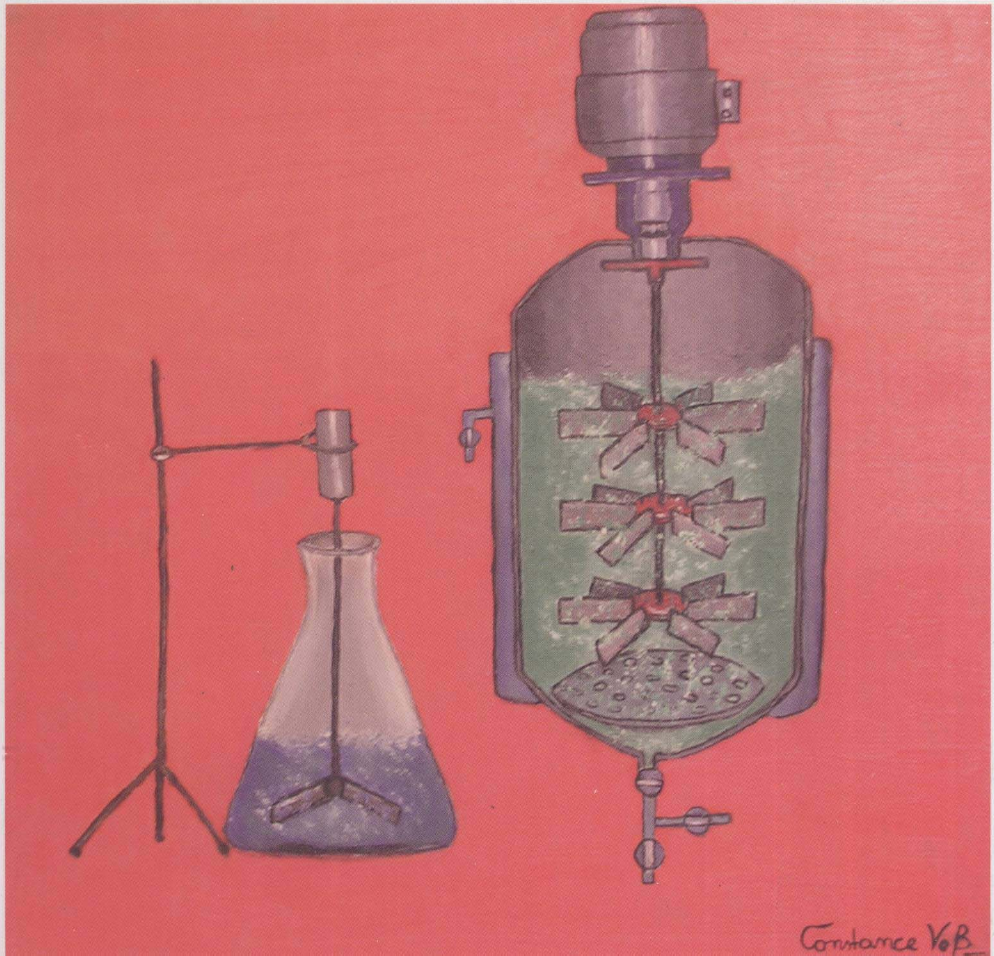
Marko Zlokarnik

WILEY-VCH

Scale-up in Chemical Engineering

Second, Completely Revised and Extended Edition



Marko Zlokarnik

Scale-Up in Chemical Engineering

Second, Completely Revised and Extended Edition

WILEY-VCH

WILEY-VCH Verlag GmbH & Co. KGaA

Author

Prof. Dr.-Ing. Marko Zlokarnik
Grillparzerstr. 58
8010 Graz
Austria
E-Mail: zloka@nextra.at

1st Edition 2002
2nd, Completely Revised and Extended Edition 2006

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.

Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the Internet at <http://dnb.ddb.de>.

Printed in the Federal Republic of Germany.
Printed on acid-free paper.

