Two-phase flows in chemical engineering

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My wife Rachel and I
want this book to remind us always
of our good friends
Edward Fletcher and Herbert Isbin
who helped us in our first steps in America

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PREFACE

Problems in the hydrodynamics and mass- and heat-transfer processes of two-phase flows in the field of chemical engineering have received extensive treatment during the last thirty years. In writing this monograph I have not attempted to cover all the specific solutions available at the present time, and it is not intended to be exhaustive either in breadth or in depth of coverage. The problems under consideration are, to a certain extent, an account of my approach to the investigation of discrete flows of gas–liquid and solid–liquid systems, which I have developed in the course of time. Most of the analytical approaches have been selected for their generality and usefulness in deducing the parameters that are of engineering interest.

It is hoped that this monograph will be useful as a text in graduate courses, as well as in self-study by those practicing engineers who not only need to solve problems involving hydrodynamics and mass transfer in two-phase flows but also to gain a deeper understanding of the more advanced methods of analysis. It may also serve as a point of departure for further research.

The book is divided into three parts. Part I, Hydrodynamics of Two-Phase Flows, contains six chapters.

Chapter 1 reviews the phenomenon of two-phase flows and discusses the fundamental concepts important in setting the stage for subsequent treatment of more complex problems.

In Chapter 2, I consider the bubble-formation phenomenon for the simplified case of bubbling from a single orifice under a wide range of conditions, as well as the transition from a bubble-to-bubble regime to the continuous gas flow (jets) regime.

Chapter 3 is devoted to the hydrodynamic aspects of mass bubbling. On the basis of the theory of developed isotropic turbulence, an equation is derived for calculating the rise velocity of a bubble in a restricted flow. The bubble size generated as a result of dynamic interactions between liquid and gas, leading to the breakup and coalescence of gaseous bubbles, is evaluated.

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The phase contact surface is examined, taking into account the polydispersity of the bubble system (considered as a statistical totality described by distribution functions).

Chapter 4 deals with the formation of dynamic two-phase flows. Since the hydrodynamic equations for one-phase flow are not applicable to calculations in two-phase flows (specifically, a gas-in-liquid dispersion), I develop a theory describing the physical mechanisms occurring in the dynamic two-phase layer and of the influence of individual parameters on the formation of the layer.

The principle of minimum total energy of a bubble layer is postulated; this energy is considered to be a function of the gas density distribution through the layer height. Starting from this principle, I derive equations suitable for calculating the hydrodynamic characteristics of the bubble layer.

The nonuniform velocity field in the bubble layer affects the intensity of the viscous forces and gives rise to convective accelerations and, consequently, inertial effects. Taking these effects into account, physical models of bubbling processes used in commercial practice are considered: "fast" bubbling, which corresponds to the ideal bubble layer having no viscosity; "slow" bubbling, which includes viscous, buoyancy, and surface forces; and "mixed" bubbling, which takes into account the combined influence of the viscous and inertia forces.

Chapter 5 analyzes two problems: cone stability and droplet entrainment. It is shown that the regime of open gaseous spray cones is unrealizable in practice in the range of gas flow rates acceptable in bubbling-flow processes, for a liquid of low viscosity.

Equations are proposed for determining the entrainment of liquid derived from the model of uniform isotropic turbulence, as is a criterion for determining the normal operating conditions of a bubble apparatus. I also examine a simplified model for the mechanism of entrainment for cellular foam conditions and present equations for calculating liquid entrainment in this case.

In Chapter 5, I also describe a statistical model for entrainment, based on the assumption that the distribution of droplet escape velocities from a bubbling layer is normal and independent of the size of the droplets.

In Chapter 6, I study the problem of steady and nonuniform motion of solid particles in liquid. I investigate the effect of system walls on particle velocities in a dilute suspension and obtain basic equations for the motion of micro- and macrosolid particles suspended in a turbulent flow.

Part II, Mass Transfer in Two-Phase Flows, contains Chapters 7 and 8.

In Chapter 7 are given the results of an investigation of the kinetic parameters for mass transfer in gas–liquid systems. Once again, using the concepts of developed isotropic turbulence, equations are presented for determining the velocity of a single bubble, and a group of bubbles, suspended in a turbulent liquid stream. Following these equations, diffusion flow to the surface and flow from a group of bubbles is calculated, including consideration of their distribution with respect to size.

