

Heat Transfer

G.F. Nellis and S.A. Klein

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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 ($\text{J/kg}_a\text{-K}$)
$c_{a,sat}''$	specific heat capacity of an air-water mixture along the saturation line on a unit mass of air basis ($\text{J/kg}_a\text{-K}$)
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, \dots	undetermined constants
C_{crit}	dimensionless coefficient for critical heat flux correlation (-)
C_D	drag coefficient (-)
C_f	friction coefficient (-)
\bar{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 ($1/\text{K}$)
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 ($W/m^2\text{-}\mu\text{m}$)
$E_{b,\lambda}$	blackbody spectral emissive power ($W/m^2\text{-}\mu\text{m}$)
Ec	Eckert number (-)
f	frequency (Hz)
	dimensionless stream function, for Blasius solution (-)
	friction factor (-)
\bar{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 ($kg/m^2\text{-s}$)
	total irradiation (W/m^2)
G_λ	spectral irradiation ($W/m^2\text{-}\mu\text{m}$)
Ga	Galileo number (-)
Gr	Grashof number (-)
Gz	Graetz number (-)
h	local heat transfer coefficient ($W/m^2\text{-K}$)
\bar{h}	average heat transfer coefficient ($W/m^2\text{-K}$)
\tilde{h}	dimensionless heat transfer coefficient for flow boiling correlation (-)
h_D	mass transfer coefficient (m/s)
\bar{h}_D	average mass transfer coefficient (m/s)
h_l	superficial heat transfer coefficient for the liquid phase ($W/m^2\text{-K}$)
h_{rad}	the equivalent heat transfer coefficient associated with radiation ($W/m^2\text{-K}$)
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)
I_e	intensity of emitted radiation (W/m ² -μm-steradian)
I_i	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	Boltzmann'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 ($1/m^2$)
$R_{semi-\infty}$	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
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)
\bar{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)
\bar{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)
\bar{v}	average y -velocity (m/s)
V	volume (m ³)
	voltage (V)
\dot{V}	volume flow rate (m ³ /s)
ν^f	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-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
$\theta X t$	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
$\theta Y t$	temperature difference solution that is only a function of y and t , for reduction of multi-dimensional transient problems
$\theta Z t$	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, $5.67 \times 10^{-8} \text{ W/m}^2\text{-K}^4$
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)
ν	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)
ξ	tilt angle (rad)
	curvature parameter for vertical cylinder, natural convection correlation
ξ_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
<i>in</i>	inner inlet
<i>ini</i>	initial
<i>int</i>	internal interface integration period
<i>l</i>	liquid
<i>lam</i>	laminar
<i>LHS</i>	left-hand side
<i>lumped</i>	lumped-capacitance
<i>m</i>	mean or bulk melting
<i>max</i>	maximum or maximum possible
<i>min</i>	minimum or minimum possible
<i>mod</i>	modified
<i>ms</i>	micro-scale carrier
<i>n</i>	normal
<i>nac</i>	without axial conduction (in heat exchangers)
<i>nb</i>	nucleate boiling
<i>nc</i>	natural convection
<i>no-fin</i>	without a fin
<i>out</i>	outer outlet
<i>p</i>	particular (or non-homogeneous) solution
<i>pf</i>	parallel-flow heat exchanger
<i>pp</i>	pinch-point
<i>r</i>	regenerator matrix at position r
<i>rad</i>	radiation, radiative
<i>ref</i>	reference
<i>RHS</i>	right-hand side
<i>s</i>	at the surface
<i>sat</i>	saturated saturated section of a heat exchanger
<i>sat,l</i>	saturated liquid
<i>sat,v</i>	saturated vapor
<i>sc</i>	sub-cool section of a heat exchanger
<i>semi-∞</i>	semi-infinite
<i>sh</i>	super-heat section of a heat exchanger
<i>sph</i>	sphere
<i>sur</i>	surroundings
<i>sus</i>	sustained solution
<i>T</i>	constant temperature boundary condition at temperature T
<i>top</i>	top

<i>tot</i>	total
<i>turb</i>	turbulent
<i>uf</i>	upward-facing
<i>unfin</i>	not finned
<i>v</i>	vapor
	vertical
	viscous dissipation
<i>w</i>	water
<i>wb</i>	wet-bulb
<i>wc</i>	wet coil
<i>x</i>	at position x
	in the x -direction
x^-	in the negative x -direction
x^+	in the positive x -direction
<i>y</i>	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
\hat{A}	Laplace transform of the function A
\bar{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