Fluidization of Fine Powders

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Fluidization of Fine Powders

Cohesive versus Dynamical Aggregation

Springer

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ISSN 1567-827X Particle Technology Series
ISBN 978-94-007-5586-4 ISBN 978-94-007-5587-1 (eBook)
DOI 10.1007/978-94-007-5587-1
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2012950314

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

To my beloved daughter Sofia

Preface

Granular materials are perfect examples of complex systems. Even though the mechanical behavior of a single grain is well understood, the behavior of a large collection of grains exhibits a rich variety of yet unexplained phenomena. Complexity is boosted when particle size is decreased below a few tens of microns. Fine powder cohesiveness leads to poor flowability, clumping, difficulty in fluidizing, irregular avalanching behavior, etc. Despite all the inconveniences, fine powder processes pervade the chemical, pharmaceutical, agricultural and mining industries among others. This book is mainly devoted to demonstrate the rich phenomenology exhibited by fine powders when they are fluidized by a gas flow. Due to its marked interdisciplinary character, the behavior of fluidized beds of fine powders cannot be understood without the sharing of knowledge between specialists on a variety of disciplines. An overall aim of the book is to contribute to develop the capacity of interdisciplinary research fields in order to understand these complex systems. This book is thus intended for academic and industrial researchers in applied physics, mechanical, chemical, and environmental engineering, who are interested in the sharing and integration of knowledge bases from this disparate set of disciplines into a single interdisciplinary subject area oriented to the special characteristics of fine powders.

Most empirical observations and numerical analysis have demonstrated that gas-fluidized beds of granular materials can only be stabilized if interparticle attractive forces reach an order of magnitude similar to particle weight, which happens when particle size is typically of the order of a few tens of microns. In the absence of sufficiently strong natural attractive forces, gas-fluidized beds of granular materials exhibit an unstable bubbling behavior. However, interparticle forces may be induced by an external field, which leads to the suppression of bubbles and subsequent stabilization as seen when a magnetic field is applied to a bubbling bed of magnetizable particles. On the other side, powders with particle size smaller than about 20 microns cannot be fluidized by a gas because interparticle forces are exceedingly large as compared to particle weight, which leads to cohesive aggregation. Cohesive aggregates may reach a size comparable to system size and cannot be fully broken by the gas flow. Instead, the gas flow becomes heterogeneously distributed in the bed and usually bypasses it through channels that hinder the gas-solids contact efficiency.

In the last years, a number of reports have appeared on the novel behavior of a new class of fine powders, which exhibit a uniform gas-fluidization behavior resembling the nonbubbling fluidlike behavior of granular materials fluidized by liquids. As opposed to cohesive aggregation, these fine particles undergo a dynamical process of aggregation in the fluidized bed which yields the formation of porous light aggregates. These aggregates, which reach an equilibrium size ruled by the balance between the local shear force exerted by the gas flow on their surface and interparticle attraction, can be fluidized by the gas in a nonbubbling fluidlike regime.

An efficient method to assist fluidization of fine cohesive powders is the addition of surface additives, which serves to decrease interparticle adhesion thus helping the gas flow to break cohesive aggregates and allowing for dynamical aggregation of the particles in a fluidlike nonbubbling regime. A fundamental question however is whether the nonbubbling fluidlike state displayed by these special fine powders can be really considered as a stable state.

Different techniques have been developed in the last years to assist fluidization by helping the gas flow to mobilize and break cohesive aggregates, which help to homogenize fluidization. The mechanism by which interparticle adhesive forces can be reduced to allow for dynamic aggregation instead of cohesive aggregation will be analyzed in this book. Turning cohesive aggregation into dynamical aggregation may have a remarkable impact on novel processes based on fluidized beds of fine powders with relevant applications on leading edge technologies such as Atomic Layer Deposition on nanoparticles and CO_2 capture by gas-fluidized beds of adsorbent powders.

Seville, Spain José Manuel Valverde Millán

Acknowledgements

Most of the results reviewed in this book were obtained by our research group at the University of Seville. Our research activity on fine cohesive powders was initiated more than 20 years ago from a collaboration with Dr. P. Keith Watson at the Wilson Research Center of Xerox Co. (Webster, NY). Members of our group initially involved in this novel research at that time were Dr. A. Castellanos, Dr. A.T. Perez, and Dr. A. Ramos. I would like to acknowledge their pioneer contribution to this work and make a special mention to Dr. Watson and Dr. Castellanos, who sparked this fruitful collaboration. It is also acknowledgeable the highly qualified assistance of Xerox engineers Frank Genovesse and Mike Morgan, who helped us with the experiments carried out at the Wilson Research Center. The later incorporation of Dr. M.A.S. Quintanilla represented a remarkable impulse to this research that was consolidated at the University of Seville with the contribution of his diligent and brilliant dedication. Further members of our group that have contributed to some of the specific topics covered in this book are Dr. M.J. Espin, Dr. C.S. Hoyo, Dr. F. Gilabert and Dr. F. Pontiga and team's members. A fundamental part of our research has been upheld by the contribution of external collaborators, among which I must acknowledge (in chronological order): Dr. Mills (University Marne-la-Valle, France), Dr. Lemaire (University of Nice, France), Dr. Pfeffer and Dr. Dave (New Jersey Institute of Technology), Dr. Hristov (University of Sofia, Bulgary), Dr. Maqueda (CSIC, Spain), and Dr. van Ommen (TUDelft, Holland). Thanks also to Michael Stephen Pohen, student from the Texas A&M University, who helped me with formatting the references of the book during his stay at the University of Seville.

