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FLOW OF TWO LIQUIDS IN A HELIX: AN ANALOGUE OF HIGH PRESSURE HELICAL BOILERS

J. KUBIE and G. C. GARDNER
Central Electricity Research Laboratories, Leatherhead, Surrey, England

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Abstract—It has been shown previously (Gardner & Kubie 1976) that a two-liquid system provides a better analogue for investigating certain aspects of high pressure boiler tube hydrodynamics than air and water at atmospheric pressure. A study is presented here of the flow of n-butyl acetate and water, and iso-amyl alcohol and water in helical coils and the general conclusion is that strongly stratified conditions of either completely separated phases or of drops of one phase in the other exist until velocities are high enough to produce drops sufficiently fine to be dispersed by the turbulence. The critical condition for the breakdown of the separated phases to produce drops is quantitatively correlated with the mass flowrates needed to avoid low quality dryout in both high pressure water and high pressure freon helical boilers. Some evidence is available to support two criteria indicating that low quality dryout will not be observed for sufficiently low pressures in steam–water systems and, perhaps, for small enough bore tubes.

1. INTRODUCTION

A previous paper (Gardner & Kubie 1976) demonstrated the usefulness of a two-liquid (water and iso-amyl alcohol) model in providing a visual representation of high pressure steam–water flows. That particular investigation was concerned with sloping tubes, such as those used on floors of modern power station boilers operating at $17\,\mathrm{MN/m^2}$. It demonstrated a condition under which the flow stratified at low qualities and a thin steam ribbon was formed under the upper tube surface, which could be responsible for corrosion failures. Air–water analogues do not exhibit the ribbon flow, chiefly because the density of the air is low compared with that of the water.

The results for the sloping tubes in terms of the phase velocity difference were quantitatively explained and, because the interfacial tension was small, as in high pressure water systems, a condition was also found when the ribbon flow could be broken into drops. This condition quantitatively correlated the occurrence of a minimum in the burnout heat flux with respect to water velocity at constant quality as determined by Chojnowski *et al.* (1974). The success of the analogue made it desirable to apply it, as described in this communication, to the helical coil boilers used in some of the Advanced Gas Cooled Reactor Power Stations. Here the slope of the tubes to the horizontal is smaller than for typical sloping floor tubes of fossil-fired boilers but there is also an unknown influence of the secondary flow induced by the helical configuration on any stratification that might occur.

The analogues used here employ n-butyl acetate and water as well as iso-amyl alcohol and water. The modelling rules are discussed in the next Section and it is shown that n-butyl acetate is a more useful light phase fluid for much of the investigation than iso-amyl alcohol. The experimental results are then presented followed by theoretical analysis. Finally the implications of the results to helical boilers are discussed.

2. MODELLING RULES

Dimensional analysis shows that it requires seven dimensionless groups to describe the two-phase flow, but it is generally impossible to make each of these equal for the analogue and the prototype. The experience already gained with modelling low-quality flows will therefore be used to choose the dimensionless groups, which should be equal in the two situations for acceptable representation, and then the application of this choice to high quality flow will be discussed.

Important aspects of the low-quality flow in straight tubes are the ribbon and stratified flow (Gardner & Kubie 1976), since they are related to the occurrence of low-quality dryout. If the ratio of the velocities of the two phases (velocity ratio) is near unity, five parameters are adequate to describe the flow. They are as follows:

the Froude number, $$Fr = \frac{f_L \rho_L V^2}{gR(\rho_H - \rho_L)\sin\alpha}; \quad [1]$$

the Weber number, $$We = \frac{\rho_H V^2}{[(\rho_H - \rho_L)\sigma g]^{1/2}}; \quad [2]$$

the light phase Reynolds number, $$Re_L = \frac{2VR\rho_L}{\mu_L}; \quad [3]$$

the heavy phase Reynolds number, $$Re_H = \frac{2VR\rho_H}{\mu_H}; \quad [4]$$

the density ratio, $$\rho = \frac{\rho_H}{\rho_L}; \quad [5]$$

where V is the mean axial velocity, g is the gravitational acceleration, $2R$ is the tube bore, α is the slope of the tube forming the helix to the horizontal, f_L is the Fanning friction factor between the wall and the light phase, σ is the interfacial tension, ρ is the density, μ is the viscosity and subscripts H and L refer to the heavy and to the light phase, respectively.

The Froude number and the density ratio determine the velocity difference between the phases, the Weber number was found to determine the condition for drop entrainment from the light phase ribbon and the two Reynolds numbers are chiefly important in determining whether the given phase is in laminar or turbulent flow.

For the helical coil we have a further group

$$\Omega = \frac{V^2}{gr} \quad [6]$$

where $2r$ is the coil diameter and which determines the balance between centrifugal and gravitational body forces and which gives an additional degree of freedom.

The first point to note is that the density ratio ρ (see table 1 for physical properties) is 0.886 for the acetate–water system and 0.826 for the alcohol–water system but 0.25 for the 18 MN/m^2 steam–water system that is being modelled. This difference has to be accepted for a simple analogue and one must be aware that it may produce differences in the type of flow observed. However, the analogue is closer to the prototype than air–water systems, where ρ is 0.0013, and is more likely to illustrate phenomena of importance.

