Fluid Dynamics of Packed Columns

Principles of the Fluid Dynamic Design of Columns for Gas/Liquid and Liquid/Liquid Systems
Jerzy Maćkowiak

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Translated by Claudia Hall
with the cooperation of Anna Ługowska-Czok

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Columns for distillation, absorption and extraction have been applied for years in chemical, petrochemical, food, energy and electronic industry. They are often equipped with different kinds of packings. Understanding of principles for packing design, internal traffic of phases within the column and implementing of theoretical models into industrial practice is of vital interest of both – students and practitioners. The book of Dr. J. Maćkowiak gives a deep insight into the fluid dynamics of packed columns. It is based on personal experience of the author and on a tremendous experimental data base on pressure drop (10,000 points), flooding points (1,2000 points) and liquid hold-up (1,100 points) measured for about 200 different types of random and structured packings. This is the biggest experimental data base published ever.

The big value of this book is also the theoretical model, called “Suspended Bed of Droplets” which is bases on the dependency between the flow resistance coefficient and packing shape. This model is predictive, i.e. it allows calculation of pressure drop and flooding gas velocity for unknown packing geometry. The model is valid for pressures from vacuum up to 100 bar and for specific liquid loads up to 250 m³ m⁻² h⁻¹. In this book the reader will find the sound theoretical analysis of two phase flow in packed column, extensive correlation of existing data for traditional and modern packings as well as practical equations which can be directly used in academic teaching courses and industrial applications.

Dr. J. Maćkowiak has committed to paper his 20 years experience as practitioner while operating company ENVIMAC GmbH and as researcher, publishing his results in journals and conference papers. Calculation methods of packed columns, presented in the book will increase the design accuracy of distillation, absorption and extraction which cause up to 60% of total processing costs in chemical industry.

Dortmund, February 2009

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Foreword by Prof. Dr. Ing. A. Mersmann, Technical University of Munich

For many years now, packed columns have been used in various domains, such as diffusional separation technology, environmental technology and biotechnology, providing a mass transfer contact area for gases and liquids. In recent decades, scientific as well as economic factors have continually led to new and more efficient packings being designed. The industry is striving to accurately dimension modern packings made with new materials and innovative geometric designs and to operate them in a reliable manner. This requires first of all the compilation and general presentation of experimental data, a difficult and time-consuming task, which the author has been undertaking for many years.

This work is based on more than 10,000 experimental pressure drop data, in excess of 1,100 liquid hold-up data and more than 1,200 flooding point data for approx. 160 different random and structured packings made of various materials commonly used in practice. The majority of this data was compiled by the author in an accurate and reproducible manner whilst working for the Institute of Thermal Separation Processes at Bochum University. This book exceeds all publications worldwide in terms of its volume of data, and the industry will be grateful to the author as well as Springer Publishing for its publication.

It is my hope and wish that, for the benefit of mankind, the comprehensive and accurate results and conclusions of this work will lead to an improvement in the design and operation of packed columns.

Alfons Mersmann
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Preface

The first German edition of the book “Fluid dynamics of packed columns with modern random and structured packings for gas/liquid systems” was published in 1991. It sold out within a few years. Added to this were numerous enquiries, in particular within the industry, prompting me to publish a second, extended edition.

A packed column remains the core element of any diffusional separation process. This underlines the need for basic design principles for packed columns, which enhance the design process by making it more accurate and reliable.

The SBD (suspended bed of droplets) model introduced in the first German edition of the book was well received by the experts and is now used by a large number of companies in the industry, as it offers improved reliability in the fluid dynamic design of packed columns. For the purpose of facilitating the design process, the SBD model was integrated into the simulation programme ChemCAD. The software programme FDPAK, which is available for Windows, has certainly contributed to the widespread use of the SBD model. The programme is very user-friendly and the calculation results are presented in tabular as well as graphic form, showing flood load, pressure drop and hold-up diagrams in the entire operating range.

The first German edition concentrates on the description of the fluid dynamics of columns with random and structured packings in the vacuum and normal pressure range of up to approx. 2 bar and for specific liquid loads of up to 100 m$^3$m$^{-2}$h$^{-1}$ for gas-liquid systems. This range covers a majority of the applications and tasks relevant in the absorption and desorption of highly and/or moderately soluble gases as well as in rectification under vacuum and normal pressure.

The importance of absorption and rectification under high pressure has steadily increased in the past 10 years, calling for an upgrading of the existing model. Fortunately, new publications emerged during the last 15 years, presenting experimental data on pressure drop, flooding point and hold-up parameters for high-pressure systems. Based on this, it was possible to and expand the validity of the correlation derived in the first German edition for determining the hold-up at flooding point to include the range of high liquid loads and therefore higher hold-up parameters (Chap. 2).

Using the SBD model, it is now possible to describe operations under higher pressure, which is very significant in practice, as it is linked to high liquid loads and low gas velocities. The SBD model has been verified using experimental data taken at high pressure of
up to 100 bar. There are some practical numerical examples at the end of each chapter, which provide an insight into the application of the model.

