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BRIEF COMMUNICATION

TWO-PHASE (VAPOR–LIQUID) FLOW PATTERN TRANSITIONS IN DUCTS OF NON-CIRCULAR CROSS-SECTION AND UNDER DIABATIC CONDITIONS

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INTRODUCTION

Simple maps related to superficial velocities have been widely used for determination of cocurrent flow vapor–liquid flow patterns since their introduction by Baker (1954). One of the most recent of these is due to Weisman *et al.* (1979) and Weisman & Kang (1981). They recognized that the needed dimensionless correlating groups varied from transition to transition and obtained separate correlations for each significant transition. They found that the various transitions could be predicted by:

Transition to annular flow

$$1.9(V_{SG}/V_{SL})^{1/8} = Ku_G^{0.2} Fr_G^{0.18} \quad [1]$$

where D = tube diameter, V_{SG}, V_{SL} = superficial gas and liquid velocities, respectively. $Ku = V_{SG}\rho_G^{1/2}/[g(\rho_L - \rho_G)\sigma]^{1/4}$, $Fr_G = V_{SG}^2/(gD)$, σ = surface tension, ρ_G, ρ_L = gas and liquid densities, respectively.

Separated–intermittent transition

$$(Fr_G)^{1/2} = 0.25(V_{SG}/V_{SL})^{1.1}. \quad [2]$$

Transition to dispersed flow

$$\left[\frac{|dp/dx|_{SL}}{(\rho_L - \rho_G)g}\right]^{1/2}\left[\frac{\sigma}{(\rho_L - \rho_G)gD^2}\right]^{-1/4} = 1.7\dagger \quad [3]$$

where g = gravitational acceleration, $|dp/dx|_{SL}$ = absolute value of pressure drop for liquid flowing alone per unit length.

Bubble to intermittent transition

$$\frac{V_{SG}}{\sqrt{(gD)}} = 0.45\left(\frac{V_{SG} + V_{SL}}{\sqrt{(gD)}}\right)^{0.78}(1 - 0.65\cos\theta) \quad [4]$$

and θ = angle of inclination.

†In previous papers, the constant 1.7 was erroneously shown as 9.7. Transition lines on the overall flow pattern map were correctly shown.

These correlations apply to both horizontal and vertical flow with the exception that the separated–intermittent transition is not seen in vertical flow.

The transition line correlations were reduced to a simple flow map with coordinates of V_{SG}/ϕ_1 and V_{SL}/ϕ_2. By defining ϕ_1 and ϕ_2 differently for each transition, the differing effects of fluid properties and line size could be handled. Table 1 indicates the appropriate expressions for ϕ_1 and ϕ_2.

The foregoing approach has found recent support. Parimi & Pritchford (1982) confirmed the effect of surface tension on the dispersed flow transition; an effect absent from most other dispersed transition correlations. Iwasyk (1982) found the annular flow transition line [1] fitted his data for the transition from annular flow with very viscous liquids but that other correlations failed.

In view of the ability of the simple flow maps to represent adiabatic data in circular cross-sections, it is desirable to see if these maps can be used for diabatic data and for non-circular ducts.

DATA IN HORIZONTAL DUCTS

In figure 1, the flow pattern map based on [1]–[4] and table 1 is compared to (a) adiabatic data taken in a horizontal annulus and (b) condensation data taken in a horizontal round tube. The bubble intermittent transition region is not shown as the tests did not extend to a low enough gas flow rate for this to be observed.

Gibson (1980) obtained the annulus data using a 2.85 cm o.d. steel pipe suspended inside a 6 m long, 5.1 cm i.d. glass tube. The test fluids were air and water at room temperature and pressures slightly above atmospheric.

Condensation data with propanol, methanol, water and refrigerant 113 were obtained by Sardesi *et al.* (1981) in a 2.44 cm i.d. tube having first an effective cooled length of 2.9 m. Only the separated annular transition was observed. For the sake of simplicity only Sardesi's water data are shown in figure 1. Data scatter tended to overshadow the small differences between systems.

