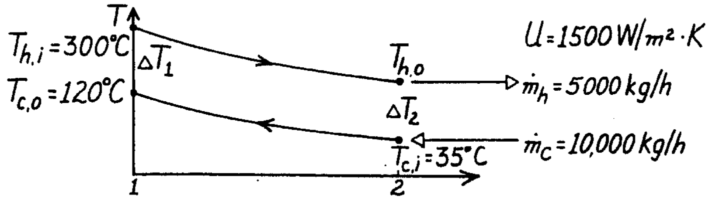
PROBLEM 11.10

KNOWN: A shell and tube HXer (two shells, four tube passes) heats 10,000 kg/h of pressurized water from 35 °C to 120 °C with 5,000 kg/h water entering at 300 °C.

FIND: Required heat transfer area, A_s.

SCHEMATIC:



ASSUMPTIONS: (1) Negligible heat loss to surroundings, (2) Negligible kinetic and potential energy changes, (3) Constant properties.

PROPERTIES: *Table A-6,* Water ($\overline{T}_c = 350K$): $c_p = 4195$ J/kg·K; *Table A-6,* Water (Assume $T_{h,o} \approx 150\,^\circ C$, $\overline{T}_h \approx 500K$): $c_p = 4660$ J/kg·K.

ANALYSIS: The rate equation, Eq. 11.14, can be written in the form

$$A_s = q/U\,\Delta T_{\ell m} \tag{1}$$

and from Eq. 11.18,

$$\Delta T_{\ell m} = F\,\Delta T_{\ell m,CF} \quad \text{where} \quad \Delta T_{\ell m,CF} = \frac{\Delta T_1 - \Delta T_2}{\ell n\,\Delta T_1/\Delta T_2}\,. \tag{2,3}$$

From an energy balance on the cold fluid, the heat rate is

$$q = \dot{m}_c\,c_{p,c}\,(T_{c,o} - T_{c,i}) = \frac{10{,}000\,\text{kg/h}}{3600\,\text{s/h}} \times 4195\,\frac{J}{kg\cdot K}\,(120-35)K = 9.905\times10^5\ W\,.$$

From an energy balance on the hot fluid, the outlet temperature is

$$T_{h,o} = T_{h,i} - q/\dot{m}_h\,c_{p,h} = 300\,^\circ C - 9.905\times10^5\ W\Big/\frac{5000}{3600}\,\frac{kg}{s} \times 4660\,\frac{J}{kg\cdot K} = 147\,^\circ C\,.$$

From Fig. 11.11, determine F from values of P and R where $P = (120-35)\,^\circ C/(300-35)\,^\circ C = 0.32$, $R = (300-147)\,^\circ C/(120-35)\,^\circ C = 1.8$ giving $F \approx 0.97$. The log mean temperature based upon CF arrangement follows from Eq. (3); find

$$\Delta T_{\ell m} = [(300-120)-(147-35)]K/\ell n\,\frac{(300-120)}{(147-35)} = 143.3K\,.$$

$$A_s = 9.905\times10^5\ W/1500\ W/m^2\cdot K \times 0.97 \times 143.3K = 4.75\,m^2\,.$$ ◁

COMMENTS: (1) Check $\overline{T}_h \approx 500K$ used in property determination; $\overline{T}_h = (300+147)\,^\circ C/2 = 497K$. (2) Using the NTU-$\epsilon$ method, determine first the capacity rate ratio, $C_{min}/C_{max} = 0.56$. Then

$$\epsilon \equiv \frac{q}{q_{max}} = \frac{C_{max}\,(T_{c,o} - T_{c,i})}{C_{min}\,(T_{h,i} - T_{c,i})} = \frac{1}{0.56} \times \frac{(120-35)\,^\circ C}{(300-35)\,^\circ C} = 0.57\,.$$

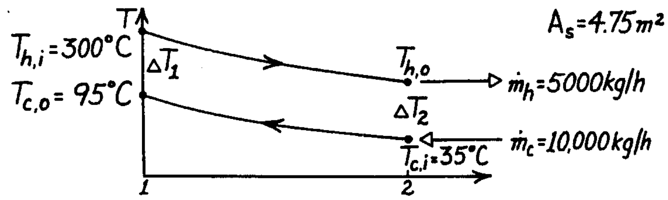
From Fig. 11.17, find that $NTU = AU/C_{min} \approx 1.1$ giving $A_s = 4.7\,m^2$.

