TWO-PHASE FLOW AND HEAT TRANSFER

Edited by

D. BUTTERWORTH and G. F. HEWITT

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List of Symbols

a	Heat transfer area (m^2).
a_b	Area of surface occupied by bubbles (m^2).
A	Channel flow area (m^2).
A	Parameter defined by eqn (9.48).
A_G	Mean flow area for gas or vapour flow (m^2).
A_L	Mean flow area for liquid flow (m^2).
Bi	Biot number, hL_s/k_s.
Bo	Boiling number, $\phi/G\lambda$.
C	Constant in eqn (4.45).
C_c	Coefficient of contraction at an abrupt reduction in flow area.
C_d	Concentration of droplets in the gas phase in annular flow (calculated on a homogeneous basis) (kg m^{-3}).
C_e	Concentration of droplets in gas core at hydrodynamic equilibrium (kg m^{-3}).
C_p	Specific heat (J kg^{-1} K^{-1}).
C_{pA}	Specific heat of component A (J kg^{-1}).
C_{pG}	Specific heat at constant pressure for the gas or vapour phase (J kg^{-1} K^{-1}).
C_{pL}	Specific heat at constant pressure for the liquid (J kg^{-1} K^{-1}).
C_T	Total molar concentration (kmol m^{-3}).
C_0	Parameter defined by eqn (5.26).
C_1	Constant in Blasius equation.
C_1	Constant in Rohsenow equation (eqn (7.1)) which is given for various fluid - surface combinations in Table 7.1.
D	Tube diameter (m).

D_b	Bubble departure diameter in nucleate boiling (m).
D_G	Diameter of gas cylinder in separate cylinder model described in § 4.4.1 (m).
D_H	Channel hydraulic mean diameter (m).
$\mathscr{D}_{AB}$	Diffusion coefficient for binary mixture of A and B (m^2 s^{-1}).
f	Friction factor.
f	Bubble frequency (s^{-1}).
f_H	Homogeneous flow friction factor.
f_L	Friction factor for the liquid flowing alone in the channel.
f_{sgc}	Single-phase friction factor corresponding to Reynolds number, $V_{gc} \rho_{gc} D/\mu_G$.
f_{sgci}	Interfacial friction factor defined by eqn (6.13).
fn( )	Used to signify that something is a function of the quantity contained in the brackets.
F	Frictional energy loss per unit mass (J kg^{-1}).
F	Correction factor for transition lines in Mandhane *et al.* (1974) map defined by eqn (11.2).
F_c	Convective heat transfer correction factor in Chen (1966) correlation.
F_G	Mass velocity scaling factor (G_w/G_f) for Freon modelling.
F_1	Gas volume flux away from shock (see Fig. 5.3) (m s^{-1}).
F_2	Gas volume flux towards shock front (see Fig. 5.3) (m s^{-1}).
g	Acceleration due to gravity (m s^{-2}).
G	"Mass velocity" in channel, i.e. the total mass flow rate divided by the channel flow area (kg m^{-2} s^{-1}).

