MULTIPHASE FLOW

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Contents

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Summary

The simultaneous flows of more than one phase are almost ubiquitous particularly in the field of chemical engineering. These multiphase flows are complex because of the infinitely deformable nature of the interface in gas/liquid and liquid/liquid flows. It the case when one of the phases is a solid, dispersed phase, the complexity arises from the non-uniform distribution of particles about the pipe cross-section and axially. In order to handle these complexities, the different distributions of flows are usually gathered into groups called flow pattern. This approach is useful for modeling the flows. Methods for identifying the occurrence of particular flow patterns are provided together with models for pressure drop specific to those flow patterns. In addition, overall, more empirical methods are outlined. The information is presented for gas/liquid (including foams), liquid/liquid (including emulsions), gas/solid and liquid solid flows. Flow in pipes and in pipe fittings are examined as well as in the geometry usually termed bubble columns used in chemical reactors. Recent developments in modeling using advanced computational techniques are introduced.

1. Introduction

Multiphase flow, the simultaneous flow of more than one phase, occurs in many facets of chemical engineering, e.g., distillation, absorption, evaporation, condensation, solvent extraction. It is particularly prevalent and important in hydrocarbon production and refining, minerals transport, power generation as well as in many environmental applications. The possible combinations of phases are: gas/liquid; gas/solid; liquid/solid; the simultaneous flow of two immiscible liquids and gas/liquid/solids. The first four can be termed two-phase flow. The last, more complex case can be found in some catalytic reactors. Hydrocarbon production can involve the flow of gas, oil, water and solids emerging from the reservoir.

A complication of these flows is that the phases can be dispersed unevenly about the pipe cross-section and axially. This has important implications for the flow particularly the pressure drop/ flow rate/geometry relationships which are central to designers. It also has import for the separation of the phases. The phase disposition can be especially complex in the case of gas/liquid and liquid/liquid flows. The extremely deformable nature of the interface leads to a large number of possible configurations. Even with gas/solids and liquid/solid flows there can be systematic variations of the temporal and spatial concentration of the dispersed solids. It is because of these factors that workers in the field have used the concept of flow patterns – general descriptions of the disposition of the phases. In the material presented below, flow patterns, methods for predicting their occurrence and models for pressure drop in pipes (and where possible pressure drop across pipe fittings) are outlined, for gas/liquid (Section 2), liquid/liquid (Section 3), gas/solids (Section 4) and liquid/solids (Section 5) flows. Foams and emulsions are considered under the gas/liquid and liquid/liquid headings. The chapter is completed by a section outlining modern computational techniques which can be very powerful in describing these complex flows.

2. Gas/Liquid Flows

The particular complications of two-phase gas/liquid flows are caused by the interface between the phases. This produces a wide range of configurations in the channel with consequences both for the hydrodynamics and for heat and mass transfer. The groupings of similar configurations are important as studies have shown that a single correlation for the whole range of gas/liquid flows from 100% liquid to 100% gas is inadequate. In addition, advanced codes for transient analysis use descriptions specific to individual flow patterns (or configurations). For this combination of phases flow pattern, the groupings of configurations taken up by the phases, are first considered (Section 2.1) followed by flow pattern maps (Section 2.2), the graphical correlation by which the

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occurrence of flow patterns have been identified. The more empirical methods employed to calculate the pressure drop for gas/liquid flows are then presented for pipes (Section 2.3), and pipe fittings and the shell side of heat exchangers (Section 2.4). Models for transitions between flow patterns (Section 2.5) and for pressure drop specific to individual flow patterns (Section 2.6) are then considered. The section is completed by a consideration of flow behavior in bubble columns (Section 2.7) and of foam flows (Section 2.8).

2.1. Flow Patterns

2.1.1. Definition and Importance of Flow Patterns

In describing the configurations taken up by gas and liquid flowing together, researchers have used a very large number of names. Some of these are alternative names for the same flow pattern, whilst others are subdivisions of more major groupings. Much of this confusion has arisen from the subjective way in which flow patterns are characterized.

Initially, identification of flow pattern was by visual observation of the flow in transparent tubes, and this remains the primary definition. Given the almost infinite number of possible shapes and states of subdivision of the phases, a large number of reported flow patterns were inevitable. However, the number of flow patterns used in any description should be limited if the descriptions are to be of practical use, and a small number of major patterns have been agreed, as described below.

