POWDER TECHNOLOGY SERIES

HEAT TRANSFER IN FLUIDIZED BEDS

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Powder Technology Series

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Many materials exist in the form of a disperse system, for example powders, pastes, slurries, emulsions and aerosols. The study of such systems necessarily arises in many technologies but may alternatively be regarded as a separate subject which is concerned with the manufacture, characterization and manipulation of such systems. Chapman & Hall were one of the first publishers to recognize the basic importance of the subject, going on to instigate this series of books. The series does not aspire to define and confine the subject without duplication, but rather to provide a good home for any book which has a contribution to make to the record of both the theory and the application of the subject. We hope that all engineers and scientists who concern themselves with disperse systems will use these books and that those who become expert will contribute further to the series.

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Preface

A prestigious form of research grant in Germany is the Sonderforschungsbereich, which provides continuous funding over a period of up to 15 years, but only as long as the work is yielding worthwhile results. We acknowledge financial support of our work at Erlangen by the Deutsche Forschungsgemeinschaft (DFG), Sonderforschungsbereich 222. Thanks to this support, the experimental results from six Dr.-Ing. dissertations have provided the basis for our book:

- Schweinzer, J. (1987) Heat transfer in bubbling fluidized beds at $Ar \geqslant 10^8$
- Seiter, M. (1990) Particle motion and solids concentration in circulating fluidized beds
- Mattmann, W. (1991) Heat transfer in pressurized circulating fluidized beds
- Burschka, A. (1993) Pulsed light method
- Dietz, S. (1994) Heat transfer in bubbling fluidized beds
- Gruber, U. (1995) Heat transfer in lean phase systems

This book is the result of the enthusiastic and trustful cooperation of its authors. Nevertheless, we are separate individuals. Chapters 1 to 12 and 19 are by O. Molerus; Chapters 13 to 18 are by K.-E. Wirth.

This book came into existence after many rewrites, patiently endured by Mrs Winter, who typed all versions of the manuscript, and by Mrs Scheffler-Kohler, who drew all the figures.

Bob Farmer and David Penfold helped us bridge the language gap to produce a readable book.

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O. Molerus and K.-E. Wirth
Erlangen
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List of symbols

Latin letters

a	width of a surface element on the heat exchanger, m
A	amplitude, m
b	mass absorption coefficient, $m^2\ kg^{-1}$
B	constant
c	heat capacity, $W\ s\ kg^{-1}\ K^{-1}$
c_c	heat capacity of the continuous phase, $W\ s\ kg^{-1}\ K^{-1}$
c_g	gas specific heat, $W\ s\ kg^{-1}\ K^{-1}$
c_p	particle material specific heat, $W\ s\ kg^{-1}\ K^{-1}$
C	constant
d_p	particle diameter, bubble diameter, m
d_{pc}	characteristic particle size of a cold system, m
d_{ph}	characteristic particle size of a hot system, m
D	diameter of optical fibre, diameter of the circulating fluidized bed (Chapter 15), m
D_p	pipe diameter, m
D_h	hydraulic diameter of the fluidized bed, m
F	cross-sectional area of the fluidized bed, m^2
f	particle exchange frequency, s^{-1}
$f(t)$	residence time distribution density, s^{-1}
f_L	particle exchange frequency at large heat exchanger surfaces, s^{-1}
$F(t)$	cumulative residence time distribution
F_H	adhesion force, N
$F_{particle}$	surface area of a particle, m^2
F_{hex}	surface area of the heat exchanger, m^2
g	gravitational acceleration, $m\ s^{-2}$
$g(u - u_{mf})$	normalized gas convective heat transfer function, defined by (7.1)
G_1, G_2	constant
h, h_{max}	heat transfer coefficient, maximum value, $W\ m^{-2}\ K^{-1}$
h_i	instantaneous heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
h_{gc}	gas convective component of heat transfer coefficient, $W\ m^{-2}\ K^{-1}$