G'	Mass flux towards wall at distance y from interface (kg m^{-2} s^{-1}).
Ga_L	Galileo number, $g\mu_L^4/\rho_L\sigma^3$.
G_c	Condensation mass flux (kg s^{-1} m^{-2}).
G_D	Deposition rate per unit surface area of film (in practice the surface area of film is taken as that of the tube) (kg m^{-2} s^{-1}).
G_E	Entrainment rate per unit surface area of film (in practice, the surface area of film is taken as that of the tube) (kg m^{-2} s^{-1}).
G_f	Mass velocity in analogous Freon system (kg s^{-1} m^{-2}).
G_G	Gas (or vapour) phase mass flow divided by the phase-flow area, W_G/A_G (kg s^{-1} m^{-2}).
G_L	Liquid mass flow per unit area in which it is flowing, W_L/A_L (kg s^{-1} m^{-2}).
G_w	Mass velocity in steam - water system (kg s^{-1} m^{-2}).
h	Heat-transfer coefficient (W m^{-2} K^{-1}).
h_G	Heat-transfer coefficient between the bulk gas and the liquid surface (W m^{-2} K^{-1}).
h_{Gn}	Gas-phase heat-transfer coefficient if no mass transfer is occurring (W m^{-2} K^{-1}).
h_i	Interface heat-transfer coefficient or effective coefficient arising from the molecular kinetic effects (W m^{-2} K^{-1}).
h_L	Heat-transfer coefficient if the liquid were flowing alone in the tube (W m^{-2} K^{-1}).
h_L	Local heat-transfer coefficient for condensate film (W m^{-2} K^{-1}).
$\bar{h}_L$	Heat-transfer coefficient for condensate film averaged over the vertical surface (W m^{-2} K^{-1}).
h_{LO}	Heat-transfer coefficient if the total fluid were flowing in the tube with liquid properties (W m^{-2} K^{-1}).

h_{mac}	Macroscopic or convective component of heat transfer coefficient in Chen (1966) correlation ($W\ m^{-2}\ K^{-1}$).
h_{mic}	Microscopic or nucleate-boiling component of heat-transfer coefficient in Chen (1966) correlation ($W\ m^{-2}\ K^{-1}$).
h_N	Heat-transfer coefficient for Nth tube from the top of vertical row of tubes ($W\ m^{-2}\ K^{-1}$).
$\bar{h}_N$	Heat-transfer coefficient averaged over N tubes in a vertical row ($W\ m^{-2}\ K^{-1}$).
$(\bar{h}_L)_{Nu}$	Heat-transfer coefficient calculated by the Nusselt (1916) analysis ($W\ m^{-2}\ K^{-1}$).
h_P	Planck's constant (J s).
h_1	Heat-transfer coefficient for top tube in a vertical column of tubes ($W\ m^{-2}\ K^{-1}$).
h^*	Combined heat-transfer coefficient between the coolant and the liquid surface on the condensing side ($W\ m^{-2}\ K^{-1}$).
H	Depth of liquid in stratified flow (see Fig. 11.2) (m).
H	Parameter defined by eqn (18.28).
H_C	Height of rectangular channel (m).
i	Enthalpy ($J\ kg^{-1}$).
i	$\sqrt{-1}$
i_G	Saturated vapour enthalpy ($J\ kg^{-1}$).
i_L	Saturated liquid enthalpy ($J\ kg^{-1}$).
i_{TP}	Two-phase enthalpy ($J\ kg^{-1}$).
j	Colburn (1933) j-factor for heat transfer.
j_{GL}	Gas relative volume flux, eqn (5.6) ($m\ s^{-1}$).
j_{LG}	Liquid relative volume flux, eqn (5.7) ($m\ s^{-1}$).
J_A	Molar flux of component A in mixture ($kmol\ s^{-1}\ m^{-2}$).

k_B	Boltzmann's constant, $1{\cdot}3805 \times 10^{-23}$ ($J\ K^{-1}$).
k_E	Effective turbulent thermal conductivity ($W\ m^{-1}\ K^{-1}$).
k_G	Thermal conductivity of gas or vapour phase ($W\ m^{-1}\ K^{-1}$).
k_k	von Karman constant, 0.36.
k_L	Thermal conductivity of liquid ($W\ m^{-1}\ K^{-1}$).
K	'Slip ratio' or ratio of gas to liquid mean velocities, u_G/u_L .
K_D	Mass-transfer coefficient for droplet deposition ($m\ s^{-1}$).
K_M	Mass-transfer coefficient ($m\ s^{-1}$).
K_w	Slip ratio in steam - water systems.
L	Channel length (m).
L_b	Boiling length (m).
L_{bf}	Boiling length in analogous Freon system (m).
L_{bw}	Boiling length in steam - water system (m).
L_s	Characteristic dimension of solid body (m).
m	Liquid-film thickness (m).
m^+	Dimensionless film thickness, $m\rho_L u^*/\mu_L$
m_m	Mass of a molecule (kg).
M	Molecular weight (kg/kmol).
n	Index in Blasius equation.
$\dot{n}$	Rate of production of nuclei per unit volume ($m^{-3}\ s^{-1}$).
N	Dimensionless group defined by eqn (5.33).
N	Number of molecules per unit volume (m^{-3}).
N	Bypass ratio: ratio of flow in the bypass channel to that in the heated channel.
N	Number of tubes in a vertical row.
$\dot{N}''$	Flux of molecules (number per unit area per unit time) ($m^{-2}\ s^{-1}$).
N_A	Avogadro's number ($6.023 \times 10^{26}\ kmol^{-1}$).
$N_{\text{Eö}}$	Eötvos number (defined by eqn (5.34)).