However, the problem remains of assigning a given flow to one of the agreed patterns. In narrow tubes, at moderate fluid velocities, visual observation is reasonably reliable, but at high velocities it is difficult to see anything, and in wider tubes and the shell side of heat exchangers only the flow near the wall can be seen. Photographs with a high-speed flash, or high speed video studies, can help to overcome the problem of high fluid velocities, although it may be noted that some steam-water studies at a top laboratory in the 1960s using flash photographs had to be analyzed by majority vote among a team of experts!

More objective methods have been suggested for flow pattern determination. An early example used measurements of time-varying cross-sectionally averaged void fraction (fraction of cross-section occupied by gas) at one cross-section in a pipe using, e.g., X-rays, and plotted the Probability Density Function (PDF) of these measurements. This is the frequency of occurrence of each value of void fraction. The significant differences in the PDF “signatures” of different flow patterns that have been reported provide a, possibly more objective, means of flow pattern identification. In these, bubbly flow gave a single peak at low void fractions, annular flow a single peak at high void fractions, and intermittent flow gave two peaks. Analysis of pressure fluctuations, or, electrical resistance techniques related to time-varying void fraction have been employed. Other approaches used more sophisticated statistical analyses of time-varying data. These more objective techniques are becoming increasingly popular, although there can still be disagreements between different investigators.

The major flow patterns for vertical up- and down-flow, horizontal flow and flow at

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other inclinations are defined below.

2.1.2. Vertical Flow in Pipes

Here, four main patterns are usually considered. These are shown schematically in Figure 1.

Bubbly flow: consists of a continuous liquid phase with the gas phase is dispersed as bubbles within it. The bubbles travel with a complex motion within the flow, may be coalescing and are generally of non-uniform size. In some situations, they congregate mainly at the pipe centre, in others, near the pipe walls, and the **wall-peaking** and **core-peaking** flows have sometimes been treated as sub-patterns of bubbly flow (Serizawa and Kataoka, 1988). At lower liquid velocities, the small bubbles must be generated either at the gas distributor or in the process of nucleate boiling, whereas at higher liquid velocities they can be formed by turbulent breakup of larger bubbles. Some workers treat these as two sub-patterns called **discrete bubbly** (or just **bubbly**) and **dispersed bubbly** flow respectively. The concentration of bubbles is not uniform but there are waves of drop concentration (void waves) in concentration which travel along the pipe
Plug flow: This flow pattern, which in vertical systems is often referred to as **slug flow**, occurs when coalescence begins, and the bubble size tends towards that of the channel. Characteristic bullet-shaped bubbles, often called Taylor bubbles, flow up the pipe surrounded by a thin film of liquid. The liquid slug between the Taylor bubbles often contains a dispersion of smaller bubbles. Recent work has shown that this flow pattern does not occur in larger diameter pipes (150 and 200 mm), where there is a direct transition from bubble to churn.

Churn flow: At higher velocities, the Taylor bubbles/liquid slugs in slug flow break down into an unstable pattern in which there is a churning or oscillatory motion of liquid in the tube. Churn flow with its characteristic oscillations is an important pattern, often covering a fairly wide range of gas flow rates. At the lower end of the range, it may be regarded as a breaking up of plug flow with occasional bridging across the tube by the liquid phase; whilst at the higher range of gas flow rates it may be considered as a degenerate form of annular flow with the direction of the film flow changing and very large waves (termed huge waves by some) being formed on the interface. In the latter range the term **semi-annular flow** has sometimes been used.

The Plug and Churn flow patterns, which both show large fluctuations in void fraction and pressure drop, are often grouped together as **intermittent flow**, particularly in shell-side flows.

