Thermo-Fluid Dynamics of Two-Phase Flow
Thermo-Fluid Dynamics of Two-Phase Flow

Second Edition

Springer
Dedication

This book is dedicated to our parents and wives.
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Preface

This book is intended to be an introduction to the theory of thermo-fluid dynamics of two-phase flow for graduate students, scientists and practicing engineers seriously involved in the subject. It can be used as a text book at the graduate level courses focused on the two-phase flow in Nuclear Engineering, Mechanical Engineering and Chemical Engineering, as well as a basic reference book for two-phase flow formulations for researchers and engineers involved in solving multiphase flow problems in various technological fields.

The principles of single-phase flow fluid dynamics and heat transfer are relatively well understood, however two-phase flow thermo-fluid dynamics is an order of magnitude more complicated subject than that of the single-phase flow due to the existence of moving and deformable interface and its interactions with the two phases. However, in view of the practical importance of two-phase flow in various modern engineering technologies related to nuclear energy, chemical engineering processes and advanced heat transfer systems, significant efforts have been made in recent years to develop accurate general two-phase formulations, mechanistic models for interfacial transfer and interfacial structures, and computational methods to solve these predictive models.

A strong emphasis has been put on the rational approach to the derivation of the two-phase flow formulations which represent the fundamental physical principles such as the conservation laws and constitutive modeling for various transfer mechanisms both in bulk fluids and at interface. Several models such as the local instant formulation based on the single-phase flow model with explicit treatment of interface and the macroscopic continuum formulations based on various averaging methods are presented and
discussed in detail. The macroscopic formulations are presented in terms of
the two-fluid model and drift-flux model which are two of the most accurate
and useful formulations for practical engineering problems.

The change of the interfacial structures in two-phase flow is dynamically
modeled through the interfacial area transport equation. This is a new
approach which can replace the static and inaccurate approach based on the
flow regime transition criteria. The interfacial momentum transfer models
are discussed in great detail, because for most two-phase flow, thermo-fluid
dynamics are dominated by the interfacial structures and interfacial
momentum transfer. Some other necessary constitutive relations such as the
turbulence modeling, transient forces and lift forces are also discussed.

Mamoru Ishii, Ph.D.

Takashi Hibiki, Ph.D.
Foreword

takes a major step forward in our quest for understanding fluids as they metamorphose through change of phase, properties and structure. Like Janus, the mythical Roman God with two faces, fluids separating into liquid and gas, each state sufficiently understood on its own, present a major challenge to the most astute and insightful scientific minds when it comes to deciphering their dynamic entanglement.

The challenge stems in part from the vastness of scale where two phase phenomena can be encountered. Between the microscopic -scale of molecular dynamics and deeply submerged modeling assumptions and the -scale of measurements, there is a -scale as broad as it is nebulous and elusive. This is the scale where everything is in a permanent state of exchange, a Heraclitean state of flux, where nothing ever stays the same and where knowledge can only be achieved by firmly grasping the underlying principles of things.

The subject matter has sprung from the authors’ own firm grasp of fundamentals. Their bibliographical contributions on two-phase principles reflect a scientific tradition that considers theory and experiment a duality as fundamental as that of appearance and reality. In this it differs from other topical works in the science of fluids. For example, the leading notion that runs through two-phase flow is that of interfacial velocity. It is a concept that requires, amongst other things, continuous improvements in both modeling and measurement. In the -scale, this gives rise to new science of the interface which, besides the complexity of its problems and the fuzziness of its structure, affords ample scope for the creation of elegant, parsimonious formulations, as well as promising engineering applications.
The two-phase flow theoretical discourse and experimental inquiry are closely linked. The synthesis that arises from this connection generates immense technological potential for measurements informing and validating dynamic models and conversely. The resulting technology finds growing utility in a broad spectrum of applications, ranging from next generation nuclear machinery and space engines to pharmaceutical manufacturing, food technology, energy and environmental remediation.

This is an intriguing subject and its proper understanding calls for exercising the rigorous tools of advanced mathematics. The authors, with enormous care and intellectual affection for the subject reach out and invite an inclusive audience of scientists, engineers, technologists, professors and students.

It is a great privilege to include the Thermo-Fluid Dynamics of Two-Phase Flow in the series Smart Energy Systems: Nanowatts to Terawatts. This is work that will stand the test of time for its scientific value as well as its elegance and aesthetic character.

