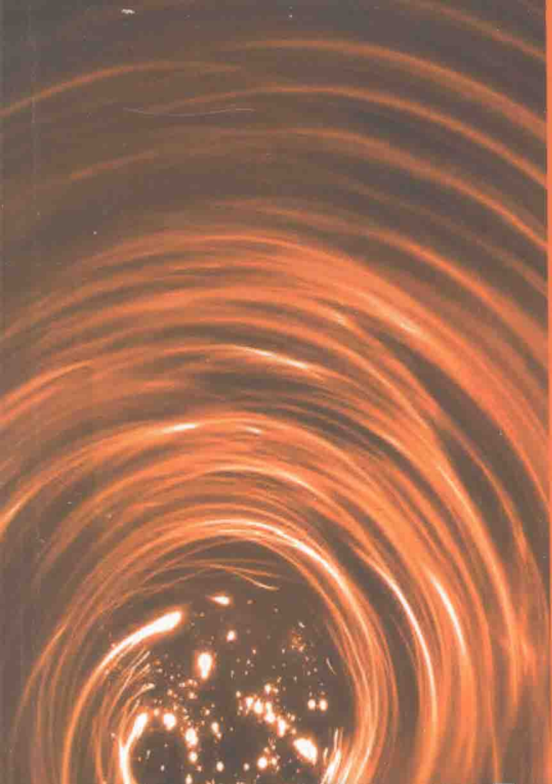

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An Introduction to Two-Phase Flow and Boiling Heat Transfer

孙立成 王建军 编

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Preface

This book is intended for both undergraduate and graduate course in two-phase flow and boiling heat transfer, especially for that involved bilingual teaching. Since most materials in terms of two-phase flow and boiling heat transfer is far more complicated for Chinese students, the autors are intended to extract fundamental and important parts from typical literatures and present in a simple way to the students, meanwhile, try to preserve the primary features of the selected contents. In addition, on the basis of the experience in bilingual teaching, the book is a framework about the issue rather than a detailed textbook. It is expectant that students can master the very basic phenomena as well as corresponding analysis methods by using of this book in a short time.

The authors are indebted to the graduate students at School of Nuclear Science and Technology, HEU, without their support this book would not have been possible.

Harbin, Heilongjiang

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Chapter 1 Introduction

1.1 What is Two-Phase Flow

A phase refers to the solid, liquid, or vapor state of matter. A multiphase flow is the flow of a mixture of phases such as gases (bubbles) in a liquid, or liquid (droplets) in gases, or solid in liquid, and so on. Two-phase flow is the simplest case of multiphase flow.

The term two-component is sometimes used to describe flows in which the phases are different chemical substance. For instance, steam-water flow is of one-component two-phase flow, while air-water flow is of two-component two-phase flow. Some two-component flows (mostly liquid-liquid) consist of a single-phase but are often called two-phase flows due to that the phases are identified as the continuous or discontinuous components.

There are many common examples of two-phase flows. Some occur in nature, such as fog, smog, smoke, rain, clouds, snow, icebergs, quick sands, dust storms, and mud. Several everyday processes involve a sequence of different two-phase flow configurations. When beer is poured from a bottle, the discharging rate is limited by the rise of slug bubbles in the neck; subsequently bubbles nucleating from defects in the walls of the glass rise to form a foam at the surface.

Examples are profuse in the industrial field. Over half of all chemical engineering is concerned with multiphase flows. Many industrial processes such as power generation, refrigeration, and distillation depend on evaporation and condensation cycles. The performance of desalination plants is limited by the 'state of the art' in two-phase technology. Steelmaking, paper manufacturing, and food processing all contain critical steps which depend on the proper functioning of multiphase devices. Many problems of air and water pollution are due to unwanted two-phase flows.

