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ANALYSIS OF FLOW REGIMES IN A VERTICAL TWO-PHASE COLUMN AND MODELLING OF THEIR TRANSITIONS

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INTRODUCTION

A knowledge of the flow-pattern characteristics of two-phase fluid in a vertical vessel, with the liquid continuum phase stagnant or moving at a very slow rate, is required for the study of many thermalhydraulic systems. Examples of such systems are the pressurizer in a conventional nuclear power plant and the riser duct of pool-type heating reactors, where the coolant flow is driven by natural circulation. A test section has been set-up to simulate these vertical two-phase systems and nine distinct flow patterns have been observed in the experiment [1]. This will be briefly reviewed in this paper. A method of generalizing the resulting flow-regime map by expressing the system conditions in terms of two dimensionless parameters will also be discussed. Finally, a proposed semi-analytical model for the flow-regime transitions will be presented.

EXPERIMENTAL FACILITY AND PROCEDURE

The experimental test section is shown schematically in Figure 1. It is made of three sections of glass pipe with an inside diameter of 5.1 cm connected vertically with Teflon spacers in between the sections. The total height of the test section is 66 cm. Five immersion-type electrical heaters are installed at the bottom of the test section. Connected in parallel to a variable transformer, the five heaters can provide a power ranging from 0 to 1 kW. A steam-bleed line connects the top part of the test section to a condenser. A steam-bleed valve is installed on the line through which the amount of steam released can be controlled. A relief valve is also installed to control system pressure. A water intake line is installed connecting the bottom of the test section to the main loop.

Three pressure transducers and three thermocouples are installed on the spacers, as shown in Figure 1. The void fraction is measured by a capacitance method.[2] Four ring-type capacitance electrodes are installed as shown.

A quasi-steady-state in the experimental test section is defined as a condition where the only mass transfer between the test section

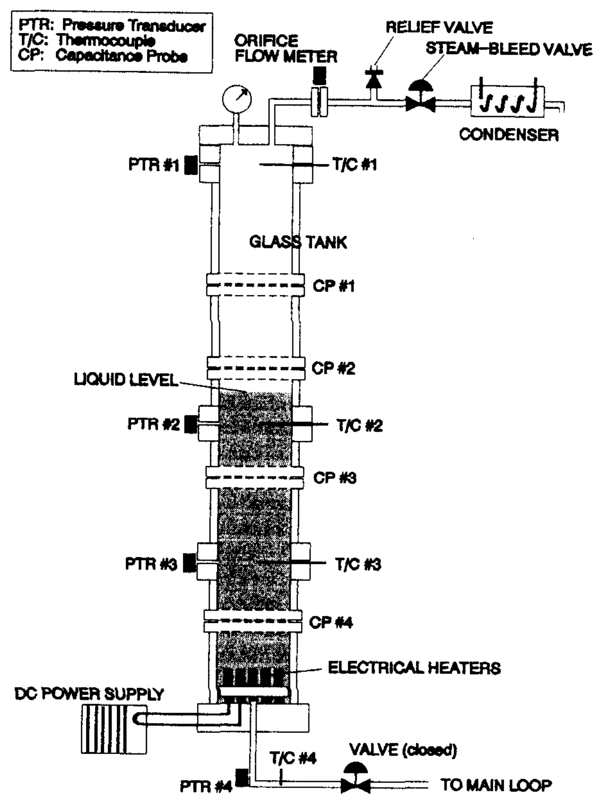

Fig. 1: Schematic of Experimental Test Section

system and its environment is through the small amount of steam released through the steam-bleed valve, and the heat input to the system from the heater is balanced by the sum of the heat loss through the wall and the energy carried out by the steam-bleed flow. It is noted, however, the amount of heat loss through the vessel glass wall is insignificant. The pressure in the system under such a quasi-steady-state condition is essentially constant. 106 quasi-steady-states, each with a different combination of heater power, relief valve set point and liquid level, are successfully generated. During the quasi-steady-state condition, the flow patterns within the liquid column at the bottom of the vessel, within the steam volume above the liquid column, and at the steam-liquid interface are visually observed and all other measurements are taken. The data obtained covers system pressure ranging from 67 kPa to 250 kPa, liquid level ranging from 8 cm (1.6D) to 41 cm (8D), and power ranging from 25 W to 900 W.

