Estimation of Gas Wall Shear Stress in Horizontal Stratified Gas-Liquid Pipe Flow

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Two-phase pipe flows occur in many industrial applications, such as condensers and evaporators, chemical processing equipment, nuclear reactors, and oil pipelines. It has been the subject of considerable research interest since the 1940s. A variety of basic mechanistic flow models for predicting the pressure gradient and liquid loading characteristics of these types of flows to assist in design calculations has emerged over the past two decades, especially for the stratified and slug flow regimes. These models generally rely on a number of basic assumptions and empirical closure equations. Possibly the most notable of these relates to the evaluation of interfacial shear stresses. However, one of the most important yet least discussed assumptions used in most of these models is that the phase wall shear stresses can be accurately estimated from correlations developed for single-phase pipe flows.

Kowalski (1987) has presented measurements of the wall shear stress at various radial locations in the gas region, and has concluded that existing methods for estimation of the gas wall shear stress seem to be adequate. However, the measurements indicated a drop in the wall shear near the gas-liquid interface, although neither the condition nor the location of this interface was reported. The results tend to suggest a relaxation of the velocity gradients in the vicinity of the interface, presumably as a result of the complex interaction of the wall and interface boundary layers. This relaxation must decrease the measured average wall shear, but since the position of the interface in relation to the maximum traverse of the probe was not reported, it is difficult to ascertain the extent of this decrease. This point has obvious implications in the overall accuracy of the empirical wall shear correlations, and clearly requires further investigation. Further, the length to diameter ratio of Kowalski's test section including the entrance region was 72, which may not have been sufficient to ensure well developed flow, especially at lower gas Reynolds numbers. If the flow was developing at the probe location, then the measured values of wall shear will be increased.

The object of this article is to present measurements of gas wall shear up to locations in close proximity to the gas-liquid interface for a variety of interface conditions in developed flow, and to determine the effects of the interface on average gas wall friction factors. In this context the interface may be smooth, rippled or wavy.

Analysis

Consider equilibrium stratified flow as shown in Figure 1. A one-dimensional momentum balance on each phase yields

$$-\frac{dP}{dz}A_L - \tau_{WL}s_L + \tau_i s_i = 0 \qquad (1)$$

$$-\frac{dP}{dz}A_G - \tau_{WG}s_G - \tau_i s_i = 0 \qquad (2)$$

Such an analysis was proposed by Govier and Aziz (1972), and it has been adopted in many mechanistic models of both stratified and slug flows, including those of Agrawal et al. (1973), Taitel and Dukler (1976), and Fan et al. (1993). Implicit in the formulation of Eqs. 1 and 2 are the assumptions of a constant density, steady horizontal unidirectional flow with a zero axial level gradient in the liquid, a straight interface, and an equal pressure gradient in the liquid and gas phases. Further, it is generally assumed that both the liquid and gas wall shear stresses are simple functions of the mean flow velocities of each phase. Using these assumptions, and solving Eqs. 1 and 2 to eliminate the pressure gradient term, the interfacial shear stress is given by

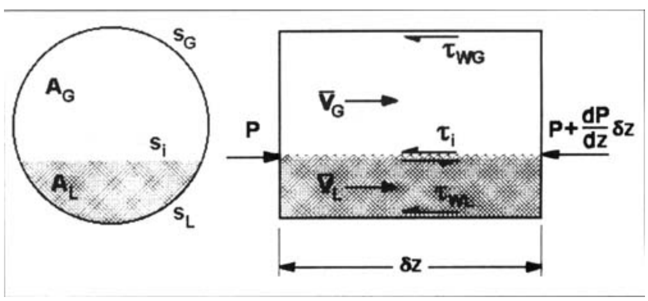

Figure 1. Geometry of stratified gas-liquid flow.

$$\tau_i = \frac{1}{s_i}[\tau_{WL}s_L(1-H_L) - \tau_{WG}s_G H_L] \quad (3)$$

where H_L is the liquid holdup, conventionally defined as

$$H_L = \frac{A_L}{A_L + A_G} \quad (4)$$

Equations 1 and 2 have also been applied to experimental data in order to estimate interfacial shear stresses from measured values of pressure gradient and liquid holdup, such as in the study of Andritsos and Hanratty (1987). Examination of Eq. 3 indicates the relative importance of the wall shear terms in the accuracy of interfacial shear stress measurement.

