MULTIPHASE FLOW WITH SOLID PARTICLES

Multiphase flow is an area of fluid dynamics that describes interactions between two or more phases of matter and is relevant across a wide range of industrial processes and natural environmental systems, from the transport of natural resources to volcanic ash flow. This book covers the topic in detail, providing clear explanations of the underlying physics behind the complex behaviour of solid particles in fluids. The forces involved in particle–fluid interactions are first used to describe the interactions between the particles, and the fundamentals of contact mechanics are then outlined and applied to model interparticle collisions. The book is illustrated with frequent worked examples and algorithms, enabling the reader to develop the required tools for simulating the flow of fluids with solid particles. This self-contained text will appeal to physicists, applied mathematicians, and mechanical engineers working in this important area of research.

PAWEL KOSINSKI is professor of energy and process technology at the University of Bergen, Norway, and has taught numerous courses in fluid dynamics, multiphase flows, and process technology. A renowned researcher in the field, he has published extensively in leading physics and engineering journals.

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PAWEL KOSINSKI
University of Bergen

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Contents

Nomenclature

α	damping parameter in the model by Tsuji et al.
α_f	volume fraction of the fluid phase
α_p	volume fraction of the particle phase
α_r	radiative absorptivity of the particle material
α_{max}	particle packing limit
$\bar{\rho}_f$	bulk density of the fluid phase
$\bar{\rho}_p$	bulk density of the particle phase
$\bar{d}_n$	particle number average size
$\bar{R}_*$	curvature during recovery
$\bar{u}_z$	surface deformation along z-axis
β	coefficient of tangential restitution, v_s/v_{s0}
β_0	limiting coefficient of tangential restitution
β_{ij}	collision frequency function (kernel)
$\boldsymbol{\omega}$	particle angular velocity
Δp	pressure loss
Δt	time step
δ	indentation (deformation)
δ_c	maximum indentation
δ_f	final indentation
δ_p	indentation that leads to the fully plastic deformation
δ_r	indentation during recovery
δ_t	tangential indentation
δ_y	indentation that leads to the elastic–plastic deformation
$\dot{E}$	energy flux
$\dot{M}$	momentum flux
$\dot{Q}$	heat transfer rate
ϵ	dissipation rate of turbulent kinetic energy per unit mass
ϵ_l	energy constant in the Lennard-Jones potential

γ	surface energy
γ_n	damping parameter in the extended linear spring and dashpot model
γ_{adh}	2γ
$\hat{\delta}$	dimensionless indentation in the model by Tsuji et al.
$\hat{v}$	dimensionless velocity in the model by Tsuji et al.
κ	$4/3E_* R_*^{1/2}$
λ	mean free path of molecules
λ_n	damping parameter in the non-linear spring and dashpot model
λ_o	damping parameter in the linear spring and dashpot model
μ_f	fluid dynamic viscosity
μ_m	suspension viscosity
μ_o	parameter in the linear spring and dashpot model
μ_r	relative viscosity
μ_T	Tabor's parameter
ν	Poisson coefficient
ν_f	fluid kinematic viscosity
Φ	flow potential
Φ_s	sphericity
Π_e	energy coupling parameter
Π_m	momentum coupling parameter
ρ_f	fluid density
ρ_p	particle material density
ρ_w or ρ_s	molecular density (wall or sphere)
σ	Stefan–Boltzmann constant
σ_l	lattice constant
σ_n	standard deviation
σ_n^2	number variance
σ_R	absorption coefficient
σ_r, σ_θ, σ_z	normal stress components
τ_f	fluid characteristic time
τ_o	shear stress maximum value
τ_t	thermal response time
τ_v	momentum response time
τ_w	wall shear
τ_{ij}	shear stress tensor
$\mathbf{F}_D$	drag force
$\mathbf{F}_M$	Magnus force
$\mathbf{F}_S$	Saffman force
$\mathbf{F}_{am}$	added mass force
$\mathbf{F}_{th}$	thermophoretic force