Nu	Nusselt number, hD/k.
Nu_L	Nusselt number based on liquid thermal conductivity, hD/k_L.
Nu_{LF}	Liquid-film Nusselt number based on film thickness.
p	Pressure (N m^{-2}).
p_c	Thermodynamic critical pressure (N m^{-2}).
p_{sat}	Saturation vapour pressure (for plane surface) (N m^{-2}).
P	Total power on tube at burnout (W).
P_v	Power input per unit volume (W m^{-3}).
P_0	Burnout power at zero inlet subcooling (W).
Pr_L	Liquid Prandtl number, $C_{pL}\mu_L/k_L$.
Pr_G	Gas phase Prandtl number, $C_{pG}\mu_G/k_G$
q	Heat energy per unit mass (J kg^{-1}).
q	Parameter given by $P_v\ (\rho_L - \rho_G)\ /\ \rho_L\rho_G\lambda\ (s^{-1})$.
$\mathbf{q}$	Heat release rate from condensing mixture (W).
$\mathbf{q}_G$	Heat release rate for cooling the gas phase (W).
Q_G	Gas (or vapour) phase volumetric flow (m^3 s^{-1}).
Q_L	Liquid-phase volumetric flow rate (m^3 s^{-1}).
Q'	Volumetric liquid flow rate per unit perimeter of channel (m^2 s^{-1}).
r	Radial distance (m).
r	Ratio of outlet to inlet velocity for two-phase region.
r_a	Parameter defined by eqn (3.49).
r_b	Bubble radius (m).
r_c	Cavity radius (m).
r_d	Droplet radius (m).
r_f	Parameter defined by eqn (3.48).
r_g	Parameter defined by eqn (3.50).
r_i	Radius at the interface (m).
r_0	Tube radius (m).
R	Universal gas constant (8314·3 J $kmol^{-1}$ K^{-1}).

Re	Reynolds number, GD/μ.
Re_b	Bubble Reynolds number, $2\rho_L u_\infty r_b/\mu_L$.
Re_G	Gas-phase superficial Reynolds number.
Re_H	Homogeneous-flow Reynolds number defined by eqn (4.25).
Re_L	Liquid-phase Reynolds number, $(1 - x)GD/\mu_L$ or $4\Gamma/\mu_L$.
Re_{LT}	Liquid-film Reynolds number at the bottom of the tube.
s	Laplace transform variable defined by $\bar{f}(s) = \int_0^\infty e^{-st} f(t)dt$ where $\bar{f}(s)$ is the Laplace transform of $f(t)$ (s^{-1}).
s	Specific entropy (J kg^{-1} K^{-1}).
S	Channel perimeter (m).
S_c	Nucleate-boiling suppression factor in Chen (1966) correlation.
Sc_G	Gas-phase Schmidt number, $\mu_G/\rho_G \mathscr{D}_{AB}$
t	Time (s).
t	Dimensionless temperature defined by eqn (19.36).
T	Temperature (K).
T_b	Bulk temperature (K).
T_G	Bulk gas temperature (K).
T_s	Film surface temperature (K).
T_{sat}	Saturation temperature (K).
T_w	Wall temperature (K).
T_0	Coolant temperature (K).
T^+	Dimensionless temperature defined by eqn (9.37).
T_s^+	Dimensionless temperature drop across the liquid film.
u	Velocity (often used for local velocity) (m s^{-1}).
$\bar{u}$	Mean velocity in condensate film (m s^{-1}).
u_b	Bubble velocity in slug flow (m s^{-1}).
u_G	Gas-phase or vapour-phase mean velocity (m s^{-1}).
u_{GV}	Relative velocity, eqn (5.4) (m s^{-1}).

