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MULTIPHASE FLOW METERING

Principles and Applications

Gioia Falcone, Geoffrey F. Hewitt,
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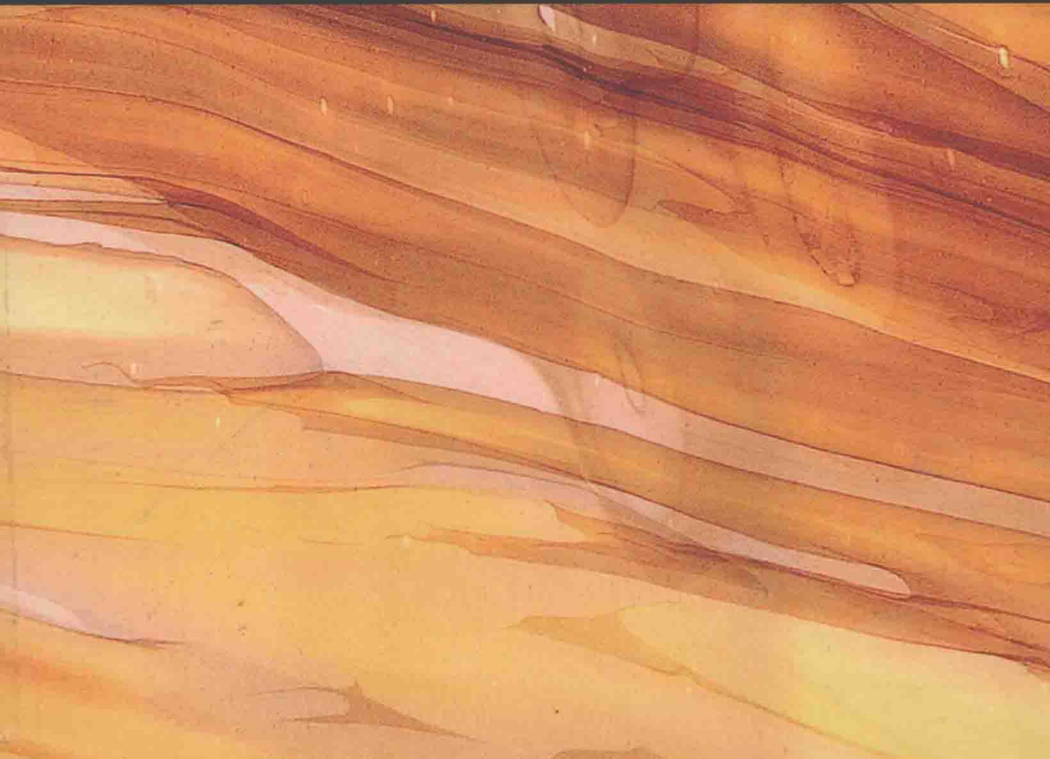

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DEVELOPMENTS IN PETROLEUM SCIENCE

MULTIPHASE FLOW METERING

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CHAPTER 1

Multiphase Flow Fundamentals

Prior to embarking on the investigation of multiphase flow metering (MFM) solutions and their capabilities, it is necessary to develop a feeling for multiphase flow. Without a clear understanding of the nature of multiphase flow, it is simply not possible to choose the best strategy to meter it. As will be shown in this section, there still remain aspects of multiphase flow that are not fully understood, which makes it very difficult to identify and overcome the challenges presented by MFM.

1.1. Introduction to Multiphase Flow

Around the world, research into multiphase flow is performed by scientists with hugely diverse backgrounds: physicists and mathematicians as well as engineers from mechanical, nuclear, chemical, civil, petroleum, environmental and aerospace disciplines.

Multiphase flow can occur in conduits as well as in porous media: the focus of this book is on the former.

As a general definition, multiphase flows consist of the simultaneous passage in a system of a stream composed of two or more phases.

Multiphase flows are the most common flow occurrences in nature. Examples are the flow of blood in the human body, the bubbles rising in a glass of cold beer and the steam condensation on windows. These flows largely depend on the nature of the constituents and their relative distribution.

The simplest case of multiphase flow is that of a two-phase flow in which the same pure component is present in two different phases. An example is given by a steam-water flow. On the other hand, if different chemical substances co-exist, the flow is usually referred to as multicomponent. This is the case of an air–water flow (two-phases, two components).