FLOW PATTERNS OBSERVED

The flow patterns observed during quasi-steady-state conditions are described below. Typical visualization of the flow patterns are shown in Figure 2.

Liquid Column: (1) **subcooled boiling**. The liquid is in natural convection mode, local nucleation of bubbles is sometimes observed, but the bulk of the liquid is in a subcooled state; (2) **bubbly flow**. The gas phase is approximately uniformly distributed in the form of bubbles flowing upward in the continuous medium of the liquid phase. The shape of the bubbles is almost spherical; (3) **froth flow** (or churn turbulent flow). The liquid and the gas phase mixture is in chaotic movement and appears frothy and disordered. The continuity of the liquid phase is repeatedly destroyed by the turbulent motion of big bubbles, whose shape is highly distorted and irregular; and (4) **intermittent mixed bubbly/froth flow**. Bubbly flow is basically observed, except a froth flow condition appears locally and sometimes throughout the liquid column on an intermittent basis. The individual froth condition usually lasts for a few seconds.

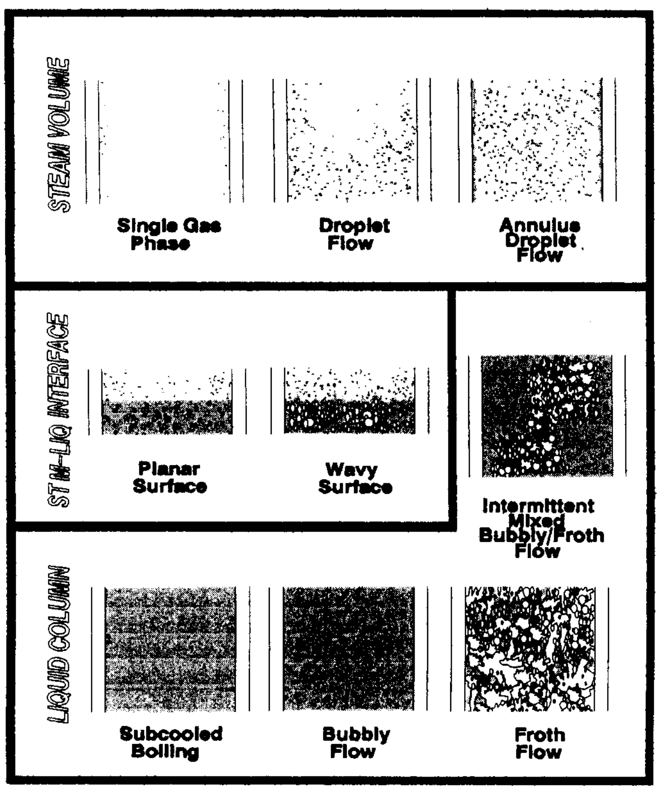

Fig. 2: Schematic of Flow Patterns Visualization

Steam Volume: (1) **single gas phase**. The space in the test section above the liquid column is basically filled with vapour. Occasionally, droplets of condensate are found, mostly near the top part of the test section; (2) **droplet flow**. Condensate droplets appear on the top part of the test section, along the test section wall and near the interface with the liquid column; and (3) **annular droplet flow**. Condensate droplets appear almost uniformly throughout the steam volume; a significant amount of liquid is flowing down the wall of the test section, merging with the liquid column below.

Steam-liquid Interface: (1) **planar surface** and (2) **wavy surface**.

The overall flow-pattern configuration in the test section system can be summarized as being four different flow regimes, as listed in Table 1. In each flow regime, one of the flow patterns described above is distinctly found in each of the liquid column, steam volume and at the interface. For example, in the Flow Regime II, the liquid column is in the bubbly flow condition. Corresponding to this, droplet flow occurs in the steam volume, while the interface is in a planar condition.