PROBLEM 11.11

KNOWN: The shell and tube HXer (two shells, four tube passes) of Problem 11.10, known to have an area 4.75m^2, provides 95°C water at the cold outlet (rather than 120°C) after several years of operation. Flow rates and inlet temperatures of the fluids remain the same.

FIND: The fouling factor, R_f.

SCHEMATIC:



ASSUMPTIONS: (1) Negligible heat loss to surroundings, (2) Negligible kinetic and potential energy changes, (3) Constant properties, (4) Thermal resistance for the clean condition is $R''_t = (1500\,W/m^2\cdot K)^{-1}$.

PROPERTIES: *Table A-6*, Water ($\overline{T}_c \approx 338K$): $c_p = 4187$ J/kg·K; *Table A-6*, Water (Assume $T_{h,o} \approx 190\,^\circ C$, $\overline{T}_h \approx 520K$): $c_p = 4840$ J/kg·K.

ANALYSIS: The overall heat transfer coefficient can be expressed as

$$U = 1/(R''_t + R''_f) \qquad \text{or} \qquad R''_f = 1/U - R''_t \qquad (1)$$

where R''_t is the thermal resistance for the clean condition and R''_f, the fouling factor, represents the additional resistance due to fouling of the surface. The rate equation, Eq. 11.14 with Eq. 11.18, has the form,

$$U = q/A_s F\,\Delta T_{\ell m,CF} \qquad \Delta T_{\ell m,CF} = (\Delta T_1 - \Delta T_2)/\ell n\,(\Delta T_1/\Delta T_2)\,. \qquad (2)$$

From energy balances on the cold and hot fluids, find

$$q = \dot{m}_c\,c_{p,c}\,(T_{c,o} - T_{c,i}) = (10{,}000/3600\ kg/s)4187\ J/kg\cdot K\,(95-35)K = 6.978\times10^5\ W$$

$$T_{h,o} = T_{h,i} - q/\dot{m}_h\,c_{p,h} = 300\,^\circ C - 6.978\times10^5\ W\big/(5000/3600\ kg/s\times 4840 J/kg\cdot K) = 196.2\,^\circ C\,.$$

The factor, F, follows from values of P and R as given by Fig. 11.11 with

$$P = (95-35)/(300-35) = 0.23 \qquad R = (300-196)/(120-35) = 1.22$$

giving $F \approx 1$. Based upon CF arrangement,

$$\Delta T_{\ell m,CF} = [(300-95)-(196-35)]\,^\circ C/\ell n\,[(300-95)/(196.2-35)] = 182K\,.$$

Using Eq. (2), find now the overall heat transfer coefficient as

$$U = 6.978\times10^5\ W/4.75m^2\times1\times182K = 806\ W/m^2\cdot K\,.$$

From Eq. (1), the fouling factor is

$$R''_f = \frac{1}{806\ W/m^2\cdot K} - \frac{1}{1500\ W/m^2\cdot K} = 5.74\times10^{-4}\ m^2\cdot K/W\,. \qquad \triangleleft$$

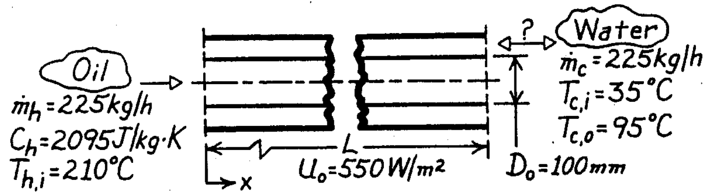
COMMENTS: Note that the effect of fouling is to nearly double ($U_{clean}/U_{fouled} = 1500/806 \approx 1.9$) the resistance to heat transfer. Note also the assumption for $T_{h,o}$ used for property evaluation is satisfactory.

PROBLEM 11.29

KNOWN: Concentric tube heat exchanger.

