FLOW REGIME MAPPING, VOID-QUALITY RELATIONS AND PRESSURE DROP IN TWO PHASE FLOW

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INTRODUCTION

Two-phase flows (e.g. steam and water) occur in many nuclear reactor components. For example, the steam generators and pressurizer in Pressurized Water Reactors and the reactor core region of Boiling Water Reactors are classic examples of where steam and water flow together as a two-phase fluid. The complexity of the processes associated with two-phase flow has required that analyst combine some form of phenomenological modeling with empirical correlations. As it is virtually impossible to find one expression that is valid over the entire range of two-phase conditions, correlations are usually developed that apply to specific "flow regimes" or flow patterns. This requires that we be able to identify these flow regimes and the transition from one flow regime or heat transfer regime to another. A number of flow regimes have been found to exist experimentally by visually observing flow patterns associated with the flow of liquid-vapor mixtures through transparent tubes. While the number and characteristics of specific flow regimes are somewhat subjective, four principal flow regimes are almost universally accepted. These include Bubbly Flow (a &b), Slug Flow (c), Churn or Churn-Turbulent (d), and Annular (e). These patterns are illustrated in Figure 1.

![Typical Flow Regimes](image)

(a) (b) (c) (d) (e)

Figure 1: Typical Flow Regimes
(From Thermohydraulics of Two-Phase Systems for Industrial Design and Nuclear Engineering, by J. M. Delhaye, M. Giot and M. L. Riethmuller)

Measurements on air-water systems can often provide insight into the behavior of more general two-phase flow systems. This typically requires that the air-water system have provisions for visualization of the flow pattern, direct measurement of the air and liquid flow rates, pressure drop and measurement of the vapor and liquid volume fractions. Visualization of the flow patterns requires that at least some portion of the test section be transparent. While a number of techniques are available for measuring volume fraction, one of the most direct is to measure the attenuation of a collimated beam of gamma rays. A two-phase/air-water facility has been constructed in the R3 Bay in the Nuclear Engineering Department. Instrumentation for pressure drop and flow rate provide an analog signal which can be interfaced to the computerized data acquisition system on the SPWRF. This facility can be used to generate flow regime "maps" which are used to predict flow patterns based on system parameters such as liquid and vapor velocities, volume fractions, etc., to validate void-quality models such as the Zuber-Findlay Model discussed in class, and to investigate the pressure loss in a two-phase system.

Flow Regime Maps

Flow regime maps are a means of predicting flow regimes based on local system variables. While no universally accepted map has been developed, typically the flow patterns are identified on the basis of liquid and vapor
velocities, volume fractions and densities. A number of flow regime maps are available in the literature. An example of one such map for vertical upflow of air and water is given in Figure 2. The coordinates are liquid and vapor fluxes ($j_f$ and $j_g$ respectively) where the liquid flux is defined as

$$j_f = \alpha_f v_l$$

and similarly for the vapor flux

$$j_g = \alpha_g v_g.$$

Figure 2: Flow pattern boundaries for vertical upflow of air and water at 15 psia (From Govier and Aziz)

**Void-Quality Relations**

It can be shown, that void and quality can be related to the Drift Velocity by

$$\alpha = \frac{1}{1 + \frac{1-x \ \rho_l}{x \ \rho_r} + \rho_g V_g \frac{G_x}{G}}$$

where $V_g$ is a correlated parameter, and generally a function of flow regime. Given void fraction, quality and mass flux, the Drift Velocity is given by

$$V_g = \frac{G_x}{\rho_g} \left\{ \frac{1}{\alpha} - 1 - \frac{1-x \ \rho_l}{x \ \rho_r} \right\}$$

**Frictional Pressure Drop**
In single-phase flow, frictional losses are correlated in the form

$$\Delta P_f = \frac{fL \rho v^2}{D \frac{g}{2 \rho_c}} = \frac{fL}{D} \frac{G^2}{2 \rho_c g_c}$$

where $f$ is the single-phase friction factor. It has been observed experimentally, that in flowing two-phase systems, the pressure drop can be much greater than that in a single-phase system with the same mass flux. The classical approach in correlating two-phase frictional losses is to multiply the equivalent single-phase loss by an empirical two-phase multiplier $\phi_{io}^2$,

$$\Delta P_f^{(2\phi)} = \frac{fL}{D} \frac{G^2}{2 \rho g c} \phi_{io}^2.$$ 

The simplest model for the two-phase multiplier is the homogeneous model which gives

$$\phi_{io}^2 = 1 + \frac{u_{fg}}{u_f} x.$$ 

**TWO-PHASE AIR WATER SYSTEM (TEQUILA)**

The two-phase air water system TEQUILA provides the capability for flow regime visualization along with simultaneous measurements of void fraction, liquid velocity, vapor velocity, vapor temperature and pressure drop. From these measurements, the flow quality and the total system mass flux can be determined.

**Flow Regime Visualization:** The viewing region of TEQUILA is a one inch diameter clear pipe. Flow patterns from bubbly to annular are clearly visible. At high liquid and vapor velocities, visualization can be enhanced through the use of a stroboscope which acts to "freeze" the vapor phase.

**Liquid Velocity:** Liquid velocity is measured directly with a paddle-wheel type flow meter placed in the flow line prior to the liquid entering the viewing section. The flow meter produces a 4-20 milliamp signal which can be read directly by the LABTECH Notebook data acquisition hardware and software on the SPWRF.

**Vapor Velocity:** Vapor velocity is measured directly by a hot wire anemometer placed in the air line prior to entering the viewing section. Like the liquid flow meter, the anemometer produces a 4-20 milliamp signal which is read by the SPWRF data acquisition system.

