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LETTERS TO THE EDITORS

PHENOMENA OF LIQUID TRANSFER IN TWO-PHASE DISPERSED ANNULAR FLOW

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THE AUTHORS [1] correlate the fraction of liquid which flows in the film in terms of a dimensionless quantity, which we may call π_1, as follows,*

$$\pi_1 = \left(\frac{\bar{\rho}}{\rho_l}\;\frac{\mu_l\omega_g}{\sigma}\right)^2. \tag{1}$$

$\bar{\rho}$ is the mean density of the gas-droplet flow, ω_g the gas velocity ρ_l and μ_l the liquid density and viscosity and σ the surface tension.

This correlating scheme agrees substantially with the results obtained by Wallis [2] and by Steen and Wallis [3, 4] as far as the effects of gas density, surface tension and liquid density are concerned. The small effect of diameter is also confirmed (Steen [3] tested diameters between $\frac{1}{2}$ in and 4 in, Wallis [2] used 0·12–0·87 in). However, the results are not in agreement with the viscosity dependence reported by Steen who found that a change of a factor of 100 in liquid viscosity did not change the entrainment characteristics as long as the liquid flow rate was high enough. Moreover, both Steen and Wallis found that below a critical liquid flow rate for a given fluid the fraction of liquid entrainment level decreased rapidly, while the Paleev–Filippovich correlation does not consider liquid flow rate as a parameter.

In my experience it is very difficult to obtain a consistent set of data at high values of entrainment because of the effect of inlet conditions and the variation of pressure down the duct in which measurements are carried out. However, the onset of entrainment does appear to be less whimsical. Steen found that the critical gas velocity for the onset of entrainment in the "thick film" regime could be expressed quite well in terms of the dimensionless group

$$\pi_2 = \frac{\omega_g\mu_g}{\sigma} \times \left[\frac{\rho_g}{\rho_f}\right]^{\frac{1}{2}}. \tag{2}$$

Data for air–water systems gave values of π_2 between 2×10^{-4} and $2{\cdot}5 \times 10^{-4}$ and data for a variety of conditions could be represented by a mean value

$$\pi_2 \sim 2{\cdot}46 \times 10^{-4}. \tag{3}$$

* Nomenclature is that used in [1].

The difference between equations (1) and (2) lies solely in the use of the liquid viscosity in place of the gas viscosity. Indeed one may write

$$\pi_2 = \frac{\mu_g}{\mu_l}(\pi_1)^{\frac{1}{2}}. \tag{4}$$

Assuming that the Paleev–Filippovich curve in their Fig. 3 is based mainly on air–water experiments at room temperature we have

$$\pi_2 \approx 1{\cdot}9 \times 10^{-2}(\pi_1)^{\frac{1}{2}}. \tag{5}$$

Thus the correlating scheme can be expressed in terms of π_2 by making a simple transformation. Expressing the ordinate in terms of the "percent entrainment" which is defined as

$$\%E = \frac{G_l - G_f}{G_l} \times 100 \tag{6}$$

we can then draw the curve shown in Fig. 1. This has the familiar shape of all the curves in Wicks and Dukler's [5]. experiments, for example. The parameter π_2 could be interpreted as a dimensionless gas velocity.

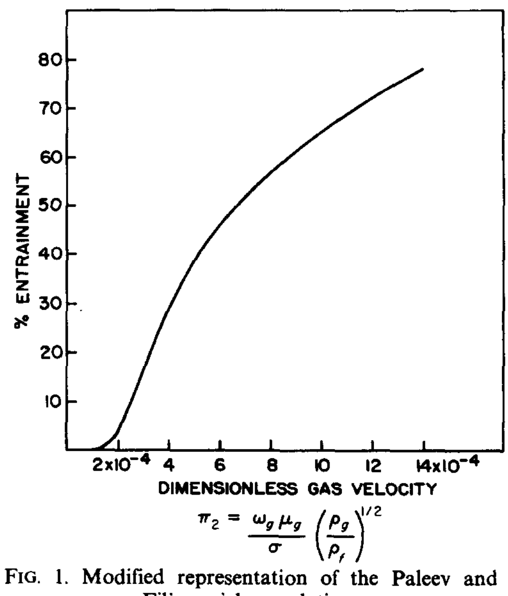

FIG. 1. Modified representation of the Paleev and Filippovich correlation.