FIND: Length of the exchanger.

SCHEMATIC:



ASSUMPTIONS: (1) Negligible heat loss to surroundings, (2) Negligible kinetic and potential energy changes, (3) Constant properties.

PROPERTIES: *Table A-6*, Water ($\overline{T}_c = (35+95)^\circ C/2 = 338K$): $c_{p,c} = 4188$ J/kg·K.

ANALYSIS: From the rate equation, Eq. 11.14, with $A_o = \pi D_o L$,

$$L = q/U_o \pi D_o \Delta T_{\ell m} .$$

The heat rate, q, can be evaluated from an energy balance on the cold fluid,

$$q = \dot{m}_c c_c (T_{c,o} - T_{c,i}) = \frac{225\,kg/h}{3600\,s/h} \times 4188\,J/kg\cdot K(95-35)K = 15{,}705\,W .$$

In order to evaluate $\Delta T_{\ell n}$, we need to know whether the exchanger is operating in CF or PF. From an energy balance on the hot fluid, find

$$T_{h,o} = T_{h,i} - q/\dot{m}_h c_h = 210^\circ C - 15{,}705\,W/\frac{225\,kg/h}{3600\,s/h} \times 2095 \frac{J}{kg\cdot K} = 90.1^\circ C .$$

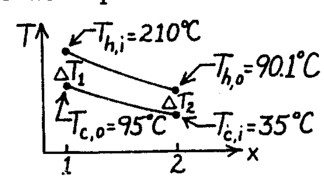
Since $T_{h,o} < T_{c,o}$ it follows that HXer operation must be CF. From Eq. 11.15,

$$\Delta T_{\ell m,CF} = \frac{\Delta T_1 - \Delta T_2}{\ell n(\Delta T_1/\Delta T_2)} = \frac{(210-95)-(90.1-35)}{\ell n(115/55.1)}\,^\circ C = 81.4^\circ C .$$

Substituting numerical values, the HXer length is

$$L = 15{,}705\,W/550W/m^2\cdot K\pi(0.10m) \times 81.4K = 1.12m .$$ ◁

COMMENTS: The ε-NTU method could also be used. It would be necessary to perform the hot fluid energy balance to determine CF operation existed. The capacity rate ratio is $C_{min}/C_{max} = 0.50$. From Eqs. 11.19 and 11.20 with q evaluated from an energy balance on the hot fluid,



$$\epsilon = \frac{T_{h,i} - T_{h,o}}{T_{h,i} - T_{c,i}} = \frac{210-90.1}{210-35} = 0.69 .$$

From Fig. 11.15, find NTU ≈ 1.5 giving

$$L = NTU \cdot C_{min}/U_o \pi D_o \approx 1.5 \times 130.94 \frac{W}{K} / 550 \frac{W}{m^2\cdot K} \cdot \pi(0.10m) \approx 1.14m .$$

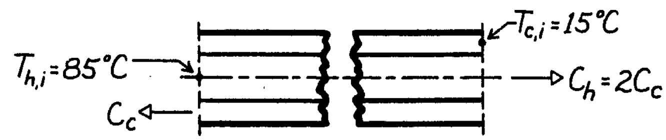
Note the good agreement by both methods.

PROBLEM 11.31

KNOWN: A *very long*, concentric tube heat exchanger having hot and cold water inlet temperatures, 85°C and 15°C, respectively; flow rate of hot water is twice that of the cold water.

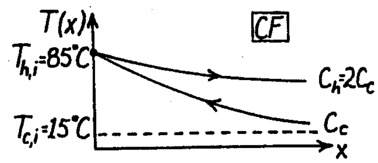
FIND: Outlet temperatures for counterflow and parallel flow operation.

SCHEMATIC:



ASSUMPTIONS: (1) Equivalent hot and cold water specific heats, (2) Negligible kinetic and potential energy changes, (3) No heat loss to surroundings.

