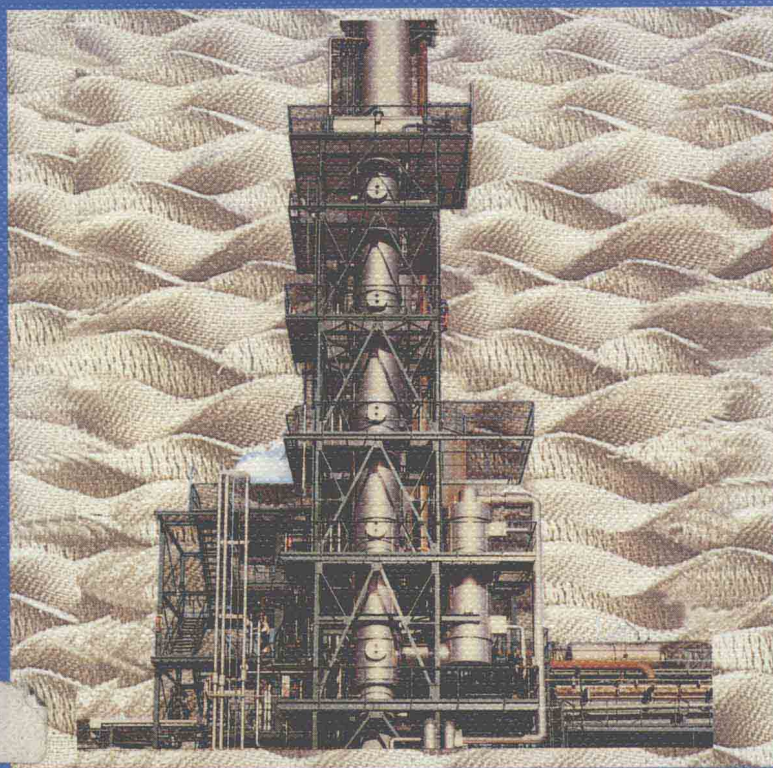


Reinhard Billet

# Packed Towers

in Processing and  
Environmental Technology



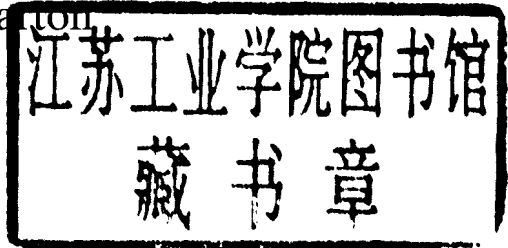
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# Packed Towers

in Processing and  
Environmental Technology

Translated by James W. Fullerton



Weinheim · New York · Basel · Cambridge · Tokyo

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Reinhard Billet

# **Packed Towers**



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## 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 AICHEMA, CHISA and AICHEMASIA 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 Wrocław.

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

$a$	$[\text{m}^2/\text{m}^3]$	total surface area per unit packed volume
$a'$	$[\text{s}/\text{m}]$	packing area per unit efficiency and per unit volumetric vapour flow rate
$a_h$	$[\text{m}^2/\text{m}^3]$	hydraulic area of packing per unit volume of packed bed
$a_{ph}$	$[\text{m}^2/\text{m}^3]$	effective interfacial area per unit packed volume
$a_s$	$[\text{m}/\text{s}]$	column shell area per unit efficiency and per unit volumetric vapour flow rate
$A$	$[\text{s}/\text{m}]$	constant, specific for the packing
$A_h$	$[\text{m}^2]$	cross-sectional area of an individual channel
$A_p$	$[\text{m}^2]$	total area of packing
$A_s$	$[\text{m}^2]$	free cross-sectional area
$B$	$[\text{s}]$	constant, specific for the packing
$\dot{B}$	$[\text{kmol}/\text{h}]; [\text{kg}/\text{h}]$	flow rate of bottom product
$c$	$[\text{kmol}/\text{m}^3]$	concentration
$c_p$	$[\text{DM}/\text{m}^3]$	costs per unit volume of packing
$c_{ps}$	$[\text{DM}/\text{m}]$	costs per unit height of column
$c_r$	$[\text{DM}]$	costs for one redistributor in a column of diameter $d_s$
$c_s$	$[\text{DM}/\text{m}^2]$	costs per unit area of column shell
$C$	$[\text{DM}]; [\text{DM}/\text{m}^3]$	costs; costs per unit volume of the packed column
$C_C$	$[\text{DM}]$	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
$d$	$[\text{m}]$	size of an element of packing
$d_h$	$[\text{m}]$	hydraulic diameter
$d_p$	$[\text{m}]$	particle diameter
$d_s$	$[\text{m}]$	column diameter
$D$	$[\text{DM}/\text{m}]$	costs factor, specific for the material and method of production of the packing
$D$	$[\text{m}^2/\text{s}]$	diffusion coefficient of transferring component
$\dot{D}$	$[\text{kmol}/\text{h}]; [\text{kg}/\text{h}]$	flow rate of distillate (overhead product)
$e$		relative efficiency, or energy parameter
$E$	$[\text{DM}/\text{m}^2]$	costs factor, specific for the material and method of construction of column shell
$E_C$		column efficiency
$E_V$	$[\text{l}/\text{s}]$	volumetric packing efficiency
$f_s$		wall factor
$f_V$		vapour load factor
$f_W$		wetting factor

