Device for Research into Falling Film Wave Structures under Shear Stress

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Techniques used to study organic film/gas systems may help gain insight into the influence of viscosity, density and surface tension on large wave inception, wave frequencies (Okada and Fujita, 1993; Nencini and Andreussi, 1982), and related gas-liquid interaction in annular flow. Organic nonconducting liquids are incompatible with the extensively used conductimetric methods (Sekoguchi et al., 1985; Zabaras and Duckler, 1988; Wasden and Duckler, 1989). Light absorption techniques like fluorescence are a promising option, provided that appropriate dyes and wavelengths on which the fluid is transparent are available. These techniques might provide results with lower base noise, allowing the application of chaos methods for wave analysis (Lacy et al., 1991).

A test was run on an externally wetted column, encased by a transparent wall to produce a falling film which can be video-recorded or photographed to obtain accurate data on wave evolution and shape. The usefulness of the results from an external falling film is a preliminary question. Figure 1 shows predicted values vs. experimental results for pressure drop in annular two-phase gas-liquid downflow (Chien and Ibele, 1964) and in biannular gas-liquid downflow [gas circulates between two cylinders with liquid flowing along the inner face of the outer cylinder and the outer face of the inner cylinder (Filho, 1985)]. In both cases, the calculation of pressure drops is based on the Wallis equation, where the values of film thickness are those experimentally measured by these authors. It can be seen that for lower-pressure drops, the ratio between experimental and measured values is similar for annular and biannular flow. This means that applying the same treatment to the outer and inner films in biannular flow does not introduce additional errors. The results show that for pressure gradients of up to 4,000 Pa/m, the deviations are similar in both cases. This condition occurs for Filho's experiments for superficial gas velocities up to 21.9 m/s and superficial liquid (water) velocities up to 0.3 m/s. This is equivalent to Re_G 40,000 and Re_L 3,000. Therefore, the results collected on outer falling films may be applied to inner falling films for moderate turbulent liquid and gas-flow rates.

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Experimental Studies

The device (Figure 2) consists of a glass column 120-cm long with an inner diameter of 28 mm and with four pressure tappings at 25-cm intervals, connected to a pressure metering board. Switches allow the measurement of absolute pressure at each tap, as well as the pressure drop from the top of the column. At the top and bottom of this column are located the gas inlet, and the gas and liquid outlets, respectively. Another hollow glass column is placed in axial position with a length of 100 cm and an outer diameter of 18 mm. The liquid

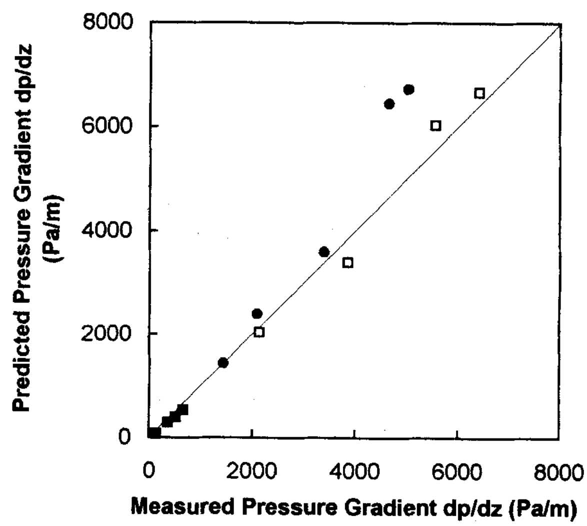

Figure 1. Predicted vs. measured pressure drops.

The trends are similar for both annular (Chien and Ibele with ReG 60,000 -■- and ReG 260,000 -□) and biannular (Filho -●) below 4,000 Pa/m. Therefore, if the same treatment yields the same results, it might be assumed that similar criteria are valid within this range.

