

ChE 306: HEAT TRANSFER
FALL 2010
Homework #5 Ch 7 & 8 (80 points)
DUE: FRIDAY, OCTOBER 8

1. Water is flowing over all of the surfaces of a 3-inch diameter, 50 foot long cylinder in cross-flow such that equation 7.52 applies to determine the Nusselt number. The water is flowing at 1.0 mph at a bulk temperature of 68 °F over the 104 °F cylinder surface at steady state.

- A. What is the heat loss rate in W?
- B. Evaluate the heat loss rate using Equation 7.53 and 7.54. Compare your answers to (A).
- C. Returning to Equation 7.52, what velocity of water is required to double the heat loss rate?

SOLN:

A. $q = h A (T_s - T_{inf})$

$D = 3 \text{ in} * 0.0254 \text{ m/in} = 0.0762 \text{ m}$

$A = \pi * D * L = \pi * 0.25 \text{ ft} * 50 \text{ ft} = 12.5\pi \text{ ft}^2 * 1 \text{ m}^2/10.764 \text{ ft}^2 = 3.647 \text{ m}^2$

$T_{inf} = 20 \text{ C} \quad T_s = 40 \text{ C}$

Must determine h.

In the correlation $Nu = C Re_D^m Pr^{1/3}$, the C & m values change depending on the Re # (see T7.2)

Look up properties of water at film temperature of 30 °C (68 F = 20 C, 104 F = 40 C).

At 303 K, from Table A.6 (using the lever rule to get properties at 303K):

specific volume = 1/density = $1.004 * 10^{-3} \text{ m}^3/\text{kg}$

viscosity = $0.6 * 769 + 0.4 * 855 = 803.4 * 10^{-6} \text{ Ns/m}^2$

$D = 0.25 \text{ ft} / 3.2808 \text{ ft/m} = 0.07512 \text{ m}$

speed = 1.0 mph = $5280 \text{ ft}/3600 \text{ s} / 3.2808 \text{ ft/m} = 0.447 \text{ m/s}$

$Re = vD/(\mu * \text{spec. vol}) = 0.447 * 0.0762 / \{(803.4 * 10^{-6}) * (1.004 * 10^{-3})\} \quad Re = 42,228$

So, from Table 7.2, C = 0.027 & m = 0.805

$Nu = 0.027 * Re^{0.805} * Pr^{1/3}$

Need more properties: Pr = 5.46 $k_f = 0.617 \text{ W/mK}$

$Nu = 0.027 * (42,227)^{0.805} * 5.46^{1/3} = 251.5$

$h = k_f/D * Nu = 0.617/0.0751 * 251.5 = 2067 \text{ W/m}^2\text{-K}$

Thus $q = 2067 * 3.647 * 20 = 151,000 \text{ W}$

B. Equation 7.53

$Nu_D = C Re^m Pr^n (Pr/Pr_s)^{1/4}$

Re is slightly different now, since all properties are evaluated at T_{infinity} except Pr_s.

specific volume = 1/density = $1.0015 * 10^{-3} \text{ m}^3/\text{kg}$

viscosity = $0.6 * 959 + 0.4 * 1080 = 1007.4 * 10^{-6} \text{ Ns/m}^2$

$D = 0.25 \text{ ft} / 3.2808 \text{ ft/m} = 0.0751 \text{ m}$

speed = 1.0 mph = $5280 \text{ ft}/3600 \text{ s} / 3.2808 \text{ ft/m} = 0.447 \text{ m/s}$

$Re = 0.447 * 0.0751 / \{(1007.4 * 10^{-6}) * (1.0015 * 10^{-3})\} \quad Re = 33,760$

So, from Table 7.4, C = 0.26 & m = 0.6 also n = 0.37 based on Pr # value < 10.

Need more properties: Pr = 7.00 $Pr_s = 4.34 \quad k_f = 0.603 \text{ W/mK}$

(props at 293 except Pr_s at 313 K)

$$\text{Nu} = 0.26 * (33,760)^{0.6} (7.00)^{0.37} * (7.00/4.34)^{1/4}$$

$$\text{Nu} = 314$$

$$h = k/D * \text{Nu} = 0.603 / .0751 * 281 = 2519 \text{ W/m}^2\text{-K}$$

$$\text{Thus } q = 2256 * 3.647 * 20 = 184,000 \text{ W}$$

FOR EQUATION 7.54

all properties are at film temperature, so Re, and Pr are the same as in part A.

$$\text{Re} = 42,228$$

$$\text{Pr} = 5.46 \text{ } k_f = 0.617 \text{ W/mK}$$

$$\text{Nu}_D = 266.9$$

$$h = k/D * \text{Nu} = (.617 / .0751) * 266.9 = 2192 \text{ W/m}^2\text{-K}$$

$$q = 2192 * 3.647 * 20 = 160,000 \text{ W}$$

So, all of the different correlations give reasonable answers (all same order of magnitude), but there's over a 10% difference between the two correlations used in part A and part B.