For the calculation of gas and liquid wall shear stresses, most investigators have reverted to relationships developed in single-phase pipe flow. Agrawal et al. (1973) have suggested that the flow of the liquid may be approximated by a channel flow, while the gas motion may be considered as a fully bounded duct flow. Consequently, the hydraulic diameters for the liquid and gas are given by

$$D_{HL} = \frac{4A_L}{s_L} \quad (5)$$

$$D_{HG} = \frac{4A_G}{s_i + s_G} \quad (6)$$

The use of Eqs. 5 and 6 allows the calculation of the true average Reynolds number of each phase, using mean velocities calculated from average phase areas. For the gas region this is given by

$$Re_G = \frac{\rho_G \bar{v}_G D_{HG}}{\mu_G} \quad (7)$$

This formulation is intended to transform the flow regions into equivalent circular ducts, in which single-phase relations may be applied. In order to calculate the gas wall friction factor, Agrawal et al. suggested the use of the smooth pipe Blasius equation, given by

$$f_G = 0.079 Re_G^{-0.25} \quad (8)$$

where the wall shear is calculated from

$$\tau_{WG} = \frac{1}{2} f_G \rho_G \bar{v}_G^2 \quad (9)$$

This equation has also been used by Russell et al. (1974). Other formulations have followed similar themes. The more widely used version of the Blasius equation is given by

$$f_G = 0.046 Re_G^{-0.2} \quad (10)$$

and has been used in the studies of Taitel and Dukler (1976), Andritsos and Hanratty (1987), Spedding and Hand (1990) and Landman (1991), among others. It should be noted that the values of f_G given by Eqs. 8 and 10 differ by 8.2% at $Re = 1 \times 10^4$.

Experiments

Measurements of gas wall shear were made in 50- and 80-mm-dia. straight, horizontal acrylic tubes. The entrance length to the 2 m test section of each tube was 10.4 m, giving entrance length-to-diameter ratios of 208 and 130, respectively. In order to minimize the effects of the pipe outlet, 3.5-m exit sections were installed on both lines.

The test sections were interchangeable and contained either the wall shear measurement apparatus, or a separate section with provision for velocity profile measurements using Pitot tubes, and liquid height measurements using resistivity probes similar to those described by Barnea et al. (1980). The pipes were carefully leveled and the maximum deviation in the test sections was less than 0.2 mm. At no stage were interfacial level gradients observed in either test section, and thus the assumption of a quasi-steady flow seems valid.

In all the experiments the fluids used were dry air and water. The air was supplied from either a reciprocating or a screw type compressor, depending on the flow rates required. In this study these rates were in the range of 3–32 L/s. Liquid was supplied from a 200-L storage tank, and was pumped to the mixing chamber by a centrifugal pump, where it was combined with the gas and directed into the test section. The liquid flow rates were varied between 0.06–0.46 L/s. The two-phase mixture was separated at the pipe outlet at atmospheric pressure, and the liquid was returned to the storage tank. Both the liquid and gas flow rates were measured with electronic differential pressure transducers connected to orifice plates. Pressure gradients in the pipe were measured with a number of static tappings located in the top wall to ensure that the flow had reached steady conditions. These pressures were measured with an inclined manometer with a maximum reading of 12.7-mm H_2O, and a resolution of 0.064-mm H_2O.