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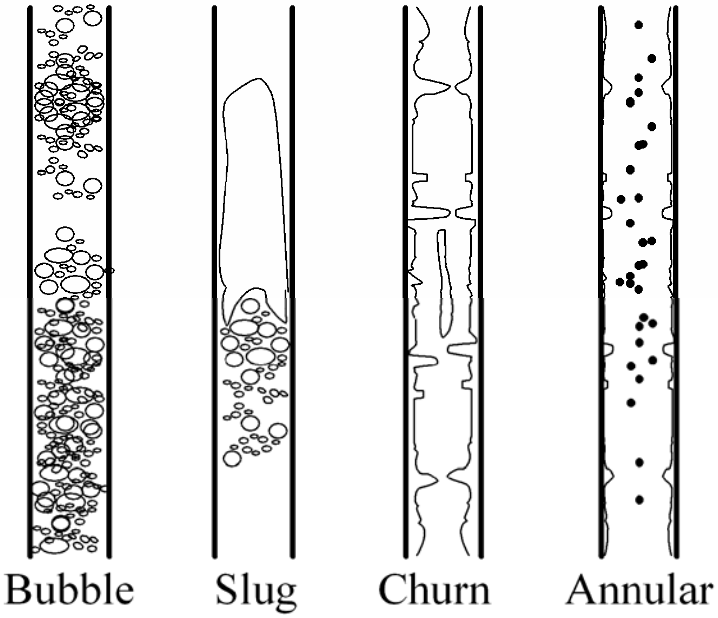

Figure 1. Flow patterns in vertical upflow

Annular flow is characterized by liquid traveling as a film on the channel walls. Part of the liquid can also be carried as drops in the central gas core. In fact, for certain flow rates, the majority of the liquid travels as drops, leading to the term **mist flow** being applied to this flow pattern in some industries. However, only in heat transfer systems where walls can become too hot to be wetted is there flow with **no** liquid film, since in adiabatic systems a minimum film flow is needed before drops can be generated. Interchange of liquid occurs between the film and the drops. Atomization of liquid to form drops does not occur over all of the film interface but from fast moving structures on the film interface which are usually termed disturbance waves. Under some circumstances bubbles of gas can be entrained within the film. At very high liquid flow rates liquid concentrations in the gas core are so high that tendrils of liquid are observed instead of droplets. This is identified as **wispy annular flow** in some flow pattern maps.

In **vertical downflow**, flow patterns are very similar to upflow with bubble, plug, churn and annular flows being reported. However, these patterns occur over different ranges of flow rates. Thus, low gas and liquid rates, which would yield bubble or slug flow in vertical upflow, produce a falling film flow, which resembles annular flow.

2.1.3. Horizontal Flow in Pipes

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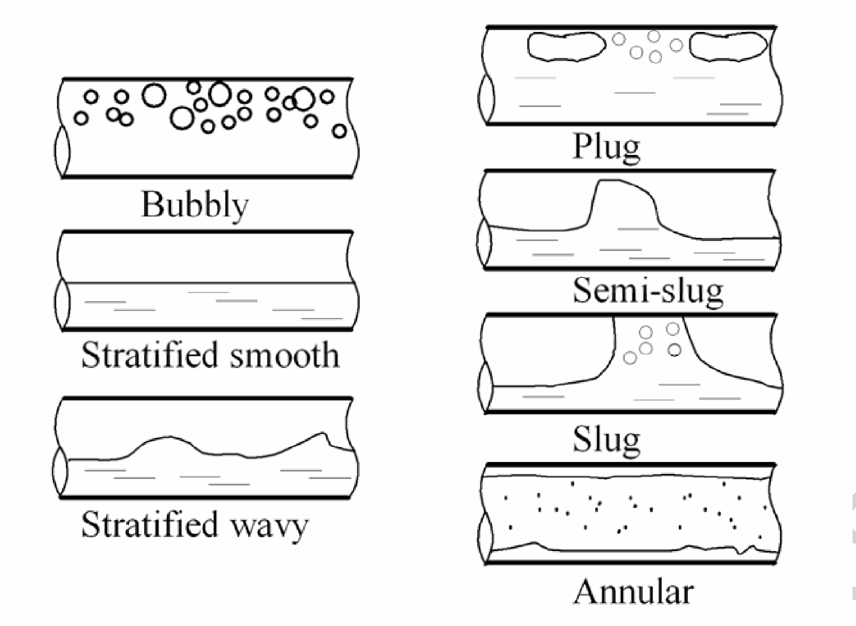

Figure 2. Flow patterns in horizontal flow

When gravity acts perpendicularly to the tube axis separation of the phases can occur. This increases the possible number of flow patterns, as shown schematically in Figure 2.

