A SIMPLIFIED METHOD OF DETERMINING FLOW PATTERN TRANSITION OF TWO-PHASE FLOW IN A HORIZONTAL PIPE

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ABSTRACT

Flow regimes are of importance in determining the operating region applicable to many prediction methods used in two-phase flow. Prediction of the flwo pattern boundaries on a flow regime map are either very crude or use methods which are very complex. However it is possible to use a simplified approach which gives acceptable estimates of the flow pattern boundaries.

INTRODUCTION

Many of the prediction methods which are used in two phase flow are often inadequate because they ignore certain important parameters such as the flow pattern regimes. Beattie (1971) and Solbrig et al. (1978) have shown that different forces are predominant in different flow regimes and hence it is unlikely that any one single correlation would apply generally to all flow patterns. Therefore it is somewhat surprising that correlations such as the Lockhart-Martinelli model (1949) are able to be used to predict results of reasonable accuracy over a wide range of flow conditions which embrace a number of different flow patterns. These are exceptions and in general correlations only give reasonable predictions if they are used under the conditions particularly the flow pattern conditions for which they are derived.

In the design of two-phase flow equipment it is desirable to ensure that a particular flow pattern is the predominant one encountered in order to obtain the optimal operating conditions. For example in reticulation systems, slugs are not desirable [c.f. Pearce (1970), Hara (1977), Allen (1977)] while in certain chemical reactors, slug flow is the most efficient with respect to mass and heat transfer as Shilimkan and Stepanek (1977) point out. In other words it is necessary to design the equipment to ensure that a particular pattern occurs. To facilitate this, various flow pattern maps have been developed. But almost all are based on, firstly visual observations which might differ depending on the individual observer, and secondly, the representation of the observed flow patterns using some combination of various possible flow variables as mapping parameters resulting in flow regime maps, many of which are lacking in generality.

More recently, mechanistic models of flow pattern transition have been analysed. Among the more notable ones are those of Quandt (1965) and Taitel & Dukler (1976, a,b). Quandt's transition criteria are rather crude although the predicted transition boundaries agreed with some of the accepted flow pattern maps under certain conditions. The analysis of Taitel & Dukler is a more thorough one and is a more realistic representation of the actual situation. This work follows closely the method of Taitel & Dukler (1976, a) giving a result that is easier to derive ana use and has the advantage that all the solutions are expressed explicity in equation form thus ensuring ease of application particularly in the field situation.

It is considered that the three transitions stratified to slug; stratified to annular; slug to annular are the most important ones in horizontal flow as is evident from the analysis of Chen (1979). Hence only these three transitions will be considered.

WAVE GROWTH

It is assumed that when a two-phase gas-liquid mixture is brought together to flow in a horizontal tube, the stratified configuration is first formed. Waves may or may not occur. At low flows, the interface is relatively smooth, being free of surface disturbances. As the flow rates are increased waves begin to appear on the interface and when the velocities are high enough, the waves will be such that the wave crests reach the top of the pipe. This growth of wave amplitude is governed by the Kelvin-Helmholtz type of instability as discussed by Kordyban & Ranov (1970).

Lord Rayleigh (1945) presented an equation governing the growth of waves. When applied to the horizontal situation, the condition for wave formation is

$$\bar{U}_G > \left[\frac{(\rho_L - \rho_G)\, g\, \delta_G}{\rho_G} \right]^{1/2} \qquad [1]$$

However, in real situations waves will grow at a much lower value of $\bar{U}_G$ than predicted by equation [1].

Wallis & Dobson (1973) showed that for wave formation, the condition is

$$\bar{U}_G > 0.5 \left[\frac{(\rho_L - \rho_G)\, g\, \delta_G}{\rho_G} \right] \qquad [2]$$

They used the model of Benjamin (1968) for a moving wavefront to arrive at the equation which was checked to be valid using a rectangular channel.

Taitel & Dukler (1976, a) in fact used the experimental results of Kordyban & Ranov to show that the gas velocity for waves to grow is

$$\bar{U}_G > (1 - \frac{\delta_L}{D}) \left[\frac{(\rho_L - \rho_G)\, g\, \delta_G}{\rho_G} \right]^{\frac{1}{2}} \qquad [3]$$

There appears to be some disagreement between equations [3] and [2]. However, a closer examination of Wallis & Dobson's results revealed that while both investigations were done using rectangular channels, Wallis & Dobson worked in the region of $\delta_L/D = 0.5$ and hence, equation [2] may be considered as a special case of equation [3]. Equation [3] will be adopted as the condition for wave growth in this work.

