Ashok Gupta
Denis Yan

MINERAL PROCESSING DESIGN AND OPERATIONS

An Introduction

Second Edition

Mineral Processing Design and Operations

An Introduction

Second Edition

Ashok Gupta
Retired Head of Metallurgy Department
WA School of Mines, Kalgoorlie
Curtin University of Technology, Western Australia

Denis Yan
Consulting Metallurgist
Minerals Engineering Technical Services
Perth, Western Australia

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD • PARIS
SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, USA

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-444-63589-1

For information on all Elsevier publications
visit our website at https://www.elsevier.com/

Typeset by Thomson Digital

Mineral Processing Design and Operations

Dedicated to all students interested in the Science and Technology of Mineral Processing

And especially to the memory of late dear Elmie Yan and also to Chitra Gupta for her patience and forbearance while preparing this manuscript.

Preface to the Second Edition

Demand for the first edition of this book prompted us to revise, enlarge and update it. The format of the second edition is in keeping with the first edition. The logic of presentation remains the same.

This edition includes additional chapters on stirrer mills and magnetic separation. The stirred mills for ultrafine grinding of minerals which were developed in the last three decades are described and discussed in detail. These are now being extensively used in large-scale operating circuits for enhanced recovery of minerals from their ore body. Magnetic, conductive and electromagnetic forces for the recovery of minerals with natural or induced magnetic, conducting and semi-conducting properties are a common beneficiation technique particularly in the mineral sands and iron ore industries. The basic elements of atomic theory that help to understand magnetic forces in minerals are explained and the designing of equipment as well as separation processes of magnetic from non-magnetic minerals based on these theories are described.

The objective of the book remains the same as that of the first edition which is to help students interested in processing minerals to economically liberate and concentrate them for down-stream extraction processes. To understand the unit as well as the integrated processes the subject has been treated somewhat mathematically with the view to apply them in actual process designs and operations. In so doing it is expected that the book would suit students from the disciplines of Metallurgy, Chemical Engineering, Process Engineering and to a limited extent Electronics Engineering, who are engaged in the beneficiation of minerals and who are at under-graduate, graduate and post-graduate levels of study. Some data provided in the appendix is expected to aid in calculations of designing and plant operations. Solutions to simple and common plant problems are provided.

In writing this second edition of the book we offer our thanks to the reviewers who offered help and guidance to improve on the first edition. Also our renewed thanks to Dr Lutz Elber and Dr Halit Eren for their help and contribution in writing Chapter 20 on Process Control. We would also like to thank the various state and university libraries who helped in supplying

up-to-date information. We would especially like to thank our publishers who prompted us to write this edition; especially Dr Kostakitas, Anitha Sivaraj and Christine McElvenny who helped us to produce this edition.

Ashok Gupta and
Denis Yan

Perth, Western Australia, November 2015

Symbols and Units

A general convention used in this text is to use a subscript to describe the state of the quantity, for example, S for solid, L for liquid, A for air, SL or P for slurry or pulp, M for mass and V for volume. A subscript in brackets generally refers to the stream, for example, (O) for overflow, (U) for underflow, (F) for feed, (C) for concentrate and (T) for tailing. There are a number of additions to this convention which are listed later.

a	a constant	–
a	amplitude	m
a_P	particle acceleration	m/s^2
a_m	media acceleration	m/s^2
A	a constant	–
A	aperture	microns
A	area	m^2
A_C	cross-sectional area	m^2
A_E	effective area	m^2
A_{EFF}	areal efficiency factor	–
A_i	abrasion index	–
A_{ij}	assay of particles in the *i*th size and *j*th density fractions	–
A_m	cross-sectional area of media	m^2
A_M	assay of mineral	%, g/t, ppm
A_O	open area	%
A_{OE}	effective open area	%
A_p	cross-sectional area of particle	m^2
A_U	underflow area	m^2
b	a constant	–
b	Rosin–Rammler distribution parameter	
B	magnetic induction, flux density	Wb/m^2, T
B_o	magnetic induction at the drum surface	Wb/m^2, T
B_S	magnetization saturation	T
B_{ij}	breakage distribution function	–
c	a constant	–
C	a constant	–