Recently, Soliman (1982) reported on the flow patterns in condensation of steam and refrigerants 12 and 113. He used horizontal tubes with internal diameters from 0.48 to 1.59 cm. These data are also shown in figure 1.

It is clear from figure 1 that the predicted transition regions are in fairly good agreement with the observed transition lines. The tendency of the observed separated–intermittent and dispersed flow observations in the annulus to be at slightly lower liquid rates than predicted is within the data scatter inherent in flow pattern observations. However, those data of Soliman (1982) for the annular transition, which were at V_{SL}/ϕ_2 values below the range of figure 1, were clearly at V_{SG} values below those predicted.

DIABATIC DATA IN VERTICAL DUCTS

Several flow pattern observations of boiling steam–water mixtures flowing upward in simple ducts are now available. The early data of Bergles & Suo (1966) taken in round tubes and Hosler's (1968) data taken in rectangular ducts have now been supplemented by those of Sekoguchi *et al.* (1981) for a round tube and Weisman *et al.* (1981b) for an annulus.†

Before comparing transition observations with the overall flow pattern map, transition lines were compared with the individual transition correlations and generally reasonable agreement was obtained. However, it was noted that the bubble–intermittent transition

†The data of Bergles *et al.* (1967) for highly subcooled inlet conditions have been ignored because of the difficulty in determining the true steam flow.

Table 1. Property and pipe diameter corrections to overall flow map†

Flow orientation		ϕ_1	ϕ_2
	Transition-to-dispersed flow	1.0	$\left(\frac{\rho_L}{\rho_{SL}}\right)^{-0.33}\left(\frac{D}{D_S}\right)^{0.16}\left(\frac{\mu_{SL}}{\mu_L}\right)^{0.09}\left(\frac{\sigma}{\sigma_S}\right)^{0.24}$
Horizontal, vertical and inclined flow	Transition-to-annular flow	$\left(\frac{\rho_{SG}}{\rho_G}\right)^{0.23}\left(\frac{\Delta\rho}{\Delta\rho_S}\right)^{0.11}\left(\frac{\sigma}{\sigma_S}\right)^{0.11}\left(\frac{D}{D_S}\right)^{0.115}$	1.0
Horizontal and slightly inclined flow	Intermittent-separated, transition		$\left(\frac{D}{D_S}\right)^{0.45}$
Horizontal flow	Wavy-stratified transition	$\left(\frac{D_S}{D}\right)^{0.17}\left(\frac{\mu_G}{\mu_{SG}}\right)^{1.55}\left(\frac{\rho_{SG}}{\rho_G}\right)^{1.55}\left(\frac{\Delta\rho}{\Delta\rho_S}\right)^{0.69}\left(\frac{\sigma_S}{\sigma}\right)^{0.69}$	1.0
Vertical and inclined flow	Bubble-intermittent transition	$\left(\frac{D}{D_S}\right)^{n}(1-0.65\cos\theta)$ $n = 0.26\,e^{0.17}(V_{SL}/V_{SL}^s)$	
Inclined flow	Wavy-intermittent transition	$1 + 5\sin\theta$	1.0

† s denotes standard conditions. $D_S = 1.0$ in. $= 2.54$ cm, $\rho_{SG} = 0.0013$ kg/l, $\rho_{SL} = 1.0$ kg/l, $\mu_{sL} = 1$ cP, $\sigma_S = 70$ dynes/cm, $V_{SL}^s = 1.0$ ft/sec $= 0.305$ m/sec.

