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FLOW PATTERNS IN VERTICAL TWO-PHASE FLOW

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Abstract—This paper is concerned with the flow patterns which occur in upwards gas-liquid two-phase flow in vertical tubes. The basic flow patterns are described and the use of flow pattern maps is discussed. The transition between plug flow and churn flow is modelled under the assumption that flooding of the falling liquid film limits the stability of plug flow. The resulting equation is combined with other flow pattern transition equations to produce theoretical flow pattern maps, which are then tested against experimental flow pattern data. Encouraging agreement is obtained.

1. INTRODUCTION

1.1 *Flow patterns*

The description of two-phase flow in tubes is complicated by the existence of an interface between the two phases. For gas-liquid two-phase flows this interface exists in a wide variety of forms, depending on the flow rates and physical properties of the phases, and also on the geometry and inclination of the tube. The different interfacial structures are called flow patterns or flow regimes. For the particular case of upwards flow in vertical tubes four main flow patterns may be distinguished, see for example Hewitt & Hall Taylor (1970). These are illustrated in figure 1 and their main features are described below.

(i) Bubble flow. In bubble flow the gas phase flows as discrete bubbles in a liquid continuum. The bubbles are usually distorted spheres.

(ii) Plug flow. When the bubble concentration in bubble flow becomes high, bubble coalescence occurs and the largest bubbles are of the same order of size as the tube diameter. Further coalescence results in the deformation of the bubble into the bullet shaped pocket of gas which is characteristic of plug flow. Plug flow then consists of these pockets of gas, commonly called plugs or Taylor bubbles, separated by regions of bubbly flow, commonly called slugs. The plugs of gas are surrounded by a thin liquid film which flows vertically downwards.

(iii) Churn flow. Churn flow is a highly disordered flow regime in which the vertical motion of the liquid is oscillatory. Churn flow possesses some of the characteristics of plug flow, with the main differences being as follows: (a) The gas plugs become narrower and more irregular. (b) The continuity of the liquid in the slug is repeatedly destroyed by regions of high gas concentration. (c) The thin falling film of liquid surrounding the gas plugs can no longer be observed.

(iv) Annular flow. In annular flow the gas flows along the centre of the tube. The liquid flows partially as a film along the walls of the tube, and partially as droplets in the central gas core.

It is possible to extend the above description of flow patterns. For example, the annular flow regime may be sub-divided into wispy and nonwispy annular flow, with wispy annular flow occurring as a result of the agglomeration of the liquid droplets in the gas core into large streaks or wisps. Furthermore, because the transitions between the various flow regimes do not occur suddenly, it is possible to observe a number of transition flow patterns which possess characteristics of more than one of the main flow patterns described above.

1.2. *Flow pattern maps*

When two-phase flow occurs in tubes, it is often important to be able to predict which flow pattern is likely to occur for any given combination of phase properties and flow rates,

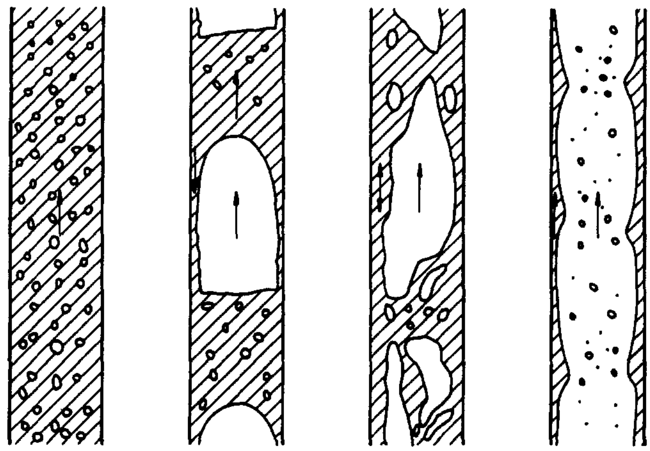


Figure 1. Flow regimes in upwards two-phase flow in vertical tubes.

and for any given tube diameter. Flow pattern predictions are usually obtained from flow pattern maps, of which there are two types as described below.

1.2.1. *Experimental flow pattern maps.* Flow pattern information for a particular fluid pair and for a particular geometry can be represented graphically to give a flow pattern map. Taitel *et al.* (1980) discussed the various coordinate systems available, and argued that the various flow pattern transitions cannot all be represented by any given coordinate pair. Attempts have been made to overcome this problem by applying different scaling parameters to the various transitions, see for example Weisman *et al.* (1979).