XIV *Key to symbols*

$F$	[DM/m <sup>3</sup> ]	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 <sup>1/2</sup> m <sup>-1/2</sup> s <sup>-1</sup> ]	vapour capacity factor related to the free column cross-section
$g$	[m/s <sup>2</sup> ]	acceleration due to gravity
$h$	[kJ/kmol]	molar enthalpy
$\Delta h$	[kJ/kmol]	molar condensation; evaporation enthalpy
$h_L$	[m <sup>3</sup> /m <sup>3</sup> ]	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 <sup>3</sup> ]	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 <sup>3</sup> ]	packing costs per unit efficiency and per unit volumetric vapour flow rate
$l_r$	[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 equilibrium 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 <sup>-3</sup> ]	packing density
$NTU$		number of transfer units in a phase
$NTU_O$		number of overall transfer units
$p$	[bar];[mbar]	pressure
$\Delta p$	[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 <sup>3</sup> m <sup>-2</sup> s <sup>-1</sup> ]	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

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

### Greek symbols

$\alpha$		relative volatility
$\beta$	$[\text{m}/\text{s}]$	mass transfer coefficient
$\epsilon$	$[\text{m}^3/\text{m}^3]$	void fraction of packing
$\eta$		efficiency
$\eta$	$[\text{kg m}^{-1}\text{s}^{-1}]$	dynamic viscosity
$\eta_C$		column efficiency
$\lambda$		stripping factor
$\mu$	$[\text{kg};\text{kmol}]$	molecular mass; molar mass
$\nu$	$[\text{m}^2/\text{s}]$	kinematic viscosity
$\xi$		coefficient of resistance
$\rho$	$[\text{kg}/\text{m}^3]$	mass density
$\sigma$	$[\text{kg}/\text{s}^2]$	surface tension
$\tau$	$[\text{s}]$	duration of contact between the phases
$\tau_V$	$[\text{N}/\text{m}^2]$	shear stress in gas flow
$\varnothing$		diameter ratio
$\psi$		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

**XVI**     *Key to symbols*

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

**Dimensionless numbers**

<i>Fo</i>	Fourier number
<i>Fr</i>	Froude number
<i>Ma</i>	Marangoni number
<i>Re</i>	Reynolds number
<i>Sc</i>	Schmidt number
<i>We</i>	Weber number

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# 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.

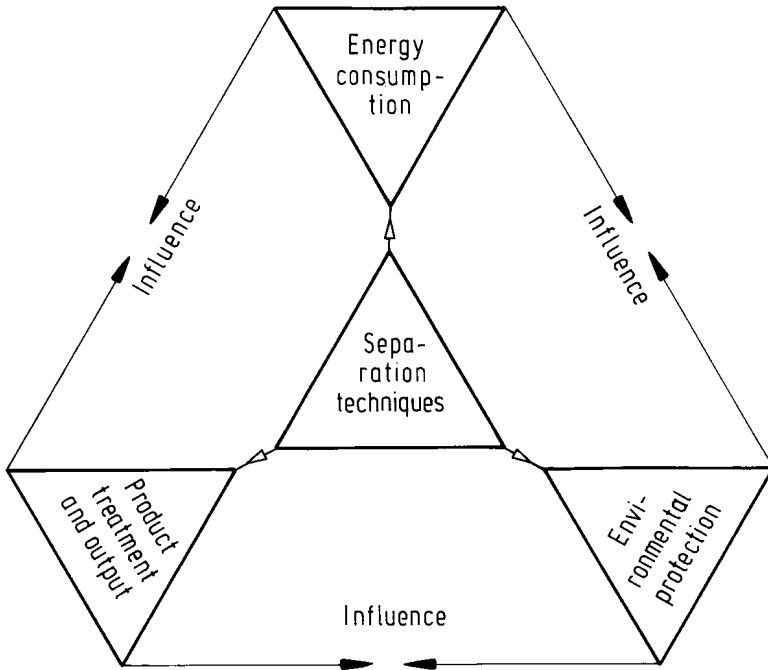


Fig. 1.1. Relationships established by separation techniques between energy consumption, processing and environmental protection