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THE PRESENCE OF SLUG FLOW IN HORIZONTAL TWO-PHASE FLOW

J. KUBIE†
Central Electricity Research Laboratories, Leatherhead, Surrey, England

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Abstract—One of the flow regimes occurring in horizontal two-phase flows is characterized by periodic large waves "surging" along the tube. This flow, called "slug" flow, has been frequently observed in low and high pressure gas liquid systems, but it has been noticed that slugging is absent in certain liquid–liquid two-phase systems. A method is developed giving the necessary conditions for the presence of slug flow. This method quantitatively explains the observed absence of slugging in certain liquid–liquid flows.

1. INTRODUCTION

One of the flow regimes occurring in horizontal two-phase gas–liquid flow is characterized by periodic large waves or liquid slugs "surging" along the tube. This flow, called slug or surge flow, can be also described as an extreme case of long bubble flow, the qualitative difference being that in the slug flow the large waves move much faster than the bulk of the liquid, whereas in the long bubble flow, the gas and the liquid move with about the same velocity and, additionally, the void fraction is substantially smaller.

Slug flow is highly desirable in intermediate quality steam–water flow in horizontal boiler tubes, since the large waves are responsible for the replenishment of the liquid on the upper surfaces of the tube and this may prevent formation of dry patches when the tube is heated (Fisher & Yu 1975). On the other hand slug flow may be responsible for large pressure transients and fluctuations of individual phase discharge rates and these aspects must also be considered.

This flow regime has been extensively observed in low and high pressure gas–liquid systems and has been correlated with certain corrosion failures of high pressure boiler tubes (Fisher *et al.* 1978). In liquid–liquid flows in horizontal tubes, however, the slug flow regime as defined above is missing. Govier & Aziz (1972) in their review of horizontal liquid–liquid flow do not indicate such a flow regime with two liquids of different densities and, more recently, the absence of slug flow was also noticed by Kubie & Gardner (1977) during their investigation of *n*-butyl acetate/water flow in a 25.4-mm tube bore helix, which was used to model the flow behaviour in high pressure steam–water helical boilers.

It has been found experimentally that slug flow originates from stratified flow when interfacial instabilities allow formation of large waves (Wallis & Dobson 1973) and there is a number of analyses available in the literature on transition from stratified to slug flow in horizontal channels. Kordyban & Ranov (1970) and Wallis & Dobson (1973) analyzed slugging in horizontal air–water flows in rectangular channels. More recently Taitel & Dukler (1976) and Gardner (1977) developed other models for the transition from stratified to slug flow. The former model is similar to that of Wallis & Dobson but Gardner's model is conceptually different, since it does not deal directly with interfacial instabilities but considers instead energetic behaviour of inviscid flow. Gardner's is the only model which is directly applicable to systems with smaller density ratios ρ_H/ρ_L, where ρ_H and ρ_L are the densities of the heavy and the light phase respectively.

It is the purpose of this paper to explain the absence of slug flow in certain liquid–liquid systems and to discuss consequences for high pressure steam–water boilers and systems used for their modelling.

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†Present address: Engineering Department, CEGB SER, Laud House, 20 Newgate Street, London EC1, England.

The extrapolation of surging criteria to systems with lower density ratios (ρ_H/ρ_L) is considered and it is shown that the relative velocity (difference between the mean velocities of the phases) required for the onset of slugging decreases with the decreasing density ratio. It is also shown that there is a limit to the maximum attainable relative velocity in horizontal stratified flow which is determined by the stability of the interface against entrainment and that this maximum relative velocity decreases in all practical cases more rapidly with decreasing density ratio than the relative velocity required for the onset of slugging, so that the range of operating parameters over which slugging can occur narrows and slug flow eventually disappears.

Some experimental evidence justifying the present approach is presented.

2. ANALYSIS

The theoretical analysis is only concerned with two-phase flows in horizontal tubes such as occur, for example, in serpentine evaporators with long horizontal passes because (i) the analysis is considerably simplified; (ii) some of the previously derived conditions for the onset of slugging are applicable; and (iii) theoretical predictions can be readily compared with available experimental data.

2.1 *Onset of slugging*

The extrapolation of the simple model of Wallis & Dobson (1973) is considered in this work. They applied the Kelvin–Helmholz theory of interfacial instability on small amplitude long waves in rectangular channels. These waves are unstable for

$$\mathrm{Fr}' \geqslant 1 \qquad [1]$$

where

$$\mathrm{Fr}' = \frac{V_L - V_H}{\left[g(\rho_H - \rho_L)\left(\dfrac{h_L}{\rho_L} + \dfrac{h_H}{\rho_H}\right)\right]^{1/2}} \qquad [2]$$

and where V_L and V_H are the mean velocities of the light and the heavy phase respectively, g is the gravitational acceleration and h_L and h_H are the depths of the light and the heavy phase respectively.