In order to measure the wall shear stress in the gas region of the flow, a single Preston tube with an external diameter of 1.2 mm was attached to the wall of each test section. The geometry of the Preston tube arrangement that was used in the experiments in the 50-mm test section is shown in Figure 2. The point of attachment of the tube was contained within a section of the pipe that allowed axial rotation, so that a

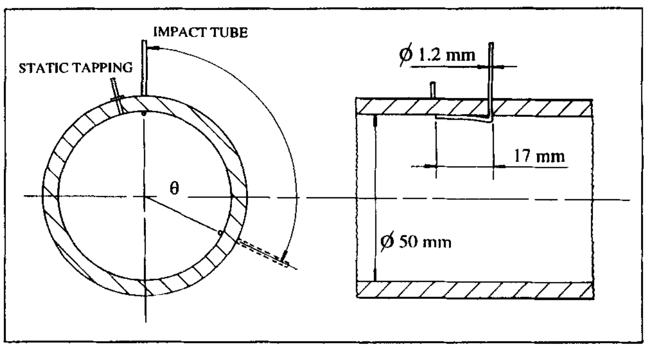

Figure 2. Preston tube arrangement in 50-mm pipe.

complete radial traverse of the gas wall could be performed down to locations in close proximity to the gas-liquid interface. This arrangement was considered preferable to that of Davis (1969), who used a number of Preston tubes to measure the gas wall shear in gas-liquid flow in a rectangular duct. For the purposes of calibration, measurements of gas wall shear stress in single-phase pipe flow were compared with the published correlations of Patel (1965). These were observed to slightly overpredict the measured data to within 5%. For improved accuracy, the measured data were correlated independently for use in this study. The location of the probe static pressure tapping was a cause for some concern and a number of configurations were examined. However, in the calibration experiments no effects of the location of this tapping were observed.

Preston tubes have the advantage of being a low cost alternative to more elaborate hot wire and LDA methods. They are also durable and thus allow measurements quite near the liquid surface without the likelihood of damage. The disadvantages of such a measuring system are that only shear stress in one direction (i.e., axial) is measured, and the measured pressure differentials are quite small, requiring accurate and sensitive pressure transducers. Since we are only interested in the one-dimensional momentum balance in this study, the first limitation is of no consequence, while the second is solved by the use of a highly responsive digital micromanometer, interfaced to the computer data acquisition system for data averaging, and calibrated to a resolution of 0.2-mm H_2O with a Betz manometer.

Patel (1973) has shown that for moderate to high Reynolds numbers the velocity profiles in the wall regions of fully developed flow over flat plates and in pipes can be considered identical. Thus, if a Preston tube is located wholly within this inner region where the shear stress is presumed to be constant, the measurements should be accurate irrespective of the overall geometry of the flow. The Preston tubes used in this study were chosen such that their d_P/D ratio was far smaller than the maximum calibrated by Patel (1965).

Measurement Procedure

Once the desired flow conditions had been set, the Preston probe was traversed clockwise (as in Figure 2) from the top of the pipe ($\theta = 0$) towards the interface ($\theta = \theta_i$), and then back again. Some pressure readings were also taken in an anticlockwise direction to ensure a symmetrical distribution of the measured values. The average interface location was determined with the aid of the resistivity probe. Where the presence of two-dimensional and unsteady roll waves was observed, the limit of the traverse was near the top of the wave crests. Measurements were generally taken at angular intervals of 10–15°, although this was refined in regions where large gradients were observed. At each location, at least two measurements were taken per traverse. This involved sampling the pressure readings from the micromanometer at 200 Hz over 10 s and calculating a local average. Various other sampling rates and times were also examined, but these did not appear to alter the results. Where the interface contained significant wavy motion, the sampled data were examined to determine whether the wave speed caused any noticeable fluctuations in measured pressure differences in the Preston tube; however, no significant relationships between these parameters was found.

Results and Discussion

The measured wall shear distributions were found to be strongly influenced by the condition of the gas-liquid interface. In the range of flow rates tested here the presence of interfacial disturbances in the form of ripples, two-dimensional waves, and unsteady roll waves were observed in addition to the stratified smooth flow regime.

A representative set of wall shear measurements is shown in Figure 3. In this instance the average interfacial location was at 111°, and the interface contained small ripples. It can be seen that while there is some scatter in the data, particularly as the interface is approached, the measured peak-to-peak values were within 5% of the local mean. This pattern of experimental scatter is typical of all the experimental results.