ANALYSIS: The heat rate for a concentric tube heat exchanger with very large surface area operating in the *counterflow* mode is



$$q = q_{max} = C_{min}(T_{h,i} - T_{c,i})$$

where $C_{min} = C_c$. From an energy balance on the hot fluid,

$$q = C_h(T_{h,i} - T_{h,o}).$$

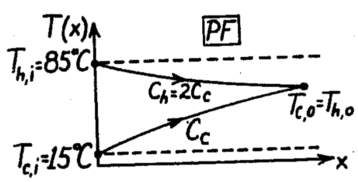
Combining the above relation and rearranging, find

$$T_{h,o} = -\frac{C_{min}}{C_h}(T_{h,i} - T_{c,i}) + T_{h,i} = -\frac{C_c}{C_h}(T_{h,i} - T_{c,i}) + T_{h,i}.$$

Substituting numerical values,

$$T_{h,o} = -\frac{1}{2}(85-15)°C + 85°C = 50°C. \quad \triangleleft$$

For *parallel flow* operation, the hot and cold outlet temperatures will be equal; that is, $T_{c,o} = T_{h,o}$. Hence,



$$C_c(T_{c,o} - T_{c,i}) = C_h(T_{h,i} - T_{h,o}).$$

Setting $T_{c,o} = T_{h,o}$ and rearranging,

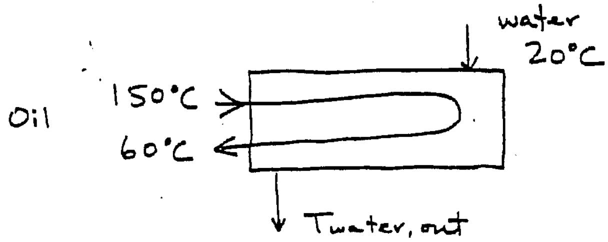
$$T_{h,o} = \left[T_{h,i} + \frac{C_c}{C_h}T_{c,i}\right] \Big/ \left[1 + \frac{C_c}{C_h}\right]$$

$$T_{h,o} = \left[85 + \frac{1}{2} \times 15\right]°C \Big/ \left[1 + \frac{1}{2}\right] = 61.7°C. \quad \triangleleft$$

COMMENTS: Note that while $\varepsilon = 1$ for CF operation, for PF operation find $\varepsilon = q/q_{max} = 0.67$.

$\boxed{\text{Part C}}$

a)



$\dot{m} = 1\ kg/s$

Calculate $T_{water,out}$ by overall energy balance

$$(\cancel{\dot{m}}C_p)_{oil}(T_{oil,in} - T_{oil,out}) = (\cancel{\dot{m}}C_p)_{water}(T_{water,out} - T_{water,in})$$

$$\frac{2120\ J/kg \cdot K\ (150°C - 60°C)}{4190\ J/kg \cdot K} + 20°C = T_{water,out} = \underline{65.5}$$

Calculate overall heat transfer coefficient based on outside area (U_o)

$$\frac{1}{U_o A_o} = \frac{1}{h_o A_o} + \frac{\ln D_o/D_i}{2\pi k L} + \frac{1}{h_i A_i}$$

$$U_o = \left(\underbrace{\frac{1}{h_o}}_{1\times10^{-3}} + \underbrace{\frac{D_o \ln D_o/D_i}{2k}}_{\sim 7.2\times10^{-5}} + \underbrace{\frac{D_o}{h_i D_i}}_{3.8\times10^{-3}} \right)^{-1}$$

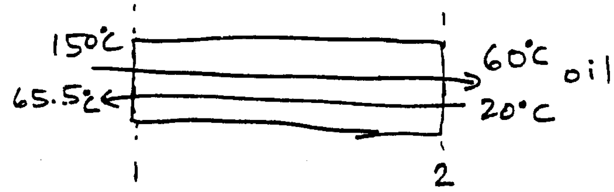
of stainless steel tube

can neglect

$$\underline{U_o = 203\ W/m^2K}$$

by LMTD method, $q = UAF\Delta T_{lm}$

↳ countercurrent



$\Delta T_1 = 84.5°C$ $\qquad \Delta T_2 = 40$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} = 59.5$$

Find F for 1-2 shell tube exchanger using Figure 11.10 in I+D.