1.2.2. *Theoretical flow pattern maps.* Taitel *et al.* (1980) presented an alternative to the experimental methods of obtaining flow pattern maps. They considered the conditions necessary for the existence of each of the flow patterns shown in figure 1, and postulated mechanisms by which the transitions between the various flow patterns might occur. They then modelled these transitions and produced a series of equations which, given the phase physical properties and the tube diameter, enabled the flow pattern boundaries to be calculated. The resulting flow pattern maps were compared with existing experimental flow pattern maps and with the authors own air-water data, and reasonable agreement was obtained. This theoretical approach to flow pattern prediction has also been used by Mishima & Ishii (1984).

1.3. *The present work*

The aims of this paper may be summarised as follows:

(i) To model the transition between plug flow and churn flow, and to develop equations with which the occurrence of this transition may be predicted.

(ii) To present a modification to the equation used by Taitel *et al.* (1980) for the determination of the stability of bubble flow, and to present a simple and effective criterion for the stability of annular flow.

(iii) To compare predicted flow pattern maps with flow pattern data for as wide a range of fluid flowrates and properties as possible, and further for a range of tube diameters. It is hoped that the comparison of the predicted flow pattern maps with experimental data will prevent errors occurring as a result of some experimental flow pattern maps being based on small amounts of data.

(iv) To suggest areas in which further work is necessary.

2. FLOW PATTERN TRANSITION MECHANISMS

2.1. *The transition from bubble flow*

Bubble flow is observed at low gas rates, irrespective of the liquid flow rate. The transition from bubble flow to one of the other flow regimes requires the agglomeration or coalescence of the bubbles to form larger vapour spaces. The two processes which control the stability of bubble flow are therefore those of bubble coalescence caused by bubble impacts, and bubble breakup caused pressure forces resulting from turbulence in the liquid phase. Taitel *et al.* (1980) have modelled the transition from bubble flow by considering the stability of nondispersed bubble flow in which the flow is not sufficiently turbulent to suppress the formation of gas plugs, and dispersed bubble flow in which turbulence acts to cause the breakdown of the bubbles into smaller spherical bubbles. The following equations were derived:

$$v_{Ls} = 3.0\, v_{Gs} - 1.15\left[\frac{g\sigma(\rho_L - \rho_G)}{\rho_L^2}\right]^{1/4} \qquad [1]$$

for the transition from non-dispersed bubble flow to plug flow (assuming that nondispersed bubble flow becomes unstable at $\alpha = 0.25$)

$$v_{Ls} + v_{Gs} = 4.0\left[\frac{D^{0.429}\sigma^{0.089}g^{0.446}}{\mu_L^{0.072}\rho_L^{0.017}}\right] \qquad [2]$$

for the transition from nondispersed bubble flow to dispersed bubble flow and

$$\alpha = 0.52 \qquad [3]$$

where

D = Tube diameter (m),
g = Acceleration due to gravity (= 9.81 m/s^2),
v_{Gs} = Gas superficial velocity (m/s),
v_{Ls} = Liquid superficial velocity (m/s),
α = Void fraction (–),
ρ_G = Gas density (kg/m^3),
ρ_L = Liquid density (kg/m^3),
μ_L = Liquid viscosity (Ns/m^2),
σ = Surface tension (N/m)

for the transition from non-dispersed bubble flow.

Equation [3] was derived on the assumption that dispersed bubble flow would become unstable if the void fraction became sufficient to indicate a cubic lattice of bubbles. In this paper the formation of a close packed lattice is assumed to limit the stability of dispersed bubble flow, so that the transition from dispersed bubble flow occurs when

$$\alpha = 0.74. \qquad [4]$$

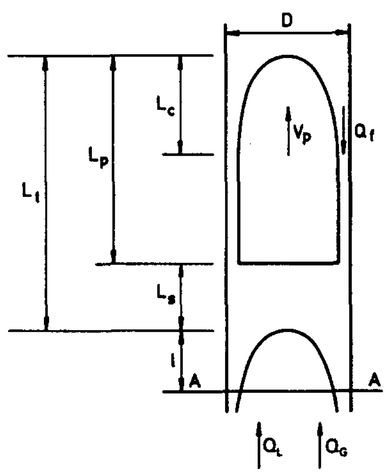
Mishima & Ishii (1984) made no distinction between dispersed bubble flow and nondispersed bubble flow, and performed a simple analysis which indicated that bubble flow would become unstable at a void fraction of $\alpha = 0.3$. An alternative to [2] has been developed by Taitel & Dukler (1976) for flow in horizontal tubes, and modified empirically by Weisman *et al.* (1979). The data used by Weisman *et al.* (1979) covered a range of tube diameters between 0.01 and 0.127 m, and the resulting correlation suggests that for flow in horizontal tubes the transition between the two bubble flow regimes is independent of the gas flow rate and that dispersed bubble flow will exist if

$$v_{Ls} \geq \frac{6.8}{\rho_L^{0.444}} \{g\sigma(\rho_L - \rho_G)\}^{0.278} \left(\frac{D}{\mu_L}\right)^{0.112}. \quad [5]$$

