The Principles and Practice of Heat Transfer

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By

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This book is dedicated to my wife Layla, who was always there for me, even on the tough days. Her steadfast commitment, kindness, devotion, and endless support will not be forgotten.

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USEFUL INFORMATION

Unit Conversion Factors

Useful conversion factors

Quantity	SI to English conversion	English to SI conversion
Length	$1\ m = 3.2808\ ft$	$1\ ft = 0.3048\ m$
Area	$1\ m^2 = 10.7639\ ft^2$	$1\ ft^2 = 0.092903\ m^2$
Volume	$1\ m^3 = 35.3134\ ft^3$	$1\ ft^3 = 0.028317\ m^3$
Velocity	$1\ \frac{m}{s} = 3.2808\ \frac{ft}{s}$	$1\ \frac{ft}{s} = 0.3048\ \frac{m}{s}$
Mass	$1\ kg = 2.2046\ lb_m$	$1\ lb_m = 0.45359237\ kg$
Density	$1\ \frac{kg}{m^3} = 0.06243\ \frac{lb_m}{ft^3}$	$1\ \frac{lb_m}{ft^3} = 16.018\ \frac{kg}{m^3}$
Force	$1\ N = 0.2248\ lb_f$	$1\ lb_f = 4.4482\ N$
Pressure	$1\ \frac{N}{m^2} = 1.45038 \times 10^{-4}\ \frac{lb_f}{in^2}$	$1\ \frac{lb_f}{in^2} = 6894.76\ \frac{N}{m^2}$
Heat, Energy, work	$1\ kJ = 0.94783\ Btu$	$1\ Btu = 1.05504\ kJ$
Heat transfer rate, Power	$1\ W = 3.4121\ \frac{Btu}{h}$	$1\ \frac{Btu}{h} = 0.29307\ W$
Heat flux	$1\ \frac{W}{m^2} = 0.317\ \frac{Btu}{h.ft^2}$	$1\ \frac{Btu}{h.ft^2} = 3.154\ \frac{W}{m^2}$
Specific energy, Specific enthalpy	$1\ \frac{kJ}{kg} = 0.4299\ \frac{Btu}{lb_m}$	$1\ \frac{Btu}{lb_m} = 2.326\ \frac{kJ}{kg}$
Specific heat capacity	$1\ \frac{kJ}{kg.K} = 0.23884\ \frac{Btu}{lb_m.°F}$	$1\ \frac{Btu}{lb_m.°F} = 4.1869\ \frac{kJ}{kg.K}$
Thermal conductivity	$1\ \frac{W}{m.K} = 0.5778\ \frac{Btu}{h.ft.°F}$	$1\ \frac{Btu}{h.ft.°F} = 1.7307\ \frac{W}{m.K}$
Heat transfer coefficient	$1\ \frac{W}{m^2.K} = 0.1761\ \frac{Btu}{h.ft^2.°F}$	$1\ \frac{Btu}{h.ft^2.°F} = 5.6782\ \frac{W}{m^2.K}$
Dynamic viscosity	$1\ \frac{kg}{m.s} = 0.672\ \frac{lb_m}{ft.s}$	$1\ \frac{lb_m}{ft.s} = 1.4881\ \frac{kg}{m.s}$
Kinematic viscosity, thermal diffusivity	$1\ \frac{m^2}{s} = 10.7639\ \frac{ft^2}{s}$	$1\ \frac{ft^2}{s} = 0.092903\ \frac{m^2}{s}$

Temperature	$T\ (°C) = (°F - 32) \times \frac{5}{9}$	$T\ (°F) = \left(°C \times \frac{9}{5}\right) + 32$
Temperature difference	$\Delta T\ (°C) = \Delta T\ (°F) \times \frac{5}{9}$	$\Delta T\ (°F) = \Delta T\ (°C) \times \frac{9}{5}$

Mathematical Multiple Symbols

Decimal multiples and sub-multiples of SI units

Decimal Multiples			Sub-Multiples		
Prefix	**Symbol**	**Equivalent**	**Prefix**	**Symbol**	**Equivalent**
zetta	Z	10^{21}	**deci**	d	10^{-1}
exa	E	10^{18}	**centi**	c	10^{-2}
peta	P	10^{15}	**milli**	m	10^{-3}
tetra	T	10^{12}	**micro**	μ	10^{-6}
giga	G	10^{9}	**nano**	n	10^{-9}
mega	M	10^{6}	**pico**	p	10^{-12}
kilo	k	10^{3}	**femto**	f	10^{-15}
hecto	h	10^{2}	**atto**	a	10^{-18}
deca	da	10^{1}	**zepto**	z	10^{-21}

