Chapter 1

INTRODUCTION

1.1 Relevance of the problem

This book is intended to be a basic reference on the thermo-fluid dynamic theory of two-phase flow. The subject of two or multiphase flow has become increasingly important in a wide variety of engineering systems for their optimum design and safe operations. It is, however, by no means limited to today's modern industrial technology, and multiphase flow phenomena can be observed in a number of biological systems and natural phenomena which require better understandings. Some of the important applications are listed below.

Power Systems

Boiling water and pressurized water nuclear reactors; liquid metal fast breeder nuclear reactors; conventional power plants with boilers and evaporators; Rankine cycle liquid metal space power plants; MHD generators; geothermal energy plants; internal combustion engines; jet engines; liquid or solid propellant rockets; two-phase propulsors, etc.

Heat Transfer Systems

Heat exchangers; evaporators; condensers; spray cooling towers; dryers, refrigerators, and electronic cooling systems; cryogenic heat exchangers; film cooling systems; heat pipes; direct contact heat exchangers; heat storage by heat of fusion, etc.

Process Systems

Extraction and distillation units; fluidized beds; chemical reactors; desalination systems; emulsifiers; phase separators; atomizers; scrubbers; absorbers; homogenizers; stirred reactors; porous media, etc.

Transport Systems
Air-lift pump; ejectors; pipeline transport of gas and oil mixtures, of slurries, of fibers, of wheat, and of pulverized solid particles; pumps and hydrofoils with cavitations; pneumatic conveyors; highway traffic flows and controls, etc.

Information Systems
Superfluidity of liquid helium; conducting or charged liquid film; liquid crystals, etc.

Lubrication Systems
Two-phase flow lubrication; bearing cooling by cryogenics, etc.

Environmental Control
Air conditioners; refrigerators and coolers; dust collectors; sewage treatment plants; pollutant separators; air pollution controls; life support systems for space application, etc.

Geo-Meteorological Phenomena
Sedimentation; soil erosion and transport by wind; ocean waves; snow drifts; sand dune formations; formation and motion of rain droplets; ice formations; river floodings, landslides, and snowslides; physics of clouds, rivers or seas covered by drift ice; fallout, etc.

Biological Systems
Cardiovascular system; respiratory system; gastrointestinal tract; blood flow; bronchus flow and nasal cavity flow; capillary transport; body temperature control by perspiration, etc.

It can be said that all systems and components listed above are governed by essentially the same physical laws of transport of mass, momentum and energy. It is evident that with our rapid advances in engineering technology, the demands for progressively accurate predictions of the systems in interest have increased. As the size of engineering systems becomes larger and the operational conditions are being pushed to new limits, the precise understanding of the physics governing these multiphase flow systems is indispensable for safe as well as economically sound operations. This means a shift of design methods from the ones exclusively based on static experimental correlations to the ones based on mathematical models that can predict dynamical behaviors of systems such as transient responses and stabilities. It is clear that the subject of multiphase flow has immense importance in various engineering technology. The optimum design, the prediction of operational limits and, very often, the safe control of a great number of important systems depend upon the availability of realistic and accurate mathematical models of two-phase flow.

1.2 Characteristic of multiphase flow

Many examples of multiphase flow systems are noted above. At first glance it may appear that various two or multiphase flow systems and their physical phenomena have very little in common. Because of this, the tendency has been to analyze the problems of a particular system, component or process and develop system specific models and correlations of limited generality and applicability. Consequently, a broad understanding of the thermo-fluid dynamics of two-phase flow has been only slowly developed and, therefore, the predictive capability has not attained the level available for single-phase flow analyses.

The design of engineering systems and the ability to predict their performance depend upon both the availability of experimental data and of conceptual mathematical models that can be used to describe the physical processes with a required degree of accuracy. It is essential that the various characteristics and physics of two-phase flow should be modeled and formulated on a rational basis and supported by detailed scientific experiments. It is well established in continuum mechanics that the conceptual model for single-phase flow is formulated in terms of field equations describing the conservation laws of mass, momentum, energy, charge, etc. These field equations are then complemented by appropriate constitutive equations for thermodynamic state, stress, energy transfer, chemical reactions, etc. These constitutive equations specify the thermodynamic, transport and chemical properties of a specific constituent material.