At the high liquid velocities under consideration the effect of slip between the two phases is negligible (Taitel *et al.* 1980 use homogeneous flow theory to calculate the void fraction). The turbulence is therefore caused by the bulk flow alone, and so there should be no tube inclination effect. Consequently, it is possible to use the correlation of Weisman *et al.* (1979) for flow in vertical tubes. The major difference between the correlations of Taitel *et al.* (1980) and Weisman *et al.* (1979) is that the latter predicts only a small tube diameter effect ($D^{0.112}$) and is in good agreement with the available data for horizontal flow. For this reason the correlation of Weisman *et al.* (1979), [5] is used in this paper to define the transition between the non-dispersed and the dispersed bubble flow regimes. The void fraction in the dispersed bubble flow regime can increase above the critical value of $\alpha_{cr} = 0.25$.

2.2 *The transition from plug flow*

The bubble flow regime becomes unstable as a result of the formation of large vapour spaces within the flow. Plug flow may be formed as a result of this process, but under some circumstances (at high liquid flow rates) plug flow may also be unstable and therefore the bubble flow may change directly to churn flow or annular flow. If the conditions allow plug flow to be formed, the large vapour spaces will assume the characteristic bullet shape. As the gas flowrate is further increased a transition between plug flow and churn flow will occur. There has been considerable difficulty in accurate identification of the plug/churn transition, largely due to confusion as to the exact definition of churn flow. Taitel *et al.* (1980)



AA	= Section through tube	(-)
D	= Tube inside diameter	(m)
l	= Distance from top of plug to AA	(m)
L_c	= Length of cap of plug	(m)
L_p	= Length of plug	(m)
L_s	= Length of slug	(m)
L_t	= Length of plug unit	(m)
Q_f	= Falling film volumetric flowrate	(m^3/s)
Q_L	= Liquid volumetric flowrate	(m^3/s)
Q_G	= Gas volumetric flowrate	(m^3/s)
V_p	= Rise velocity of gas plug	(m/s)

Figure 2. Model of plug flow.

modelled churn flow as an entry condition associated with the existence of plug flow further along the tube, and the resulting equations require a knowledge of the length of the tube. Such information is often not given in many experimental reports, and the model of Taitel *et al.* (1980) is therefore difficult to compare with experiment. Mishima & Ishii (1984) used a void fraction limitation to define the transition between plug flow and churn flow, but their modelling requires the unreasonable assumption that the length of the gas plug is the distance between the top of the plug and the point at which the film thickness decreases to the value given by [8]. Mishima & Ishii (1984) also appeared to have used Bernoulli's equation when the flow is unsteady, possibly resulting in uncertainties in the void fraction calculation.

In this paper the transition from plug flow to churn flow is assumed to occur as a result of the gas flowrate in the plugs increasing until it causes the flooding of the falling liquid film surrounding the plug. This mechanism has previously been suggested by Nicklin & Davidson (1962).

Figure 2 shows the model of plug flow used in the following analysis. Consecutive gas plugs rise in a vertical tube, separated by regions of liquid flow. If the plug flow occurs as a development of bubble flow, and not as a result of the way in which the phases are mixed at the tube entrance (see section 3), the regions of liquid flow will be bubbly. For the purposes of this analysis the small amount of gas which flows as bubbles in the liquid slugs is neglected. As is shown in figure 2 the gas plug rises at an absolute velocity v_p. The liquid film adjacent to the gas plug flows downwards as a free falling film at a velocity v_f. Nicklin *et al.* (1962) present the following equation which may be used to calculate the rise velocity of the gas plug:

$$v_p = 1.2\left(\frac{Q_G + Q_L}{A}\right) + 0.35\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}, \qquad [6]$$

where

A = Tube cross-sectional area (m^2),
v_p = Absolute velocity of the gas plug (m/s),
Q_G = Gas volumetric flowrate (m^3/s)
Q_L = Liquid volumetric flowrate (m^3/s).

