8. Internal Forced Convection

8.1. General Procedure

1. Find fluid properties from Appendix 1 at bulk mean temperature $T_b = (T_i + T_e)/2$
   - ρ, μ, k, c_p, Pr, ν
2. Determine mean velocity V_{avg}
3. Determine the type of flow (laminar or turbulent)
   - Laminar: $\text{Re} < 2300$
   - Turbulent: $\text{Re} > 4000$
4. Determine the Nusselt number, Nu, using the appropriate correlation
   - Check if $l_{h,\text{laminar}}$ and $l_{t,\text{laminar}}$ is less than L. If so, use Table 1
   - Else, use empirical correlations
5. Determine the heat transfer coefficient h using Nu, k, and A_s

8.2. Variable Definitions

- Nu: Nusselt number
- Re: Reynolds number
- Pr: Prandtl number
- μ: Dynamic viscosity
- ν: Kinematic viscosity
- k: Thermal conductivity
- h: Convection heat transfer coefficient
- D_h: Hydraulic diameter
- A_s: Surface area
- A_c: Cross-sectional area
- V_{avg}: Average velocity
- T_b: Bulk mean temperature
- T_i: Inlet temperature
- T_e: Exit temperature
- $\dot{m}$: Mass flow rate
- $\dot{q}$: Heat flux
- ΔT_{lm}: Log mean temperature difference

8.3. Formulas

$$\begin{aligned}
\dot{m} &= \rho V_{\text{avg}} A_c \\
\text{Re} &= \frac{\rho V_{\text{avg}} D_h}{\mu} = \frac{V_{\text{avg}} D_h}{\nu} \\
D_h &= \frac{4A_c}{\text{Perimeter}} = D|_{\text{circular}} = a|_{\text{square}} \\
&= \left.\frac{2ab}{a+b}\right|_{\text{rectangular}} = \left.\frac{4ab}{a+b}\right|_{\text{channel}} \\
\text{Nu} &= \frac{hD_h}{k} \\
A_s &= \pi DL|_{\text{circular}} = 4ab|_{\text{rectangular}} \\
A_c &= \pi\frac{D^2}{4}|_{\text{circular}} = ab|_{\text{rectangular}} \\
l_{h,\text{laminar}} &= 0.05\text{Re}D_h \\
l_{t,\text{laminar}} &= 0.05\text{RePr}D_h = \text{Pr}l_{h,\text{laminar}} \\
l_{h,\text{turbulent}} &\approx l_{t,\text{turbulent}} = 10D_h
\end{aligned}$$

Constant $\dot{q}$:

$$T_e = T_i + \frac{\dot{q}}{\dot{m}c_p}$$

$$\dot{q} = h(T_s - T_b)$$

Constant T_s:

$$\begin{aligned}
T_e &= T_s - (T_s - T_i)\exp\left(-\frac{hA_s}{\dot{m}c_p}\right) \\
T_s &= \frac{T_e - T_i\exp\left(-\frac{\dot{m}C_p}{hA_s}\right)}{1-\exp\left(-\frac{\dot{m}C_p}{hA_s}\right)} \\
\dot{Q} &= hA_s\Delta T_{\text{lm}} \\
T_{\text{lm}} &= \frac{T_i - T_e}{\ln[(T_s - T_e)/(T_s - T_i)]}
\end{aligned}$$

For fully developed laminar flow, use Table 1.

For entry region in a circular tube where T_s = constant, use:
(Edwards et al., 1979) $\text{Nu} = 3.66 + \dfrac{0.0658(D/L)\text{RePr}}{1+0.04[(D/L)\text{RePr}]^{2/3}}$

For entry region in a circular tube where the difference between T_s and T_b is large, use:

(Sieder and Tate, 1936) $\text{Nu} = 1.86\left(\dfrac{\text{RePr}D}{L}\right)^{1/3}\left(\dfrac{\mu_b}{\mu_s}\right)^{0.14}$

$$0.6 < \text{Pr} < 5, \quad 0.0044 < \frac{\mu_b}{\mu_s} < 9.75$$

All properties for Sieder and Tate should be evaluated at T_b except μ_s which should be evaluated at T_s.

For entry region between two isothermal parallel plates, use:
(Edwards et al., 1979) $\text{Nu} = 7.54 + \dfrac{0.03(D_h/L)\text{RePr}}{1+0.016[(D_h/L)\text{RePr}]^{2/3}}$

$$\text{Re} \leq 2800$$

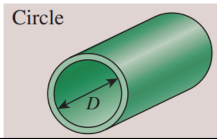
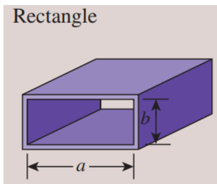
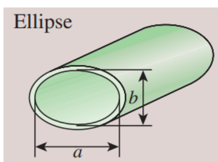
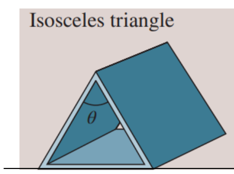
For turbulent flow in a circular tube, use:

$$\text{(Dittus-Boelter, 1930) Nu} = 0.023\text{Re}^{0.8}\text{Pr}^n$$

$$n = 0.4 \text{ (Heating)}, \quad n = 0.3 \text{ (Cooling)}$$

Tables

Table 1: Nusselt number and friction factor for fully developed laminar flow in tubes of various cross sections ($D_h = 4A_c/P$, $Re = V_{\text{avg}} D_h/\nu$, and $\text{Nu} = hD_h/k$) (**Table 8-1 in textbook**)

Tube Geometry	a/b or $\theta°$	Nu		f
		T_s = constant	$\dot{q}_s$ = constant	
	—	4.36	3.66	64/Re
	a/b			
	1	2.98	3.61	56.92/Re
	2	3.39	4.12	62.20/Re
	3	3.96	4.79	68.36/Re
	4	4.44	5.33	72.92/Re
	6	5.14	6.05	78.80/Re
	8	5.60	6.49	82.32/Re
	∞	7.54	8.24	96.00/Re
	a/b			
	1	3.66	4.36	64.00/Re
	2	3.74	4.56	67.28/Re
	4	3.79	4.88	72.96/Re
	8	3.72	5.09	76.60/Re
	16	3.65	5.18	78.16/Re
	$\theta°$			
	10	1.61	2.45	50.80/Re
	30	2.26	2.91	52.28/Re
	60	2.47	3.11	53.32/Re
	90	2.34	2.98	52.60/Re
	120	2.00	2.68	50.96/Re