It is now necessary to specify the prototype that is to be modelled. A large diameter, 3 m, helical coil was chosen, which typically has a tube bore of 12.7 mm and maximum inlet water

Table 1. Physical properties of the analogue and prototype fluids

	Temperature (°C)	Density (kg m^{-3})	Viscosity (Ns/m^2)	Interfacial tension with water (J/m^2)
Water	20	998	0.00102	—
n-Butyl acetate	20	884	0.0007	0.0145
Iso-amyl alcohol	20	828	0.0048	0.00486
Water (180 bar)	357	543	0.000064	—
Steam (180 bar)	357	133	0.000026	0.0026

velocity of about 3 m/s. For reasons which will become clear later, the analogue was chosen to have a bore of 25.4 mm. Assuming that the friction factors are the same for the model and the prototype it can be determined from the Froude number of [1] that

$$\left.\begin{aligned} \frac{V_A}{V_P} &= 0.36, \\ \frac{V_B}{V_P} &= 0.29 \end{aligned}\right\} \quad [7]$$

where subscript A refers to the alcohol–water system, B refers to the butyl acetate–water system and P to the prototype. If these velocity ratios are used to determine the ratio of model to prototype light phase Reynolds numbers, it is found that it is 0.022 for alcohol and 0.14 for acetate, which illustrates the advantage of the acetate system. Moreover, a light phase acetate ribbon will usually be in turbulent flow, whereas an alcohol ribbon would not. The advantage in choosing a larger bore model tube is also obvious, in that it increases the model Reynolds numbers.

If the Weber number of [2] is used to determine the appropriate velocity ratio, it is found that

$$\left.\begin{aligned} \frac{V_A}{V_P} &= 0.69, \\ \frac{V_B}{V_P} &= 0.82. \end{aligned}\right\} \quad [8]$$

Therefore, although Froude and Weber numbers cannot be simultaneously modelled with the tube bore chosen, it can be expected that the critical effects due to the Weber number will occur within the experimental range if the velocities of [7] are employed as basic modelling parameters. Furthermore, it is apparent from [6] and [7] that in order to model the low quality stratification the model coil diameter should be about a tenth of the prototype and 300 mm was chosen as a compromise between the acetate and the alcohol systems. A coil of this diameter is about the smallest that can readily be bent from a 25 mm bore copper tube, which is a practical reason for modelling a relatively large diameter coil.

It is concluded that modelling on the basis of the dimensionless groups [1], [2] and [6] is reasonably close. The density ratio ρ is rather high and a transition to the type of phenomena that are observed in air and water is to be expected at smaller density ratios, but it is not known if it would be apparent at the condition of the prototype. Reynolds numbers for the acetate–water systems are sufficiently large for the flows of the separate stratified liquids to be turbulent, which should be satisfactory. It remains to point out that, at high quality, one additionally expects to be concerned with the drop size of water in the light phase. This size should be substantially dependent on the Weber number and therefore the analogue should again be suitable.

3. EXPERIMENTAL APPARATUS AND TECHNIQUE

The apparatus, shown diagramatically in figure 1, is in principle similar to that used previously (Gardner & Kubie 1976) and will be described only briefly. The test section consisted of six turns of 25.4 mm bore copper tube turning a 292 mm helix diameter. The slope of the tube was 1 : 10. A 230 mm long glass section for visual observations was incorporated in the fourth turn from the inlet and the glass was joined to the copper by a specially designed coupling which maintained a continuous smooth bore without any significant lip. Ball valves

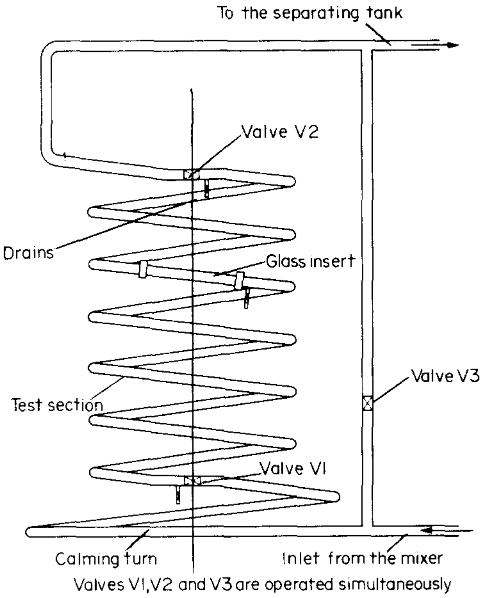

Figure 1. Diagram of the experimental apparatus.

were placed at the beginning and the end of the test section. One turn of copper tube, which was of a slightly larger diameter than the turns of the test section, was placed immediately upstream of the test section and served as a calming section.

A bypass, containing another ball valve, was provided over the test section. All three valves of the test section and of the bypass were linked to operate simultaneously so as to isolate the test section and redirect the flow through the bypass. The two fluids flowing through the test section were trapped and could be drained through three drains within the test section. The volumes of each fluid were measured and the voidage calculated. It was assumed that the voidage in the glass insert was the same as the mean voidage in the test section, since the test section was preceded by a calming turn.

The two liquids were introduced through a mixer such that one of the liquids was introduced axially into the centre of the tube and the other also axially but through an annulus and hence near the wall. Provisions were made for interchanging the two liquids to investigate the effect of the method of liquid injection. The water was pumped into the mixer by a centrifugal pump and the appropriate organic liquid by a canned centrifugal pump. The flowrates of both liquids were measured by rotameters and regulated by valves. All rotameters were calibrated by the manufacturer and the calibrations were checked *in situ*.

Both liquids were discharged into a large circulating tank, where they separated by buoyancy forces. Baffles were placed in the tank to increase the path travelled by the mixture in order to increase the residence time of both phases and thus to promote separation. The separated liquids were then drawn from the tank by their respective pumps. The separation was not perfect at high flowrates when a small amount of one of the liquids was drawn into the pump of the other liquid and emulsified. Experiments then had to be performed quickly before too much emulsification occurred. Make-up water to the circulating tank was taken from the town's supply and filtered through a glass 'millipore' filter to remove silica and other solid material which would cause scum on interfaces.