The current edition will introduce a generally valid procedure of the single pressure drop calculating based on the knowledge of the form factor $P$ and an additional model for calculating the pressure drop of irrigated structured and random packings, based on the knowledge of the law of resistance $\psi_{LV} = f(Re_L)$ for two-phase counter-current flows and of the liquid hold-up $h_{L0}$ in the entire operating range up to flooding point. This model is suitable for applications, in which the only available data for determining the law of resistance is experimental pressure drop data for a two-phase system (no given pressure drop data for dry random packings), or in which the pressure drop above the loading line for low viscous mixtures needs to be determined more accurately.

A large amount of experimental data has shown that this model generates satisfactory results up to flooding point for laminar $Re_L < 2$ as well as for turbulent liquid flow $Re_L > 2$.

The correlation for determining the gas velocity at flooding point introduced in the first edition has been modified further and can now also be applied to any type of structured packing, tube columns with regularly stacked Pall rings, Hiflow rings and Białecki rings and regularly stacked layers of Pall rings, Raschig rings, Hiflow rings and Białecki rings. Following the latest findings, it has been possible to mathematically compute various loading capacities of structured column internals of types X and Y with flow channels at different gradients. This has also been taken into account in the expanded general correlation for calculating the gas velocity at flooding point, which makes this correlation applicable to any type of column internal.

Chapter 7 introduces for the first time the basic fluid dynamics principles of packed columns for liquid/liquid extraction. The previously mentioned SBD model for gas/liquid systems is transferable to liquid/liquid systems. The method used to calculate the gas velocity at flooding point of the disperse and continuous phases will be explained by means of some numerical examples.

The guiding idea behind this book was to develop a closed, consistent concept for designing packed columns for gas/liquid and liquid/liquid systems, in order to make the calculation of individual parameters more transparent and create a basis for objective comparisons between different column internals.

In contrast to other studies, this book uses a different approach for logging processes within packed columns, which is based on the specific flow behaviour of droplet systems. The occurrence of droplet systems in packed columns was confirmed by Bornhütter and Mersmann in 1991. Hence, despite the highly complicated processes of two-phase flows in packed columns, it was possible to form straightforward, user-friendly correlations, which are ideal for practical applications when it comes to developing solutions for a wide range of tasks. The simple correlations are particularly advantageous when comparing a large number of different columns internals. In addition, this book should help scientists as well as students to gain a better understanding of flow processes in gas/liquid and liquid/liquid systems.

As opposed to other studies, this book draws on the publications of other authors to support and expand the application ranges of the SBD model. However, it does not use
them for the illustration and comparison of different calculation models. This work is based on more than 10,000 experimental pressure drop data, in excess of 1,200 flooding point data and approx. 1,100 liquid hold-up data for nearly 200 different types of packings. Compared to the 1st edition, the figures have more or less doubled.

What is particularly significant from a scientific point of view, is the knowledge that the experimental work and test systems under vacuum and high pressure previously required for the research and development of new types of column design can be reduced to just a few steps, thus allowing the user to determine the model parameters of the SBD model fast and with minimal experimental effort using the air/water test system. It is worth noting that tests using single-phase air flows under ambient conditions are sufficient to determine the system-independent law of resistance \( \psi = f(Re \nu) \). In the case of simple types of packing, it is possible to determine the resistance factor of single-phase flow simply based on the geometric configuration without requiring experimental evidence, as described in Chap. 3. It is therefore possible to transfer the entire fluid dynamics of one type of column internal to any application in diffusional separation technology.

J. Maćkowiak
Summary

For many years now, there has been a constant demand for low pressure drop column internals in rectification, absorption, stripping and liquid/liquid extraction. The prevailing trend in the chemical industry is to replace tray columns with those containing modern structured and random packings. When planning the design of packed columns, it therefore particularly important to use reliable methods for predicting the mass transfer and hydrodynamic behaviour of the two-phase flow.

For this reason, the book is aimed at illustrating the basic principles of the fluid dynamic design of columns with modern random and structured packings, using a new design concept which can be applied to any type of packing.

One of the author’s priorities was the practical aspect of the work, since the standard approach to rectification, absorption and extraction as the core areas of thermal process engineering is purely empirical.

The design data for gas/liquid and liquid/liquid systems presented in the current edition are strongly interlinked and based on the SBD model for both systems.

The design process for gas/liquid systems is based on correlations which have been experimentally derived and verified. The process allows the calculation of the flooding point, pressure drop and hold-up for gas/liquid systems virtually in the entire operating range up to flooding point. The following features of the process should be highlighted:

The model parameters are calculated for a given packing density using the water/air system under normal conditions. The experiments conclude that these model parameters for the separation of mixtures in rectification technology in the vacuum to high pressure range are applicable for the entire operating range. Hence, the experimental work can be minimised to just a few steps using only the air/water system under normal conditions.

