THE INVESTIGATION OF FLOW REGIMES IN A LIQUID COLUMN WITH GAS PHASE GENERATED AT THE BOTTOM

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ABSTRACT

This paper describes a study of the flow-pattern characteristics of two-phase fluid in a vertical vessel, with the liquid continuum phase stagnant and the gas phase generated at the bottom of the vessel. An experimental test section to observe the flow pattern and to measure other relevant parameters under this condition has been developed. Nine flow patterns in the liquid column, in the steam volume above the liquid column and on the interface between the liquid column and the steam volume have been determined to be functions of system pressure, net energy input and fluid inventory. A method of generalizing the flow-regime map for this type of system configuration is discussed.

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 pressurizers 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 schematic of a typical pressurizer used in a water-cooled power reactor is shown in Figure 1(a). Prediction of the pressurizer behaviour in response to the power reactor operating or to accidental transients is of particular concern in the design and analysis of the reactor primary heat transport system (PHTS). Many pressurizer models are reported in the literature or currently used in the nuclear industry. Examples are those developed, chronologically, by Gorman,[1] Nahavandi and Makkenchery,[2] and Baggoura and Martin.[3] In most of these studies, the thermodynamic state(s) of the fluid in the pressurizer is pre-assumed. Mathematical models are then set-up based on this assumption. The models are usually adequate in predicting pressurizer behaviour qualitatively. However, inconsistent performance of the models for different PHTS transients is generally reported.[4,5] It is believed that the major drawback of these pressurizer models is the lack of understanding of the detailed physical phenomena in the pressurizer. Recently, there has been a renewed interest in the systematic study of local thermalhydraulic phenomena in the pressurizer. An example is the work by Kim et.al.,[5] in which phenomena such as heat transfer to walls, interface mass transfer and stratification of insurge fluid have been reinvestigated.

One of the fundamental phenomena in the pressurizer that has not been systematically investigated is its flow-pattern characteristics. Generally, bubbly flow is assumed to exist in the liquid column at the bottom of the pressurizer and the top part is assumed to be filled with steam with dispersed droplets. Based on the authors' knowledge, verification of this flow-pattern configuration for all possible pressurizer conditions has not been made yet. Neither has there been any study on the transition of the flow regime from that described above to other possible flow-pattern configurations.

An example of pool-type reactors that may benefit from the study of vertical systems with stagnant liquid is the SES-10 reactor. It is from the first generation of the SLOWPOKE family of small nuclear heating reactors developed by AECL.[6] One of the important features of these pool-type reactors is that the flow of reactor PHTS coolant is driven by natural circulation. A schematic of the PHTS of an SES-10 is shown in Figure 1(b). The system consists of a core module, a riser duct and heat exchangers, all submerged in a pool.

The study of a hypothetical Loss of Heat Load Accident in a reactor such as SES-10 is of interest to the designer of the reactor. In the accident, it is assumed that because heat continues to be generated in the core, the coolant temperature has reached saturation, and the water level has been reduced to a level below

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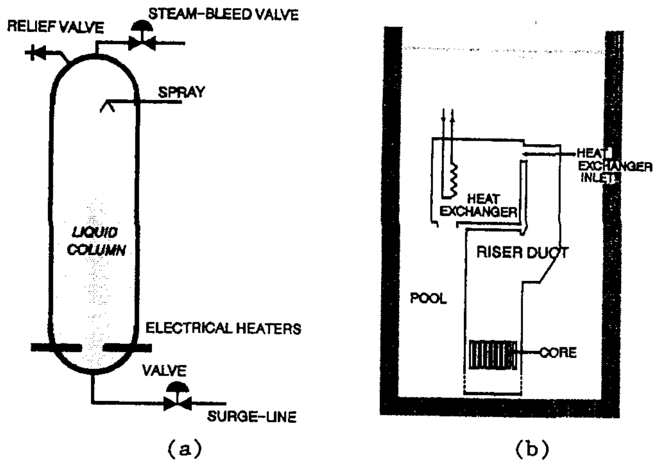

Fig. 1: (a) Schematic of a Typical Pressurizer; (b) Schematic of SES-10 Reactor PHTS

the heat-exchanger inlets due to the continued boiling-off of the coolant. Knowledge of the flow patterns in the riser duct under this hypothetical condition is important for an analysis of the accident.

