1 Coordinate Systems and Vector Math

$(x,y,z) \Leftrightarrow (r,\theta,z)$ $x = r\cos\theta$ $r=\sqrt{x^2+y^2}$ $y = r\sin\theta$ $\theta = \tan^{-1}\frac{y}{x}$

$\hat{e}_r = \cos\theta\hat{e}_x + \sin\theta\hat{e}_y$ $\hat{e}_\theta = -\sin\theta\hat{e}_x + \cos\theta\hat{e}_y$

$(x,y,z) \Leftrightarrow (\rho,\theta,\phi)$ $x=\rho\sin\theta\cos\phi$ $\rho=\sqrt{x^2+y^2+z^2}$ $y=\rho\sin\theta\sin\phi$ $\theta=\cos^{-1}\frac{z}{\rho}$ $z=\rho\cos\theta$ $\phi=\text{sgn}(y)\cos^{-1}\frac{z}{\sqrt{x^2+y^2}}$

$\hat{e}_\rho = \sin\theta\cos\phi\hat{e}_x + \sin\theta\sin\phi\hat{e}_y + \cos\theta\hat{e}_z$
$\hat{e}_\theta = \cos\theta\cos\phi\hat{e}_x + \cos\theta\sin\phi\hat{e}_y - \sin\theta\hat{e}_z$
$\hat{e}_\phi = -\sin\phi\hat{e}_x + \cos\phi\hat{e}_y$

$(r,\theta,z) \Leftrightarrow (\rho,\theta,\phi)$ $r=\rho\sin\phi$ $\rho=\sqrt{r^2+z^2}$ $z=\rho\cos\phi$ $\theta=\tan^{-1}\frac{r}{z}$

Open cylinder: $dA_S = Rd\theta dz \to A_S = \int_0^\ell\int_0^{2\pi} R\,d\theta dz = 2\pi R\ell$

Sphere: $dA_S = R^2\sin\theta d\theta d\phi \to A_S = \int_0^{2\pi}\int_0^{\pi} R^2\sin\theta d\theta d\phi = 4\pi R^2$

$\vec{v}\cdot\vec{w} = v_1w_1+v_2w_2+v_3w_3 = |\vec{v}||\vec{w}|\cos\theta$

$\vec{v}\times\vec{w} = (v_2w_3-v_3w_2)\hat{\imath} - (v_1w_3-v_3w_1)\hat{\jmath} + (v_1w_2-v_2w_1)\hat{k}$

$|\vec{v}\times\vec{w}| = |\vec{v}||\vec{w}||\sin\theta|$

$\angle\vec{v}\vec{w} = \cos^{-1}\left(\frac{\vec{v}\cdot\vec{w}}{|\vec{v}||\vec{w}|}\right)$ $\hat{v} = \frac{\vec{v}}{|\vec{v}|}$ $\vec{v}_{(\|\hat{w})} = \vec{v}\cdot\frac{\vec{w}}{|\vec{w}|}$

2 Equations and Laws

Torricelli: $\vec{v} = \sqrt{2g\hbar}$

Newton's Law of Viscosity: $\boldsymbol{\tau}_{ij} = \mu\left(\frac{\partial\vec{v}_i}{\partial x_j} + \frac{\partial\vec{v}_j}{\partial x_i}\right)$

Fourier's Law of Heat Conduction: $\Phi_Q = \frac{\dot{Q}_x}{A} = -k\nabla T$

Newtonian Constitutive: $\boldsymbol{\tau} = \mu\left[\nabla\vec{v} + (\nabla\vec{v})^\intercal\right]$

Continuity: (micro m) $\frac{\partial\rho}{\partial t} + \vec{v}\cdot\nabla\rho = \rho(\nabla\cdot\vec{v})$

Navier-Stokes: (micro $\vec{P}$) $\rho\left(\frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v}\right) = -\nabla P + \mu\nabla^2\vec{v} + \rho\vec{g}$

