Heat Transfer

G.F. Nellis and S.A. Klein

NOMENCLATURE

a_i	i^{th} coefficient of a series solution
A_c	cross-sectional area (m^2)
A_{min}	minimum flow area (m^2)
A_p	projected area (m^2)
A_s	surface area (m^2)
$A_{s,fin}$	surface area of a fin (m^2)
A_{tot}	prime (total) surface area of a finned surface (m^2)
AR	aspect ratio of a rectangular duct
AR_{tip}	area ratio of fin tip to fin surface area
Att	attenuation (-)
B	parameter in the blowing factor (-)
BF	blowing factor (-)
Bi	Biot number (-)
Bo	boiling number (-)
Br	Brinkman number
c	specific heat capacity (J/kg-K)
	concentration (-)
	speed of light (m/s)
c''_a	specific heat capacity of an air-water mixture on a unit mass of air basis (J/kg_a-K)
$c''_{a,sat}$	specific heat capacity of an air-water mixture along the saturation line on a unit mass of air basis (J/kg_a-K)
c_{eff}	effective specific heat capacity of a composite (J/kg-K)
c_{ms}	ratio of the energy carried by a micro-scale energy carrier to its temperature (J/K)
c_v	specific heat capacity at constant volume (J/kg-K)
C	total heat capacity (J/K)
$\dot{C}$	capacitance rate of a flow (W/K)
C_1, C_2, ...	undetermined constants
C_{crit}	dimensionless coefficient for critical heat flux correlation (-)
C_D	drag coefficient (-)
C_f	friction coefficient (-)
$\overline{C}_f$	average friction coefficient (-)
C_{lam}	coefficient for laminar plate natural convection correlation (-)
C_{nb}	dimensionless coefficient for nucleate boiling correlation (-)
C_R	capacity ratio (-)
$C_{turb,U}$	coefficient for turbulent, horizontal upward plate natural conv. correlation (-)
$C_{turb,V}$	coefficient for turbulent, vertical plate natural convection correlation (-)
Co	convection number (-)
CTE	coefficient of thermal expansion (1/K)
D	diameter (m)
	diffusion coefficient (m^2/s)
D_h	hydraulic diameter (m)
dx	differential in the x-direction (m)
dy	differential in the y-direction (m)

e	size of surface roughness (m)
err	convergence or numerical error
$\dot{E}$	rate of thermal energy carried by a mass flow (W)
E	total emissive power (W/m^2)
E_b	total blackbody emissive power (W/m^2)
E_λ	spectral emissive power (W/m^2-μm)
$E_{b,\lambda}$	blackbody spectral emissive power (W/m^2-μm)
Ec	Eckert number (-)
f	frequency (Hz)
	dimensionless stream function, for Blasius solution (-)
	friction factor (-)
$\overline{f}$	average friction factor (-)
f_l	friction factor for liquid-only flow in flow boiling (-)
F	force (N)
	correction-factor for log-mean temperature difference (-)
$F_{0-\lambda_1}$	external fraction function (-)
$F_{i,j}$	view factor from surface i to surface j (-)
$\hat{F}_{i,j}$	the 'F-hat' parameter characterizing radiation from surface i to surface j (-)
f	friction factor (-)
fd	fractional duty for a pinch-point analysis (-)
Fo	Fourier number (-)
Fr	Froude number (-)
Fr_{mod}	modified Froude number (-)
g	acceleration of gravity (m/s^2)
$\dot{g}$	rate of thermal energy generation (W)
$\dot{g}'''$	rate of thermal energy generation per unit volume (W/m^3)
$\dot{g}'''_{eff}$	effective rate of generation per unit volume of a composite (W/m^3)
$\dot{g}'''_v$	rate of thermal energy generation per unit volume due to viscous dissipation (W/m^3)
G	mass flux or mass velocity (kg/m^2-s)
	total irradiation (W/m^2)
G_λ	spectral irradiation (W/m^2-μm)
Ga	Galileo number (-)
Gr	Grashof number (-)
Gz	Graetz number (-)
h	local heat transfer coefficient (W/m^2-K)
$\overline{h}$	average heat transfer coefficient (W/m^2-K)
$\tilde{h}$	dimensionless heat transfer coefficient for flow boiling correlation (-)
h_D	mass transfer coefficient (m/s)
$\overline{h}_D$	average mass transfer coefficient (m/s)
h_l	superficial heat transfer coefficient for the liquid phase (W/m^2-K)
h_{rad}	the equivalent heat transfer coefficient associated with radiation (W/m^2-K)
i	index of node (-),