The phases present in a multiphase flow are composed of:

1. Solids, which are normally in the form of relatively small particles. The solid phase is incompressible and has non-deformable interfaces with the surrounding fluids.
2. Liquids, which are also relatively incompressible, but their interfaces with the other phases are deformable.
3. Gases, where the phase is compressible and deformable.

The most common class of multiphase flows are two-phase flows and these include the following:

- Gas–solid flows, where solid particles are suspended in gases, which are of industrial importance in pneumatic conveying, in the combustion of pulverised fuel and in fluidised beds.
- Liquid–liquids flows, which include emulsion flows of oil and water in pipelines (of interest in the present context) and flows through packed columns, pulsed columns, stirred contacters and pipeline contacters in liquid–liquid solvent extraction.
- Liquid–solid flows, which are widely encountered in hydraulic conveying of solid material. Suspensions of solids in liquids also occur in crystallisation systems.
- Gas–liquid flows, which are probably the most important form of multiphase flow and is found widely in industrial applications.

Three-phase flows are also of practical significance, examples being as follows:

(1) Gas–liquid–solid flows, which are found in froth flotation as a means of separating minerals and in carrying out gas–liquid reactions in the presence of a particulate solid catalyst.
(2) Gas–liquid–liquid flows, which constitute the central case covered in the present study where the flows are respectively oil, water and natural gas. Such flows are also found in the condensation or evaporation of emmissible liquid mixtures (e.g. the condensation of a mixture of steam and hydrocarbons).
(3) Solid–liquid–liquid flows, which may occur if sand was mixed with oil and water in the pipeline.

The most difficult case is that of a four-phase flow with oil–water–gas–sand mixtures. Another example of a four-phase flow is that of the freeze desalination process where butane liquid is injected into saline water and icicles are formed. Here, the flow is a mixture of butane liquid, water liquid, ice particles and butane vapour.

In the present context, the types of multiphase flow which are of interest are gas–liquid flows (oil–natural gas), liquid–liquid flows (oil–water), gas–liquid–liquid flows (natural gas–oil–water) and solid–liquid–liquid–gas flows (sand–oil–water–natural gas).

In a typical offshore oil and gas development, the above types of multiphase flow are encountered in the wells, in the flowlines and risers transporting the fluids from the wells to the platform and in the multiphase flowlines that carry the produced fluids to the treatment facilities at shore. Each of these types of flow will be discussed in Section 1.3, with particular reference to the nature of the flows (flow patterns).

1.2. Brief History of Multiphase Flow

The existence of phase changes has been known to mankind for thousands of years. Boiling and melting phenomena can be ordinarily observed in nature (e.g. water evaporation, lava solidification, ice melting). Tracking the history of how multiphase flow was identified, described and put to the use of human development is not an easy task. In what follows, only a selection of historical milestones is presented to suggest the span of scientific background that is behind the current understanding of multiphase flows and, as a result, of their metering solutions.

Perhaps from an original idea by Archimedes of Syracuse (287–212 BC), Leonardo da Vinci (1452–1519) proposed the idea of a steam-powered cannon based on heat and water generating expanding steam to propel a projectile. In fact, a similar steam cannon was used during the American Civil War (Reti, 1962).

From the analyses of the relationships between temperature, pressure and volume of gases in 1645 by British Physicist and Chemist Robert Boyle, to the pressure cooker built in 1680 by Denis Papin, an associate of Boyle's, the use of energy to drive a piston in a cylinder was conceived (Brush, 2003) and led to the development of steam engines. In 1698, Thomas Savery made the first attempt to use of steam power at an industrial scale to pump water out of mines, but his attempts were not fully successful: his combined vacuum and pressure water pump had limited pumping height and was prone to boiler explosions. The Industrial Revolution, which began in the 18th century, saw the establishment of steam-powered engines, beginning with Newcomen's steam-powered atmospheric engine in 1710–1712, which combined the findings of Savery and Papin.

In 1732, Hermann Boerhaave observed that a water drop does not immediately vaporise when deposited on metal that is hotter than the boiling temperature of water. Johann Gottlob Leidenfrost (1756) later described this phenomenon, the so-called Leidenfrost effect, as a result of experiments that he conducted by placing single water drops in an iron spoon heated red-hot in a fireplace and timing the duration of the drop.

In 1761, Joseph Black, a professor in Medicine and Chemistry at the University of Glasgow, conceived the concepts of latent heat of fusion (melting) and latent heat of vaporisation (boiling) when observing that ice absorbed heat without changing temperature while melting (Ogg, 1965).