Gen. eqn. of motion: (micro $\vec{P}$) $\rho\left(\frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v}\right) = -\nabla P + \nabla\cdot\boldsymbol{\tau} + \rho\vec{g}$

Energy: (micro E) $\rho\left(\frac{\partial\hat{E}}{\partial t} + \vec{v}\cdot\nabla\hat{E}\right) = -\nabla\cdot\Phi_Q - \nabla(P\vec{v}) + \nabla\cdot(\boldsymbol{\tau}\cdot\vec{v}) + \breve{Q}$

Thermal energy: ($\Delta P, \Delta\rho=0$) $\rho\hat{C}_P\left(\frac{\partial T}{\partial t} + \vec{v}\cdot\nabla T\right) = k\nabla^2T + \boldsymbol{\tau}^\intercal : \nabla\vec{v} + \breve{Q}$

Hagen-Poiseuille: $\dot{V} = \frac{\pi R^4(\rho g\ell\cos\theta + \Delta P)}{8\mu\ell}$

3 Fluid Mechanics

$\dot{V} = A_\sigma\langle\vec{v}\rangle = \frac{\dot{m}}{\rho}$ $(\rho\vec{v}) = \frac{\dot{m}}{A_\sigma}$ $\rho_1A_{\sigma1}\langle\vec{v}_1\rangle = \rho_2A_{\sigma2}\langle\vec{v}_2\rangle$

$\frac{\Delta P}{\rho} + \frac{\Delta(\vec{v}^2)}{2\alpha} + g\Delta z + \sum\hat{F} = \frac{\dot{W}_{\text{s,by}}}{\dot{m}}$ $\alpha^{\approx 1,\text{ turbulent}}_{=0.5,\text{ laminar}}$

3.1 Force Losses

Re$= \frac{\langle\vec{v}\rangle\rho\varnothing}{\mu}$ $f = \frac{\varnothing}{\ell}\frac{\Delta P}{2\rho\langle\vec{v}\rangle^2} = \frac{2\vec{F}_\text{d}}{\rho\langle\vec{v}\rangle^2 2\pi r\ell}$ Fr$= \frac{\langle\vec{v}\rangle^2}{g\varnothing}$

$f_{\text{smooth, lam}} = 16/\text{Re}$ $f_{\text{smooth, trb}} = 0.079\text{Re}^{-0.25}$

$\hat{F}_{\text{straight pipe}} = 4f\frac{\ell}{\varnothing}\frac{\langle\vec{v}\rangle^2}{2} = \frac{\Delta P}{\rho}$ $\hat{F}_{\text{fitting}} = K_\text{f}\frac{\langle\vec{v}\rangle^2}{2}$

$\sum\hat{F} = \sum_i 4f_i\frac{\ell_i}{\varnothing_i}\left(\frac{\langle\vec{v}\rangle_i^2}{2}\right) + \sum_j K_{\text{f},j}\left(\frac{\langle\vec{v}\rangle_j^2}{2}\right)$

$\varnothing_\text{h} = \frac{4A_\sigma}{\text{Perimeter}}$ $\tilde{H}_i = \frac{\hat{F}_i}{g}$ $\tilde{H} = \frac{\Delta P}{\rho g}$

$\vec{F}_\text{d} = \frac{1}{2}\rho\langle\vec{v}\rangle^2A_\sigma C_\text{d}$

Drop: $C_\text{d} = \frac{2V_{\text{body}}(\rho_{\text{body}}-\rho)g}{\rho A_\sigma v_\infty^2}$ $\vec{v}_\infty = \sqrt{\frac{2V_{\text{body}}(\rho_{\text{body}}-\rho)g}{\rho A_\sigma C_\text{d}}}$

3.2 Quantities of Interest

$\hat{n} \equiv \langle n_1,\ n_2,\ n_3\rangle$ $\boldsymbol{\sigma} = -P\mathbf{I} + \boldsymbol{\tau}$

