Applied Multiphase Flow in Pipes and Flow Assurance
Oil and Gas Production
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Acknowledgments

The authors gratefully acknowledge the petroleum engineering programs at Kuwait University and the University of Tulsa for their support during the preparation of this textbook. As we taught production and design classes at these universities, it became increasingly apparent that an undergraduate textbook that includes modern multiphase flow in pipes technology and its role in flow assurance of production systems simply did not exist.

Much of the technology for predicting the behavior of multiphase flow in pipes and selected areas of flow assurance has been developed over the past 40 years by graduate students, faculty, and staff of the Tulsa University Fluid Flow Projects (TUFFP). The authors gratefully acknowledge the tremendous support of the 80 domestic and international oil and gas production, service, consulting, and software companies and government agencies that provided TUFFP funding for this technology development.

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This textbook is dedicated to Al-Safran’s parents and Brill’s family.
Preface

Why This Book?
Since there are several books available on multiphase flow in oil and natural gas production, why have we written this textbook? Existing books fall into two groups: older books, which miss the recent advancements in multiphase flow, and newer books, which focus on the complex mathematical formulations of recent multiphase flow modeling and are not appropriate for undergraduate students. This textbook responds to the need for a more current source that is simple to read and understand and also presents recent advancements and applications of multiphase flow in production engineering. The main characteristics of this textbook are:

• A current, yet application-focused and simple-to-read textbook on multiphase flow in pipes.
• A book to equip petroleum engineers with an appropriate understanding of multiphase flow in pipes necessary to efficiently use the steady-state simulators available in the industry.
• A book that focuses on the fundamental physics of multiphase flow and provides simplified mathematical models, which makes it a practical book for undergraduate petroleum engineering students and practicing engineers.

Central Idea
The central idea of this textbook is to convey the process of designing and operating the components of a petroleum production system that involve multiphase flow, as shown in the inner circle of Fig. 1. This requires determining the multiphase flow pattern, liquid volume (holdup), and pressure gradient along the piping system, as shown in the middle circle of Fig. 1. The input parameters to determine these three variables are the in-situ fluid physical properties and flow rates. This textbook takes the reader from the outer circle inward in a step-by-step and simple approach, providing the conceptual understanding and mathematical tools to carry out a design and/or operational study.
Nomenclature and Units

Much of the technology for multiphase flow in pipes was developed outside of the petroleum industry. Consequently, there will be some confusion in the nomenclature because many of the important publications have different nomenclature and terminology. Occasionally, it will be necessary to define new symbols or deviate from those recommended by SPE. As much as possible, this textbook uses the standard symbols adopted in SPE (1986).

SI is the official abbreviation, all languages, for the International System of Units (Le Système International d’Unités). However, engineering units (SPE 1984) still are used frequently in many parts of the world, as well as throughout this textbook. Appendix A of this book lists the nomenclature, fundamental dimensions, and SI and/or engineering systems of units of the variables.

Organization

Predicting flow behavior when multiphase flow occurs in wells and pipelines requires an understanding of concepts that are not part of the curriculum in most engineering disciplines. Before multiphase flow technology can be mastered, one must first have an adequate knowledge of single-phase flow fluid mechanics, vapor/liquid equilibrium (VLE), and fluid physical properties for multicomponent hydrocarbon systems. Thus, a significant part of this textbook will be devoted to a review of these important topics.

Chapter 1 starts with the basic definition of multiphase flow, followed by a brief description of the significance of multiphase flow during the production and transportation of oil and gas. The overall production system is presented, together with concepts that must be considered by a production engineer. The future outlook of multiphase flow technology is then presented. A brief review of the history of multiphase flow is presented in which some landmark publications are identified that had a lasting influence on our understanding of the total system involved in flowing fluids from the reservoir to surface storage and processing facilities.

Chapter 2 concentrates on a review of important single-phase, steady-state flow concepts for both incompressible Newtonian and compressible fluids. A description of single-phase non-Newtonian fluid flow is also presented.

