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R & D NOTES

Wall Shear Measurements by Electrochemical Probe for Gas-Liquid Two-Phase Flow in Vertical Duct

G. COGNET, M. LEBOUCHE, and M. SOUHAR

Institut National Polytechnique de Lorraine
Nancy, France

For over 40 years, gas-liquid two-phase flows have been very important in the field of industrial sciences as their heat and mass transfer properties, particularly in chemical, oil and nuclear engineering.

These flows are usually classified according to the relative configuration of the two phases, mainly by geometrical and visual criteria (buble, slug, annular flows, etc.).

To better understand the transport phenomena in these rather complicated flows, we need more experimental data, among which is the momentum transferred to the wall by the shear stress. Usually this quantity is indirectly obtained from overall measurements (total pressure drop, average void fraction, etc.). In vertical ducts, the pressure loss by friction is small compared with the total pressure drop and the pressure loss by gravity (weight of the fluid column); therefore, a small error concerning these two terms may involve a considerable uncertainty for the friction. This leads to the interest on the direct measurement of the local wall shear stress.

The electrochemical technique using probes mounted flush to the wall appeared to be convenient for that purpose.

TECHNIQUE OF MEASUREMENT AND EXPERIMENTAL CONDITIONS

In the electrochemical method called "Polarography," the electrolysis current, I, which results from the transfer of active ions to the electrode, is controlled by hydrodynamic conditions (Reiss and Hanratty, 1962; Lebouché and Cognet, 1967; Mizushina, 1971).

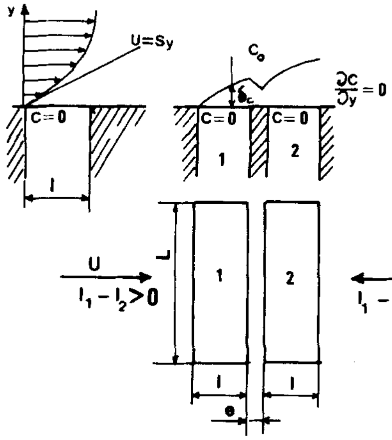

Figure 1. Electrochemical method: single and double probe.

For a small rectangular probe mounted flush to the wall and cross to the flow direction, the mass transfer is related to the local wall shear, S, in dimensionless form (Reiss and Hanratty, 1962)

$$Kl/\mathcal{D} = 0.807(Sl^2/\mathcal{D})^{1/3} \tag{1}$$

K is the average mass transfer coefficient at the probe; l, its width in the flow direction; L, its length; and $\mathcal{D}$ the diffusion coefficient of the active ion.

A single probe is not suitable to measure the friction when both direct and reverse flows occur, as can be observed in vertical two-phase flow. In this case, a double-probe technique has to be used (Figure 1). If two parallel rectangular electrodes are separated by a thin insulating sheet, the current received at the upstream electrode (1) is greater that the current at the downstream one (2); so the sign of the difference of the two intensities indicates direct- or reverse-flow conditions. When the effect of the isolating separation (e) on the concentration boundary layer development is negligible (for $e \ll 1$) we have (Labbé, 1975):

$$(K_1 - K_2)l/\mathcal{D} = 0.21(Sl^2/\mathcal{D})^{1/3} \tag{2}$$

where K_i is the mass transfer coefficient at the i electrode (i = 1 or 2). This relation shows that the value and the direction of the wall shear stress can be obtained from a double probe.

The experimental circuit is schematically represented on Figure 2. The vertical circular duct (internal diameter D = 44 mm, length H = 7,300 mm) is fed at its lower end with the liquid from a tank and with the gas from an injector. The test element located at $\mathcal{L}$ = 5,300 mm from the entrance ($\mathcal{L}/D$ = 120) is equipped with rectangular wall probes (single and double: l = 0,1 mm; L = 1 mm; e < 0,01 mm), which have been made out of a platinum ribbon.

