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BRIEF COMMUNICATION

THE EFFECT OF LIQUID FLOW RATE ON FLOODING IN VERTICAL ANNULAR COUNTERCURRENT TWO-PHASE FLOW

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INTRODUCTION

When a liquid film flows down the inside of a vertical tube and gas flows upwards in its core, there is a critical condition which is usually called the flooding limit. The two-phase flow literature is not consistent in its definition and explanation of this phenomenon: here flooding will be defined as the condition where a small increase in gas velocity causes a breakdown of the falling liquid film and the transport of a slug of liquid up the tube. Hewitt & Wallis (1963) suggested that flooding is associated with the growth of large waves on the film surface. A falling liquid film has both long wavelength gravity waves which carry the bulk of the flow, and short wavelength capillary waves. In countercurrent flow the amplitude of the gravity waves increases with gas velocity and, at the critical value, the waves grow sufficiently to bridge the tube and form a slug of liquid which is forced up the tube by the gas flow. Other viewpoints exist. Moalem-Maron & Dukler (1981) have suggested that flow reversal can occur in the film before gravity waves have grown sufficiently to bridge the tube, and that this phenomenon should also be considered as a cause of flooding. Tien *et al.* (1980) regard entrainment as a precursor to bridging, and many other authors have used correlations describing the onset of entrainment of droplets and of bridging interchangeably to define the flooding limit. However, at low liquid flow rates there can be considerable entrainment of liquid into the gas stream while the amplitude of the gravity waves is relatively small. In the course of the experimental program reported here, it was found that significant entrainment was not a necessary precursor to the formation of a liquid slug, and thus the onset of entrainment as a flooding criterion was discarded.

Depending on the particular equipment or application under consideration it may be convenient to view flooding as setting a limit on the allowable gas flow rate, liquid flow rate, or tube diameter. We shall initially regard the superficial gas velocity j_G at flooding to be of primary interest. Based on theoretical considerations j_G might be expected to depend on the liquid flow rate, the tube diameter, fluid properties, and perhaps on the entrance and exit configurations. Imura *et al.* (1977) give a good review of experimental studies performed prior to 1975. Notable more recent experimental investigations are those of Imura *et al.* (1977), Chung *et al.* (1980), and Bharathan & Wallis (1983). Both Imura *et al.* and Chung *et al.* made comprehensive investigations into the effects of tube diameter, liquid properties, and entrance/exit configurations. The results of Bharathan & Wallis are more limited in scope and are restricted to ~290 K water. Most previous studies have been limited to relatively low liquid flow rates. For example, Imura *et al.* tested a maximum film Reynolds number $\mathrm{Re}_L = j_L D/\nu_L = 4320$ (for *n*-heptane in a 2.42 cm diameter tube). Here j_L is superficial liquid velocity, D tube diameter, and ν kinematic viscosity. Their maximum value of Re_L for water was 2030 in a 1.60 cm tube. Bharathan & Wallis tested up to $\mathrm{Re}_L = 2700$ in a 2.5 cm tube and $\mathrm{Re}_L = 7700$ in a 5.1 cm tube. Chung *et al.* tested higher values of Re_L, up to 14,000 in a 3.18 cm tube.

The apparatus used in the present study was designed with the primary purpose of obtaining gas side mass transfer coefficients for the water–air system over a wide range of liquid flow rates, and thus was particularly suitable for investigating the effect of liquid flow rate on flooding. We report here flooding data in a 5.08 cm diameter tube for a range of film Reynolds numbers from 3400 to 22,000, with the resulting superficial gas velocities at flooding varying from 5.6 to 3.3 m/s. A slot type water distributor and a nozzle type air inlet were used.

APPARATUS AND PROCEDURES

The test rig is comprised of a closed water loop and an open air loop as shown in figure 1. The test section is a 5.08 cm (2 in.) inside diameter, 2.5 m long glass tube. The film is formed by a slot type distributor with the water supplied from a constant head tank 2.1 m above. The slot width is 3.4 mm which is equal to the average film thickness at $Re_L = 30{,}000$ given by the Brötz formula (Brötz 1954), and the entrance to the slot was carefuly rounded to minimize the pressure drop through the distributor. A sharp edge was machined on the end of the air exhaust tube so as to maintain a stable water-air interface. The collector design is similar to that used by Gilliland & Sherwood (1934) and Goodfellow (1980). The calming section for the air inlet supports a sharp-edged nozzle which is positioned in the flare on bottom of the test section tube. Three nozzle exit diameters were used. The largest equals $D-2\delta = 4.40$ cm where D is the test section diameter of 5.08 cm and δ is Brötz film thickness at $Re_L = 30{,}000$; the other two were 15 and 25% smaller, respectively.