Chapter 3 presents homogeneous two-phase flow in pipes. It starts with a physical description, followed by calculation of homogeneous mixture properties and pressure gradient. The authors present several applications of homogeneous two-phase flow with practical examples. A brief introduction of the drift flux model is presented at the end of Chapter 3.

Chapters 4 and 5 are the main chapters of this textbook and present nonhomogeneous, two-phase flow in pipelines and wells, respectively. These chapters start with physical descriptions of the slippage phenomenon and flow pattern, which are followed by flow pattern, liquid holdup, and pressure gradient predictions using both empirical and mechanistic modeling approaches.

In Chapter 6, the authors present the physical and theoretical aspects of two-phase flow through restrictions and piping components for both homogeneous and nonhomogeneous flows. The chapter begins with the physical concepts of single- and two-phase flow through chokes, followed by flow-regime-dependent empirical and theoretical predictions. Pressure drop and flow rate across chokes for homogeneous and nonhomogeneous flow are then discussed and shown by examples.

Chapter 7 presents a simple approach for single-phase and homogeneous two-phase heat transfer in a production system. This chapter is considered introductory material for multiphase flow assurance.

Chapter 8 is a detailed presentation of flow assurance that includes the definition, significance, types, causes, predictions, and remedies of the phenomena. Chapter 8 concludes with a presentation of the integrated flow assurance work flow process, which summarizes the entire chapter. Several examples are presented throughout the chapter to demonstrate the solution procedures of the presented models.

Chapter 9 is dedicated to the Tulsa University Fluid Flow Projects’ unified mechanistic model. The chapter highlights the differences between the comprehensive mechanistic models presented in Chapters 4 and 5, followed by the theoretical features of the unified model. The calculation procedure of the unified model is demonstrated in three long-hand solved examples of horizontal and vertical flows.

Chapter 10 combines all material covered in previous chapters into a chapter on the overall production system. The chapter concludes with a comprehensive design example problem.

Chapter 11 is an introduction to transient multiphase flow in pipes. In this chapter, the concepts and application of transient flow are presented. A comparison between steady-state and transient flows is also presented, and a guidance is provided on when to use a steady-state solution to approximate a transient event. The chapter ends with a simplified transient modeling approach and a description of two commercial, transient, multiphase flow simulators used in the oil and gas industry.

Appendix A lists the nomenclature used in this book. Appendices B and C contain methods to predict fluid physical properties and in-situ volumetric flow rates using black-oil and compositional models, respectively. Appendices B and C contain example problems to demonstrate the solution procedures.
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Chapter 1

Introduction to Multiphase Flow in Pipes

1.1 Definition of Multiphase Flow

Multiphase flow is the area of fluid mechanics that deals with the simultaneous flow of two or more immiscible phases of matter (gas, liquid, or solid). Although this phenomenon may occur in many industrial applications, this textbook focuses on the application of multiphase pipe flow in oil and natural gas production systems, specifically wells, surface flowlines, and system restrictions such as wellhead chokes. In this book, the terms “multiphase” and “two-phase” are used interchangeably.

1.2 Significance of Multiphase Pipe Flow in Oil and Gas Production

Multiphase flow technology has become increasingly important for the economic transportation of well streams from the reservoir to processing facilities. Multiphase flow is a common occurrence in oil and gas production in wells and transportation through pipelines.

1.2.1 Wells. As the pressure drops in production tubing because of fluid flow and reduction of hydrostatic head, dissolved gas in the oil evolves, forming a gas/liquid two-phase flow. In addition to oil and gas phases, produced water and solids, such as sand, introduce multiphase flow in the well tubing, which further complicates the flow behavior and characteristics. Furthermore, as the temperature drops going up the well, dissolved solids may precipitate, adding a solid phase to the flow stream, which may be either deposited within or transported along the well tubing. In the case of gas lift wells, a gas phase is injected into the tubing, causing two-phase flow. Horizontal well production exhibits a complex, undulated multiphase flow with complex fluid influx geometry, making multiphase flow even more challenging.

