NOMENCLATURE

b	Width of roughness elements, helical channel, lobes of twisted tubes, space between tubes within a bundle, m
$c_f = 2\tau_w/\rho u_\infty^2$	Friction coefficient
c_p	Specific heat, J/kg · K
D	Diameter of the curvature of a coiled passage, m
d_0	Diameter of the cylinder, of the zero shear stress surface, describing a coiled tube, m
d_1, d_2	Diameters of washed surfaces of tubes comprising an annular or helical channel, m
d_e	Equivalent diameter of channel, m
E	Voltage across the anemometer wires, V
F	Net cross-sectional area, heating-wall surface, m^2
G	Working-fluid flow rate, kg/sec; coefficient
$G(k^+), G_1(k^+)$	Thermal functions of roughness
$H = \delta^*/\delta^{**}$	Shape factor
h	Height of helical passage, m
I	Current, A
k	Height of roughness projections, m
$k^+ = ku_*/\nu$	Dimensionless height of roughness projections at temperature T_f
l	Mixing length, length of channel, m
p	Pressure, Pa
Δp	Pressure differential, Pa
Q	Heat flux, W
q	Heat flux density, W/m^2
$R(k^+), R_1(k^+)$	Hydrodynamic functions of roughness
r	Tube radius, current radius, m
r_0	Radius of cylinder, of zero shear stress surface, m
$r_0^+ = r_0 u_*/\nu$	Dimensionless radius
s	Spacing between roughness elements, pitch of helical channel, of twisted tubes, m
s_1	Pitch of tubes within a bundle, m
T	Temperature, K

U	Potential drop, V
u, v, w	Velocity components, m/sec
u', v', w'	Velocity fluctuations, m/sec
u_0	Bulk velocity, m/sec
u_∞	Free-stream velocity, m/sec
u_r, u_τ	Radial and tangential velocity components, m/sec
$u_* = \sqrt{\tau_w/\rho}$	Friction velocity, m/sec
$u^+ = u/u_*$	Dimensionless velocity
$\mathbf{V}$	Total-velocity vector, m/sec
x, y, z	Cartesian coordinates
x	Length, distance from start of heating, m
x_0	Virtual start of turbulent boundary layer, m
y	Current distance along the radius, calculated from the surface of tubes or cylinder, m
$y^+ = yu_*/\nu$	Dimensionless distance
$y_R = r_0 \ln(r/r_0)$	Coordinate of axisymmetric boundary layer, m
$y_R^+ = r_0^+ \ln(r/r_0)$	Dimensionless coordinate
α	Heat-transfer coefficient, $W/m^2 \cdot K$; angle, radius
δ	Thickness of boundary layer, of wall, m
δ^*	Displacement thickness, m
δ^{**}	Momentum thickness, m
ε_q	Eddy thermal diffusivity, m^2/sec
ε_τ	Eddy viscosity, m^2/sec
η	Efficiency
$\vartheta = T_w - T$	Temperature differential, K
$\vartheta_* = q_w/\rho c_p u_*$	Characteristic temperature, K
$\vartheta^+ = \vartheta/\vartheta_*$	Dimensionless temperature
$\varkappa$	Universal constant
$\Lambda = l/\delta_x$	Normalized mixing length
λ	Thermal conductivity, $W/m \cdot K$
μ	Dynamic viscosity, $N \cdot sec/m^2$
ν	Kinematic viscosity, m^2/sec
ξ	Hydraulic drag coefficient
Π	Channel perimeter, m
ρ	Density, kg/m^3
τ	Shear stress, N/m^2
φ	Angle, degrees
$\Psi = T_w/T_f$	Temperature factor
$\mathrm{Fr}_M = s^2/d_0 d_e$	Modified Froude number

$\mathrm{Nu} = \alpha d_e/\lambda$, $\mathrm{Nu}_x = \alpha x/\lambda$	Nusselt numbers at pertinent reference parameters
$\mathrm{Pr} = \mu c_p/\lambda$	Prandtl number
$\mathrm{Pr}_T = \varepsilon_\tau/\varepsilon_q$	Turbulent Prandtl number
$\mathrm{Re} = u_0 d_e/\nu$ $\mathrm{Re}_{r_0} = u_\infty r_0/\nu$ $\mathrm{Re}_x = u_\infty x/\nu$ $\mathrm{Re}_{\delta^*} = u_\infty \delta^*/\nu$	Reynolds numbers at pertinent reference parameters
$\mathrm{St} = \alpha/\rho c_p u_\infty$ $= \mathrm{Nu}/\mathrm{Re}\,\mathrm{Pr}$	Stanton number at pertinent reference parameters
$Tu_\infty = \sqrt{\overline{u'^2}}/u_\infty$	Turbulence intensity

Subscripts

0	At the plate, for a smooth surface, for the channel as a whole
1	Inner tube, zone of annular channel
2	Outer tube, zone of annular channel
∞	In the free stream, in the stabilized heat-transfer region
f	In the flow
in	At the inlet
out	At the exit
s	For sand roughness
t	In the tube
tr	Upon transition from partial to complete manifestation of roughness
w	At the wall
$\Psi = 1$	At constant physical properties
$\overline{(\ )}$	Averaging

Other symbols are defined in the text.