Typesetting Kühn & Weyh, Satz und Medien, Freiburg
Printing Betzdruck GmbH, Darmstadt
Bookbinding Litges & Dopf Buchbinderei GmbH, Heppenheim
Cover Design aktivComm, Weinheim
Front Cover Painting by *Ms. Constance Voß*, Graz 2005

ISBN-13: 978-3-527-31421-5
ISBN-10: 3-527-31421-0

Preface to the 1st Edition

In this day and age, chemical engineers are faced with many research and design problems which are so complicated that they cannot be solved by numerical mathematics. In this context, one only has to think of processes involving fluids with temperature-dependent physical properties or non-Newtonian flow behavior. Fluid mechanics in heterogeneous physical systems exhibiting coalescence phenomena or foaming, also demonstrate this problem. The scaling up of equipment needed for dealing with such physical systems often presents serious hurdles which can frequently be overcome only with the aid of partial similarity.

In general, the university graduate has not been adequately trained to deal with such problems. On the one hand, treatises on dimensional analysis, the theory of similarity and scale-up methods included in common, "run of the mill" textbooks on chemical engineering are out of date. In addition, they are seldom written in a manner that would popularize these methods. On the other hand, there is no motivation for this type of research at universities since, as a rule, they are not confronted with scale-up tasks and are therefore not equipped with the necessary apparatus on the bench-scale.

All of these points give the totally wrong impression that the methods referred to are – at most – of only marginal importance in practical chemical engineering, because otherwise they would have been dealt with in greater depth at university level!

The aim of this book is to remedy this deficiency. It presents dimensional analysis – this being the only secure foundation for scale-up – in such a way that it can be immediately and easily understood, even without a mathematical background.

Due to the increasing importance of biotechnology, which employs non-Newtonian fluids far more frequently than the chemical industry does, variable physical properties (e.g., temperature dependence, shear-dependence of viscosity) are treated in detail. It must be kept in mind that in scaling up such processes, apart from the geometrical and process-related similarity, the physical similarity also has to be considered.

The theoretical foundations of dimensional analysis and of scale-up are presented and discussed in the first half of this book. This theoretical framework is demonstrated by twenty examples, all of which deal with interesting engineering problems taken from current practice.

Scale-Up in Chemical Engineering. 2nd Edition. M. Zlokarnik

ISBN: 3-527-31421-0

The second half of this book deals with the integral dimensional-analytical treatment of problems taken from the areas of mechanical, thermal and chemical process engineering. In this respect, the term "integral" is used to indicate that, in the treatment of each problem, dimensional analysis was applied from the very beginning and that, as a consequence, the performance and evaluation of tests were always in accordance with its predictions.

A thorough consideration of this approach not only provides the reader with a practical guideline for their own use; it also shows the unexpectedly large advantage offered by these methods.

The interested reader, who is intending to solve a concrete problem but is not familiar with dimensional-analytical methodology, does not need to read this book from cover to cover in order to solve the problem in this way. It is sufficient to read the first seven chapters (ca. 50 pages), dealing with dimensional analysis and the generation of dimensionless numbers. Subsequently, the reader can scrutinize the examples given in the second part of this book and choose that example which helps to find a solution to the problem under consideration. In doing so, the task in hand can be solved in the dimensional-analytical way. Only the practical treatment of such problems facilitates understanding for the benefit and efficiency of these methods.

In the course of the past 35 years during which I have been investigating dimensional-analytical working methods from the practical point of view, my friend and colleague, Dr. *Juri Pawlowski*, has been an invaluable teacher and adviser. I am indebted to him for innumerable suggestions and tips as well as for his comments on this manuscript. I would like to express my gratitude to him at this point.

In closing, my sincere thanks also go to my former employer, the company BAYER AG, Leverkusen/Germany. In the "Engineering Department Applied Physics" I could devote my whole professional life to process engineering research and development. This company always permitted me to spend a considerable amount of time on basic research in the field of chemical engineering in addition to my company duties and corporate research.

Marko Zlokarnik

Preface to the 2nd Edition

The first English edition of this book (2002) received a surprisingly good reception and was sold out during the course of the year 2005. My suggestion to prepare a new edition instead of a further reprint was willingly accepted by the J.Wiley-VCH publishing house.

I would like to express my sincere thanks to the editors, Ms. Dr. Barbara Böck und Ms. Karin Sora.

Over the last five years I have held almost thirty seminars on this topic in the "Haus der Technik" in Essen, Berlin and Munich, in "Dechema" in Frankfurt and also in various university institutes and companies in the German speaking countries (Germany – Austria – Switzerland). Meeting young colleagues I was thus able to detect any difficulties in understanding the topic and to find out how these hurdles could be overcome. I was anxious to use this experience in the new edition.