1.2.2 Pipelines. In offshore fields, produced fluids are transported to shore through long, large-diameter export pipelines for subsequent separation and processing. Tiebacks are often long pipelines that transport untreated produced fluids from marginal fields to an existing platform. These pipeline systems almost always exhibit multiphase flow. Onshore flowlines and export pipelines are multiphase flow systems that require proper design and operation for safe and economic business. Accurate prediction of flow pattern, liquid holdup, pressure drop, and flow characteristics along these pipeline systems is essential to enhance not only pipeline design, sizing, and routing, but also design of downstream separation and processing facilities to ensure safe and economic business operation (see Example 1.1).

1.2.3 Wellhead Chokes. Wellhead chokes and other restrictions are integral parts of an oil and gas production system. Multiphase flow across these restrictions is common and complex. The diversity of the flow through restrictions can cause critical or subcritical, as well as homogeneous or nonhomogeneous, multiphase flow. Predicting the flow regime (i.e., critical vs. subcritical) and the pressure drop is crucial for estimating and controlling the system flow rate. In addition, restrictions can impose flow assurance problems, among them formation of emulsions, deposition of solids as a result of sudden cooling, and erosion of pipe caused by high velocities during flow through restrictions.
1.2.4 Other System Components. Recent in-line technologies such as multiphase flowmeters, multiphase flow pumps, water knockout systems, and gas/liquid compact cyclones (GLCCs) have become important parts of the production system, especially in mature fields. Predicting multiphase flow characteristics upstream of these devices is critical for their efficiency and integrity. In addition, understanding the flow behavior inside internal parts improves future design and reliability.

1.3 Petroleum Production System

The petroleum production system consists of two main parts—namely, the porous/permeable rock system (reservoir) and the piping system. The reservoir is where the hydrocarbons are stored, and the piping system is the means to transport the reservoir fluids from the reservoir to a processing facility. **Fig. 1.1** shows a schematic of the production system with the following primary components:

- Reservoir: porous and permeable rock contains the hydrocarbons.
- Wellbore: vertical, deviated, or horizontal pipe connects the reservoir to the surface.
- Wellhead: combination of valves and chokes controls the flow.
- Flowline: horizontal and slightly inclined pipe transports reservoir fluids.
- Separator: large vessel separates reservoir fluids.

Secondary components such as a gravel pack, a subsurface safety valve, and others may sometimes exist. Export pipelines (not shown in Fig. 1.1) are single-phase or two-phase large-diameter pipelines used to carry processed fluids from the processing facility to a final destination, such as a chemical processing plant or export facility. This book covers multiphase flow in the piping components of the production system—namely, in the wellbore tubing, flowline/pipeline, and wellhead choke.

In the production system, fluids entering the wellbore from the reservoir can range from an undersaturated oil to a single-phase gas. Free water can accompany the fluids as a result of water coning, waterflooding, production of interstitial water, or water condensing in the well. Alternatively, a free-gas saturation in an oil reservoir can result...
in a gas/liquid mixture entering the well. Retrograde condensation can result in hydrocarbon liquids condensing in a gas/condensate reservoir so that a gas/liquid mixture again enters the wellbore. Even when single-phase gas or liquid flow exists near the bottom of a well, multiphase flow can occur throughout most of the wellbore. This is because of the evolution of gas from oil or the condensation of gas with reduction of pressure and temperature as the fluids flow up the well.

Although many of the wells drilled on land tend to be nearly vertical, current trends are toward pad drilling and horizontal wells. Wells drilled offshore and in other hostile environments such as the Arctic are normally directional or deviated. Inclination angles can vary from vertical near the surface to horizontal near the production zone. Flow rates of gas, oil, and water vary widely. Tubing diameters can be as small as 0.0254 m (1 in.) or as large as 0.2286 m (9 in.). Flow can also occur in a casing/tubing annulus. Depths can range from a few hundred meters to more than 6,000 m (≈20,000 ft). Pressures can be as small as a few hundred kPa or as high as 150 MPa (≈22,000 psia). Temperatures can be greater than 200°C (≈400°F) or approach the freezing point of water. Oil viscosities in wellbores can be less than 0.001 Pa·s (1 cp) or greater than 10 Pa·s (10,000 cp).

