

FLUID DYNAMICS
AND SCALE-UP IN
PROCESS ENGINEERING
(Theory and Logic in Practice)

Frederick A. Zenz

Edited By
Jonathon Zenz
Eileen Dantas

Copyright © 2015
Published by Jon Zenz Consulting, LLC
Poughkeepsie, NY

All rights reserved
Visit Pemmcorp.com for all inquiries and contact information

Table of Contents

Preface	ix
Chapter 1: Determining the Forces Exerted on Structural Members Immersed in Fluid	
Beds and Atop Conveying Lines	1
Part One – Deflection of Cantilevered Horizontal Members.....	1
Part Two – Fixed Members in Fluid Bed (Water and Catalyst) Strain Gage Tests.....	9
Conclusions of Part One and Two	14
Part Three – Impact Forces on Capped Risers.....	17
Chapter 2: Flow Regimes and Pressure Drop Correlations in 2-Phase Co-Current	
Horizontal Gas-Liquid and Gas-Solids Flow.....	23
Flow Regimes.....	23
Pressure Drop	24
Flow Regimes in Gas-Solids Flow.....	34
Chapter 3: Flow and Internal Physical Characteristics of Particulate Solids in Bulk	
Tunnels, Domes, Arching, and Stream Trajectories	37
The Gravity Flow Equation	37
Bin and Hopper Design.....	41
Base Pressures and Stresses.....	42
Contained Vertical and Lateral Pressures.....	44
Pressure and Flushing Effects in Bulk Flow.....	44
Effect of Interstitial Media	46
Wall Surface Texture	48
Cavities, Tunnels (Domes), Arching (Bridging) in Hopper Design.....	49
Angle of Nip (Compaction and Crushing).....	53
Fluidized Solids Flow through Orifices, Under Pressure	53
Impact Force or Pressure of Single Particles	54
Two-Phase Gravity Flow of Gases, Liquids, and Bulk Solids.....	54
Stream Trajectories	55
Chapter 4: Co-Current and Saturation Multi-Phase Flow	
The Phase Diagram – Choking and Saltation	
Dilute and Dense Phase Flow	61
The Phase Diagram – Choking and Saltation	61
Transition to Dense Phase Transport	66
Mass Lift or Extrusion Flow.....	66
Riser Design Dilute Phase Rate Calculations (Particle-Gas).....	67
Gas and Particle Flow Profiles.....	67
Flow Profile, Refluxing, and Wall Layers.....	73
Chapter 5: Particle Agglomeration, Adhesion, and Deposition	
The Thermal Gradient Effect	77
Particle to Particle Adhesion	77
Particle to Surface Adhesion	81
Adherence of Gas Bubbles and Liquid Drops	83
The Thermal Gradient Correlations	84

Chapter 6: Particle Mixing and Permeation Rates Vertically and Horizontally in Aerated Beds	89
Vertical Mixing in Fluidized Beds	89
Vertical Solids Mixing Time	91
Horizontal or Lateral Mixing Rates in Fluidized Beds	98
Solids Mixing Gradients	99
Permeation of Fines	99
Gas Residence Time	104
Spacing between Solids Feed Points	104
 Chapter 7: Downflow Particle Segregation in Aerated and Moving Beds	109
Categories of In-Bed Particle Movement	109
Segregating Conditions	109
Rate of Particle Segregation	114
The Correlation of Curran and Gorin	114
The Data of R. Jackson	115
The Investigations of S.K. Iya	117
Segregation in Downflow through Moving Beds	117
 Chapter 8: Plenums, Distributors and Grids, Manifolds, and Attrition	
The 11° Included Angle Gas Jet	121
Generic Plenum and Grid Forms	121
Function of the Plenum or “Wind Box”	122
Sparger Design Criteria	122
Plenum Design Configurations	127
Packed Plenums	128
Bundled Reactors	128
Pipe Grids	128
Multi-Level Grids	129
Tuyeres and Caps	131
Inserts, Filtered, and Tortuous Perforations	132
Penetrated Grids	133
Non-Fouling Grids	133
“Thick” Grids	134
Shrouded Grids	134
Grid Pressure Drop	137
Particle Attrition	140
Attritors	141
Grid Supports and Seals	144
Grid Warpage	145
 Chapter 9: Scale-Up and Conversion	
Bubbles from Jets through Merger, Growth, and Maximum Size	147
Bubble Size and Jet Penetration	148
Bubble Merger and Growth	154
Maximum Bubble Size	158
Residence Time	158
Gas-Catalyst Contact and Predicted Conversions	159
Internals, Baffling, and Flow Distribution	163
Contact Effectiveness Factor, C_{eff}	164