The primary objective of the current study is to obtain a complete description of flow patterns and their transitions in an experimental test section simulating the vertical systems described above. This will provide a basis for deriving a flow-regime map for systems such as the pressurizer and the riser duct of the pool reactor. Based on this, a methodology for a complete study of these systems can be systematically developed.

EXPERIMENTAL FACILITY AND PROCEDURE

The experimental test section is shown schematically in Figure 2. It is part of a pressurizer experimental loop facility, although the rest of the loop is not utilized in the current study. The test section is made of three sections of glass pipe with an inside diameter of 5.1[b] 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 surge line connecting the bottom of the test section to the main loop is used only as a water intake line in the current series of experiments and the valve on the line is closed during the experiment.

Three Validyne model DP-15 pressure transducers and three type T thermocouples are installed on the spacers, as shown in Figure 2. The void fraction is measured by a capacitance method.[7] Four ring-type capacitance electrodes are installed as shown. Using a push-button switch, the electrodes are connected, one at a time, to a Bonton model 72B capacitance meter.

The generation of a flow-regime map is only possible if the flow patterns are observed at steady-states or conditions near steady-states. A quasi-steady-state in the experimental test section is defined as a condition such that the only mass transfer between the 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 negligible. The pressure in the system under such a quasi-steady-state condition is essentially constant.

The quasi-steady-state in the experimental test section corresponds to the almost steady-state condition of a pressurizer isolated from the PHTS, and to a very slow transient condition in a pool reactor riser duct following a Loss of Load Accident. The system pressures in both

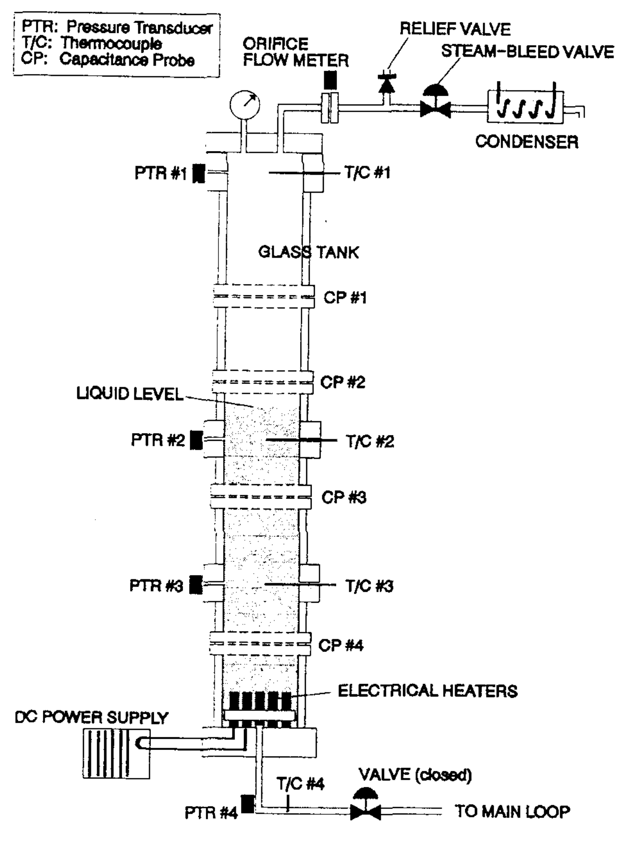

Fig. 2: Schematic of Experimental Test Section

[b]Flow area is about 1:1500 and 1:700 scale of that of a typical pressurizer and of a pool-type reactor rise duct respectively

cases are such that they can be considered constant within periods of interest when the dynamics of such systems are studied.

