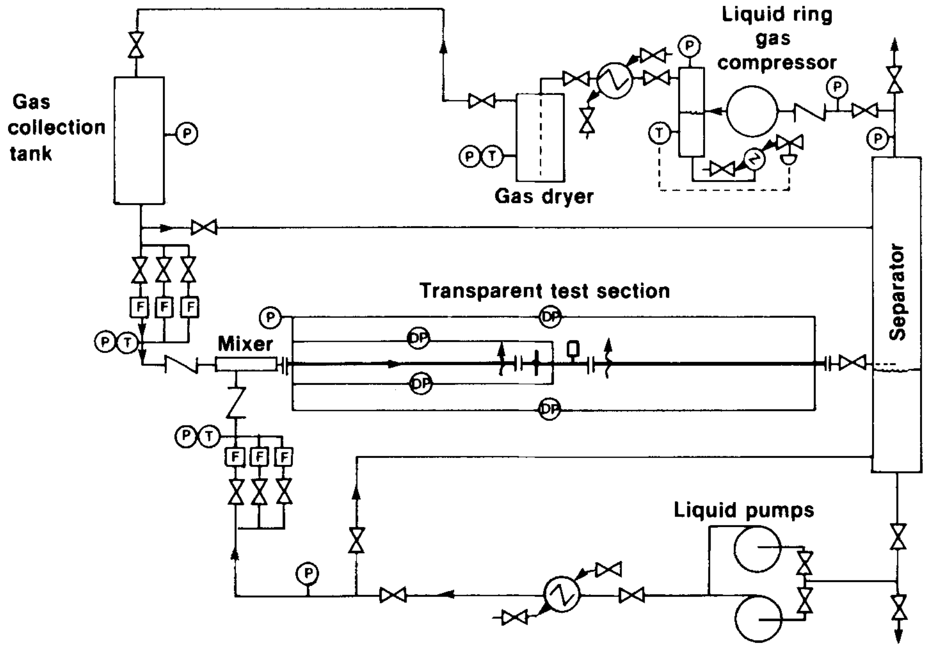

Figure 2. Diagram of test facility showing locations of measuring instruments.
F, flow rate; *P*, pressure; *T*, temperature
void fraction; flush probes; split-film probes

culated values. The calibrations are plotted as $\tau_w^{1/3}$ vs. E^2 in Figure 3, and show the expected linear trend. Calibration constants were $A_1 = 41.33$ and $B_1 = 8.2$ for air; $A_1 = 40.6$ and $B_1 = 8.32$ for Freon gas at a pressure of 225 kPa; $A_1 = 41.7$ and $B_1 = 8.6$ for Freon gas at a pressure of 420 kPa; and $A_1 = 39.0$ and $B_1 = 38.4$ for water.

The liquid flush probe was operated at a very low overheat to avoid bubble generation on the film surface. The effect of varying water temperature was overcome by adjusting the overheat resistance.

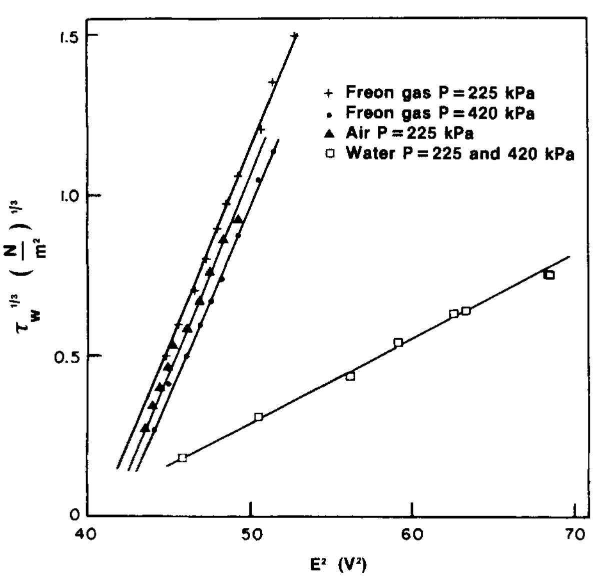

Figure 3. Shear probe calibrations curve.