C. Since we are already in the highest range for Re for the correlation, the C & m values will be the same if v increases (as long as it doesn't cause $\text{Re} > 400,000$... this correlation won't work)

To double the q, we must also double h, since A & (Ts-Tinf) do not change.

To double h, must double Nu, since k_f and Pr do not change

To double Nu, must double Re_D^m , since C & $\text{Pr}^{1/3}$ will not change.

Re_D^m can be rewritten as $v^m D^m / \nu^m \mu^m$.

But D, specific volume and viscosity are constants.

So v_2^m must be twice the value of v_1^m

$$v_2^m = 2 * v_1^m$$

$$v_2/v_1 = 2^{(1/m)}$$

$$v_2 = 1 \text{ mph} * 2^{(1/0.805)} = 2.37 \text{ mph}$$

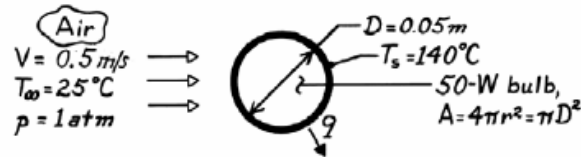
This will only multiply the Reynolds number by 2.37, so the Re will be less than 400,000 and the C and m values in Table 7.2 still hold.

2. Air at 25 °C passes over a 50-W light bulb at 0.5 m/s. The light bulb may be approximated as a sphere with a 5 cm diameter and surface temperature of 140 °C.
- What is the rate of heat loss by convection to the air?
 - If the surroundings temperature is also 25 °C and the emissivity of the light bulb is 0.89, what is the rate of heat loss by radiation to the air (again, you may assume the light bulb is a sphere and ignore the threaded base in your calculation)?
 - What total fraction of the light bulb energy (50-W) is lost as heat?

KNOWN: Conditions associated with airflow over a spherical light bulb of prescribed diameter and surface temperature.

FIND: Heat loss by convection.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Uniform surface temperature.

PROPERTIES: Table A-4, Air ($T_\infty = 25^\circ\text{C}$, 1 atm): $\nu = 15.71 \times 10^{-6} \text{ m}^2/\text{s}$, $k = 0.0261 \text{ W/m}\cdot\text{K}$, $\text{Pr} = 0.71$, $\mu = 183.6 \times 10^{-7} \text{ N}\cdot\text{s}/\text{m}^2$; Table A-4, Air ($T_s = 140^\circ\text{C}$, 1 atm): $\mu = 235.5 \times 10^{-7} \text{ N}\cdot\text{s}/\text{m}^2$.

ANALYSIS: The heat rate by convection is

$$q = \bar{h} (\pi D^2) (T_s - T_\infty)$$

where \bar{h} may be estimated from the Whitaker relation

$$\bar{h} = \frac{k}{D} \left[2 + \left(0.4 \text{Re}_D^{1/2} + 0.06 \text{Re}_D^{2/3} \right) \text{Pr}^{0.4} \left(\frac{\mu}{\mu_s} \right)^{1/4} \right]$$

where

$$\text{Re}_D = \frac{VD}{\nu} = \frac{0.5 \text{ m/s} \times 0.05 \text{ m}}{15.71 \times 10^{-6} \text{ m}^2/\text{s}} = 1591.$$

Hence,

$$\bar{h} = \frac{0.0261 \text{ W/m}\cdot\text{K}}{0.05 \text{ m}} \left\{ 2 + \left[0.4(1591)^{1/2} + 0.06(1591)^{2/3} \right] (0.71)^{0.4} \left(\frac{183.6}{235.5} \right)^{1/4} \right\}$$

$$\bar{h} = 11.4 \text{ W/m}^2 \cdot \text{K}$$

and the heat rate is

$$q = 11.4 \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \pi (0.05 \text{ m})^2 (140 - 25)^\circ\text{C} = 10.3 \text{ W.} \quad <$$

COMMENTS: (1) The low value of \bar{h} suggests that heat transfer by free convection may be significant and hence that the total loss by convection exceeds 10.3 W.