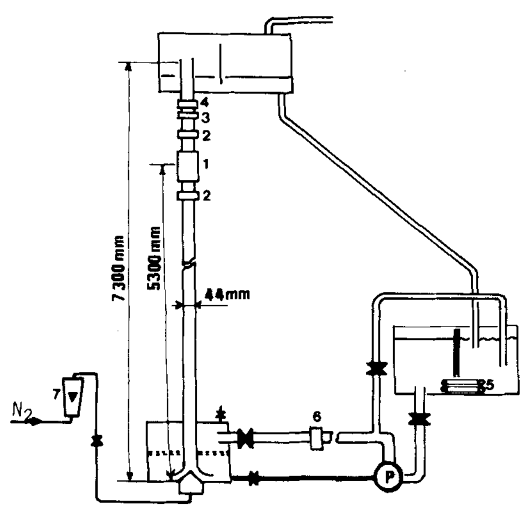

Figure 2. Experimental circuit. 1. Test section (probes: microcathodes) 2. Pressure taps 3. Anode 4. Thermometer 5. Heat exchanger 6. Orifice meter 7. Rotameter P. Pump

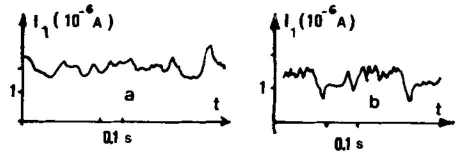

Figure 3. Typical signal delivered by a single probe. a: bubble flow b: plug flow

The convenient liquid for the electrochemical method is an aqueous solution of Ferri Ferro cyanide of potassium (concentration C_o = 2.8 10^{-6} mol/cm^3) with a large amount of potassium chloride as indifferent electrolyte (10^{-3} mol/cm^3). At 18°C (controlled temperature of the loop), its physical properties are respectively:

- Density: ρ_L = 1,020 kg/m^3
- Kinematic Viscosity: ν_L = 1.06 10^{-6} m^2/s

The diffusion coefficient of the Ferricyanide (active ion in the potential conditions which are imposed on the electrodes) is $\mathcal{D}$ = 6.8 10^{-10} m^2/s (Souhar, 1979) and the Schmidt number $Sc = \nu_L/D$ = 1,566.

The gas is nitrogen supplied by high-pressure bottles; in standard conditions, its density is ρ_{GS} = 0.115 kg/m^3. All the runs were performed in bubble and slug regimes, the corresponding mean velocity being 0.15 < U_L < 1.35 m/s for the liquid and 0.03 < U_{GS} < 3.70 m/s for the gas. The relations 1 and 2 have been established with constant concentration as infinite conditions. A numerical calculation of the concentration field (Labbé, 1975) shows that for high Schmidt numbers ($Sc > 10^3$) the concentration boundary layer thickness (δ_c) in a dimensionless presentation

$$\delta^+ = \delta_c \sqrt{S/\nu_L}$$

is smaller than unity.

So it can be considered that the method is effective as long as the wall is covered with a liquid film. When it happens to be dry, no more current is delivered by the probe which then acts as a phase detector.

SINGLE AND DOUBLE PROBES: QUALITATIVE RESULTS

A single probe gives the absolute value of the wall shear in the liquid phase and possibly in the void fraction. For all the runs it has been checked that the electrode always delivers a current, which means that the wall is continuously wetted with liquid in both regimes.

The current, I, recorded in the bubble flow (Figure 3a) is approximately the same as the one observed in single-phase turbulent flow but with much higher fluctuation rate. In the slug flow (Figure 3b) we obtain a typical signal pattern corresponding to the alternative passage of the liquid plug and the gas slug in front of the electrode.

The difference of currents, $I_1 - I_2$, obtained from a double probe, gives the algebraic value of the wall shear. This is particularly interesting in the slug flow. The signal record, Figure 4, may be interpreted as follows.

During the passage of a liquid plug, the flow is upwards. The signal, positive with a great fluctuation rate, looks chaotic as in turbulent or in bubble regime. When the front of a gas slug approaches the probe level, the liquid near the wall is decelerated and

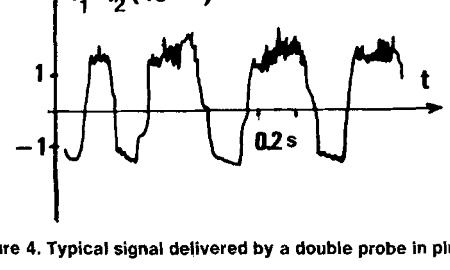

Figure 4. Typical signal delivered by a double probe in plug flow.

