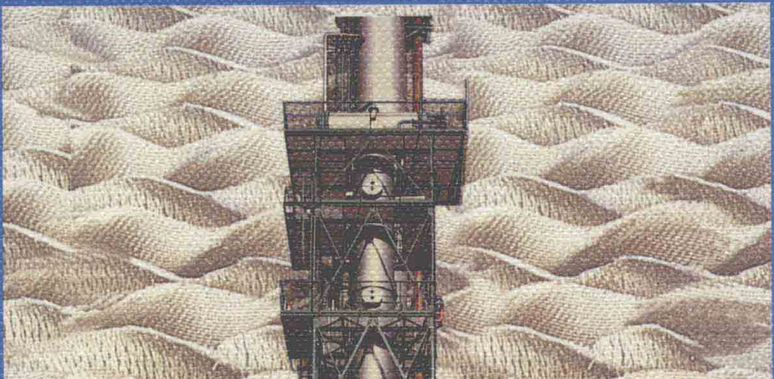
Reinhard Billet

Packed Towers

in Processing and Environmental Technology



VCH

Reinhard Billet

Packed Towers

in Processing and Environmental Technology

Translated by James W. Fulla ton

VCH
Weinheim · New York · Basel · Cambridge · Tokyo

Professor Dr.-Ing. Reinhard Billet
Institut für Thermo- und Fluiddynamik
Fakultät für Maschinenbau
Ruhr-Universität Bochum
Universitätsstraße 150
D-44801 Bochum

Published jointly by
VCH Verlagsgesellschaft mbH, Weinheim (Federal Republic of Germany)
VCH Publishers, Inc., New York, NY (USA)

Editorial Directors: Louise Elsam, Karin Sora
Production Manager: Peter Biel

Library of Congress Card No. applied for.

British Library Cataloguing-in-Publication Data:
A catalogue record for this book is available from the British Library.

Die Deutsche Bibliothek – CIP-Einheitsaufnahme
Billet, Reinhard:
Packed towers in processing and environmental technology/
Reinhard Billet. Transl. by James W. Fullarton. – 1. ed. –
Weinheim ; New York ; Basel ; Cambridge ; Tokyo : VCH, 1995
ISBN 3-527-28616-0

Printed on acid-free and low-chlorine paper

Composition: Hagedornsatz GmbH, D-68519 Viernheim
Printing: Betzdruck GmbH, D-64219 Darmstadt
Bookbinding: Industrie- und Verlagsbuchbinderei Heppenheim GmbH, D-64646 Heppenheim

Printed in the Federal Republic of Germany

Reinhard Billet

Packed Towers

VCH

Distribution:
VCH, P.O. Box 10 11 61, D-69451 Weinheim (Federal Republic of Germany)
Switzerland: VCH, P.O. Box, CH-4020 Basel (Switzerland)
United Kingdom and Ireland: VCH, 8 Wellington Court, Cambridge CB1 1HZ (United Kingdom)
USA and Canada: VCH, 220 East 23rd Street, New York, NY 10010-4606 (USA)
Japan: VCH, Eikow Building, 10-9 Hongo 1-chome, Bunkyo-ku, Tokyo 113 (Japan)

ISBN 3-527-28616-0

Preface

In the chemical and allied industries, there is a continuously rising trend towards separation processes that are operated in packed columns with systematically stacked or randomly dumped beds. It was initiated by the 1973 oil crisis and the associated demand for saving fuel by optimum design and operation of the processes. Another factor that has contributed towards the widespread adoption of packed beds in industry has been the increasing severity of ecological legislation. Since they can be operated under more moderate conditions, packed columns are superior to plate columns in coping with the demands of saving energy and protecting the environment.

Thus packed columns can offer the following advantages:

- They allow lower energy consumption in separation processes that entail a large number of theoretical stages.
- They can more readily satisfy the requirements for the economic use of heat pumps.
- They permit thermally instable mixtures to be separated at lower temperatures at the foot of the column and can thus minimize or even completely avoid products of decomposition or polymerization reactions that may be responsible for pollution.
- In absorbers, particularly those for off-gas scrubbing, they require compressors of lower power ratings than those installed in plate columns.