Lefteri H. Tsoukalas, Ph.D.
The authors would like to express their sincere appreciation to those persons who have contributed in preparing this book. Professors N. Zuber and J. M. Delhaye are acknowledged for their early input and discussions on the development of the fundamental approach for the theory of thermo-fluid dynamics of multiphase flow. We would like to thank Dr. F. Eltawila of the U.S. Nuclear Regulatory Commission for long standing support of our research focused on the fundamental physics of two-phase flow. This research led to some of the important results included in the book. Many of our former students such as Professors Q. Wu, S. Kim and X. Sun and Drs. X.Y. Fu, S. Paranjape, B. Ozar, Y. Liu and D. Y. Lee contributed significantly through their Ph.D. thesis research. Current Ph.D. students J. Schlegel, S. W. Chen, S. Rassame, S. Miwa and C. S. Brooks deserve many thanks for checking the manuscript. The authors thank Professor Lefteri Tsoukalas for inviting us to write this book under the new series, “Smart Energy Systems: Nanowatts to Terawatts”.

Acknowledgments
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.

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 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.

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

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

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

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

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.

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 multiphase 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.
### Classification of two-phase flow (Ishii, 1975)

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

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
1. Introduction

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

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. Two-fluid model considering structural materials in a control volume, namely, porous media formulation is also presented.
The singular characteristic of two-phase or of two immiscible mixtures is the presence of one or several interfaces separating the phases or components. Examples of such flow systems can be found in a large number of engineering systems as well as in a wide variety of natural phenomena. The understanding of the flow and heat transfer processes of two-phase systems has become increasingly important in nuclear, mechanical and chemical engineering, as well as in environmental and medical science.

In analyzing two-phase flow, it is evident that we first follow the standard method of continuum mechanics. Thus, a two-phase flow is considered as a field that is subdivided into single-phase regions with moving boundaries between phases. The standard differential balance equations hold for each subregion with appropriate jump and boundary conditions to match the solutions of these differential equations at the interfaces. Hence, in theory, it is possible to formulate a two-phase flow problem in terms of the local instant variable, namely, \( F = F(x,t) \). This formulation is called a local instant formulation in order to distinguish it from formulations based on various methods of averaging.

Such a formulation would result in a multiboundary problem with the positions of the interface being unknown due to the coupling of the fields and the boundary conditions. Indeed, mathematical difficulties encountered by using this local instant formulation can be considerable and, in many cases, they may be insurmountable. However, there are two fundamental importances in the local instant formulation. The first importance is the to study the separated flows such as film, stratified, annular and jet flow, see Table 1-1. The formulation can be used there to study pressure drops, heat transfer, phase changes, the dynamic and stability of an interface, and the critical heat flux. In addition to the above applications, important examples of when this formulation can be used
include: the problems of single or several bubble dynamics, the growth or
collapse of a single bubble or a droplet, and ice formation and melting.

The second importance of the local instant formulation is as a
using various
averaging. When each subregion bounded by interfaces can be considered
as a continuum, the local instant formulation is mathematically rigorous.
Consequently, two-phase flow models should be derived from this
formulation by proper averaging methods. In the following, the general
formulation of two-phase flow systems based on the local instant variables is
presented and discussed. It should be noted here that the balance equations
for a single-phase one component flow were firmly established for some
time (Truesdell and Toupin, 1960; Bird et al, 1960). However, the axiomatic
construction of the general constitutive laws including the equations of state
was put into mathematical rigor by specialists (Coleman, 1964; Bowen,
1973; Truesdell, 1969). A similar approach was also used for a single-phase
diffusive mixture by Muller (1968).

Before going into the detailed derivation and discussion of the local
instant formulation, we review the method of mathematical physics in
connection with the continuum mechanics. The next diagram shows the
basic procedures used to obtain a mathematical model for a physical system.

As it can be seen from the diagram, a physical system is first replaced by a
mathematical system by introducing mathematical concepts, general axioms
and constitutive axioms. In the continuum mechanics they correspond to
variables, field equations and constitutive equations, whereas at the singular
surface the mathematical system requires the interfacial conditions. The
latter can be applied not only at the interface between two phases, but also at
the outer boundaries which limit the system. It is clear from the diagram that
the continuum formulation consists of three essential parts, namely: the
derivations of field equations, constitutive equations, and interfacial
conditions.

Now let us examine the basic procedure used to solve a particular
problem. The following diagram summarizes the standard method. Using
the continuum formulation, the physical problem is represented by idealized
boundary geometries, boundary conditions, initial conditions, field and
constitutive equations. It is evident that in two-phase flow systems, we have interfaces within the system that can be represented by general interfacial conditions. The solutions can be obtained by solving these sets of differential equations together with some idealizing or simplifying assumptions. For most problems of practical importance, experimental data also play a key role. First, experimental data can be taken by accepting the model, indicating the possibility of measurements. The comparison of a solution to experimental data gives feedback to the model itself and to the various assumptions. This feedback will improve both the methods of the experiment and the solution. The validity of the model is shown in general by solving a number of simple physical problems.