In Chapter 8, I investigate the mass-transfer phenomenon in liquid–solid particle systems for a turbulent flow. Using the concepts of isotropic turbulence, equations are derived for calculating the velocities of solid particles whose size is considerably less, or more, than the internal scale of turbulence. On the basis of the diffusion boundary-layer theory, equations are obtained for calculating the coefficients of mass transfer to these particles, taking into account their distribution with respect to size.

Part III, Application to Chemical and Biochemical Processes, contains two chapters.

Chapter 9 is devoted to the design of a bubble-type chemical reactor. Liquid-phase oxidation reactions are referred to as chain-branched termination reactions with a square termination. This enables me to describe the complex chemical process of hydrocarbon oxidation in terms of a combination of elementary reactions, characterized by the numerical values of various constants.

I also investigate the influence of oxygen partial pressure on the oxidation rate and tar formation rate as a function of the dimensionless parameters of the process.

The macrokinetics of hydrocarbon oxidation in the liquid phase is studied in order to eliminate the diffusion limitation imposed on the process by the transfer of molecular oxygen.

By considering a material balance for the gaseous reagent I develop a method for designing a bubble-type reactor for hydrocarbon oxidation in the liquid phase, providing a scaling method for a commercial process in the kinetic regime.

In Chapter 10 these methods are used to investigate the design of a microbiological reactor (fermenter). I show that cultivation of microorganisms is associated with intensive mixing, which provides a uniform distribution of microorganisms in the bulk of a culture medium, air dispersion, and transfer of mass to the cell surface for utilization. It also provides for the removal of metabolism products from the reaction zone. By analyzing the intracellular processes, I show that the transfer of mass to the reaction surface is the limiting stage of the entire process.

An equation is proposed for determining the specific rate of growth of organisms as a function of the physical properties of the medium, the dimensions and density of the particles, the concentration of materials in the bulk of the solution, the liquid velocity, and the characteristic dimensions of the apparatus in which turbulence is produced. On the basis of these investigations, the design of a biochemical reactor is suggested.

The inclusion of practical aspects of the subject as an integral part of the monograph is intended to serve as a supplement to, rather than a substitute for, a strong foundation in chemical engineering fundamentals.

On the personal level, I would like to share the history of this book with its readers. This monograph was originally written in Soviet Russia after the author had been dismissed from his position for applying to leave the country and while waiting for the exit visa. The manuscript was then sent, page by page, by various routes, to Mr. Greville Janner, Q.C.M.P., in London, who passed it to Professor Kenneth Denbeigh, Member of the Royal Society and Principal of Queen Elizabeth College. While I was still in Moscow, Mr. Janner and Professor Denbeigh encouraged and helped me to find a publisher for this book. All thanks are due them, because without their help, this book would not have been possible.

Thanks are also due the large number of people who helped to transport the manuscript to England but who, unfortunately, must remain anonymous.

I would also like to thank my editor, Philip Kemp-Pritchard, for helping me to bring the monograph into its final form.

I owe a deep debt of gratitude to Professors Edward Fletcher and Herbert Isbin of the University of Minnesota for their help with the manuscript and valuable suggestions, and to the University of Minnesota and State University of New York at Stony Brook for supplying me with every possible practical help to facilitate my work.

I also wish to acknowledge with thanks the assistance given by the faculty and staff of the Chemical Engineering Department of the University of Missouri at Rolla and to thank Professors M. E. Findley, A. I. Liapis, G. K. Patterson, and D. J. Siehr for helpful comments regarding the manuscript. In particular, I am greatly indebted to Professor J. W. Johnson, chairman of the Chemical Engineering Department, who read the whole manuscript and who provided useful suggestions.

D. A.

LIST OF SYMBOLS

A	local cross-sectional area; interface contact area
A_b	cross-sectional area of bubble
A_m	cross-sectional area of membrane
A_l	cross-sectional area of laboratory reactor
Bo	Bond number
C_D	drag coefficient
C_W	constant that is numerically equal to maximum reaction rate
D	pipe diameter; diffusivity
D_m	mixer diameter
D_o	orifice diameter
D_{turb}	turbulent diffusivity
$\overline{D}$	longitudinal mixing coefficient
E	total kinetic energy of injected gas; total energy of mixture; spectral energy density/mass/wavenumber
E_b	energy of bubble
E_f	energy of liquid
Eu	Euler number
F_b	buoyancy force
F_D	drag force
F_σ	surface-tension force
F_0	form drag
Fo	Fourier diffusion number
Fr	Froude number
Ga	Galileo number
Ho	homochronity number
K	droplet free-ascent-velocity correction factor; respiratory coefficient
K_E	energy coefficient
K_f	friction factor
K_{tb}	recuperated catalyst
$K_{t_{ox}}$	oxidized catalyst
L_d	work done against drag
L_k	kinetic energy of bubble