(2) The surface of the bulb also dissipates heat to the surrounding by radiation. Further, in an actual light bulb, there is also heat loss by conduction through the socket.

*b. Heat loss by radiation: $q = Ae_o (T_s^4 - T_{sur}^4) = 4 \pi r^2 * e * o * (413 \text{ K}^4 - 298 \text{ K}^4)$*

*$e = 0.89; o = 5.67 * 10^{-8} \text{ W/m}^2\cdot\text{K}^4$*

*$q = 4 \pi r^2 * (0.025 \text{ m})^2 * 0.89 * 5.67 \text{E}-8 * (413 \text{ K}^4 - 298 \text{ K}^4) = 8.4 \text{ W}$*

c. % lost as heat = $(10.3 + 8.4 \text{ W}) / 50 \text{ W} = 37.4\%$

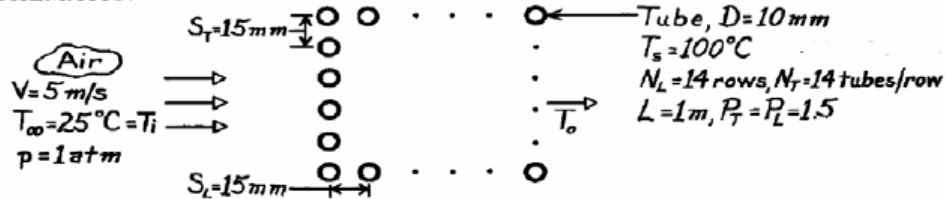
3. Air flowing at 5 m/s at 25 °C and 1 atm is used on the outside of a tube bank to condense steam at 100 °C flowing through the tubes. The outer surface temperature of the tubes can be assumed to be 100 °C. The tubes are 1m long and have an outside diameter of 10 mm and inside diameter of 8 mm. The tube bank has 196 total tubes arranged in a square, aligned array with $S_T = S_L = 15$ mm.
- A. Use Equation 7.64 to determine the total rate of heat transfer to the air.
- B. Use Figure 7.13 to find the friction factor and estimate the pressure drop associated with the airflow.

*I answered questions about problem 3 saying that you can assume that $T_{in} = T_{out}$. If so, then the answer is $q = h A (T_s - T_{inf}) = 200 * 196 * \pi * 0.01 m * 1 m * (100 - 25 C) = 92.3 kW$*
If you had assumed (more correctly) that the air heats up, you would have determined that $T_{out} = 72.3 °C$, which is substantially warmer than T_{in} , and the equation for q would correctly use the log mean temperature difference, as is shown in the solution below.... answers may be off.

KNOWN: Surface temperature and geometry of a tube bank. Velocity and temperature of air in cross flow.

FIND: (a) Total heat transfer, (b) Air flow pressure drop.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Negligible radiation, (3) Uniform surface temperature.

PROPERTIES: Table A-4, Atmospheric air ($T_\infty = 298$ K): $\nu = 15.8 \times 10^{-6} \text{ m}^2/\text{s}$, $k = 0.0263 \text{ W/m}\cdot\text{K}$, $\text{Pr} = 0.707$, $c_p = 1007 \text{ J/kg}\cdot\text{K}$, $\rho = 1.17 \text{ kg/m}^3$; ($T_s = 373$ K): $\text{Pr} = 0.695$.

ANALYSIS: (a) The total heat transfer rate is

$$q = \bar{h} N \pi D L \frac{(T_s - T_i) - (T_s - T_o)}{\ln[(T_s - T_i)/(T_s - T_o)]} = \bar{h} N \pi D L \Delta T_{lm}$$

$$\text{With } V_{\max} = \frac{S_T}{S_T - D} V = \frac{15 \text{ mm}}{5 \text{ mm}} 5 \text{ m/s} = 15 \text{ m/s}, \text{Re}_{D,\max} = \frac{15 \text{ m/s}(0.01 \text{ m})}{15.8 \times 10^{-6} \text{ m}^2/\text{s}} = 9494. \text{ Tables 7.7}$$

and 7.8 give $C = 0.27$, $m = 0.63$ and $C_2 \approx 0.99$. Hence, from the Zukauskas correlation

$$\overline{\text{Nu}}_D = 0.99 \times 0.27 (9494)^{0.63} (0.707)^{0.36} (0.707/0.695)^{1/4} = 75.9$$

$$\bar{h} = \overline{\text{Nu}}_D k/D = 75.9 \times 0.0263 \text{ W/m}\cdot\text{K}/0.01 \text{ m} = 200 \text{ W/m}^2 \cdot \text{K}$$