The following test procedure is adopted in the experiment. First, the steam-bleed valve is closed and the relief valve setting is set to a constant level equal to a desired system pressure. Liquid water at a temperature close to the saturation temperature is delivered to the test section through the intake line until the liquid level reaches a desired value; the valve on the intake line is then closed. The heaters are turned on and the heater power is raised to the desired value.

Because the relief valve opens each time the system pressure reaches its set point, the system pressure periodically rises and falls, but it eventually reaches a constant value near the relief valve set point. A quasi-steady-state condition is finally reached whereby heat input from the heaters is approximately balanced by the sum of the heat loss to the test section wall and the energy carried out by the steam relieved.

During the quasi-steady-state condition, the flow patterns within the liquid column, within the steam volume above the liquid column, and at the steam-liquid interface are visually observed, the swelled liquid level is measured, the pressure, temperature and void fraction at their points of measurement are recorded, and the steam flow and heater power are also recorded. Additional measurements include liquid level and void fraction before start-up of the heater power and after cooling down of the test section, following the end of a test. The same test procedure is repeated for different settings of heater power, relief valve set point and liquid level. 106 sets of data, each with a different combination of settings, were successfully generated. The data 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 in the liquid column, the steam volume and the steam-liquid interface during quasi-steady-state conditions are described below. Typical visualization of the flow patterns are shown in Figure 3.

Liquid Column

Four distinctive flow patterns were observed in the liquid column:

(1) **subcooled boiling**: the liquid is in natural convection mode; local nucleation of bubbles is sometimes observed, but the liquid temperature, especially that measured far from the bottom of the test section, is lower than the saturation temperature;

(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;

(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.

Steam Volume

Flow patterns in the steam volume are not as obvious as they are in the liquid column. However, three types of flow patterns were observed:

(5) **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;

(6) **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;

(7) **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

Two flow patterns were observed in the steam-liquid interface:

(8) **planar surface**

(9) **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 the first flow regime, the liquid column is in the subcooled condition (flow pattern no. 1). At this condition, a single phase (flow pattern no. 5) usually occurs in the steam volume, while the steam-liquid interface is in a planar condition (flow pattern no. 8).

In the second flow regime, when the liquid column is in the bubbly flow (flow pattern no. 2) condition, droplet flow (flow pattern no. 6) occurs in the steam volume, while the interface is still in the planar condition.

In the third flow regime, intermittent mixed bubbly/froth flow (flow pattern no. 4) occurs in the liquid column. Droplet flow still present in the steam volume. However, the steam-liquid interface is in a wavy condition (flow pattern no. 9).

Finally, the froth flow (flow pattern no. 3) condition in the liquid column corresponds to an annular droplet flow (flow pattern no. 7) condition in the steam volume. Under this condition, the wavy surface occurs at the steam-liquid interface. This flow-pattern configuration is categorized as the fourth flow regime.

FLOW-REGIME MAP SPECIFIC TO THE CURRENT SYSTEM

The quasi-steady-state flow regimes depend on the experimental system parameters, which are heater power, system pressure and liquid level. An example of this dependency is shown in Figure 4, where the heater power and the liquid level are used as the coordinates; data points with pressure between 75 kPa and 145 kPa are selected and plotted and the corresponding flow-pattern is indicated. When various similar plots with different pressure groups are compared, lines separating the flow regimes can be drawn, as shown in Figure 4. For example, any point located between the solid line and the dashed line represents a quasi-steady-state condition, at which flow regime no. I is observed; i.e., the liquid column is in the bubbly flow condition, the steam volume is in the droplet flow condition and the steam-liquid interface is flat.