$\dot{m} = (\vec{v}\cdot\hat{n})A_\sigma\rho$ $\frac{\text{d}\vec{P}}{\text{d}t} = (\vec{v}\cdot\hat{n})A_\sigma\rho\vec{v}$

$\dot{V} = \iint_S(\hat{n}\cdot\vec{v})\big|_{\text{sfc}}dS$ $\langle\vec{v}_{\text{flow}}\rangle = \frac{\dot{V}}{\int_0^\hbar\int_0^\ell dxdy}$

$\vec{F} = \iint_S[\hat{n}\cdot\boldsymbol{\sigma}]\big|_{\text{sfc}}dS$ $\vec{F}_z = \hat{e}_z\cdot\vec{F}$

$\vec{\tau} = \iint_S[\vec{r}\times(\hat{n}\cdot\boldsymbol{\sigma})]\big|_{\text{sfc}}dS$

3.3 Macroscopic Balance

$\frac{\text{d}\vec{P}}{\text{d}t} + \sum\left(\frac{1}{\beta}\rho A\cos\theta\langle\vec{v}\rangle^2\hat{v}\right)_i = \sum(-PA\hat{n})_i + \vec{F}_{\text{r (on fluid)}} + m_{\text{cv}}\vec{g}$

$\beta^{\approx 1,\text{ turbulent}}_{=0.75,\text{ laminar}}$ $\cos\theta = \hat{n}_i\cdot\hat{v}_i$ $\hat{v}_i = \langle v_1,\ v_2,\ v_3\rangle_i$

4 Heat Transfer

Conduction: $\frac{\dot{Q}_x}{A} = -k\frac{\text{d}T}{\text{d}x} = \frac{k(T_1-T_2)}{\Delta x}$ $k[=]\frac{\text{W}}{\text{m K}}, \frac{\text{kg m}}{\text{s}^3\text{ K}}$

1-D: $T_{xyz} = -\frac{C_1}{k}x + C_2$ $T_{r\theta z} = -\frac{C_1}{k}\ln r + C_2$

Generalised: $\dot{Q} = \frac{T_1-T_N}{\sum R_i}$ $R_i \equiv \frac{\Delta x_i}{k_iA} = \frac{1}{h_iA}$ $U = \frac{1}{A\sum R_i}$

Convection: $|\frac{\dot{Q}_x}{A}| = h|(T_{\text{bulk}} - T_{\text{wall}})|$

Nu $\equiv \frac{h\ell'}{k}$ Pr $\equiv \frac{\hat{C}_P\mu}{k}$ Gr $\equiv \frac{\ell'^3\rho^2g\beta\Delta T}{\mu^2}$ $\ell' \in \{\varnothing, \delta, \ell\}$

$\beta \equiv T_{\text{film}}^{-1}$ $T_{\text{film}} = \frac{T_{\text{bulk}}+T_{\text{wall}}}{2}$

4.1 Heat Exchangers

$\dot{Q} = UA\Delta T_{\text{lm}}f_T$ $\dot{Q}_{\text{water}} = \dot{m}\hat{C}_P\Delta T$ $\dot{Q}_{\text{steam}} = \dot{m}\Delta_{\text{vap}}\hat{H}$

$\Delta T_{\text{lm}} = \frac{(T_{\text{out, shell}}-T_{\text{in, tube}})-(T_{\text{in, shell}}-T_{\text{out, tube}})}{\ln\frac{T_{\text{out, shell}}-T_{\text{in, tube}}}{T_{\text{in, shell}}-T_{\text{out, tube}}}} = \frac{\Delta T_{\text{side A}}-\Delta T_{\text{side B}}}{\ln\frac{\Delta T_{\text{side A}}}{\Delta T_{\text{side B}}}}$

$U_\text{I} = \left(\frac{1}{h_\text{I}} + \frac{(R_\text{O}-R_\text{I})A_\text{I}}{k_AA_{\text{lm}}} + \frac{A_\text{I}}{A_\text{O}h_\text{O}}\right)^{-1}$