	index of eigenvalue (-),
	index of term in a series solution (-),
	specific enthalpy (J/kg-K)
	square root of negative one, $\sqrt{-1}$
i_a''	specific enthalpy of an air-water mixture on a per unit mass of air basis (J/kg_a)
I	current (ampere)
Ie	intensity of emitted radiation (W/m^2-μm-steradian)
Ii	intensity of incident radiation (W/m^2-μm-steradian)
j	index of node (-)
	index of eigenvalue (-)
J	radiosity (W/m^2)
j_H	Colburn j_H factor (-)
k	thermal conductivity (W/m-K)
k_B	Bolzmann's constant (J/K)
k_c	contraction loss coefficient (-)
k_e	expansion loss coefficient (-)
k_{eff}	effective thermal conductivity of a composite (W/m-K)
Kn	Knudsen number (-)
l_1	Lennard-Jones 12-6 potential characteristic length for species 1 (m)
$l_{1,2}$	characteristic length of a mixture of species 1 and species 2 (m)
L	length (m)
L^+	dimensionless length for a hydrodynamically developing internal flow (-)
L^*	dimensionless length for a thermally developing internal flow (-)
L_{char}	characteristic length of the problem (m)
$L_{char,vs}$	the characteristic size of the viscous sublayer (m)
L_{cond}	length for conduction (m)
L_{flow}	length in the flow direction (m)
L_{ml}	mixing length (m)
L_{ms}	distance between interactions of micro-scale energy or momentum carriers (m)
Le	Lewis number (-)
M	number of nodes (-)
	mass (kg)
m	fin parameter (1/m)
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}''$	mass flow per unit area (kg/m^2-s)
m_{ms}	mass of microscale momentum carrier (kg/carrier)
mf	mass fraction (-)
MW	molar mass (kg/kgmol)
n	number density ($\#/m^3$)
n_{ms}	number density of the micro-scale energy carriers ($\#/m^3$)
$\dot{n}''$	molar transfer rate per unit area ($kgmol/m^2$-s)
N	number of nodes (-)
	number of moles (kgmol)
N_s	number of species in a mixture (-)
Nu	Nusselt number (-)

$\overline{Nu}$	average Nusselt number (-)
NTU	number of transfer units (-)
p	pressure (Pa)
	pitch (m)
P	*LMTD* effectiveness (-)
	probability distribution (-)
p_∞	free-stream pressure (Pa)
$\tilde{p}$	dimensionless pressure (-)
Pe	Peclet number (-)
per	perimeter (m)
Pr	Prandtl number (-)
Pr_{turb}	turbulent Prandtl number (-)
$\dot{q}$	rate of heat transfer (W)
$\dot{q}_{i \text{ to } j}$	rate of heat transfer from surface i to surface j (W)
$\dot{q}_{max}$	maximum possible rate of heat transfer, for an effectiveness solution (W)
$\dot{q}''$	heat flux, rate of heat transfer per unit area (W/m^2)
$\dot{q}''_s$	surface heat flux (W/m^2)
$\dot{q}''_{s,crit}$	critical heat flux for boiling (W/m^2)
Q	total energy transfer by heat (J)
$\tilde{Q}$	dimensionless total energy transfer by heat (-)
r	radial coordinate (m)
	radius (m)
$\tilde{r}$	dimensionless radial coordinate (-)
R	thermal resistance (K/W)
	ideal gas constant (J/kg-K)
	LMTD capacitance ratio (-)
$R_{\bar{A}}$	thermal resistance approximation based on average area limit (K/W)
R_{ac}	thermal resistance to axial conduction in a heat exchanger (K/W)
R_{ad}	thermal resistance approximation based on adiabatic limit (K/W)
R_{bl}	thermal resistance of the boundary layer (K/W)
R_c	thermal resistance due to solid-to-solid contact (K/W)
R_{conv}	thermal resistance to convection from a surface (K/W)
R_{cyl}	thermal resistance to conduction through a cylindrical shell (K/W)
R_e	electrical resistance (ohm)
R_f	thermal resistance due to fouling (K/W)
R_{fin}	thermal resistance of a fin (K/W)
$R_{i,j}$	the radiation space resistance between surfaces i and j (1/m^2)
R_{iso}	thermal resistance approximation based on isothermal limit (K/W)
$R_{\bar{L}}$	thermal resistance approximation based on average length limit (K/W)
R_{pw}	thermal resistance to conduction through a plane wall (K/W)
R_{rad}	thermal resistance to radiation (K/W)
$R_{s,i}$	the radiation surface resistance for surface i (1/m^2)
$R_{semi\text{-}\infty}$	thermal resistance approximation for a semi-infinite body (K/W)