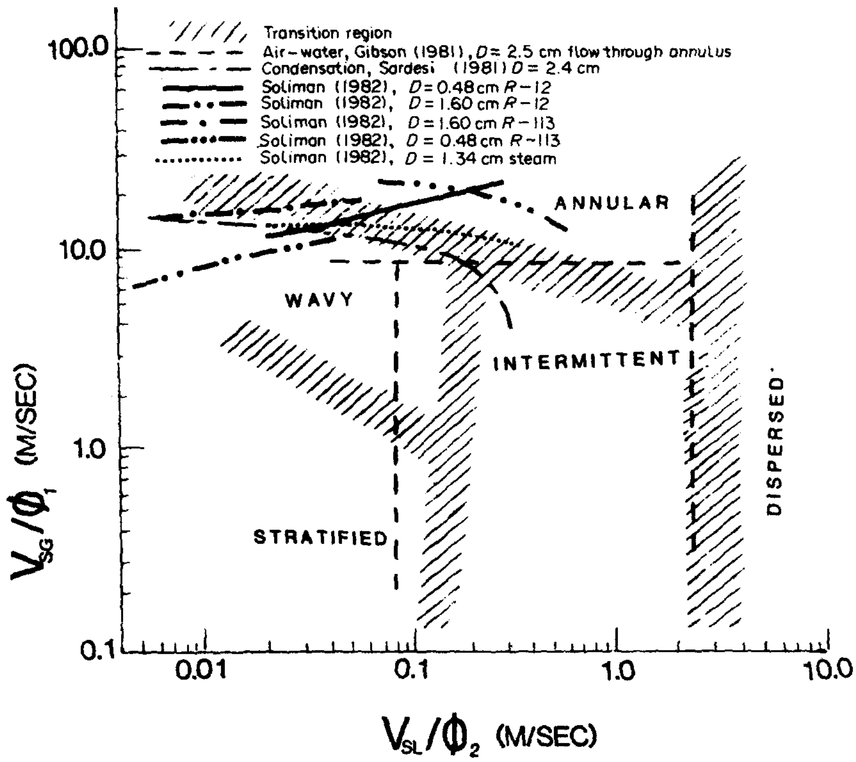
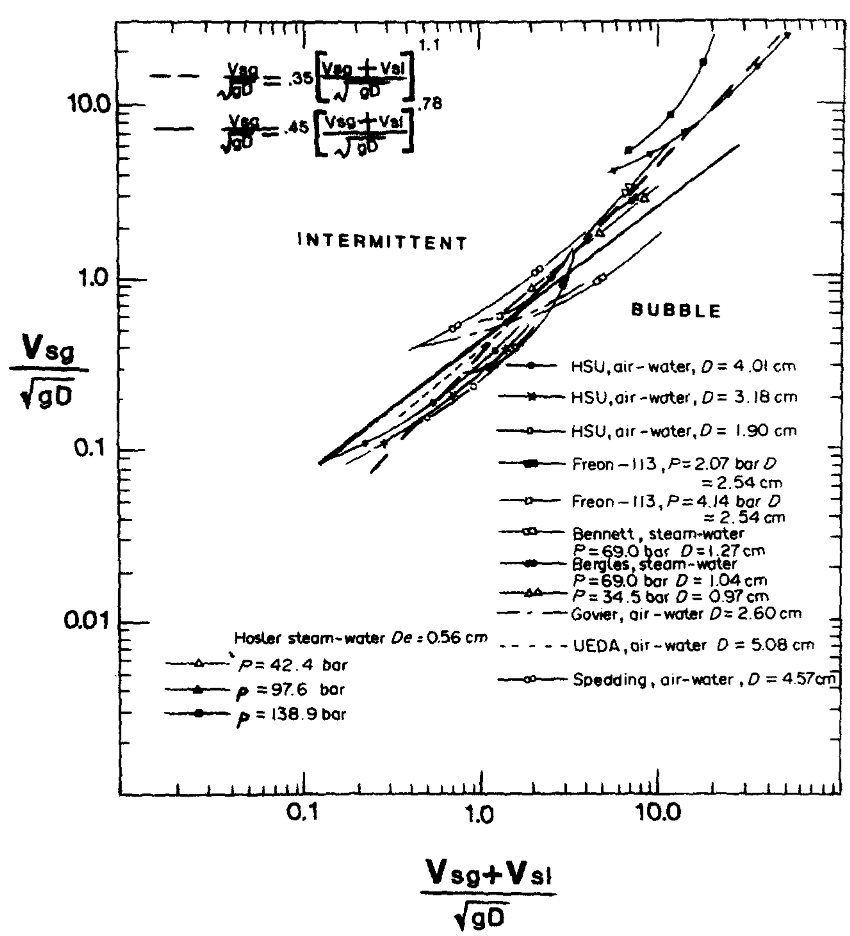