The model also allows the calculation of flooding point and hold-up parameters for liquid/liquid systems virtually in the entire operating range up to flooding point.
The content of this book is divided into seven chapters. The first six chapters deal with gas/liquid systems (Part 1); Chapter 7 is dedicated to liquid/liquid extraction. The structure of the first five chapters largely matches the calculation steps applied in the fluid dynamic design of packed columns for gas/liquid systems. Chapter 1 briefly describes the structure of packed columns and their significance for the separation of mixtures under vacuum conditions as well as for absorption and desorption. It also outlines the design processes commonly used today. This is followed by an analysis of the hydraulic behaviour of packed columns and their relevant parameters, with Chap. 2 examining the flooding point of the lower operating range and Chap. 3 determining the pressure drop of dry random packings. Chapters 4 and 5 deal with the pressure drop of irrigated random packings and their liquid hold-up parameters.

The correlations derived in Chaps. 2, 3 and 4 can be used to calculate the apparatus diameter and determine the pressure drop and liquid hold-up in a given operating range and at flooding point.

For the purpose of illustrating the topics, each chapter begins with a brief overview of the most relevant work on the respective topic as judged by the author, followed by the presentation of the chosen approach.

The results of this work are summarised in Chap. 6. The Tables 6-1a–c contain the geometric column data, such as packing density N₀, specific geometric surface of packing elements a₀, void fraction ε₀, specific weight G of 1 m³ according to the manufacturer. In addition, the chapter contains all numerical values of the parameters required for the fluid dynamic design of approx. 200 randomly and regularly stacked packing elements well as tube columns and structured packings.

By using the equations derived for the calculation of each parameter, it was possible to condense the extensive research material, which is discussed in the summary of the results of this work in Chap. 6. The end of each chapter contains example calculations to illustrate the individual correlations for determining the vapour load factor at the flooding point of the liquid hold-up as well as the pressure drop of irrigated and dry random packing elements. The numerical examples are practice-oriented and explain the correlations mentioned before, based on the examples of different packings.

The references relating to the individual chapters are listed at the end of each chapter. The book boasts comprehensive tables and charts with information on experimental data and test conditions, highlighting the enormous volume of tests as well as the scope
of application offered by this process. Following Chap. 6 is a description of FDPAK, the well-known and extensively used software programme for the fluid dynamic design of packed columns.

The correlations most commonly used in this work are compiled and explained in a separate list of symbols at the beginning of the book.

The first German edition of the book was written between 1988 and 1990 and the second one evolved between 1997 and 2002. The first English addition is based on experimental data stemming from more than 200 – mostly modern – random and structured packings between 1965 and 2008.

The tests were mainly carried out by the author using distillation plants with diameters of 0.15/0.22/0.5 m and absorption plants with diameters of 0.15/0.22/0.3 m and 0.45/0.6 m as well as industrial plants with diameters of 0.8/1.2/1.6/1.8/3 m owned by ENVIMAC Engineering GmbH. A considerable amount of test data on rectification ($d_S = 0.5$ m) and absorption ($d_S = 0.3$ m) originates from the author’s work as Scientific Assistant at the Institute for Chemical Engineering, Technical University of Wrocław/Polen (1970–1976). In co-operation with Dr. Ing. S. Filip, Dr. Ing. Z. Ługowski, Dr. Ing. S. Suder and Dr. Ing. habil. A. Koziol from the Technical University of Wrocław, the author carried out a number of studies on modern packings at industrial plants, which are also referred to in this monograph. Some of the test results, in particular the rectification data for metal Pall rings (15–80 mm), stem from the findings of Prof. Billet. Further test data on extraction and rectification processes were taken from a number of scientific studies, which were personally conceived and overseen by the author at the Institute for Thermal Separation Processes at Bochum University, under Prof. Dr. Ing. R. Billet.

In 1990, a database was created for the purpose of evaluating all experimental data, including literature data. It currently holds more than 1,200 experimental flooding point data, in excess of 1,100 liquid hold-up data and more than 10,000 pressure drop data for irrigated random and structured packings. The number of test mixtures is 32. The result is a comprehensive data pool, which is constantly being updated with the addition of new experimental data.

The progress in terms of the accuracy in designing packed columns for gas/liquid and liquid/liquid system is considerable. The results of this work have led to accurate predictions of the fluid dynamic behaviour of random packing elements, simply based on their geometric form without requiring any chemical engineering tests.
A special thank you goes to Prof. Dr. Ing. A. Mersmann, Technical University of Munich, for many fruitful discussions and valuable suggestions for the draft of the first German edition, Prof. Dr.-Ing. A. Górak, Technical University of Dortmund, for reviewing the first English edition, as well as to my friend Prof. Dr. Ing. habil. A. Koziol, Technical University of Wroclaw and Dr. Ing. J. Szust, ENVIMAC Engineering GmbH, for his contribution towards the development of the FDPAK programme and evaluating the flooding point data.

My son, Dipl. Ing. Jan Maćkowiak, proof-read the second German edition thoroughly and converted it to the correct format for printing.

Mrs Dipl. Ing. Anna Ługowska-Czok prepared the first English edition for printing and produced the complex graphs showing flooding point and pressure drop parameters in order to illustrate the spread of the experimental data.

I would also like to thank Mrs Claudia Hall for the translation of this book as well as her co-operation and valuable contributions to the English edition.

I would particularly like to thank my wife Nathalie and my children Jan and Anna for their patience, and all those who have supported me in writing this book.

Jerzy Maćkowiak, 2009