R_{sph}	thermal resistance to conduction through a spherical shell (K/W)
R_{tot}	thermal resistance of a finned surface (K/W)
R_{univ}	universal gas constant (8314 J/kgmol-K)
R_c''	area-specific contact resistance (K-m^2/W)
R_f''	area-specific fouling resistance (K-m^2/W)
Ra	Rayleigh number (-)
Re	Reynolds number (-)
Re_{crit}	critical Reynold number for transition to turbulence (-)
RH	relative humidity (-)
RR	radius ratio of an annular duct (-)
s	Laplace transformation variable
	generic coordinate (m)
S	shape factor (m)
	channel spacing (m)
Sc	Schmidt number (-)
Sh	Sherwood number (-)
$\overline{Sh}$	average Sherwood number (-)
St	Stanton number (-)
t	time (s)
t_{sim}	simulated time (s)
th	thickness (m)
tol	convergence tolerance
T	temperature (K)
T_b	base temperature of fin (K)
T_{film}	film temperature (K)
T_m	mean or bulk temperature (K)
T_s	surface temperature (K)
T_{sat}	saturation temperature (K)
T_∞	free-stream or fluid temperature (K)
T^*	eddy temperature fluctuation (K)
T'	fluctuating component of temperature (K)
$\overline{T}$	average temperature (K)
TR	temperature solution that is a function of r, for separation of variables
Tt	temperature solution that is a function of t, for separation of variables
TX	temperature solution that is a function of x, for separation of variables
TY	temperature solution that is a function of y, for separation of variables
th	thickness (m)
U	internal energy (J)
	utilization (-)
u	specific internal energy (J/kg)
	velocity in the x-direction (m/s)
u_{char}	characteristic velocity (m/s)
u_f	frontal or upstream velocity (m/s)
u_m	mean or bulk velocity (m/s)
u_∞	free-stream velocity

u^*	eddy velocity (m/s)
u^+	inner velocity (-)
$\tilde{u}$	dimensionless x-velocity (-)
u'	fluctuating component of x-velocity (m/s)
$\overline{u}$	average x-velocity (m/s)
UA	conductance (W/K)
v	velocity in the y- or r-directions (m/s)
v_δ	y-velocity at the outer edge of the boundary layer, approximate scale of y-velocity in a boundary layer
v_{ms}	mean velocity of micro-scale energy or momentum carriers (m/s)
$\tilde{v}$	dimensionless y-velocity (-)
v'	fluctuating component of y-velocity (m/s)
$\overline{v}$	average y-velocity (m/s)
V	volume (m^3)
	voltage (V)
$\dot{V}$	volume flow rate (m^3/s)
vf	void fraction (-)
w	velocity in the z-direction (m/s)
$\dot{w}$	rate of work transfer (W)
W	width (m)
	total amount of work transferred (J)
x	x-coordinate (m),
	quality (-)
$\tilde{x}$	dimensionless x-coordinate (-)
X	particular solution that is only a function of x
$x_{fd,h}$	hydrodynamic entry length (m)
$x_{fd,t}$	thermal entry length (m)
X_{tt}	Lockhart Martinelli parameters (-)
y	y-coordinate (m),
	mole fraction (-)
y^+	inner position (-)
$\tilde{y}$	dimensionless y-coordinate (-)
Y	particular solution that is only a function of y
z	z-coordinate (m)