$$T_s - T_o = (T_s - T_i) \exp\left(-\frac{\pi D N \bar{h}}{\rho V N_T S_T c_p}\right) = 75^\circ \text{C} \exp\left(-\frac{\pi \times 0.01 \text{ m} \times 196 \times 200 \text{ W/m}^2 \cdot \text{K}}{1.17 \text{ kg/m}^3 \times 5 \text{ m/s} \times 14 \times 0.015 \text{ m} \times 1007 \text{ J/kg}\cdot\text{K}}\right)$$

$$T_s - T_o = 27.7^\circ \text{C}.$$

Hence

$$q = 200 \text{ W/m}^2 \cdot \text{K} \times 196 \pi (0.01 \text{ m}) 1 \text{ m} \frac{75^\circ \text{C} - 27.7^\circ \text{C}}{\ln(75/27.7)} = 58.5 \text{ kW}. \quad <$$

(b) With $\text{Re}_{D,\max} = 9494$, $(P_T - 1)/(P_L - 1) = 1$, Fig. 7.13 yields $f \approx 0.32$ and $\chi = 1$. Hence,

$$\Delta p = N \chi \left(\rho V_{\max}^2 / 2 \right) f = 14 \times 1 \left(\frac{1.17 \text{ kg/m}^3 (15 \text{ m/s})^2}{2} \right) 0.32$$

$$\Delta p = 590 \text{ N/m}^2 = 5.9 \times 10^{-3} \text{ bar}.$$

4. Consider the tube bank in problem 3.

- A. If the 196 tubes were replaced with a single pipe to transport the steam, what (inside) diameter pipe would be required to give the same cross-sectional area as all of the tubes?
B. Assuming this pipe has a 1 mm-thick wall (the same as the tubes above), how long must this pipe be to have the same total heat loss rate as the tube bank in part A? (Use Eq. 7.53)
Assume the air is in cross-flow over the pipe, which has a surface T of 100 °C.

A. The cross-sectional area must be the same in both cases.

$$A_c (\text{tubes}) = N * \pi / 4 * D_i^2 = 196 * 3.14159 / 4 * (0.008 \text{ m})^2$$
$$A_c = 0.00985 \text{ m}^2 \text{ (note: inside diameter must be used here!)}$$

$$A_c (\text{single pipe}) = 4.92 \text{ m}^2 = \pi / 4 * D_i^2$$
$$D_i = (0.00985 \text{ m}^2 * 4 / 3.14159)^{1/2}$$
$$D_i = 0.112 \text{ m (11 cm- over 4 inches)}$$

B. must use outside diameter of the single pipe to find A_s .

$$A_s = \pi D_o L = 3.14159 * (0.112 + 0.002 \text{ wall on both sides}) * L \text{ (unknown).}$$
$$A_s = 0.358L$$

$$q = \text{same as in question 3} = 92300 \text{ W}$$
$$T_s = 100 \text{ C}$$
$$T_{inf} = 25 \text{ C}$$

Using Eq. 7.53,
(props @ $T_{inf} = 25\text{C}$)
$$Nu = C Re^m Pr^n (Pr/Pr_s)^{1/4}$$

$$n = 0.37 \text{ (Pr} < 10)$$

C & m depend on Re range

$$Re = vD/nu = 5 \text{ m/s} * 0.112 \text{ m} / (15.89 * 10^{-6} \text{ m}^2/\text{s})$$
$$Re = 35,242$$

so, C = 0.26 and m = 0.6
Pr = 0.707
Pr_s = 0.695 (interpolating)

$$Nu = 0.26 * (35242)^{0.6} * (0.707)^{0.37} * (0.707/0.695)^{1/4}$$
$$Nu = 122.8$$
$$h = Nu * k_f / D_o = 122.8 * 0.0263 \text{ W/mK} / 0.114 \text{ m}$$
$$h = 28.3 \text{ W/m}^2\text{-K}$$

$$q = 92300 = 28.3 * \pi * D_o * L * (100 - 25 \text{ C})$$
$$L = 92300 / (28.3 * 3.14159 * 0.114 * 75 \text{ C})$$
$$L = 121 \text{ m. (significantly longer than 1 meter for the tube bundle!)}$$

5. Ethylene glycol at 23 °F passes through a 1-inch schedule 40 steel pipe that has a constant inner surface temperature of 122 °F. The pipe is 60 feet long.