Beds of packing are also being used to an increasing extent for direct heat transfer between liquids and gases (or vapours) and for liquid-liquid extraction. The trend runs parallel to striking improvements in the design of traditional packing and has also led to the development of completely new packing geometries. However, the results obtained in process engineering studies did not always agree satisfactorily with the traditional relationships given in the literature. Consequently, research work had to be directed at devising new correlations and models for the efficiency and operating characteristics of packed columns with the aim of developing physically well-founded design methods that are applicable to all types of packing used in industry. The book "Packed Towers in Processing and Environmental Technology" is intended as a contribution towards this aim.

The reliability of the methods presented here has been demonstrated by results gained in comprehensive experiments that embraced more than sixty types of metallic, ceramic, and plastics packing of various geometries and dimensions and were performed on systems that covered a wide range of physical properties in the liquid and the gas or vapour phases.

These pilot-plant experiments were carried out over a period of more than 20 years in the course of the author's activities in research and industry. The results thus obtained provided a sound basis upon which a theoretical model could be developed to describe the hydrodynamics and mass transfer in packed columns. The experiments also served to verify the scientific accuracy of the models and thus to ensure close agreement between theory and practice.

The author has presented papers on the subject at meetings held by various engineering institutions, including the VDI, EFCE and AIChE, and at the ACHEMA, CHISA and ACHEMASIA fairs. He has also held seminars on packed columns, e.g. in the Conicet Institute, Santa Fe and Bahia Blanca, Argentina; at the Glitsch Symposium in Dallas, Texas, USA; the Korean Institute of Energy Research in Taejon, South Korea; the Petrobras in Rio de Janeiro; the Belo Horizonte University in Brazil, and the Tientsin University in China. The book has been written in response to many requests for a review of the engineering aspects in packed columns.

The author wishes to take this opportunity of expressing his most sincere thanks to all those who assisted him in the experimental work, to Dr. M. Schultes for his valuable cooperation in evaluating the examples, to M. Ernst for her commitment in typing the German manuscript, to Th. Cipa for his assistance in proof-reading, and – in particular – to J. W. Fullarton for translating the work into English.

Bochum, January 1994 R. Billet

Biography

Reinhard Billet gained his Dipl.-Ing. (in 1953) and Dr.-Ing. (in 1957) degrees in Process and Chemical Engineering at the Technical University of Karlsruhe. From 1954–1960, he was a Scientific Assistant under Professor E. Kirschbaum at the Plant and Process Engineering Institute of Karlsruhe University. In 1960, he joined the staff of the BASF Chemical Engineering Research Department and was subsequently involved in plastics production, plant design, environmental protection, and industrial safety.

In 1975, he was appointed Professor of Process Engineering and called to the Chair for Thermal Separation Processes; and 1992, to the Chair for Process and Environmental Engineering at the Ruhr-University of Bochum. During the period 1983/1984, he acted as the Dean of the Faculty of Mechanical Engineering.

Professor Billet was awarded the Ring of Honour of the German Institute of Engineers (VDI) in 1964; and, in 1986, the Medal for Outstanding Merit, by the Technical University of Wroclaw.

Most of his research work has been in the fields of evaporation, distillation, absorption, liquid-liquid extraction, and environmental engineering. He has written over 200 scientific articles, four university booklets, and three monographs in German. His book „Industrielle Destillation“ has been translated into English, Czechoslovakian, and Chinese; „Verdampfung und ihre technischen Anwendungen“, into English and Chinese; and „Energieeinsparung bei thermischen Stofftrennverfahren“, into Polish. The “Proceedings of the Packed Column Analysis and Design Seminar” is also available in Korean and Chinese. The results of his research work have been presented at national and international congresses and meetings.

Professor Billet is a member of the VDI Panel of Experts on the thermal separation of gases and liquids and the European Federation of Chemical Engineering (EFCE) Working Party on Distillation, Absorption and Extraction. He is also a member of the New York Academy of Sciences.