Measurement of gas Reynolds shear stress $\rho_g \overline{u'v'}$ and mean gas velocity

The gas Reynolds shear stress and the mean gas velocity were measured by a split-film probe (TSI model 1287). The sensor of the probe had two electrically independent films on a single quartz fiber. Each film was connected to the linearized anemometer (TSI model 1054A) combined with a correlator (TSI model 1015C) and RMS meter (TSI model 1076).

To express the relation between the cross product of velocity fluctuations, $\overline{u'v'}$, and the mean square value of voltage signals from anemometers $\overline{e_1^2}$, and $\overline{e_2^2}$, the following relation was used (TSI, 1980):

$$\overline{u'v'} = \frac{2(\overline{e_1^2} - r^2\overline{e_2^2})}{c(m-1)U_g^{m-2}} \tag{11}$$

where $r = E_1/E_2$, E_1 and E_2 are the bridge voltage outputs, and constants $c = 0.63$ and $m = 0.8175$ were obtained by calibrating the probe in an air flow at 225 kPa. The mean square values of the voltage signals $\overline{e_1^2}$ and $\overline{e_2^2}$ were measured by the RMS meter. The calibration curve for the average longitudinal gas velocity, U_g, was processed in the form

$$\frac{E_1^2 + r^2E_2^2}{(t_s - t_e)} = 0.157U_g^{0.37} \tag{12}$$

where t_s is the surface temperature of the sensor and t_e is the air temperature in the channel.

The split-film probe was normally run at an overheat of about 1.5. One film of the probe had a fixed resistance; the second film required a fine adjustment of the resistance to equalize temperatures between the two films.

Measurement of void fraction

Single-beam gamma densitometers measured the void fractions. Each consisted of a sealed americium-241 source in a shielded cask, beam collimators, a NaI(TI) scintillation detector, and a signal processing system. For the conditions studied, the measurement error was less than 5%. The densitometers were calibrated for smooth and wavy stratified flows using shaped Lucite pieces.

Measurement of flow rates and pressure drop

Turbine flowmeters measured the volumetric flow rates of the water and gas. The gas turbine flowmeters were calibrated against orifice plates for both air and Freon gas at test condition pressures. The accuracy of the measurement was ±2%. Pressure drop measurements were obtained with a Miriam manometer with a range of 10.1 cm of water and a resolution of 0.05 cm.

Results and Discussion

Wall shear stress

The wall shear stress was measured at different circumferential locations around the pipe, to calculate circumferential average values. To do this, the test section was rotated in small steps. Typical wall-to-gas shear stress distributions encountered in two-phase stratified flow are shown in Figure 4. This figure shows that the major variations of wall shear stress occur close to the wall-gas-liquid interface. The measured wall shear stress distribution is different from those that were observed in rectangular channels (Davis, 1969).

The wall friction factor was calculated from

$$f_{wk} = \frac{2\tau_{wk}}{\rho_k U_k^2} \tag{13}$$

where $k = \ell, g$.

Figure 5 compares the experimental values of the wall-to-gas friction factor, f_{wg}, with theoretical smooth-tube values given by Eq. 14 from Taitel and Dukler (1976) and Eq. 15 from Agrawal et al. (1973):