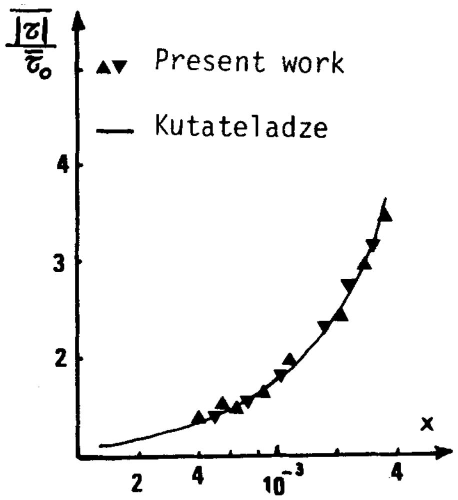

Figure 5. Experimental results of wall in friction in plug flow. Comparison with Kutateladze's data.

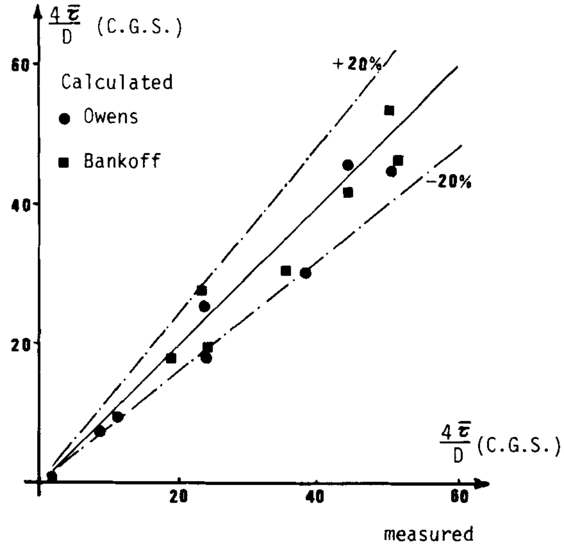

Figure 7. Comparison of experimental results in bubble flow with Owens and Bankoff model's.

a liquid film is formed around the slug that can fall down if its weight is too high against the gas friction in upwards direction. The shape of the negative part of the signal suggests at first a downwards acceleration, then a relative stabilization of the falling film, possibly disturbed by small bubbles carried by the flow and waves appearing on the free surface. A sudden upwards acceleration at the end of the sequence indicates the bottom of the slug and the arrival of the next liquid plug.

WALL FRICTION: RESULTS AND DISCUSSION

Each run has been conducted at a fixed liquid velocity U_L, while the gas velocity U_{GS} is being changed. The current delivered by each probe was converted in voltage, recorded, and then processed by a computer for linearization and time-averaging (Souhar, 1979). Owing to the low frequencies of the main fluctuations of the signals, it can be assumed that the relations 1 and 2 remain valid even in such unsteady conditions (Delage, 1979). So the mean absolute value of the friction is:

$$\overline{|\tau|} = \mu_L \overline{|S|} = \alpha \bar{I}^3 \text{ from a single probe}$$

and its time-averaged algebraic value

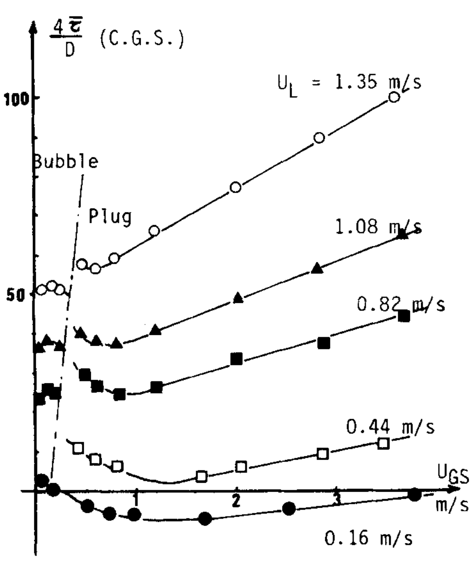

Figure 6. Pressure drop by wall friction.

$$\bar{\tau} = \mu_L \bar{S} = \beta \overline{(I_1 - I_2)^3} \text{ from a double probe}$$

α and β coefficients depend on the electrode geometry and fluid properties.

Mean Absolute Value of the Friction: $\overline{|\tau|}$

The absolute value of the friction is compared with the friction ($\bar{\tau}_o$) measured in the one-phase flow for the same U_L. The ratio $\overline{|\tau|}/\bar{\tau}_o$ is reported on Figure 5 against mass fraction x for U_L = 1.08 m/s and 1.33 m/s. There is a close agreement with the results given by Kutateladze and Nakoryakov (1975) from experiments made in a smaller duct (I.D. = 15 mm), but at nearly the same reduced distance from the injection ($L/\mathcal{D}$ = 103).