Dukler & Taitel (1976, a) used a rather cumbersome equation for wave growth involving a differential of the liquid flow area with respect to depth as shown by the following equation:

$$\bar{U}_G > (1 - \frac{\delta_L}{D}) \left[\frac{(\rho_L - \rho_G)\, g\, A_G}{\rho_G \left(\frac{dA_L}{d\delta_L} \right)} \right]^{\frac{1}{2}} \qquad [4]$$

RELATIONSHIP BETWEEN AIR GAP AND HOLDUP

In a circular conduit, because of the pipe section curvature, the height of the air gap in an equilibrium stratified flow is not as simply related to the holdup or voidage as is the case of a rectangular channel. Since the holdup in a circular conduit may be easily evaluated from the stratified flow holdup equations derived by Spedding & Chen (1979), it is desirable to have a simple relationship between the air gap and the holdup for substitution into equation [3].

The relationship between δ_G and $\bar{R}_G$ may in fact be arrived at by a simple geometrical consideration and the solution obtained by a numerical method as shown in Figure 1. It is possible to relate δ_G/D to $\bar{R}_G$ by a number of best-fit straight lines to obtain a very high degree of accuracy. However for reasons that will become clear two straight lines are fitted to the solution with the change over point at $R_G = 0.5$. Hence

for $\bar{R}_G < 0.5$ $\qquad \delta_G/D = 0.80\ \bar{R}_G^{\,0.69}$ $\qquad$ [5]

for $\bar{R}_G \geq 0.5$ $\qquad \delta_G/D = \bar{R}_G$ $\qquad$ [6]

The representation of equation [6] for the range $\bar{R}_G > 0.5$ appeared to be rather crude. But it is felt that the introduction of more accurate curve fittings would complicate an otherwise relatively simple method. Moreover, since flow pattern predictions always involve a rather large degree of inaccuracy, the errors introduced in equation [6] is not believed to be sufficiently large to cause an effective offset of the prediction. It is also possible to write $\delta_L/D = 0.80\ \bar{R}_L^{\,0.69}$ for $\bar{R}_G$ 10.5 resulting in $\delta_G/D = (1 - 0.80\ \bar{R}_L^{\,0.69})$, but this will offer no great advantage.

Substitution of equation [5] and [6] to equation [3] gives, for wave growth for $R_G < 0.5$

$$\bar{U}_G > 0.80\ \bar{R}_G^{\,0.69} \left[\frac{(\rho_L - \rho_G) g (0.80) D\ \bar{R}_G^{\,0.69}}{\rho_G} \right]^{\frac{1}{2}} \qquad [7]$$

For $\bar{R}_G \geq 0.5$

$$\bar{U}_G > \bar{R}_G \left[\frac{(\rho_L - \rho_G)\, g\, \bar{R}_G\, D}{\rho_G} \right]^{\frac{1}{2}} \qquad [8]$$

Equation [7] and [8] will determine whether the equilibrium stratified flow will remain as stratified flow or have wave crests rising to the top of the flow tube to result in either annular or slug flow. The conditions for annular-slug flow transition will now be discussed.

SLUG-ANNULAR FLOW TRANSITION

Taitel & Dukler reasoned that if an unstable wave is formed and reaches the top of the channel, the resultant flow pattern will be slug or annular depends on whether the equilibrium stratified flow had a liquid level of greater or less than half the height of the flow channel. If the equilibrium liquid level was greater than half the channel height, there will be sufficient liquid to maintain continuity in the liquid phase thus blocking off the entire flow cross-section when a wave is swept up to reach the top of the flow channel, and consequently, slug flow is formed. Otherwise, annular flow will prevail.

It is now clear why the $(\delta_G/D) - \bar{R}_G$ relationship is divided into two ranges with the change over point at $R_G = 0.5$. When $\bar{R}_G$ is less than 0.5, the resultant flow pattern may be slug or stratified depending on the results of equation [7] and when $\bar{R}_G$ is greater than 0.5, the resultant flow pattern may be annular or stratified depending on the results of equation [8].