TABLE 1: Summary of Flow Pattern Configuration

Flow Regime	Flow Patterns		
	Liquid Col.	Interface	Steam Vol.
I	Subcool.Boiln	↑ -- Planar -- ↓	Sing.Gas Phs
II	Bubbly		↑ -- Droplet -- ↓
III	Interm.Mixed	↑ -- Wavy -- ↓	
IV	Froth		Annl.Droplet

DEVELOPMENT OF FLOW-REGIME MAP

The quasi-steady-state flow regimes are found to depend on system parameters, which are heater power, system pressure and liquid level. Expressing these system parameters in terms of appropriate dimensionless parameters, a generalized flow-regime map applicable to other systems such as the pressuriser and the riser duct can be developed. Derivation of dimensionless parameters requires values of other parameters such as average system pressure, average liquid temperature and average void fraction in the liquid column. Calculation of these parameters from experimentally measured parameters is described in [1].

Two dimensionless parameters were found to be sufficient for describing the flow-regime map. One of them is the ratio between the liquid level and the test section inside diameter. It is defined as the dimensionless liquid level, L^*:

$$L^* = z_{LIQ} / D. \qquad (1)$$

The other dimensionless parameter is the average void fraction in the liquid column, α_L. The relationship between α_L and heater power Q_{HTR}, can be analytically derived based on a simple drift-flux concept, as described below.

The cross-sectional averaged relative velocity between the gas phase and the liquid phase, u_{gf}, is the difference between the cross-sectional averaged velocities of the gas phase and that of the liquid phase:[3]

$$u_{gf} = u_g - u_f \qquad (2)$$

u_f can be assumed to be negligible in the present system. Expressing u_g in terms of the cross-sectional averaged superficial gas phase velocity, u_{gs}, and α_L, the following is obtained:

$$u_{gf} = u_{gs} / \alpha_L. \qquad (3)$$

The superficial gas velocity can be expressed as:

$$u_{gs} = \frac{4 \ (Q_{HTR} - Q_W) \ (v_g - v_f)}{\pi \ D^2 \ (h_g - h_f)}, \qquad (4)$$

and the relative phase velocity u_{gf} can also be interpreted as the bubble terminal velocity [4]:

$$u_{gf} = C \left[\frac{\sigma \ g \ (\rho_f - \rho_g)}{\rho_f^{\,2}} \right]^{1/4} \qquad (5)$$

where C is a constant. Combining Eqn.(3), (4) and (5), and expressing Eqn.(4) in terms of saturated densities, the following can be written:

$$\alpha_L = \frac{1}{C} Q^* \qquad (6)$$

where Q^* is defined as a dimensionless net heat input to the test section:

$$Q^* = \frac{4 \ (Q_{HTR} - Q_W) \ (\rho_f - \rho_g)^{3/4}}{\pi \ D^2 \ (h_g - h_f) \ \rho_f^{1/2} \ \rho_g \ (g \ \sigma)^{1/4}} \qquad (7)$$

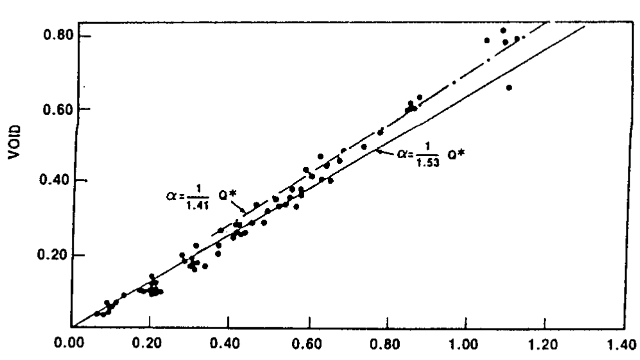

Fig. 3: Plot of Average Void Fraction in Liquid Column Vs. Dimensionless Net Heat Input

Data obtained in the present study are plotted in Figure 3 with α_L versus Q^*. Eqn.(6) with C equal to 1.53, as originally suggested by Harmathy,[5] and with C equal to 1.41, as suggested by Zuber[6] for froth flow condition, are superimposed on the plot. The equations fit the data well. It is noted the higher values of α_L correspond to conditions at or near the froth flow regime.

The generalized flow-regime map is obtained by plotting the experimental data in terms of the two dimensionless parameters. This is shown in Figure 4. For clarity, only the flow patterns in the liquid column are indicated. The area on the map is clearly divided into regions of distinct flow regimes, which suggests the adequacy of the two dimensionless parameters.