An experimental run consisted of setting the required flowrates, observing and photographing the flow patterns, then isolating the test section and measuring the volumes of both liquids trapped within the test section. Since acetate was the better modelling liquid for the light phase, it was used in the majority of experiments.

4. EXPERIMENTAL OBSERVATIONS

This section gives a brief description of various parameters controlling the flow. The terminology used to identify circumferential positions when describing the flow patterns is illustrated in figure 2.

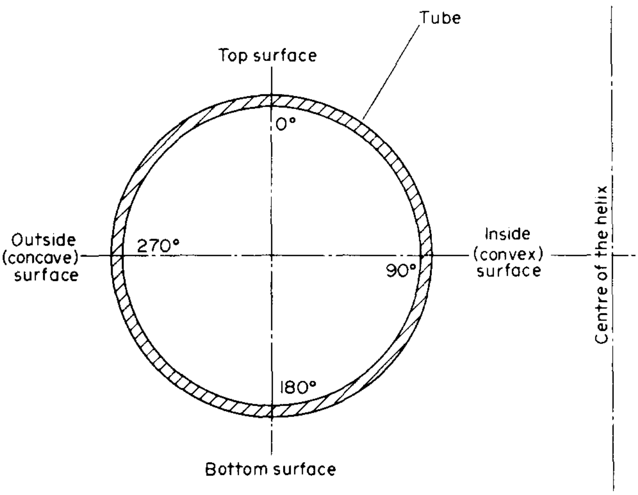

Figure 2. Terminology adopted for description of the flows.

Simplified flow regime diagrams for the two systems used (acetate–water and alcohol–water) are shown in figure 3, which demonstrates that each system exhibit two distinctly different behaviour patterns for constant superficial water velocities, V_{HS}, with increasing superficial velocity of the light phase, V_{LS}. For superficial water velocities not greater than 0.6 m/s for acetate–water and 0.8 m/s for alcohol–water, there is a ribbon of the light phase travelling near the top of the tube for a range of light phase flowrates. The ribbon is probably established by the smearing action of the light phase drops against the top surface of the tube and the amount of the light phase necessary for the establishment of the ribbon increases with superficial water velocity. As the mean velocity of both phases increase above, say, 0.6–0.8 m/s, the ribbon starts to break up into drops. The above points are illustrated in figure 4 showing photographs of the flow regimes associated with the flow of acetate and water in the present system for a constant low superficial water velocity of 0.2 m/s. Each photograph depicts the side elevation and the plan view of the flow regimes obtained simultaneously by means of a mirror. The figure demonstrates the initial formation, growth and subsequent break up of the ribbon into drops as the superficial acetate velocity increases.

For superficial water velocities greater than 0.8–1.0 m/s, the ribbon of the light phase does not appear and only drop flow is observed, with either drops of the light phase in water (at low superficial velocities of the light phase) or with water drops in the light phase (at high superficial velocities of the light phase). This is demonstrated in figure 5 which shows photographs of the flow regimes occurring during the flow of acetate and water in the present system for a constant high superficial water velocity of 0.8 m/s.

Figures 6 and 7 show the plots of relative velocity, ΔV, defined as the difference between the actual velocities of both phases, against the fractional area occupied by the light phase (voidage), A, for constant superficial water velocities of 0.2 m/s and 0.8 m/s respectively. The flow regimes in these figures illustrate once more the observed flow patterns. Figures 6 and 7 further show that the relative velocity for the acetate–water system goes through a maximum as the light phase flowrate increases. This is due to the presence of the ribbon and its subsequent breakdown into drops. The drops decrease in size, and their velocity approaches that of the

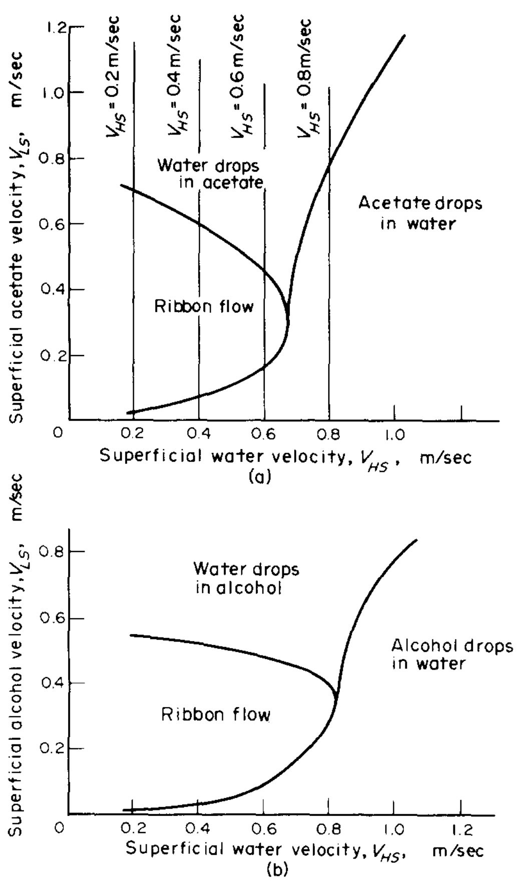

Figure 3. Simplified flow regime diagrams for the flow of (a) acetate and water, and (b) alcohol and water in the helix.

continuous phase as A and V_{LS} increase. Where both systems are characterized by the ribbon flow, the relative velocity for the acetate–water system is about 0.1–0.2 m/s greater than that of the alcohol–water system which is due to the higher viscosity of the alcohol, as can be confirmed by the type of calculations made for this regime by Gardner & Kubie (1976). It is further observed that, as the relative velocity increases, the ribbon moves to the outside surface of the tube.

The plot of the velocity ratios (V_L/V_H) against the fractional area, A, for the flow of acetate and water is shown in figure 8 for several values of constant superficial water velocities. The velocity ratios also pass through a maximum. Finally, as the superficial water velocity increases, the divergence of the velocity ratios from unity decreases. For $V_{HS} > 1.0$ m/s, the velocity ratio is within 10% of unity.