C	Curie constant	–
C	circulation ratio or load	–
C	concentration (mass solid/volume of slurry)	kg/m^3
C_A	concentration of air	kg/m^3
C_C	average concentration of solids in the compression zone	kg/m^3
C_{CRIT}	critical concentration	kg/m^3
C_D	drag coefficient	–
C_F	correction factor	–
C_F	concentration of the feed (mass of solid/volume of slurry)	kg/m^3
C_i	concentration of species i	kg/m^3
C_O	initial concentration (mass of solid/volume of slurry)	kg/m^3
C_{MAX}	maximum concentration (mass of solid/volume of slurry)	kg/m^3
$C_{MS(F)}$	concentration of solids in the feed by mass	%
$C_{S(C)}$	concentration of solid (C = concentrate, F = feed, T = tail, f = froth, P = pulp)	–
$C_{S(U)}$	solids concentration in the underflow (O = overflow, F = feed)	%
C_t	concentration at time t (mass of solid/volume of slurry)	kg/m^3
C_T	correction factor or transfer coefficient	–
C_U	concentration of the underflow (mass of solid/volume of slurry)	kg/m^3
$C_{VS(F)}$	concentration of solids in the feed by volume	%
CC	concentration criterion	–
CI	confidence interval	–
CR	confidence range	–
CV	coefficient of variation	–
C_∞	concentration at infinite time	kg/m^3
d	a constant	–
d	particle size, diameter	m
d_{32}	Sauter mean diameter	m
d_{50}, d_{50C}	cut or separation size, corrected cut size	microns
d_B	ball diameter	cm, m
d_C	cylpeb diameter	mm
d_{cutter}	cutter opening	m
d_d	disc diameter	m
d_F	63.2% passing size in the feed	m
d_H	diameter of helix stirrer	m
d_L	liberation size	m
d_m	media diameter	m
d_M	mill diameter	m
d_{MAX}	largest dimension	m
d_{MIN}	smallest dimension	m
d_{MID}	mid-range dimension	m
d_N	nominal diameter	m
d_w	wire diameter	m

D	discharge mass ratio (liquid/solid)	–
D	displacement, distance, diameter	m
D^*	dimensionless parameter	–
D_C	cyclone diameter	m
D_I	inlet diameter	m
D_O	overflow diameter	m
D_U	underflow diameter	m
e	a constant	–
e^+, e^-	quantity of charge	C
E	energy	kWh
E	potential difference	V
E_B	energy of rebound	Wh
E_C	corrected partition coefficient	–
E_G	specific grinding energy	kWh/t
E_i	partition coefficient of size i = recovery of size *i* in the U/F	–
E_o	uniform electric filed strength	N/C, V/m
E_O	efficiency based on oversize	–
E_p	Ecart probability, probable error of separation	–
E_S	surface electric field intensity	N/C, V/m
E_T	total energy	kW
E_U	efficiency based on undersize	–
f	a constant	–
$f(J_B)$	ball load-power function	–
f_P, f_F	function relating to the order of kinetics for pulp and froth	–
$f(r)$	ball wear rate	kg/h
$f(s)$	suspensoid factor	–
f_i	mass fraction of size *i* in the circuit feed	–
F_{80}	80% passing size of feed	microns
F	feed size	cm, microns
F	floats at SG	–
F	froth stability factor	–
F	feed mass ratio (liquid/solid)	–
F_B	Rowland ball size factor	–
F_B	buoyancy force	N
F_C	Bond mill factor	–
F_C	centrifugal force	N
F_d	diffusion force	N
F_D	drag force	N
F_e	electrostatic force	N
F_E	electric dipole force	N
F_f	frictional force	N
F_g	gravitational force	N
F_{gt}	tangential component of gravitational force	N

F_G	correction factor for extra fineness of grind	–
F_i	settling factor	–
F_i	inertia or centrifugal force	N
$F_\downarrow$	electric field gradient force	N
F_M	magnetic force	N
F_{MR}	radial component of magnetic force	N
F_{OS}	correction factor for oversized feed	–
F_R	correction factor for low reduction ratio	–
F_S	mass flow rate	kg/s, t/h
F_S	Bond slurry or slump factor	–
F_v	viscous force (drag)	N
g	gravitational constant (9.81)	m/s^2
G	grade (assay)	%, g/t, ppm
G, G_{bp}	net grams of undersize per revolution	g/rev
G'	grinding parameter of circulating load	–
ΔG	free energy	J
h	parameter = x/σ	–
h_1, h_1*	distances within the conical section of a mill	M
H	hindrance factor	–
H	height	m, cm
H	magnetic field strength	A/m
H_B	height of rebound pendulum	m
H_B	height of bed	m
H_C	height of ball charge	m
H_C	height of the start of the critical zone in sedimentation	m
H_{OF}	height of the clarification zone (overflow)	m
H_R	height of rest	m
H_S	hindered settling factor	–
H_t	height at time t	m
H_U	mudline height at the underflow concentration	m
H_∞	height after infinite time	m
i	current	A
I	impact crushing strength	kg.m/mm
I	imperfection	–
J_B	fraction of mill volume occupied by bulk ball charge	–
J_C	fraction of mill volume in cylindrical section occupied by balls and coarse ore	–
J_G	superficial gas velocity	m/s
J_R	fraction of mill volume occupied by bulk rock charge	–
J_P	fraction of mill volume filled by the pulp/slurry	–
k	constant	–
K	Boltzmann's constant, 1.381×10^{-23}	J/K
k_A, $k_A^{'}$	rate constant for air removal via froth and tailings respectively	–