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

The simultaneous effect of all three control parameters can be more clearly shown by combining plots similar to Figure 4, but for different pressure groups, into a three-dimensional map, as shown in Figure 5. All three of the system parameters--system pressure (P), heater power (Q_{HTR}) and liquid level (z_{LIQ}) are used as axes of the map. The three surfaces divide the space into four sub-spaces, each corresponding to a flow regime. For clarity, experimental data points are not plotted in Figure 5.

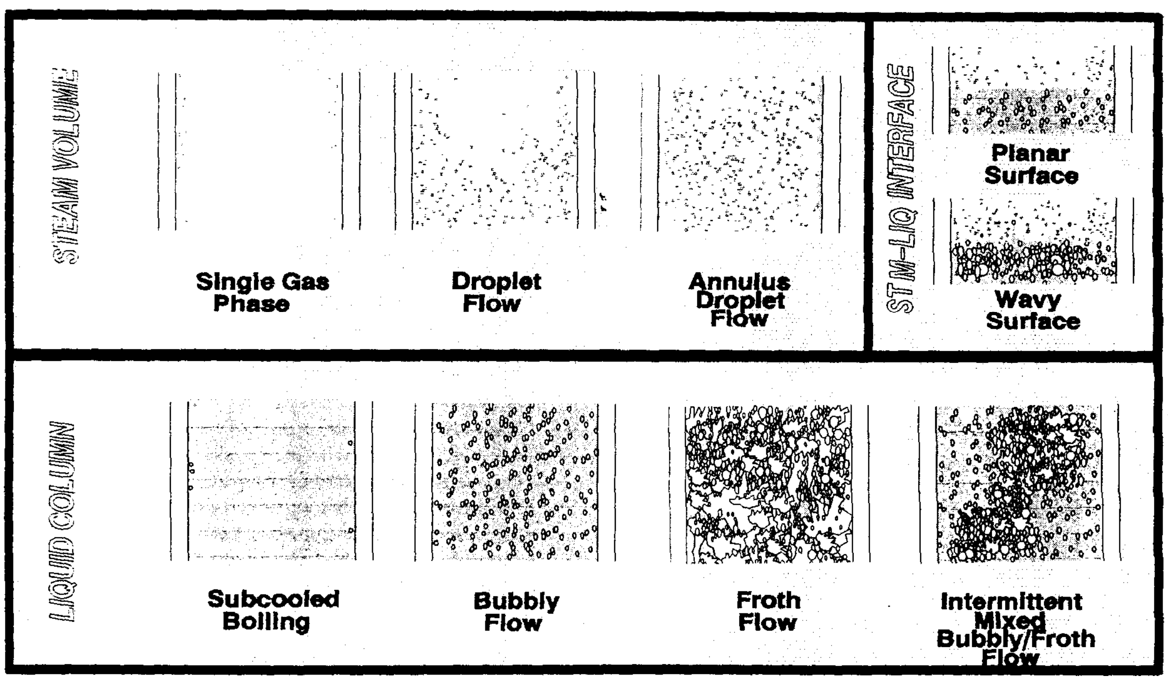

Fig. 3: Schematic of Flow Patterns Visualization

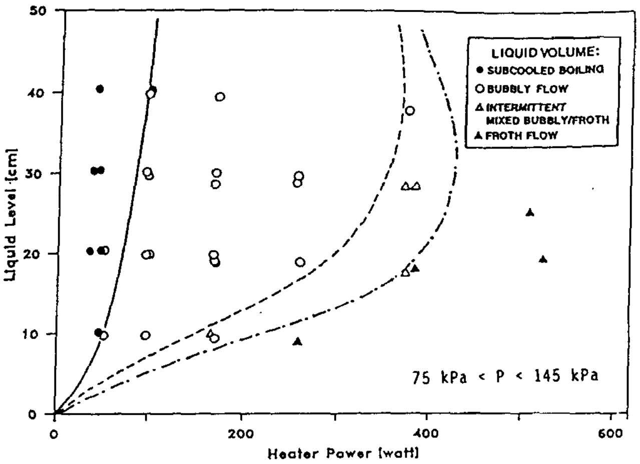

Fig. 4: Plot of Flow Pattern Dependency on Heater Power and Liquid Level For System Pressure Between 75 kPa and 145 kPa

