FLUIDISED PARTICLES

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J. F. Davidson
Frontmatter
More Information

TO
THE MEMORY OF
T. R. C. FOX

FLUIDISED PARTICLES

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PREFACE

This book is the outcome of five years' work on the fluidisation of solid particles; although the work is far from complete, the stage has been reached at which a reasonably connected picture can be given of the mechanism of fluidisation. The main thesis advanced is that the behaviour of fluidised beds can be explained in terms of the behaviour of bubbles of fluidising fluid within the bed of particles. This leads to a relatively simple picture of an aggregatively fluidised bed, and to a possible explanation of the difference between aggregative and particulate fluidisation. The treatment brings out the remarkable similarity between the behaviour of bubbles in a fluidised bed and in an ordinary liquid.

The scope of the book is deliberately limited; attention is concentrated on a bed of particles in a fixed vessel and fluidised by gas or liquid, the gas–solids system being of major interest because of its considerable industrial importance. These terms of reference exclude, for example, the pneumatic conveying of particles, and heat transfer from a fluidised bed to the walls of the containing vessel. However, it is believed that these phenomena will come to be explained on the basis of the principles here set forth. The rheology of powders—which some authors regard as a branch of fluidisation—is also not included: at the present time this seems to stand more as a subject by itself. On the other hand, fluidisation might be regarded as a branch of rheology, a fluidised bed of particles being a rheological fluid with special properties.

An attempt has been made to make the book complete in itself by providing, where necessary, analysis of a supporting and ancillary kind in appendices. Nevertheless, it is hoped that the thread of the argument in the main text may be followed without reference to the appendices. Some parts of the theory are published here for the first time, in particular the discussion in Chapter 4 of the pressure distribution in the neighbourhood of a rising bubble, and the analysis of data in the literature on catalytic reactors, given in Chapter 6. Some of the ideas set out are of a speculative nature, and to some degree they are presented as a stimulus to further research. An example of this is the theory given in Chapter 5 concerning the stability of bubbles in fluidised beds, for this has not been established in detail, although it appears to give a reasonable semi-quantitative explanation for the differences between aggregative and particulate fluidisation.

Although the study of fluidisation has not reached the stage at which large reactors can be designed solely from first principles, a number of results are given which should aid the process designer or plant operator. However, it is hoped that the main help such readers will derive from the text is a physical understanding of fluidisation phenomena. Such an understanding is ultimately far more important than a knowledge of a dimensionless correlation derived from laboratory-size experiments; for this type of correlation is not often based on a physical appreciation of the processes involved, and in any case should not be used in conditions which differ from those of the experiments from which it was derived. It has been possible to include only a few data from large reactors; data on large fluidised reactors are as conspicuous by their absence from the literature as the reactors themselves are conspicuous by their presence in oil refineries, but it is felt that the theory presented is sufficiently based on first principles to allow it to be applied with some confidence to full-scale systems.

For those who teach Chemical Engineering, and for students of it, this book should provide examples of the application of the principles of fluid mechanics to problems of genuine chemical engineering interest. Much of today's textbook theory of fluid mechanics was inspired by the study of hydraulics and aeronautics; much of the theory given in the following pages was inspired by the study of processes of importance to chemical engineers, and therefore it is hoped that some of it—for example, that on bubble rise and bubble formation at an orifice—will find a central place in courses on fluid mechanics for chemical engineers. Although only part of the book is suitable for undergraduate teaching, the whole of it might form the background to a postgraduate course, where its incomplete nature should provide the right challenge for research.

We would like to acknowledge our debt to the research students who have done so much of the work we describe; their energy and enthusiasm have been a constant source of inspiration. We are grateful to Dr K-A. Melkersson for helpful criticism of the draft at an early stage, and to Dr N. Epstein for suggestions with regard to Chapter 1. We would also like to thank Miss M. Sansom for her skilful typing of the manuscript. One of us (J.F.D.) would like to acknowledge the support of the University of Delaware during a visit in 1960 when the ideas for much of Chapter 6 were formulated. We are indebted to Dr P. N. Rowe for providing Plates II, III and V, which are published by kind permission of the United Kingdom Atomic Energy Authority, and to Mr J. Hardebol for providing Plate XI, which is published by kind permission of the Institution of Chemical Engineers.