Bubbly flow, like the equivalent pattern in vertical flow, consists of gas bubbles dispersed in a liquid continuum. However, except at very high liquid velocities when the intensity of the turbulence is enough to disperse the bubbles about the cross section, gravity tends to make bubbles accumulate in the upper part of the pipe as illustrated. In **Stratified flow** liquid flows in the lower part of the pipe with the gas above it. The interface is smooth. An increase of gas velocity causes waves to form on the interface of stratified flow to yield **Wavy flows. Plug flow** is characterized by bullet shaped gas bubbles as seen in vertical flow. However here they travel along the top of the pipe. **Slug flow**, like plug flow, is intermittent. The gas bubbles are bigger whilst the liquid slugs contain many smaller bubbles. At large levels of aeration, they are called **frothy** surges or **semi-slug**, if the surges do not fill the pipe completely. However, this might be more correctly considered as part of wavy flow. A continuous gas core with a complete wall film characterizes **annular flow.** As in vertical flow, some of the liquid can be entrained as drops in the gas core. Gravity causes the film to be thicker on the bottom of the pipe but as the gas velocity is increased the film becomes circumferentially more uniform.

2.1.4. Pipes at Other Inclinations

Gas/liquid flow in inclined pipes is characterized by flow patterns similar to those described above for vertical and horizontal flows. For **inclined upflow**, the range of conditions occupied by slug-type flows, increases considerably starting at even small inclinations from the horizontal. For **inclined downflow** the range of conditions for slug-type flows diminish considerably.

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2.2. Flow Pattern Maps

2.2.1. Vertical Flow in Pipes

Early work often represented the observed flow patterns on two-dimensional diagram in terms of system variables. The most common variables used are the liquid and gas superficial velocities (volumetric flow rate/cross sectional area of the pipe). Since variables other than the superficial velocities are known to affect the flow pattern, maps of this kind are specific to a particular combination of fluids and geometry. However, they are simple to use, and unlike the case of single-phase Newtonian flow where the single parameter of Reynolds number brings all flows together, it is by no means clear exactly which other variables should be included. No reliable universal flow map has yet been produced.

The commonest way of constructing a flow map is to identify the flow pattern at a set of conditions covering the field, and then to sketch in boundary lines separating the different patterns. Because of problems in correctly identifying flow patterns, it often happens that a few experimental points lie on the wrong side of these lines, and the lines would be better regarded as transition zones, of indeterminate width. This should always be remembered when using maps on which only the boundary lines appear.

For **vertical upflow**, flow pattern maps based on superficial velocities have been published since the 1960's and are still being produced. Some workers have presented maps where the superficial velocities are modified by factors in the form of ratios of actual physical properties to standard values raised to different powers. A popular approach, which tries to incorporate some physical reality, is that of Hewitt and Roberts (1969), shown in Figure 3. The data were plotted as gas momentum flux ($\rho_g u_{gs}^2$) against liquid momentum flux ($\rho_l u_{ls}^2$), and data for air/water at 3 bar and steam/water at 35 and 70 bar were brought together by this approach. Here the square root of those parameters, $u_{ls}\sqrt{\rho_l}, u_{gs}\sqrt{\rho_g}$, are employed.

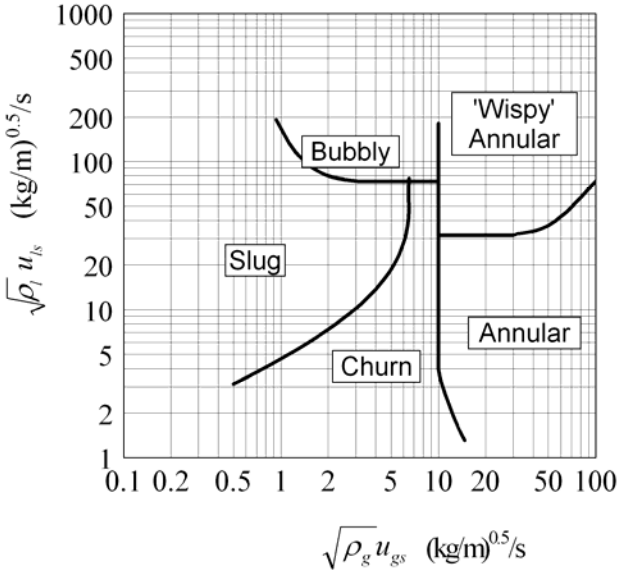

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Figure 3. Modified form of the flow pattern map of Hewitt and Roberts (1969) - vertical upflow

Another approach, put forward by Bennett *et al.* (1965), is to plot data as mass flux *versus* quality. This is useful for evaporating systems, where liquid and vapor contain the same component, as the map quickly reveals the distribution of patterns in an evaporator tube (quality increasing at constant mass flux). Figure 4 shows typical boundaries for a steam/water system at one pressure.