Greek Symbols

α	thermal diffusivity (m^2/s)
	absorption coefficient (1/m)
	absorptivity (-), total hemispherical absorptivity (-)
	surface area per unit volume (1/m)
α_{eff}	effective thermal diffusivity of a composite (m^2/s)
α_λ	hemispherical absorptivity (-)
$\alpha_{\lambda,\theta,\phi}$	spectral directional absorptivity (-)
β	volumetric thermal expansion coefficient (1/K)
δ	film thickness for condensation (m)

	boundary layer thickness (m)
δ_d	mass transfer diffusion penetration depth (m)
δ_m	momentum diffusion penetration depth (m)
	momentum boundary layer thickness (m)
δ_{vs}	viscous sublayer thickness (m/s)
δ_t	energy diffusion penetration depth (m)
	thermal boundary layer thickness (m)
Δi_{fus}	latent heat of fusion (J/kg)
Δi_{vap}	latent heat of vaporization (J/kg)
Δp	pressure drop (N/m^2)
Δr	distance in *r*-direction between adjacent nodes (m)
ΔT	temperature difference (K)
ΔT_e	excess temperature (K)
ΔT_{lm}	log-mean temperature difference (K)
Δt	time step (s)
	time period (s)
Δt_{crit}	critical time step (s)
Δx	distance in *x*-direction between adjacent nodes (m)
Δy	distance in *y*-direction between adjacent nodes (m)
ε	heat exchanger effectiveness (-)
	emissivity or emittance (-), total hemispherical emissivity (-)
ε_{fin}	fin effectiveness (-)
ε_H	eddy diffusivity for heat transfer (m^2/s)
ε_λ	hemispherical emissivity (-)
$\varepsilon_{\lambda,\theta,\phi}$	spectral, directional emissivity (-)
ε_M	eddy diffusivity of momentum (m^2/s)
ε_1	Lennard-Jones 12-6 potential characteristic energy for species 1 (J)
$\varepsilon_{1,2}$	characteristic energy parameter for a mixture of species 1 and species 2 (J)
ϕ	porosity (-)
	phase angle (rad)
	spherical coordinate (rad)
η	similarity parameter (-)
	efficiency (-)
η_{fin}	fin efficiency (-)
η_o	overall efficiency of a finned surface (-)
κ	von Kármán constant
λ	dimensionless axial conduction parameter (-)
	wavelength of radiation (μm)
λ_i	i^{th} eigenvalue of a solution (1/m)
μ	viscosity ($N\text{-}s/m^2$)
ν	frequency of radiation (1/s)
θ	temperature difference (K)
	angle (rad)
	spherical coordinate (rad)

$\tilde{\theta}$	dimensionless temperature difference (-)
θ^+	inner temperature difference (-)
θR	temperature difference solution that is only a function of r, for separation of variables
θt	temperature difference solution that is only a function of t, for separation of variables
θX	temperature difference solution that is only a function of x, for separation of variables
θXt	temperature difference solution that is only a function of x and t, for reduction of multi-dimensional transient problems
θY	temperature difference solution that is only a function of y, for separation of variables
θYt	temperature difference solution that is only a function of y and t, for reduction of multi-dimensional transient problems
θZt	temperature difference solution that is only a function of z and t, for reduction of multi-dimensional transient problems
ρ	density (kg/m^3)
	reflectivity (-), total hemispherical reflectivity (-)
ρ_e	electrical resistivity (ohm-m)
ρ_{eff}	effective density of a composite (kg/m^3)
ρ_λ	hemispherical reflectivity (-)
$\rho_{\lambda,\theta,\phi}$	spectral, directional reflectivity (-)
σ	surface tension (N/m),
	molecular radius (m)
	ratio of free-flow to frontal area (-)
	Stefan-Boltzmann constant, 5.67×10^{-8} $W/m^2\text{-}K^4$
τ	time constant (s)
	shear stress (Pa)
	transmittivity (-), total hemispherical transmittivity (-)
τ_{diff}	diffusive time constant (s)
τ_{lumped}	lumped capacitance time constant (s)
τ_λ	hemispherical transmittivity (-)
$\tau_{\lambda,\theta,\phi}$	spectral, directional transmittivity (-)
τ_s	shear stress at surface (N/m^2)
υ	kinematic viscosity (m^2/s)
ω	angular velocity (rad/s)
	humidity ratio (kg_v/kg_a)
	solid angle (steradian)
Ω_D	dimensionless collision integral for diffusion (-)
Ψ	stream function (m^2/s)
ζ	tilt angle (rad)
	curvature parameter for vertical cylinder, natural convection correlation
ζ_i	the i^{th} dimensionless eigenvalue (-)