J. F. D.
D. H.

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SYMBOLS AND NOTATION

A	radius of circle of penetration; cross-sectional area of tube
A_m	cross-sectional area of passage
a	radius of bubble; surface area per unit volume of packing
B	arbitrary constant in Bernoulli's theorem
b	radius of cylinder or sphere
$C_1\,C_2$	arbitrary constants
C_i	inlet concentration of carbon tetrachloride (Szekely, 1962)
C_0	concentration of cumene (Mathis and Watson, 1956); outlet concentration of carbon tetrachloride (Szekely, 1962)
c	concentration at any point; constant defined by (2.23)
c'	c_H/c_0
c^*	surface concentration of solute gas
c_0	concentration in bubble and at bed entry
c_b	concentration within bubble
c_{bH}	concentration within bubbles leaving the top of the bed
c_D	drag coefficient for an isolated sphere
c'_D	drag coefficient for a particle in a packed bed
c_f	pipe friction coefficient
c_H	concentration of mixed gas leaving bed
c_p	concentration within particulate phase
c_{pH}	concentration within the gas leaving the particulate phase
D	tube diameter
D_e	diameter of sphere having the bubble volume
D_{em}	maximum value of D_e
D_f, D_{f1}, D_{f2}	frontal diameter of bubble
D_G	gas-phase diffusion coefficient
d	particle diameter
d_H	hydraulic mean diameter = 4 × area/perimeter
F	force on an isolated sphere; flow quantity (Lewis, Gilliland and Glass, 1959)
F'	force on particle in packed bed
Fr	Froude number $= U_0^2/gd$
f	packing friction factor $= \dfrac{\Delta p d \epsilon^3}{L\rho U^2(1-\epsilon)}$
G	gas volume flow-rate

g	acceleration of gravity
H	bed height or height of liquid column
H_0	bed height at incipient fluidisation; height of liquid column with no air flow
H_S	settled height of bed
h	bubble height
J	pressure gradient at infinity
K	permeability constant
K_{AB}	transfer coefficient (Mathis and Watson, 1956)
K_d	transfer coefficient (Massimilla and Johnstone, 1961)
k	reaction velocity constant
k'	kH_0/U
k_d	transfer coefficient (Pansing, 1956)
k_G	mass transfer coefficient between a bubble and its surface
L	length of fixed bed
L_0, L_1, L_2	bubble entrance effects
ΔL	initial distance between bubbles
l	perimeter of passage
M	mass equivalent to the accelerated fluid
m	$U_b/U_{b\infty}$
$\mathrm{d}m$	mass of fluid element
m_1, m_2	roots of quadratic equation
N	number of bubbles per unit volume; number of spheres per unit packed volume
N_c	transfer of diffusing substance from curved surface of bubble
n	frequency of bubbles per sec; index given by (1.20)
P	$p_f + p_p$
ΔP	defined in fig. 29
p	pressure in percolating fluid, and in fluid flowing round spherical-cap bubble
p_0	pressure within bubble
p_f	pressure within fluidising fluid
p_R	pressure recovery below spherical-cap bubble
Δp_f	defined in fig. 29
Δp	pressure difference across length L of packing; partial pressure difference (Pansing, 1956)
p_p	pressure equivalent of inter-particle forces

Q	$q+k_G S$
q	rate of exchange between a bubble and the particulate phase
R	radius of spherical cap; universal gas constant
Re	Reynolds number $= \rho U d/\mu$ or $\rho u_m d_H/\mu$
Re′	$\mathrm{Re}/(1-\epsilon)$
Re_0	$\rho U_0 d/\mu$
r	bubble radius; polar coordinate
S	surface area of rising bubble
s	distance travelled from orifice by bubble centre
T	temperature of bed
t	time
Δt	time interval between bubble injections
t_c	coalescence time
t_s	time for bubble to reach surface
U	superficial velocity of fluidising fluid
U_0	superficial velocity of fluidising fluid at incipient fluidisation
U_1, U_2	velocities of leading and following bubbles
U_A	absolute rising velocity of bubble
U_b	rising velocity of bubble in stagnant liquid
$U_{b\infty}$	value of U_b in a large mass of liquid
U_c	upward velocity within bubble
U_R	relative velocity between bubbles
U_t	terminal velocity of particle
U_W	absolute velocity of the wake behind a bubble
u	absolute velocity of fluidising fluid
u_0	interstitial velocity of fluidising fluid at incipient fluidisation
u_m	mean velocity of fluid in passage
u_x, u_y, u_r, u_θ	components of u
V	bubble volume
V_m	maximum volume of bubble
v	particle velocity
v_x, v_y, v_r, v_θ	components of v
W	velocity of ideal fluid
W_s	flow-rate into all bubbles from particulate phase (May, 1959)

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w	velocity of ideal fluid
w_x, w_y, w_r, w_θ	components of w
w_s	surface velocity
X	$QH/U_A V$ = number of transfer units
x	horizontal coordinate; fraction of cumene converted (Mathis and Watson, 1956)
y	vertical coordinate; distance from bubble surface
z	vertical coordinate measured from bubble top
α	semi-angle measured round spherical-cap bubble
α_1	maximum value of α
β	$1-U_0/U$
ϵ	mean voidage fraction of fixed or fluidised bed
ϵ_0	value of ϵ at incipient fluidisation
η	defined in (C. 8)
θ	polar coordinate
λ	inclination of passage
μ	viscosity of fluid
ν	kinematic viscosity of fluidising fluid, or of the fluidised bed
ρ	density of fluid
$\Delta\rho$	$\rho_s-\rho_f$
ρ_c	density of continuous phase
ρ_f	density of bubble phase
ρ_L	liquid density
ρ_p	bulk density of particulate phase
ρ_s	density of solid particle
τ_0	wall shear stress
Φ	defined by (C. 6)
Φ_1	maximum value of Φ
ϕ	velocity potential
ψ	stream function
ψ_f	stream function of fluidising fluid