In the case of a high flow rate reticulation system, such as the one at the geothermal field at Wairakei, New Zealand, the predominant flow patterns are slug and annular flow. For the efficient operation of the system, it is important that the flow pattern is predicted accurately and conveniently. Since the flow rates are high and therefore the phases are both in the turbulent flow regimes, the equation governing the equilibrium stratified flow may be chosen appropriately from Spedding & Chen (1979). The conditions for slug and annular flow may be more conveniently written as

For Slug Flow to occur $\qquad \bar{R}_G/\bar{R}_L < 1.0$

For Annular Flow to occur $\qquad \bar{R}_G/\bar{R}_L > 1.0$

The equation to be used for predicting $\bar{R}_G/\bar{R}_L$ when its value is close to unity is from Spedding & Chen (1979)

$$\frac{\bar{R}_G}{\bar{R}_L} = 1.48 \left(\frac{Q_G}{Q_L} \right)^{0.77} \left(\frac{\rho_G}{\rho_L} \right)^{0.34} \left(\frac{\mu_G}{\mu_L} \right)^{0.09} \qquad [9]$$

Thus, to check whether the flow is annular or slug, it is merely a matter of determining whether equation [9] is greater or less than unity. Equation [9] may also be expressed in terms of the dryness fraction.

It is to be pointed out that the diameter has no effect on the slug-annular transition when both phases are in the turbulent flow regime in the equilibrium stratified flow situation. The diameter is still of no effect if both phases were in the laminar flow regime although this is not a common practical situation. However, if the phases were in dissimilar flow regimes in the equilibrium stratified flow situation, the slug-annular transition will be affected by the diameter since the equation for $\bar{R}_G/\bar{R}_L$ contain the diameter term.

APPLICATION OF THE FLOW PATTERN TRANSITION EQUATIONS

The equations obtained together with the appropriate equilibrium stratified flow equations derived by Spedding & Chen (1979) are used to calculate the U_{LS} and U_{GS} at transition for comparison with the flow regime maps of Mandhane et al. (1974) and Taitel & Dukler (1976, a). Figure 2 shows the predicted transition boundaries for a 4.55 cm diameter pipe plotted against those given by Mandhane et al. Also plotted are the transition lines obtained by Taitel & Dukler for a 5.0 cm diameter pipe corresponding to the transitions analysed in this work. Agreement is excellent. Data obtained in this work are plotted in Figure 3 with the transition lines obtained in this work. Again, agreement is excellent. It is to be noted that Mandhane's transition boundaries were derived using data obtained mainly from 1.3 to 5.0 cm diameter pipes. Pipe diameter effect may also be investigated using these equations but since Taitel & Dukler have already carried out the examination, it will not be repeated here.

Harrison (1975) has in fact shown that the flow regime map of Mandhane is superior to the Baker chart when applied to the Wairakei geothermal. steam-water system. It is therefore envisaged that the analysis carried out here should prove useful in the geothermal field for determining the annular-slug transition.

CONCLUSIONS

In this work, three flow pattern transitions were examined in the light of the equilibrium stratified holdup prediction equations derived by Spedding & Chen (1979). The three transitions: stratified-annular, stratified-slug, and annular-slug, are perhaps the most important ones in the study of gas-liquid flow, since pressure drop and holdup data representations may be grouped into these three flow regimes as shown by Chen (1979). Other sub-divisions of these transitions were not examined partly for this reason and partly because the intention of the analysis is to illustrate at least one other use of the stratified flow equations derived by Spedding & Chen (1979).

The very crude relationships obtained by using piecewise straight line curve fit for δ_G/D and R_G appear to be quite valid and as a result, lead to a greatly simplified set of equations. The advantages that this analysis has over that of Taitel & Dukler are listed as follows:

(a) No complicated dimensionless equations are involved;

(b) No graphs are essential for the evaluation of the equations since all the solutions are expressed explicitly in equation forms;

(c) Because all controlling situations are expressed in simple equation form, it is possible for the use of one simple equation to determine the annular-slug transition. This should prove useful in a field situation such as that of a geothermal or an oil field;

(d) The form of equation for unstable wave growth in a circular conduit has been greatly simplified in terms of $\bar{R}_G$ instead of the form invovling a differential as suggested by Taitel & Dukler.