Key to symbols

a	$[\mathrm{m}^2/\mathrm{m}^3]$	total surface area per unit packed volume
a'	[s/m]	packing area per unit efficiency and per unit volumetric vapour flow rate
a_h	$[\mathrm{m}^2/\mathrm{m}^3]$	hydraulic area of packing per unit volume of packed bed
a_{Ph}	$[\mathrm{m}^2/\mathrm{m}^3]$	effective interfacial area per unit packed volume
a_s	[m/s]	column shell area per unit efficiency and per unit volumetric vapour flow rate
A	[s/m]	constant, specific for the packing
A_h	$[\mathrm{m}^2]$	cross-sectional area of an individual channel
A_p	$[\mathrm{m}^2]$	total area of packing
A_s	$[\mathrm{m}^2]$	free cross-sectional area
B	[s]	constant, specific for the packing
$\dot{B}$	[kmol/h];[kg/h]	flow rate of bottom product
c	$[\mathrm{kmol/m}^3]$	concentration
c_P	$[\mathrm{DM/m}^3]$	costs per unit volume of packing
c_{Ps}	[DM/m]	costs per unit height of column
c_r	[DM]	costs for one redistributor in a column of diameter d_S
c_s	$[\mathrm{DM/m}^2]$	costs per unit area of column shell
C	[DM]; $[\mathrm{DM/m}^3]$	costs; costs per unit volume of the packed column
C_C	[DM]	capital investment costs for a packed column
C_h		packing constant to allow for liquid holdup
C_L		packing constant to allow for mass transfer in liquid
C_P		packing constant to allow for pressure drop
C_S		costs of the packing to be evaluated in relation to those of a random bed of 50-mm Pall rings
C_V		packing constant to allow for mass transfer in gas
d	[m]	size of an element of packing
d_h	[m]	hydraulic diameter
d_P	[m]	particle diameter
d_s	[m]	column diameter
D	[DM/m]	costs factor, specific for the material and method of production of the packing
D	$[\mathrm{m}^2/\mathrm{s}]$	diffusion coefficient of transferring component
$\dot{D}$	[kmol/h];[kg/h]	flow rate of distillate (overhead product)
e		relative efficiency, or energy parameter
E	$[\mathrm{DM/m}^2]$	costs factor, specific for the material and method of construction of column shell
E_C		column efficiency
E_V	[1/s]	volumetric packing efficiency
f_S		wall factor
f_V		vapour load factor
f_W		wetting factor

F	[DM/m^3]	costs factor, specific for the material and method of construction of column shell
$\dot{F}$	[kmol/h];[kg/h]	flow rate of feed
F_V	[kg$^{1/2}$m$^{-1/2}$s^{-1}]	vapour capacity factor related to the free column cross-section
g	[m/s^2]	acceleration due to gravity
h	[kJ/kmol]	molar enthalpy
Δh	[kJ/kmol]	molar condensation; evaporation enthalpy
h_L	[m^3/m^3]	liquid holdup
H	[m]	effective height of fill of column packing
H_i	[m]	height of inlet zone in a bed of packing
HTU	[m]	height of a mass transfer unit
HTU_O	[m]	overall height of a mass transfer unit
k	[m/s]	overall mass transfer coefficient
K	[DM s/m^3]	total costs, i. e. for the bed of packing and the column shell, per unit efficiency and per unit volumetric vapour flow rate
K_p; K_s	[DM s/m^3]	packing costs per unit efficiency and per unit volumetric vapour flow rate
l_τ	[m]	length of flow path for phase contact
L	[kmol/h]	flow rate of carrier liquid
$\dot{L}$	[kmol/h];[kg/h]	flow rate of liquid
m_{yx};m_{YX}	[kmol/kmol]	slope of equillibrium line
M		maldistribution
n_h		number of flow channels
n_t		number of theoretical stages corresponding a bed height H
N		number of separation units
N	[m^{-3}]	packing density
NTU		number of transfer units in a phase
NTU_O		number of overall transfer units
p	[bar];[mbar]	pressure
Δp	[mbar];[mmWG]	pressure drop
P	[bar];[mbar]	boiling pressure of a component
q		liquid distribution coefficient
$\dot{Q}$	[kJ/h]	energy consumption
s	[m]	film thickness
s	[m]	thickness of the basic material, i. e. sheet, foil or fibre, of the packing elements
$\dot{S}$	[kmol/h]	flow rate of carrier steam
t	[s]	time
t_L	[s]	liquid phase residence time
T	[K]	temperature
u_L	[m^{3}m^{-2}s^{-1}]	liquid load (also related to hour)
$\bar{u}_L$	[m/s]	local liquid velocity
u_V	[m/s]	superficial gas or vapour velocity
$\bar{u}_V$	[m/s]	average effective gas or vapour velocity
v'	[s]	volume of packing material per unit efficiency and volumetric gas or vapour load

v_V	[$m^3/(m^3/s)$]	specific column volume
V	[kmol/h]	flow rate of carrier gas
$\dot{V}$	[kmol/h];[kg/h]	flow rate of gas or vapour
w	[kg/m^3]	specific gravity of packing
w'	[$kg\ m^{-3}s^{-1}$]	packing weight per unit volumetric flow rate of gas or vapour and unit efficiency
x	[kmol/kmol]	mole fraction in liquid phase
X	[kmol/kmol]	molar load fraction of transfer component in liquid
y	[kmol/kmol]	mole fraction in gas or vapour phase
Y	[kmol/kmol]	molar load fraction of transfer component in gas or vapour
Z	[m^{-2}]	number of liquid distributor outlets
Z_h	[m^{-2}]	number of flow channels per unit area of column cross-section