$U_\text{O} = \left(\frac{A_\text{O}}{A_\text{I}h_\text{I}} + \frac{(R_\text{O}-R_\text{I})A_\text{O}}{k_AA_{\text{lm}}} + \frac{1}{h_\text{O}}\right)^{-1}$

$A_{\text{lm}} = \frac{A_\text{O}-A_\text{I}}{\ln(A_\text{O}/A_\text{I})}$ $A_i = 2\pi R_i\ell$

Fouling: $U_\text{I} = \left(\frac{1}{h_\text{I}} + \frac{1}{h_{\text{d,I}}} + \frac{(R_\text{O}-R_\text{I})A_\text{I}}{k_AA_{\text{lm}}} + \frac{A_\text{I}}{A_\text{O}h_\text{O}} + \frac{A_\text{I}}{A_\text{O}h_{\text{d,O}}}\right)^{-1}$

$C_{\min} \equiv \min\{(\dot{m}\hat{C}_P)_\text{H},\ (\dot{m}\hat{C}_P)_\text{C}\}$ $C_{\max} \equiv \max\{(\dot{m}\hat{C}_P)_\text{H},\ (\dot{m}\hat{C}_P)_\text{C}\}$

$\epsilon_{\text{counter}} \equiv \frac{1-e^{\left[\frac{-UA}{C_{\min}}\left(1-\frac{C_{\min}}{C_{\max}}\right)\right]}}{1-\frac{C_{\min}}{C_{\max}}e^{\left[\frac{-UA}{C_{\min}}\left(1-\frac{C_{\min}}{C_{\max}}\right)\right]}}$ $\epsilon_{\text{co}} \equiv \frac{1-e^{\left[\frac{-UA}{C_{\min}}\left(1+\frac{C_{\min}}{C_{\max}}\right)\right]}}{1+\frac{C_{\min}}{C_{\max}}}$

$\dot{Q} = \epsilon C_{\min}(T_{\text{H,shell}} - T_{\text{C,tube}})$

4.2 Radiation

$A_\Omega = \frac{\dot{Q}_{\text{absorbed}}}{\dot{Q}_{\text{incident}}}$ $\varepsilon_\Omega = \frac{\dot{Q}_{\text{emitted}}}{\dot{Q}_{\text{emitted,blackbody}}}$ Blackbody: $A_\Omega, \varepsilon_\Omega = 1$

$\frac{\dot{Q}_{\text{emitted}}}{A} = \varepsilon_\Omega\sigma T^4$ $\dot{Q}_{\text{abs,net}} = A\varepsilon_\Omega\big|_{T_{\text{sfc}}}\sigma(T_{\text{sfc}}^4 - T_{\text{bulk}}^4)$

$\sigma \equiv 5.676\text{E}{-8}\ \frac{\text{J}}{\text{s m}^2\text{ K}^4}$

$h_{\text{rad}} = \frac{\varepsilon|_{T_{\text{sfc}}}\sigma(T_{\text{sfc}}^4-T_{\text{bulk}}^4)}{T_{\text{sfc}}-T_{\text{bulk}}}$ $\dot{Q}_{\text{cnv+rad}} = (h_{\text{cnv}} + h_{\text{rad}})A(T_{\text{sfc}} - T_{\text{bulk}})$

$\frac{\dot{Q}_{1\to2}}{A} = \frac{\sigma(T_1^4-T_2^4)}{\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1}$ N heat shields: $\frac{\dot{Q}_{1\to2}}{A} = \frac{1}{N+1}\frac{\sigma(T_1^4-T_2^4)}{\sum\frac{1}{\varepsilon}-1}$

5 Fluid Mechanics Cases

Hydrostatic column: $P_\perp = P_\top + \rho g\hbar$

U-manometer: $P_A - P^{\ominus} = (\rho_{\text{fl}} - \rho_A)\,g\hbar_{\text{fl}} + (\rho_B - \rho_A)\,g\hbar_B$