u_i	Velocity at interface ($m\ s^{-1}$).
u_L	Liquid-phase mean velocity ($m\ s^{-1}$).
u_{LS}	Liquid-surface velocity around slug-flow-type bubble rising in static liquid ($m\ s^{-1}$).
u_{LV}	Relative liquid velocity, eqn (5.5) ($m\ s^{-1}$).
u_m	Velocity at pipe axis, eqn (5.14) ($m\ s^{-1}$).
u_s	Slug-flow bubble rise velocity ($m\ s^{-1}$).
u_∞	Rise velocity of single bubble in an infinite fluid ($m\ s^{-1}$).
u^*	Friction velocity, $\sqrt{(\tau_0/\rho_L)}$ ($m\ s^{-1}$).
U	Internal energy per unit mass ($J\ kg^{-1}$).
U	Overall heat-transfer coefficient ($W\ m^{-2}\ K^{-1}$).
v	Fluid specific volume ($m^3\ kg^{-1}$).
v_G	Gas (or vapour) phase specific volume ($m^3\ kg^{-1}$).
v_H	Homogeneous specific volume, $xv_G + (1 - x)v_L$ ($m^3\ kg^{-1}$).
v_{TP}	Two-phase effective specific volume based on accelerational term of the two-phase momentum equation, $x^2v_G/\alpha + (1 - x)^2/(1 - \alpha)$ ($m^3\ kg^{-1}$).
V	Total superficial velocity $V_L + V_G$ ($m\ s^{-1}$).
V_b	Vapour bubble volume per unit surface area (m).
V_G	Superficial velocity of gas or vapour phase ($m\ s^{-1}$).
V_{gc}	Gas core velocity (equation 6.15).
V_L	Superficial velocity of liquid phase ($m\ s^{-1}$).
V_G^*	Dimensionless gas-phase superficial velocity defined by eqn (2.3).
V_G^*	Dimensionless gas-phase velocity defined by eqn (11.8).
V_L^*	Dimensionless liquid-phase superficial velocity defined by eqn (2.4).
w	Work done per unit mass ($J\ kg^{-1}$).
w	Width of surface in stratified flow (see Fig. 11.2) (m).

W	Total flow rate in channel (kg s^{-1}).
W_G	Gas-phase or vapour-phase mass flow rate (kg s^{-1}).
W_L	Liquid-phase mass flow rate (kg s^{-1}).
W_{LE}	Entrained liquid flow rate (kg s^{-1}).
W_{LF}	Liquid-film flow rate (kg s^{-1}).
W^+	Dimensionless film flow rate, $W_{LF}/2\pi r_0 \mu_L$.
x	Gas (or vapour) phase mass-flow fraction or 'quality' (taken as thermodynamic quality in Chapter 8).
x	Cartesian coordinate direction (m).
x_a	Quality at the onset of annular flow.
x_{BO}	Burnout quality.
x_d	Thermodynamic quality at bubble departure.
x_f	Burnout quality in analogous Freon system.
x_w	Burnout quality in steam - water system.
x_o	Burnout quality at zero inlet subcooling.
x'	True quality in subcooled boiling.
X	Lockhart-Martinelli (1949) parameter defined by eqn (4.4).
X	Parameter defined by eqn (11.3).
X_{tt}	Lockhart-Martinelli (1949) parameter when both phases are in turbulent motion: $X_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\left(\frac{\mu_L}{\mu_G}\right)^{0.1}$
y	Distance from the wall (m).
y	Cartesian coordination direction (m).
y	Distance from liquid surface (m).
y^+	Friction distance parameter $yu^*\rho_L/\mu_L$.
Y	Parameter defined by eqn (11.4).
Y_b	Bubble height (m).
z	Axial distance along channel or tube (m).
z_n	Distance along the channel at the inception of nucleate boiling (m).