LIST OF SYMBOLS

A	$[L^2]$	flow area
D	$[L]$	pipe diameter
g	$[L\ T^{-2}]$	gravitational acceleration
Q	$[L\ T^{-1}]$	volumetric flow rate
$\bar{R}$	$[-]$	holdup
$\bar{U}$	$[L\ T^{-1}]$	actual average velocity
	$[L\ T^{-1}]$	superficial velocity
δ	$[L]$	phase thickness or depth
μ	$[M\ L^{-1}\ T^{-1}]$	dynamic viscosity
ν	$[L^2\ T^{-1}]$	kinematic viscosity
ρ	$[M\ L^{-3}]$	density

<u>subscripts</u>

G gas

L liquid

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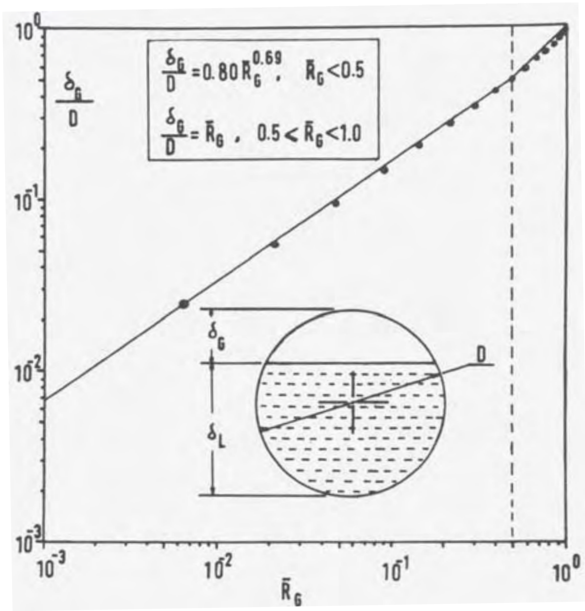

Figure 1 Relationship between δ_G/D and $\bar{R}_G$.

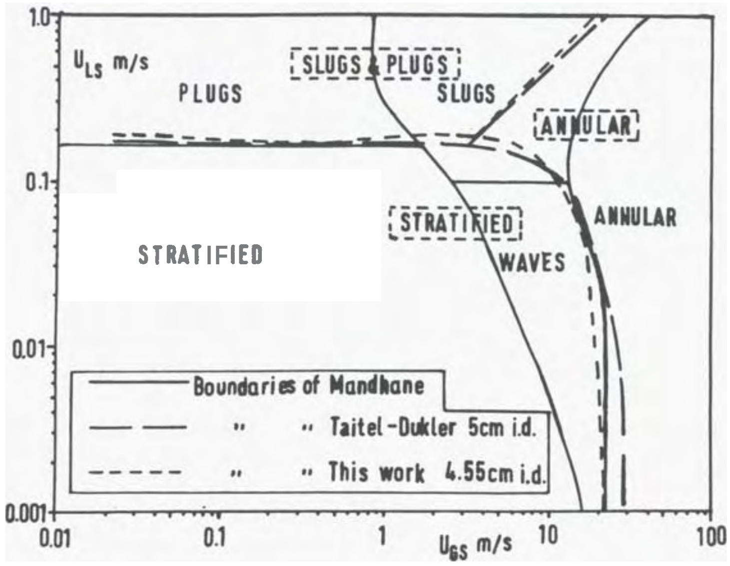

Figure 2 Comparison of the stratified-slugs and plugs-annular flow pattern transitions derived in this work with those of Taitel & Dukler and Mandhane et al.

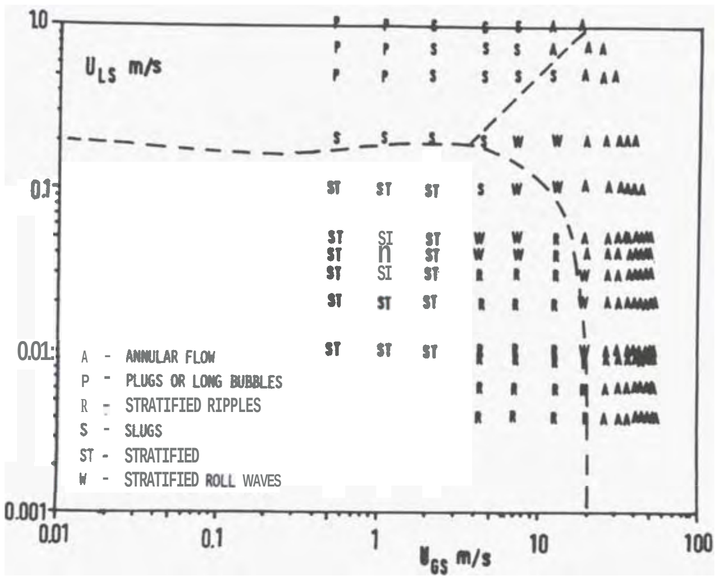

Figure 3 Comparison of predicted against observed flow patterns