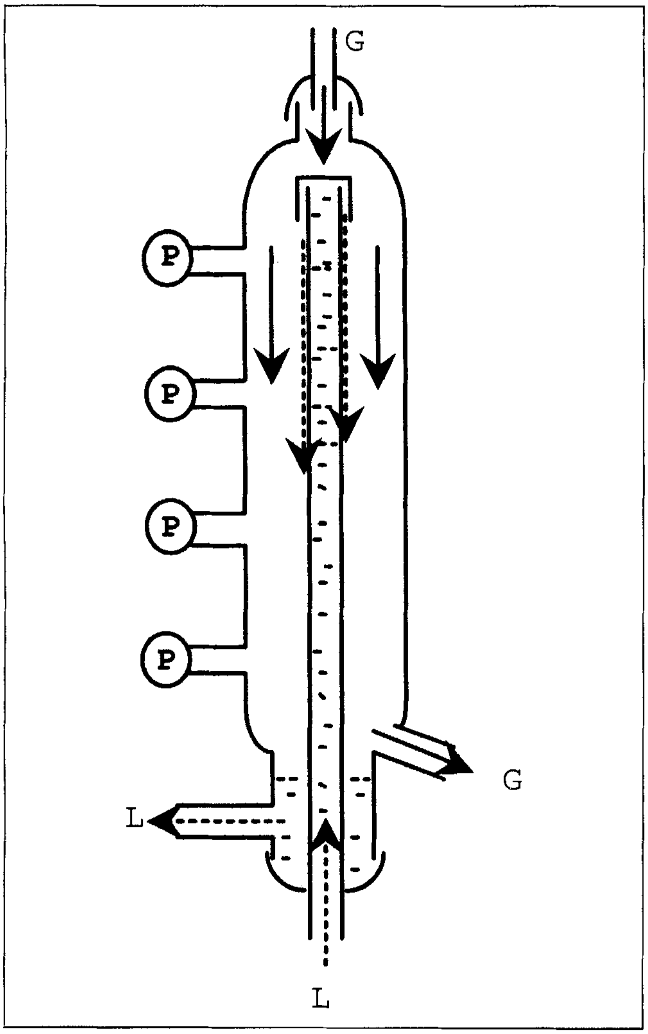

Figure 2. Experimental device.

enters the device through this tube, evenly distributing itself in a film flowing downward along the outer wall of the tube.

Liquid is fed by gravity. Flow rates are between 10^{-6} to 2.5×10^{-5} m^3/s. The air flow is supplied by a Elektror SD2 compressor with flow rates between 5×10^{-4} and 6×10^{-3} m^3/s. Fluid viscosities were measured with a Ubbelohde viscometer. Fluid densities were measured with Siebert und Kühn API viscometers (0 to 81 API) for fuels, and a Bosch S2000 densimeter for aqueous solutions. Surface tensions were measured with a PROLABO automated plate tensiometer. Aqueous solutions and most tested hydrocarbons

Table 1. Fluid and Solution Properties

System	σ (N/m)	ν ($\times10^6 m^2/s$)	ρ (kg/m^3)
NaOH 4M	0.083	2.50	1,200
0.6% But-OH (aq)	0.052	0.91	1,000
6% But-OH (aq)	0.030	1.22	985
0.13% CMC	0.053	4.87	1,000
0.26% CMC + 7% But-OH	0.032	10.61	1,000
0.52% CMC + 7% But-OH	0.033	24.86	993
Diesel/Vacuum Gas oil	0.031	9.10	854

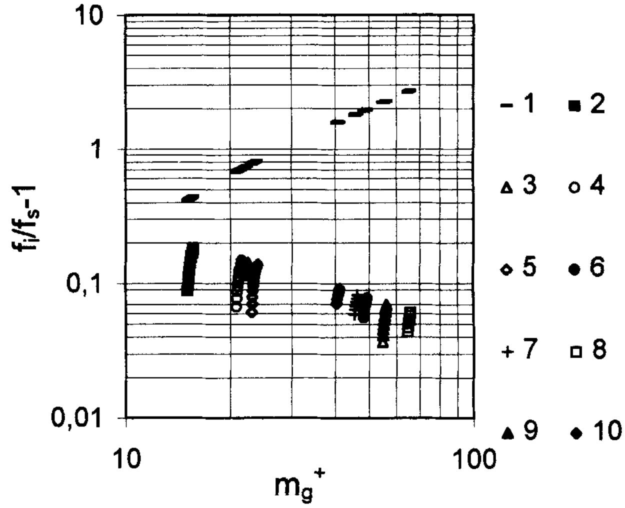

Figure 3. Relative increase of roughness vs. dimensionless film thickness.

(1) Data from Charvonia, Chien and Ibele and Andreussi and Zanelli, as shown by Asali et al. The rest are our experimental results. (2) water; (3) NaOH 4M; (4) butanol 0.6%; (5) butanol 6%; (6) CMC 0.13%; (7) CMC 0.26% + butanol 7%; (8) CMC 0.52% + butanol 7%; (9) CMC 0.39% + butanol 7.2%; (10) diesel-gas oil.

behave as Newtonian fluids. Reagents were NaOH AR from ANALEMA (Spain), *n*-Butanol AR from PROBUS (Spain), and Carboxymethylcellulose from ANALEMA. Kerosene, light and heavy naphthas, diesel and vacuum gas-oil were supplied by courtesy of the REPSOL refinery at La Coruña (Spain). Re_G value range was from 4,000 to 11,000. Re_L value range was from 20 to 700. Table 1 shows the values of surface tension, kinematic viscosity, and density for various solutions and liquids.

Results

No entrainment was observed in any of the runs. Water films were smooth for very low liquid rates in the upper section of the column, and then ring and ripple wave trains appeared at greater distances from the top of the column. Higher liquid rates and higher surface tensions shift the inception point for large waves upward. Higher gas rates, lower surface tension, and lower viscosities shift the inception point downstream. Organic fluids like naphthas with very low viscosities did not behave differently from smooth walls.