As a kind of typical two-phase flow, gas - liquid flow occurs in many applications. The motions of bubbles in a liquid as well as droplets in a conveying gas stream are examples of gas - liquid flows. Bubble columns are commonly used in several process industries. Atomization to generate small droplets for combustion is important in power generation systems. Steam-water flows in pipes and heat exchangers are very common in power systems such as fossil fuel plants and nuclear reactors. Gas - liquid flows in pipes can assume several different configurations ranging from bubbly flow to annular flow, in which there is a liquid layer on the wall and a droplet laden gaseous core flow.

1.2 Methods of Analysis

Two-phase flows obey all of the basic laws of fluid mechanics. The situations for two-phase flow are more complicated, however. The solution of the rigorous differential conservation equations is impractical, and a set of tractable conservation equations is needed instead, and to seek to solve these equations by the use of various simplifying assumptions. Following are the three typical assumptions:

1. the 'homogeneous' flow models

It is a simplest approach to the problem, where the two-phase flow is assumed to be a single-phase flow having pseudo properties arrived at by suitably weighting the properties of the individual phases.

2. the 'separated' flow models

In this approach the two-phases of the flow are considered to be artificially segregated. Two sets of basic equations can now be written, one for each phase. Alternatively, the equations can be combined. In either case information must be forthcoming about the area of the channel occupied by each phase (or alternatively, about the velocities of each phase) and about the frictional interactions with the channel wall. In the former case additional information concerning the frictional interaction between the phases is also required. This information is inserted into the basic equations, either from separate empirical relationships in which the void fraction and the wall shear stress are related to the primary variables, or on the basis of simplified models of the flow.

3. the 'flow pattern' models

In this more sophisticated approach the two phases are considered to be arranged in one of three or four definite prescribed geometries. These geometries are based on the various configurations or flow patterns found when a gas and a liquid flow together in a channel. The basic equations are solved within the framework of each of these idealized representations. In order to apply these models it is necessary to know when each should be used and be able to predict the transition from one pattern to another.

1.3 Notation

Before proceeding with the analysis of two-phase flow it will be necessary to define some of the relevant terminology. This section introduces the primary variables throughout the book and derives some simple relationships between them for one-dimensional flow. A certain familiarity with the simple relationships among some of the parameters will enable the analysis to be understood more rapidly.

The total mass flow rate is represented by the symbol M (kg/s). The total flow is the sum of individual flow rates. Thus,

$$M = M_l + M_g \tag{1-1}$$

The mass flow rate divided by the flow area is give the name 'mass velocity' or 'mass flux'. The total mass velocity (kg/m²s) across an area A and that of each phase is defined by

$$G = \frac{M}{A} \tag{1-2}$$

$$G_g = \frac{M_g}{A} \tag{1-3}$$

$$G_l = \frac{M_l}{A} \tag{1-4}$$

The volumetric flow rate is represented by the symbol Q (m³/s). The total volumetric rate of flow is obvious:

$$Q = Q_l + Q_g \tag{1-5}$$

Where

$$Q_l = \frac{M_l}{\rho_l} \tag{1-6}$$

$$Q_g = \frac{M_g}{\rho_g} \tag{1-7}$$

The **mass quality** is defined as the ratio of the gas flow rate to the total mass flow rate,

$$x = \frac{M_g}{M_g + M_l} = \frac{M_g}{M} \tag{1-8}$$

For a heated pipe, the so-called **equilibrium quality or thermodynamic quality** can be calculated by the heat balance

$$x = \frac{M_g}{M} = \frac{1}{h_{lg}}\left(\frac{4zq}{DG} - \Delta h_i\right) \tag{1-9}$$

Where h_{lg} is the latent heat of vaporization and Δh_i is the enthalpy of inlet subcooling.