α	Void fraction or fraction of volume occupied by the gas (or vapour) phase.
α_e	Void fraction at exit of channel.
α_f	Void fraction in analogous Freon system.
α_m	Void fraction at pipe axis, eqn (5.15).
α_T	Thermal diffusivity, $k_L/C_{pL}\rho_L$ ($m^2 s^{-1}$).
α_w	Void fraction in steam - water system.
β	Gas (or vapour) phase volumetric flow fraction.
β	Parameter defined by eqn (9.44).
γ	Empirical parameter in eqn (12.1).
Γ	Parameter defined by eqn (4.11).
Γ	Film flow rate per unit width of surface ($kg\ s^{-1}\ m^{-1}$).
Γ'	Condensate mean flow rate produced per unit length of tube ($kg\ s^{-1}\ m^{-1}$).
Γ_L	Film flow per unit width of surface at distance L down surface ($kg\ m^{-1}\ s^{-1}$).
δ_H	Thickness of equivalent laminar film for heat transfer (m).
δ_M	Thickness of equivalent laminar film for mass transfer (m).
ΔG	Gibbs free energy of nucleus formation (J).
Δi_i	Difference between inlet enthalpy and the saturation enthalpy ($J\ kg^{-1}$).
Δp	Pressure drop or pressure difference ($N\ m^{-2}$).
ΔT_d	Subcooling at bubble departure point (K).
ΔT_e	'Effective' wall superheat in Chen (1966) correlation (K).
ΔT_{sat}	Wall superheat, $T_w - T_{sat}$ (K).

ΔT_{sub}	Subcooling, $T_b - T_{sat}$ (K).
ε	Turbulent eddy diffusivity (of either heat or momentum) (m^2s^{-1}).
ε_H	Turbulent eddy diffusivity of heat (m^3s^{-1}).
ε_M	Turbulent eddy diffusivity of momentum (m^2s^{-1}).
ε	Dimensionless subcooling parameter defined by eqn (19.35).
η	Dimensionless distance from film surface, y/m.
θ	Angle between pipe axis and the horizontals illustrated in Fig. 3.2 (degrees or radians).
θ	Angle shown in Figs. 11.2 and 19.12 . (degrees or radians).
κ	Bankoff parameter, eqns (5.16) and (5.17).
λ	Latent heat of vaporisation (J kg^{-1}).
λ	Parameter defined by eqn (2.1).
λ_c	Critical wavelength (m).
λ_D	Wavelength for fastest growing waves (m).
λ_f	Latent heat in analogous Freon system (J kg^{-1}).
λ_w	Latent heat in steam - water system (J kg^{-1}).
Λ	Parameter defined by eqn (4.10).
μ	Viscosity (kg m^{-1} s^{-1}).
μ_A	Viscosity of air at ambient temperature and pressure (kg s^{-1} m^{-1}).
μ_G	Gas or vapour viscosity (kg s^{-1} m^{-1}).
μ_E	Effective viscosity (kg m^{-1} s^{-1}).
μ_H	Homogeneous flow viscosity (kg m^{-1} s^{-1}).
μ_L	Liquid viscosity (kg s^{-1} m^{-1}).
μ_w	Water viscosity at atmospheric temperature (kg s^{-1} m^{-1}).
ξ	Contact angle (degrees or radians).