Wallis & Dobson found that the onset of slugging was correlated by the Froude number of [2] and that at the onset of slugging it was equal to 0.5. However since they were dealing with air and water they neglected h_H/ρ_H in comparison with h_L/ρ_L and hence they did not investigate the effect of the density of the heavy phase. It is assumed here that, for systems where inertia forces are considerably greater than viscous and interfacial forces, the empirically determined constant of 0.5 can be applied more generally. This implies that the influence of h_H/ρ_H is accounted for by using the above definition of the Froude number.

The hypothesis that the onset of slugging in horizontal rectangular channels can be correlated with the onset of instability of small amplitude long interfacial waves is extended to flows in horizontal circular pipes as follows. The velocity of these waves, c, is given by Gardner (1977) as

$$\frac{\rho_H(V_H - c)^2}{(\rho_H - \rho_L)gA_H} P_I + \frac{\rho_L(V_L - c)^2}{(\rho_H - \rho_L)gA_L} P_I = 1$$

where P_I is the width of the two-phase interface and A_L and A_H are the cross-sectional areas occupied by the light and the heavy phase respectively. These waves become unstable for

$\mathrm{Fr} \geqslant 1$ where

$$\mathrm{Fr} = \frac{V_L - V_H}{\left[g(\rho_H - \rho_L)\left(\frac{A_H}{P_I\rho_H} + \frac{A_L}{P_I\rho_L}\right)\right]^{1/2}} \qquad [3]$$

and as above the onset of slugging is assumed to take place for $\mathrm{Fr} = 0.5$. This can be rearranged and the critical relative velocity for the onset of slugging can be expressed as

$$V_L - V_H = 0.5\left(\frac{\rho_H - \rho_L}{\rho_L} gR\right)^{1/2} \psi_D \qquad [4]$$

where

$$\psi_D = \left[\frac{\theta - \sin\theta\cos\theta}{2\sin\theta}\left(1 - \frac{\rho_L}{\rho_H}\right) + \frac{\pi}{2\sin\theta}\frac{\rho_L}{\rho_H}\right]^{1/2} \qquad [5]$$

and where R is the radius of the tube and 2θ is the angle subtended by the light phase to the two-phase interface (figure 1). The function ψ_D is plotted vs θ for various values of the density ratio ρ_H/ρ_L in figure 1.

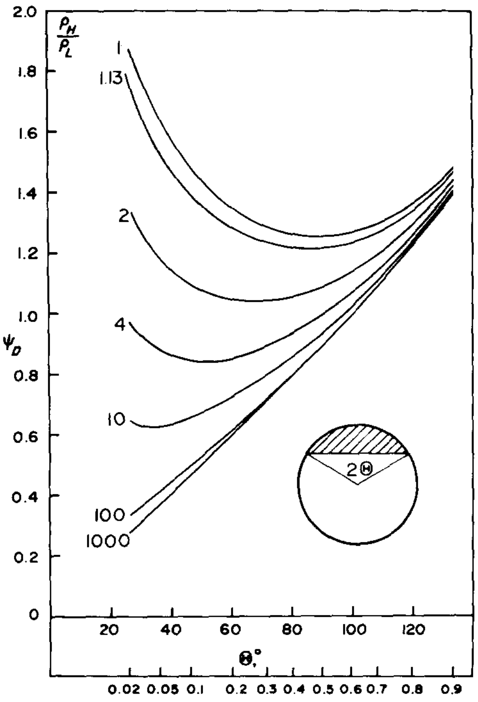


Figure 1. Plot of function ψ_D vs voidage A.

2.2 *Relative velocity in stratified flow*

In order to determine if slugging is possible in a particular system the relative velocity under stratified conditions has to be known. It can be shown, by assuming that the pressure gradient in both phases is the same that the equilibrium condition for stratified flow without mass transfer in horizontal tubes may be expressed as

$$f_L\rho_L V_L^2\frac{P}{A}-f_H\rho_H V_H^2\frac{1-P}{1-A}+2\tau_i\frac{V_L-V_H}{|V_L-V_H|}\frac{sP}{A(1-A)}=0 \quad [6]$$

where

$$P=\theta/\pi \quad [7]$$

$$A=\theta/\pi-\sin 2\theta/2\pi \quad [8]$$

$$s=\sin\theta/\theta \quad [9]$$

and where τ_i is the interfacial shear and f_L and f_H are the friction factors between the wall and the light and the heavy phase respectively.