h_{pc}	particle convective component of heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_L	heat transfer coefficient at large heat exchanger surface, $W\,m^{-2}\,K^{-1}$
h_l	surface-averaged heat transfer coefficient of a particle, $W\,m^{-2}\,K^{-1}$
H	height, m
H_{CFB}	total height of the circulating fluidized bed (CFB), m
$h_{cond\ particle}$	heat transfer coefficient for one particle caused by heat conduction in the gas, $W\,m^{-2}\,K^{-1}$
h_{cond}	heat transfer coefficient caused by heat conduction in the gas, $W\,m^{-2}\,K^{-1}$
h_{conv}	heat transfer coefficient caused by heat convection in the gas, $W\,m^{-2}\,K^{-1}$
H_{mf}	height of the solids at minimum fluidization, m
h_l	height of the lower steady-state section, m
h_{ts}	heat transfer coefficient in CFBs when two steady-state sections occur, $W\,m^{-2}\,K^{-1}$
h_{os}	heat transfer coefficient in CFBs when one steady-state section occurs, $W\,m^{-2}\,K^{-1}$
h_{rad}	heat transfer coefficient in CFBs caused by radiation, $W\,m^{-2}\,K^{-1}$
$h_{rad\ effective}$	heat transfer coefficient in CFBs effectively caused by radiation, $W\,m^{-2}\,K^{-1}$
I	dimensionless heat transfer coefficient, defined by (7.7)
I_0	intensity of unattenuated radiation, s^{-1}
I	intensity of attenuated radiation (Chapter 13), s^{-1}
J	dimensionless heat transfer coefficient, defined by (7.8)
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
k_c	thermal conductivity of the continuous phase, $W\,m^{-1}\,K^{-1}$
k_e	effective thermal conductivity in a particle packet, $W\,m^{-1}\,K^{-1}$
k_{eff}	effective thermal conductivity, defined by (7.9), $W\,m^{-1}\,K^{-1}$
k_g	gas thermal conductivity, $W\,m^{-1}\,K^{-1}$
k_p	particle material thermal conductivity, $W\,m^{-1}\,K^{-1}$
K	lift force, N
l	length, m
l_l	$\equiv \left[\dfrac{\mu}{\sqrt{g}(\rho_p-\rho_g)}\right]^{2/3}$, laminar flow length scale, m
ΔL	length of a pipe element, m
l_t	$\equiv \left[\dfrac{\mu}{\sqrt{g(\rho_p-\rho_g)\rho_g}}\right]^{2/3}$, turbulent flow length scale, m
l_0	mean free path of gas molecules, m
L, L_0	digital luminosity, initial value
L	length of the γ-ray beam in the circulating fluidized bed (Chapter 13), m

L_p	packing or pipe length, m
M	minimum length of heat exchanger, m
M_p	mass of the solids in the CFB, kg
M_c	mass of the continuous phase, kg
$\dot{M}_p$	solids mass flow rate, kg s^{-1}
$\dot{M}_g$	gas mass flow rate, kg s^{-1}
n, n_{p0}	number of particles, initial value (Chapter 2)
n	number of particle rows (Chapter 3)
P	power input, W
p	pressure, N m^{-2}
$p(u - u_{mf})$	normalized particle convective heat transfer, defined by (7.11)
Δp	pressure drop, N m^{-2}
ΔP_{CFB}	total pressure drop in the riser of a CFB, N m^{-2}
P_1, P_2	constants
P_1^*, P_2^*	constants
q_{12}	radiative heat flux from object 1 to object 2, W m^{-2}
$\dot{Q}$	energy transfer per unit time, W
r	integration variable, m
r_0	characteristic particle dimension, m
R	aerodynamic resistance force, N
R	radius (Chapter 3), m
s	characteristic length of surface asperities, m
s_{min}	minimum effective surface asperities according to (3.25), m
S_p	particle surface area, inner pipe surface area, m^2
t	time, s
Δt	time interval, s
T_m	mean temperature, K
T_p	particle temperature, K
T_{susp}	suspension temperature, K
T_w	wall temperature, K
ΔT	temperature difference, K
ΔT_{log}	logarithmic temperature difference, K, defined by (3.6)
T_0	entrance temperature of the gas, K
T_1	exit temperature of the gas, K
u	superficial gas velocity, m s^{-1}
u_{mf}	superficial gas velocity at minimum fluidization condition, m s^{-1}
$u(y)$	shear field velocity, m s^{-1}
u_l	lateral particle velocity, m s^{-1}
u_v	vertical particle velocity, m s^{-1}
u_x	x-component of the velocity vector in Cartesian coordinates, m s^{-1}
v	mean pipe flow velocity, superficial velocity of the continuous phase, m s^{-1}
v_{max}	maximum particle transport velocity, m s^{-1}
v_G	velocity of the gas in the dilute phase, m s^{-1}

v_p	velocity of a particle, m s^{-1}
v_g	velocity of the gas, m s^{-1}
v_{rel}	relative velocity, m s^{-1}
V	particle velocity in shear field, m s^{-1}
V_{fl}	fluid volume, m^3
V_{bed}	volume of a fluidized bed, m^3
$\dot{V}$	volumetric flow rate of the continuous phase, m^3 s^{-1}
w	velocity of the strands, m s^{-1}
w_f	single-particle fall velocity, m s^{-1}
W	probability
x, y, z	Cartesian coordinates, m
X	coordinate, m
ΔX	length, m
y	coordinate, m
Y	coordinate, m