The water flow rate is measured by a bank of three rotameters. To ensure an absence of organic contaminants all materials in the liquid flow loop are either glass, brass, stainless steel, or galvanized steel, with seals of either teflon or viton The circulation pump has a magnetic drive system, and as a further precaution, an activated carbon filter is fitted in the entrance to the constant head tank. The air loop is comprised of a Roots blower, a positive displacement gas flow meter, and an orifice plate system for calibration of the flow

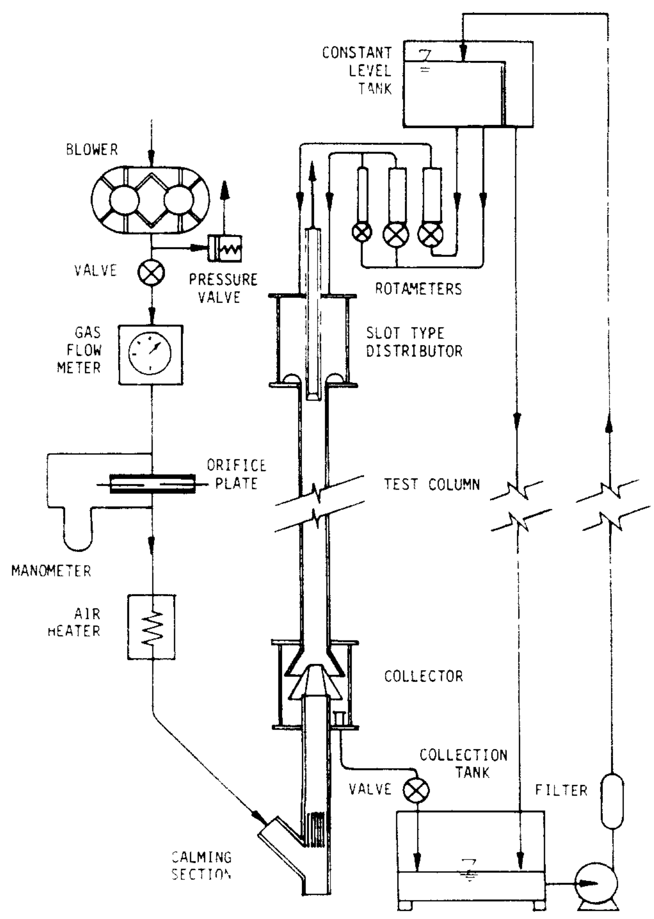

Figure 1 Schematic of the test rig

meter. Before commencing the experimental program all components of the water loop were thoroughly cleaned. At various intervals during the test program the water quality was checked using the Crits organic ring test (Crits 1961), and the water replaced if necessary.

To run a series of tests the blower was started and adjusted to give the back pressure required for the maximum desired air flow. The constant head tank was filled and the water flow to the distributor initiated. The distributor was filled by allowing an excess flow through the rotameters and bleeding off trapped air via a bleed valve on top of the distributor. Once full, the valve was closed, and the flow reduced into the test range. The system was kept running throughout flooding testing with short settling periods between each test. To perform a test the water flow rate was set and the air flow increased slowly until the tube flooded: the corresponding air flow rate was recorded. Up to six flooding tests were performed at each water flow rate and the orifice pressure drops arithmetically averaged. The water flow rate was checked before being reset to a new value. Ambient air temperature and pressure, and the water temperature were recorded for the calculation of fluid properties. The test procedure was performed over a water flow rate range of 170 – 1070 cm^3/s for each of the three air inlet cones.

