**PROBLEM 8.22**

**KNOWN:** Flow rate of engine oil through a long tube.

**FIND:** (a) Heat transfer coefficient, $h$, (b) Outlet temperature of oil, $T_{m,o}$.

**SCHEMATIC:**

![SCHEMATIC](image)

**ASSUMPTIONS:** (1) Steady-state conditions, (2) Constant properties, (3) Combined entry conditions exist.

**PROPERTIES:** Table A-5, Engine Oil ($T_s = 100^\circ C = 373 K$): $\mu_s = 1.73 \times 10^{-2} N \cdot s/m^2$; Table A-5, Engine Oil ($T_m = 77^\circ C = 350 K$): $c_p = 2118 J/kg \cdot K$, $\mu = 3.56 \times 10^{-2} N \cdot s/m^2$, $k = 0.138 W/m \cdot K$, $Pr = 546$.

**ANALYSIS:** (a) The overall energy balance and rate equations have the form

$$q = \dot{m} \ c_p \ (T_{m,o} - T_{m,i}) \quad q = \bar{h} A_s \Delta T_{1m} \quad (1,2)$$

Using Eq. 8.42b, with $P = \pi D$, and Eq. 8.6

$$\frac{\Delta T_0}{\Delta T_i} = \frac{T_s - T_{m,o}}{T_s - T_{m,i}} = \exp \left( - \frac{PL}{\dot{m} c_p} \cdot \bar{h} \right). \quad (3)$$

For laminar and combined entry conditions, use Eq. 8.57

$$\bar{Nu}_D = 1.86 \left( \frac{Re_D Pr}{L/D} \right)^{1/3} \left( \frac{\mu}{\mu_s} \right)^{0.14} = \left( \frac{238 \times 546}{30m/3 \times 10^{-3} m} \right)^{1/3} \left( \frac{3.56}{1.73} \right)^{0.14} = 4.83$$

$$\bar{h} = \bar{Nu}_D \frac{k}{D} = 4.83 \times 0.138 W/m \cdot K \times 3 \times 10^{-3} m = 222 W/m^2 \cdot K. \quad <$$

(b) Using Eq. (3) with the foregoing value of $\bar{h}$,

$$\left( \frac{100 - T_{m,o}}{100 - 60} \right)^\circ C = \exp \left( - \pi \times 3 \times 10^{-3} m \times 30 m \times 0.02 kg/s \times 2118 J/kg \cdot K \times 222 W/m^2 \cdot K \right) \quad T_{m,o} = 90.9^\circ C. \quad <$$

**COMMENTS:** (1) Note that requirements for the correlation, Eq. 8.57, are satisfied.

(2) The assumption of $T_m = 77^\circ C$ for selecting property values was satisfactory.

(3) For thermal entry effect only, Eq. 8.56, $\bar{h} = 201 W/m^2 \cdot K$ and $T_{m,o} = 89.5^\circ C$. 
PROBLEM 8.26

KNOWN: Ethylene glycol flowing through a coiled, thin walled tube submerged in a well-stirred water bath maintained at a constant temperature.

FIND: Heat rate and required tube length for prescribed conditions.

SCHEMATIC:

ASSUMPTIONS: (1) Steady-state conditions, (2) Tube wall thermal resistance negligible, (3) Convection coefficient on water side infinite; cooling process approximates constant wall surface temperature distribution, (4) KE, PE and flow work changes negligible, (5) Constant properties, (6) Negligible heat transfer enhancement associated with the coiling.

PROPERTIES: Table A-5, Ethylene glycol (T_m = (85 + 35)/2 = 60°C = 333 K): \( c_p = 2562 \) J/kg\( \cdot \)K, \( \mu = 0.522 \times 10^{-2} \) N\( \cdot \)s/m\(^2\), \( k = 0.260 \) W/m\( \cdot \)K, Pr = 51.3.

ANALYSIS: From an overall energy balance on the tube,

\[
q_{\text{conv}} = \dot{m} c_p \left( T_{m,o} - T_{m,i} \right) = 0.01 \text{ kg/s} \times 2562 \text{ J/kg(35 – 85)°C} = -1281 \text{ W.} \tag{1}
\]

For the constant surface temperature condition, from the rate equation,

\[
A_s = \frac{q_{\text{conv}}}{h_{\text{conv}} \Delta T_{\ell m}} \tag{2}
\]

\[
\Delta T_{\ell m} = \left( \Delta T_o - \Delta T_i \right) / \ln \left( \frac{\Delta T_o}{\Delta T_i} \right) = \left[ \left( 35 - 25 \right)^\circ \text{C} - \left( 85 - 25 \right)^\circ \text{C} \right] / \ln \frac{35 - 25}{85 - 25} = 27.9^\circ \text{C}. \tag{3}
\]

