9. (15 pt BONUS) In the research & development division of your company, a new process using ethylene glycol is being developed, but the ethylene glycol must be chilled before being returned to it's storage tank. Since you don't have time to build a new heat exchanger, you decide to go to Toys Я Us and buy a large kiddie swimming pool that you can fill with water and coil flexible plastic tubing submerged in the water to cool the ethylene glycol from 86 to 28 ^{o}C. This is a creative solution--- maybe not the best, but you need to know the length of plastic tubing to get from the warehouse. Given:

1. Ethylene glycol leaves a reaction tank at 3.0 kg/min at 86 ^{o}C and must be cooled to 28 ^{o}C.
2. A large volume of water will fit into the kiddie pool such that the water can be assumed to remain isothermal at 17 ^{o}C throughout the process.
3. All of the ethylene glycol enters a single plastic tube that is made of Tygon (k = 0.12 W/m-K) and has an inner diameter of 0.7 cm and outer diameter of 0.9 cm.
4. You may assume that the tubing has been used before and has inner and outer fouling factors equivalent to being used with refrigerating liquids (Table 11.1).
5. Clearly state any other assumptions you make to solve the problem.
6.

Properties of Water (or see Table A.6)	Properties of Ethylene Glycol
β = expansion coefficient = 227.5 * 10^{-6} K^{-1}	see Table A.5
ν = kinematic viscosity = 9.61 * 10^{-7} m^2/s	
α = thermal diffusivity = 1.45 * 10^{-7} m^2/s	
Pr = Prandtl Number = 6.62	
k = thermal conductivity = 0.606 W/m-K	
V = specific volume = 1.002 * 10^{-3} m^3/kg	

A. Determine the required heat transfer rate in Watts.

B. Determine the convective heat transfer coefficient for the ethylene glycol (you may assume fully developed flow and that the inner walls are at a constant temperature).

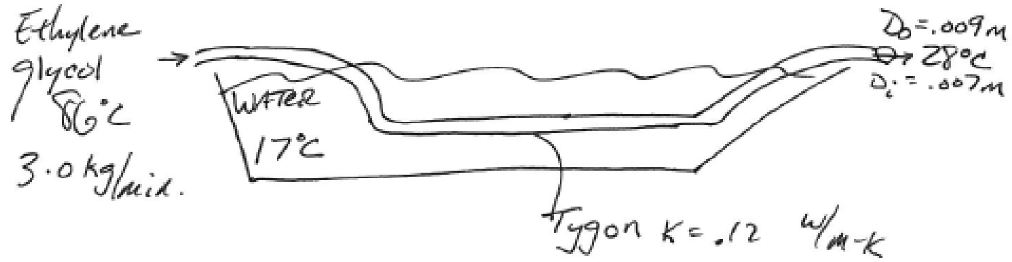
C. Determine the convective heat transfer coefficient for the stagnant water. For this calculation only, assume that the temperature of the outer surface of the flexible tubing is 27 ^{o}C and does not change with position. You may also assume that the plastic tubing is positioned horizontally in the water.

D. Determine UA in terms of length (your answer will be some # * L)

E. How long should the tubing be?

F. Give five (5) inexpensive suggestions that would reduce the length of tubing required.

(A-6) Draw a problem diagram. Label the known temperatures, flow rates and dimensions.



(B-8) Determine the required heat transfer rate in Watts.
Is this a DESIGN or RETROFIT problem?

→ Needs to find L.

$$q = \dot{m} C_p (T_{in} - T_{out})$$

$$= \left(3.0 \frac{kg}{min}\right)\left(2.549 \frac{kJ}{kg\text{-}K}\right)\left(\frac{1\ min}{60\ s}\right)(58°C)\left(\frac{1000\ W}{1\ kJ/s}\right)$$

$$= \boxed{7390\ W}$$

↑ Determine EG properties at $T_{MEAN} = \frac{86+28}{2} = 57°C$ (or 330 K)

(C-12) Determine the convective heat transfer coefficient (h_i) for the ethylene glycol. You may assume fully developed flow and that the inner walls are at a constant temperature.

INTERNAL FLOW - Ch 8.

$$D_i = .007\ m$$

$$v = \frac{\dot{m}}{\rho A_c} = \frac{(3\ kg/min)\left(\frac{1\ min}{60\ s}\right)}{(1089.5\ kg/m^3)\left(\frac{\pi}{4}(.007 m)^2\right)} = 1.19 \frac{m}{s}$$

$$Re = \frac{vD}{\nu} = \frac{(1.19\ m/s)(.007\ m)}{(5.15 \times 10^{-6}\ m^2/s)} = 1620$$

FOR LAMINAR, fully Developed, constant T_s

$$Nu_D = 3.66 = \frac{hD}{k_f}$$

$$h_i = \frac{3.66(0.26\ W/m\text{-}K)}{(.007\ m)} = \boxed{136 \frac{W}{m^2\text{-}K}}$$

(D-12) Determine the convective heat transfer coefficient (h_o) for the water.