At the moment of writing this book, the research of our group on fine cohesive powders is being supported by the "Consejeria de Innovacion, Ciencia y Empresa (Junta de Andalucia)" within the European Regional Development Fund contracts FQM-5735 and by the Spanish Government Agency "Ministerio de Ciencia e Innovacion" (contract FIS2011-25161). Previous research activities were supported by these institutions through diverse public research projects as well as by Xerox Foundation and Xerox Corporation.

Contents

List of Symbols

Acronyms

ABF	Agglomerate bubbling fluidization
AFM	Atomic Force Microscopy
APF	Agglomerate particulate fluidization
SFE	Solidlike to fluidlike to elutriation
SFB	Solidlike to fluidlike to bubbling
SPT	Seville Powder Tester
a	Interparticle contact radius
A	Hamaker constant
A_v	Vibration amplitude
B	Magnetic flux density
Bo_g	Granular Bond number
Bo_g^*	Inter-aggregate Bond number
BT	CO_2 breakthrough times
d_a	Typical size of surface asperities
d_p	Particle size
d^*	Simple-aggregate size
d^{**}	Complex-aggregate size
D	Fractal dimension
D_b	Largest stable size of an isolated bubble
D^*	Fractal dimension of a complex-aggregate
D_a	Global fractal dimension for the complex-aggregate
E	Electric field strength
f_m	Interparticle magnetic force
f_{vdW}	Interparticle van der Waals force
F_0	Interparticle attractive force
F_{at}	Attractive force at interparticle contact
F_c	Interparticle contact load force
F_C	Electrostatic Coulomb force
F_D	Drag force on a isolated sphere
F_e	Electrostatic force

Fr	Froude number
F_S	Stokes drag force
F_t	Interparticle adhesion force
g	Gravitational acceleration
g_{ef}	Effective acceleration
h	Powder bed height
H	Magnetic field of strength
H_c	Contact hardness
H_i	Hurst exponent
k	Ratio of simple-aggregate size to particle size
k^*	Ratio of complex-aggregate size to simple-aggregate size
k^{**}	Ratio of complex-aggregate size to primary particle size
K	Spring constant
m_p	Particle mass
n	Richardson-Zaki exponent
N	Number of particles in an simple-aggregate
N^*	The number of simple-aggregates in the complex-aggregate
N^{**}	Number of primary particles in a complex-aggregate
p	Particle-phase pressure
p_m	Pressure on interparticle contact area
P_0	Effective load on interparticle contact
P_y	Critical load for the initiation of plastic yield
Q	Particle electrostatic charge
Qmr	Charge to mass ratio
Q^{**}	Complex-aggregate charge
$R(t)$	Fluidized bed local reflectance
RCP	Random close packing
RLP	Random loose packing
Re	Particle Reynolds numbers
SAC	Surface additive coverage
T	Temperature
u_e	Elastic wave velocity
u_ϕ	Propagation velocity of a voidage disturbance
U_b	Isolated bubble rising velocity
v_b	Bubbling transition gas velocity
v_c	Critical gas velocity at solidlike stabilization
v_f	Fluctuation velocity
v_{mf}	Minimum fluidization gas velocity
v_{p0}	Settling velocity of an individual particle
v_s	Powder bed settling velocity
v^*	Terminal settling velocity of an individual aggregate
V	Voltage
w	Work of adhesion
W	Powder bed weight per unit area
W_p	Particle weight

y Yield stress in compression
Y Young's modulus
z_0 Distance of closest approach between two molecules

Greek Symbols
α Relative magnetic permeability
Δp Gas pressure drop
Δv_g Nonbubbling fluidlike regime interval width
ϵ Dielectric permittivity
ε Powder free volume
ϕ Particle volume fraction
ϕ_b Particle volume fraction at the onset of bubbling
ϕ_J Particle volume fraction at the jamming transition
Φ Gas flow rate
γ Shear strain
γ_s Surface energy
λ Elastic modulus of the powder bed
λ_c Compression index
μ Fluid viscosity
μ_f Fluid magnetic permeability
μ_p Particle magnetic permeability
ν Poisson ratio
ρ Powder bulk density
ρ_f Fluid density
ρ_p Particle density
ρ^* Simple-aggregate density
ϕ^* Volume fraction of simple-aggregates in a fluidized bed
ϕ^{**} Complex-aggregate volume fraction
σ Powder yield stress
σ_t Powder tensile yield stress
σ_c Consolidation stress
χ_p Particle magnetic susceptibility
ω Angular frequency
ζ Average number of contacts per particle