$$R = \frac{20 - 65.5°C}{60 - 150°C} \cong 0.51 \qquad P = \frac{60 - 150°C}{20 - 150°C} \cong 0.70$$

$$\rightarrow \quad F \cong 0.75$$

Find Exchanger Area

$$q = \dot{m} C_p \Delta T = U_o A_o F \Delta T_{lm}$$

$$\hookrightarrow \quad A_o = \frac{\dot{m} C_p \Delta T}{U_o F \Delta T_{lm}}$$

$$\frac{(1\ kg/s)(2120\ J/kg\cdot K)(90°C)}{(203\ W/m^2K)(0.75)(59.5°C)} = \boxed{21\ m^2 = A_o}$$

or by ε-NTU method,

Oil is C_{min} and $C_r = \frac{C_{min}}{C_{max}} = \frac{(1)(2120)}{(1)(4190)} = 0.506$

$$\varepsilon = \frac{\cancel{C}_{oil}\ \Delta T_{oil}}{\cancel{C}_{oil}\ (T_{oil,in} - T_{water,in})} = \frac{150 - 60}{150 - 20} = 0.692$$

using Eq 11.31b from Table 11.4,

$$NTU = -(1+C_r^2)^{-1/2} \ln \frac{E-1}{E+1}$$

$$E = \frac{2/\epsilon - (1+C_r)}{(1+C_r^2)^{1/2}} = 1.235$$

$$NTU = 2.01$$

$$NTU = \frac{U_o A_o}{C_{min}} = 2.01 \rightarrow A_o = \frac{(2.01)(2120)(1)}{(203)}$$

$$= \boxed{21 \, m^2}$$

b) (15 points)
Goo will change U_o by adding another layer of heat transfer resistance.

$$(*) \quad U_o = \left(\frac{1}{h_o} + \frac{D_o \ln(D_o/D_i)}{2k_{ss}} + \frac{D_o \ln(D_i/D_{goo})}{2k_{goo}} + \frac{D_o}{D_{goo} h_i} \right)^{-1}$$

where D_{goo} is the inner diameter of the tube with goo.
(D_i is the original, clean, inner diameter of tube)

Given the same A_o from a)
by LMTD method,
Need to find new $T_{water,out}$ using overall energy balance

$$\frac{(2120)(150-80)}{4190} + 20 = 55.4°C$$

$$U_o = \frac{[\dot{m} C_p \Delta T]_{oil}}{A_o F \, \Delta T_{lm,\,countercurrent}}$$

Recalculate $\Delta T_1, \Delta T_2, \Delta T_{lm}$, R, P, F as in part a)

$$\begin{aligned} \Delta T_1 &= 94.6°C \\ \Delta T_2 &= 60°C \end{aligned} \quad \rightarrow \quad \Delta T_{lm,\,countercurrent} = 76°C$$

$$\begin{aligned} R &= 0.51 \\ P &= 0.54 \end{aligned} \quad \rightarrow \quad F \cong 0.92$$

$$U_o = \frac{(1)(2190)(150-80)}{(21)(0.92)(76)} = \underline{104.4 \ W/m^2K}$$

by ε-NTU method,

$C_r = 0.506$ as before

$$\varepsilon = \frac{150-80}{150-20} = 0.538$$

$$E = 1.970$$

$$NTU \cong 1 = \frac{U_o A_o}{C_{min}}$$

$$U_o = C_{min}/A_o = \frac{2120}{21} = \underline{101.0 \ W/m^2K}$$

With U_o, use (*) to find D_{goo}, or goo thickness as $\frac{D_i - D_{goo}}{2} = \delta_{goo}$.

Can solve for D_{goo} by iterating Eq (*) or using various simplifications.