LIST OF SYMBOLS

Parameter	Definition
a	Design parameter
$a_1, a_2\ a_3$	Coefficients in Eq. 3.39
A	Area, (m^2)
b	Design parameter
B.C.	Boundary condition
C, C_1, C_2	Constants in equations
$C_{C\text{-}N}$	Crank–Nicolson coefficient defined in Eq. A.21.b
C_{FZ}	Forster-Zuber coefficient defined in Eq. 7.27
CS	Control system
CV	Control volume
cp	Specific heat, (kJ/kg.˚C)
d	diameter, (m)
$\mathcal{D}$	Diffusion coefficient, (m^2/s)
e	Total energy per unit mass, (kJ/kg)
E	Parameter defined in Eq. 8.32.b
f	Friction factor
fp	Fin pitch, (m)
F	Convective factor multiplier in Eq. 7.39.a or parameter defined elsewhere
F_c	Mixture correction factor (F_c) is equal to (1.0) for pure fluids and azeotropes; it is less than (1.0) for mixtures, Eq. 6.16
F_e	Fin efficiency equals (1.0) for the plain tube and is close to unity for the finned tube structure, Eq. 6.16
F_t	Temperature difference correction factor
Fr	Froud number
g	Gravitational converging factor
G	Mass velocity, (kg/m^2 s)
Ga	Galileo number
h	Heat transfer coefficient, (W/m^2 K)
h_{fo}	Fouling coefficient, (W/m^2 K)
H	Heat exchanger height or vertical tube length, (m)
H.F	High flow velocity
H.T	High-temperature
i	Fluid specific enthalpy, (kJ/kg)
i_{fg}	Latent heat of vaporization, (kJ/kg)

j	Colburn j-factor defined by Eq. 5.65, or y-axis node coordinate
J_{TP}	The mixture volumetric flux
k	Thermal conductivity, (W/m K)
K_1	Constant defined in Eq. 5.34.c
K_2	Constant defined in Eq. 5.34.d
l	Length, (m)
ℓ	Height of circular fin or plate fin length in the flow direction, (m)
L	Front length of heat exchanger or tube length, (m)
$L.T$	Low-temperature
m	Index in equations or fluid mass
$\dot{m}$	Mass flow rate, (kg/s)
n	Index in Eq. 5.33 or a constant defined elsewhere
N	Number of tube rows or tubes
N_r	Number of tubes in a vertical column
N_{Sn}	Scriven number defined in Eq. 6.32
N_t	Total number of tubes
NTU	Number of transfer units, Dimensionless.
Nu	Nusselt number, Dimensionless
p	Fluid pressure, (kpa, bar)
P	Power, (kW)
p_t	Tube pitch in heat exchanger
Pe	Peclet number
Pr	Prandtl number (Dimensionless)
$p+1$	Iteration number in the time domain
$q, \dot{Q}$	Heat transfer rate, (kW)
$\acute{q}$	Heat transfer rate per unit length, (kW/m)
$\dot{q}$	Heat generation per unit volume, (kW/m^3)
$\ddot{q}$	Heat flux, (kw/m^2)
r	Radius, (m)
$\Delta r, \Delta\theta, \Delta z$	Discretization in cylindrical coordinates
$\Delta r, \Delta\theta, \Delta\phi$	Discretization in spherical coordinates
R	Resistance, (m.˚C/W)
$\mathcal{R}$	Circulation ratio, Eq. 7.7
Ra	Roughness scale
Re	Reynolds number (Dimensionless)
St	Stanton number
S_p	Center to center tube spacing
t	Fin thickness (m) or time (s)
T	Temperature, (℃)

$T(x,y,z,t)$	Temperature transient function in cartesian coordinates
$T(x,\theta,z,t)$	Temperature transient function in cylindrical coordinates
$T(x,\theta,\phi,t)$	Temperature transient function in spherical coordinates
ΔT	Temperature difference, (deg C)
v	Fluid velocity, (m/s)
V	Volume
$\dot{V}$	Fluid volumetric flow rate, (m^3/s)
U	Overall heat transfer coefficient, (W/m^2 K)
$\acute{U}$	Superficial velocity, (m/s)
W	Heat exchanger width, (m)
$\dot{W}$	Work rate, (kW)
We	Weber number; $We = \frac{\dot{m}^2\, d}{\sigma\, \rho_l}$
x	x-axis or position along a plat length, (m) or liquid mass fraction in mixtures, or flow quality
$\Delta\acute{x}$	The difference between the mass fractions of vapor and liquid of the more volatile component
X	Liquid mole fraction of a component in a mixture
X_L	Longitudinal tube spacing in the flow direction, (m)
X_T	Transverse tube spacing perpendicular to the flow direction, (m)
$\Delta x, \Delta y, \Delta z$	Discretization in cartesian coordinates
y	y-coordinate, (m), or vapor mass fraction
Y	Vapor mole fraction of a component in a mixture
z	z-axis coordinate or elevation, (m)