For a flow rate of 3 g/s, determine:

- A. The hydrodynamic entry length for fully developed flow ($x_{FD,h}$)
- B. The thermal entry length for fully developed flow ($x_{FD,t}$)
- C. The convective heat transfer coefficient, h (in either W/m^2-K or $Btu/h-ft^2-°F$)
- D. The outlet temperature of ethylene glycol in °F (using eq. 8.41 b)
- E. The total heat transfer rate in Btu/h. (using eq. 8.34)

Notes: To avoid iterations, you may use 62.6 °F to determine the fluid properties. Also, schedule 40 refers to a specific pipe size; you will need to look up the actual diameter in a piping table (use Perry's Handbook or perhaps your fluid dynamics book or on-line resources).

*First, you need to look up the diameter of 1 inch schedule 40 pipe.
Outside diameter = 1.315 inches, wall thickness = 0.133 inches
Thus the pipe has an inner diameter of 1.049 inches (or 0.0266 m)*

*Second, the fluid properties can be found in Table A.5:
(at 62.6 F = 17 C = 290 K)*

density = 1118.8 kg/m³

heat capacity = 2.368 kJ/kg-K

*kinematic viscosity = 22.1 * 10⁻⁶ m²/s*

Pr = 236

k_f = 0.248 W/m-K

Conversions: Length = 60 feet = 18.29 m

Surface Temperature = T_s = 50 C = 323 K

Inlet Temperature = 23 F = -5 C = 268 K

A & B. entry lengths:

If laminar flow:

$x_{FD,h} / D = 0.05 Re_D$

$x_{FD,t} / D = 0.05 Re_D Pr$

Need Re!

*velocity = mass flow rate / (density * cross-sectional area)*

m = 0.003 kg/s

density = 1118.8 kg/m³

*$A_c = \pi/4 * D_i^2 = \pi/4 * (0.0266m)^2 = 5.56 * 10^{-4} m^2$*

Thus v = 0.00482 m/s

*A. $Re = vD/\nu = 0.00482 m/s * 0.0266 m / 22.1 * 10^{-6} m^2/s = 5.80$ (REALLY LAMINAR)*

A. $x_{FD,h} = 0.0266 m * 0.05 * 5.80 = 0.0077 m = 0.025 ft$ (much shorter than the tube)!

B. $x_{FD,t} = 0.0266 m * 0.05 * 5.80 * 236 = 1.82 m = 5.97 ft$ (still much shorter than the tube)!

C. Convective Heat Transfer Coefficient

*$h = Nu * k_f / D = f(Re, Pr, k_f, D)$*

Find h for this flow rate using the proper correlations

Picking Correlations

Is it fully developed or still in the thermal entry region?

This is only important for laminar flow.

Since $x_{FD,t} = \sim 6$ ft (much shorter than the tube), the fluid will be fully developed, and Eq. 8.55 can be used: $Nu = 3.66$

$$Nu = 3.66 = h D / k_f$$

$$h = 3.66 * .248 \text{ W/mK} / 0.0266 \text{ m}$$

$$\boxed{C. h = 34.1 \text{ W/m}^2\text{K} = 6.0 \text{ Btu/h-ft}^2\text{-F}}$$

D. Outlet temperature:

$$q = m c_p (T_o - T_i) = h A dT_{lm} = h A (T_o - T_i) / \ln((T_s - T_i) / (T_s - T_o))$$

We don't know q , T_o .

Use equation 8.41 b (page 502), to find the outlet temperature.

$$T_o = T_s - (T_s - T_i) * \exp(-\pi * D * L * h / m c_p)$$

$$= 50 \text{ C} - (50 - -5 \text{ C}) * \exp(-\pi * 0.0266 \text{ m} * 18.29 \text{ m} * 34.1 \text{ W/m}^2\text{-K}) / (0.003 \text{ kg/s} * 2368 \text{ J/kg-K})$$

$$\boxed{D. T_o = 49.96 = 50 \text{ }^\circ\text{C} = 121.93 \text{ }^\circ\text{F} \text{ (the whole fluid warms because the flow rate is so slow!)}$$

E. Use either $q = m c_p (T_o - T_i)$ OR $q = h A dT_{lm}$

$$q = m c_p (T_o - T_i) = 0.003 \text{ kg/s} * 2368 \text{ J/kg-K} * (50 - -5) = 390 \text{ W} * 3.4121 \text{ Btu/h / W} = \underline{1332 \text{ Btu/h}}$$

$$q = h A dT_{lm} = 6.0 * \pi * 1.049/12 \text{ ft} * 60 \text{ ft} * (121.93 - 23) / (\ln(122-23)/(122-121.93))$$

$$= 714 \text{ Btu/h} \text{ (this has a large degree of error due to how close the outlet}$$

temperature is to the surface temperature... the internal energy change is the better way to determine total q here.)