$\mathbf{J}$	impulse
$\mathbf{J}_n$	impulse along the normal direction
$\mathbf{J}_t$	impulse along the tangential direction
$\mathbf{M}$	moment of momentum
$\mathbf{n}$	unit vector (normal direction)
$\mathbf{r}$	particle location vector
$\mathbf{T}$	torque
$\mathbf{t}$	unit vector (tangential direction)
$\mathbf{u}$	fluid velocity
$\mathbf{u}_r$	relative velocity
$\mathbf{v}$	particle velocity
$\mathbf{v}_{12,0}$	relative pre-collisional velocity
$\mathbf{v}_{12}$	relative post-collisional velocity
$\mathbf{v}_{n0}$	relative velocity along the normal direction
$\mathbf{v}_{s0}$	relative surface velocity
$\mathbf{v}_{t0}$	relative velocity along the tangential direction
Kn	Knudsen number
Nu	Nusselt number
Pr_f	fluid Prandtl number
Re_g	shear Reynolds number
Re_p	particle Reynolds number
Re_R	rotational Reynolds number
St	Stokes number
$\tilde{f}_m$	particle mass frequency
$\tilde{F}_n$	cumulative number distribution function
$\tilde{f}_n$	particle number frequency
ε	particle radiative emissivity
A	surface area
a_c	maximum contact radius
A_H	Hamaker constant
A_p	projected area
a_p	contact radius that leads to the fully plastic deformation
A_v	viscoelastic coefficient (model by Brilliantov et al.)
a_y	contact radius that leads to the elastic–plastic deformation
b_1	coefficient used when modelling elastic–plastic deformations
b_2	coefficient used when modelling elastic–plastic deformations
C	Cunningham correction factor
C_D	drag force coefficient
c_f	fluid heat capacity
C_M	lift force coefficient

c_n	damping paramater
c_p	particle heat capacity
C_R	torque coefficient
C_S	Saffman lift force coefficient
C_{ij}	correlation coefficient
d	particle diameter
D_o	gap between surfaces on the molecular level
E	Young's modulus
e	coefficient of restitution
E_*	effective Young's modulus
E_k	total kinetic energy
E_{loss}	mechanical energy loss
f	friction coefficient
F_B	Basset force magnitude
f_m	mass density distribution function
f_n	number density distribution function
g	gravitational acceleration
h	heat transfer coefficient
I	particle moment of inertia
K_1, K_2, S	parameters in Walton and Braun's model
k_B	Boltzmann's constant
k_f	fluid thermal conductivity
k_n	spring constant
k_p	particle thermal conductivity
k_t	tangential stiffness (spring constant)
L_B	distance covered due to Brownian motion
L_{ave}	average distance between particles
M	molecular weight
m	particle mass
m_f	mass of the displaced fluid
n	number density
N_{ij}	number of collisions between particles from classes i and j
P	contact force
p	fluid pressure or contact pressure
P_c	maximum contact force
P_f	dissipative force (models by Kuwabara and Kono, and Brilliantov et al.)
p_m	average contact pressure
P_n	contact force (normal direction)
p_o	maximum value of the contact pressure

P_p	contact force that leads to the fully plastic deformation
P_t	contact force (tangential direction)
P_y	contact force that leads to the elastic–plastic deformation
p_y	contact pressure that leads to elastic–plastic deformation
Q	heat
q_w	heat flux
R	particle radius
R	universal gas constant
R_*	effective radius
R_g	specific gas constant
T	temperature
t	time
t_c	total duration of collision
t_d	collision time
T_p	fluid temperature
T_p	particle temperature
t_p	compression duration
t_r	recovery duration
U	elastic energy
u_x, u_y, u_z	displacement coordinates
V	fluid volume
V	potential energy (Chapter 5)
v_1	post-collisional relative velocity
v_o	initial relative velocity
W	work
W_p	work that leads to the fully plastic deformation
W_r	work during recovery
W_y	work that leads to the elastic–plastic deformation
Y	yield stress in tension/compression