$$f_{wg} = 0.046(Re_g^*)^{-0.2} \tag{14}$$

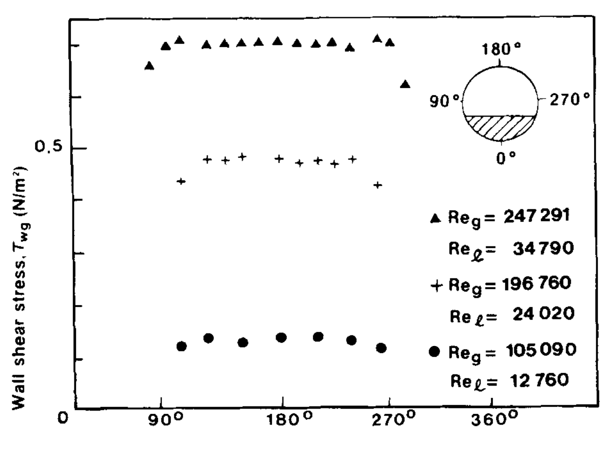

Figure 4. Variation of wall-to-gas shear stress around circumference of pipe in Freon gas-water flow, P = 225 kPa.

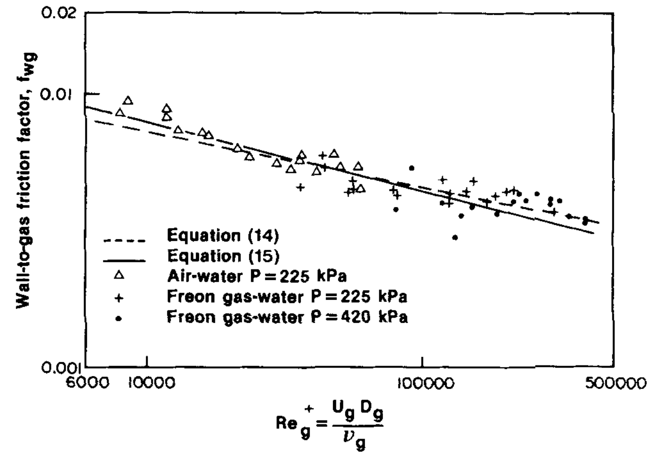

Figure 5. Comparison of wall-to-gas friction factor results with Eqs. 14 and 15.

$$f_{wg} = 0.079(Re_g^*)^{-0.25} \tag{15}$$

where

$$Re_g^* = \frac{4U_g\alpha A}{\nu_g(S_g + S_i)} \tag{16}$$

The experimental measurements agree reasonably well with Eqs. 14 and 15.

The wall-to-liquid shear measurements were conducted for various flow rates and void fractions up to $\alpha = 0.86$; at higher void fractions it was difficult to measure the wall shear distribution accurately over the small perimeter. In Figure 6 our wall-to-liquid shear data are compared with the equation of Agrawal et al. (1973):

$$f_{w\ell} = 0.079(Re_\ell^*)^{-0.25} \tag{17}$$

where

$$Re_\ell^* = \frac{4(1-\alpha)U_\ell A}{\nu_\ell S_\ell}.$$

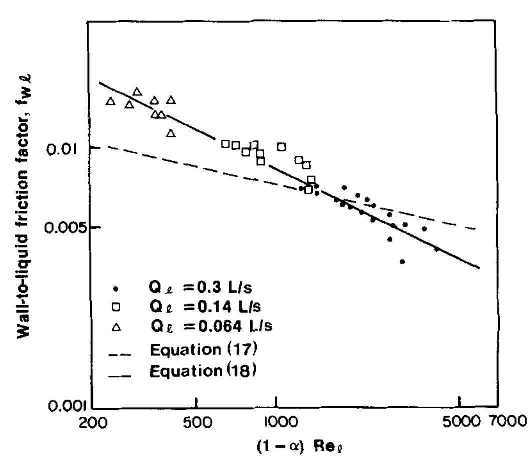

Figure 6. Wall-to-liquid friction factor data.