The critical velocity for the onset of entrainment is seen to occur at about $\pi_2 = 1{\cdot}8 \times 10^{-4}$ which is somewhat less than found by Steen.

The real test of which viscosity is appropriate comes if one compares the two theories for a fluid other than water. Figure 2 shows such a comparison for a silicone fluid with 5 centistoke kinematic viscosity. The theory in terms of π_2 gives good agreement at low values of entrainment while the Paleev–Filippovich theory is off consistently by a factor of about $\frac{1}{5}$ which is the viscosity ratio. For fluids of higher viscosities the comparison gets progressively worse.

Figure 2 also shows that entrainment is much less at very

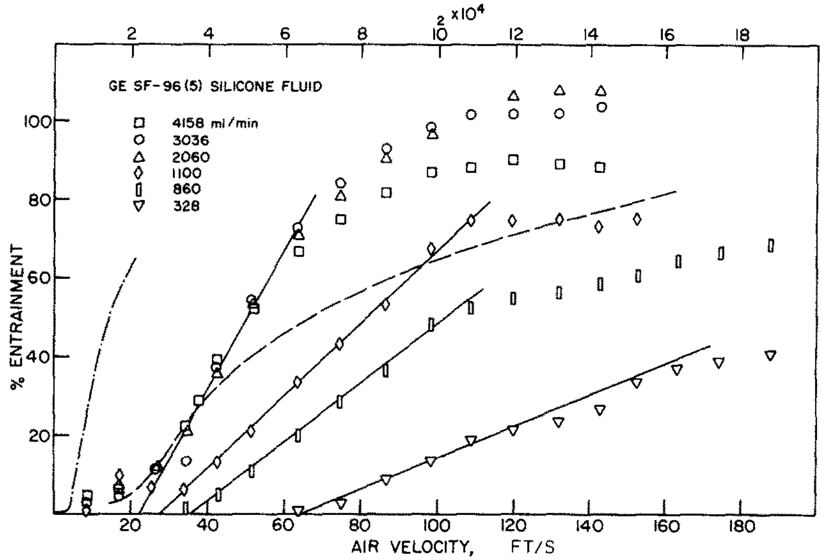

FIG. 2. Comparison between Steen's data [2] for a 5 centistoke fluid (ρ_l = 0·92 gs/cm³), the original correlation and the modified correlation described in the text (vertical tube $\frac{5}{8}$ in × 58 in, atmospheric pressure Silicone fluid σ = 20 dyn/cm, ν = 5 centistokes).
—·—·— Curve of Paleev and Filippovich
------- Modified curve using gas viscosity instead of liquid viscosity.