- layers are thin relative to diameter so can approximate as planar

$$U_o = \left(\frac{1}{h_o} + \frac{\delta_{ss} A_o}{k_{ss} A_m} + \frac{\delta_{goo} A_o}{k_{goo} A_i} + \frac{1 A_o}{h_i A_i} \right)^{-1}$$

Assumed thickn of goo sma

So $A_{goo} \sim$

δ_{ss} thickness of stainless steel $\left(\frac{D_o - D_i}{2} \right)$

A_m mean of inner and outer area

$$104 = \left(\frac{1}{1000} + \frac{0.001}{15} \left(\frac{15}{14} \right) + \frac{\delta_{goo}}{0.139} \left(\frac{15}{13} \right) + \frac{1}{300} \left(\frac{15}{13} \right) \right)^{-1}$$

$$\boxed{\begin{aligned} \delta_{goo} &\cong 5.7 \times 10^{-4}\ m \\ &\cong 0.6\ mm \end{aligned}}$$

seems reasonable

Additional Notes for Problem 1:

- Oil could have been on shell-side rather than tube-side. Only changes R and P, but F and results remain the same.

- The overall heat transfer resistance for the "goo" case could have been expressed as

$$\frac{1}{U_{o,new} A_o} = \frac{1}{U_{o,old} A_o} + R''_{f,i}$$

where $$R''_{f,i} = \frac{\ln(D_i / D_{goo})}{2\pi k_{goo} L}$$

Part D: (solution 1)

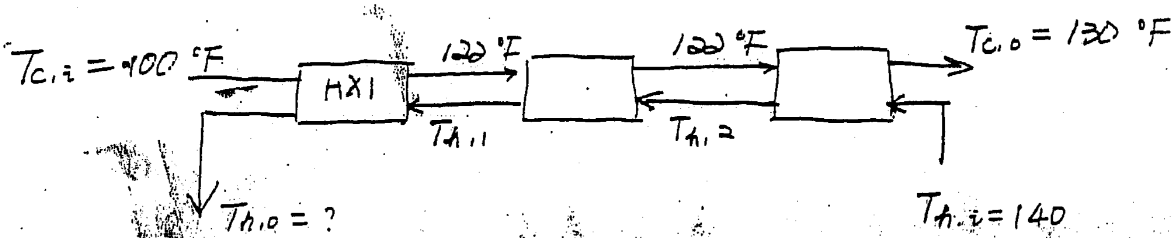
There are several points worth noting in this problem

i) $T_{c,i} < T_{melt} < T_{c,o}$ for compene, which means we need to divide the HX into three sections. (See figure below)

ii) Cold stream consists of compene and water. But the solubility in each other is negligible. So the condition leads to:

$$\underset{\text{cold stream}}{C_{p,c}} = \underset{\text{water}}{x_w C_{p,w}} + (1-x_w)\underset{\text{solid (compene)}}{C_{p,s}}$$

iii) Outlet temperature of hot stream can tell you if co-current flow is possible.



(Assume it's counter-current flow for the moment).

Overall energy balance:

$$① \quad q_T = m_h C_{p,h}(T_{h,i} - T_{h,o}) = \dot m_c \underbrace{C_{p,c_1}}_{\text{specific heat of cold stream in HX1}} (122 - T_{c,i}) \quad \} \text{HX1}$$

$$+ \; \dot m_c \underbrace{x_s}_{\text{weight percent of compene}} \underbrace{\Delta H_f}_{\text{Heat of fusion}} \quad \} \text{HX2}$$

$$+ \; \dot m_c C_{p,c_3}(T_{c,o} - 122) \quad \} \text{HX3}$$

$$C_{p\,c_1} = C_{ps}\, x_s + C_{p,w}\, x_w = 0.38 \times 0.2 + 1.0 \times 0.8 = 0.876 \text{ Btu/lb.°F}$$
$$C_{p\,c_3} = 0.40 \times 0.2 + 1.0 \times 0.8 = 0.88 \text{ Btu/lb °F}.$$

(2pts)

From eq ①, we solve for $T_{h,o}$

$$② \quad T_{h,o} = T_{h,i} - \frac{q_T}{\dot m_h} = 140 - \frac{2.35 \times 10^5}{\dot m_h}$$

(a) $\dot{m}_h = 9000$ lb/hr

$$T_{h,o} = 140 - \frac{2.35\times10^5}{9000} = 114\ °F.$$

Since $T_{h,o} < T_{c,o}$ it is impossible to have co-current flow as heat can't be transferred from a colder stream to a hotter so only count-current flow is OK.