The following topics have beed added to the new edition:

1. The chapter on "Variable physical properties", particularly non-Newtonian liquids, has been completely reworked. The following new examples have been added: Particle strength of solids in dependence on particle diameter, *Weissenberg*'s phenomenon in viscoelastic fluids, and coalescence phenomena in gas/liquid (G/L) systems.
2. The problems of scale-up from miniplants in the laboratory, was examined more closely.
3. Two further interesting examples deal with the dimensional analysis of the tableting process and of walking on the moon's surface.
4. The examples concerning steady-state heat transfer include that in pipelines and in mixing vessels in addition to bubble columns.
5. Mass tranfer in G/L systems has been restructured in order to present the differences in the dimensional-analytical treatment of the surface and volume aeration more clearly.
6. A brief historic survey of the development of the dimensional analysis and of scale-up is included.
7. There are 25 exercises and their solutions.

Scale-Up in Chemical Engineering. 2nd Edition. M. Zlokarnik

ISBN: 3-527-31421-0

In order not to overextend the size of the book, some examples from the first edition, in which a few less important topics were treated, have been omitted.

I would like to thank my friend and teacher, Dr. Juri Pawlowski, for his advice in restructuring various chapters, especially the section dealing with rheology.

Graz, December 2005 *Marko Zlokarnik*

Symbols

Latin symbols

a	volume-related phase boundary surface $a \equiv A/V$
a	thermal diffusivity; $a \equiv k/(\rho C_p)$
A	area, surface
c, Δc	concentration, concentration difference
c	velocity of sound in a vacuum
C_p	heat capacity, mass-related
c_s	saturation concentration
d	characteristic diameter
d_b	bubble diameter, usually formulated as "*Sauter* mean diameter" d_{32}
d_{32}	*Sauter* mean diameter of gas bubbles and drops, respectively
d_p	particle diameter
D	vessel diameter, pipe diameter
D	diffusivity
D_{eff}	effective axial dispersion coefficient
E	energy
	enhancement factor in chemisorption
	activation energy in chemical reactions
	efficiency factor of the absorption process
f	functional dependence
F	force
F	degree of humidity
g	acceleration due to gravity
G	mass flow
G	gravitational constant
h	heat transfer coefficient
H	height
	base dimension of the amount of heat
J	*Joule's* mechanical heat equivalent
k	reaction rate constant
	thermal conductivity
	proportionality constant (Section 8.5)

Scale-Up in Chemical Engineering. 2nd Edition. M. Zlokarnik

ISBN: 3-527-31421-0

$\mathbf{k}$	*Boltzmann* constant
k_G	gas-side mass transfer coefficient
k_L	liquid-side mass transfer coefficient
k_La	volume-related liquid-side mass transfer coefficient
k_F	flotation rate constant
K	consistency index (Section 8.5)
l	characteristic length
L	base dimension of length
m	mass
m	flow index (Section 8.5)
mol	amount of substance
M	base dimension of mass
n	stirrer speed
N	base dimension of amount of substance
	number of stages
N_x	normal stress ($x = 1$ or 2); (Section 8.5)
p, Δp	pressure, pressure drop
P	power, power of stirrer
q	volume throughput
Q	heat flow
r	rank of the dimensional matrix
	reaction rate
R	heat of reaction
$\mathbf{R}$	universal gas constant
S	cross-sectional area ($\propto D^2$)
S_i	coalescence parameters (in i numbers)
t	running time
T	base dimension of time
T	temperature
$\boldsymbol{T}$	absolute temperature
u	tip speed ($u = \pi nd$)
U	overall heat transfer coefficient (Example 23)
v	velocity, superficial velocity
V	volume
z	number

Greek symbols

α	angle
β	specific breakage energy (Example 31)
β_0	temperature coefficient of density,
γ	deformation
γ_0	temperature coefficient of viscosity
$\dot{\gamma}$	shear rate