Find the Reynolds number to determine flow conditions,

\[
\text{Re}_D = \frac{4 \dot{m}}{\pi D \mu} = \frac{4 \times 0.01 \text{ kg/s}}{\pi \times 0.003 \text{ m} \times 0.522 \times 10^{-2} \text{ N} \cdot \text{s/m}^2} = 813. \tag{4}
\]

Hence, the flow is laminar and, assuming the flow is fully developed, the appropriate correlation is

\[
\text{Nu}_D = \frac{\text{Nu}}{D} = 3.66, \quad \text{Nu} = \frac{k}{D} = 3.66 \times 0.260 \frac{\text{W}}{\text{m} \cdot \text{K}} / 0.003 \text{m} = 317 \text{ W/m}^2 \cdot \text{K}. \tag{5}
\]

From Eq. (2), the required area, \( A_s \), and tube length, \( L \), are

\[
A_s = 1281 \text{ W}/317 \text{ W/m}^2 \cdot \text{K} 	imes 27.9^\circ \text{C} = 0.1448 \text{ m}^2
\]

\[
L = A_s / \pi D = 0.1448 \text{ m}^2 / \pi (0.003 \text{m}) = 15.4 \text{ m.} \tag{6}
\]

COMMENTS: Note that for fully developed laminar flow conditions, the requirement is satisfied: \( Gz^{-1} = (L/D) / \text{Re}_D \text{ Pr} = (15.3/0.003) / (813 \times 51.3) = 0.122 > 0.05 \). Note also the sign of the heat rate \( q_{\text{conv}} \) when using Eqs. (1) and (2).
**PROBLEM 8.77**

**KNOWN:** Flow rate and inlet temperature of air passing through a rectangular duct of prescribed dimensions and surface heat flux.

**FIND:** Air and duct surface temperatures at outlet.

**SCHEMATIC:**

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\[ \text{Air} \]
\[ \dot{m} = 3 \times 10^{-4} \text{ kg/s} \]
\[ T_{m,i} = 300 \text{ K} \]
\[ L = 1 \text{ m} \]
\[ W = 16 \text{ mm} \]
\[ Q_s = 600 \text{ W/m}^2 \]
\[ T_{s,o} \]
```

**ASSUMPTIONS:** (1) Steady-state conditions, (2) Uniform surface heat flux, (3) Constant properties, (4) Atmospheric pressure, (3) Fully developed conditions at duct exit, (6) Negligible KE, PE and flow work effects.

**PROPERTIES:** Table A-4. Air \( T_m = 300 \text{ K}, 1 \text{ atm} \): \( c_p = 1007 \text{ J/kg·K}, \mu = 184.6 \times 10^{-7} \text{ N·s/m}^2 \), \( k = 0.0263 \text{ W/m·K}, \text{Pr} = 0.707 \).

**ANALYSIS:** For this uniform heat flux condition, the heat rate is

\[
q = q_s^* A_s = q_s^* [2(L \times W) + 2(L \times H)]
\]

\[
q = 600 \text{ W/m}^2 [2(1\text{m} \times 0.016\text{m}) + 2(1\text{m} \times 0.004\text{m})] = 24 \text{ W}.
\]

From an overall energy balance

\[
T_{m,o} = T_{m,i} + \frac{q}{\dot{m} c_p} = 300 \text{ K} + \frac{24 \text{ W}}{3 \times 10^{-4} \text{ kg/s} \times 1007 \text{ J/kg·K}} = 379 \text{ K}.
\]

The surface temperature at the outlet may be determined from Newton’s law of cooling, where

\[
T_{s,o} = T_{m,o} + q^*/h.
\]

From Eqs. 8.67 and 8.1

\[
D_h = \frac{4 A_c}{P} = \frac{4(0.016\text{m} \times 0.004\text{m})}{2(0.016\text{m} + 0.004\text{m})} = 0.0064 \text{ m}
\]

\[
Re_D = \frac{\rho u_m D_h}{\mu} = \frac{\dot{m} D_h}{A_c \mu} = \frac{3 \times 10^{-4} \text{kg/s} (0.0064\text{m})}{64 \times 10^{-6} \text{m}^2 (184.6 \times 10^{-7} \text{ N·s/m}^2)} = 1625.
\]

Hence the flow is laminar, and from Table 8.1

\[
h = \frac{k}{D_h} 5.33 = \frac{0.0263 \text{ W/m·K}}{0.0064 \text{ m}} = 5.33 = 22 \text{ W/m}^2 \cdot \text{K}
\]

\[
T_{s,o} = 379 \text{ K} + \frac{600 \text{ W/m}^2}{22 \text{ W/m}^2 \cdot \text{K}} = 406 \text{ K}.
\]

**COMMENTS:** The calculations should be reperformed with properties evaluated at \( T_m = 340 \text{ K} \). The change in \( T_{m,o} \) would be negligible, and \( T_{s,o} \) would decrease slightly.