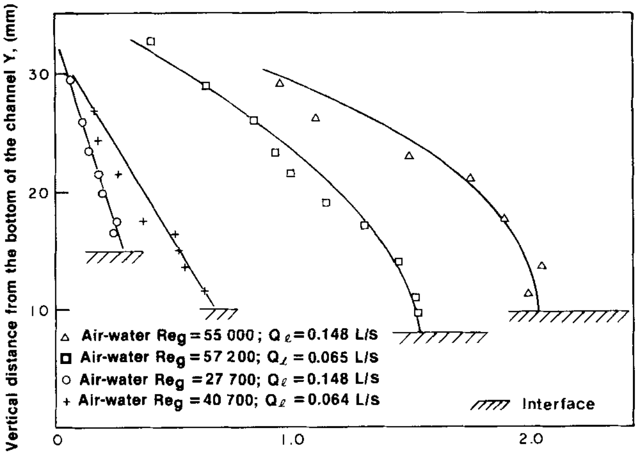

Figure 7. Reynolds shear stress profiles.

The discrepancy obtained is likely due to the fact that Eq. 17 was originally derived by assuming single-phase flow. The present data were found to be fitted by the following equation:

$$f_{w\ell} = 0.263\,[(1-\alpha)Re_\ell^+]^{-0.5} \tag{18}$$

where $Re_\ell^+ = (j_\ell D)/\nu_\ell$.

Reynolds shear stress

Figure 7 shows typical gas phase Reynolds shear stress profiles at Re_g = 30,330 to 57,200 and Q_ℓ = 0.064 to 0.148 L/s. As can be seen, the shear stress distribution deviates from linearity close to the interface at high gas velocities ($Re_g > 55{,}000$, $U_g > 7$ m/s). Also, the increase of the water and air flow rates leads to an increase of the Reynolds shear stress, $\rho_g \overline{u'v'}$, at a given location Y. Gas velocity profiles and turbulent shear stress distributions are presented in Figure 8. The data demonstrate clearly the existence of the displacement between the zeros of the turbulent shear stress ($\rho_g \overline{u'v'} = 0$) and the maximum in the gas velocity profile ($dU_g/dY = 0$). The measurements of the gas phase velocity showed that the plane of maximum velocity shifted toward the upper wall as the gas flow rate was increased.

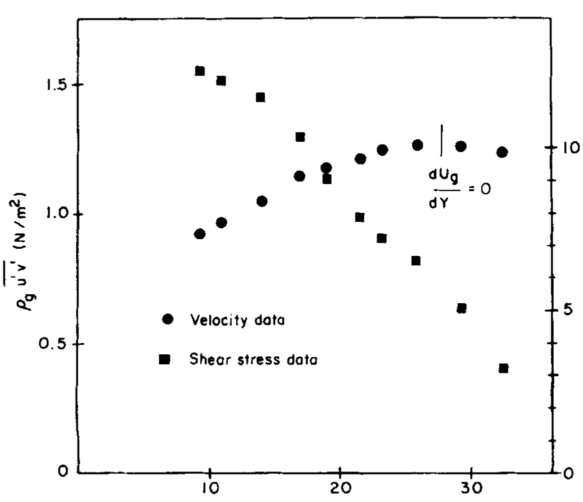

Figure 8. Mean gas velocity and turbulent shear stress profiles for wavy stratified flow.

Table 1. Interfacial Shear Stress

Run	U_g m/s	U_ℓ m/s	Re_g	Re_ℓ	h_ℓ mm	$\tau_i(\Delta P)$ N/m²	$\tau_{i(\overline{u'v'})}$ N/m²
ST197	3.52	0.303	24,260	17,490	15.7	0.155	0.165
ST198	4.4	0.322	30,330	18,560	15.0	0.28	0.29
ST199	5.68	0.423	39,150	25,000	12.45	0.7	0.72
ST200	7.09	0.5	48,870	30,170	10.6	1.485	1.26
ST201	8.3	0.606	57,200	36,560	9.8	2.27	1.97
ST202	8.25	0.375	56,870	21,650	8.0	1.97	1.56
ST203	5.8	0.264	40,000	15,590	10.1	0.6	0.67
ST204	5.2	0.333	35,840	19,640	14.67	0.45	0.5

Results obtained from a flow momentum balance, $\tau_{i(\Delta p)}$, and from Reynolds shear stress profile, $\tau_{i(\overline{u'v'})}$.