Chapter 10: Nozzles and Eductors	
Injecting Liquids, Solutions, and Slurries	169
Overhead, Wall, and Grid Feed	169
Feed Rate, Flashing, and Nozzle Configurations.....	171
Nozzle Design	174
Eductors as Injectors	174
Operating Characteristics	177
Particle Flow Induction	178
Gas Eductor Design Example.....	180
 Chapter 11: Standpipe to Riser Configurations, Sizing, and Aeration	
Non-Mechanical Valves	183
Pressure Balance.....	183
Non-Mechanical Valves	187
Standpipe Aeration Rates and Tap Locations.....	192
Standpipe Vibration	195
Sweeping Dense Phase Flow.....	196
 Chapter 12: Entrainment of Droplets, Particles, and Molecules	
Critical Velocities and Swaged Reactors.....	199
Liquid Droplets.....	199
Liquid Droplet Size.....	199
Predicted and Observed Droplet Entrainment Rates	199
Solid Particle Entrainment.....	200
The Aerodynamically Equivalent Sphere.....	204
Entrainment Rate and Composition	207
Entrainment from Expanded Vessel Diameters	207
Settling Rates of Droplets and Particles	213
 Chapter 13: Particle Recovery with Cyclones	217
Basic Design Dimensions.....	217
The Natural Vortex Length, NVL.....	218
Dipleg Pressure Balance.....	225
Dipleg Termini	227
Correlating Collection Efficiency	234
Particle Attrition in Cyclones	238
Studies of Cyclone Dimensions	239
 Chapter 14: Baffles, Trays, Staging, and Residence Time	247
Longitudinal and Spiral Baffles	247
Residence Time and Bubble Size.....	250
Contact Time and Solids Dispersion	250
A Logical Approach to Baffle Configuration	252
Scalloped Baffles in Process Design.....	252
 Chapter 15: Viscosity and Surface Tension of Bulk Solids	257
Defining a Powder's Viscosity	257
Defining a Powder's Surface Tension.....	258
The Data of Bingham and Wikoff.....	263

Chapter 16: Counter-Current Flow, Choking, and the 80% Optimum	
The Ingersoll-Rand Equation	267
Limiting Capacity of Structured Internals	267
Optimum Design Point for Structured Internals	270
Random Packings and Hybrid Baffles	271
The Ingersoll-Rand Equation.....	273
The “Flooding”-“Choking” Transition.....	275
Phase Transitions in Fluidized Beds	276
Pressure “Head” Effects on Counter-Current Flooding.....	278
 Chapter 17: The Froude Number	 283
The Froude Number in Naval Architecture	283
The Froude Number in Vertebrate Zoology	283
The Froude Number in Macroscopic Particle and Microscopic Molecule Flow.....	284
The Froude Number in “Social” Sciences	287
 Chapter 18: Single Particle and Flowing Bulk Solids	
Heat Transfer to and from Surfaces	291
Dense Phase Bulk Flow Contact.....	291
Dilute Phase Flowing Suspensions	294
The Nusselt-Reynolds Rationale.....	298
Burning Rates and Temperature Effects on Metallurgy	298
Single Particles	301
Mass Transfer from, to, and between Molecular Species	306
 Chapter 19: Thermo-Dynamics vs Temperature-Velocity Correlating Molecular Structure and Bulk Properties	
The Vanishing Point Temperature of Hydrocarbons	309
Physical Properties.....	309
Molecular and Particle Clustering.....	313
The Vanishing Point Conditions.....	316
Abundance Ratio Paper	317
Molecular Enthalpy vs Temperature Excitation.....	320
Critical Temperature, Vapor Pressure, and Hydrocarbon Cracking	320
Particulate Mass vs Velocity Excitation	320
 Chapter 20: Separation of Particulates in Cyclones with Fractional Seconds of Residence Time.....	 323
1984	323
1941-48	324
1961	327
1962	328
1964-1974	329
1975	331
1978	332
1980	332
1981	333
1983	334
1987	335
1989	335