From $q = UA\,(LMTD)$

$$\Rightarrow \quad A = A_1 + A_2 + A_3 = \frac{1}{U}\left(\frac{q_1}{LMTD_1} + \frac{q_2}{LMTD_2} + \frac{q_3}{LMTD_3}\right)$$

Energy Balance over each HX:

HX1: $q_1 = \dot{m}_h C_{p,h} (T_{h,1} - T_{h,o}) = \dot{m}_c C_{p,c,l} (122 - T_{c,i}) = 96360$ Btu/hr

$$\Rightarrow \quad T_{h,1} = \frac{q_1}{\dot{m}_h C_{p,h}} + T_{h,o}$$

$$= \frac{96360}{9000\times1} + 114 = 124.7\ °F$$

$(LMTD)_1 = 6.7\ °F$

HX2: $q_2 = \dot{m}_h C_{p,h} (T_{h,2} - T_{h,1}) = \dot{m}_c \chi_3 \Delta H_f = 103000$ Btu/hr

$$T_{h,2} = \frac{103000}{9000\times1} + 124.7 = 136.1\ °F$$

$(LMTD)_2 = 6.9\ °F$

HX3. $q_3 = \dot{m}_c C_{p,c,s} (130 - 122) = 35040$ Btu/hr.

$(LMTD)_3 = 11.9\ °F$

Summarize the above results in a table:

HX	1	2	3
q_i	96360	103000	35040
$(LMTD)_i$	6.7	6.9	11.9
A_i (ft²)	71.9	74.6	14.7
A_{total}		161.2	

(2pts)

$$L = \frac{A}{\pi D} = \frac{161.2}{\pi \times 2/12} = 307.9\ ft \qquad (2pts)$$

(b). $\dot{m}_h = 7000$ lb/hr.

From eq ②, we can find (2pts)

$$T_{h,c} = 107\ °F.$$

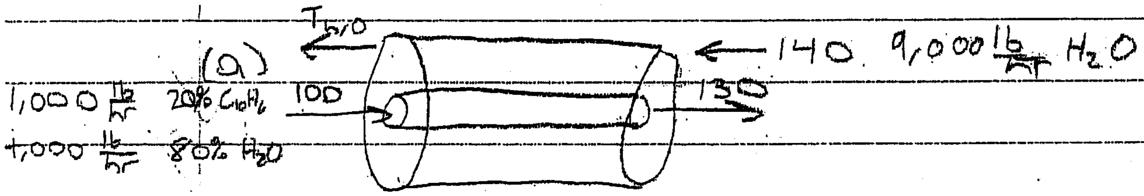
Follow same procedure as in (a), we find (2pts)

$$T_{h,1} = 121\ °F < 122\ °F$$

There is a pinch point in HX2; Cannot work.

Part D (solution 2)

Assumptions: ① Negligible heat loss to the surroundings
② Negligible potential + kinetic energy changes
③ constant properties
④ Fully developed conditions for the H_2O and $C_{10}H_{16}$ (U independent of x)

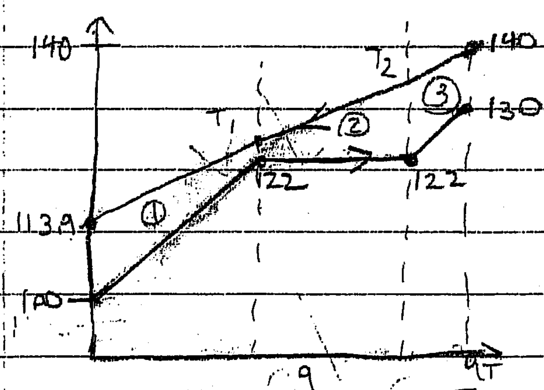


$$q_T = \left[(\dot{m} C_p \Delta T)_{C_6H_{10},s} + (\dot{m} \Delta H_{fusion})_{C_6H_{10}} + (\dot{m} C_p \Delta T)_{C_6H_{10},l} + (\dot{m} C_p \Delta T)_{H_2O}\right]_C$$
$$= (\dot{m} C_p \Delta T)_H$$