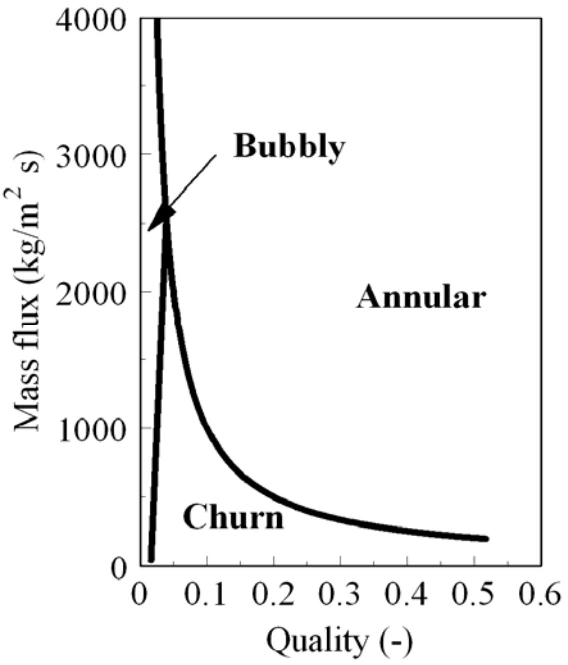

Figure 4. Flow pattern map after Bennett *et al.* (1965).

Vertical Downflow in Pipes, being less prevalent than upflow, has received less attention. Available studies are almost all for air/water in small diameter pipes. Figure 5 shows a map published by Barnea *et al.* (1982). There has not yet been a systematic comparison of the divers flow patterns maps published for vertical downflow.

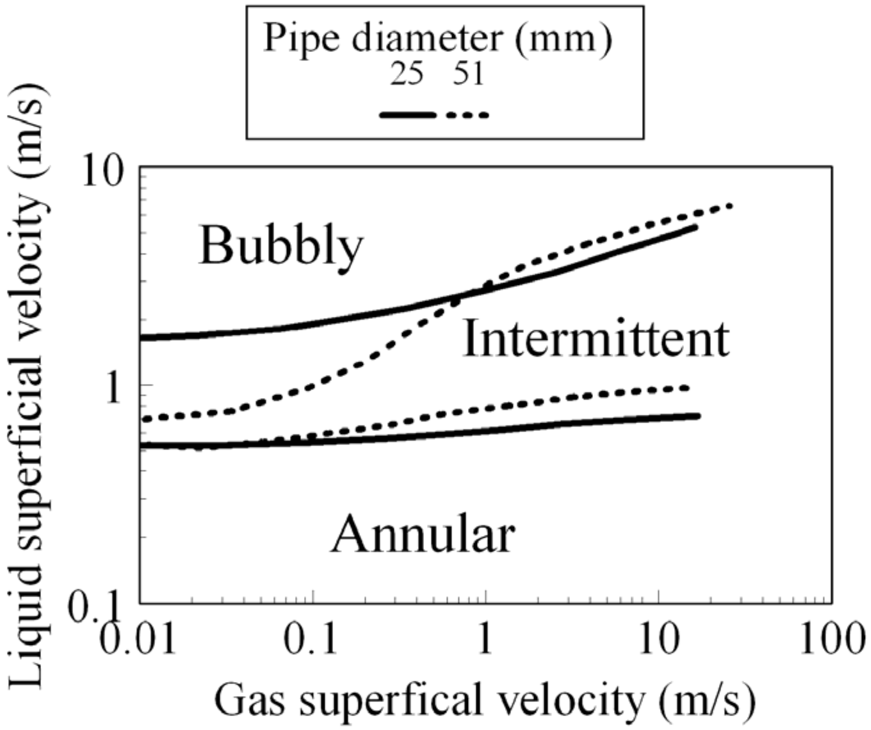

Figure 5. Flow pattern map for vertical downflow - after Barnea *et al.* (1982)

2.2.2. Horizontal Flow in Pipes

In **horizontal flows** the flow pattern map of Baker (1954) still has great popularity. To its credit, it is simple and based on industrially relevant data (gas/condensate flows at high pressure in 5"-10" lines). Subsequent work has shown some of its transition boundaries to be poor. Much more popular is the composite map of Taitel and Dukler (1976) illustrated in Figure 6. The basis of this is explained in Section 2.6.