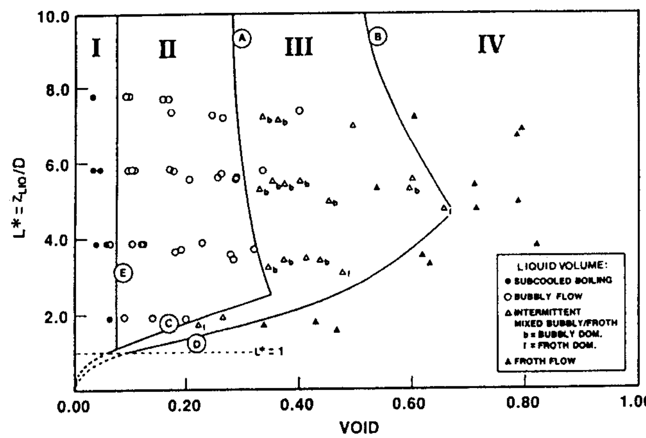

Fig. 4: Generalized Flow Regime Map For Vertical System With Stagnant Water

MODELLING OF FLOW REGIME TRANSITIONS

Transition line A in Figure 4 is modelled based on an 'Entry Region Taylor Bubble Overtaking' concept. The concept is then extended semi-empirically to model transition line B. Transition lines C and D are semi-empirically modelled by considering wall proximity at the bottom of the vessel and will not be discussed in this paper. The modelling is concentrated on the transition in the liquid column, as there is an one-to-one correspondence between the flow pattern in the liquid and the overall flow regimes in the system.

Generally, in a fully developed flow with bubbly flow pattern, as void fraction increases to a value between 0.25 and 0.3, dispersed bubbles become so closely packed and slug flow usually occurs as a result of bubble coalescence. *Taitel et.al.[4] describe the froth (churn) flow* as an entry region phenomena associated with a slug flow observed in the fully developed flow region. A hypothesis was made that if the very same flow and liquid condition for slug flow was observed on a shorter (<16D) flow conduit, the slug flow would not be observed, while the froth flow could still be observed. Slug flow was not observed in the present experiment because the liquid levels in the current test section were well less than 16D.

The above hypothesis and the concept of slug flow formation by overtaking Taylor bubbles is applied to the analysis of transition from bubbly flow pattern to intermittent mixed bubbly/froth flow pattern observed in the liquid column. When gas phase is rapidly generated, short and unstable Taylor bubbles are formed and move upward toward the steam-liquid interface. A Taylor bubble moving in the wake of a preceding Taylor bubble tends to overtake it. If all the Taylor bubbles successfully reach the interface before the subsequent ones are able to overtake them, bubbly flow pattern will be observed. This is because Taylor bubbles are unstable, recirculating liquid in the liquid slugs and near the steam-liquid interface has enough inertia to break them up into smaller bubbles.

On the other hand, at the first instant a Taylor bubble is able to overtake its preceding one within the liquid column, an intermittent froth flow pattern will be observed. This is because as the two Taylor bubbles merge, liquid film around the Taylor bubbles penetrates deeply into the liquid slug, creating a highly agitated mixture and a frothy appearance will be observed in the region of merging.

The original mathematical formulation developed by Taitel et.al.[4] is now expanded to derive an equation for the transition line A in Figure 4. The time t needed for a Taylor bubble to overtake its proceeding one was shown to be a function of the initial distance between the two bubbles, ℓ, and the length of stable liquid slug at fully developed region, L_S:[4]

$$t = \frac{L_S}{1.61\sqrt{gD}}\left[e^{4.6\ell/LS} - 1\right]. \qquad (8)$$

Taking t = 0 as the time the second bubble is about to enter the liquid column (above the heater region), the criterion for the first occurrence of the overtaking of the bubbles within the liquid column can be expressed as:

$$z_{LIQ} - L_H > \ell_{TB} + \ell + 0.2174 L_S\left[e^{4.6\ell/LS} - 1\right] \qquad (9)$$

where L_H is the height of the heater elements and ℓ_{TB} is the length of the Taylor bubble, assumed to be proportional to D: $\ell_{TB} = \delta$ D.