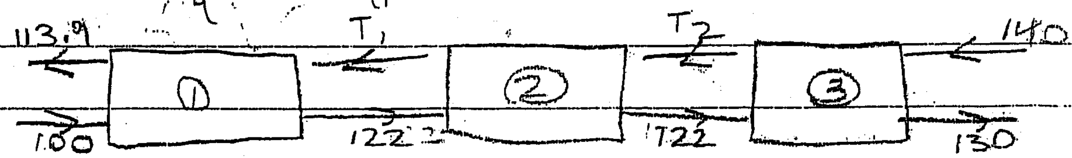
$\Rightarrow 1000(0.38 \times 22 + 103 + 8 \times 0.4) + 4{,}000(30) = 9{,}000(140 - T_{h,o})$

$\Rightarrow \boxed{T_{h,o} = 113.9°F}$

$\therefore$ heat exchanger must be counter-current since $T_{c,o} > T_{h,o}$.



To find L, model heat exchanger as 3 seperate heat exchangers
$L = L_1 + L_2 + L_3$



T_1: $q_1 = \left[(\dot{m}C_p\Delta T)_{C_6H_{10}/S} + (\dot{m}C_p\Delta T)_{H_2O}\right]_c = (\dot{m}C_p\Delta T)_{H, H_2O}$

$= 1000(22\times.38) + 4000(22) = 9000(T_1 - 113.9)$

$\Rightarrow \boxed{T_1 = 124.6^\circ F}$

T_2: $q_2 = (\dot{m}\Delta H_{fus}) = (\dot{m}C_p\Delta T)_{H, H_2O}$

$= (1000)(103) = 9000(T_2 - 124.6) \Rightarrow \boxed{T_2 = 136.1^\circ F}$

$q_i = UA\Delta T_{lm} \Rightarrow A_1 = \dfrac{q_1}{U\Delta T_{lm,1}}$, $A_2 = \dfrac{q_2}{U\Delta T_{lm,2}}$, $A_3 = \dfrac{q_3}{U\Delta T_{lm,3}}$

$$A_1 = \frac{9000(124.6-113.9)}{200\left[\dfrac{(124.6-122)-(113.9-100)}{\ln\frac{124.6-122}{113.9-100}}\right]} = 70.9\,ft^2$$

$$A_2 = \frac{103{,}000}{200\left[\dfrac{(136.1-122)-(124.6-122)}{\ln\left(\frac{136.1-122}{124.6-122}\right)}\right]} = 75.3\,ft^2$$

$$A_3 = \frac{9{,}000(140-136.1)}{200\left[\dfrac{(140-130)-(136.1-122)}{\ln\left(\frac{140-130}{136.1-122}\right)}\right]} = 14.75\,ft^2$$

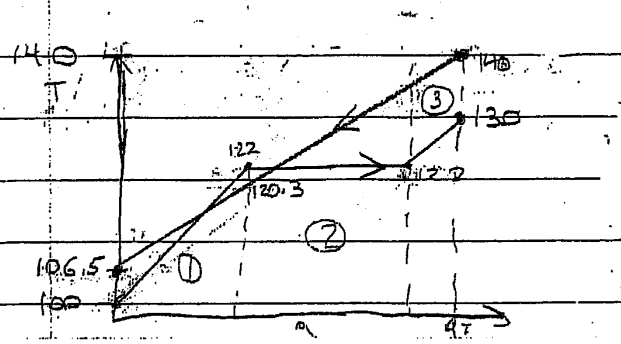
$A = A_1 + A_2 + A_3 \Rightarrow \boxed{L} = \dfrac{A}{\pi D} = \dfrac{160.95}{\pi\left(\frac{1}{6}\right)} = \boxed{307.4\,ft}$

(b) Redoing calculations for temperatures:

$1000(.38\times22 + 103 + 8\times0.4) + 4000(30) = 7000(140 - T_{h,o})$

$\Rightarrow \boxed{T_{h,o} = 106.5^\circ F}$

$1000(22\times.38) + 4000(22) = 7{,}000(T_1 - 106.5) \Rightarrow \boxed{T_1 = 120.3^\circ F}$



We find there is a pinch point $\therefore$ can't work