RESULTS AND DISCUSSION

Figure 2 shows the experimental results in the form of a plot of superficial gas velocity j_G versus film Reynolds number Re_L (or equivalently the superficial liquid velocity j_L, since $Re_L = j_L D/\nu_L$). The effect of nozzle diameter is seen to be greatest in the midrange of film Reynolds number, with the intermediate size nozzle giving the highest gas flow rates at flooding. It was observed that, whereas in most tests flooding initiated at the bottom of the column, in this midrange of film Reynolds number and with the two smaller nozzles, flooding initiated some distance up the column. It appears that the intermediate size nozzle gave the smallest air flow entrance effect. Notwithstanding the effect of nozzle diameter, figure 2 shows clearly that the gas flow rate at flooding becomes essentially independent of liquid flow rate at film Reynolds numbers above about 15,000. Indeed, the smallest nozzle gave a clear minimum in j_G at $Re_L = 15,000$ with an increase of about 8% as Re_L increases to 22,000. It is this constant gas flooding velocity at high liquid flow rates which is an important result of our study.

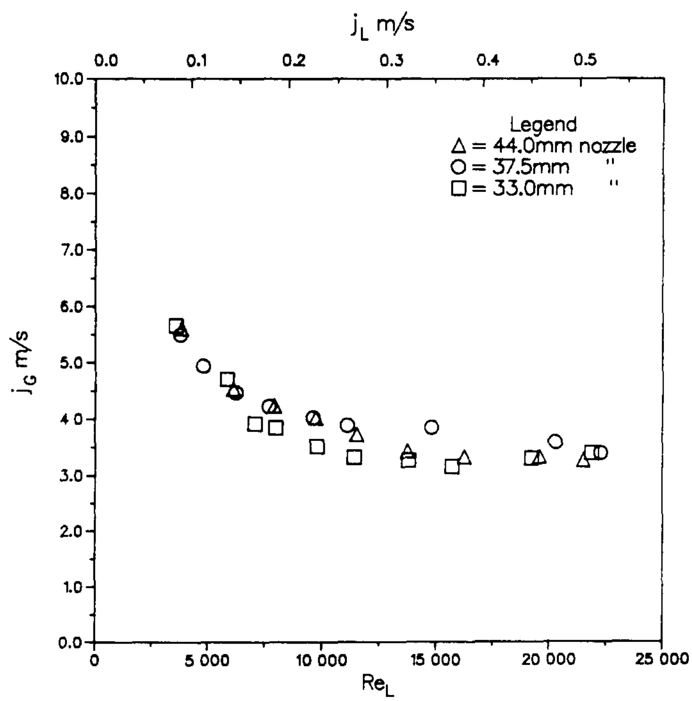

Figure 2. Superficial gas velocity at flooding vs film Reynolds number (and superficial liquid velocity) for three nozzle sizes.

Perhaps the most widely used correlation of flooding is that of Wallis (1961), which is commonly used in the form (Wallis 1969)

$$j_G^{*1/2} + j_L^{*1/2} = C_1, \quad C_1 = 0.8 - 0.9, \qquad [1]$$

where $j_i^* = j_i \rho_i^{1/2}/[gD(\rho_L - \rho_G)]^{1/2}$. Figure 3 shows a plot of $j_G^{*1/2}$ versus $j_L^{*1/2}$ where it is seen that the data certainly do not fall on a straight line, and in fact j_G^* is mostly larger than the maximum value given by the correlation, which corresponds to $C_1 = 0.9$. With smooth entrances Bharathan & Wallis (1983) correlated their data for a 5.1 cm diameter tube and $j_L^{*1/2}$ up to 0.45 with $C_1 = 0.82$: clearly our nozzle entrances gave somewhat higher gas flow rates at flooding. It is clear from figure 3 that the Wallis correlation cannot be extrapolated to high liquid flow rates. To emphasize what is perhaps obvious, the correlation with $C_1 = 0.9$ predicts a zero gas flooding velocity at $j_L^{*1/2} = 0.9$, which corresponds to a film Reynolds number in our tests of 19,000, for which in fact the superficial gas velocity is ~3.5 m/s

The Tien correlation (1977) has a similar shortcoming. In the form suggested by Chung *et al.* (1980) the correlation is

$$K_G^{1/2} + 0.8\, K_L^{1/2} = C_2, \quad C_2 = 2.1\, \tanh(0.8\, D_h^{*1/4}), \qquad [2]$$

where $K_i = j_i \rho_i^{1/2}/[g\sigma(\rho_L - \rho_G)]^{1/4}$, $D_h^* = D_h[g(\rho_L - \rho_G)/\sigma]^{1/2}$. Here ρ is density, g is the gravitional acceleration, and σ is surface tension. In the present tests $C_2 \simeq 1.95$. The correlation is shown in figure 4, where it is seen that, while the correlation gives the correct magnitude of the gas flooding velocity in the midrange of liquid flow rates, the correlation is quite inadequate in its representation of the dependence of gas flooding velocity on liquid flow rate. The reason why the Tien correlation is more successful than the Wallis correlation with respect to magnitude of gas flooding velocity is due to the fact that the constants given by Chung *et al.* were based on data up to $\mathrm{Re}_L = 14{,}000$, whereas the C_1 value in the Wallis correlation is essentially based on data for Re_L below 5000.