In order to calculate the relative velocity from[6] the interfacial shear must be known. It is assumed here that it is given by

$$\tau_i=\tfrac{1}{2}\gamma f_L\rho_L(V_L-V_H)^2 \quad [10]$$

where f_L is the friction factor between the wall of the tube and the light phase and γ is a correction factor which takes into account, for example, the topography of the interface and the density ratio. Assuming further that $f_L=f_H$ for the turbulent flow of both phases considered here and substituting[10] in[6], the relative velocity is found to be

$$V_L-V_H=V_{HS}\psi_S \quad [11]$$

where

$$\psi_S=\left\{\left[1+\left(\frac{\rho_H}{\rho_L}\frac{A}{P}\frac{1-P}{1-A}-1\right)\left(1+\frac{\gamma s}{1-A}\right)\right]^{1/2}-1\right\}\Big/(1-A+\gamma s) \quad [12]$$

and where V_{HS} is the superficial velocity of the heavy phase.

The interfacial shear stress was investigated, for example, by Cohen & Hanratty (1968), Davis (1969) and Kordyban (1974) in air-liquid flows in horizontal channels and the correction coefficient γ was found to vary from about 1 (for smooth interfaces) to about 4. There are no data available on interfacial shear stress in liquid–liquid flows in circular tubes. However, for reasons which become clear later, the present analysis is limited to void fractions, A of not more than 0.5. Then even a four fold increase in γ increases the relative velocity at the most by 46, 33 and 23% for the density ratios of 1000, 10 and 2 respectively and the sensitivity of the relative velocity on γ decreases with the decreasing density ratio, ρ_H/ρ_L. Hence, for simplicity, the value of $\gamma=1.0$ is used in[12] throughout this work. The function ψ_S for $\gamma=1.0$ is plotted vs θ for various values of the density ratio in figure 2(a) and 2(b).

2.3 *Limits on the relative velocity and the void fraction*

Equations[11] and [12] show that the relative velocity is independent of the dimensions of the tube and is proportional to the superficial velocity of the heavy phase. This implies that the relative velocity could be as large as required (depending on the superficial velocity of the heavy phase) and that slugging could occur in all two-phase flow systems which exhibit stratification. However, there is a limit on the maximum relative velocity since, if either of the phase velocities exceeds certain critical values, the interface will be broken and the entrained drops will inhibit a further increase in the relative velocity and thus prevent the onset of slugging.

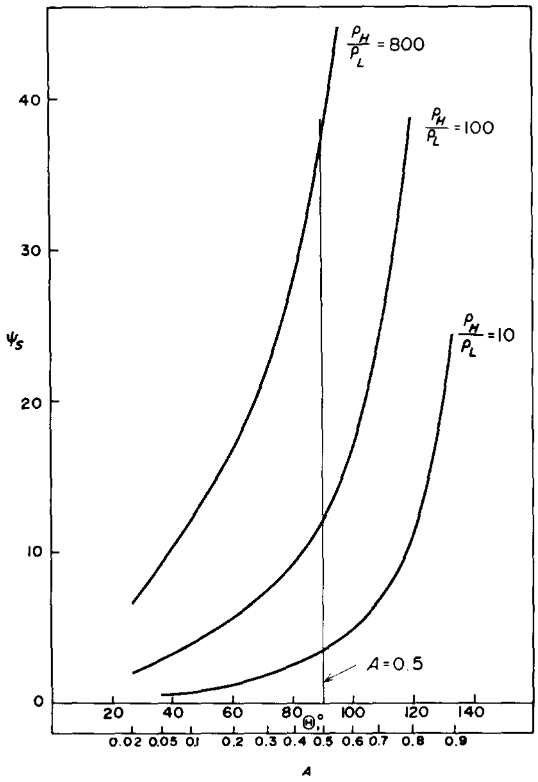


Figure 2(a). Plot of function ψ_S vs voidage A.

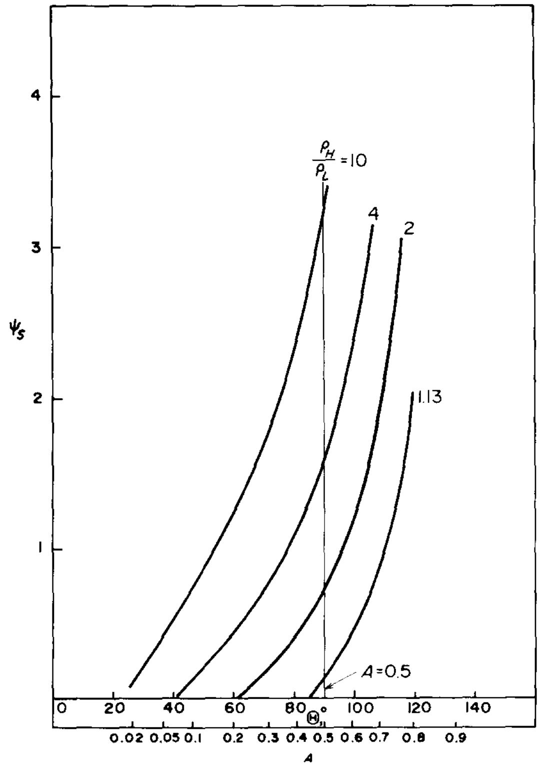


Figure 2(b). Plot of function ψ_S vs voidage A.