5. THEORETICAL DISCUSSION AND ANALYSIS

Previous theoretical work by Gardner & Kubie (1976), which was related to experiments with straight sloping tubes, showed that the mechanics of ribbon flow is understood and that the conditions for breakdown of the ribbon into drops can be explained. It was also shown that ribbon flow was related to the occurrence of dryout in high pressure boilers. The helical coil differs from the straight sloping section by the presence of secondary flows which are described in the next section. It is of interest to see how far these flows change the previous predictions as well as to examine any new phenomena that occur.

The extrapolation of the analogue results to high pressure steam–water systems will be discussed but it must be remembered that quantitative results must usually come from high pressure rigs. This is especially true where the influence of heat flux is important. The analogue can indicate possibly harmful conditions and is useful in illustrating, for example, the flow conditions which are to be associated with wall temperature measurements, which are often the major output from high pressure boiling experiments.

5.1 *Initial formation of the ribbon*

It can be seen from figure 3 that for all but the lowest water velocities, fairly large flowrates of the light phase are required before continuous ribbon (low quality stratified flow) is formed. On the other hand no drop regime was observed with straight tubes with slopes of up to 22° to the horizontal, provided that the critical water velocity for ribbon break-up, discussed in the next section, was not exceeded. Such a drop regime only became obvious for straight tube slopes above 30°, whereas the tube of the helix sloped at 6°. It seems probable that the secondary flow pattern whose usual approximation is illustrated in figure 9, and which is known to occur in coils with single phase flows, was responsible for the drop regime. A core flow, which is substantially uniform, is shown travelling from the inside to the outside of the tube. The flow recirculates to the inside of the coil as a boundary layer of substantially uniform thickness, driven by the pressure difference generated by the centrifugal effects of the helical flow. This boundary layer moves across any ribbon that is trying to form thus having a disruptive influence on it.

However, a question remains as to whether a steam ribbon could form at all in a steam–water system with a smaller density ratio of say, 0.25, irrespective of the type of the flow. A ribbon does not occur at the one extreme of an air–water system at atmospheric pressure (Fisher & Yu 1975) but it is present at the other extreme of the present two-liquid analogue with density ratios of 0.826 and 0.886. Two sets of data for helical coils with more

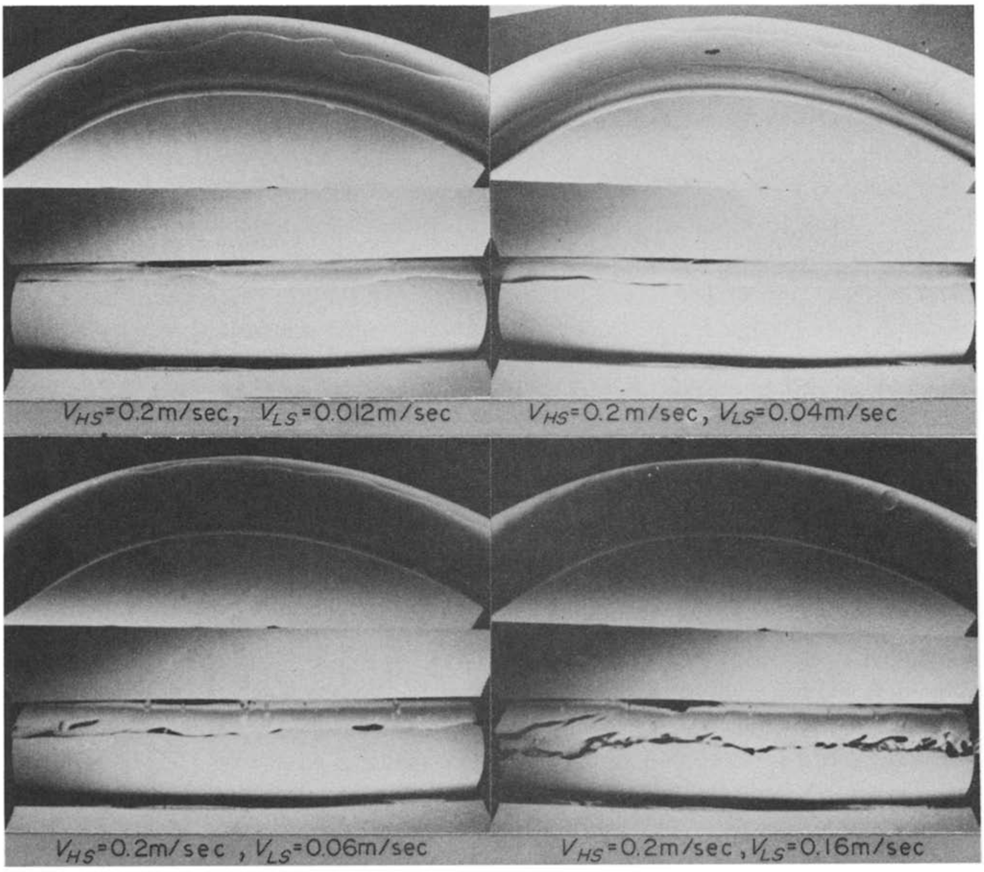

Figure 4a. Plan and side views of acetate–water flow for $V_{HS} = 0.2$ m/s.