Interfacial shear stress in wavy stratified flow

The interfacial shear stress was determined in two ways:

1. From the flow momentum balance using measured values of wall shear stresses and void fraction at $\alpha \leq 0.86$ or of wall-to-gas shear stress, void fraction, and pressure drop at $\alpha > 0.86$
2. From the Reynolds shear stress profile

These methods were compared for the different runs. All the results are summarized in Table 1. At high Reynolds numbers ($Re_g > 55{,}000$), the interfacial shear, τ_i, determined from the flow momentum balance is 13 to 20% greater than that obtained from the Reynolds shear profile. The difference may be due to the increase of the interface area as a result of the wave formation, which causes the true value of τ_i to be smaller than that determined from the flow momentum balance. In Figure 9, the present Freon gas-water data were compared with the most commonly used correlations for rectangular channels. Very poor agreement was found.

The classical relation between average and friction velocities for rough internal flow (Sinai, 1983) may be applied to gas flow

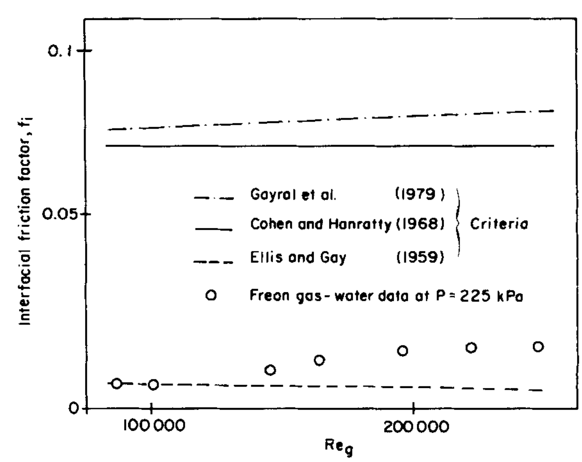

Figure 9. Comparison of interfacial friction factor data and analytical criteria for Freon gas-water flow, P = 225 kPa.

over a wave liquid surface in a circular pipe:

$$\frac{U}{U_\tau} = F\left(\frac{D}{\epsilon}\right), \tag{19}$$

where ϵ is the roughness height.

Pimsner and Toma (1977) showed that the roughness height of a rippled surface may be formulated in terms of the liquid film thickness and gas phase and liquid phase Reynolds numbers. Then

$$\frac{U}{U_\tau} = F\left(\frac{D}{h_\ell}, Re_g, Re_\ell\right). \tag{20}$$

If we assume that

$$\frac{U_\tau}{U} \simeq \sqrt{\frac{f_i}{2}} \tag{21}$$

and $h_\ell/D \simeq (1-\alpha)$, Eq. 18 may be expressed as

$$f_i = F[(1-\alpha)^{-1}, Re_g, Re_\ell] \tag{22}$$

or, assuming a power relation, as

$$f_i = C_1(1-\alpha)^a Re_g^b Re_\ell^d. \tag{23}$$

This equation may be written in a linear logarithmic form and the constants, k, a, b, and d, evaluated by the usual regression methods. The interfacial friction factor, f_i, was evaluated to be (Taitel and Dukler, 1976)

$$f_i = 2\tau_i/\rho_g(U_g - U_\ell)^2 \tag{24}$$

The present data were found, Figure 10, to be fitted by the following equation:

$$f_i = 7.5 \times 10^{-5}(1-\alpha)^{-0.25} Re_g^{-0.3} Re_\ell^{0.83} \tag{25}$$