6. Repeat Problem 5 for ethylene glycol flow rates of

- A. 200 g/s, and
- B. 60 kg/s.

Note: if you need to evaluate a fluid property at the surface temperature, use 350 K.

C. For all three flowrates (3 g/s, 200g/s, and 60kg/s), if you were asked to run a second iteration for each problem, what temperature would you use to look up fluid properties?

Everything in RED in problem 5 applies to Problem 6A.

A & B. entry lengths:

If laminar flow:

$$x_{FD,h} / D = 0.05 Re_D$$

$$x_{FD,t} / D = 0.05 Re_D Pr$$

If turbulent: $x_{FD,t} = x_{FD,h} = 10 * D$.

Need new Re!

$$velocity = 0.322 \text{ m/s}$$

The only difference from problem 1 is the Re, which is 100 * bigger than part A.

$$Re = vD/\nu = 0.322 \text{ m/s} * 0.0266 \text{ m} / 22.1 * 10^{-6} \text{ m}^2/\text{s} = 388 \text{ (LAMINAR)}$$

$$\text{A. } x_{FD,h} = 0.05 * 388 * 0.0266 \text{ m} = 0.52 \text{ m (shorter than the tube)}$$

$$\text{B. } x_{FD,t} = 122 \text{ m} = 400 \text{ ft (much longer than the tube)}$$

C. Because of $x_{FD,t}$, the fluid does not have time to become fully developed in the 60 foot length of pipe and equation 8.56 must be used for Nu. (8.57 won't work because Pr for EG is too high.)

$$\begin{aligned} \text{For problem 2: } Nu &= 3.66 + 0.0668 D/L Re Pr / (1 + 0.04 * (D/L Re Pr)^{2/3}) \\ &= 3.66 + 0.0668 * 0.0266 \text{ m} / 18.29 \text{ m} * 388 * 236 / (1 + 0.04 * ((0.0266 \text{ m} / 18.29 \text{ m} * 388 * \\ &236)^{2/3}) \end{aligned}$$

$$Nu = 8.01$$

$$\text{C. } h = 8.01 * .248 \text{ W/mK} / 0.0266 \text{ m} = 74.7 \text{ W/m}^2\text{K}$$

D. Then using equation 8.41 b

$$T_o = T_s - (T_s - T_i) * \exp(-\pi * D * L * h / m c_p)$$

$$= 50 \text{ C} - (50 - 5 \text{ C}) * \exp(-\pi * 0.0266 \text{ m} * 18.29 \text{ m} * 74.7 \text{ W/m}^2\text{-K}) / (0.2 \text{ kg/s} * 2368 \text{ J/kg-K})$$

$$= 6.78 \text{ }^\circ\text{C} = 44.2 \text{ }^\circ\text{F}$$

(at this higher flowrate, the fluid warms only somewhat because the flow rate is faster)

$$\text{E. } q = 0.2 * 2368 * (6.8 - 5) = 5590 \text{ W} * 3.4121 \text{ Btu/h} / \text{W} = 19,000 \text{ Btu/h}$$

For an ethylene glycol flow rate = 60 kg/s

Everything in RED in problem 5 applies to Problem 6B.

A & B. entry lengths:

If turbulent: $x_{FDt} = x_{FD,h} = 10 * D$.

Need new Re!

velocity = 96.5 m/s

$Re = 96.5 \text{ m/s} * \dots = 116,000$ (TURBULENT)

$$\boxed{\text{A. \& B. } x_{FDt} = x_{FD,h} = 10 * D = 0.266 \text{ m}}$$

C. Here the flow is turbulent, so there are 3 choices (8.60, 8.61 and 8.62).

8.60 won't work since Pr is too large.

either of the other 2 equations is OK to use. 8.61 is a little better since it is for the higher Re numbers, so I will choose that one.

use $Nu = 0.027 Re^{4/5} Pr^{1/3} * (\mu/\mu_s)^{0.14}$

$\mu = 0.0247 \text{ N-s/m}^2$

$\mu_s = 0.00342 \text{ N-s/m}^2$

$Nu = 0.027 * 116,000^{4/5} * 236^{1/3} * (0.0247/0.00342)^{0.14}$

$Nu = 2478$

$$\boxed{h = 2478 * .248 \text{ W/mK} / 0.0266 \text{ m} = 23,100 \text{ W/m}^2\text{K}}$$