James Watt began his studies on steam power at the University of Glasgow in 1761, as Black's assistant, and in 1769 he patented an improved Newcomen steam engine, leading the way to a new age of industrial development (Ogg, 1965).

The establishment of thermodynamics in the 19th century, which lead to the development of the conservation of energy, was triggered by the investigations of Count Rumford in 1796–1798 (Rumford, 1969) and James Joule in 1845 (Joule, 1845) on the concept of the mechanical equivalent of heat. According to this concept, motion and heat are mutually interchangeable.

Between 1852 and 1856, Joule and William Thomson (Lord Kelvin) had a fruitful collaboration that included the discovery of the Joule–Thomson effect, also called the Kelvin–Joule effect (Thomson, 1856).

In 1915, Wilhelm Nusselt made significant contributions to convective heat transfer and introduced what is referred to as the Nusselt number that is a dimensionless convective heat transfer coefficient (Çengel, 2003).

The period 1930–1940 saw fundamental work on nucleate pool boiling. As defined by Kandlikar and Chung (2006), pool boiling refers to the process in which the liquid is essentially quiescent and vapour bubbles rise as a result of buoyancy forces induced by gravity or other body forces. One of the most relevant works is that by Nukiyama (1934), who presented a boiling curve based on a study where electrically heated nichrome and platinum wires where used.

In the period 1940–1950, further advances in nucleate boiling were made and the first two-phase pressure drop models started to be developed, primarily for chemical and process industry applications. In particular, Lockhart and Martinelli (1949) presented a model for frictional pressure drop in horizontal, separated two-phase flow and introduced a parameter that is still in use today. McAdams et al. (1949) experimentally obtained the curve for forced convective sub-cooled boiling of water, thus extending the pioneering work of Nukiyama.

The years between 1950 and 1960 saw intensive work in the aerospace and nuclear sectors, which triggered more studies on two-phase flow, heat transfer and nucleate pool boiling. Baker (1954) proposed a flow regime map characterising the transitions between two-phase patterns in horizontal, adiabatic flow.

In the period 1960–1970, an intensive two-phase flow modelling effort was made, which also included several large-scale two-phase flow experiments to further investigate heat transfer phenomena (boiling and condensation). See, for example, the studies by Wallis (1962), Hewitt and Wallis (1963), Chisholm (1967), Hewitt and Roberts (1969) and Hewitt and Hall-Taylor (1970).

The modelling effort continued until the 1980s, with focus on nuclear reactor safety, critical flow and also with the advent of computer coding. See, for example, the works by Henry and Fauske (1971), Ishii and Grolmes (1975), Ishii et al. (1976), Taitel and Dukler (1976), Hewitt et al. (1979), Hewitt and Whalley (1980) and Taitel et al. (1980).

In the 1980s, significant work was done to extend the investigation of multiphase flow patterns to different pipe inclinations and diameters, and different operating pressures and rates. See, for example, Barnea et al. (1982), Dukler and Taitel (1986), Barnea (1987) and Oliemans (1987). This period also saw the development of computational fluid dynamics (CFD) to solve practical fluid flow problems and most of the commercial CFD packages that are available today were originated at this time. Until then, researchers had to write their own codes to perform fluid dynamics calculations. Several MFM research projects also took place in the 1980s, focused on applications for the oil and gas industry and commercial multiphase flow loops were started to be built, for the experimental investigation of flow at an industrial scale. As more and more experimental data became available for the validation and fine-tuning of multiphase flow modelling codes, commercial simulators entered the marked and became essential tools that are still in use today in the oil and gas industry.

The advances of computing power in the 1990s meant increasingly complex-modelling techniques could be coded towards fast solutions. Flow phenomena that were previously simplified to one-dimensional (1D) problems to limit the otherwise prohibitive computing times could be extended to two dimensional (2D) and three dimensional (3D). This work is still ongoing, and as our understanding of multiphase flow pushes its horizons, so does the technology for metering it.

1.3. Types of Multiphase Flows, Flow Patterns and Flow-Pattern Maps

Let us build on Section 1.1, by describing below the main types of multiphase flow encountered in the oil and gas industry and how they are related to the concept of 'flow patterns'.