GENERALIZATION OF THE FLOW-REGIME MAP

In order to apply the information disclosed in the system-dependant flow-regime map shown in Figure 5 to other systems, such as the pressurizer and the riser duct of pool-type reactors, the map has to be generalized by expressing it in some appropriate dimensionless parameters. The derivation of the dimensionless parameters requires values of many parameters, such as pressure, temperature, void fraction, and fluid properties. Since the actual values of these parameters generally vary axially within the system and the values of the experimental parameters were local measurements, average values of these parameters in the liquid column and in the steam volume must be calculated. This is to ensure a consistency of the analysis. The IDRIFF code[8] was used as a convenient tool to calculate the average values of all the required parameters. The code was specially developed to simulate a vertical two-phase system such as the one being studied. A set of lumped formulated homogeneous two-phase conservation equations is applied to the liquid column and the steam volume. In addition, a set of one-dimensional drift-flux equations is applied within each of the liquid column and steam volume to calculate profiles of two-phase parameters.

For each quasi-steady-state test, starting from the known initial condition, the condition in the test section was simulated with the IDRIFF code until the final quasi-steady-state condition was reached and the local values of pressure, temperature and void fraction, as well as heater power, steam-bleed flow and water level, match those directly measured from the experiment. The average values of pressure, temperature over the whole steam volume and the liquid column, and the average void fraction in the liquid column, are then calculated. The average steam pressure is taken as the overall system pressure in the test section for the purpose of the current analysis.

The simulation also served verified the relevance of the experimental data sets. Two types of data sets were not included in the data base used for the current flow-regime analysis: (1) data sets with a notable discrepancy between