Examination of Figure 3 highlights the relaxation of the wall shear near the interface as reported by Kowalski (1987). However, Kowalski did not observe the subsequent rise adjacent to the interface, which serves to increase the overall average value. For low liquid flow rates, where there was insufficient liquid momentum for the buildup of large waves, the measurements shown in Figure 3 are representative of all the observed profiles, although as the gas velocity was increased the trough was observed to move slightly away from the interface. This effect is likely to be due to the shift in the velocity profile of the gas to compensate for the increased roughness of the interface.

For higher liquid flow rates, a similar distribution of measured values was observed for low gas velocities. However, as the gas flow was increased the interfacial structure became increasingly wavy and a reversal in the measured shear profiles was observed, an example of this being shown in Figure 4. This reversal serves to increase the average value of the gas wall shear and may be caused by separation of the gas flow from the wave crests. The effect became more pronounced with increasing gas flow rate. It is interesting to note that the same qualitative distribution of wall shear measurements was observed in the 80-mm pipe over the same range

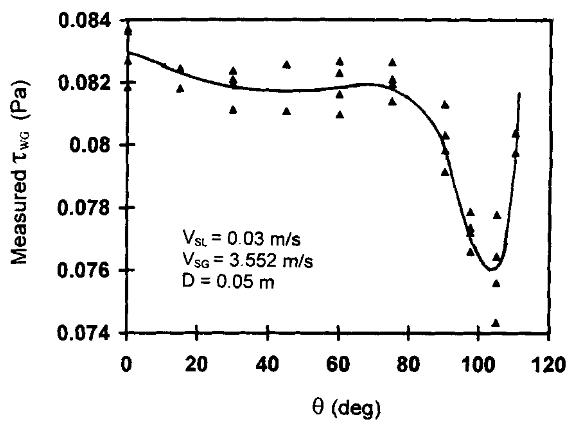

Figure 3. Typical gas wall shear stress profile for stratified/ripple flow.

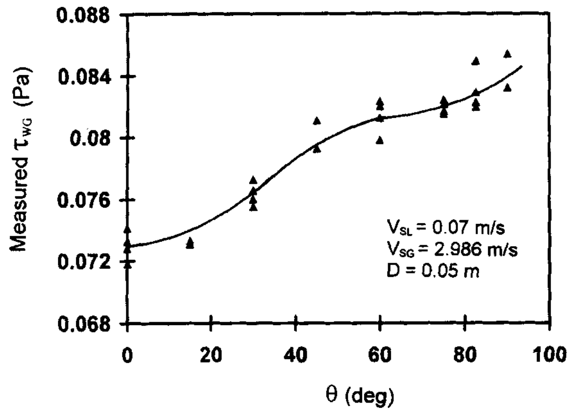

Figure 4. Typical gas wall shear stress profile for stratified/wavy flow.

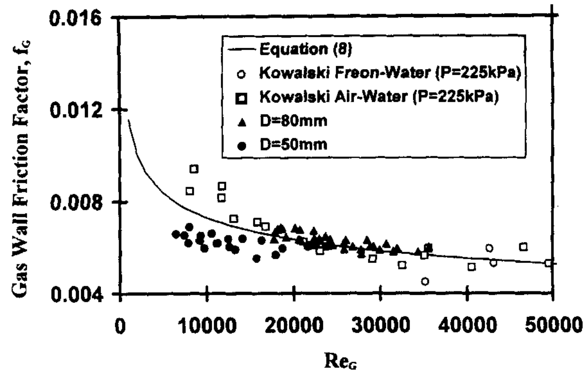

Figure 6. Comparison of measured gas wall friction factor with data of Kowalski (1987).

of interfacial conditions, although the peak-to-peak values near the interface were generally smaller.