The second term on the r.h.s. gives the rise velocity of a large bubble in a stagnant liquid. It has been derived theoretically by Davis & Taylor (1949). The first term on the r.h.s. adds the liquid velocity at the centre line, because 1.2 is the approximate ratio of centre line to average velocity in fully developed turbulent flow. The gas volumetric flowrate in the plug Q_p may then be calculated as follows:

$$Q_p = \left\{1 - \frac{4\delta}{D}\right\}\left\{1.2(Q_G + Q_L) + 0.35A\left[\frac{gD(\rho_L - \rho_G)}{\rho_L}\right]^{1/2}\right\}, \qquad [7]$$

where σ = falling film thickness (m).

Smith *et al.* (1982) have shown that the film thickness of the falling film surrounding the gas plug tends towards the film thickness calculated by Nusselt (1916). The following equation may therefore be used to relate the film thickness to the falling film volumetric flowrate:

$$\delta_N = \left(\frac{3Q_f\mu_L}{\pi g D\rho_L}\right)^{1/3}, \qquad [8]$$

where

δ_N = Nusselt film thickness (m),
Q_f = Falling film volumetric flowrate (m^3/s).

Finally, the principle of continuity of volume may be used to give the equation:

$$Q_p = Q_f + (Q_G + Q_L), \quad [9]$$

where Q_f is measured in the opposite direction to Q_p, Q_G and Q_L. Equations [7], [8] and [9] can now be solved iteratively to evaluate the gas flowrate in the plug, the falling film flowrate, and the falling film thickness, in terms of the flowrates and properties of the phases and the tube diameter.

Several investigations have examined the conditions under which falling liquid films may be caused to flood, and there is considerable evidence (Wallis 1961, 1962, Hewitt & Wallis 1963) to suggest that the following semi-empirical equation may be used to predict the flooding gas and liquid flowrates:

$$(v_{Gs}^*)^{1/2} + (v_{Ls}^*)^{1/2} = C, \quad [10]$$

where C is a constant and v_{Gs}^* and v_{Ls}^* are the gas and liquid dimensionless superficial velocities defined by the equations

$$v_{Gs}^* = v_{Gs}\rho_G^{1/2}[gD(\rho_L - \rho_G)]^{-1/2} \quad [11]$$

$$v_{Ls}^* = v_{Ls}\rho_L^{1/2}[gD(\rho_L - \rho_G)]^{-1/2} \quad [12]$$

In this paper, [10] is used to predict the position of the boundary between plug flow and churn flow with

$$v_{Gs}^* = \frac{Q_p}{A}\rho_G^{1/2}[gD(\rho_L - \rho_G)]^{-1/2}, \quad [13]$$

$$v_{Ls}^* = \frac{Q_f}{A}\rho_L^{1/2}[gD(\rho_L - \rho_G)]^{-1/2}. \quad [14]$$

The above argument requires the assumption that the gas plug is sufficiently long for the film thickness to decrease to the Nusselt film thickness δ_N. If this assumption is invalid the film thickness at the bottom of the gas plug can be calculated. The length of the "cap" of the plug is defined as the distance between the top of the plug and the point at which the falling film thickness becomes constant. At the top of the plug viscous forces are negligible (Nicklin *et al.* 1962) and the application of Bernoulli's theorem to this region gives the velocity of the liquid film relative to the nose of the plug:

$$v_{fp}' = (2gl)^{1/2}, \quad [15]$$

where

l = Distance from top of plug (m),
v_{fp}' = velocity of liquid film relative to top of plug (m/s).

The net volumetric flowrate across AA in figure 2 is $(Q_G + Q_L)$ and therefore

$$Q_G + Q_L = v_p A_g - [A - A_G][(2gl)^{1/2} - v_p], \quad [16]$$

where

A_G = The cross-sectional area available for gas (m^2).

The cap of the plug ends when the film thickness decreases to the Nusselt film thickness so that at this point

$$A_G = \frac{\pi}{4}(D - 2\delta_N)^2. \quad [17]$$

Combining [16] and [17] gives the length of the cap in terms of known quantities:

$$L_c = \left\{\left[\frac{Av_p - (Q_G + Q_L)}{(2g)^{1/2}}\right]\Big/\left[A - \frac{\pi}{4}[D - 2\delta_N)^2\right]\right\}^2. \quad [18]$$

Taitel *et al.* (1980) presented observations and arguments which lead to the conclusion that the average stable length of the liquid slugs in plug flow is insensitive to the gas and liquid flowrates and tends towards a value of approximately twenty times the tube diameter. The approximate average gas plug length may now be determined, assuming the gas plug to be cylindrical. The gas flowrate is given by the product of the plug volume and the plug frequency:

$$Q_G = \left[\frac{\pi L_p v_p (D - 2\delta_N)}{4(L_p + 20D)}\right], \quad [19]$$

where L_p = Length of plug (m).