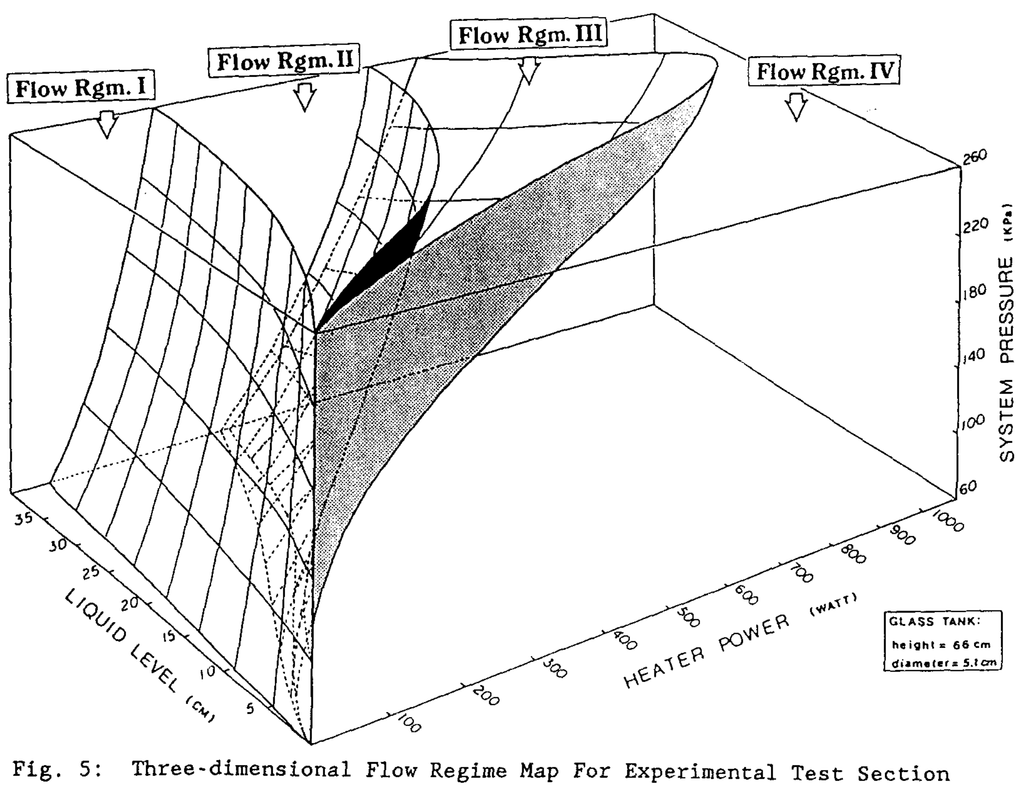

Fig. 5: Three-dimensional Flow Regime Map For Experimental Test Section

the value of steam flow measured in the experiment and that predicted by IDRIFF, which was likely caused by the existence of two-phase mixture in the orifice flow meter during the experiment; and (2) data sets with an irregular value of experimentally measured void fraction, which may be caused by a transition of flow pattern during the perceived quasi-steady-states. Among the 106 sets of experimental data available, 78 were verified as relevant to the current analysis and used in the generalization of the flow-regime map. Maximum discrepancies between the code's prediction and experimental measured values of all data retained for the current analysis are listed in Table 2.

Two dimensionless parameters were found to be sufficient for describing the flow-regime map. It is desirable to determine dimensionless parameters in such a way that the effects of two of the three system parameters, Q_{HTR} and z_{LIQ}, are represented. It is assumed that the effect of pressure P can automatically be exemplified by the presence of appropriate water thermodynamic properties, which relate to pressure through equations of state. One of the dimensionless parameters 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 appropriate dimensionless parameter to represent Q_{HTR} is the average void fraction in the liquid column, α_L. The relationship between the two 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 velocity of the gas phase, u_g, and the cross-sectional averaged velocity of the liquid phase u_f:[9]

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

Since the liquid in the vertical system under the current study is basically stagnant with little local circulation, u_f can be assumed to be negligible. Expressing u_g in terms of the cross-sectional averaged superficial gas phase velocity, u_{gs}, and the averaged void fraction in the liquid column, α_L, the following is obtained:

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

From this equation and knowing that u_{gf} depends only on water properties, an equation relating the α_L to Q_{HTR} can be derived if a relationship between the superficial gas-phase velocity u_{gs} and the heater power Q_{HTR} is found.

Physically, the velocity of the gas phase results from the boiling of liquid by the heaters at the bottom of the test section. Due to heat input from the heaters, vapour is created from the liquid through phase change and is thrust into the test section system by the buoyancy force. Hence the superficial gas velocity can be expressed as:

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

where v_g and v_f are, respectively, the saturated gas phase and liquid-phase specific volume, and h_g and h_f are, respectively, the saturated gas phase and liquid-phase specific enthalpies. Q_W, the heat loss to the environment from the test section wall, has been included as a correction, so only the net heat input is accounted for. In terms of the saturated densities, Eqn.(4) can be written as:

$$u_{gs} = \frac{4\ (Q_{HTR} - Q_W)\ (\rho_f - \rho_g)}{\pi\ D^2\ (h_g - h_f)\ \rho_f\ \rho_g} \qquad (4a)$$

Returning to Eqn.(3), it has been suggested that[10] the relative phase velocity u_{gf} can be interpreted as the bubble terminal velocity as originally derived by Harmathy[11]:

TABLE 2: Comparison of IDRIFF's Prediction and Experimental Measured Data

Parameter	Maximum Discrepancy	Remarks
steam flow	2.5%	single ph.steam flow only
heater power	0.0%	exp. value is used as simulation boundary cond.
relief valve set-point	0.0%	exp. value is used as simulation boundary cond.
liquid level	3.0%	initial liq. inventory is used as initial condition
steam press.	0.6%	local value
liquid press.	2.0%	local value
steam temp.	1.5%	local value
liquid temp .	2.0%	local value
void fract. in liq.Col.	29.0%	local, equiv.to 5% absolute void frac. when exp. measured value is 17%
steam v. mass	0.0%	IDRIFF prediction is adopted. Total mass in test section measured is used as init. cond.
liq.col. mass	0.0%	IDRIFF prediction is adopted. Total mass in test section measured is used as init. cond.