Sphere creep: $\vec{F}_\text{d} = 6\pi R\mu\vec{v}_\infty$ $\vec{v}_\infty = \frac{4(\rho_{\text{body}}-\rho)\varnothing^2g}{18\mu}$ Re $= \frac{24}{C_\text{d}}$

Sphere drop: $C_\text{d} = \frac{4(\rho_{\text{body}}-\rho)\varnothing g}{3\rho v_\infty^2}$ $\vec{v}_\infty = \sqrt{\frac{4(\rho_{\text{body}}-\rho)\varnothing g}{3\rho C_\text{d}}}$

5.1 Poiseuille Flow of Newtonian Fluid in Tube (Figure 1)

$P(z) = \frac{P_\ell-P_0}{\ell}z + P_0$ $\boldsymbol{\tau}_{rz}(r) = \frac{P_\ell-P_0-\rho g\ell}{2\ell}r$

$\vec{v}(r) = \langle 0,\quad 0,\quad \frac{(\rho g\ell+P_0-P_\ell)R^2}{4\mu\ell}(1-\left[\frac{r}{R}\right]^2)\rangle$

$\langle\vec{v}_z\rangle = \frac{\int_0^{2\pi}\int_0^R\vec{v}_zr\ drd\theta}{\int_0^{2\pi}\int_0^R r\ drd\theta}$ $\vec{F}_{z,\text{wall}} = \int_0^\ell\int_0^{2\pi}\boldsymbol{\tau}\big|_{r=R}Rd\theta dz$

$\dot{V} = \int_0^{2\pi}\int_0^R\vec{v}_zrdrd\theta = \pi R^2\langle\vec{v}_z\rangle$

5.2 Newtonian Fluid Flow Down Inclined Plane (Figure 2)

$g = \langle g\sin\theta,\quad 0,\quad g\cos\theta\rangle$ $\vec{v} = \langle 0,\quad 0,\quad \vec{v}_z\rangle$

$\vec{v}_z(x) = \frac{\rho g\cos\theta}{2\mu}(\hbar^2 - x^2)$ $\langle\vec{v}_z\rangle = \frac{\int_0^w\int_0^\hbar\vec{v}_zdxdy}{\int_0^w\int_0^\hbar dxdy}$

$\dot{V} = \int_0^w\int_0^\hbar\vec{v}_z\ dxdy = w\hbar\langle\vec{v}_z\rangle$ $\vec{F}_{z,\text{wall}} = \int_0^\ell\int_0^w\boldsymbol{\tau}_{xz}\big|_{x=\hbar}dydz$

6 Heat Transfer Cases

Across rect. slab: $T = \frac{T_2 - T_1}{\Delta x} x + T_1 \qquad T_1 > T_2$

Across slab between bulk fluids, Newton's Law of Cooling B.C.:

$$\frac{\dot{Q}_x}{A} = \frac{T_{\text{b}1} - T_{\text{b}2}}{\frac{1}{h_1} + \frac{\Delta x}{k} + \frac{1}{h_2}} \qquad T_{\text{b}1} > T_{\text{b}2}$$

$$T = T_{\text{b}1} - \frac{(T_{\text{b}1} - T_{\text{b}2})\frac{1}{k}}{\frac{1}{h_1} + \frac{\Delta x}{k} + \frac{1}{h_2}} x + \frac{(T_{\text{b}1} - T_{\text{b}2})\frac{1}{h_1}}{\frac{1}{h_1} + \frac{\Delta x}{k} + \frac{1}{h_2}}$$

Cyl. shell: $\frac{\dot{Q}_r}{A} = \frac{T_1 - T_2}{\ln \frac{R_{\text{O}}}{R_{\text{I}}}} \frac{k}{r} \qquad \frac{T_2 - T}{T_2 - T_1} = \frac{\ln \frac{R_{\text{O}}}{r}}{\ln \frac{R_{\text{O}}}{R_{\text{I}}}}$