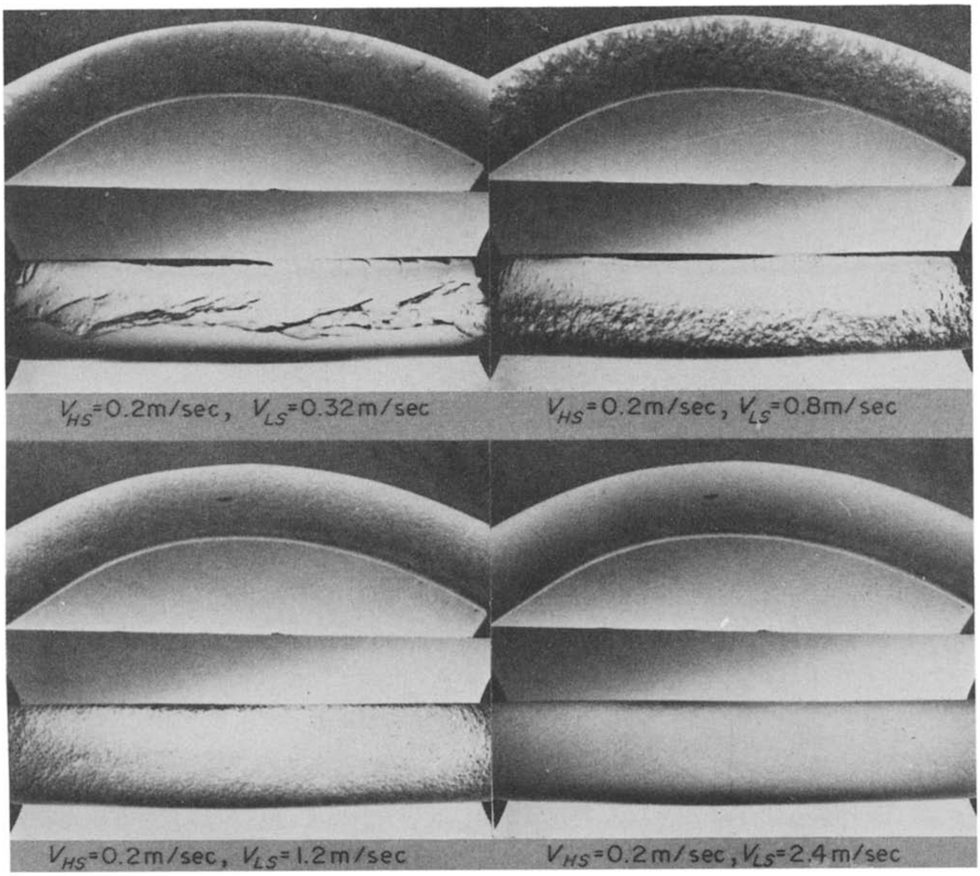

Figure 4b. Plan and side views of acetate–water flow for $V_{HS} = 0.2$ m/s.

appropriate density ratios are as follows: (i) Carver *et al.* (1964) found low quality dryout for a steam–water flow in 10.8 mm bore helical boiler operating at 180 bar and (ii) Horrocks & Jones (1976) found low quality dryout for a freon flow in 13 mm bore helical coil operating at 30 and 24 bar but found no evidence of it when the system was operating at 17 bar. Additionally, Chojnowski *et al.* (1974) found evidence of the low quality dryout down to, at least, 110 bar for steam and water flow in a 32 mm bore straight sloping tube.

There are three major forces which influence the possible stratification which leads to the ribbon formation, if secondary flow, which only alters the position of the ribbon, is not considered: Shear and buoyancy forces which promote the ribbon formation and interfacial tension forces which hinder it. Thus two dimensionless groups of relevance to the problem of ribbon formation may be formed:

$$\Sigma = \frac{\sigma}{(\rho_H - \rho_L)gl^2}, \qquad [9]$$

$$\Phi = \frac{\sigma}{f_L \rho_L V_L{}^2 l} \qquad [10]$$

where V_L is the mean velocity of the light phase and l is a typical dimension. The ribbon will have a better chance to form for smaller values of groups Σ and Φ. Now Gardner & Kubie (1976) showed that in the case of straight tubes the maximum voidage for ribbon flow for zero relative velocity between the phases is given by