Subscript

a	Air
act	Actual value
ap	Apparent value
ass	Assumed value
aug	Augmentation or enhancement
b	Boiling
bore	Borehole
B	Bulk fluid, tube bundle
c	Cold side, cross-sectional, or characteristic
cal	Calculated value
co	Corrected
cond	Condenser
cr	Critical

d	Value calculated at the tube diameter
des	Desuperheating process
e	Exit port
enh	Enhanced or enhancement
eq	Equivalent or Equilibrium
est.	Estimated value
evap	Evaporator
f	Film value or defined elsewhere
fo	Fouling
g	Gas state
G-T	Gewa-TX or Gewa-T
h	Hot side or homogeneous
ho	Horizontal
H	Hydraulic or heater
H.E	Heat Exchanger
H-F	HighFlux
i	Interior, inside, or inlet
id	Ideal
iso	Isothermal
l	Liquid state
L-F	Low Finned
lo	Liquid phase only
in	Inlet
m	Mean value
m_1, m_2, m_3	Constants in Eq. 6.17
max	Maximum
min	Minimum
m,n	Node number in the x-y plane in a finite difference scheme
mix	Mixture
net	Net value
o	Outside, outlet, or defined elsewhere
out	Outlet port value
p	Plate or particle in a porous surface
pla	Plain surface
po	Pore
r	Reduced
Ref	Refrigerant
s	Surface value or measured at surface condition
S	Nucleate boiling suppression factor
sat	Saturated at operating pressure
sp	Single-phase

Str	Stratified flow
sub	Subcooled process
sur	Surrounding environment
t	Total, bare tube value or thermal
T-B	Turbo-B
th	Thermal value
TP	Two-phase flow
tur	Turbulent
vr	Vertical
w	Water-side or wall

Greek Symbols

α	Thermal diffusivity, (m^2/s) or void fraction (%)
β	Ration percentage Parameter
γ	Number of fins per meter (m^{-1})
Γ	Friction factor defined in Eq. 5.34.b or condensation loading (kg/m s)
δ_E	Thickness of porous layer, (m)
ϵ	Emissivity in radiation concept defined in Eq. 1.25 or roughness (m)
ε	Heat exchanger effectiveness
ξ	Accuracy or discrepancy, (%) or surface factor in Eq. 6.17
η	Efficiency or improvement factor
θ	Inclination heating element angle
μ	Fluid viscosity, (Pa.s)
ρ	Fluid density, (kg/m^3)
σ	Surface tension, (N/m)
τ_p	Number of tubes per row
ϑ	Froud rate defined in Eq. 7.20.b
φ	Porosity of matrix, (%)
ψ	Deviation value, (%)
ω	Constant in Eq. 7.43.c and Eq. 7.43.d
ω_{vent}	Air vent capacity in surface conensers, (kg/s)
ω_m	Mass transfer coefficient, (m/s)
∞	Free stream value
ς_0	Nondimensional Laplace constant is defined in Eq. 7.21.b

ABBREVIATIONS

Parameter	Definition
ACC	Air-Cooled Condenser
BTCS	Backward Time, Centered Space
CHF	Critical Heat Flux
CHP	Combined Heat and Power
C.M	Cooling Medium
CTCS	Central Time, Centered Space
DNB	Departure from Nucleate Boiling
DWC	Dropwise Condensation
E.S	Energy Source
FPD	Frictional Pressure Drop
FD	Finite Difference
FTCS	Forward Time, Centered Space
FWC	Filmwise Condensation
GSHE	Ground Source heat Exchanger
H.F	Heat Flux
HTC	Heat Transfer Coefficient
IOC	Inverse Opal Condensation
ONB	Onset of Nucleate Boiling
ORC	Organic Rankine Cycle
PFD	Process Flow Diagram
PFPD	Parallel Flow-Parallel Orientation
ROI	Return on Investment
RORC	Regenerative Organic Rankine Cycle
SLIPS	Slippery Liquid-Infused Porous Surfaces
SORC	Simple Organic Rankine Cycle
SRC	Simple Rankine Cycle
WCC	Water-Cooled Condenser

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