The stability of the interface against entrainment was investigated by Gardner & Kubie (1976) during a study of two-phase liquid–liquid flows in pipes. They found that the critical velocity for the breakdown of the stratified flow into drops, V_C, was given by

$$\frac{\rho f V_c^2}{(\Delta\rho g\sigma)^{1/2}} = 1.4 \qquad [13]$$

where σ is the interfacial tension, $\Delta\rho$ is the differential between the phase densities, and ρ and f are the appropriate values of the density and the wall friction factor; to calculate the critical velocity of the heavy phase V_{HC}, ρ_H and f_H are used and to calculate the critical velocity of the light phase V_{LC}, ρ_L and f_L are used. It was also inferred from experimental evidence that[13] could be used to predict the disruption of stratified flow in high pressure steam–water and freon vapour/freon liquid flows. However, it should be noted that in all these cases the density ratio was less than or equal to about 10. Examination of the work of Davis (1969) and Ishii & Grolmes (1975) indicates that in gas–liquid systems[13] substantially overpredicts the critical gas velocity required for the breakdown of the water film and thus application of[13] in cases where the density ratio is more than 10 is doubtful.

Furthermore, there also seems to be a limit on the maximum voidage, A, for which transition to stable slugging in circular tubes can occur. Taitel & Dukler (1976) suggest that this maximum voidage is 0.5. They picture the wave as a sinusoid and argue that a stable slug can form only when the supply of liquid in the pipe is sufficient to maintain such a slug. If the water level is above the centre line ($A < 0.5$), the peak of the wave will reach the top before the trough reaches the bottom of the pipe, and then blockage of the gas passage and slugging can result. When the liquid level is below the centre line ($A > 0.5$), the inverse will be true, which will make slugging impossible.

It can be then shown that for all these conditions ($A \leq 0.5$) and all practical purposes the phase which is responsible for the breakdown of the interface is the heavy phase. Hence from[4], [5], [11], [12] and [13] the necessary condition for the onset of slugging in horizontal pipes is

$$\Lambda = \frac{2V_{HS}\psi}{(gR)^{1/2}\left(\frac{\rho_H - \rho_L}{\rho_L}\right)^{1/2}} \geq 1. \qquad [14]$$

subject to

$$A \leq 0.5 \qquad [15]$$

$$V_{HS} \leq \left[\frac{1.4(\Delta\rho g\sigma)^{1/2}}{\rho_H f_H}\right]^{1/2}(1 - A) \qquad [16]$$

where

$$\psi = \psi_S/\psi_D \qquad [17]$$

and ψ is plotted in figure 3. Equations [14]–[17] probably hold well for $\rho_H/\rho_L \leq 10$, but can give only trends for $\rho_H/\rho_L > 10$.

It can be seen from [14]–[17] that Λ is a function of the properties of both phases and the radius of the tube. For a given value of A, the maximum possible value of V_{HS} can be calculated from [16] and then the maximum value of the function Λ (denoted Λ^M) can be obtained from [14]. If the present hypotheses are correct, Λ^M greater than unity indicates that slug flow can be present and Λ^M smaller than unity that transition to slugging cannot occur.

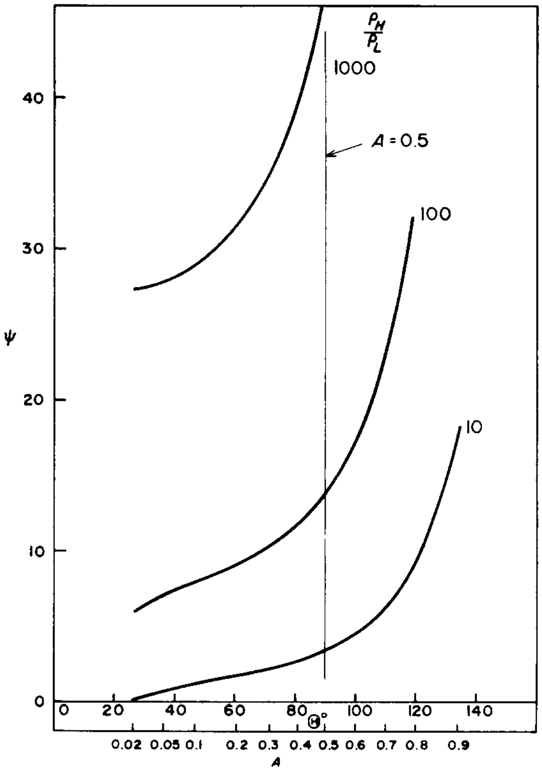


Figure 3(a). Plot of function ψ vs voidage A.