Figure 1. Comparison of horizontal data and overall flow pattern map.



lines of Hosler (1968) were at Froude number values beyond those previously correlated (see figure 2). Upon addition of these data, it appeared that the data at the highest Froude numbers were better correlated by a line of steeper slope; viz.

$$\frac{V_{SG}}{\sqrt{gD}} = 0.35\left[\frac{V_{SG}+V_{SL}}{\sqrt{gD}}\right]^{1.1}. \qquad [5]$$

When used in conjunction with the overall flow map, the corresponding values ϕ_1 and ϕ_2 are

$$\phi_1 = (D_S/D)^{0.1} \text{ and } \phi_2 = 1.0. \qquad [6]$$

It is recommended that [5] be used for $(V_{SL}/\phi_2) \geq 0.15$ and that [4] be used at lower values. The flow pattern maps of figures 3 and 4 are drawn in this fashion.

Figure 3 compares the available data to the slightly revised flow map. Generally, fairly reasonable agreement is obtained between the data and transition lines. However, at the two highest pressures examined by Hosler (1968), the intermittent-bubble transition lie above predictions. There is also some indication that the transition to dispersed flow may be taking place at somewhat higher liquid velocities than predicted.

In examining the transition to annular flow, it will be noted that at low values of V_{SL}, the data of Weisman *et al.* (1981) fall below the transition line. It should be noted that Choe *et al.* (1978) pointed out that their air–water data for the annular transition in a 1.15 cm tube fell below the data obtained in tubes which were 2.5 cm or larger at low values of V_{SL}. The transition region these investigators noted for the 1.15 cm tube is shown by the dotted area. The data of Weisman *et al.* taken in an annulus with a De of 1 cm, fall close to this region. The same trend is seen with the horizontal condensing data of Soliman (1982) at low values of V_{SL} (see figure 1).

VERTICAL FLOW IN ROD BUNDLES

Steam–water flow pattern data for rod bundles are now available at several pressures from the studies of Bergles *et al.* (1968) and the later tests of Peterson & Williams (1978). Recently the air–water data of Venkateswarara *et al.* (1982) have appeared. None of these data were at high enough liquid flow rates for true dispersed flow to have been observed. While Peterson & Williams (1978) refer to froth flow, an examination of their test indicates that they mean "Churn" flow which is part of the intermittent region.

The available data and the predicted transitions are shown in figure 4. Again it is seen that generally reasonable agreement is obtained with the annular and intermittent–bubble transition. Note that this general agreement is obtained without modification of the map useful for simple ducts. The only somewhat anomolous data are the bubble intermittent transition data of Peterson & Williams (1978) at 27.6 bar.

It will be noted that the tendency for annular transition data to fall somewhat below the predictions at low values of V_{SL} is again observed. As in figure 3, this may be attributed to the small size of the lines examined.

CONCLUSION

The simplified flow pattern map, developed for adiabatic round tube data and illustrated in figures 2–4, is in generally reasonable agreement with diabatic data and data in non-circular ducts. With allowance for the annular transition being somewhat below predictions in small size lines, the map appears to provide reasonable flow pattern predictions at moderate pressures. For the most part, the observed deviations are within the scatter inherent in flow pattern observations. Further examination of the intermittent–bubble transition at high pressure and with heating is needed. In addition, further diabatic tests in line sizes of 2.5 cm and above are desirable.