The continuum approach in single-phase thermo-fluid dynamics is widely accepted and its validity is well proved. Thus, if each subregion bounded by interfaces in two-phase systems can be considered as continuum, the validity of local instant formulation is evident. By accepting this assumption, we derive and discuss the field equations, the constitutive laws, and the interfacial conditions. Since an interface is a singular case of the continuous field, we have two different conditions at the interface. The balance at an interface that corresponds to the field equation is called a jump condition. Any additional information corresponding to the constitutive laws in space, which are also necessary at interface, is called an interfacial boundary condition.

1.1 Single-phase flow conservation equations

1.1.1 General balance equations

The derivation of the differential balance equation is shown in the following diagram. The general integral balance can be written by introducing the fluid density $\rho_k$, the efflux $J$ and the body source $\phi_k$ of any quantity $\psi_k$ defined for a unit mass. Thus we have
\[
\frac{d}{dt} \int_{V_m} \rho_k \psi_k \, dV = -\oint_{A_m} \mathbf{n}_k \cdot \mathbf{j}_k \, dA + \int_{V_m} \rho_k \phi_k \, dV \tag{2-1}
\]

where \( V_m \) is a material volume with a material surface \( A_m \). It states that the time rate of change of \( \rho_k \psi_k \) in \( V_m \) is equal to the influx through \( A_m \) plus the body source. The subscript \( k \) denotes the \( \text{th} \)-phase. If the functions appearing in the Eq.(2-1) are sufficiently smooth such that the Jacobian transformation between material and spatial coordinates exists, then the familiar differential form of the balance equation can be obtained. This is done by using the Reynolds transport theorem (Aris, 1962) expressed as

\[
\frac{d}{dt} \int_{V_m} \mathbf{F}_k \, dV = \int_{V_m} \frac{\partial \mathbf{F}_k}{\partial t} \, dV + \oint_{A_m} \mathbf{F}_k \mathbf{v}_k \cdot \mathbf{n} \, dA \tag{2-2}
\]

where \( \mathbf{v} \) denotes the velocity of a fluid particle. The Green’s theorem gives a transformation between a certain volume and surface integral, thus

\[
\int_V \nabla \cdot \mathbf{F}_k \, dV = \oint_A \mathbf{n} \cdot \mathbf{F}_k \, dA. \tag{2-3}
\]

Hence, from Eqs.(2-2) and (2-3) we obtain

\[
\frac{d}{dt} \int_{V_m} \mathbf{F}_k \, dV = \int_{V_m} \left[ \frac{\partial \mathbf{F}_k}{\partial t} + \nabla \cdot (\mathbf{v}_k \mathbf{F}_k) \right] \, dV. \tag{2-4}
\]

Furthermore, we note that the Reynolds transport theorem is a special case of Leibnitz rule given by

\[
\frac{d}{dt} \int_V \mathbf{F}_k \, dV = \int_V \frac{\partial \mathbf{F}_k}{\partial t} \, dV + \int_A \mathbf{F}_k \mathbf{u} \cdot \mathbf{n} \, dA \tag{2-5}
\]
where \((\ )\) is an arbitrary volume bounded by \((\ )\) and \(u \cdot n\) is the surface displacement velocity of \((\ )\).

In view of Eqs.(2-1), (2-3) and (2-4) we obtain a differential balance equation

\[
\frac{\partial \rho_k \psi_k}{\partial t} + \nabla \cdot (\psi_k \rho_k \psi_k) = -\nabla \cdot J_k + \rho_k \phi_k. \tag{2-6}
\]

The first term of the above equation is the time rate of change of the quantity per unit volume, whereas the second term is the rate of convection per unit volume. The right-hand side terms represent the surface flux and the volume source.

### 1.1.2 Conservation equation

The conservation of mass can be expressed in a differential form by setting

\[
\psi_k = 1, \quad \phi_k = 0, \quad J_k = 0 \tag{2-7}
\]

since there is no surface and volume sources of mass with respect to a fixed mass volume. Hence from the general balance equation we obtain

\[
\frac{\partial \rho_k}{\partial t} + \nabla \cdot (\rho_k \nu_k) = 0. \tag{2-8}
\]

The conservation of momentum can be obtained from Eq.(2-6) by introducing the surface stress tensor \(T\) and the body force \(g_k\), thus we set

\[
\psi_k = v_k, \quad J_k = -T_k = p_k I - \tau_k, \quad \phi_k = g_k \tag{2-9}
\]

where \(I\) is the unit tensor. Here we have split the stress tensor into the pressure term and the viscous stress \(\tau\). In view of Eq.(2-6) we have

\[
\frac{\partial \rho_k \nu_k}{\partial t} + \nabla \cdot (\rho_k \nu_k \nu_k) = -\nabla p_k + \nabla \cdot \tau_k + \rho_k g_k. \tag{2-10}
\]