If the value of the plug length calculated from [19] is greater than the length of the plug cap from [18] the film thickness at the bottom of the plug will be the Nusselt film thickness, and no further calculations are necessary. If the approximate plug length is less than the cap length the exact length of the plug can be calculated by evaluating the following integral:

$$\text{Volume of plug} = \int_0^{L_p} A_G \, dl \quad [20]$$

from which, using [16]

$$\frac{Q_G}{v_p}(L_p + 20D) = \int_0^{L_p} A - \left[\frac{Av_p - (Q_G + Q_L)}{(2g)^{1/2}}\right] dl. \quad [21]$$

The film thickness at the bottom of the plug may now be calculated from [16] and [17] using the value of L_p calculated above. Finally the modified value of Q_p may be calculated from [7] and the likely flow pattern determined using [10]. For air-water systems Hewitt *et al.* (1965) and Whalley & McQuillan (1983) have observed that the conditions under which a falling liquid film floods are sensitive to the length of the falling film region. This length effect can be incorporated by using the results of Whalley & McQuillan (1983) to predict the effect of the plug length on the value of the constant C in [10].

2.3. *The transition to annular flow*

If the gas flowrate becomes sufficiently high the annular flow pattern will be observed. Taitel *et al.* (1980) consider that annular flow occurs when the gas flowrate becomes high enough to suspend entrained liquid droplets. They balance the drag and gravity forces acting on a droplet and obtain an inequality which must be satisfied if annular flow is to exist:

$$v_{Gs} \geq 3.2[g\sigma(\rho_L - \rho_G)/\rho_G^2]^{1/4}. \quad [22]$$

This inequality has the same form as the equation presented by Pushkina & Sorokin (1969) to predict the flooding of a falling liquid film. In their derivation, Taitel *et al.* (1980) incorrectly assumed that entrained droplets are gradually accelerated as they move into the gas core.

In this paper the simple inequality presented below is used to predict the existence of annular flow:

$$v_{Gs}^* \geq 1. \qquad [23]$$

v_{Gs}^* is a modified Froude number, representing a comparison between inertia and gravity forces, and the critical value of unity has been observed empirically for air-water by Hewitt & Wallis (1963) and for steam water by Bennett *et al.* (1980). The use of [23] rather than [22] is made because it gives better results, see section 3.

3. COMPARISON WITH EXPERIMENT

In this section the following equations are used to predict the positions of the flow regime boundaries.

Nondispersed to dispersed bubble: [5].
From nondispersed bubble: [1] and [5].
From dispersed bubble: [4].
Plug to churn: [10].
To annular: [23].

These equations have been included in a computer program which produces predicted flow pattern maps for any given phase properties and tube diameters. These maps may then be compared with experimental flow pattern maps and data. The following will affect the level of agreement obtained:

(i) Experimental flow pattern data is inevitably subjective. Particular problems occur due to the different flow pattern definitions used by different authors, and also due to the difficulties involved in the identification of transition flows.

(ii) The experimental flows may not in all cases have been fully developed so that, for example, a flow pattern identified as bubbly may have been a developing plug flow.

(iii) The models discussed in section 2 assume that the flow patterns have developed as a result of boiling (a gradual increase in the mass quality). However, in some experimental situations the phases are mixed at the flow inlet, and under some circumstances the resulting flow pattern will depend on the way in which the phases are mixed. For example, plug flow may be observed at very low gas flowrates if the mixing technique allows the gas to enter the tube intermittently as plugs.

Table 1 summarises the data used for the comparisons between the flow pattern maps and experimental flow pattern data, giving details of the relevant fluid properties, the tube diameter, the number of data points used, and also of the flow pattern delineation technique used in each investigation. Figures 3–8 are examples of the comparison between the flow pattern maps and experimental flow pattern data. In the comparisons no distinction was made between dispersed and nondispersed bubble flow, because the two flows have similar characteristics and are not separately identified in some sets of flow pattern data. A complete series of figures is given by McQuillan & Whalley (1983). The nomenclature used in figures 3–8 is described in figure 3. The agreement between the theoretical flow pattern predictions and the experimental flow pattern observations is generally good, for both air-water and other fluids.

A comparison was made between the success with which [22] and [23] were able to predict the transition to annular and the results were as follows:

(i) Equation [22] resulted in the correct prediction of 949 out of 1399 data points.

(ii) Equation [23] resulted in the correct prediction of 980 out of 1399 data points.