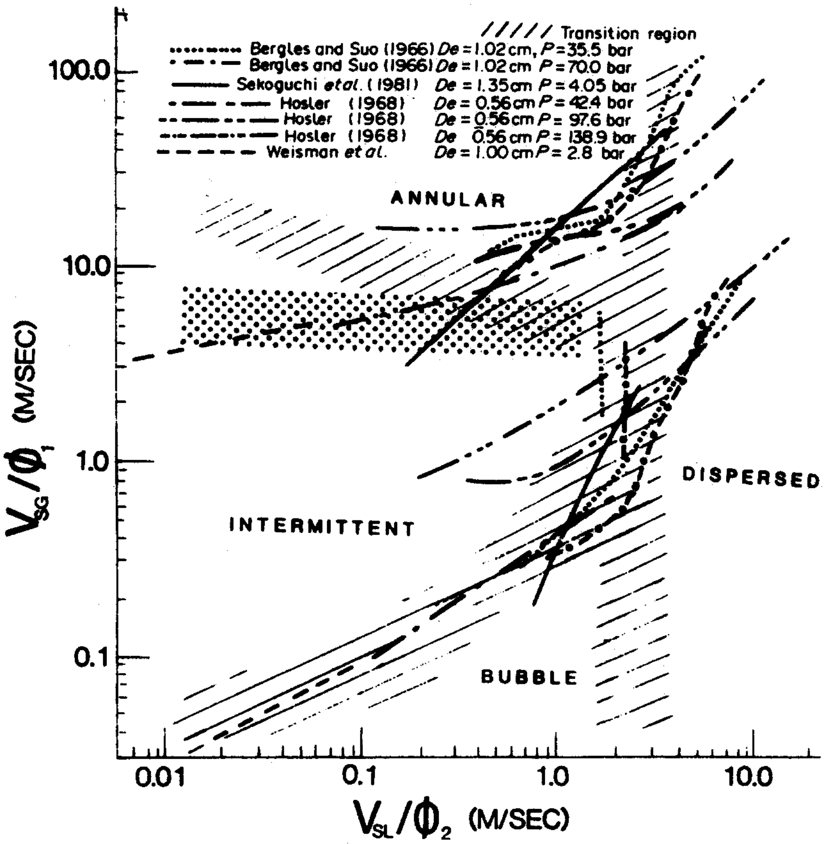


Figure 3. Comparison of diabatic data in vertical lines to overall flow pattern map.

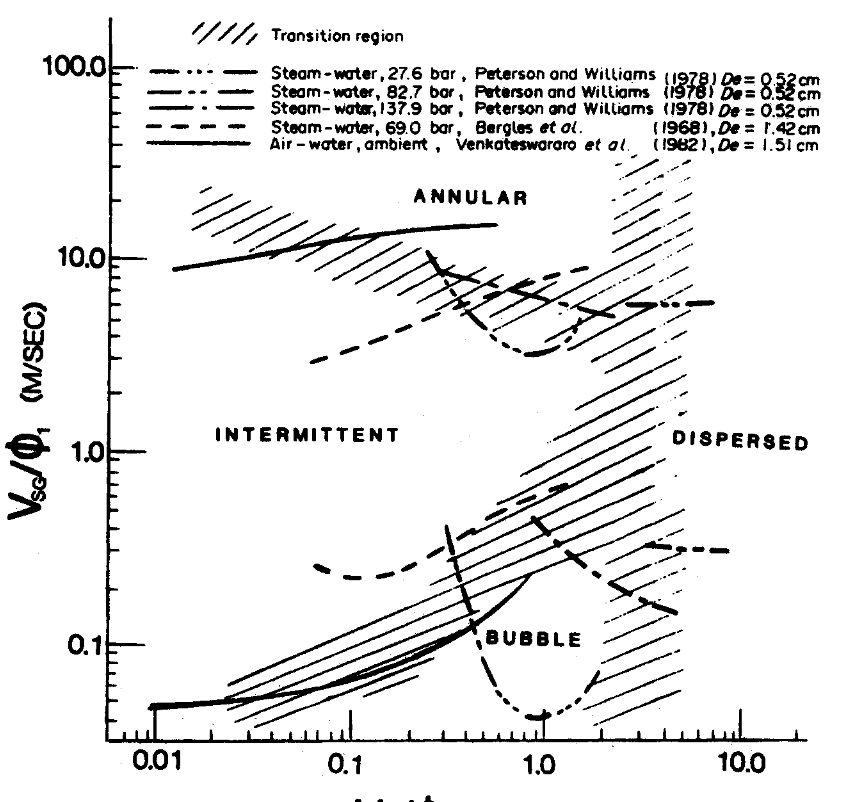


Figure 4. Comparison of available rod bundle data and overall flow pattern map for upward vertical flow.

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