$$A_M = 0.5\left(\frac{\rho_L}{\rho_H}\right)^{1.54} \qquad [11]$$

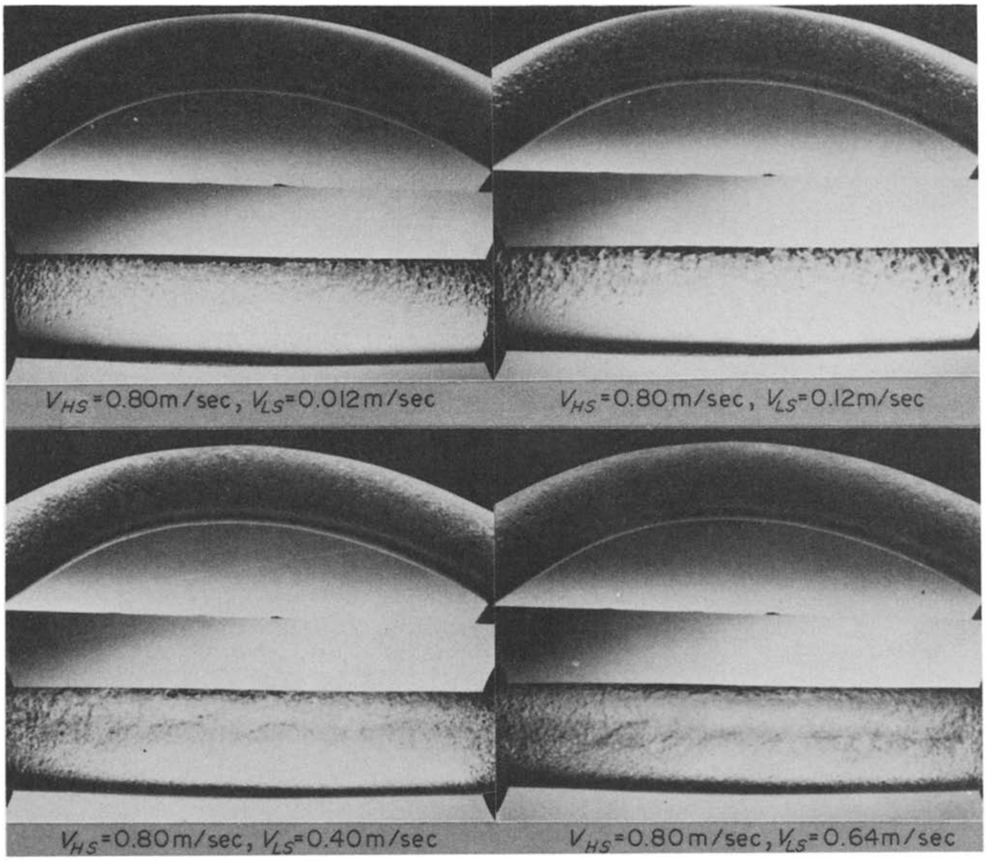

Figure 5. Plan and side views of acetate–water flow for $V_{HS} = 0.8$ m/s.

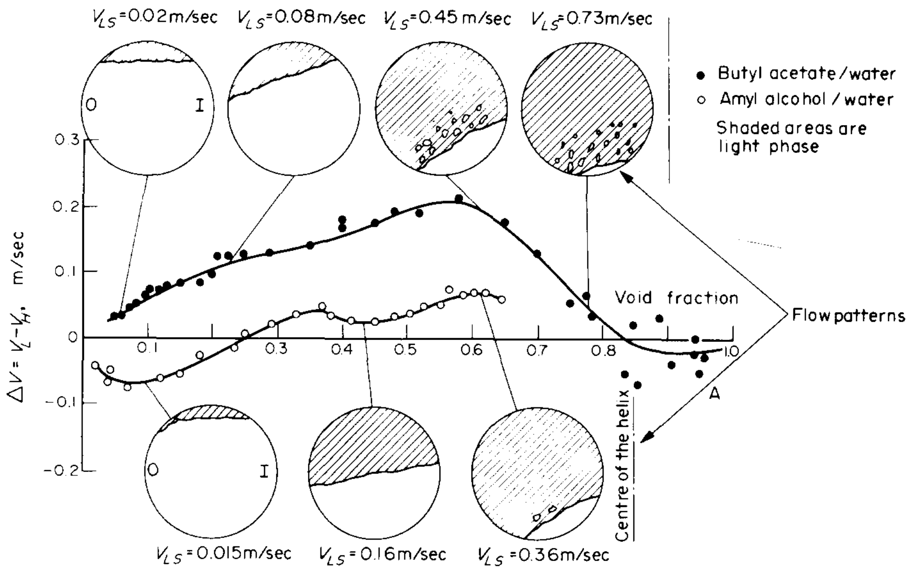

Figure 6. A plot of the relative velocity, ΔV, against the fractional area, A, for $V_{HS} = 0.2$ m/s.

if the friction factors of both phases are equal, which is a suitable approximation for turbulent flows of both phases. A_M can be considered a characteristic voidage for the problem at hand, since the ribbon should be most stable with no relative velocity. The typical dimension, l, is therefore chosen as the maximum depth of the light phase ribbon corresponding to A_M and it

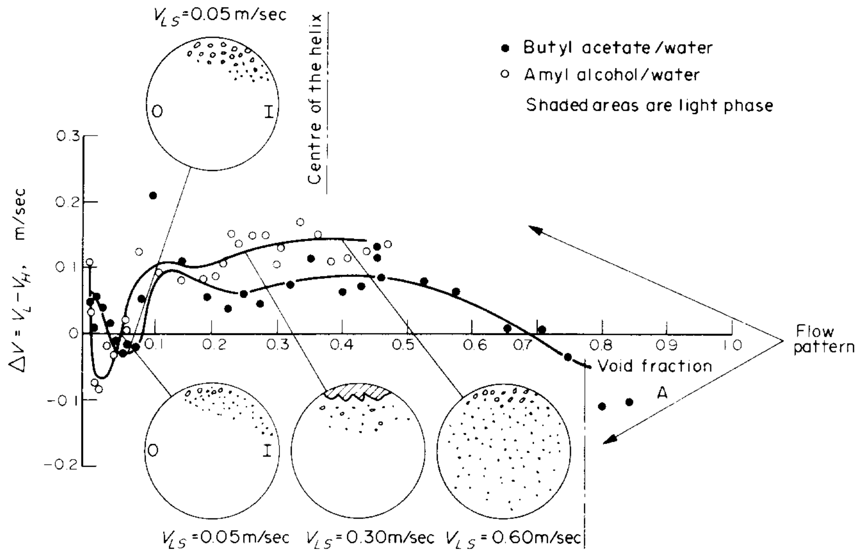

Figure 7. A plot of the relative velocity, ΔV, against the fractional area, A, for $V_{HS} = 0.8$ m/s.