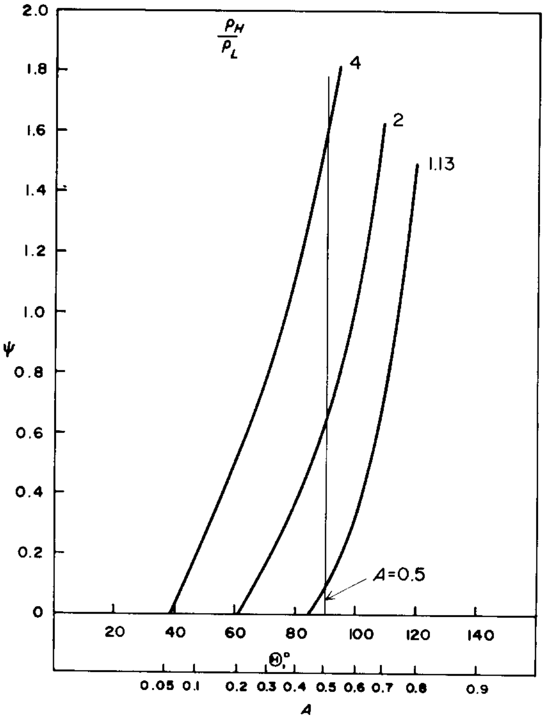


Figure 3(b). Plot of function ψ vs voidage A.

Lastly it should be noted that Λ increases with decreasing radius of the tube ($\Lambda \propto 1/R^{1/2}$). Hence the tube diameter could be chosen sufficiently small to make Λ greater than unity and slugging could then occur. This will only be possible if the surface tension forces allow stratification in the first place. This was tested during experimental work described below.

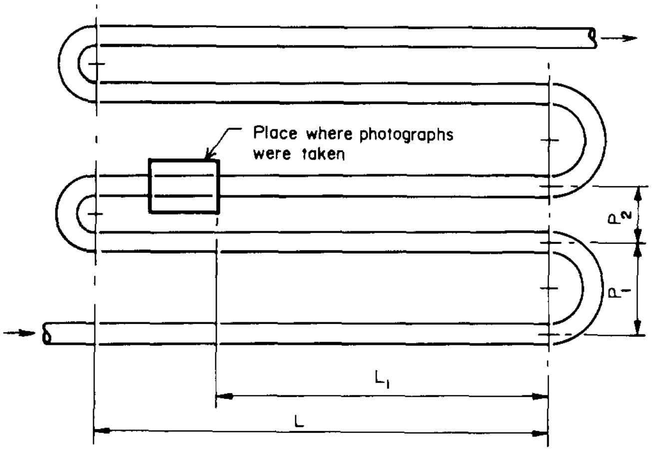
3. EXPERIMENTAL WORK

As mentioned previously slug flow was not present for the flow of acetate and water in a 0.025 m bore helical coil (Kubie & Gardner 1976). If the tube were horizontal, Λ^M would be below unity for $A = 0.5$ (as shown in table 2). To test the hypotheses of the previous section, three glass serpentines were built with dimensions shown in figure 4. Acetate and water were pumped into the bottom inlets of the test sections at known flowrates and the flow regimes were observed visually and photographed. Detailed description of the flow patterns is not given. It suffices to mention that in the largest serpentine (tube diameter $D = 0.0254$ m) stratification was followed by partial and complete breakdown of the acetate layer into drops and slug flow was not observed. Sketches of typical photographs are shown in figure 5. In the two smaller serpentines ($D = 0.0072$ m and $D = 0.0044$ m) stratification, slugging and breakdown of the acetate layer were all observed. Some development of the flow took place downstream of the bends where some of the smaller slugs became unstable and disappeared. The flow became stable, however, about 20 pipe diameters downstream of the bends. Sketches of typical photographs for $D = 0.0072$ m are shown in figure 6 which shows that slugging was observed for $A \simeq 0.5$. Hence the conclusion from the experimental work is that with acetate and water flowing in serpentines, slug flow does not occur in tubes with bores greater than or equal to 0.0254 m but it can occur in tubes with bores equal to or below 0.0072 m.