The distance between the two Taylor bubbles, ℓ, can be derived by incorporating an expression for α_L in a slug column as suggested by Fernandes [7]:

$$\alpha_L = (1-R)\,\alpha_{TB} + R\,\alpha_{LS}, \qquad (10)$$

where R is the ratio of ℓ to the sum of ℓ and ℓ_{TB}. α_{TB} and α_{LS} is the void fraction in the Taylor bubble section of the column and in the liquid slug section of the column, respectively. α_{LS} is taken as 0.25 for consistency with the normal transition of a bubbly flow to a slug flow. α_{TB} is derived by considering the volume of a Taylor bubble suggested by Griffith [8]:

$$\alpha_{TB} = 0.913 - 0.526\, D/\ell_{TB}. \qquad (11)$$

Together, these give an expression for ℓ as follow:

$$\ell = \frac{(0.913 - 0.526/\delta - \alpha_L)}{(\alpha_L - 0.25)}\,\delta\, D \qquad (12)$$

The length of stable liquid slug at fully developed region, L_S, is taken as 16D. An equation for the transition line A in Figure 4 can now be converted from Eqn.(9) and expressed as follow:

$$(z_{LIQ} - L_H)/D = (1 + w)\delta + 3.48(e^{0.2875w\delta} - 1) \qquad (13)$$

$$\text{where } w = \frac{(0.913 - 0.526/\delta - \alpha_L)}{(\alpha_L - 0.25)}$$

By approximating the volume of the Taylor bubble by the formula for a half-ellipsoid; also assuming the first generation of the Taylor bubble will have a minimum surface area and hence its volume is to be equal to a sphere with diameter equal to D, δ is found equal to 1.0. Eqn.(13) with $\delta = 1.0$ is plotted as line A in Figure 4. The agreement with data is excellent.

Eqn.(13) with $\delta = 3.0$ has been found to fit date well as a transition between the intermittent flow and the froth flow (line B in Figure 4). This implies that, if three subsequent merges of the Taylor bubbles within the liquid column is possible, overtaking of the bubbles by another is always guaranteed. The particular choice of 3 for δ is considered system dependent.

CONCLUSION

The flow-pattern characteristics of two-phase fluid in a vertical two-phase system has been analyzed in the current study. A generalized flow-regime map has been developed by expressing the system parameters in terms of two dimensionless parameters: the dimensionless liquid level and the averaged void fraction in liquid column. An 'Entry Region Taylor Bubble Overtaking' model has been developed. The transition from the bubbly flow to the intermittent mixed bubbly/froth flow has been successfully formulated based on the model. The other transitions are formulated semi-analytically.

REFERENCES

1. R. SOLLYCHIN, W.J. GARLAND, and J.S. CHANG, "The Investigation of Flow Regimes In A Liquid Column With Gas Phase Generated At The Buttom", 27th ASME/AIChE/ANS National Heat Transfer Conference, July 1991
2. J.S. CHANG, R. GIRALD, R. RAMAN and F.B.P. TRAN, "Measurement of Void Fraction in Vertical Gas-Liquid Two-Phase Flow by Ring Type Capacitance Transducers", T.R. Hedrick et.al. ed.: Mass Flow Measurements-1984, vol.17, 93, ASME Press (1984)
3. J.G. COLLIER, Convective Boiling and Condensation, 2nd Ed., McGraw-Hill (1972)
4. Y. TAITEL, D. BORNEA, and A.E. DUKLER, "Modelling Flow Pattern Transition for Steady Upward Gas Liquid Flow in Vertical Tube", A.I.Ch.E. Journal, 26, 3 (1980)
5. T.Z. HARMATHY, "Velocity of Large Drops and Bubbles in Medium of Infinite of Restricted Extent", A.I.Ch.E. Journal, 6, 2 (1960)
6. N. ZUBER, F.W. STAMB, G. BIJWARD and P.G. KROEGER, "Steady State and Transient Void Fraction in Two-Phase System", GEAP 5417 (1967)
7. R.D. FERNANDES, R. SEMIAT, A.E. DUKLER, "A Hydrodynamic Model For Gas Liquid Slug Flow in Vertical Tubes", A.I.Ch.E Journal, 29,981 1983
8. P. GRIFFITH, G.B. WALLIS, "Two-phase Slug Flow", J.Heat Transfer, 83, 367, 1961

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