It is to be expected, therefore, that the conceptual models for multiphase flow should also be formulated in terms of the appropriate field and constitutive relations. However, the derivation of such equations for multi-phase flow is considerably more complicated than for single-phase flow. The complex nature of two or multiphase flow originates from the existence of multiple, deformable and moving interfaces and attendant significant discontinuities of fluid properties and complicated flow field near the interface. By focusing on the interfacial structure and transfer, it is noticed that many of two-phase systems have a common geometrical structure. It is recalled that single-phase flow can be classified according to the structure of flow into laminar, transitional and turbulent flow. In contrast, two-phase flow can be classified according to the structure of interface into several major groups which can be called flow regimes or patterns such as separated flow, transitional or mixed flow and dispersed flow. It can be expected that many of two-phase flow systems should exhibit certain degree of physical similarity when the flow regimes are same. However, in general, the concept of two-phase flow regimes is defined based on a macroscopic volume or length scale which is often comparative to the system length scale. This implies that the concept of two-phase flow regimes and regime-dependent model require an introduction of a large length scale and associated limitations. Therefore, regime-dependent models may lead to an analysis that cannot mechanistically address the physics and phenomena occurring below the reference length scale.

For most two-phase flow problems, the local instant formulation based on the single-phase flow formulation with explicit moving interfaces encounters insurmountable mathematical and numerical difficulties, and therefore it is not a realistic or practical approach. This leads to the need of a macroscopic formulation based on proper averaging which gives a two-phase flow continuum formulation by effectively eliminating the interfacial discontinuities. The essence of the formulation is to take into account for the various multi-scale physics by a cascading modeling approach, bringing the micro and meso-scale physics into the macroscopic continuum formulation.

The above discussion indicates the origin of the difficulties encountered in developing broad understanding of multiphase flow and the generalized method for analyzing such flow. The two-phase flow physics are fundamentally multi-scale in nature. It is necessary to take into account these cascading effects of various physics at different scales in the two-phase flow formulation and closure relations. At least four different scales can be important in multiphase flow. These are 1) system scale, 2) macroscopic scale required for continuum assumption, 3) mesoscale related to local structures, and 4) microscopic scale related to fine structures and molecular transport. At the highest level, the scale is the system where system transients and component interactions are the primary focus. For example, nuclear reactor accidents and transient analysis requires specialized system analysis codes. At the next level, macro physics such as the structure of interface and the transport of mass, momentum and energy are addressed. However, the multiphase flow field equations describing the conservation principles require additional constitutive relations for bulk transfer. This encompasses the turbulence effects for momentum and energy as well as for interfacial exchanges for mass, momentum and energy transfer. These are meso-scale physical phenomena that require concentrated research efforts. Since the interfacial transfer rates can be considered as the product of the interfacial flux and the available interfacial area, the modeling of the interfacial area concentration is essential. In two-phase flow analysis, the void fraction and the interfacial area concentration represent the two fundamental first-order geometrical parameters and, therefore, they are closely related to two-phase flow regimes. However, the concept of the two-phase flow regimes is difficult to quantify mathematically at the local point because it is often defined at the scale close to the system scale.

This may indicate that the modeling of the changes of the interfacial area concentration directly by a transport equation is a better approach than the conventional method using the flow regime transitions criteria and regime-dependent constitutive relations for interfacial area concentration. This is particularly true for a three-dimensional formulation of two-phase flow. The next lower level of physics in multiphase flow is related to the local microscopic phenomena, such as: the wall nucleation or condensation; bubble coalescence and break-up; and entrainment and deposition.

1.3 Classification of two-phase flow

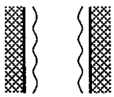
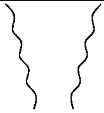
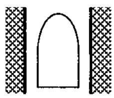
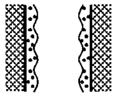
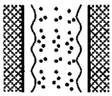
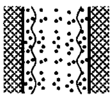
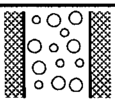
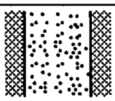
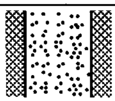
There are a variety of two-phase flows depending on combinations of two phases as well as on interface structures. Two-phase mixtures are characterized by the existence of one or several interfaces and discontinuities at the interface. It is easy to classify two-phase mixtures according to the combinations of two phases, since in standard conditions we have only three states of matters and at most four, namely, solid, liquid, and gas phases and possibly plasma (Pai, 1972). Here, we consider only the first three phases, therefore we have:

1. Gas-solid mixture;
2. Gas-liquid mixture;
3. Liquid-solid mixture;
4. Immiscible-liquid mixture.

It is evident that the fourth group is not a two-phase flow, however, for all practical purposes it can be treated as if it is a two-phase mixture.