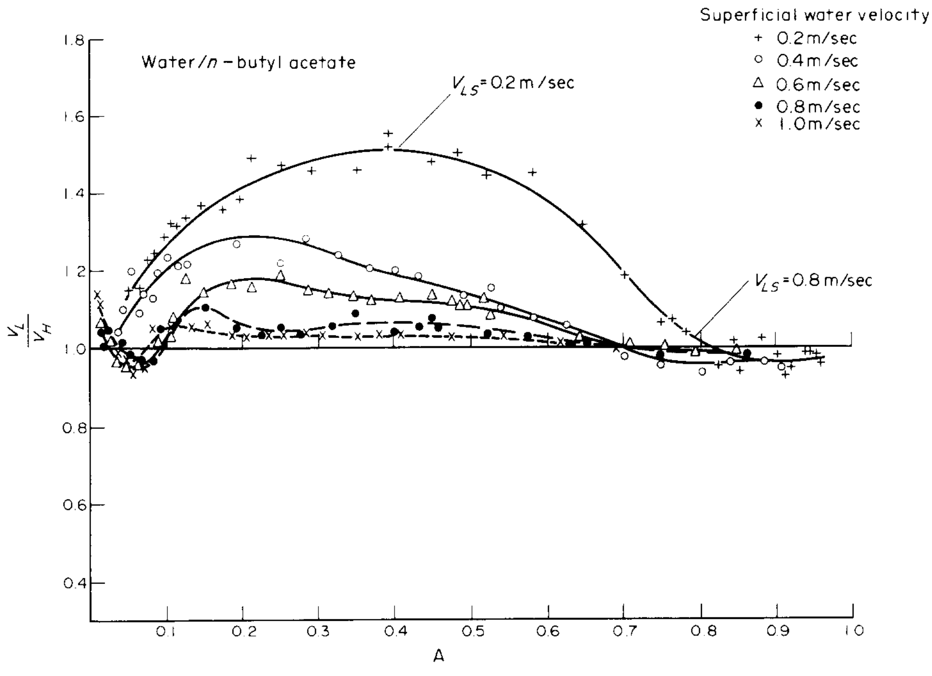

Figure 8. A plot of the velocity ratio against the fractional area, A, for the flow of acetate and water.

can be shown that l is given with a maximum error of 8% by

$$\frac{l}{R} = \left(\frac{\rho_L}{\rho_H}\right)^{1.04} \quad [12]$$

provided that $0.001 < \rho_L/\rho_H < 1.0$. If the necessary conditions for the ribbon formation are required, the largest possible value of V_L in [10] should be used. It is shown in the next section that for zero relative velocity, the largest value of V_L is given by

$$\frac{(\rho_H f_H)^{1/2} V_L}{[(\rho_H - \rho_L) g\sigma \cos\alpha]^{1/4}} = 1.1. \quad [13]$$

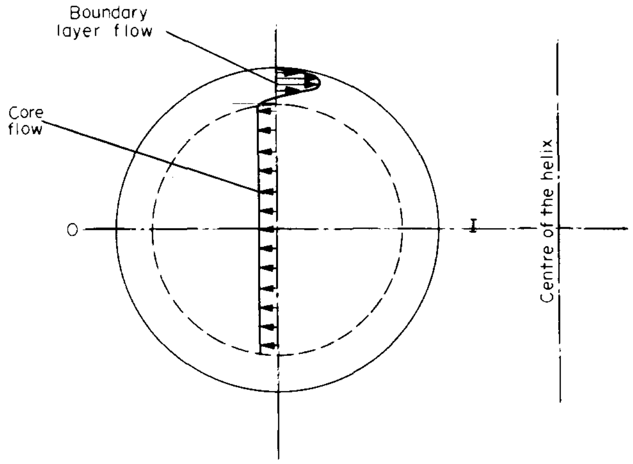

Figure 9. Secondary flow in a curved pipe.

Substituting [12] and [13] into [9] and [10], one finally obtains:

$$\Sigma = \frac{\sigma}{(\rho_H - \rho_L)gR^2}\left(\frac{\rho_H}{\rho_L}\right)^{2.08}, \qquad [14]$$

$$\Phi = \frac{1}{1.2\cos^{1/2}\alpha}\left(\frac{\rho_H}{\rho_L}\right)^{2.04}\left[\frac{\sigma}{(\rho_H - \rho_L)gR^2}\right]^{1/2}. \qquad [15]$$

Values of Σ and Φ for the experimental data discussed above are shown in table 2, which provides some evidence that, in order to prevent the low quality dryout, Σ should be greater than about unity and Φ should be greater than about ten. There is still insufficient evidence for choice between the criteria or even to show that they do not have to be further modified. However, a tentative conclusion can be made that in tubes of smaller bores, which will make both Σ and Φ greater, the low quality dryout is less likely. It is interesting to note that the criterion of [14] implies that for the air–water system air ribboning would be found when small quantities of air are present in pipes of about 6 m diameter. The criterion of [15] implies that about 380 m diameter pipe would be required.

Table 2. Values of the functions Σ and Φ for various two-phase flows

Reference	System	Pressure (bar)	R (m)	f_L (–)	Σ (–)	Φ (–)
Low quality dryout or ribbon flow observed						
Carver *et al.* (1964)	Steam–water	180	0.0054	0.0035	0.455	2.29
Horrocks &	Freon	30	0.0065	0.0035	0.076	1.04
Jones (1976)	Freon	24	0.0065	0.0035	0.294	3.08
Chojnowski *et al.*	Steam–water	180	0.016	0.0035	0.052	0.77
(1974)	Steam–water	160	0.016	0.0035	0.113	1.60
	Steam–water	140	0.016	0.0035	0.267	3.25
	Steam–water	110	0.016	0.0035	0.91	8.5
Present study	Acetate–water	1	0.0127	0.0065	0.103	0.3
Low quality dryout or ribbon flow not observed						
Horrocks & Jones (1976)	Freon	17	0.0065	0.0035	1.30	10.5
Fisher & Yu (1975)	Air–water	1	0.0127	0.0035	50000	150000

5.2 *Breakdown of the ribbon into drops*

It has been shown in the preceding section that, in order to allow the formation of the ribbon at all, certain necessary conditions must be satisfied. In this section we will consider the additional influence of the liquid velocity on the ribbon break-up.