L_σ	surface-tension energy of bubble
M	charge of *o*-xylene; mass flow rate/area of mixture; mass diffusion rate
M_b	liquid mass entrained/bubble
M_e	catalyst mass
M_f	droplet mass
M_g	gas mass flow rate
M_{ij}	mass flux tensor
N	valency of metal; number of bubbles/time; total number of bubbles; number of eddies/mass/wavenumber; number of cells
$N_{\max}$	maximum number of cells
N_0	original number of cells
N_c	number of liquid cones
N_s	Stokes number
P	power input/volume; power consumption; steric factor
P_{O_2}	oxygen partial pressure
Pe	Peclet number
Q	gas flow rate; particle volumetric flow rate
Q_l	liquid volume; liquid flow rate
Q'	oxygen dissolution rate
R	equivalent radius of liquid cones
Re	Reynolds number
R	radical
S	plate surface area; total bubble surface area; total particle surface area; total cell surface area
Sc	Schmidt number
Sh	Sherwood number
T	tank diameter
U	characteristic velocity of flow; liquid flow rate; effective slip velocity
V	bubble volume; particle volume; working volume of apparatus
V_a	liquid volume equivalent to additional mass
V_{av}	average bubble volume
V_d	displaced bubble volume
V_E	final bubble volume
V_F	initial bubble volume
V_f	liquid volume
V_t	mixture volume
W	oxidation rate
W_e	enzyme reaction rate
W_i	initiation rate
W_{tf}	tar formation rate
W'	rate of oxygen diffusion; oxidation rate/system volume; catalytic oxidation rate
We	Weber number

Y	total mass of entrained drops/area/time
Y_0	total entrainment/area/time
Y_c	entrainment component independent of height/area/time
$\mathbf{Y}$	entrainment coefficient/area/time
Z	collision factor

a	specific surface area
a_e	eddy acceleration
a_f	fluid acceleration
a_p	particle acceleration
a_r	relative acceleration
b	weir length
c	local concentration; concentration of solute or hydrocarbon
c_0	bulk concentration
c_e	oxygen concentration in exhaust
c_{eq}	equilibrium concentration
c_i	initial hydrocarbon concentration; concentration at wall
c_{in}	concentration at interface
c_k	catalyst concentration
c_p	particle concentration; concentration of products
c_s	concentration of saturated solution; speed of sound in gas
c'	reaction product concentration
d	droplet diameter; diameter of pipe, apparatus, or reactor
d_{av}	average bubble diameter
d_b	bubble diameter; bubble diameter at release
d_m	impeller diameter
d_p	particle diameter
d_{pr}	propeller diameter
$\bar{d}$	dimensionless bubble diameter
dE	total energy of layer
dE_1	potential energy of layer
dE_2	kinetic energy of layer; dissipation in layer
dE_3	surface tension energy
e	eddy energy; total bubble energy density
e_b	bubble energy dissipation
f	frequency of particles crossing cross-sectional area; probability density
h	liquid column height
k	work of suspension; coefficient of apparent additional mass; mass-transfer coefficient
k_d	correction factor for equipment diameter
k_f	liquid mass-transfer coefficient
k_{f_s}	liquid surface mass-transfer coefficient
k_{f_v}	liquid volume mass-transfer coefficient