The second classification based on the interface structures and the topographical distribution of each phase is far more difficult to make, since these interface structure changes occur continuously. Here we follow the standard flow regimes reviewed by Wallis (1969), Hewitt and Hall Taylor (1970), Collier (1972), Govier and Aziz (1972) and the major classification of Zuber (1971), Ishii (1971) and Kocamustafaogullari (1971). The two-phase flow can be classified according to the geometry of the interfaces into three main classes, namely, separated flow, transitional or mixed flow and dispersed flow as shown in Table 1-1.

Table 1-1. Classification of two-phase flow (Ishii, 1975)

Class	Typical regimes	Geometry	Configuration	Examples
Separated flows	Film flow		Liquid film in gas Gas film in liquid	Film condensation Film boiling
	Annular flow		Liquid core and gas film Gas core and liquid film	Film boiling Boilers
	Jet flow		Liquid jet in gas Gas jet in liquid	Atomization Jet condenser
Mixed or Transitional flows	Cap, Slug or Churn-turbulent flow		Gas pocket in liquid	Sodium boiling in forced convection
	Bubbly annular flow		Gas bubbles in liquid film with gas core	Evaporators with wall nucleation
	Droplet annular flow		Gas core with droplets and liquid film	Steam generator
	Bubbly droplet annular flow		Gas core with droplets and liquid film with gas bubbles	Boiling nuclear reactor channel
Dispersed flows	Bubbly flow		Gas bubbles in liquid	Chemical reactors
	Droplet flow		Liquid droplets in gas	Spray cooling
	Particulate flow		Solid particles in gas or liquid	Transportation of powder

Depending upon the type of the interface, the class of separated flow can be divided into plane flow and quasi-axisymmetric flow each of which can be subdivided into two regimes. Thus, the plane flow includes film and stratified flow, whereas the quasi-axisymmetric flow consists of the annular and the jet-flow regimes. The various configurations of the two phases and of the immiscible liquids are shown in Table 1-1.

The class of dispersed flow can also be divided into several types. Depending upon the geometry of the interface, one can consider spherical, elliptical, granular particles, etc. However, it is more convenient to subdivide the class of dispersed flows by considering the phase of the dispersion. Accordingly, we can distinguish three regimes: bubbly, droplet or mist, and particulate flow. In each regime the geometry of the dispersion can be spherical, spheroidal, distorted, etc. The various configurations between the phases and mixture component are shown in Table 1-1.

As it has been noted above, the change of interfacial structures occurs gradually, thus we have the third class which is characterized by the presence of both separated and dispersed flow. The transition happens frequently for liquid-vapor mixtures as a phase change progresses along a channel. Here too, it is more convenient to subdivide the class of mixed flow according to the phase of dispersion. Consequently, we can distinguish five regimes, i.e., cap, slug or churn-turbulent flow, bubbly-annular flow, bubbly annular-droplet flow and film flow with entrainment. The various configurations between the phases and mixtures components are shown in Table 1-1.

Figures 1-1 and 1-2 show typical air-water flow regimes observed in vertical 25.4 mm and 50.8 mm diameter pipes, respectively. The flow regimes in the first, second, third, fourth, and fifth figures from the left are bubbly, cap-bubbly, slug, churn-turbulent, and annular flows, respectively. Figure 1-3 also shows typical air-water flow regimes observed in a vertical rectangular channel with the gap of 10 mm and the width of 200 mm. The flow regimes in the first, second, third, and fourth figures from the left are bubbly, cap-bubbly, churn-turbulent, and annular flows, respectively. Figure 1-4 shows inverted annular flow simulated adiabatically with turbulent water jets, issuing downward from large aspect ratio nozzles, enclosed in gas annuli (De Jarlais et al., 1986). The first, second, third and fourth images from the left indicate symmetric jet instability, sinuous jet instability, large surface waves and skirt formation, and highly turbulent jet instability, respectively. Figure 1-5 shows typical images of inverted annular flow at inlet liquid velocity 10.5 cm/s, inlet gas velocity 43.7 cm/s (nitrogen gas) and inlet Freon-113 temperature 23 °C with wall temperature of near 200 °C (Ishii and De Jarlais, 1987). Inverted annular flow was formed by introducing the test fluid into the test section core through thin-walled, tubular nozzles coaxially centered within the heater quartz tubing, while vapor or gas is introduced in the annular gap between the liquid nozzle and the heated quartz tubing. The absolute vertical size of each image is 12.5 cm. The visualized elevation is higher from the left figure to the right figure.