4. DISCUSSION

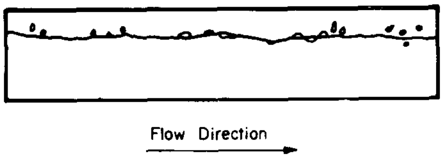
4.1 *Onset of slugging*

The analysis developed in section 2 is applied to the flow of acetate and water, air and water, freon vapour and freon liquid and steam and water at various pressures; however, it

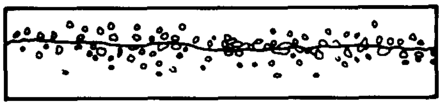


	Serpentine I	Serpentine II	Serpentine III
Bore, mm	25.4	7.2	4.4
L, mm	2000	1000	1000
P_1, mm	140	49	32
P_2, mm	70	30	14
L_1, mm	1600	500	500

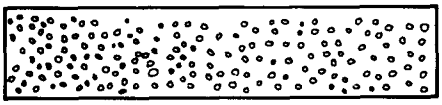
Figure 4. Diagram of the serpentines.



(a) Stratified flow, V_{HS} = 39.5 cm/s, V_{LS} = 10 cm/s

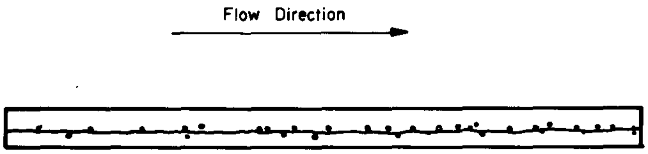


(b) Stratified flow with entrained drops.
V_{HS} = 39.5 cm/s, V_{LS} = 23.5 cm/s



(c) Dispersed flow, V_{HS} = 39.5 cm/s, V_{LS} = 39.5 cm/s

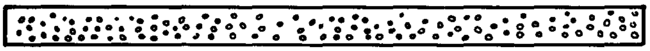
Figure 5. Sketches of the flow patterns in the 25.4-mm bore serpentine.



(a) Stratified flow, V_{HS} = 26.3 cm/s. V_{LS} = 20.9 cm/s

(b) Surge flow, V_{HS} = 26.3 cm/s. V_{LS} = 27.0 cm/s

(c) Surge flow, V_{HS} = 26.3 cm/s, V_{LS} = 29.4 cm/s



(d) Dispersed flow, V_{HS} = 26.3 cm/s, V_{LS} = 73.7 cm/s

Figure 6. Sketches of the flow patterns in the 7.2-mm bore serpentine.

should be noted that there are certain reservations and restrictions. The major one is that the analysis is restricted only to systems in which the density ratio is less than 10, i.e. exactly to those systems where the equation for the onset of slugging was not separately tested. In systems with the density ratio greater than 10 the analysis is applied only formally. All relevant properties of the above fluids are given in table 1. The values of Λ^M (obtained with "equal" sign in [16]) for $A = 0.5$, 0.3 and 0.7 are presented in table 2. It should be noted that Λ^M was not calculated for the flow of acetate and water for $A = 0.3$, since the relative velocity was negative in these cases.

It can be observed from table 2 that in cases in which $\rho_H/\rho_L \leq 10$, the values of Λ^M decrease with the decreasing voidage, A. Hence it can be concluded that in general slugging is more probable for higher voidages and if one is looking for the presence of slug flow it is sufficient to investigate the behaviour of the system for the largest value of voidage which will allow slug flow. Taitel & Dukler (1976) suggest that this voidage is 0.5 and hence the behaviour of Λ^M for $A = 0.5$ is investigated first. Now, slug flow was visually observed in atmospheric steam–water and air–water flows (Fisher & Yu 1975) where $\Lambda^M_{0.5} \simeq 13$. The presence of slug flow was inferred in steam–water flow at 60 bar (Lis & Strickland 1970) where $\Lambda^M_{0.5} \simeq 7$ and in freon vapour–freon liquid flow at 30 bar (Fisher *et al.* 1978) where $\Lambda^M_{0.5} \simeq 2.9$. During the present experimental work with acetate and water in serpentines, slugging was observed for tube diameters of 0.0072 and 0.0044 where $\Lambda^M_{0.5} \simeq 1.2$ and 1.5 respectively and not observed for the tube diameter of 0.0254 m where $\Lambda^M_{0.5} = 0.76$.

All the above results lend support to the analyses developed in this work though there are uncertainties in the overall approach. The major one seems to be the requirement that the

Table 1. Relevant properties of examined fluids

Fluid	Pressure (bar)	Density (kg/m^3)	Interfacial tension with water (J/m^2)	Interfacial tension with freon liquid (J/m^2)
Water	1	1000	-	-
Air	1	1.25	0.072	-
Butyl Acetate	1	884	0.0145	-
Water	210.55	452	-	-
	180	540	-	-
	110	670	-	-
	17	860	-	-
	1.7	947	-	-
Steam	210.55	201	0.00047	-
	180	130	0.0028	-
	110	62.2	0.010	-
	17	8.6	0.036	-
	1.7	0.97	0.055	-
Freon Liquid	30	955	-	-
Freon Vapour	30	210	-	0.001