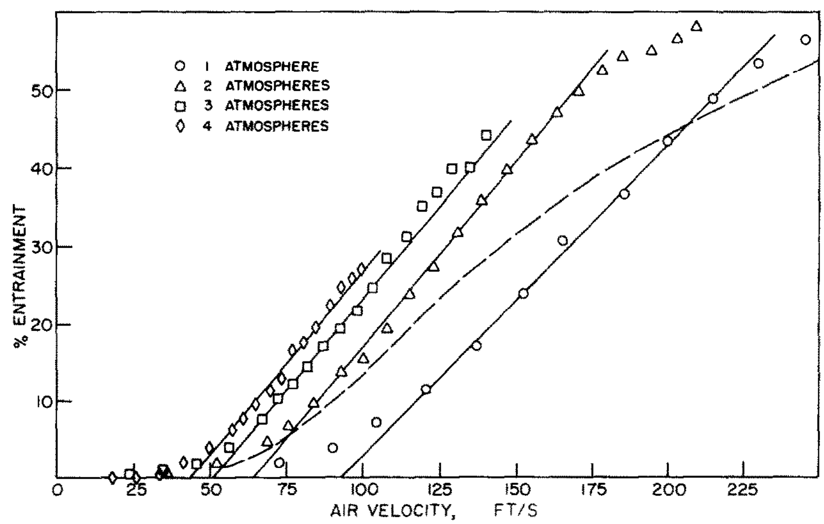

FIG. 3. Sample data of Steen [2] for an air–water system showing the effect of pressure. (Water flow rate 0·25 gallons per minute, vertical tube $\frac{5}{8}$ in I.D. × 58 in long.)
— — — — — — Curve of Paleev and Filippovich at one atmosphere.

low liquid flow rates, indicating an increased film stability due to viscous effects. This trend has not yet been analysed quantitatively with any certainty. The curves can be approximated over much of their length by straight lines and one can arbitrarily define the "critical gas velocity" as the point at which these lines hit the axis.

Figure 3 shows some of Steen's data with an air–water system at several pressures. In this case the representations in terms of π_1 or π_2 coincide. The trend with pressure is consistent with both theories but the data are displaced somewhat from the correlation (a lot less than the maximum scatter in the original graph, however).

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PHENOMENA OF LIQUID TRANSFER IN TWO-PHASE DISPERSED ANNULAR FLOW
COMMENTS ON G. B. WALLIS' DISCUSSION

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IN HIS discussion Wallis' points concerning the paper of Paleev and Filippovich are well taken. His comparison of viscosity effects in Fig. 2 clearly shows the inapplicability of the Paleev and Filippovich expression π_1 to correlate the quantity of entrainment. Wallis claims that both π_1 and π_2 show the correct trends with pressure, although in Fig. 3 the percent entrainment is plotted versus air velocity, V_G, only. His point would have been more strongly made by using $V_G \sqrt{(\rho_G)}$ as the abscissa instead of V_G.

Both groups π_1 and π_2 suffer from the absence of any dependence on liquid rate, although this is a variable of major importance, as Wallis' Fig. 2 shows.

A more general dimensional analysis consideration might result from inclusion of other relevant forces, also. These might include viscous forces in the gas and inertial forces in the liquid. The following table shows the formulas for each of these, normalized by the interfacial forces:

		Forces: inertial	Forces: viscous
Phase	Gas	$R_1 = \dfrac{\rho_G V_G^2 L}{\sigma g_c}$	$R_3 = \dfrac{\mu_G^2}{\rho_G \sigma g_c L}$
	liquid	$R_4 = \dfrac{\rho_L V_L^2 L}{\sigma g_c}$	$R_2 = \dfrac{\mu_L^2}{\rho_L \sigma g_c L}$

Paleev and Filippovich argue that π_1 should be a correlating group because in terms of the above groups, (1) R_1 and R_2 are the "determining criteria" for gas–liquid interactions in spray-nozzle applications, and (2) the product R_1R_2 does not involve the characteristic length L, which must vanish for a liquid of infinite depth.

As substitution shows,

$$\pi_1 = R_1R_2$$

Wallis' group π_2 can be expressed as

$$\pi_2 = \frac{R_1^2R_3}{R_4}$$

assuming liquid and gas velocities are equal, which may not be a bad assumption for the droplets already in the gas phase; for the droplets being generated from the liquid film surface, however, equal gas and liquid velocity is not the case. The effect of liquid flow rate thus could enter via the term R_4.

Both π_1 and π_2 do not involve L, the characteristic length dimension. Indeed, it is possible to show that there is an infinite set of powers a_i ($i = 1, 2, 3, 4$) to which the R_i's can be raised which lead to a product R

$$R = R_1^{a_1}R_2^{a_2}R_3^{a_3}R_4^{a_4}$$