Annulus, Newton's Law of Cooling B.C. (Figure 3):

$$\frac{\dot{Q}_r}{A} = \frac{T_{\text{b}1} - T_{\text{b}2}}{\frac{1}{h_{\text{O}} R_{\text{O}}} + \frac{1}{k} \ln \frac{R_{\text{O}}}{R_{\text{I}}} + \frac{1}{h_{\text{I}} R_{\text{I}}}} \left(\frac{1}{r}\right) \qquad T_{\text{b}1} > T_{\text{b}2}$$

$$T = T_{\text{b}2} + \frac{(T_{\text{b}1} - T_{\text{b}2})(\ln \frac{R_{\text{O}}}{r} + \frac{k}{h_{\text{O}} R_{\text{O}}})}{\frac{k}{h_{\text{O}} R_{\text{O}}} + \ln \frac{R_{\text{O}}}{R_{\text{I}}} + \frac{k}{h_{\text{I}} R_{\text{I}}}}$$

Wire with generation: $\frac{T - T_s}{\dot{Q} R^2 (4k)^{-1}} = 1 - \left(\frac{r}{R}\right)^2$

Very large h: use Fourier's Law

7 Heat Transfer Correlations

7.1 Forced Convection

$$\dot{Q} = \langle h \rangle A \Delta \langle T \rangle = \langle h \rangle A \tfrac{1}{2} [(T_{\text{wall}} - T_{\text{bulk,in}}) + (T_{\text{wall}} - T_{\text{bulk,out}})]$$

Lam., $\leftrightarrow$ pipe, $\{\text{Re} < 2100,\ \text{RePr}\frac{\varnothing}{\ell} > 100\}$:

$$\langle \text{Nu} \rangle = \frac{\langle h \rangle \varnothing}{k} = 1.86 \left(\text{RePr}\frac{\varnothing}{\ell}\right)^{1/3} \left(\frac{\mu_{\text{bulk}}}{\mu_{\text{wall}}}\right)^{0.14}$$

Trb., smooth pipe, $\{\text{Re} > 6000,\ 0.7 < \text{Pr} < 16000,\ \ell/\varnothing > 60\}$:

$$\text{Nu}_{\text{lm}} = \frac{h_{\text{lm}} \varnothing}{k} = 0.027 \text{Re}^{0.8} \text{Pr}^{1/3} \left(\frac{\mu_{\text{bulk}}}{\mu_{\text{wall}}}\right)^{0.14}$$

Trb., air (1 atm), pipe: $h_{\text{lm}} = \frac{3.52 \vec{v}^{0.8}}{\varnothing^{0.2}}$

Trb., water, pipe, $\{4 \le T \le 105\,°\text{C}\}$: $h_{\text{lm}} = 1429(1 + 0.0146T)\frac{\vec{v}^{0.8}}{\varnothing^{0.2}}$

Organic liquid: $h_{\text{lm}} = 423 \frac{\vec{v}^{0.8}}{\varnothing^{0.2}}$

Around sphere, $\{1 \le \text{Re} \le 7\text{E}4, 0.6 \le \text{Pr} \le 400\}$: $\text{Nu} = 2 + 0.6 \text{Re}^{\frac{1}{2}} \text{Pr}^{\frac{1}{3}}$

7.2 Immersed Body

Flow $\parallel$ plate, $\{\text{Re} < 3\text{E}5 \wedge \text{Pr} > 0.7\}$: $\text{Nu} = 0.664 \text{Re}^{0.5} \text{Pr}^{1/3}$

Flow $\parallel$ plate, $\{\text{Re} > 3\text{E}5 \wedge \text{Pr} > 0.7\}$: $\text{Nu} = 0.0366 \text{Re}^{0.8} \text{Pr}^{1/3}$

Flow $\perp$ cyl, $\{\text{Pr} > 0.6\}$: $\text{Nu} = C \text{Re}^m \text{Pr}^{1/3}$