D. $T_o = T_s - (T_s - T_i) * \exp(-\pi * D * L * h / m cp)$

$= 50 \text{ C} - (50 - -5 \text{ C}) * \exp(-\pi * 0.0266 \text{ m} * 18.29 \text{ m} * 23100 \text{ W/m}^2\text{-K}) / (60 \text{ kg/s} * 2368 \text{ J/kg-K})$

$$\boxed{T_o = 7.1 \text{ }^\circ\text{C} = 44.8 \text{ }^\circ\text{F}}$$

(This is a much higher flowrate, so the fluid has little time to pass through the pipe; however, it is more effective than the laminar flow in part B because the turbulence greatly improves the convective heat transfer and much more heat is transferred, giving a slightly higher outlet temperature compared to problem 2.)

$$\boxed{E. q = 60 * 2368 * (7.1 - -5) = 1.72 \text{ MW} * 3.4121 \text{ Btu/h} / \text{W} = 5.87 * 10^6 \text{ Btu/h}}$$

6C. For the three flowrates, if you were asked to run a second iteration for each problem, what temperature would you use to look up fluid properties?

For 3 g/s, new "mean temperature" is $(-5 + 49.96) / 2 = 22.48 \text{ C} = 72.5 \text{ }^\circ\text{F}$.

For 200 g/s, new mean fluid temperature is $(-5 + 6.8) / 2 = 0.9 \text{ C} = 33.6 \text{ }^\circ\text{F}$.

For 60 kg/s, new mean fluid temperature is $(-5 + 7.1) / 2 = 1.05 \text{ C} = 33.9 \text{ }^\circ\text{F}$.

7. Pharmaceutical products are often sterilized by heating prior to packaging. In this case, the pharmaceutical product is heated from 25 to 75 °C by passing it through a 10 m long stainless steel tube with a diameter of 12.7 mm. The tube is wrapped with electrical tape to deliver a constant heat flux into the tube. The fluid enters the tube with a fully developed velocity profile and a uniform temperature at a flowrate of 0.2 m/s.

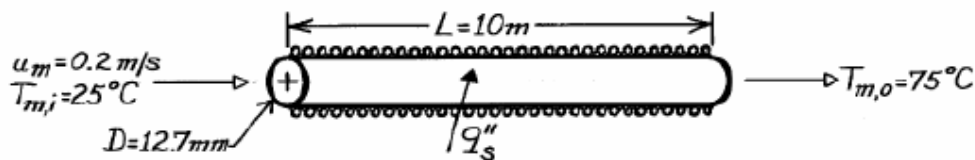
Fluid properties: density = 1000 kg/m³; heat capacity = 4000 J/kg·K, viscosity (μ) = 0.002 kg/s·m, thermal conductivity = 0.8 W/m·K, Pr = 10.

- A. What heat flux is required to reach 75 °C at the outlet?
 B. What is the surface temperature on the inside of the pipe at the exit?

KNOWN: Inlet and outlet temperatures and velocity of fluid flow in tube. Tube diameter and length.

FIND: Surface heat flux and temperatures at $x = 0.5$ and 10 m.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Constant properties, (3) Negligible heat loss to surroundings, (4) Incompressible liquid with negligible viscous dissipation, (5) Negligible axial conduction.

PROPERTIES: Pharmaceutical (given): $\rho = 1000 \text{ kg/m}^3$, $c_p = 4000 \text{ J/kg}\cdot\text{K}$, $\mu = 2 \times 10^{-3} \text{ kg/s}\cdot\text{m}$, $k = 0.80 \text{ W/m}\cdot\text{K}$, Pr = 10.

ANALYSIS: With

$$\dot{m} = \rho VA = 1000 \text{ kg/m}^3 (0.2 \text{ m/s}) \pi (0.0127 \text{ m})^2 / 4 = 0.0253 \text{ kg/s}$$

Eq. 8.34 yields

$$q = \dot{m} c_p (T_{m,o} - T_{m,i}) = 0.0253 \text{ kg/s} (4000 \text{ J/kg}\cdot\text{K}) 50 \text{ K} = 5060 \text{ W}.$$

The required heat flux is then

$$q_s'' = q/A_s = 5060 \text{ W} / \pi (0.0127 \text{ m}) 10 \text{ m} = 12.682 \text{ W/m}^2. \quad <$$