You may assume that the water is stagnant (no forced convection). For this calculation only (part C), you may also assume that the temperature of the outer surface of the flexible tubing is 27 °C and does not change with position. You may also assume that the plastic tubing is positioned horizontally in the water.

h_o. Free convection on horizontal tubes.

$Re = 0$

$$Ra_D = \frac{g\beta(T_s - T_\infty)D^3}{\nu\alpha} = \frac{(9.8\,\frac{m}{s^2})(227.5\times10^{-6}\,K^{-1})(27-17)(.009\,m)^3}{(9.61\times10^{-7}\,\frac{m^2}{s})(1.45\times10^{-7}\,\frac{m^2}{s})}$$

$= 116{,}638$

2 Correlations work:

(9.33) $Nu_D = C\,Ra_D^{\,n}$ OR (9.34) $Nu_D = \left(0.6 + \frac{.387\,Ra_D^{1/6}}{\left(1+\left(\frac{.559}{Pr}\right)^{9/16}\right)^{8/27}}\right)^2$

$= 0.48\,(116{,}638)^{0.25}$ — OR — $Nu_D = 9.81$

$Nu_D = 8.87$

$$h_o = \frac{Nu_D\,k_f}{D_o} = \frac{8.87 * .606\ W/m\text{-}K}{(.009\ m)}$$

$h_o = 597\ W/m^2\text{-}K$ — OR — $h_o = 661\ W/m^2\text{-}K$

(E-12) Determine UA in terms of length
(your answer will be some # * L)

$$UA = \frac{1}{\frac{1}{h_o A_o} + \frac{R''_{f_o}}{A_o} + \frac{\ln D_o/D_i}{2\pi k L} + \frac{R''_{f_i}}{A_i} + \frac{1}{h_i A_i}}$$

$A_o = \pi D_o L$

$A_i = \pi D_i L$

Factor out L.

$R''_f = .0002\ m^2\text{-}K/W$ both in + out.

$$UA = \frac{L}{\frac{1}{\pi(597)(.009)} + \frac{.0002}{\pi(.009)} + \frac{\ln .009/.007}{2\pi\,(0.12\ W/m\text{-}K)} + \frac{.0002}{\pi(.007)} + \frac{1}{(136)\pi(.007)}}$$

$$= \frac{L}{0.0592 + .0071 + .3333 + .0091 + .3344}$$

$UA = 1.346\,L$ (W/K)

OR using $h_o = 661$, $UA = 1.356\,L$

(F-10) How long should the tubing be?

Using LMTD —— OR —— ε - NTU

$q = UA \, \Delta T_{lm}$

$7390 \, W = (1.346 \, L) * \frac{(86-17)-(28-17)}{\ln\left(\frac{86-17}{28-17}\right)}$

$L = \frac{7390}{1.346 \, (31.6°C)}$

$L = \boxed{173 m}$

$\varepsilon = \frac{q}{q_{MAX}} = \frac{\Delta U_{EG}}{\dot{m} C_{P_{EG}} (T_{h_i} - T_{c_i})}$

[WATER has an ∞ capacity here]

$\varepsilon = \frac{\dot{m}_{EG} C_{P_{EG}} (86-28)}{\dot{m}_{EG} C_{P_{EG}} (86-17)} = 0.84$

$C_r = \frac{C_{min}}{C_{max}} = 0$, with $C_{max} = \infty$

$\therefore \; NTU = -\ln(1-\varepsilon) = 1.836$

$1.346 L = UA = NTU * C_{min}$
$= 1.836 * 3.0 \, kg/min \left(\frac{1 \, min}{60 s}\right) 2.549 \frac{KJ}{kg K} \, 1000 \frac{W}{KJ/s}$
$= 234.02 \, W/K$

$\therefore \boxed{L = 174 m}$

BONUS. (5 pts)
Give five (5) inexpensive suggestions that would reduce the length of tubing required.

- Use A metal (copper) tube.
- Add ice to the water bath.
- Buy fish to swim in the WAter to improve mixing. (or Any mixing)
- Buy clean tubing to Reduce fouling factors.
- Use A smaller Diameter tube to increase Re for ethylene glycol
- Use tubing with A thinner wall