Table 1. Experimental flow pattern data

Reference	Gas liquid	Physical Properties: Gas density (kg/m³)	Liquid density (kg/m³)	Liquid viscosity (Ns/m² × 10³)	Surface tension (N/m)	Tube diameter (m)	Delineation technique	Number of data points
Berryman (1983)	Air Water	1.29	1000.0	1.0	0.072	0.025	Visual	82
Taitel *et al.* (1980)	Air Water	1.29 1.29	1000.0 1000.0	1.0 1.0	0.072 0.072	0.025 0.051	Visual	106 75
Barnea *et al.* (1980)	Air Water	1.29	1000.0	1.0	0.072	0.025	Conductance probe	5
Tutu (1982)	Air Water	1.29	1000.0	1.0	0.072	0.05	Pressure fluctuation	8
Govier *et al.* (1957)	Air Water	2.9	1000.0	1.0	0.072	0.026	Visual	109
Spedding and Thanh Nguyen (1979)	Air Water	1.29	1000.0	1.0	0.072	0.045	Visual	223
Annunziato and Giradi (1983)	Air Water	1.29	1000.0	1.0	0.072	0.092	Visual	105
Bonfanti *et al.* (1979)	Nitrogen Water	25.1 25.1	999.0 999.0	1.06 1.06	0.072 0.072	0.078 0.105	Visual	27 22
Bennett *et al.* (1965)	Steam Water	17.5 36.5	810.0 740.0	0.115 0.096	0.029 0.017	0.0127 0.0127	Visual + X-ray photography	54 44
Bergles and Suo (1966)	Steam Water	17.5 36.5	810.0 740.0	0.115 0.096	0.029 0.017	0.01 0.01	Conductance probe	35 58
Sorokin *et al.* (1978)	Steam Water	10.0– 55.0	688.0– 850.0	0.087– 0.130	0.011– 0.036	0.0133	Conductance probe	44
Mayinger and Zetzmann (1976)	Refrigerant-12 Refrigerant-12	107.0	1130.0	0.132	0.0035	0.014		23
Baker (1965)	Refrigerant-11 Refrigerant-11	23.2 32.2 51.2 61.4	1350.0 1307.0 1250.0 1228.0	0.294 0.270 0.242 0.234	0.012 0.010 0.0081 0.0074	0.018* 0.018* 0.018* 0.018*	Visual + gamma-ray attenuation	43 53 32 38
Weisman and Kang (1979)	Refrigerant-113 Refrigerant-113	14.3 27.2	1455.0 1386.0	0.405 0.317	0.0124 0.0098	0.025 0.025	Visual	123 90

*Denotes the use of mean hydraulic diameter for a rectangular test section.

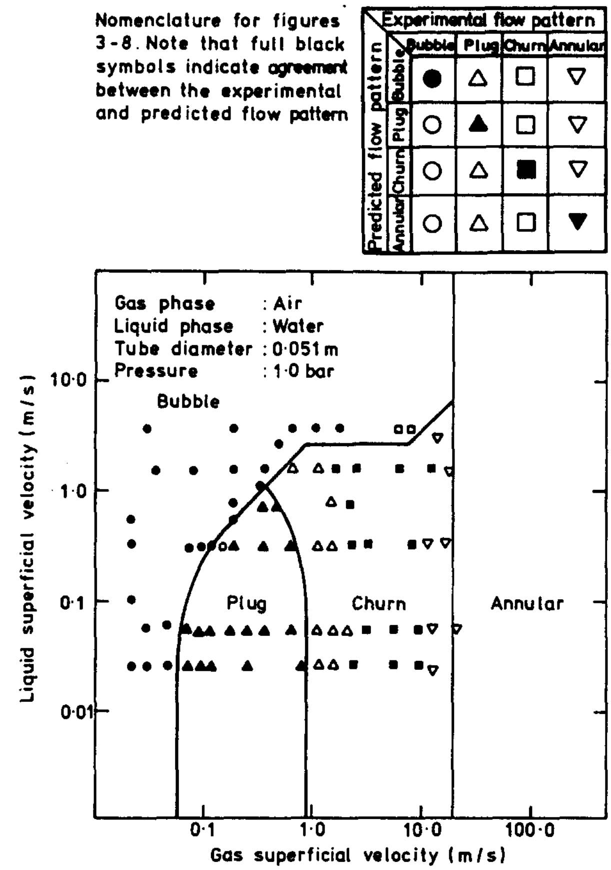


Figure 3. Comparison of the predictions of the present work with experimental flow pattern data. Reference: Taitel *et al.* (1980).