Mean Algebraic Value of the Friction $\bar{\tau}$

Figure 6 presents the part of the pressure gradient corresponding to the mean friction as a function of the gas velocity U_{GS}, with U_L as parameter

$$-\left.\frac{dp}{dz}\right|_f = \frac{4\bar{\tau}}{D}$$

- In the bubble regime the friction increases, reaches a maximum, and then decreases, but remains always positive as U_{GS} increases.
- In the slug regime the friction begins to decrease, goes through a minimum, and then increases quasilinearly. For $U_L < 0.4$ m/s, the mean friction can become negative; therefore, it can be shown (Souhar and Cognet, 1979) that the negative friction (downwards) of the falling film at the wall, in average, is greater than the positive friction (upwards) of the liquid plug.
- The change of friction is very sharp between the bubble and the slug flows, so the dotted line nearly joining the discontinuity of each curve represents an objective criterion of separation between the two regimes.
- The results are compared with the classical correlations: in the bubble regime, the discrepancy with Owen and Bankoff models (1960), Figure 7, is about 20%; for the slug regime (Figure 8), the agreement with Lockart and Martinelli's correlation (1949) is good for $U_L > 0.4$ m/s.

CONCLUSION

This work shows the advantage of the electrochemical method with double differential electrodes for local and instantaneous

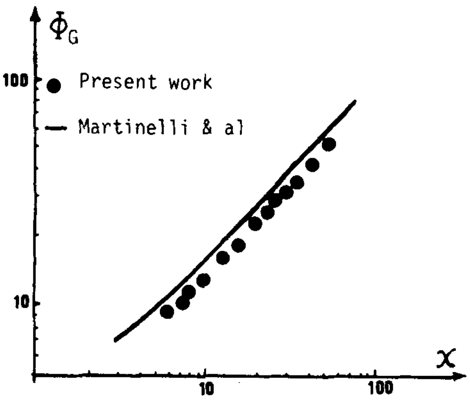

Figure 8. Comparison of experimental results in plug flow with Martinelli's data.

measurements of wall friction in a two-phase flow. By more elaborate statistical processing of the signal received from the probes, we hope to obtain more precise data about the structure and transfer properties of such flows near the wall as has already been done in a one-phase turbulent flow.

NOTATION

C_o	= concentration of active ions, mol/cm^3
D	= internal diameter of the circular duct, mm
$\mathcal{D}$	= diffusion coefficient of active ion, m^2/s
F	= Faraday's constant
$I, I_1 - I_2$	= currents delivered by single probe, double probe, A
K	= mass transfer coefficient $K = I(nFC_oLl)^{-1}$
L	= duct length from gas injector to the measuring probe, mm
l, L	= width and length of rectangular probe, mm
n	= number of electrons involved in the electrochemical reaction
p	= pressure, Pa
S	= wall shear, s^{-1}
T	= temperature
U	= velocity, m/s

Greek Letters

ρ	= Density kg/m^3
μ,ν	= Dynamic viscosity Pl; Kinematics viscosity m^2/s
τ	= Wall friction, $\overline{}$ time average, $\vert\ \vert$ absolute value
$\delta_c,\delta+$	= Concentration boundary layer thickness, dimensionless value of δ_c
χ,ϕ_G	= Martinelli's parameters

$$\chi^2 = \left(-\frac{\partial p}{\partial z}\right)_{L,o} \Big/ \left(-\frac{\partial p}{\partial z}\right)_{G,o}$$

$$\phi_G^2 = \left(\frac{4\tau}{D}\right) \Big/ \left(-\frac{\partial p}{\partial z}\right)_{G,o}$$

Subscripts

G,GS	= gas, gas standard conditions
L	= liquid
o	= one-phase flow

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Dimensionless Presentation of Performance Data for Fans and Blowers

E. N. LIGHTFOOT, P. S. THORNE, and L. L. STOLL

Department of Chemical Engineering
Univeristy of Wisconsin
Madison, WI 53706

The purpose of this paper is to show how dimensional analysis and simple physical arguments can be used to extend the utility of available performance data for such low-pressure fans and blowers as those used in ventilation systems. Our development arose in response to our desire to reduce the numbers of tables and graphs now supplied for describing the performance of a blower series, and to our need to extend the data supplied by manufacturers to operating conditions beyond those described.

The primary result of our development is to show that, for any one device, all properly-scaled measures of performance depend essentially on only one parameter, the scaled throughput, Q^*

Correspondence concerning this paper should be addressed to P. S. Thorne.