Table 2. Table of Λ^M for various fluids and various values of the voidage

A	light phase	heavy phase	pressure (bar)	tube radius (m)	Λ^M
0.3	steam	water	210.5	0.0127	0.91
	steam	water	180	0.0127	3.0
	steam	water	110	0.0127	6.1
	steam	water	17	0.0127	11.5
	steam	water	1.7	0.0127	13.7
	air	water	1	0.0127	14.3
	freon	freon	30	0.0127	1.8
0.5	acetate	water	1	0.0127	0.76
	acetate	water	1	0.0036	1.2
	acetate	water	1	0.0022	1.5
	steam	water	210.5	0.0127	1.9
	steam	water	180	0.0127	4.1
	steam	water	110	0.0127	6.8
	steam	water	17	0.0127	9.4
	steam	water	1.7	0.0127	13.2
	air	water	1	0.0127	13.7
	freon	freon	30	0.0127	2.9
0.7	acetate	water	1	0.0127	2.7
	acetate	water	1	0.0036	4.2
	acetate	water	1	0.0022	5.1
	steam	water	210.5	0.0127	2.5
	steam	water	180	0.0127	4.6
	steam	water	110	0.0127	6.9
	steam	water	17	0.0127	10.7
	steam	water	1.7	0.0127	12.2
	air	water	1	0.0127	12.2
	freon	freon	30	0.0127	3.5

voidage for the onset of slugging is limited to $A \leq 0.5$. It can be observed from table 2 that if this voidage were 0.7 instead of 0.5 the approach would be at fault, since it would give $\Lambda^M_{0.7}$ greater than unity for the flow of acetate and water in 0.0254 in diameter tube where slugging was not observed. Nevertheless, even in this case Λ^M decreases as slugging becomes more difficult. Hence the limiting voidage of $A = 0.5$, suggested by Taitel & Dukler (1976), can be regarded, at least, as an empirical constant introduced into the present model to obtain agreement between the prediction of the model and experimental results. Hence the *necessary* condition for the possible presence of slug flow in horizontal pipes is $\Lambda^M_{0.5}$ greater than unity, where $\Lambda^M_{0.5}$ is given by [14]–[17] as

$$\Lambda^M_{0.5} = 1.18\left[\frac{\sigma}{g\Delta\rho\left(Rf_H\frac{\rho_H}{\rho_L}\right)^2}\right]^{1/4}\frac{\left(1+2.27\frac{\Delta\rho}{\rho_L}\right)^{1/2}-1}{\left(1+\frac{\rho_L}{\rho_H}\right)^{1/2}}. \qquad [18]$$

Slug flow is not possible for $\Lambda^M_{0.5}$ smaller than unity. The presence or absence of slug flow for $\Lambda^M_{0.5}$ greater than unity depends, of course, on the actual phase velocities in each particular case and the properties of the fluids, which sometimes may not allow stratification in the first place.

4.2 *Influence of interfacial tension*

It could be argued that interfacial tension was of primary importance during the present experimental work with acetate-water flow in small bore tubes. The influence of the interfacial tension is considered as follows: There are three major forces with possible influence on initial stratification and onset of slugging: inertia, interfacial tension and buoyancy forces. Thus the effect of interfacial tension may be represented by two dimensionless groups. They are, for example, the Froude number, which is the ratio of inertia to buoyancy forces and the Weber number which is the ratio of inertia to interfacial forces and which is defined as

$$\mathrm{We} = \frac{\rho_L V_L^2 l}{\sigma} \qquad [19]$$

where l is a typical dimension of the tube assumed here to be equal to the radius of the tube, R.

The Weber numbers for the flow of acetate and water in 0.0254 m, 0.0072 m and 0.0044 bore tubes and typical acetate velocities of 0.7 m/s are respectively 380, 100 and 65. Since during the present experimental work well stratified flow was observed just prior to slugging for the Weber numbers of the above magnitudes, the interfacial tension forces are not dominant during the onset of slugging. This argument is further supported by other aspects of the present experimental work since a train of acetate bubbles and not stratified flow was observed at low velocities when the Weber number was low.

4.3 *Implication for modelling*

The modelling of isothermal gas–liquid flow without mass transfer was recently discussed by Chesters (1975). Since one of the similarity parameters is the density ratio ρ_H/ρ_L, rigorous modelling of high pressure steam–water flow is not feasible with a simple analogue. A possible alternative approach based on the results of the present work is discussed below for the flow in horizontal pipes.

As mentioned in section 2, Λ^M can be calculated for each particular value of the voidage by using the "equal" signs in [16]. It can be shown from [14] and [16] that in all systems a critical value of the voidage will be reached at which $\Lambda^M = 1$ and thus for all voidages smaller than the critical value, slug flow will no longer be possible. For $\Lambda^M < 1$ the flow pattern may be either bubble or stratified flow depending on the value of the critical voidage, since if this critical voidage is small only bubble flow is possible; otherwise also stratified flow may be present.