If the group $(fi/fs-1)$ is plotted against the dimensionless film thickness m_g^+ (Figure 3), it can be seen that the interfacial friction factors fall below the reference markers. Asali et al. derived their expression from data by Andreussi and Zanelli, Charvoria and Chien and Ibele (1964). Water and NaOH 4M, with surface tensions 0.07 and 0.083 N/m and viscosities 10^{-6} m^2s^{-1} and 2.5 10^{-6} m^2s^{-1}, show a stronger shift than the series Butanol 6%, CMC 0.13%, CMC 0.26% + Butanol 7%, and CMC 0.52% + Butanol 7% with surface tensions about 0.03 N/m and viscosities from 1.2 to 24 10^{-6} m^2s^{-1}. It can also be seen that the solutions with lower viscosities show stronger variations in their superficial friction factors when increasing m_g^+. The results show that the increase in superficial friction is consistent with the effect of surface tension on the onset of larger waves, but is not directly related to the effect of viscosity on wave onset. The fact that waves below a critical height do not induce additional roughness is known in the literature (Hewitt and Hall-Taylor, 1970, cited by Asali et al.) and can explain this behavior. Within the same range of gas-flow rates, and assuming a value of 0.1 for $f_i/f_s - 1$ as the criterion for the beginning of rough film, it can be seen that lower viscosity fluids begin to build up additional resistance at lower values of nondimensional film thickness.

Conclusions

The results for outer and inner wetted wall films may be correlated up to gas velocities of 20 m/s. Thereafter, divergence will appear. Within this range, external wetted wall devices may be useful for the research of wave patterns and the quantification of their effect on momentum, mass, and heat transfer. Advantages are easy access to the film surface without disturbance, the feasibility of fluid independent research methods, and methodology simplification, such as no need for continuous purges in the conduits leading from pressure meters to pressure taps (Dallman, Laurinat, cited by Asali et al.). The results from the test suggest that surface tension has a strong effect on frictional loss even in nonentrained annular flow.

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Notation

- A_G = gas-phase cross section
- A_{TL} = liquid film cross section
- f_i = gas friction factor at the liquid interface
- f_s = gas friction factor over a smooth wall, $0.046\ Re_G^{-0.2}$
- g = gravity acceleration
- dp/dl = pressure drop
- p = pressure
- P_{CW} = perimeter of the outer casing of the annular section conduit
- P_{TI} = perimeter of the gas-liquid film interface
- P_{TW} = perimeter of the inner tubing
- Re_G = gas Reynolds number
- U = gas velocity
- Γ = local mass flow rate per unit width
- μ = liquid viscosity
- ν = kinematic viscosity
- ρ = density
- σ = surface tension
- τ_C = characteristic shear stress, $\tau_C = 2/3\ \tau_w + 1/3\ \tau_i$
- τ_i = interfacial shear stress
- τ_w = wall shear stress

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Appendix: Model Equations

The model for the calculation of the friction factors considers that friction exists between gas and the outer casing, between the gas and the liquid film, and between the liquid film and the inner tubing.

$$\left(\frac{dp}{dz}\right)_{TL} + \tau_{TW}\frac{P_{TW}}{A_{TL}} - \tau_{TI}\frac{P_{TI}}{A_{TL}} + \rho_L g = 0 \qquad \text{film on the inner column} \quad (1)$$

$$\left(\frac{dp}{dz}\right)_{G} + \tau_{G}\frac{P_{CW}}{A_{G}} - \tau_{TI}\frac{P_{TI}}{A_{G}} + \rho_G g = 0 \qquad \text{gas core} \quad (2)$$

$$\left(\frac{dp}{dz}\right)_{TL} = \left(\frac{dp}{dz}\right)_{G} \qquad \text{equilibrium condition} \quad (3)$$

Walls are smooth and follow the Blasius equation. The correlations by Asali et al. (1985) were applied to obtain estimates for film height and friction factors.

$$\frac{f_i}{f_s} - 1 = 0.045\, Re_G^{-0.2}(m_g^+ - 5.9) \quad (4)$$

$$\frac{\delta U_G f_s}{\nu_G} = \frac{1.414 m_g^+}{1 + C_1(m_g^+ - 5.9)^{1/2}} \quad (5)$$

$$m_g^+ = 0.34\, Re_L^{0.6}\frac{\nu_L}{\nu_G}\left(\frac{\rho_L}{\rho_G}\frac{\tau_i}{\tau_C}\right) \quad (6)$$

$$f_s = 0.046\, Re_G^{-0.2} \quad (7)$$

C_1 was assumed to be 0.045, as values of 0.025 and 0.035 did not significantly produce different results and any choice would be arbitrary.

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