Re	m	C
$1 - 4$	0.330	0.989
$4 - 40$	0.385	0.911
$40 - 4 \times 10^3$	0.466	0.683
$4 \times 10^3 - 4 \times 10^4$	0.618	0.193
$4 \times 10^4 - 2.5 \times 10^5$	0.805	0.0266

7.3 Natural Convection

$\updownarrow$ plane/cyl: $\text{Nu} = \frac{h\ell}{k} = a(\text{GrPr})^m$

Geometry	GrPr	a	m
$\updownarrow$ plane/cyl., $\{\hbar < 1\,\text{m}\}$	$< 10^4$	1.36	0.2
	$10^4 - 10^9$	0.59	0.25
	$> 10^9$	0.13	1/3
$\leftrightarrow$ cyl., $\{\varnothing < 0.2\,\text{m}\}$	$< 10^{-5}$	0.49	0
	$10^{-5} - 10^{-3}$	0.71	0.04
	$10^{-3} - 1$	1.09	0.1
	$1 - 10^4$	1.09	0.2
	$10^4 - 10^9$	0.53	0.25
	$> 10^9$	0.13	1/3
$\leftrightarrow$ plate, $\top$heated / $\perp$cooled	$10^5 - 2 \times 10^7$	0.54	0.25
	$2 \times 10^7 - 3 \times 10^{10}$	0.14	1/3
$\leftrightarrow$ plate, $\perp$heated / $\top$cooled	$10^5 - 10^{11}$	0.58	0.2

7.3.1 Simplified Natural Convection

Geometry	GrPr	h ($T[=]\text{K}, \ell[=]\text{m}$)
	Air at 1 atm	
$\updownarrow$ plane, cyl.	$10^4 - 10^9$	$1.37(\Delta T/\ell)^{0.25}$
	$> 10^9$	$1.24(\Delta T)^{1/3}$
$\leftrightarrow$ cyl.	$10^3 - 10^9$	$1.32(\Delta T/\varnothing)^{0.25}$
	$> 10^9$	$1.24(\Delta T)^{1/3}$
$\leftrightarrow$ plate, $\top$heated / $\perp$cooled	$10^5 - 2 \times 10^7$	$1.32(\Delta T/\ell)^{0.25}$
	$2 \times 10^7 - 3 \times 10^{10}$	$1.52(\Delta T)^{1/3}$
$\leftrightarrow$ plate, $\perp$heated / $\top$cooled	$3 \times 10^5 - 10^{10}$	$0.59(\Delta T/\ell)^{0.25}$
	Water at 294 K	
$\updownarrow$ plane, cyl.	$10^4 - 10^9$	$127(\Delta T/\ell)^{0.25}$
	Organic liquids at 294 K	
$\updownarrow$ plane, cyl.	$10^4 - 10^9$	$59(\Delta T/\ell)^{0.25}$

7.3.2 Enclosed Spaces

Geometry	$\text{Gr}_\delta\text{Pr}$	Nu_δ
$\updownarrow$ plates, gas, $\{\ell/\delta < 3\}$	< 2000	1.0
	$6 \times 10^3 - 2 \times 10^5$	$\frac{0.20(\text{Gr}_\delta\text{Pr})^{0.25}}{(\ell/\delta)^{1/9}}$
	$2 \times 10^5 - 2 \times 10^7$	$\frac{0.073(\text{Gr}_\delta\text{Pr})^{1/3}}{(\ell/\delta)^{1/9}}$
$\updownarrow$ plates, liquid	< 1000	1.0
	$1000 - 10^7$	$\frac{0.28(\text{Gr}_\delta\text{Pr})^{0.25}}{(\ell/\delta)^{0.25}}$
$\leftrightarrow$ plates, gas, $\{T_\perp > T_\top\}$	$7 \times 10^3 - 3 \times 10^5$	$0.21(\text{Gr}_\delta\text{Pr})^{0.25}$
	$> 3 \times 10^5$	$0.061(\text{Gr}_\delta\text{Pr})^{1/3}$
$\leftrightarrow$ plates, gas, $\{T_\perp > T_\top\}$	$1.5 \times 10^5 - 1 \times 10^9$	$0.069(\text{Gr}_\delta\text{Pr})^{1/3}\text{Pr}^{0.074}$