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k_g	gas mass-transfer coefficient
k_h	correction factor for equipment height
k_i	reaction-rate constants; rate constant of desorption
k_s	mass-transfer coefficient/effective area
k_v	mass-transfer coefficient/effective volume
l	flow characteristic length
l_c	axis ratio
m	bubble instantaneous mass; diffused mass of bubble; diffused mass in cell model
m_i	diffusional flow of mass to particle
$\dot{m}$	mass transfer/time
m'	mass transfer/area
$\dot{m}'$	mass transfer/area/time
n	rotation rate; number of revolutions; turbulent frequency; number of bubbles/volume
p_a	ambient pressure
p_e	exhaust pressure
p_f	liquid pressure
p_g	gas pressure
p_o	gas pressure at orifice
$\bar{p}$	mean pressure
$\bar{p}_g$	time-averaged gas pressure
p'	fluctuating pressure
q	relative gas flow rate; average gas flow rate into bubble
r	eddy size
r_b	instantaneous bubble radius
r_c	cell radius; critical bubble size
r_d	eddy size of viscous effect; drop radius
r_e	bubble radius at detachment; energy-containing eddy size
r_0	maximum radius of entrained eddies
r_p	particle radius
r^*	radical size
s	distance of bubble center below surface; fractional rate of renewal of elements
s_{av}	average bubble surface area
s_b	bubble surface area
s_0	contaminated area of bubble
u	velocity parallel to surface
u_{f_i}	fluid velocity vector
u_i	velocity vector
u_o	velocity outside boundary layer
u_{p_i}	particle velocity vector
u_r	particle terminal velocity

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u_i'	fluctuating velocity vector
$\bar{u}_i$	mean velocity vector
v	instantaneous local gas velocity; velocity perpendicular to surface; gas velocity in annular space
v_b	bubble velocity
v_d	droplet absolute velocity
$v_{d\infty}$	droplet absolute velocity in infinite medium
v_e	small eddy characteristic velocity
v_f	liquid velocity
v_g	gas velocity
v_{gr}	bubble surface velocity relative to liquid
v_i	velocity vector
v_o	gas mean velocity at orifice
$v_{o(\mathrm{crit})}$	critical mean velocity at orifice
v_p	particle velocity
v_r	bubble velocity relative to liquid; relative velocity of droplet or particle
v_s	gas superficial velocity; solid superficial velocity; flow superficial velocity
v_{sf}	liquid superficial velocity
v^i	ideal fluid flow velocity
v_τ	velocity defining turbulent motion
v^*	shear velocity
$\bar{v}_p$	average particle velocity
x_1	height of two-phase mixture
y_e	element thickness

α	longitudinal turbulent intensity; acceleration coefficient for chemical reaction
β	universal constant; measure of radical spent in tar formation
γ	universal constant
δ	membrane thickness; diffusion sublayer; boundary layer thickness
δ_b	turbulent buffer layer thickness
δ_c	critical membrane thickness
δ_{eff}	effective film thickness
δ_0	viscous sublayer
ϵ	energy dissipation/mass/time
ϵ_t	dissipated turbulent energy
$\bar{\epsilon}$	mean viscous energy dissipation/mass/time
ζ	dimensionless cell count
η	Kolmogoroff length scale; dimensionless relative tar formation rate; order of reaction rate with respect to oxygen
θ	relative output/reactor volume
θ_k	active center "density"
κ	wavenumber

κ_e	wavenumber of energy-containing eddies
κ_d	wavenumber of eddies with viscous effect
λ	microscale of turbulent eddies
μ	dimensionless cell growth rate; mixture dynamic viscosity
μ_f	liquid dynamic viscosity
μ_g	gas dynamic viscosity
$\mu_{\max}$	maximum rate of microorganism growth
ν	kinematic viscosity; dimensionless oxidation rate
ν_f	liquid kinematic viscosity
ν_{tf}	tar formation rate
ν'	dimensionless catalytic oxidation rate
ρ	dimensionless radical concentration; mixture density
ρ_f	fluid density
ρ_g	gas density
ρ_p	particle density
$\bar{\rho}$	mean mixture density
ρ'	fluctuating mixture density
σ	dimensionless catalyst concentration; surface tension
σ_b	bubble diameter standard deviation
σ_{b_s}	bubble surface area standard deviation
σ_{b_v}	bubble volume standard deviation
τ	characteristic time; eddy duration at surface; eddy time scale
τ_f	bubble formation time
τ_{ij}	stress tensor
τ_0	time between bubbles
τ_s	shear stress
ϕ	gas void fraction; solid content of mixture; velocity potential
ϕ_{av}	average gas void fraction
$\bar{\phi}$	mean void fraction
ϕ'	fluctuating void fraction
ψ	stream function; foam specific gravity
ω	dimensionless oxygen concentration
ω_n	gas motion natural frequency
Δ	determinant
Δc	concentration gradient
Δp	pressure difference
ΔE	activation energy
ΔU	change in average velocity
Ω_n	membrane natural frequency