for

$$22{,}600 \le Re_g = \frac{U_g D}{\nu_g} \le 430{,}600$$

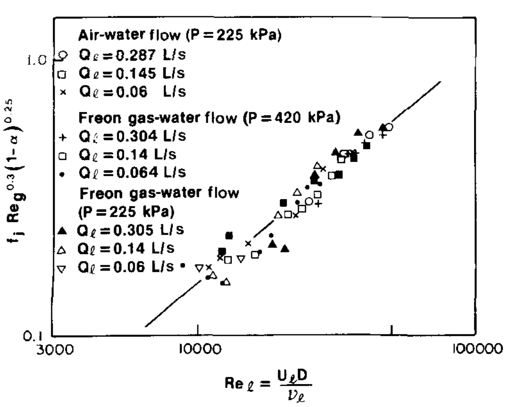

Figure 10. Interfacial friction factor data for wavy stratified flow.

$$8{,}800 \le Re_\ell = \frac{U_\ell D}{\nu_\ell} \le 47{,}800.$$

The interfacial friction data reported in literature (Hanratty and Engen, 1957; Ellis and Gay, 1959; Davis, 1969; Gayral et al., 1979; Besfamiliny et al., 1982; Tsiklauri et al., 1979) are compared with values predicted by Eq. 25 in Figure 11. There is good agreement; however, the data of Gayral et al. (1979) are overpredicted by Eq. 25 for low gas Reynolds numbers.

Interfacial shear stress in smooth stratified flow

The interfacial friction results from the present work for smooth stratified flow are plotted in Figure 12. Also shown is the correlation recommended by Agrawal et al. (1973):

$$f_i = 2[0.804(Re_g^*)^{-0.285}]^2. \tag{26}$$

Our data did not accurately fit this equation; possibly because Eq. 26 was originally derived by Ellis and Gay (1959) as a correlation for the wall friction factor. The following equation represented our smooth stratified flow data better:

$$f_i = 0.96(Re_g^+)^{-0.52} \tag{27}$$

where $Re_g^+ = (j_g D)/\nu_g$.

Equation 27 is only valid for smooth stratified flow. Visual observations of the interfacial structure in stratified flow were conducted to determine the wavy-smooth stratified transition in air-water and Freon 12 gas-water flows. The occurrence of the transition could be predicted by

$$Re_g^+ \le 8.78 \times 10^3 (Re_\ell^+)^{-0.405}\left(\frac{\nu_\ell}{\nu_g}\right)^{0.72}\left[\frac{\sigma}{gD^2(\rho_\ell - \rho_g)}\right]^{-0.9} \tag{28}$$

The correlation in Eq. 28, and previously reported data for air-water flows at 100 kPa in 25.5 mm dia. horizontal pipes (Barnea et al., 1980), and in 51 mm dia. pipes (Weisman et al., 1979) are

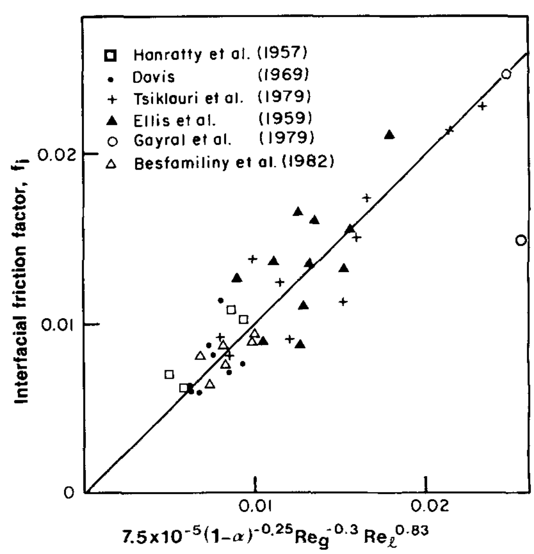

Figure 11. Comparison of correlation, Eq. 25, with other published data.