7.4 Boiling and Condensation

Boiling, $\leftrightarrow$, $\{\frac{\dot{Q}}{A} < 16\text{kW m}^{-2}\}$: $h = 1043(\Delta T[\text{K}])^{1/3}$

Boiling, $\leftrightarrow$, $\{16 < \frac{\dot{Q}}{A} < 240\text{kW m}^{-2}\}$: $h = 5.56(\Delta T[\text{K}])^3$

Boiling, $\updownarrow$, $\{\frac{\dot{Q}}{A} < 3\text{kW m}^{-2}\}$: $h = 537(\Delta T[\text{K}])^{1/7}$

Boiling, $\updownarrow$, $\{3 < \frac{\dot{Q}}{A} < 63\text{kW m}^{-2}\}$: $h = 7.95(\Delta T[\text{K}])^3$

Boiling, forced convection: $h = 2.55(\Delta T[\text{K}])^3 e^{P[\text{kPa}]/1551}$

Boiling, film, $\leftrightarrow$ tube: $h = 0.62 \left[\frac{k_{(\text{v})}^3 \rho_{(\text{v})} (\rho_{(\text{l})} - \rho_{(\text{v})}) g (\Delta_{\text{vap}} \hat{H} + 0.4 \hat{C}_{P,(\text{v})} \Delta T)}{\varnothing \mu_{(\text{v})} \Delta T}\right]$

Cnd., film, bottom of $\updownarrow$ sfc.: $\text{Re} = \frac{4\dot{m}_\perp}{\ell' \mu_{(\text{l})}}$ $\substack{<1800\text{:turbulent} \\ >1800\text{:laminar}}$ $\quad \ell' = \substack{\pi\varnothing\,(\text{tube}) \\ \ell\,(\text{plate})}$

Cnd., film, lam., $\updownarrow$ tube: $\text{Nu} = 1.13 \left[\frac{\rho_{(\text{l})} (\rho_{(\text{l})} - \rho_{(\text{v})}) g \Delta_{\text{vap}} \hat{H}(T_{\text{sat}}) \ell^3}{\mu_{(\text{l})} k_{(\text{l})} \Delta T}\right]^{0.25}$

Cnd., film, trb., $\updownarrow$ tube: $\text{Nu} = 0.0077 \left(\frac{\rho_{(\text{l})}^2 g \ell^3}{\mu_{(\text{l})}^2}\right)^{\frac{1}{3}} \text{Re}^{0.4}$

Cnd., film, lam., outside N stacked $\leftrightarrow$ cyl.: $\text{Nu} = 0.725 \left[\frac{\rho_{(\text{l})} (\rho_{(\text{l})} - \rho_{(\text{v})}) g \Delta_{\text{vap}} \hat{H} \varnothing_{\text{O}}^3}{N \mu_{(\text{l})} k_{(\text{l})} \Delta T}\right]^{0.25}$

8 Figures

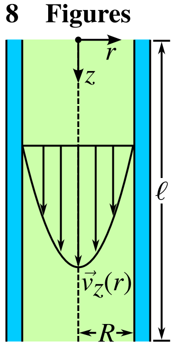

Figure 1

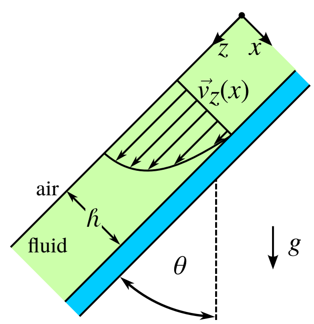

Figure 2

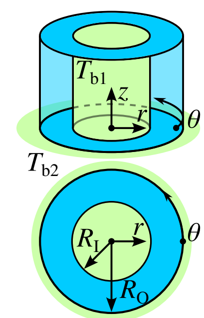

Figure 3

References

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