ρ	Density (kg m^{-3}).
ρ_A	Density of air under atmospheric conditions (kg m^{-2}).
ρ_{gc}	Gas-core density given approximately by eqn (6.14) (kg m^{-3}).
ρ_G	Gas-phase or vapour-phase density (kg m^{-3}).
ρ_H	Homogeneous density, $1/v_H$ (kg m^{-3}).
ρ_L	Liquid-phase density (kg m^{-3}).
ρ_{TP}	Two-phase density based on the gravitational term of the two-phase momentum equation $\alpha\rho_G + (1 - \alpha)\rho_L$ (kg m^{-3}).
ρ_w	Water density at atmospheric temperature (kg m^{-3}).
σ	Surface tension (N m^{-1}).
σ	Parameter defined by eqn (9.50).
σ_c	Condensation coefficient: fraction of molecules. hitting the surface which are absorbed.
σ_e	Evaporation coefficient: fraction of molecules. leaving the surface which escape.
σ_w	Surface tension of water at atmospheric. temperature (N m^{-2}).
τ	Shear stress (N m^{-2}).
τ	Transit time (s).
τ_i	Interfacial shear stress (N m^{-2}).
τ_{in}	Interfacial shear stress for no mass transfer (N m^{-2}).
τ_0	Wall shear stress (N m^{-2}).
ϕ	Wall heat flux (W m^{-2}).
ϕ_c	Convective component of heat flux (W m^{-2}).
ϕ_{BO}	Burnout heat flux (W m^{-2}).
ϕ_{crit}	Critical heat flux (W m^{-2}).
ϕ_{con}	Condensing heat flux in subcooled boiling (W m^{-2}).
ϕ_G	Heat flux from the bulk gas to the interface (W m^{-2}).

ϕ_i	Heat flux at the liquid surface (interfacial heat flux at the liquid side of the interface).
ϕ_n	Nucleate-boiling component of heat flux ($W\ m^{-2}$).
ϕ_{no}	Heat flux illustrated in Fig. 8.6 ($W\ m^{-2}$).
ϕ_{sat}	Critical heat flux for saturated boiling ($W\ m^{-2}$).
ϕ_{sub}	Critical heat flux for subcooled boiling ($W\ m^{-2}$).
Φ_G	Two-phase frictional multiplier defined by eqn (4.2).
Φ_{GO}	Two-phase frictional multiplier defined by eqn (4.3).
Φ_L	Two-phase frictional multiplier defined by eqn (4.2).
Φ_{LO}	Two-phase frictional multiplier defined by eqn (3.45) (see also eqn (4.3)).
ψ	Parameter defined by eqn (2.2).
ω	Frequency of oscillation ($rad\ s^{-1}$).
ω_A	Mole fraction of component A in mixture.
ω_{AG}	Mole fraction of A in the gas-phase bulk.
ω_{AS}	Mole fraction of component A at the liquid surface.
$\frac{dp}{dz}$	Pressure gradient ($N\ m^{-3}$).
$\left(\frac{dp}{dz}\right)_B$	Pressure gradient during subcooled boiling ($N\ m^{-3}$).
$\frac{dp_a}{dz}$	Accelerational component of pressure gradient ($N\ m^{-3}$).
$\frac{dp_F}{dz}$	Frictional component of pressure gradient ($N\ m^{-3}$).
$\left(\frac{dp_F}{dz}\right)_G$	Frictional pressure gradient for the gas (or vapour) phase flowing alone in the channel ($N\ m^{-3}$).

$\left(\frac{dp_F}{dz}\right)_{GO}$ Frictional pressure gradient for the total flow flowing with gas (or vapour) physical properties ($N\ m^{-3}$).

$\left(\frac{dp_F}{dz}\right)_{L}$ Frictional pressure gradient for the liquid phase flowing alone in the channel ($N\ m^{-3}$).

$\left(\frac{dp_F}{dz}\right)_{LO}$ Frictional pressure gradient for the total flow flowing with liquid physical properties ($N\ m^{-3}$).