Superscripts

o	at infinite dilution

Subscripts

a	air
abs	absorbed
ac	axial conduction (in heat exchangers)
an	analytical
app	apparent
	approximate
b	blackbody
bl	boundary layer
bottom	bottom
c	condensate film
	corrected
C	cold
	cold-side of a heat exchanger
cc	complex conjugate, for complex combination problems
char	characteristic
cf	counter-flow heat exchanger
cond	conduction, conductive
conv	convection, convective
crit	critical
CTHB	cold-to-hot blow process
dc	dry coil
df	downward facing
diff	diffusive transfer
eff	effective
emit	emitted
evap	evaporative
ext	external
f	fluid
fc	forced convection
fd,h	hydrodynamically fully developed
fd,t	thermally fully developed
fin	fin, finned
h	homogeneous solution
H	hot
	hot-side of a heat exchanger
	constant heat flux boundary condition
hs	on a hemisphere
HTCB	hot-to-cold blow process
i	node *i*
	surface *i*
	species *i*
j	node *j*

	surface *j*
in	inner
	inlet
ini	initial
int	internal
	interface
	integration period
l	liquid
lam	laminar
LHS	left-hand side
lumped	lumped-capacitance
m	mean or bulk
	melting
max	maximum or maximum possible
min	minimum or minimum possible
mod	modified
ms	micro-scale carrier
n	normal
nac	without axial conduction (in heat exchangers)
nb	nucleate boiling
nc	natural convection
no-fin	without a fin
out	outer
	outlet
p	particular (or non-homogeneous) solution
pf	parallel-flow heat exchanger
pp	pinch-point
r	regenerator matrix
	at position *r*
rad	radiation, radiative
ref	reference
RHS	right-hand side
s	at the surface
sat	saturated
	saturated section of a heat exchanger
sat,l	saturated liquid
sat,v	saturated vapor
sc	sub-cool section of a heat exchanger
semi-∞	semi-infinite
sh	super-heat section of a heat exchanger
sph	sphere
sur	surroundings
sus	sustained solution
T	constant temperature boundary condition
	at temperature *T*
top	top

tot	total
turb	turbulent
uf	upward-facing
unfin	not finned
v	vapor
	vertical
	viscous dissipation
w	water
wb	wet-bulb
wc	wet coil
x	at position *x*
	in the *x*-direction
x^-	in the negative *x*-direction
x^+	in the positive *x*-direction
y	at position *y*
	in the *y*-direction
∞	free-stream, fluid
90°	solution that is 90° out of phase, for complex combination problems

Other notes

A	arbitrary variable
A'	fluctuating component of variable A
	value of variable A on a unit length basis
A''	value of variable A on a unit area basis
A'''	value of variable A on a unit volume basis
A	dimensionless form of variable A
$\hat{A}$	a guess value or approximate value for variable A
$\widehat{A}$	Laplace transform of the function A
$\overline{A}$	average of variable A
$\underline{A}$	denotes that variable A is a vector
$\underline{\underline{A}}$	denotes that variable A is a matrix
dA	differential change in the variable A
δA	uncertainty in the variable A
ΔA	finite change in the variable A
$O(A)$	order of magnitude of the variable A