1994	336
2001	337
2004	337
2006	337
2007	338
2010	338
Chapter 21: Single Particle and Powder Saltation Velocities	
Size Distribution and Long Distance Conveying of Particulate Solids in Industrial Practice	
Reactor Design from Fixed through Fluid Bed to Riser.....	339
Jet Penetration and Bed Surface Tension	339
“Fluid” Beds of Liquids and Powders.....	345
Perturbations in the Transition from Laminar to Turbulent Flow	347
Surface and Vibration Effects.....	351
Transitions in Heat Transfer under Augmented Solids Flow.....	351
Sizing Fluidized Bed and Riser Reactors from Fixed Bed Data	353
Two-Phase Gas-Solids Flow in Horizontal Conduits.....	356
Chapter 22: Quantitative Analogies in Bulk vs Single Particle Flow in Horizontal and Vertical Orientation at the Transition Point in Parabolic Curvatures	
371	
The Small Particle Enigma.....	371
The Coarser Catalytic and Reactant Particles.....	371
Epilogue.....	377
Index.....	383

Preface

This book covers the author's and a host of his colleague's industrial design as well as research and development experiences, gained over the years from 1942 to 2012. In the words of Johannes Kepler in his 1609 *Astronomia Nova*: "What matters to me is not merely to impart to the reader what I have to say, but above all to convey to him the reasons, subterfuges, and lucky hazards which led me to my discoveries." The contents are intended to serve process engineers as a source tested correlations tracked to related theory in fluid dynamics, for the design and arrangements of reactors, process vessels and internals, handling gases, liquids, and particulate solids, passing through single and multi-phase, co- and counter-current flow. It is replete with examples encountered in the design and operation of numerous specifically cited industrial processes, as well as accompanying illustrative calculations. Corporate entities are not in all instances identified in order to preserve confidentialities where deemed appropriate.

The subject matter is presented in 22 chapters dealing with recurring questions in design, and the resolution of past un-published failures. Every chapter contains new data and engineering design correlations never before published in book or other form. The breadth of contents can serve as a text for a graduate, or continuing education, course in practical process, design engineering. Several chapters are descriptive of correlating functions, their origin, and numerous analogous observations that obviate the logic in terms understandable to a layman. Fluid dynamics underlies and defines every observed level in scale of size and motion. Process engineering encompasses the relatively limited ranged in scale lying within the capability to physically construct.

Much of the content has resulted from the financial and technical and technical support of domestic and foreign corporations and their past and present principal and responsible personnel in research, development and design, such as John Chiu and Herb Andrus (Alstom Power), John York (Q.O. Chemicals), Peter Slater (Conoco Philips), Mel Pell (duPont), Barry Tarmy and John Matsen (Exxon), G. Papa (Snamprogetti, Milan), P. LaBourt-Ibarre (Rhone-Poulenc, Paris), D. Durand (BP Chemicals, S.N.C., Fr.), H. Singh (E.I.L., New Delhim India), M. Cecchini (Lonza S.P.A., Milan), A. Avidan (Mobil), J. Barberio (Gt. Lakes Chemicals), S. Bunk and R. Samu (Dorr-Oliver Technip), W. Heumann (Fisher Klosterman), J. Wells (Philips Petroleum), P. Mangin (B.P. Chimie, France), F. E. and J.A. Zenz (PemmCorp), K. Weitz (Ducon), J. Ross (Stone & Webster), C.T. Burris (Man. College), and their staffs, as well as the early mentoring and support from Leo Friend, Walter Lobo (M.W. Kellogg), Manson Benedict, A.M. Squires, P.C. Keith (Hydrocarbon Research), and a host of colleagues met and worked with over the years.

To preserve readers' recognition of nomenclature, experimental functions, and variables, as they were first presented by their authors, few have been altered. The reader is therefore cautioned with regard to units such as time, size, and velocity in applying any functions that are not dimensionless. Making each chapter relatively self sufficient results in some repetition of underlying bases between chapters, which are often cross-referenced, and in retrospect connect and multiplicity of otherwise narrowly viewed phenomena.

Written over a period of 10 years, encompassing 70 years of experimental and design consulting experiences, results in numerous cited references not necessarily following in timely sequences. The reader is assumed to be aware of related contents of *Fluidization and Fluid-*

Particle Systems published by Reinhold in 1960, which serves as background to the subsequent 55 years covered in this volume.

Frederick A. Zenz
August 1, 2015

Additional Acknowledgments:

Elizabeth Zenz
Shawn Sala
Scott Sala
Alex Mans
Anthony Micarelli

Cover Design by Liz Zenz