Greek letters

α	constant
β	constant
γ	accommodation coefficient
δ	characteristic dimension for the space around the particles at particulate fluidization, m
δ_l	laminar boundary layer thickness, m
δ_{tr}	boundary layer length scale in the transitional regime, m
δ_{turb}	boundary layer length scale in the turbulent flow regime, m
ε	void fraction
ε_{mf}	minimum fluidization void fraction
$\varepsilon_{1,2}$	emissivities of solid bodies 1, 2
ε_p	emissivity of the particles
ε_w	emissivity of the wall
ε_{rad}	emissivity of the system
ε^*	mass-related power input, W kg^{-1}
ε_l	local void fraction
ε_{wall}	void fraction in the vicinity of the CFB wall
θ	time, s
ϑ_w	wall temperature, °C
ϑ_{susp}	suspension temperature, °C
ϑ_p	particle temperature, °C
ϑ	temperature (Chapter 16), °C
μ	viscosity, kg m^{-1} s^{-1}
μ_c	gas viscosity in a cold system, gas viscosity of the continuous phase in Chapters 17 and 18, kg m^{-1} s^{-1}
μ_h	gas viscosity in a hot system, kg m^{-1} s^{-1}

ν kinematic viscosity, kinematic viscosity of the continuous phase, $m^2\,s^{-1}$
ρ density, $kg\,m^{-3}$
ρ_b bulk density, $kg\,m^{-3}$
ρ_c density of the continuous phase, $kg\,m^{-3}$
ρ_g gas density, $kg\,m^{-3}$
ρ_{gc} gas density in a cold system, $kg\,m^{-3}$
ρ_{gh} gas density in a hot system, $kg\,m^{-3}$
ρ_p particle density, $kg\,m^{-3}$
σ Stefan–Boltzmann constant $= 5.67 \times 10^{-8}$, $W\,m^{-2}\,K^{-4}$
τ mean residence time, s
φ angle
Φ sphericity, dimensionless pressure drop in Chapters 15 and 16, defined by (15.2)
Φ_D pressure drop shape factor
ω cyclic frequency, s^{-1}

Dimensionless groups

$$\mathrm{Ar} \equiv \frac{d_p^3 g(\rho_p - \rho_g)\rho_g}{\mu^2}$$ Archimedes number

$$C_D \equiv \frac{R}{[(\pi d_p^2)/4](\rho_g/2)u^2}$$ drag coefficient

$$\mathrm{Co} \equiv \frac{k_g Cst}{\rho_p c_p d_p^3}$$ dimensionless contact time

$$\mathrm{Bi} \equiv \frac{h d_p}{k_p}$$ Biot number

$$\mathrm{Dr} \equiv \frac{\Delta P}{\Delta L}\frac{d_p^3}{\rho_g \nu^2}\frac{1}{1-\varepsilon}$$ pressure drop number with fixed bed percolation

$$\mathrm{Eu} \equiv \frac{4}{3}\frac{(\rho_p - \rho_g)d_p g}{\rho_g u^2}\varepsilon^2$$ Euler number

$$\mathrm{Fr} \equiv \frac{v^2}{d_p g}$$ Froude number

$$\mathrm{Fr}_p \equiv \frac{v}{\sqrt{\dfrac{\rho_p - \rho_g}{\rho_g} d_p g}}$$ particle Froude number

$$\mathrm{Fr}_{pwf} \equiv \frac{w_f}{\sqrt{\dfrac{\rho_p - \rho_g}{\rho_g} d_p g}}$$ particle Froude number built with the terminal free-fall velocity of a single particle

$\mathrm{Fr}_{\mathrm{p\ umf}} \equiv \dfrac{u_{\mathrm{mf}}}{\sqrt{\dfrac{\rho_{\mathrm{p}} - \rho_{\mathrm{g}}}{\rho_{\mathrm{g}}} d_{\mathrm{p}} g}}$ particle Froude number built with the minimum fluidization velocity

$\mathrm{Nu}, \mathrm{Nu}_{\mathrm{max}} \equiv \dfrac{h d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number, maximum value

$\mathrm{Nu}_{\mathrm{cond\ particle}} \equiv \dfrac{h_{\mathrm{cond\ particle}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number for a particle in the Stokes regime

$\mathrm{Nu}_{\mathrm{cond}} \equiv \dfrac{h_{\mathrm{cond}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number caused by heat conduction in the gas