With

$$\text{Re}_D = \rho VD/\mu = 1000 \text{ kg/m}^3 (0.2 \text{ m/s}) 0.0127 \text{ m} / 2 \times 10^{-3} \text{ kg/s}\cdot\text{m} = 1270$$

the flow is laminar and Eq. 8.23 yields

$$x_{fd,t} = 0.05 \text{Re}_D \text{Pr} D = 0.05 (1270) 10 (0.0127 \text{ m}) = 8.06 \text{ m}.$$

Hence, with fully developed hydrodynamic and thermal conditions at $x = 10 \text{ m}$, Eq. 8.53 yields

$$h(10 \text{ m}) = \text{Nu}_{D,fd} (k/D) = 4.36 (0.80 \text{ W/m}\cdot\text{K} / 0.0127 \text{ m}) = 274.6 \text{ W/m}^2 \cdot \text{K}.$$

Hence, from Newton's law of cooling,

$$T_{s,o} = T_{m,o} + (q_s'' / h) = 75^\circ\text{C} + (12.682 \text{ W/m}^2 / 274.6 \text{ W/m}^2 \cdot \text{K}) = 121^\circ\text{C}. \quad <$$

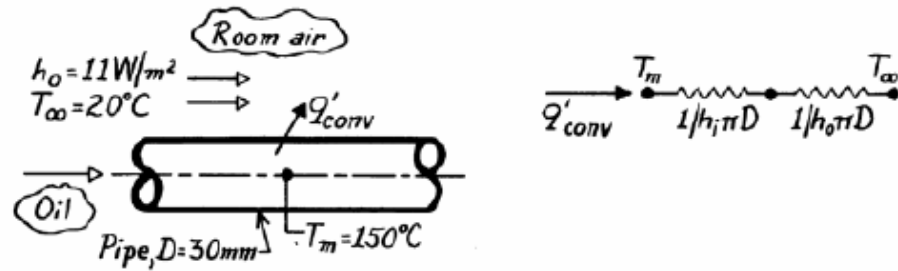
8. Work Incropera and DeWitt Problem 8.51.

Note: "thin-walled" in the problem means that the thermal resistance due to conduction through the pipe can be ignored. This is often the case in heat exchanger-type problems, because the thermal conductivity of the metal pipe is usually not a significant barrier to heat transfer compared to the convection terms on both sides of the pipe. Also, note that "slowly flowing" can be used to mean that the flow is laminar; assume that the pipe is long enough that the flow is fully developed.

KNOWN: Oil flowing slowly through a long, thin-walled pipe suspended in a room.

FIND: Heat loss per unit length of the pipe, q'_{conv} .

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Tube wall thermal resistance negligible, (3) Fully developed flow, (4) Radiation exchange between pipe and room negligible.

PROPERTIES: Table A-5, Unused engine oil ($T_m = 150^{\circ}\text{C} = 423\text{K}$): $k = 0.133 \text{ W/m}\cdot\text{K}$.

ANALYSIS: The rate equation, for a unit length of the pipe, can be written as

$$q'_{\text{conv}} = \frac{(T_m - T_{\infty})}{R'_t}$$

where the thermal resistance is comprised of two elements,

$$R'_t = \frac{1}{h_i \pi D} + \frac{1}{h_o \pi D} = \frac{1}{\pi D} \left(\frac{1}{h_i} + \frac{1}{h_o} \right)$$

The convection coefficient for internal flow, h_i , must be estimated from an appropriate correlation. From practical considerations, we recognize that the oil flow rate cannot be large enough to achieve turbulent flow conditions. Hence, the flow is *laminar*, and if the pipe is very long, the flow will be *fully developed*. The appropriate correlation is

$$\text{Nu}_D = \frac{h_i D}{k} = 3.66$$

$$h_i = \text{Nu}_D \frac{k}{D} = 3.66 \times 0.133 \frac{\text{W}}{\text{m}\cdot\text{K}} / 0.030 \text{ m} = 16.2 \text{ W/m}^2\cdot\text{K}$$

The heat rate per unit length of the pipe is

$$q'_{\text{conv}} = \frac{(150 - 20)^{\circ}\text{C}}{\frac{1}{\pi(0.030\text{m})} \left(\frac{1}{16.2} + \frac{1}{11} \right) \frac{\text{m}^2\cdot\text{K}}{\text{W}}} = 80.3 \text{ W/m.} \quad <$$

COMMENTS: This problem requires making a judgment that the oil flow will be laminar rather than turbulent. Why is this a reasonable assumption? Recognize that the correlation applies to a constant surface temperature condition.