The critical voidage for steam–water flow at 180 bar in a 25 mm bore horizontal tube is about 0.11 (corresponding to steam quality of about 3%). If l in the Weber number is assumed to be equal to the maximum depth of the steam layer, the Weber number then is (for the typical steam velocity of 1 m/s) about 200 and this indicates that stratified flow is possible.

This provides an important implication for the modelling of high pressure steam–water flow in horizontal tubes where stratified and slug flow are mainly responsible for dryout at low and intermediate qualities (Fisher *et al.* 1978) and the group Λ^M becomes a substitute modelling parameter. Thus for low quality modelling of high pressure steam–water flow where $\Lambda^M < 1$, analogues with similar values of Λ^M should be used and for intermediate and high quality modelling analogues with $\Lambda^M > 1$ should be employed. Two simple analogue satisfy the respective criteria. First, for an acetate–water flow in a 25-mm bore tube, the group Λ^M is smaller than unity for all void fractions smaller than 0.5 and secondly, for an atmospheric air–water flow in a 25-mm bore tube a formal application of the present method shows that Λ^M is greater than unity for all practical values of the void fraction. Thus the acetate–water analogue should be only used for the modelling of low quality and the atmospheric air–water rig for the modelling of intermediate and high quality high pressure steam–water flow in horizontal tubes.

5. CONCLUSIONS

A method giving the necessary condition for the presence of slug flow in various two-phase flows in horizontal pipes has been developed. This method shows that the range of operating parameters over which slugging can occur narrows as the ratio of phase densities decreases and slugging can eventually disappear. This explains the absence of slugging in certain liquid–liquid flows.

It has been also demonstrated that there is a new parameter which should be considered when modelling high pressure steam–water flows. In particular, it has been shown that two-liquid analogues are more suitable at lower qualities and that low pressure air–water analogues are more suitable for intermediate and high qualities.

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7. REFERENCES

CHESTERS, A. K. 1975 The applicability of dynamic similarity criteria to isothermal, liquid–gas, two-phase flow without mass transfer. *Int. J. Multiphase Flow* **2**, 191–212.

COHEN, L. S. & HANRATTY, T. J. 1968 Effect of waves at a gas–liquid interface on a turbulent air flow. *J. Fluid Mech.* **31**, 467–479.

DAVIS, E. J. 1969 Interfacial shear measurement for two-phase gas–liquid flow by means of Preston tubes. *Ind. Engng Chem. Fundament.* **8**, 153–159.

FISHER, S. A. & YU, S. K. W. 1975 Dryout in serpentine evaporators. *Int. J. Multiphase Flow* **1**, 771–791.

FISHER, S. A., HARRISON, G. S. & PEARCE, D. L. 1978 Premature dryout in conventional and nuclear evaporators. *6th Int. Heat Transfer Conf.*, Toronto.

GARDNER, G. C. 1977 Motion of miscible and immiscible fluids in closed horizontal and vertical ducts. *Int. J. Multiphase Flow* **3**, 305–318.

GARDNER, G. C. & KUBIE, J. 1976 Flow of two liquids in sloping tubes: An analogue of high pressure steam and water. *Int. J. Multiphase Flow* **2**, 435–451.

GOVIER, G. W. & AZIZ, K. 1972 *The Flow of Complex Mixtures in Pipes*. Van Nostrand Reinhold, New York.

ISHII, M. & GROLMES, M. A. 1975 Inception criteria for droplet entrainment in two-phase concurrent film flow. *A.I.Ch.E. J.* **21**, 308–318.

KORDYBAN, E. 1974 Interfacial shear in two-phase wavy flow in closed horizontal channels. *Trans. ASME, J. Fluids Engng* **96**, 97–102.

KORDYBAN, E. & RANOV, T. 1970 Mechanism of slug formation in horizontal two-phase flow. *Trans. ASME, J. Basic Engng* **92**, 857–864.

KUBIE, J. & GARDNER, G. C. 1977 Flow of two liquids in a helix: An analogue of high pressure helical boilers. *Int. J. Multiphase Flow* **3**, 353–366.

LIS, J. & STRICKLAND, J. A. 1970 Local variations of heat transfer in a horizontal steam evaporator tube. *4th Int. Heat Transfer Conf.*, Paris, Vol. 5, B4.6.

TAITEL, Y. & DUKLER, A. E. 1976 A model for predicting flow regime transitions in horizontal and near horizontal gas–liquid flow. *A.I.Ch.E. J.* **22**, 47–55.

WALLIS, G. B. & DOBSON, J. E. 1973 The onset of slugging in horizontal stratified air–water flow. *Int. J. Multiphase Flow* **1**, 173–193.