The behaviour and shape of the interfaces between phases in a multiphase mixture dictates what is referred to as the 'flow regime' or the 'flow pattern'. There are competing forces or mechanisms occurring within the multiphase fluid at the same time. The balance between these forces determines the flow pattern.

There are several factors that dictate the flow pattern of a multiphase flow in a conduit:

- Phase properties, fractions and velocities.
- Operating pressure and temperature.
- Conduit diameter, shape, inclination and roughness.
- Presence of any upstream or downstream pipe work (e.g. bends, valves, T-junctions).
- Type of flow: steady state, pseudo steady state or transient.

Flow pattern classifications were originally based on visual observations of two-phase flow experiments in the laboratory. The experimental observations were mapped on 2D plots (called 'flow-pattern maps') and the boundaries between regimes determined. Different investigators used different coordinates for their maps (e.g. mass flow rates, momentum fluxes or superficial velocities), in search for parameters independent of the given experimental set-up. However, the judgement of the observed regime was inevitably very subjective.

For three-phase flow, the investigation of oil–water–natural gas flow regimes for the oil and gas industry immediately showed the complexity of defining the liquid–liquid mixing patterns, superimposed on the existing complexities of flow regimes arising from the gas–liquid interactions per se' (Hewitt, 2005).

In what follows, a description of the main flow regimes that characterise gas–liquid, liquid–liquid, gas–liquid–liquid and solid–liquid–liquid–gas flows is presented.

1.3.1. Gas–liquid flows

The factors governing the interfacial distribution (flow regimes) in a gas–liquid flow are complex. They include surface tension, wetting, dispersion, coalescence, body forces and heat flux effects. Nevertheless, it has been possible to classify the type of interfacial distribution in certain broad categories (flow regimes), even though the detailed nature of the flow will still depend on the relative significance of the influencing factors. Thus, although the classification of flow regimes is a very useful starting point, it does not in itself allow a complete specification of the system. It should also be stressed that the relative importance of the influencing factors changes gradually with phase flow rates, and that the transition from one regime to another is not usually sharply defined. It is for this reason that the delineation of flow regimes is often somewhat subjective.

The regimes in *vertical* gas–liquid flows are illustrated in Figure 1.1. The regimes are as follows.

1.3.1.1. Bubble flow

Here, the liquid phase is continuous and a dispersion of bubbles flows within the liquid continuum. The bubbles are subject to complex motion within the flow, maybe coalescing, and are generally of non-uniform size.

1.3.1.2. Slug (or plug) flow

This flow pattern occurs when the bubble size is that of the channel, and characteristic bullet-shaped bubbles are formed, often interspersed with a dispersion of smaller bubbles.

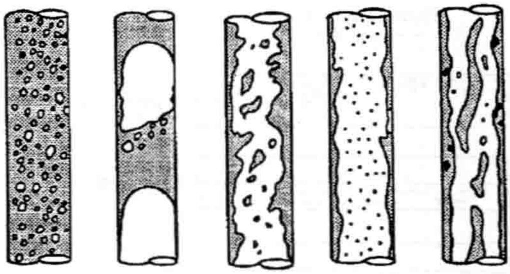

Figure 1.1 Flow patterns in vertical flow.

1.3.1.3. Churn flow

At higher flow velocities, the slug flow bubbles breakdown leading to an unstable flow regime in which there is, in wide bore tubes, an oscillatory motion of the liquid, hence the name churn flow.

1.3.1.4. Annular flow

Here, the liquid flows on the wall of the tube as a film and the gas flows in the centre. Usually, some of the liquid phase is entrained as small droplets in the core; at high flows, it is also common for bubbles of gas to be entrained in the liquid film.

1.3.1.5. Wispy annular flow

In this regime, there are characteristic liquid 'wisps' in the gas core presumably due to the coalescence of the large concentration of entrained droplets, which exist in this type of flow. The flow occurs characteristically at rather high mass fluxes and low qualities.

The gas–liquid flow regimes in *horizontal* pipes are illustrated in Figure 1.2. They are as follows.

1.3.1.6. Bubble flow

Here, as in vertical flow, the phase is composed of bubbles dispersed in the liquid phase. However, due to the effect of buoyancy forces on the bubbles, they tend to accumulate in the upper part of the pipe as shown in Figure 1.2.

1.3.1.7. Stratified flow

This regime occurs when the gravitational separation is complete. The liquid flows along the bottom of the tube and the gas along the top part of the tube as shown in Figure 1.2.