In order to examine the validity of existing full pipe flow correlations for predicting gas-phase wall shear, the measured wall shear data required averaging. Since the measurements were not taken at equal angular increments due to large gradients near the interface, the following weighting method was used

$$\bar{\tau}_{WG} = \frac{\sum_{1}^{N} 0.5(\tau_{W_{N+1}} + \tau_{W_N})\theta_N}{\sum_{1}^{N} \theta_N} \tag{11}$$

where N is the number of measurement intervals, and τ_{WN} and τ_{WN+1} are the local average values on the endpoints of each interval. The calculated average values are compared with the Blasius friction factor correlations in Figure 5. For higher gas-phase Reynolds numbers (i.e., $Re_G > 2 \times 10^4$), the correlations and measured data tend to converge, and the absolute errors between predicted and measured data are to the order of 5%. This accuracy is probably due to the fact that as the gas-flow rate is increased, the liquid holdup generally diminishes and the gas region becomes increasingly circular, resembling full pipe flow. However, at low gas phase Reynolds numbers the measured data diverge rapidly from the empirical correlations as the gas-flow rate is decreased. While Eq. 8 was the most accurate of the empirical equations at these Reynolds numbers, the calculated values overpredicted the measured ones to the order of 20–30%. It is interesting to note that despite the qualitative variations in measured shear profiles which appear to be dependent on the structure of the interface, the average friction factor data exhibit relatively little scatter, suggesting that the liquid holdup may be more significant at lower gas flows than the interfacial condition.

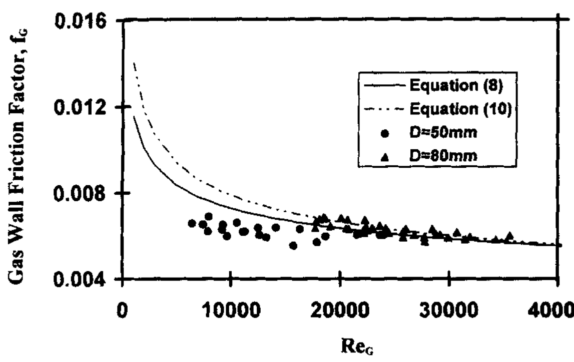

Figure 5. Comparison of measured gas wall friction factor with Eqs. 8 and 10.

The measured data are compared with those of Kowalski (1987) in Figure 6. They show that there is a wide discrepancy between the two sets of data and Eq. 8 where $Re_G < 2 \times 10^4$. It should be noted, however, that Kowalski measured wall shear extremely close to the inlet of the test section, where the flow is likely to be developing and thus the velocity gradients at the wall are expected to be higher. It is interesting to note that measurements of liquid wall shear presented in the same article were also significantly higher than those predicted with Eq. 8 at low Reynolds numbers. In general, for single-phase flow, fully developed conditions can be expected after entrance lengths of 125 diameters (Massey, 1989), while the entire length of the experimental test section of Kowalski was 72 diameters. Kang and Kim (1993) have measured gas wall shear in two-phase rectangular duct flow and have found that the inlet conditions increased the measured wall shear over theoretical values in developing flow. For higher Reynolds numbers, the data of Kowalski also approaches the values measured in this study, and those predicted by Eq. 8. This is probably because the increased turbulence levels in the gas region act to shorten the length required for development of the two-phase flow. Finally, for $6 \times 10^3 < Re_G < 3 \times 10^4$ the present data are best correlated by

$$f_G = 0.015 Re_G^{-0.094}, \tag{12}$$

although, as noted previously, at these Reynolds numbers the friction factor is likely to be a more complicated function of the two-phase flow parameters. Further experimental data is required to establish whether expressions of the type given by Eq. 17 can be used with confidence in two-phase flow calculations at low gas Reynolds numbers and high liquid holdups.

However, assumptions regarding the universality of the velocity profiles in the inner region begin to break down as the turbulent/laminar transition is approached, precluding the use of Preston tubes for wall shear measurements in the lower Reynolds number range.

Notation

A = area
d_P = Preston tube outer diameter
D = pipe diameter
f = friction factor
P = pressure
s = perimeter or length
$\bar{v}$ = mean phase velocity
z = coordinate in direction of flow
μ = dynamic viscosity
ρ = density
τ = shear stress

Subscripts

H = hydraulic
S = superficial
W = wall

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