There is evidence of the shortcomings of the Wallis correlation in the results of some other workers. Hewitt *et al.* (1965) present results for a 1.25 cm tube which show a substantially different behavior even at low liquid flow rates. For higher liquid flow rates other data in the literature is sparse and contradictory For example, Richter (1981) presents

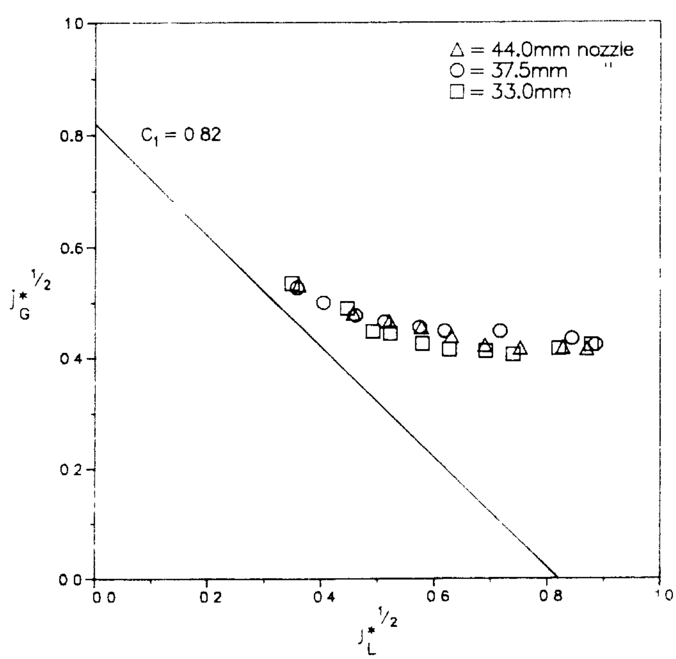

Figure 3 Evaluation of the Wallis flooding correlation

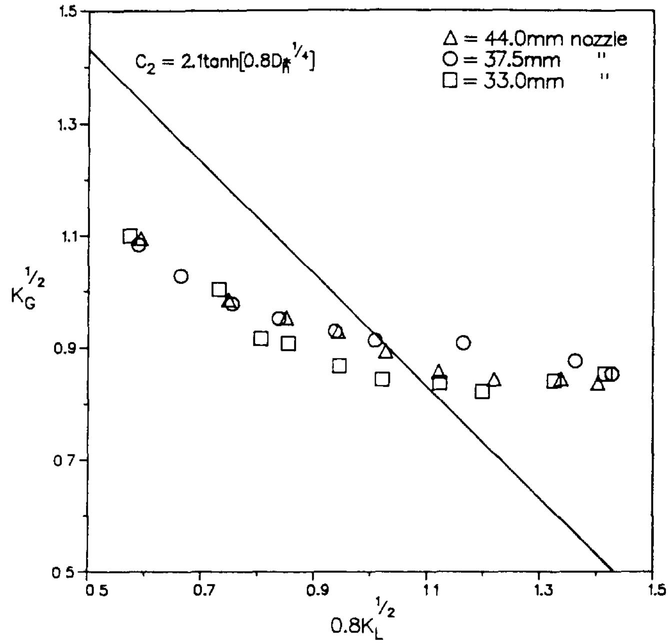

Figure 4 Evaluation of the Tien flooding correlation

data which indicates the possibility of the gas velocity at flooding becoming constant at high liquid flow rates, as do Wallis *et al.* (1980) as their "boundary A" data for a 5 cm tube. On the other hand, the data presented by Sudo & Ohnuki (1984) shows no such trend. Wallis *et al.* conclude that boundary A type data is apparatus dependent: their system had a square inlet from a plenum chamber and they note that boundary A corresponds to a situation where water has not built up in the plenum chamber to form a pool, whereas once the pool had formed the data agreed well with the Wallis correlation.

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