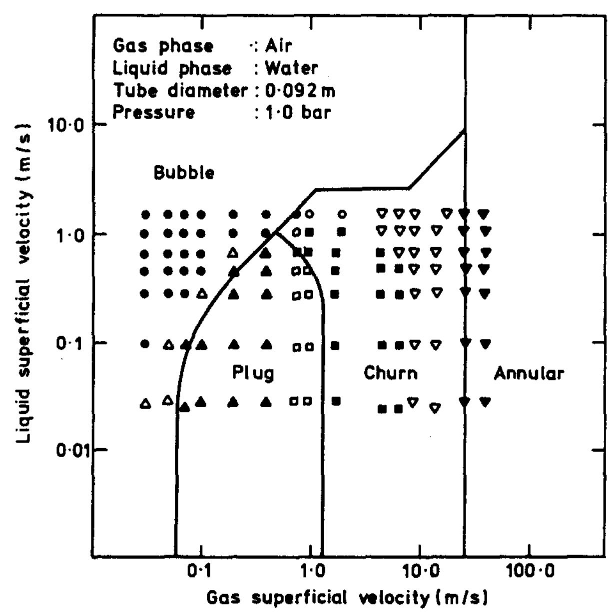


Figure 4. Comparison of the predictions of the present work with experimental flow pattern data. Reference: Annunziato & Giradi (1983).

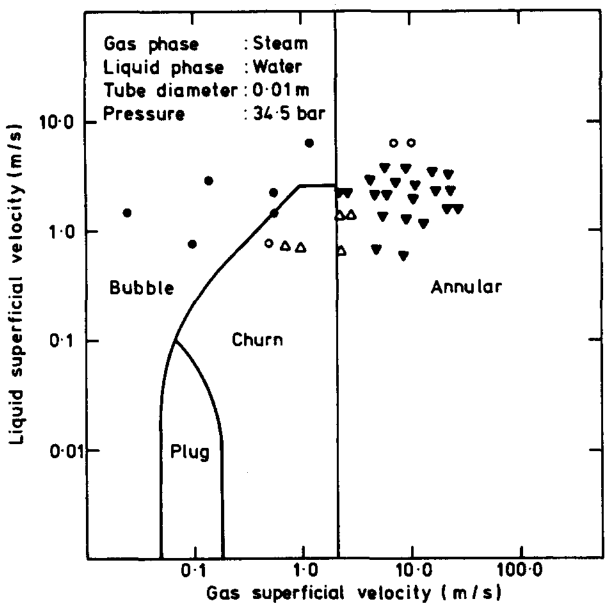


Figure 5. Comparison of the predictions of the present work with experimental flow pattern data. Reference: Bergles & Suo (1966).

During the course of the comparisons the predicted plug/churn transition was found to be insensitive to the calculated film thickness. The use of [8] to calculate the film thickness was therefore considered to be sufficiently accurate, even for turbulent falling films approaching flooding.

Table 2 presents a statistical analysis of the results. From this table it may be seen that whilst the transitions from bubble flow and to annular flow are well predicted, the theoretical plug-churn transition is not always in good agreement with observations. This could be partially due to the difficulty in identifying the transition experimentally (see, for example, the spread of the transition lines in experimental flow pattern maps given by Taitel *et al.* 1981).

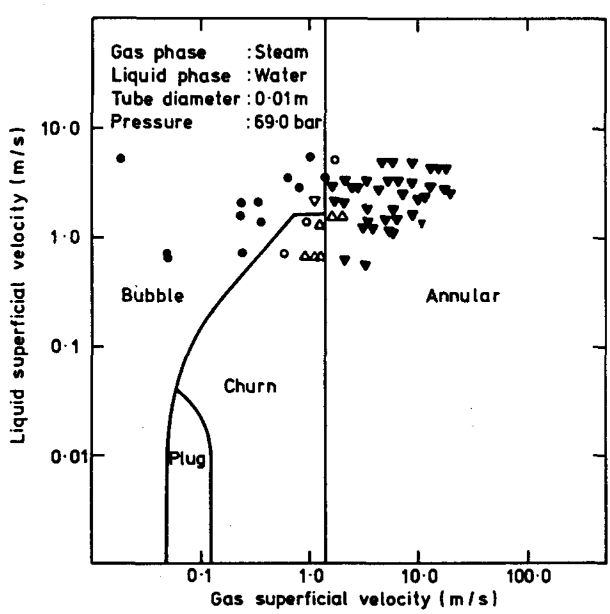


Figure 6. Comparison of the predictions of the present work with experimental flow pattern data. Reference: Bergles & Suo (1966).