k_C, k_{C50}	screening rate constant, crowded condition, normal and half size	t/h/m^2
k_e	Coulomb's constant, 8.99 × 10^9	Nm^2/C^2
k_F, k_S	rate constant for fast and slow component respectively	min^{-1}
k_i	comminution coefficient of fraction coarser that *i*th screen	–
k_S, k_{S50}	screening rate constant, separated condition, normal and half size	m^{-1}
K	constant	–
K	ratio of vertical to horizontal media pressure	–
K	flatness factor	–
K_{D0}	material constant	–
KE	kinetic energy	kW
L	length	m
L_A	aperture size	m
L_{AE}	effective aperture	m
L_C	length of cyclone	m
L_{CYL}, L_{CONE}	length of cylindrical and cone sections	m
L_D	drum radius	m
L_E	distance between electrodes	m
L_{EFF}	effective grinding length	m
L_F	Nordberg loading factor	–
L_{MIN}, L_{MAX}	minimum and maximum crusher set	m
L_r	distance from centre of rotation	m
L_T	crusher throw	m
L_V	length of vortex finder	m
L_{VF}	length from end of vortex finder to apex of a cyclone	m
m	moisture (wet mass/dry mass)	–
m	mass	g
m	mineralogical factor	kg/m^3
$m_{i(U)}$	mass of size *i* in the underflow (F = feed)	kg
m_k	mass fraction of makeup balls of size *k*	–
$m(r)$	cumulative mass fraction of balls less than size *r*	–
m_T	mass rate of ball replacement per unit mass of balls	kg/h.t
$m_{U(F)}$	mass fraction of undersize in the feed	
$m_{U(O)}$	mass fraction of undersize in the oversize	–
$m_{U(U)}$	mass fraction of undersize in the undersize	–
M	magnetization	A/m
M	mass	kg, t
M_1	mass of new feed	g
M_B	mass of block	kg
M_B	mass of balls	kg
M_C	mill capacity	t/h
M_C	mass of crushing weight	kg
M_F	mass of feed	t
M_F	mass of fluid	kg

M_{FT}	mass of floats	kg, t
M_F	Nordberg mill factor	–
M_i	mass/mass fraction of *i*th increment	kg, t
M_{oi}	cumulative mass fraction retained on *i*th screen at zero time	–
M_{ij}	mass percent of the *i*th size fraction and *j*th density fraction	%
M_{MIN}	minimum mass of sample required	kg, t
M_P	mass of particle	kg
M_r	cumulative mass fraction of balls of size *r* in the charge	–
M_R	mass of rock	kg
M_R	mass fraction of rock to total charge (rock + water)	–
M_S	mass of striking pendulum	kg
M_S	mass of solid	kg, t
$M_{S(f)}$	mass of solid in froth	–
$M_{S(F)}, _{S(C)}, _{S(T)}$	mass of solid feed, concentrate and tailing respectively	kg, t
M_{SK}	mass of sinks	kg, t
$M_{S(P)}$	mass of solid in the pulp	kg, t
M_W	mass of water	kg, t
$\Delta M(t)$	mass of top size particle	kg, t
n	number of revolutions/min	min^{-1}
n	number of increments, measurements	–
n	order of rate equation	–
n	number of unpaired electrons	–
$n(r)$	cumulative number fraction of balls of size less than r	–
n_S	number of sub-lots	–
N	number of mill revolutions	–
N	revolutions per second	s^{-1}
N	number of strokes/min	min^{-1}
N	number	–
N	concentration of ions per unit volume	m^{-3}
N'	number of particles/gram	g^{-1}
N_o	Avogado's number, molecules/mol	–
N_L	number of presentations per unit length	m^{-1}
N_m	number of media per unit volume	m^{-3}
N_S	number of stress events	–
o_i	mass fraction of size *i* in the overflow	–
p	Probability	–
p_i	mass fraction of size *i* in the new feed	–
P	product size	microns
P	proportion of particles	–
P	pressure	Pa
P	powers roundness factor	–
P	jig power	W
P	JKSimFloat ore floatability parameter	–