In some cases it is convenient to express fluid flows in terms of a superficial velocity (or sometimes 'volumetric flux'), i. e. the volume flow rate of the phase divided by the total cross-sectional area. The superficial velocity of the gas is

$$j_g = \frac{Q_g}{A} = \frac{M_g}{\rho_g A} \tag{1-10}$$

And similarly, the superficial velocity of the liquid is

$$j_l = \frac{Q_l}{A} = \frac{M_l}{\rho_l A} \tag{1-11}$$

The **mixture superficial velocity** is defined as the sum of the superficial velocity of each phase,

$$j = j_g + j_l = \frac{Q_g + Q_l}{A} \tag{1-12}$$

The volumetric quality is defined as the ratio of the gas volumetric flow rate to the total volumetric flow rate,

$$\beta = \frac{Q_g}{Q_g + Q_l} = \frac{Q_g}{Q} \tag{1-13}$$

The ratio of the cross-sectional of the gas to the total cross-sectional area is known as the void fraction or voidage, which is a very important parameter in two-phase flow and is denoted by α,

$$\alpha = \frac{A_g}{A},\ 1 - \alpha = \frac{A_l}{A} \tag{1-14}$$

It is not difficult to deduce the relationship between quality x and void fraction α,

$$\alpha = \frac{1}{1 + \frac{1-x}{x}\frac{\rho_g}{\rho_l}\frac{u_g}{u_l}} = \frac{1}{1 + \frac{1-x}{x}\frac{\rho_g}{\rho_l}S} \qquad (1-15)$$

Where u_g and u_l represent the mean velocity of gas and liquid, respectively,

$$u_g = \frac{Q_g}{A_g} = \frac{M_g}{\rho_g A_g} = \frac{j_g}{\alpha} \qquad (1-16)$$

$$u_l = \frac{Q_l}{A_l} = \frac{M_l}{\rho_l A_l} = \frac{j_l}{1-\alpha} \qquad (1-17)$$

and S is the slip ratio which is defined as

$$S = \frac{u_g}{u_l} \qquad (1-18)$$

Drift velocity is defined as the difference between the mean velocity of gas or liquid and the superficial velocity,

$$u_{gj} = u_g - j \qquad (1-19)$$

$$u_{lj} = u_l - j \qquad (1-20)$$

Chapter 2 Flow Pattern and Flow Pattern Map

2.1 Introduction

The main complicating feature of two-phase flow arises from that there exist interfaces between two phases. The interfacial distribution varies with wide possibility depending on the flow condition. The types of interfacial distribution are conveniently classified into several categories, which are referred to as 'flow regime' or 'flow pattern'. The hydrodynamic behavior of two-phase flows is far more complicated than that of single-phase flow. The pressure drop, void fraction, or velocity distribution, etc. for instance, varies systematically with the observed flow pattern (or regime), just as in the case of a single-phase flow, whose behavior depends on whether the flow is in the laminar or turbulent regime.

The flow regime is the most important attribute of any two-phase flow problem. The behavior of a gas-liquid mixture, including many of the constitutive relations that are needed for the solution of two-phase conservation equations, depends strongly on the flow regimes. Methods for predicting the ranges of occurrence of the major two-phase flow regimes are thus useful, and often required, for the modeling and analysis of two-phase flow systems.

2.2 Flow Patterns in Vertical Flows

2.2.1 Flow patterns in vertical co-current flow

Consider a steady-state flow in a long tube with a constant low or moderate liquid flow rate, as shown in Fig. 2.1, where the flow may experience bubbly flow, slug flow, churn flow, wispy-annular flow and annular flow with the gas volumetric flow rate increasing gradually.