Greek symbols

α		relative volatility
β	[m/s]	mass transfer coefficient
ε	[m^3/m^3]	void fraction of packing
η		efficiency
η	[$kg\ m^{-1}s^{-1}$]	dynamic viscosity
η_C		column efficiency
λ		stripping factor
μ	[kg;kmol]	molecular mass; molar mass
ν	[m^2/s]	kinematic viscosity
ξ		coefficient of resistance
ϱ	[kg/m^3]	mass density
σ	[kg/s^2]	surface tension
τ	[s]	duration of contact between the phases
τ_V	[N/m^2]	shear stress in gas flow
$\varnothing$		diameter ratio
ψ		flow parameter

Subscripts

B	bottom product
C	continuous phase
D	distillate (overhead product)
e	effective
F	feed
Fl	flood point
L	liquid
o	surface
P	pilot plant
Ph	interface

s	film thickness; column shell
S	loading point
T	technical or industrial scale
V	vapour or gas
W	wetting

Dimensionless numbers

Fo	Fourier number
Fr	Froude number
Ma	Marangoni number
Re	Reynolds number
Sc	Schmidt number
We	Weber number

Contents

1 Introduction

The clamour for energy-saving techniques in almost all branches of industry has acted as a spur in the development of thermal separation equipment. The design and process engineering improvements that have ensued entail that feedstocks are subjected to less severe treatment and can thus be optimally exploited. They also entail production under ecologically favourable conditions (cf. Fig. 1.1).

A typical example is provided by low-pressure-drop packing in the vacuum rectification of mixtures that are unstable to heat and that necessitate a large number of theoretical stages for their thermal separation. The attendant decrease in the total pressure drop and operation under vacuum ensure that the temperature at the bottom of the column is comparatively low. Hence, decomposition products that are detrimental to the environment can be largely avoided, i. e. atmospheric pollution is reduced and less residues have to be disposed of. Another advantage is that the reduction in the average column pressure brought about by vacuum operation increases the average relative volatility of the components in the mixture and thus reduces energy consumption.

Low-pressure-drop, high-performance packing is an essential requirement in the economic design of an integrated separation plant, because it permits heat pumps to be installed and a number of columns to be linked together.

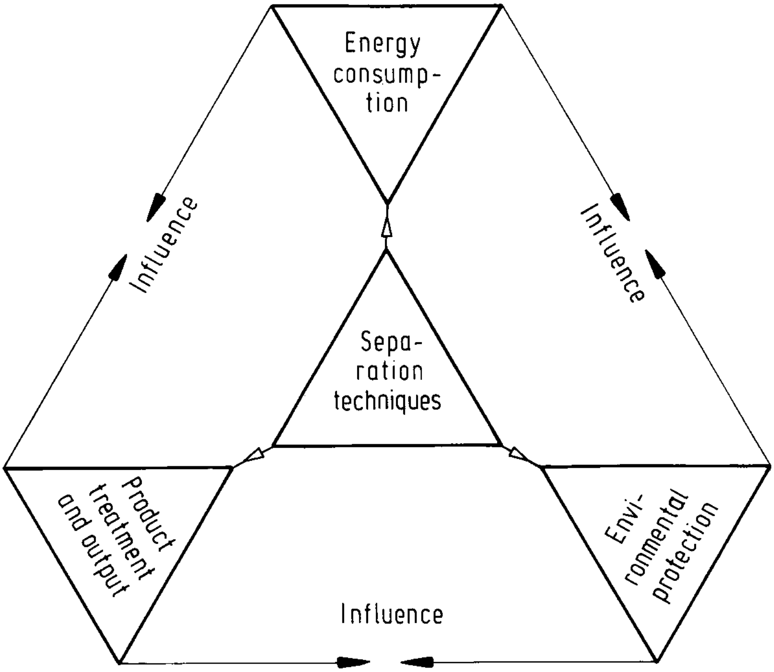


Fig. 1.1. Relationships established by separation techniques between energy consumption, processing and environmental protection