P	probability	–
P_{80}	80% passing size of product	microns
P_A, P_C, P_E, P_F	probability of adherence, collision, emergence, froth recovery	–
P_{CON}	power of the conical part of a mill	kW
P_{CYL}	power for the cylindrical part of a mill	kW
P_D	particle distribution factor	–
P_F	pinning factor	–
P_g	pressure due to gravity	N/m^2
P_G	proportion of gangue particles	–
P_{ij}	proportion of particles in the *i*th size and *j*th density fractions	–
P_L	liberation factor	–
P_m	grinding media pressure	N/m^2
P_M	proportion of mineral particles	–
P_M	mill power	kW
P_{NET}	net mill power draw	kW
P_{NL}	no load power	kW
P_{OS}	period of oscillation	s
P_R	relative mill power	–
P_S	particle shape factor	–
P_S	power at the mill shaft	kW
PE	potential energy	kW
ΔP	pressure drop	kPa
q	alternate binomial probability = $1 - p$	–
Q	capacity	t/h
Q_1, Q_2	point charges	C
Q_B	makeup ball addition rate	kg/day
Q_B	basic feed rate (capacity)	t/h/m
$Q_{MS(O)}$	flowrate of solids by mass in the overflow (U = U/F, F = feed)	t/h
$Q_{MS(C)}$	mass flow of solid in concentrate	t/h
$Q_{M(F)}$	capacity, of feed slurry by mass	t/h
Q_O	tonnage of oversize material	t/h
Q_U	capacity of the underflow	t/h
$Q_{V(C), (T), (F)}$	flowrate by volume in concentrate, tailing and feed respectively	m^3/h
$Q_{V(f)}$	flowrate by volume in the froth	m^3/h
$Q_{VL(O)}$	capacity (flowrate) of liquid by volume in the overflow (U = underflow, F = feed)	m^3/h
$Q_{V(O)}$	flowrate by volume of overflow (pulp) (U = underflow)	m^3/h
$Q_{VOL(U)}$	flowrate by volume of entrained overflow liquid in the U/F	m^3/h
$Q_{VOP(U)}$	flowrate by volume of entrained overflow pulp in the U/F	m^3/h
$Q_{VOS(U)}$	flowrate by volume of entrained overflow solids in the U/F	m^3/h
$Q_{VS(O)}$	flowrate by volume of solids in the overflow (U = U/F, F = feed)	m^3/h
Q_W	ball wear rate	mm/h
r	radius	m

r	ratio of rate constants = $k_A^{'}/(k_A + k_A^{'})$	–
r_o	fraction of test screen oversize	–
r_1, r_2	radius within the conical section of a mill	m
r_p	particle radius	m
r_v	vector radius	m
R	radius	m
R	recovery	%
R	reduction ratio	–
$\bar{R}$	the mean radial position of the active part of the charge	m
R'	fractional recovery, with respect to the feed to the first cell	–
R'	mass of test screen oversize after grinding	g
R_1, R_2, R_3	Dietrich coefficients	–
R_C	radius of cone at a distance L_i from cylindrical section	m
Re_A, Re_C	Reynolds number in the apex and cone section respectively	–
Re_P	particle Reynolds number	–
R_F	froth recovery factor	–
R_i	radial distance to the inner surface of the active charge	m
R_o	mass of test screen oversize before grinding	g
R_P	radial distance of particle from the centre of a mill	m
R_{RO}	optimum reduction ratio	–
R_T	radius at the mill trunnion	m
R_V	recovery of feed volume to the underflow	–
R_∞	recovery at infinite time	–
S	speed	m/s
S	sinks at SG	–
S	surface area	m^2
S	spacing, distance	m
S^*	dimensionless parameter	–
S_B	surface area of ball	m^2
S_B	bubble surface area flux	s^{-1}
S_F	Nordberg speed factor	–
S_i	breakage rate function	min^{-1}
SE	stress energy	Nm
SE_{Vb}	specific energy per unit volume at level b	Nm/m^3
SG, SG_S	specific gravity, specific gravity of solid	–
SI	stress intensity of grinding media	Nm
t	time	h, min, s
t_{10}	size that is one tenth the size of original particle	mm
$\bar{t}_A$	mean time taken for active part or charge to travel from the toe to the shoulder	s
t_D	detention or residence time	h
$\bar{t}_F$	mean time for free fall from the shoulder to the toe	s