**Vapor Volume Fraction:** Vapor volume fraction is measured by use of a gamma densitometer. The densitometer relates the vapor volume fraction to the attenuation of a collimated photon beam as it passes through the viewing section. As air and water have very different mass attenuation coefficients, the count rate is a strong function of the amount of vapor present in the pipe. The void fraction can be shown to be related to the count rate, subject to certain assumptions, by

$$\alpha = \frac{\ln(C / C_i)}{\ln(C_g / C_i)}$$

where:

- $C = $ Count rate for an arbitrary volume fraction
- $C_i = $ Count rate for all liquid in the pipe ($\alpha = 0$)
- $C_g = $ Count rate for all air in the pipe ($\alpha = 1$).

In a flowing two phase system, the count rate and the void fraction at any location are a function of time and the flow regime. In flow regimes where the liquid and vapor are uniformly dispersed along the channel (e.g. bubbly and annular) the void fraction will be relatively constant with time. In slug flow, the void fraction in the "viewing
window” of the densitometer will change significantly as the vapor slugs pass into view. The average void fraction can be determined by

$$\bar{\alpha} = \frac{1}{t} \int_0^t \alpha(t') dt'$$

where the time dependent void fraction is obtained from the time dependent count rate using the equation above. The time dependent count rate can be obtained directly from the counting system.

**Flow Quality:** The flow quality is defined to be the flow fraction of vapor in a two phase system, i.e.

$$x = \frac{\dot{m}_g}{\dot{m}_l + \dot{m}_g}$$

At steady state, the liquid and vapor flow rates in the viewing section are the same as the liquid and vapor flow rates measured in the individual flow lines. As the cross sectional area of the three flow paths are the same, this implies flow quality is given by

$$x = \frac{\rho_g v_g}{\rho_l v_l + \rho_g v_g}$$

where the liquid and vapor properties are those measured in their respective flow lines. It should be noted, that in an air-water system, the vapor density is much lower than that in a steam-water system, and as a result care must be taken in the selection of liquid and vapor velocities in order to achieve reasonable values of quality. This is illustrated in Figure 3 below for an air density of 0.076 lbm/ft³.

**Total System Mass Flux:** The mass flux in the viewing section is given by

$$G = \frac{\dot{m}}{A_x} = \frac{\dot{m}_g + \dot{m}_l}{A_x} = \rho_l v_l + \rho_g v_g$$

as the cross sectional areas are equal. The liquid and vapor properties are again measured in their respective flow lines.
EXPERIMENTAL PROCEDURE: FLOW REGIME MAPPING AND VOID-QUALITY RELATIONS

The objective of this laboratory is to study the evolution of two-phase flow patterns and develop void-quality relationships for an air-water system.

1) Determine the count rate in the viewing section under zero flow conditions for all air and all water in the pipe.

2) For constant values of mass flux, measure void fraction, liquid velocity and vapor velocity over the full range of flow conditions. Note the flow regime for each measurement (you may wish to record the flow patterns photographically). Low liquid velocities can be obtained simply by natural circulation. Caution should be taken at high liquid and vapor flows as vibrations in the piping system can alter the source-detector geometry for the gamma densitometer.

3) Plot flow regime versus liquid and vapor flux on the Govier and Aziz map. Compare your results to this map and the Hewitt and Roberts map given in the references (Todreas and Kazimi). Note, at steady state, the liquid mass flow rate in the liquid line and the viewing section are equal. The same holds true for the vapor mass flow rate. This implies

$$\rho_k v_k A_k \bigg|_{\text{line}} = \alpha_k \rho_k v_k A_k \bigg|_{\text{viewing section}}$$

where $k = l, g$ indicates the appropriate phase. Since the cross sectional areas are equal, and if we assume the densities are constant,

$$v_k \bigg|_{\text{line}} = \alpha_k v_k \bigg|_{\text{viewing section}} = j_k \bigg|_{\text{viewing section}}.$$
4) Plot void fraction as a function of quality and mass flux. You should indicate different flow regimes with different symbols. This will indicate if there is a flow regime dependence. Compute the Drift Velocity as a function of flow regime and compare your results to those in the literature.

EXPERIMENTAL PROCEDURE: TWO-PHASE PRESSURE FRICTIONAL LOSSES

1) Measure the pressure drop under single-phase liquid and single phase vapor conditions from zero velocity to full flow in the horizontal piping section.

2) Measure liquid velocity, vapor velocity and pressure drop over the full range of flow conditions. Note the flow regime for each measurement (you may wish to record the flow patterns photographically). Low liquid velocities can be obtained simply by natural circulation. Caution should be taken at high liquid and vapor flows. Note: The pipe diameter in the horizontal section is smaller than that where the liquid and vapor velocities are measure and the proper corrections should be made.

3) Compute and plot the frictional pressure drop as a function of mass flux for both single-phase and two-phase conditions.

4) Compute and plot the two-phase friction multiplier as a function of quality and mass flux. Note:

\[ \phi_{\text{G}}^2 = \frac{\Delta P_{\text{G}}^{\phi}}{\Delta P_{\text{G}}^{\phi}} \frac{\rho_f}{\rho_g} \]

Compare to the homogeneous multiplier.

5) Correlate the two phase multiplier in terms of the Martinelli Parameter

\[ \chi^2 = \left( \frac{\mu_l}{\mu_g} \right)^{0.2} \left( \frac{1 - x}{x} \right)^{1.8} \left( \frac{\rho_g}{\rho_f} \right) \]