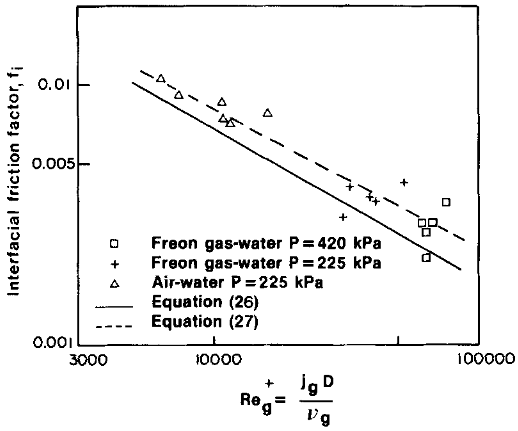

Figure 12. Interfacial friction factor data for smooth stratified flow.

shown in Figure 13. A predicted boundary separates the wavy and smooth stratified flow regimes satisfactorily.

Summary

Hot-film anemometory techniques have been employed successfully in this work to measure the wall and Reynolds shear stress in horizontal stratified flow. The interfacial shear stress was determined from a flow momentum balance and from the Reynolds shear measurements.

Based on the present data, empirical correlations have been proposed for predicting the wall-to-liquid and interfacial friction factors. The analytical results are in good agreement with other interfacial shear data.

Future work should examine the effect of pipe diameter and the physical properties of the liquid wave formation and, hence the interfacial shear stress. It may be also worthwhile to measure the interfacial shear stress in countercurrent flow for comparison with cocurrent data.

Acknowledgment

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Notation

A = flow cross-sectional area
A_1, B_1 = constants, Eq. 10
c = constant, Eq. 11
D = channel diameter
$\overline{e_1^2}, \overline{e_2^2}$ = mean square value of voltage signal
E, E_1, E_2 = output voltages
f = friction factor
F = function
h = average flow height of phase
j = superficial velocity; $j_g = U_g \alpha$; $j_\ell = U_\ell (1 - \alpha)$
m = constant, Eq. 11
dP/dx = pressure drop per unit length
Q = volumetric flow rate
Re = Reynolds number
r = constant, Eq. 11
S = perimeter
T = temperature
U = average longitudinal velocity of phase
$\overline{u'v'}$ = cross product of velocity fluctuations
Y = distance from wall

Greek letters

α = void fraction
γ = angle subtended at center of pipe by gas-liquid interface
ϵ = roughness characteristic
ν = dynamic viscosity
μ = kinematic viscosity
σ = surface tension
ρ = density
τ = shear stress

Subscripts

g = gas phase
i = interphase
h = hydraulic diameter
k = phase
ℓ = liquid phase
w = wall
τ = friction velocity

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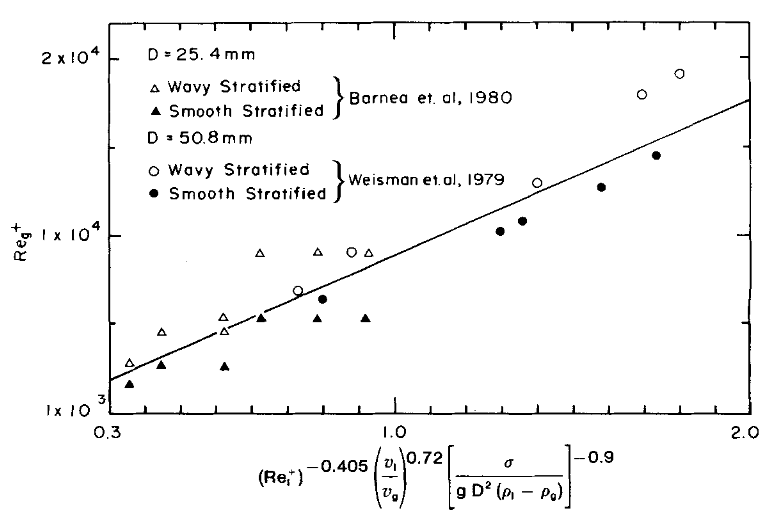

Figure 13. Comparison of wavy-smooth stratified flow regime data with Eq. 28.

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