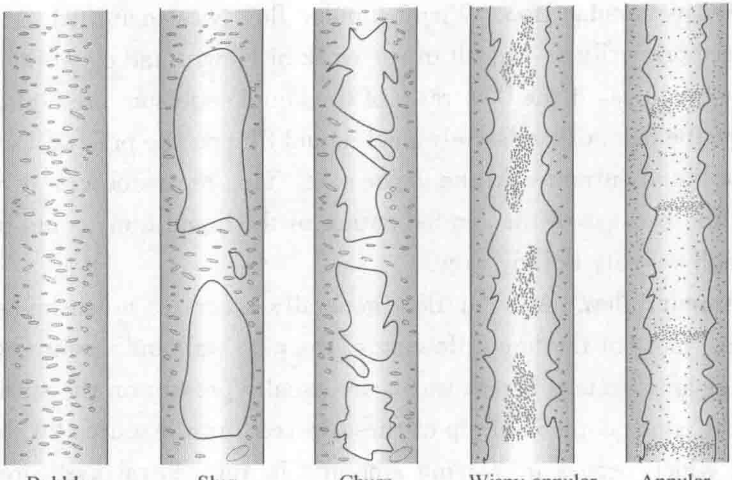

Fig. 2. 1 Flow patterns in vertical flow

(a) Bubbly flow. In bubbly flow the gas or vapor phase is distributed as discrete bubbles in a continuous liquid phase. At one extreme the bubbles may be small and spherical and at the other extreme the bubbles may be large with a spherical cap and a flat tail. In this latter state although the size of bubbles does not approach the diameter of the pipe, there may be some confusion with slug flow.

(b) Slug flow. In slug flow regime, bullet-shaped bubbles (Taylor bubbles) have approximately hemispherical caps and are separated from another by liquid slugs. These liquid slugs may or may not contain smaller entrained gas bubbles carried in the wake of the large bubble. A Taylor bubble nearly occupies the entire cross section and is separated from the wall by a thin liquid film. The length of the Taylor bubble may vary considerably.

(c) Churn flow. Sometimes referred to as semi-annular or slug-annular flow, churn flow is formed by the breakdown of the large vapor bubbles in slug flow. The gas or vapor flows in a more or less chaotic manner. The vapor shear on the liquid-vapor interface may approximate a value that just can balance the combined effects of the imposed pressure gradient and the downward gravitational force of the liquid film. Although the mean velocity of the liquid film is upward, the liquid experiences intermittent upward and downward motion, resulting in a highly agitated flow and irregular interface.

(d) Wispy-annular flow. Wispy-annular flow was identified as a distinct flow pattern primarily as a result of the work of Hewitt and co-workers. At intermediate qualities, if the flow rates of the liquid and vapor are high, the flow often takes the form of a relatively thick liquid film on the pipe wall with heavy 'wisps' of liquid entrained in the vapor core. This region occurs at high mass velocities and because of the aerated nature of the liquid film, could be confused with high velocity bubbly flow.

(e) Annular flow. Annular flow generally occurs at much higher quality levels, with most of the liquid flowing at the pipe wall and a continuous vapor core. Large amplitude coherent waves are usually present on the surface of the film and the continuous break up of these waves forms a source for droplet entrainment which occurs in varying amounts in the central gas core. In this case, as distinct from the wispy-annular pattern, the droplets are separate rather than agglomerated.

No satisfactory general method has yet been developed to allow the correct flow pattern to be designated for a specified local flow condition. There are a variety of reasons for this deficiency. One reason is that the flow pattern is more a subjective judgment than an objective measurement. A second primary reason is that although the flow pattern is a strong function of the local parameters such as the volumetric quality, other less easily defined variables such as the method of forming the two-phase flow, the amount of the departure from local hydrodynamic equilibrium, and the presence of trace contaminants in the system all considerably influence the particular pattern.

2.2.2 Flow patterns in vertical heated channels

When a phase change occurs as the two-phase mixture flows along the channel, different flow regimes are generally observed at different positions along its length. Fig. 2.2 shows a schematic representation of a vertical tubular channel heated by a uniform low heat flux and fed at its base with liquid just below the saturation temperature. Boiling may be initiated before the bulk liquid reaches the saturation temperature. At this initial stage of the boiling process, the void fraction is low and bubbly flow results.

As the vaporization process continues, with the production of more vapor the bubble population increases with length and coalescence takes place to form