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GAS-LIQUID FLOWS

Barry J. Azzopardi
Lady Trent Professor of Chemical Engineering

Multiphase Flow Research Group, Nottingham Fuel and Energy Centre,
School of Chemical, Environmental and Mining Engineering,
University of Nottingham, University Park, Nottingham NG7 2RD, U.K.

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FOREWORD

It is with great pleasure that I welcome this book by Professor Barry Azzopardi to the Series. Multiphase flows, and in particular the gas-liquid flows which are the subject of this book, are found in a very wide variety of industrial applications ranging from pipelines to boilers, from condensers to nuclear power plant, from mass transfer equipment such as distillation towers to chemical reactors etc. etc. Of course, multiphase flows are highly complex and, in most industrial applications, often turbulent in nature; they are therefore notoriously difficult to predict. Recognising the complexity of the flows, and taking proper account of the flow patterns, is a necessary precursor to the development of prediction methods. This book is written largely from that standpoint.

Professor Azzopardi and I have collaborated for many years and share a lifelong interest in the subject of multiphase flow. As I am sure the reader will agree, Professor Azzopardi's enthusiasm for, and commitment to this subject comes out strongly from what is written here. The book firmly reflects Professor Azzopardi's personal view of the subject, developed over many years of research and the book will be a valuable source, not only to new readers coming to the subject for the first time, but also to those more experienced who will gain new insights (as I have) from what is written.

G. F Hewitt
Series Editor

PREFACE

If I were asked "why do you study gas/liquid flows?" I would have to reply that I do it because it is fascinating and because the research provides knowledge required for design and simulation of many industrial processes. These flows are fascinating because of the infinite way in which the interface between gas and liquid can arrange itself. In the early 1990's, when I gave my Inaugural Lecture here at Nottingham I chose the title "Bubbles, Drops and Waves". I have been involved with these three friends for many years and, not surprisingly, they make frequent appearances in the pages which follow.

The oscillations and zig-zagging motion of bubbles have an artistic quality to them. Drops are at their most spectacular at their creation. The shapes formed by the distorting large drop during breaking up in gas streams are paralleled by the process of entrainment of drops from the crests of disturbance waves in annular flows. These lordly forms are as spectacular as any science fiction creation. The periodic surges which occur in annular flow are often called waves. Whether they are true waves in the mathematical sense is open to question. However, to see the coherent rings travelling up the vertical pipe for several meters is something not easily forgotten.

The stating point for this monograph lies in the course on Two-Phase Flow and Heat Transfer given by the United Kingdom Atomic Energy Authority at its establishments at Harwell and Winfrith and to which I contributed whilst a member of the staff at Harwell. In 1990, when I moved to the University of Nottingham I expanded the material to a course for final year Master of Engineering students in Chemical Engineering. In addition, the work was adapted for post experience courses given for HTFS (then part of AEA Technology and now owned by Aspen Tech) for technical staff from industrial companies, for British Energy and at the International Centre for Mechanical Sciences in Udine, Italy. The presentation of some of those short courses was shared by Dr John Hills, now retired from Nottingham, and Dr Wayne Clark, now with BNFL, Berkeley. The contribution of John Hills to the development of ideas particularly regarding models for flow pattern transitions is much appreciated.

However, my interest in multiphase flow and gas/liquid flows in particular was first kindled when I joined the late Professor Michael Lacey of the Chemical Engineering Department at Exeter University as a PhD student. His approach made me appreciate the fascinating nature of gas/liquid flows. The interest in the subject was reinforced when I moved to the Department of Engineering Science at Oxford University and then to the Harwell Laboratory of United Kingdom Atomic Energy Authority. There, working with Professor Geoff Hewitt and the late Dr Peter Whalley, there were ample opportunities for studying bubbles, drops and waves in a most stimulating environment.

My moving to Nottingham in 1990 increased my involvement in bubbles through more of a decade of fruitful collaboration with Dr John Hills. John was always full of ideas, happy to discuss two-phase flow and, on our journeys to places around the world, a most knowledgeable and enthusiastic tourist. Thankfully John still comes in occasionally and shares some of the beauties of two-phase flow. Though I had had involvement with PhD students during the Harwell period, the move to Nottingham much increased my supervision. Working with these was a sharing experience.

Working in the field Has resulted in many international contacts, person with whom it has been and still is a pleasure to interact. There are many items in this volume which are only possible by the data contributed by these persons too numerous to name.

In preparing the material presented in this volume I have been guided by two desires. Firstly, I wanted to ensure that material over the whole history of two-phase flow was remembered. Secondly, I was seeking to bring out the communality of features across flow patterns and geometries. I trust I have, at least in part, succeeded.

Barry Azzopardi
Nottingham, October 2005

CHAPTER 1

INTRODUCTION

1.1 MULTIPHASE FLOW

In many branches of engineering the major preoccupation of those involved in research, design and operation is the flow of fluids. However, it is not the flow of just gases or of just liquids that they are focused on. An examination of the flows in many pieces of equipment from the hydrocarbon production, power generation and chemical industries would also reveal that many, if not most, flows involve more than one phase. In other words, multiphase flow is ubiquitous. It occurs in relatively simple equipment such as pipelines but also in the much more complex geometries found in heat exchangers, chemical reactors and phase separators. It will become clear from the material presented in this book that an understanding of multiphase flow is vital for the design of safe and environmentally friendly equipment, as well as for its construction at minimum capital cost and for its efficient operation.

In many cases, the two phases are gas (or vapour) and liquid. There are, however, many other possible combinations - solid/gas (fluidized beds, pneumatic conveying), solid/liquid (hydraulic conveying), two immiscible liquids (oil/water), and occasionally more than two phases (gas/oil/water). This text, however, concentrates on gas (or vapour)/liquid systems.

Multiphase flow is extremely complex. Its study has attracted much effort over a long period, and has resulted in a large number of equations and correlations, many of which are empirical.

1.2 GAS/LIQUID FLOW

Within multiphase flow gas/liquid flow probably occurs more than any other combination of phases. Research in this field initially developed as separate topics according to the motivating industry: oil/gas production; nuclear or fossil fuelled power generation; reboilers and condensers for the refining and chemical process industry. Nowadays there is much more contact and interchange between these groups. This is an important step as there is experimental evidence that there are distinct similarities between the behaviour of multiphase flows in equipment as diverse as oil or gas wells, thermal cracking furnaces and boiler tubes in power stations. In these examples, the fraction of vapour increases as the flow proceeds up the tube. In an oil well, this is because the

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