Fluids entering the wellbore often flow through a complicated well-completion region consisting of perforations, fractures, and gravel packs. The effect of this region must be included when coupling the well to the reservoir through inflow performance relationship (IPR) procedures. Most wells contain some type of well-control device that requires produced fluids to flow through a restriction. This can vary from a bottomhole choke to a remotely controlled, variable-size surface choke. Wells can be produced by artificial-lift mechanisms involving a submersible pump or gas injection.

The broad variations in flow variables encountered in producing wells has made the development of prediction methods much more difficult. Techniques that work for gas/condensate wells do not necessarily work for oil wells. Assumptions that are valid for some wells are totally invalid for others.

1.4 Role of Production Engineer

In general, the role of a production engineer in the petroleum industry is twofold: to safely and economically design a new production system; and/or, to operate and optimize an existing one. In both cases, the ultimate objective of the production engineer is to maximize profit by optimizing flow rate in a safe environment. To achieve this goal, an accurate prediction of flow behavior and characteristics along the production system must be determined a priori. The three main flow behavior parameters that the production engineer should predict along the production system on which most of the design and operation aspects depend are

- Flow pattern
- Pressure gradient
- Liquid volume (holdup)

Prediction of the foregoing flow parameters (detailed in subsequent chapters), coupled with both proper understanding of the flow behavior and engineering sense and intuition, can lead to an optimal flow rate, maximum economic profit, and safe operation. The following example illustrates the importance of predicting the foregoing flow parameters and their relationship to pipeline and separation facility design.

Example 1.1—Two-Phase Pipeline Design. A production engineer is asked to design a two-phase pipeline to transport 50 million std m$^3$/d of gas with certain liquid loadings from an offshore platform to an onshore processing facility at 7-MPa arrival pressure (Olieamens 1994). The design should consider the following criteria:

- Delivery of 50 million std m$^3$/d of gas at 7-MPa arrival pressure
- Minimum capital cost (CAPEX), minimum operating cost (OPEX), and optimized net present value (NPV)
- Environmentally safe operation

Solution. The production engineer calculated the following parameters along the pipeline:

- Flow pattern
- Pressure gradient
- Liquid volume

Figs. 1.2 and 1.3 illustrate the pressure gradient and liquid volume along a pipeline, respectively. Calculations were performed for three different pipeline diameters to help select the optimum pipeline size. Note that Fig. 1.2 suggests selection of the largest pipeline diameter of 101.6 cm to minimize the offshore compression capacity to 11 MPa and thus minimize the cost. However, Fig. 1.3 shows that selection of the 101.6-cm pipeline diameter results in the largest liquid volume along the pipeline of approximately 4800 m$^3$, which requires a larger and more expensive slug catcher and more-frequent pigging operations to remove liquid from the line. Therefore, an economic analysis must be carried out to select the most cost-effective design that reduces CAPEX and OPEX.
The unusual behavior of increasing liquid volume with increasing gas flow rate is a result of retrograde condensation taking place in the pipeline.

Another important design aspect is flow assurance. For example, it is important to accurately predict flow pattern along the pipeline because it is related to pipeline corrosion. A corrosion inhibitor is often injected at the platform. The inhibitor is transported in the liquid phase along the pipe to protect the pipeline internal wall from corrosion. It may be very important for efficient operation to design the pipeline so that the entire pipeline wall is exposed to the corrosion inhibitor. This can be achieved when the flow pattern is a favorable one where the liquid phase wets the entire internal diameter (i.e., annular or slug flow and not stratified flow). Failure to consider the flow pattern in pipeline design may lead to rapid pipeline corrosion.