For **inclined flows** Spedding and Nguyen (1980), Gould (1972) and Mukerjee and Brill (1985) give maps for steep inclination. In addition the Taitel and Dukler (1976) approach can handle small deviations from the horizontal.

Information available on flows in horizontal pipes with **non-Newtonian liquids** and liquids with suspended solids has been collected by Chhabra and Richardson (1985). They present specific flow pattern maps for both vertical and horizontal flows.

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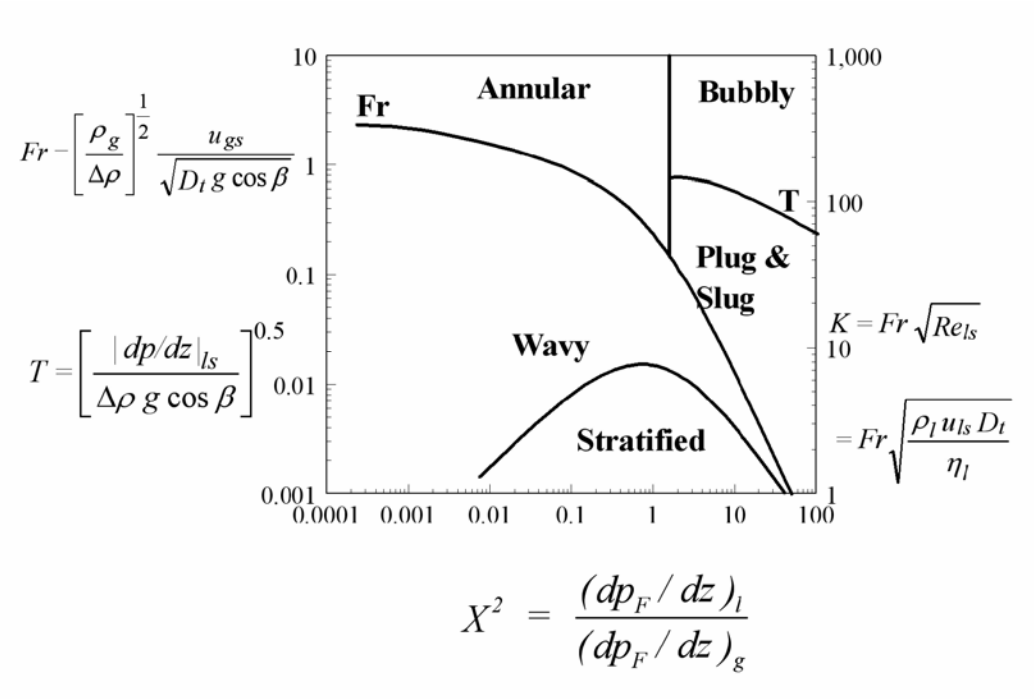

Figure 6. Flow pattern map of Taitel and Dukler (1976) - horizontal flow

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Biographical Sketch

Barry Azzopardi was born in Gibraltar; he obtained his B.Tech. in Chemical Engineering (1972) at the University of Bradford (UK). In 1977, he obtained his Ph.D. in Chemical Engineering from the University of Exeter, UK. After post doctoral experience at the Department of Engineering Science, University of Oxford, Dr. Azzopardi was a Principal Scientific Officer at the Harwell Laboratory of the United Kingdom Atomic Energy Authority. In 1990 he moved to take up the Lady Trent Chair of Chemical Engineering at the University of Nottingham which he still holds. He was Head of the

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Department of Chemical Engineering until 1997. At Nottingham, he has taught at undergraduate and graduate levels in the Department of Chemical Engineering and later in the School of Chemical and Environmental Engineering. Professor Azzopardi' research focus is mainly on multiphase flow, drop size measurement and gas cleaning. He has been coordinator of diverse research projects within the mentioned areas. He was Chairman of the Working Party on Multiphase Flow of the European Federation of Chemical Engineers. Professor Azzopardi is also author of more than 90 scientific publications in refereed journals and more than 150 presentations in international congresses. He is author of the book, *Gas Liquid Flows*. He is an editor of Chemical Engineering Research and Design and member of Editorial Boards for different journal. He evaluates research projects in Norway, the Netherlands, Canada, Israel ad the United Kingdom. He has been visiting professor in Canada and Chile.

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