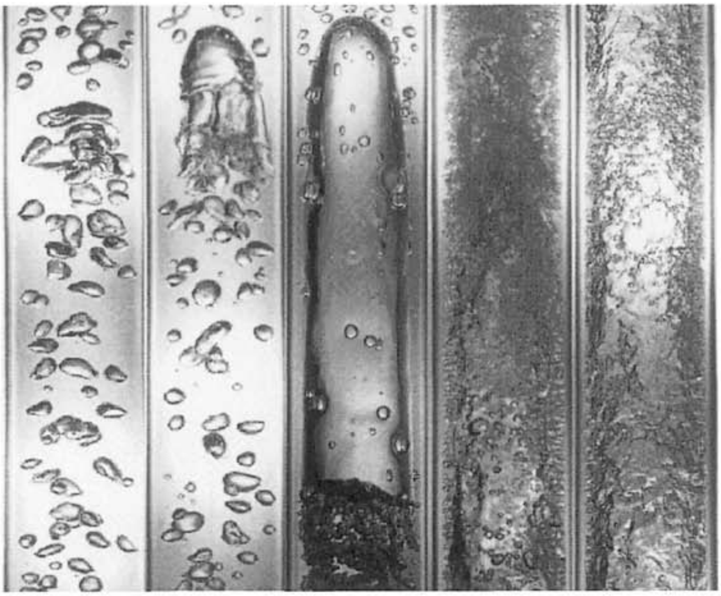


Figure 1-1. Typical air-water flow images observed in a vertical 25.4 mm diameter pipe

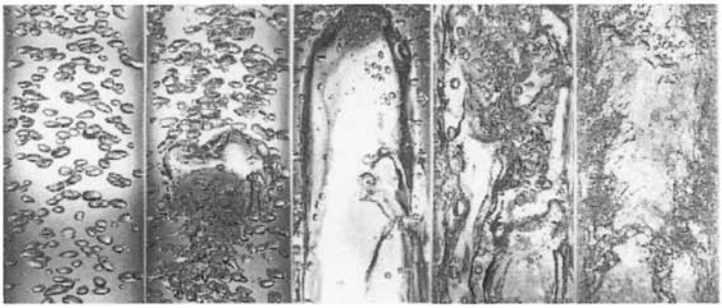


Figure 1-2. Typical air-water flow images observed in a vertical 50.8 mm diameter pipe

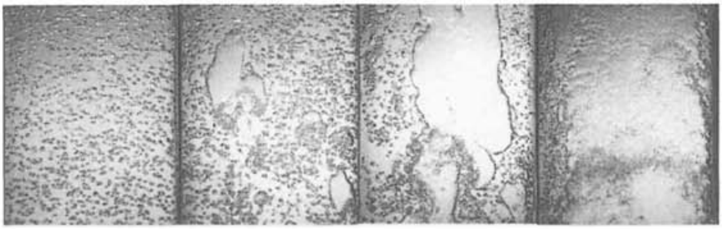


Figure 1-3. Typical air-water flow images observed in a rectangular channel of 200 mm × 10 mm