1.5 Historical Overview of Multiphase Flow in Pipes

Many of the concepts used today for analyzing flowing and gas lift wells were developed by Gilbert (1954). He divided the production system into three distinct categories: inflow performance from the reservoir, vertical-lift performance in the well, and bean or choke performance. Graphical techniques were presented for coupling these categories together to permit analyzing individual-well problems. It is interesting to note that this same procedure is still followed today under the names of production systems analysis or NODAL™ analysis. However, the methods for describing the performance of each category have been vastly improved. Gilbert also presented a clear description of the unsteady flow behavior or “heading” that can exist in a well and how to minimize or eliminate the phenomenon. The concepts recommended by Gilbert were expanded and clarified by Nind (1964).
The historical background of attempts to improve the prediction of vertical-lift performance for wells has been especially interesting. Brill and Arirachakaran (1992) divided this history into three partially overlapping periods. Fig. 1.4 illustrates the three periods in addition to future projections.

1.5.1 The Empirical Period (1950–75). Most early investigators used two-phase flow data obtained from laboratory test facilities, with a few researchers using field data. Fluids were treated as homogeneous mixtures. However, gas and liquid phases were permitted to travel at different velocities, with slippage effects being accounted for through empirical liquid holdup correlations. Empirical flow pattern maps such as the ones developed by Baker (1954), Ros (1961), and Beggs and Brill (1973) were used, often based on dimensionless groups. Steady-state pressure-gradient equations were developed on the basis of conservation of momentum and mass principles applied to the homogeneous mixtures. Frictional pressure losses relied on single-phase flow equations, resulting in extensive use of mixture Reynolds numbers, as in the Beggs and Brill (1973) two-phase flow correlation.

In general, the empirical period resulted in a collection of empirical correlations in which accuracy was limited by the lack of inclusion of basic physical mechanisms. Even when these mechanisms were partially included, their investigation was severely hampered by the unavailability of sufficiently accurate instrumentation and real-time data-acquisition systems.

1.5.2 The Awakening Years (1970–85). The empirical correlations for predicting pressure gradient, coupled with the introduction of the personal computer (PC) in the early 1980s, dramatically improved practical tools available to petroleum engineers. Procedures for connecting wells to reservoirs through simple IPR techniques abounded. The true concept of NODAL™ or production system analysis was born (Brown 1980).

Unfortunately, it was quickly recognized that there were many problems with the methods available. Empirical flow pattern maps were inadequate. Flow pattern transitions, previously thought to be dependent mostly on flow rates (or superficial velocities), were found to be very sensitive to other parameters, especially inclination angle. Empirical liquid holdup correlations for each flow pattern were equally inadequate. The assumption of a homogeneous mixture was oversimplified. It became clear that no matter how much data were gathered either...
in laboratory test facilities or from carefully tested field installations, the accuracy of the predictions could not improve without the introduction of more basic physical mechanisms.

Fortunately, progress in this area had already been made by other industries, particularly the nuclear industry, several years before. Although the fluids used for these studies (steam/water) were trivial by comparison to those encountered in the petroleum industry, the methods used to formulate conservation equations were much more advanced. Therefore, the 1970s saw a trend in the petroleum industry to adopt some basic physical mechanisms already in use in the nuclear industry. Two classic papers dealing with multiphase flow in horizontal pipes by Dukler and Hubbard (1975) and Taitel and Dukler (1976) clearly show that mechanistic models for slug flow and flow pattern prediction had already become available.

1.5.3 The Modeling Era (1980–Present). Petroleum industry challenges in the 1980s required a much better understanding of multiphase flow technology, beginning the modeling period. Investigators recognized that improved understanding of multiphase flow in pipes required a combined experimental and theoretical approach. Sophisticated test facilities were constructed that used new instrumentation for measuring important variables, and high-speed PC-based data-acquisition hardware and software. This advancement was transformed into improved mechanistic models to better describe the physical phenomena occurring.

An important improvement in steady-state mechanistic models was the work on predicting flow pattern transitions for all inclination angles by Taitel and Dukler (1976), Taitel et al. (1980), Barnea et al. (1982a, 1982b, and 1985), and Barnea (1986, 1987). This opened the door for designing improved models for each of the flow patterns and linking the various models together through unified flow pattern transition criteria. Combined or “comprehensive” mechanistic models were published by Ozon et al. (1987), Hasan and Kabir (1988), Xiao et al. (1990), Ansari et al. (1994), and Chokshi (1994). Their attempts to evaluate the models with field data confirm that the modeling approach is more accurate and precise than empirical correlations. Furthermore, it is now possible to continue improvement of these mechanistic models as experimental research is conducted on the basic mechanisms of multiphase flow.