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

where C is a constant. A value of 1.53 was originally suggested for C by Harmathy.

Combining Eqn.(3), (4a) and (5), 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:

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

Data obtained in the present study are plotted in Figure 6 with α_L versus Q^*. Eqn.(6) with C equal to 1.53 is superimposed on the plot. The equation fits the data well, especially for lower values of the void fraction. The higher values of void fraction correspond to conditions at or near the froth (churn-turbulent) flow regime. Zuber[12] suggested the use of 1.41 for the value of C under churn-turbulent conditions. Eqn.(6) with C equal to 1.41 is also plotted in Figure 6. The modified equation generally fits data at higher void fractions well.

The generalized flow-regime map was obtained by converting data used to compile the original flow-regime map, Figure 5, into the two dimensionless parameters. This is shown in Figure 7, where the two dimensionless parameters are used as the coordinates and data points (with their flow patterns indicated) are plotted. For clarity, only the flow patterns in the liquid column are indicated, as there is a one-to-one correspondence between the flow pattern in liquid and the overall type of the flow regime. The area on the map is clearly divided into regions of distinct flow regimes, which suggests that the choice of the two dimensionless parameters is adequate in generalizing the flow-regime map obtained from the current experiment.

The modelling of the transitions between flow regimes in Figure 7 is described in a separate paper.[13]

CONCLUSION

The flow-pattern characteristics of two-phase fluid in a vertical system, with a configuration similar to that of a pressurizer and to that of the riser duct in a pool-type reactor, has been investigated in the current study. The following has been concluded:

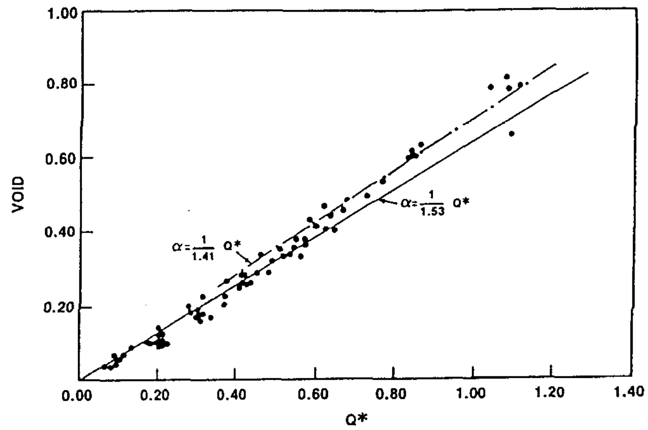

Fig. 6: Plot of Average Void Fraction in Liquid Column Vs. Dimensionless Net Heat Input

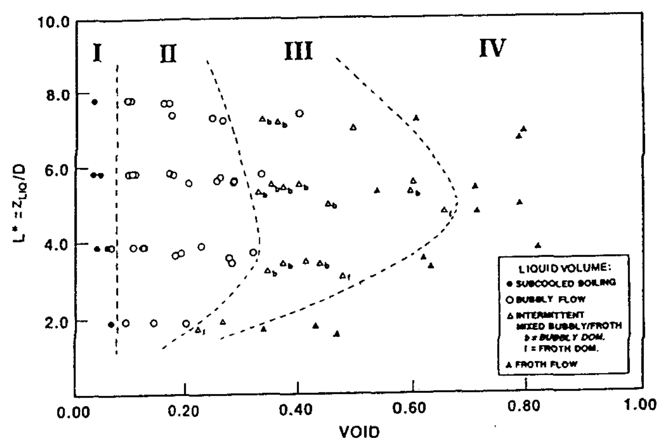

Fig. 7: Generalized Flow Regime Map For Vertical System With Stagnant Water

(1) Nine flow patterns have been determined in the vertical system described above. In the liquid column, four flow patterns have been identified: subcooled boiling, bubbly, intermittent mixed bubbly/froth and froth flow. In the steam volume above the column, the flow pattern may be in single phase, droplet or annular droplet flow condition. And at the steam-liquid interface, the surface is in either a planar or wavy condition.