$\mathrm{Nu}_{\mathrm{conv}} \equiv \dfrac{h_{\mathrm{conv}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number caused by heat convection in the gas

$\mathrm{Nu}_{\mathrm{ts}} \equiv \dfrac{h_{\mathrm{ts}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number in CFBs when two steady-state sections occur

$\mathrm{Nu}_{\mathrm{os}} \equiv \dfrac{h_{\mathrm{os}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number in CFBs when one steady-state section occurs

$\mathrm{Nu}_{\mathrm{rad}} \equiv \dfrac{h_{\mathrm{rad}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number caused by radiation

$\mathrm{Nu}_{\mathrm{rad\ effective}} \equiv \dfrac{h_{\mathrm{rad\ effective}} d_{\mathrm{p}}}{k_{\mathrm{g}}}$ Nusselt number effectively caused by radiation

$\mathrm{Nu}_{\mathrm{c}} \equiv \dfrac{h d_{\mathrm{p}}}{k_{\mathrm{c}}}$ Nusselt number built with the thermal conductivity of the continuous phase

$\mathrm{Nu}_{\mathrm{p}} \equiv \dfrac{h D_{\mathrm{p}}}{k_{\mathrm{g}}}$ pipe flow Nusselt number

$\mathrm{Pe} \equiv \dfrac{\rho_{\mathrm{g}} c_{\mathrm{g}} d_{\mathrm{p}} u}{k_{\mathrm{g}}}$ Peclet number

$\mathrm{Pe}_{\mathrm{fl}} \equiv \dfrac{\rho_{\mathrm{g}} c_{\mathrm{g}} d_{\mathrm{p}} \sqrt{[(\rho_{\mathrm{p}} - \rho_{\mathrm{g}})/\rho_{\mathrm{g}}] d_{\mathrm{p}} g}}{k_{\mathrm{g}}}$ fluidization Peclet number

$\mathrm{Pe}_{\mathrm{p}} \equiv \dfrac{\rho_{\mathrm{g}} c_{\mathrm{g}} D_{\mathrm{p}} v}{k_{\mathrm{g}}}$ pipe flow Peclet number

$\mathrm{Pr} \equiv \dfrac{c_{\mathrm{g}} \mu}{k_{\mathrm{g}}}$ Prandtl number

$\mathrm{Pr}_{\mathrm{c}} \equiv \dfrac{c_{\mathrm{c}} \mu_{\mathrm{c}}}{k_{\mathrm{c}}}$ Prandtl number of the continuous phase

$\frac{r_0}{\delta} \equiv \left[\frac{\zeta}{\sqrt[3]{1-\varepsilon}} - 1\right]^{-1}$	length ratio, $\zeta = 0.9$ for a fluidized bed, $\zeta = 0.95$ for a fixed bed
Re	Reynolds number, different definitions
$Re_\varepsilon \equiv \frac{\upsilon d}{\varepsilon \nu}$	Reynolds number built with the interstitial fluid velocity
$Re_{rel} \equiv \frac{\upsilon_{rel} d_p}{\nu}$	Reynolds number built with the relative velocity
$Re_{umf} \equiv \frac{u_{mf} d_p}{\nu}$	Reynolds number built with the minimum fluidization velocity
$Re_w \equiv \frac{w d_p}{\nu}$	Reynolds number built with the velocity of the downward-falling wall strands
$Re_{wf} \equiv \frac{w_f d_p}{\nu}$	Reynolds number built with the terminal free-fall velocity of a single particle
$Sta \equiv \frac{h d_p}{\rho_g c_g d_p u}$	Stanton number
Sta_1	Stanton number for the first particle row
Sta_n	mean Stanton number for n rows of particles
$Sta_w \equiv \frac{h_{conv}}{\rho_g c_g w}$	Stanton number for the wall strands
$\pi_1 \equiv \frac{d_p^3 g(\rho_p - \rho_g)^2}{\mu^2}$	
$\pi_2 \equiv \frac{\rho_p}{\rho_g}$	
$\pi_3 \equiv \frac{c_g \mu}{k_g} \equiv Pr$	Prandtl number
$\pi_4 \equiv \frac{c_p \mu}{k_g}$	
$\pi_5 \equiv \frac{k_p}{k_g}$	

$\pi_6 \equiv \dfrac{hd_p}{k_g} \equiv \mathrm{Nu}$ Nusselt number

$\Omega^{1/3} \equiv \left[\dfrac{\rho_g^2}{\mu g(\rho_p - \rho_g)}\right]^{1/3} u$ dimensionless gas velocity

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