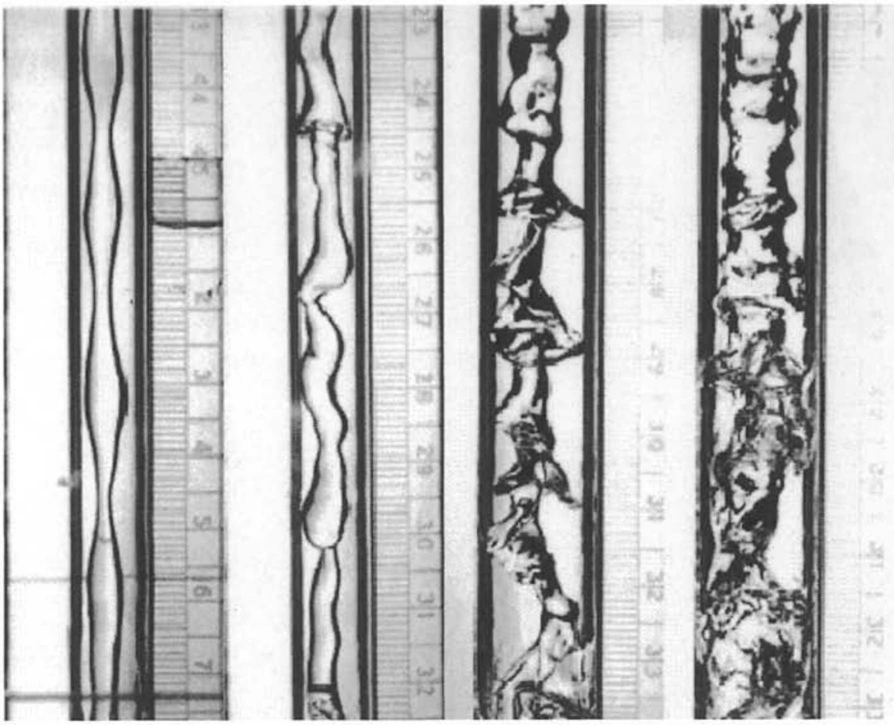


Figure 1-4. Typical images of simulated air-water inverted annular flow (It is cocurrent down flow)

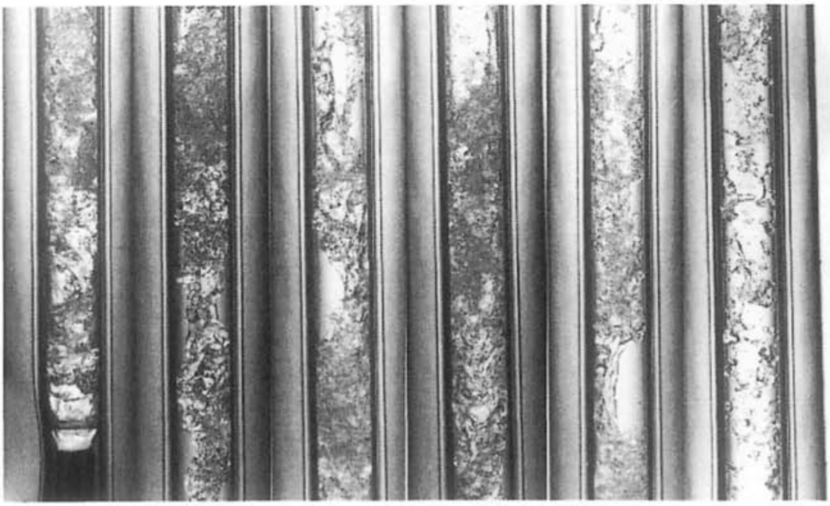


Figure 1-5. Axial development of Inverted annular flow (It is cocurrent up flow)

1.4 Outline of the book

The purpose of this book is to present a detailed two-phase flow formulation that is rationally derived and developed using mechanistic modeling. This book is an extension of the earlier work by the author (Ishii, 1975) with special emphasis on the modeling of the interfacial structure with the interfacial area transport equation and modeling of the hydrodynamic constitutive relations. However, special efforts are made such that the formulation and mathematical models for complex two-phase flow physics and phenomena are realistic and practical to use for engineering analyses. It is focused on the detailed discussion of the general formulation of various mathematical models of two-phase flow based on the conservation laws of mass, momentum, and energy. In Part I, the foundation of the two-phase flow formulation is given as the local instant formulation of the two-phase flow based on the single-phase flow continuum formulation and explicit existence of the interface dividing the phases. The conservation equations, constitutive laws, jump conditions at the interface and special thermo-mechanical relations at the interface to close the mathematical system of equations are discussed.

Based on this local instant formulation, in Part II, macroscopic two-phase continuum formulations are developed using various averaging techniques which are essentially an integral transformation. The application of time averaging leads to general three-dimensional formulation, effectively eliminating the interfacial discontinuities and making both phases co-existing continua. The interfacial discontinuities are replaced by the interfacial transfer source and sink terms in the averaged differential balance equations

Details of the three-dimensional two-phase flow models are presented in Part III. The two-fluid model, drift-flux model, interfacial area transport, and interfacial momentum transfer are major topics discussed. In Part IV, more practical one-dimensional formulation of two-phase flow is given in terms of the two-fluid model and drift-flux model. It is planned that a second book will be written for many practical two-phase flow models and correlations that are necessary for solving actual engineering problems and the experimental base for these models.