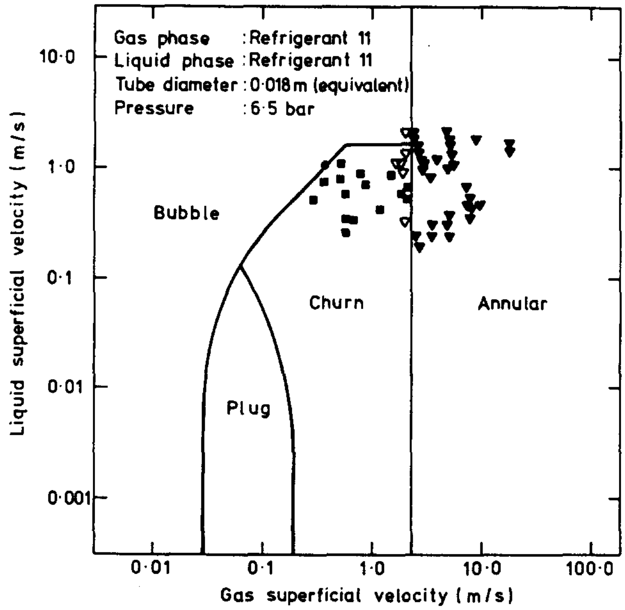


Figure 7. Comparison of the predictions of the present work with experimental flow pattern data. Reference: Baker (1965).

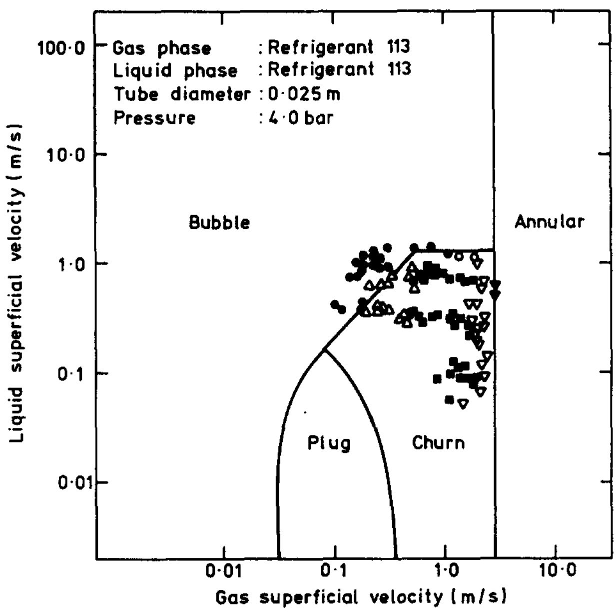


Figure 8. Comparison of the predictions of the present work with experimental flow pattern data. Reference: Weisman & Kang (1979).

Table 2. Statistical analysis of flow pattern predictions. 70.1% of the 1399 data points are correctly predicted

	Experimental Flow Pattern			
	Bubble	Plug	Churn	Annular
Predicted Flow Pattern				
Bubble	182	36	3	4
Churn	36	126	9	0
Plug	25	180	317	97
Annular	4	13	12	355

Table 3. Statistical analysis of flow pattern predictions. 84.1% of the 1399 data points are correctly predicted

	Experimental Flow Pattern	
	Intermittent	Continuous
Predicted Flow Pattern		
Intermittent	632	158
Continuous	64	545

Table 3 emphasises the difficulty in predicting the plug/churn transition by grouping the flow patterns as intermittent (plug and churn) and continuous (bubble and annular). Better statistical agreement is then obtained. Tables 2 and 3 assume that flow pattern transitions occur suddenly, and give no information detailing the position of the flow pattern points relative to the flow pattern boundaries. If the statistical analysis is repeated with allowance made for transition regions by plotting transition bands rather than transition lines the agreement between experiment and theory would improve as may be seen from figures 3–8.

3.1. *Further work*

Further work in the following areas would help improve the predictive methods outlined above:

(i) There has been little investigation of the flow patterns observed in tubes of diameters above 0.05 m. Further work in this area is necessary.

(ii) Investigation of the plug/churn transition for non–air-water systems to test the validity of the assumption that flooding occurs when according to [10] with $C = 1.0$.

(iii) Flow pattern work would be made more informative by the development and standardisation of objective flow pattern definition and determination.

4. CONCLUSIONS

A method for the prediction of the likely flow pattern for the upflow of a gas-liquid two-phase mixture in a vertical tube has been presented. The predictions have been compared with a range of experimental flow pattern data, and in most cases the agreement has been good. The use of the predictive technique described above with therefore yield more reliable flow pattern information than will the use of experimental flow pattern maps for fluids or geometries other than those used to obtain the experimental flow pattern information.

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