Δ	difference
δ	thickness of film, layer, wall
ε	gas hold-up in the liquid
ε	mass-related power, $\varepsilon \equiv P/\rho V$
ζ	friction factor in pipe flow
Θ	base dimension of temperature
	contact angle
	time constant (Chapter 8)
θ	duration of time
Λ	macro-scale of turbulence
λ	relaxation time (Section 8.5)
	Kolmogorov's micro-scale of turbulence
μ	dynamic viscosity
μ	scale factor, $\mu \equiv l_T/l_M$
ν	kinematic viscosity
ρ	density
ρC_p	heat capacity, volume-related
σ	surface tension, phase boundary tension
	tensile strength
τ	mean residence time, $\tau = V/q$
	shear stress
τ_0	yield stress
φ	portion (volume, mass)
ϕ	degree of filling

Indices

c	continuous phase
d	dispersed phase
e	end value
F	flock
G	gas (gaseous)
L	liquid
min	minimum
M	model-scale
0	start condition
p	particle
s	saturation value
	height of the layer
S	solid, foam
t	condition at time t
T	technological-scale, full-scale
w	wall

Contents

Scale-Up in Chemical Engineering. 2nd Edition. M. Zlokarnik

ISBN: 3-527-31421-0

1
Introduction

A chemical engineer is generally concerned with the industrial implementation of processes in which the chemical or microbiological conversion of material takes place in conjunction with the transfer of mass, heat, and momentum. These processes are *scale-dependent*, i.e., they behave differently on a small scale (in laboratories or pilot plants) than they do on a large scale (in production). Also included are heterogeneous chemical reactions and most unit operations. Understandably, chemical engineers have always wanted to find ways of simulating these processes *in models* in order to gain knowledge which will then assist them in designing new industrial plants. Occasionally, they are faced with the same problem for another reason: an industrial facility already exists but does not function properly, if at all, and suitable measurements have to be carried out in order to discover the cause of these difficulties as well as to provide a solution.

Irrespective of whether the model involved represents a "scale-up" or a "scale-down", certain important questions will always apply:

- How small can the model be? Is one model sufficient or should tests be carried out with models of different sizes?
- When must or when can physical properties differ? When must the measurements be carried out on the model with the original system of materials?
- Which rules govern the adaptation of the process parameters in the model measurements to those of the full-scale plant?
- Is it possible to achieve complete similarity between the processes in the model and those in its full-scale counterpart? If not: how should one proceed?

These questions touch on the theoretical fundamentals of models, these being based on dimensional analysis. Although they have been used in the field of fluid dynamics and heat transfer for more than a century – cars, aircraft, vessels and heat exchangers were scaled up according to these principles – these methods have gained only a modest acceptance in chemical engineering. The reasons for this have already been explained in the preface.

The importance of dimensional-analytical methodology for current applications in this field can be best exemplified by practical examples. Therefore, the main

Scale-Up in Chemical Engineering. 2nd Edition. M. Zlokarnik

ISBN: 3-527-31421-0

emphasis of this book lies in the integral treatment of chemical engineering problems by dimensional analysis.

From the area of *mechanical* process engineering, stirring in homogeneous and in gassed fluids, as well as the mixing of particulate matter, are treated. Furthermore, atomization of liquids with nozzles, production of liquid/liquid dispersions (emulsions) in emulsifiers and the grinding of solids in stirred ball mills is dealt with. As peculiarities, scale-up procedures are presented for the flotation cells for waste water purification, for the separation of aerosols in dust separators by means of inertial forces and also for the temporal course of spin drying in centrifugal filters.

From the area of *thermal* process engineering, the mass and heat transfer in stirred vessels and in bubble columns is treated. In the case of mass transfer in the gas/liquid system, coalescence phenomena are also dealt with in detail. The problem of simultaneous mass and heat transfer is discussed in association with film drying.

In dealing with *chemical* process engineering, the conduction of chemical reactions in a tubular reactor and in a packed bed reactor (solid-catalyzed reactions) is discussed. In consecutive-competitive reactions between two liquid partners, a maximum possible selectivity is only achievable in a tubular reactor under the condition that back-mixing of educts and products is completely prevented. The scale-up for such a process is presented. Finally, the dimensional-analytical framework is presented for the reaction rate of a fast chemical reaction in the gas/liquid system, which is to a certain degree, limited by mass transfer.

Last but not least, in the final chapter it is demonstrated by a few examples that different types of motion in the *living world* can also be described by dimensional analysis. In this manner the validity range of the pertinent dimensionless numbers can be given. The processes of motion in Nature are subject to the same physical framework conditions (restrictions) as the technological world.