(2) A flow-regime map has been generated for the particular experimental test section system used in the current study. It is completely described by three system parameters: the system pressure, heater power and liquid level.

(3) A generalized flow-regime map has been obtained by replacing the three system parameters with two dimensionless parameters: the dimensionless liquid level and the averaged void fraction in liquid column. The relationship between the void

fraction and the heater power is derived based on a drift-flux concept. The result indicates that the choice of the two dimensionless parameters is adequate in generalizing the flow-regime map.

Further study of the appropriateness of the two dimensionless parameters suggested above is essential for a complete understanding of the flow regime in vertical two-phase systems with stagnant liquid. A larger-scale test section can be built to conduct similar flow pattern experiments so that the adequacy of the two dimensionless parameters can be verified. A positive verification will be the first step in developing a methodology for the systematic study of systems such as the pressurizer and the riser duct in a pool-type reactor.

NOMENCLATURE

D	Test section inside diameter
g	Acceleration due to gravity
h	Specific enthalpy
L^*	Dimensionless liquid level
P	System pressure
Q_{HTR}	Heater power
Q_W	Heat loss through test section wall
Q^*	Dimensionless net heat input
T_L	Average temperature in liquid column
u	Cross-sectional area averaged velocity
u_{gf}	Cross-sectional area averaged relative velocity between phases
u_{gs}	Cross-sectional area averaged superficial gas-phase velocity
v	Specific volume
x	Averaged steam quality in liquid column
z_{LIQ}	Liquid level
α_L	Averaged void fraction in liquid column
ρ	Density
σ	Liquid surface tension

subscript f	liquid phase
subscript g	gas phase

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FOREWORD

Starting in 1985 with the Denver meeting, the American Nuclear Society, through its Thermal Hydraulics Division (THD), has joined the ASME and the AIChE in organizing the National Heat Transfer Conference. This volume presents the contributions of the ANS-sponsored (or cosponsored) sessions for the 1991 meeting in Minneapolis. It is the fifth volume and follows the 1987 Pittsburgh, 1988 Houston, and 1989 Philadelphia meeting volumes in a series of proceedings published annually, except for every fourth year when the International Heat Transfer Conference is held. With the publication of this volume, the series becomes even more well established.

Our general intent is to contribute toward the synergistic effects of a truly national heat transfer conference. With this intent we will present the more fundamentally oriented research activity in nuclear thermohydraulics at this conference. More direct nuclear applications will form the basis for our participation at the winter national ANS meeting.

We are committed to maintaining and enhancing the well-established quality standards of the National Heat Transfer Conference. We require three peer reviews of full-length papers and allow time for the necessary exchanges with the authors to reach an adequate level of revision and response to the referees' concerns. Responsibility for acceptance lies with the session chairs or co-chairs. The whole effort is monitored by the NHTC/ANS Technical Program Co-Chair and the Thermal Hydraulics Division Editorial Subcommittee and its panel of experts for the purpose of providing long-term guidance, stability, and uniformity in quality standards.

The ANS Thermal Hydraulics Division is proud of the high quality of these proceedings and would like to express its thanks to all authors, session organizers, the ANS publications department and Ellen Burke for putting it all together and keeping the project on schedule.

To reduce publication costs while allowing flexibility for quality papers that would be damaged by abbreviation to the usual eight-page length, we have instituted a policy of requiring $100 for each additional and necessary page. The necessity of each additional page is determined by the referees and the session chairs. Further, it is our policy that each author receive a complimentary copy of the proceedings.

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