The critical condition for the breakdown of a stratified ribbon into drops for a straight tube was derived by Gardner & Kubie (1976) as being given by the critical value of the following dimensionless group

$$We = \frac{(\rho_H f_H) V_H^2}{(\Delta\rho g\sigma \cos\alpha)^{1/2}} \tag{16}$$

where V_H is the mean velocity of the heavy phase. The critical value of [16] was found experimentally to be approximately

$$We_c^{1/2} = 1.2. \tag{17}$$

Drops might be present with the ribbon flow at smaller values of the water velocity but they became numerous once the critical value of V_H, given by [16] and [17], was exceeded. This critical value also corresponded to the minima in the burnout heat flux with respect to velocity, as determined by Chojnowski *et al.* (1974), for steam and water at pressures from 110 to 180 bar.

The data used to obtain [17] were from experiments with a small proportion of the light phase, when the heavy (water) phase velocity was dominant in causing ribbon break-up. For this reason the subscript H is employed in [16]. However it should be noted that the alternative case, where there is a small proportion of heavy phase, is also possible. This was sometimes achieved in the present experiments and the condition for the heavy phase ribbon break-up into drops in the light phase was then observed. Table 3 shows this result for the helix and the corresponding critical Weber number, but also shows two results where the heavy phase velocity caused the break-up. The friction factors given in the table were calculated from Ito's (1959) correlation for curved tubes, using the physical properties of the appropriate phase, the phase velocity and the tube diameter to calculate the Reynolds number. In any particular instance, of course, an estimate should be made as to whether either phase will partly break the other up into drops.

Table 3. Critical conditions for the ribbon break-up for acetate–water flow

V_{HS} (m/s)	V_{HC} (m/s)	V_{LC} (m/s)	$f \times 10^3$	$We_c^{1/2}$ of [16]
0.2		0.70	8.33	0.95
0.4	0.74		8.6	1.08
0.6	0.77		8.5	1.12

The average value of $We_c^{1/2}$ is given for the helix (from table 3) as

$$We_c^{1/2} = 1.05 \tag{18}$$

which is 13% lower than for the straight tube. This is within the error of judging the critical condition, though it must be emphasized that this agreement is only found by employing the friction factor for a curved tube.

The critical Weber number of [18] is believed to be relevant to the occurrence of low-quality dryout in high-pressure boiling experiments (where the necessary conditions of section 5.1 are satisfied) and the visual observations are believed to represent conditions actually occurring within the boiler tube. The following investigations on boiling in helices support this view. They all show that the effect of the heat flux is not very important and that low-quality dryout is hydrodynamic in nature:

(i) Horrocks & Jones (1976) worked with freon in an electrically heated helix ($R = 0.0065$ m, $r = 0.425$ m). Their observations may be summarized as follows. Low-quality dryout was only observed for pressures above 24 bar, which may be compared with the critical pressure of 39.6 bar, and for low mass velocities. At 30 bar, low quality dryout occurred for a freon mass flowrate of 475 kg/m^2 s but not for a mass flowrate of 1184 kg/m^2 s. Using [16] and appropriate freon properties we find that

$$0.71 < We_c^{1/2} < 1.76. \qquad [19]$$

At 24 bar, low-quality dryout was just discernible for a mass flowrate of 630 kg/m^2 s, giving

$$We_c^{1/2} \simeq 0.80. \qquad [20]$$

(ii) Carver *et al.* (1964) obtained results with steam and water at 180 bar in two different helices ($R_1 = R_2 = 0.005$ m, $r_1 = 0.40$ m, $r_2 = 1.65$ m). Similar observations to those of Horrocks & Jones (1976) above were made. For the small coil no low quality dryout was observed and, since the minimum mass velocity was 380 kg/m^2 s, we deduce that

$$We_c^{1/2} < 0.68. \qquad [21]$$

For the large diameter helix, low quality dryout was observed for a mass flowrate of 678 kg/m^2 s and was not observed for a mass flowrate of 1357 kg/m^2 s. Inspection of the experimental data reveals that

$$0.56 \leqslant We_c^{1/2} < 1.10. \qquad [22]$$

The above review of information indicates $(We_c)^{1/2}$ to be in the neighbourhood of unity or close to the value of 1.05 of the analogue. It appears that $(We_c)^{1/2}$ may be somewhat lower in the helix than in the straight tube, which is probably due to the influence of the secondary flow. This is supported by the observation of Carver *et al.* (1964) who noticed that the low quality dryout was more prominent in a larger diameter helical coil where the secondary flow was less strong. However, no firm conclusion can be drawn on this point without further experimental work.

6. DISCUSSION AND APPLICATION

The flow phenomena observed at low qualities in helices resemble those previously found in straight sloping tubes. However, the helical coil configuration is superior to the straight tube in avoiding stratification in two respects. First, the secondary flow has an additional disruptive effect upon the light phase ribbon, so that greater light phase flowrates are required to form a continuous ribbon. Secondly, the friction factor is higher and, therefore, the velocity at which the ribbon flow will be broken down, according to the critical Weber number of [18], is smaller. In a typical helical boiler with a maximum mass velocity of about 1800 kg/m^2 s, for example, ribbon breakdown would be expected to cause the disappearance of low quality dryout at loads in excess of 20–30%. The lower friction factor for a comparable straight tube would increase this critical load to between 25 and 35%.

A major difference that was observed between the present analogue and air–water or relatively low-pressure steam–water flows was the absence of surge and annular flows. One cannot be sure that these types of flow will be absent in high pressure steam–water flow but, at least, it is to be expected that their presence will be less obvious.

Once a dispersed drop regime was formed in the analogue it is possible that the drops were too small to make effective contact with the wall so as to build up an annular flow, but it is not possible at present to make this statement quantitative.

Surge flow is absent because velocity differences between the phases are small with two liquids and thus the initiation of the surge flow cannot take place.

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