At the same time that improved experimental research was being conducted, efforts were expanded in developing improved theoretical methods. The two-fluid modeling approach pioneered by the nuclear industry was adopted for the development of transient codes for application to petroleum industry problems by Taitel et al. (1980), Black et al. (1990), Bendiksen et al. (1991), and Pauchon et al. (1993). This approach involves writing separate equations for each phase that describe conservation of mass, momentum, and energy, resulting in a six-equation problem that must be solved simultaneously using numerical simulation techniques. Empirical correlations and simplified closure relationships were still necessary for some parameters. Improved correlations for these parameters became possible as a result of the experimental research being conducted. The resulting transient codes are capable of simulating a variety of applications that are time-dependent, such as pipeline inlet/outlet flow rates or pressure changes, pipeline pigging, startup/shutdown, and terrain slugging.

A recent improvement in the development of steady-state mechanistic modeling is the “unified” modeling of multiphase pipe flows (Zhang et al. 2003b). Unified modeling is a new approach in which the predictions of both flow pattern transition and flow behavior are incorporated into a single model based on slug dynamics. This modeling, which covers the entire inclination-angle range (−90° to +90° from horizontal), eliminates the discontinuity in flow pattern transition prediction. In addition, the unified modeling approach tends to be realistic in its assumption that slug flow is the predominant flow pattern existing in a pipe, a pattern from which other flow patterns develop. It has been found that this is an effective and successful approach for multiphase flow modeling.

Thus, the current state of the art in multiphase flow in pipes is the emergence of both two-fluid transient simulators and steady-state mechanistic models that more accurately describe the physical phenomena that occur. Transient simulators have the capability of analyzing complex time-dependent problems but often suffer from convergence problems. The improved technology also carries an additional cost. Both transient simulators and mechanistic models are complex and require specialized training to understand and use. Interpretation of results is better carried out by engineers with a specialized background who are fully aware of any simplifying assumptions or limitations that have been included in the developments.

1.6 Future of Multiphase Flow in Pipes

What multiphase production technology developments will evolve in the future? The answer to this question is closely related to the future challenges that face the upstream petroleum industry.

1.6.1 Petroleum Industry Future Challenges. As existing petroleum reservoirs mature, production of interstitial and injected water imposes rheology, hydrodynamic, and flow assurance challenges, such as emulsions, complex
three-phase hydrodynamics, and corrosion. These challenges are further exacerbated when production of other injected fluids used in chemical, thermal, and miscible floods is considered. Furthermore, sufficient flow energy (pressure) to transport the required flow rates of hydrocarbons from reservoirs to processing facilities is a major issue in mature reservoirs. The use of artificial-lift methods such as electrical submersible pumps and gas lift and the use of surface multiphase pumps may introduce flow assurance issues such as creation of tight emulsions in water-producing wells or organic/inorganic solid formation resulting from sudden heating and compression of fluids.

Major oil companies and large independent oil companies have sold most of their low-profit onshore fields to smaller, independent oil companies. Majors are now concentrating on exploration and development of higher-risk, more profitable reservoirs. Many of these discoveries are in deepwater regions in the Gulf of Mexico and areas in the world such as Brazil and West Africa. Other target areas are heavy-oil onshore and offshore reservoirs with large potential reserves. All these target areas present serious technical challenges. For example, in order to develop remote, deepwater offshore fields economically, a cost-effective approach often involves flowing the wells to an existing platform through long multiphase flowlines (Oliemans 1994). In these flowlines, flow assurance issues such as organic/inorganic solid formation and deposition (hydrates, paraffin, asphaltene, scale), high-viscosity cold flow, erosion/corrosion, terrain slugging, and flowline/platform/riser severe slugging become important.

Onshore heavy-oil production and transportation also introduces several flow assurance issues relating to the nature of the produced fluids and the recovery techniques used to extract oil from the reservoirs. The flow of very-high-viscosity oils may impair the economic deliverability of wells as a consequence of complex and poorly understood flow characteristics and inaccurate predictions using existing two-phase flow models (Gokcal et al. 2006). Emulsion formation with heavy oil complicates the rheology and downstream separation because of large density and viscosity differences. In addition, heavy-oil production requires special recovery techniques that affect the production and transportation of the oil. For example, the cold heavy-oil production with sand technique allows the production of sand to maximize recovery. This, in turn, complicates the flow structure and can result in eroding and/or plugging the system components. Cyclic-steam-stimulation and steam-assisted-gravity-drainage recovery techniques result in water production and hot fluids that may cause tight emulsions, system corrosion, and thermal fatigue. Therefore, heavy-oil system design and operation require appropriate modeling tools based on sound physical understanding of the flow behavior to ensure environmentally safe and cost-effective design and operation.

Increasing attention to environmental issues adds a major challenge to multiphase flow technology. For example, zero gas flaring and carbon dioxide emission and protection of marine and land environment are required to address today’s global concerns. Transportation of exhaust gases and unwanted produced fluids is a viable alternative to protect the environment. Furthermore, to ensure system integrity and safety, a low tolerance of uncertainty must be adopted, and this requires more-accurate and field-validated prediction models.

1.6.2 Multiphase Technology Future Direction. The future issues noted in the preceding subsection challenge current multiphase technology. Great effort must be devoted to expand the current technology envelope in order to cope with future challenges. Several technical issues are of high priority to the multiphase flow community. For example, three-phase flow in pipelines and well tubing is extremely important to future multiphase phase technology. Three-phase flow patterns, as well as water holdup and flow characteristics such as emulsions, dispersions, and dispersed-phase droplet size distribution, are significant in the design of a transport system and downstream processing facilities.

Mechanistic modeling of heat transfer that is dependent on flow pattern is critical in system thermal management to overcome flow assurance challenges of organic/inorganic solid formation/deposition. Formation of asphaltene, paraffins, hydrates, and scales must be predicted with a high degree of accuracy to design operationally safe and cost-effective systems.

The main issue of heavy-oil multiphase technology is whether current conventional oil modeling is adequate. Engineers must determine whether accuracies of existing pressure loss and liquid holdup predictions are acceptable for economic design and reliable operation. A preliminary high-viscosity two-phase flow study by Gokcal et al. (2006) showed current modeling capabilities to be inadequate. Therefore, existing two-phase flow mechanistic modeling must be revised for use with heavy oil. For example, current flow pattern maps must be assessed according to the hydrodynamics of heavy-oil, two-phase flows. Furthermore, new empirical closure relationships must be developed to replace existing ones that were developed for conventional oils.

Modeling of both natural and imposed transients in multiphase flow is the least developed technology, yet it is the highest in economic impact and environmental safety. Improved prediction of liquid slug behavior such as growth, dissipation, and initiation along extremely long and large-diameter pipelines is required for the design.
of slug catchers and separators. Prediction of liquid accumulation along pipelines is crucial for design of pigging operations and corrosion inhibitor programs. Current transient models may not be capable of predicting severe slugging for deepwater applications involving very long and large-diameter platform/riser systems. Improvement of current transient slug-tracking models should be a future priority for safety reasons.

Fortunately, the petroleum industry and the multiphase flow technology community realize the upcoming future challenges and are vigorously addressing them. Providing technically sound, environmentally safe, and economically profitable solutions to future challenges is never an easy matter. However, progress can be made and requires collective efforts. For example, governmental and industrial funding of research is a key issue in this effort. More importantly, efforts to find solutions require an interdisciplinary research approach. For instance, flow assurance issues require input from physical chemists, chemical engineers, process engineers, and petroleum engineers to find a comprehensive solution. Similarly, three-phase flow in pipes requires collaborative efforts of material scientists, fluid dynamicists, and engineers. Although the future seems challenging and complex, it also looks interesting and full of adventures. This book is a step toward solving these future challenges.