Example: A countercurrent-flow, single-pass (1-1) heat exchanger has been designed to condense and cool 7500 lb/hr of methanol. The exchanger is to contain 800 copper tubes having an O.D. of 0.500 in. and an I.D. of 0.282 in. The methanol is to enter the unit as superheated vapor at 250 deg F (saturation temperature = 150 deg F) and is to leave as a liquid at 70 deg F. Demineralized water, initially at 50 deg F is to flow through the tubes and is to leave at 160 deg F. For design estimates, the following data were used.

(1) Specific heats in Btu/(lb-deg F): water, 1.00; methanol vapor, 0.47; methanol liquid, 0.60.

(2) Latent heat of condensation of methanol at 150 deg F is 263 Btu/lb.

(3) Film coefficients , including fouling resistances, in Btu/(hr-sq ft-deg F): for water in tubes, 180; for methanol in shell – condensing vapor 300; cooling liquid 20; desuperheating vapor 30; neglect thermal resistance of copper tube walls.

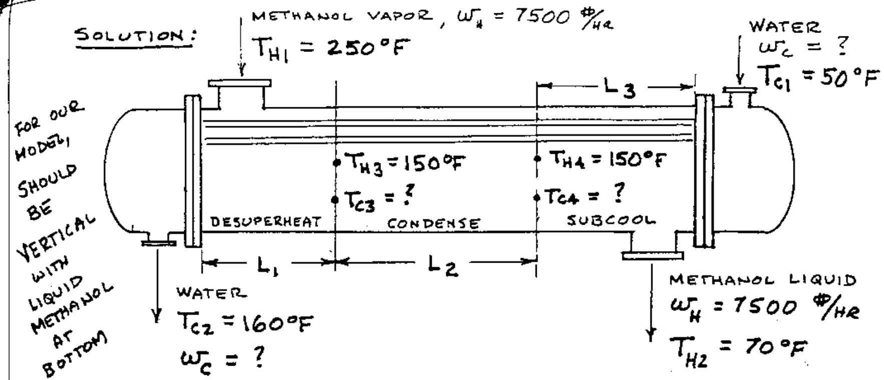
Calculate the following:

(a) Cooling water flow rate, lb/hr.

(b) The length of heat exchanger required.

One of the design engineers has suggested that cooling water requirements could be reduced if an exit water temperature of 180 deg F were allowed. Are there serious objections to this suggestion? If so, back them up with numerical calculations.

SOLUTION:



PART (a):

$q_{\text{DESUPERHEAT SECTION}} = 7500 \frac{\#}{HR} \cdot 0.47 \frac{BTU}{\#\text{-}°F} (250-150)°F = 352,500 \frac{BTU}{HR}$

$q_{\text{CONDENSING SECTION}} = 7500 \frac{\#}{HR} \cdot 263 \frac{BTU}{\#} = 1,972,500 \frac{BTU}{HR}$

$q_{\text{SUBCOOLING SECTION}} = 7500 \frac{\#}{HR} \cdot 0.60 \frac{BTU}{\#\text{-}°F} (150-70)°F = 360,000 \frac{BTU}{HR}$

$q_{\text{TOTAL}} = 2,685,000 \frac{BTU}{HR}$

$$q_{TOTAL} = w_c \cdot c_{pc} (T_{c2} - T_{c1})$$

$$w_c = \frac{q_{TOTAL}}{c_{pc}(T_{c2}-T_{c1})} = \frac{2,685,000 \text{ BTU/HR}}{1.00 \frac{BTU}{\#\cdot°F}(160-50)°F} = 24,409 \frac{\#}{HR}$$

PART (b):

TO FIND LENGTH OF TUBES REQUIRED, WE MUST:

(1) FIND T_{C3} & T_{C4} FROM ENERGY BALANCES

(2) CALCULATE $(\Delta T)_{lm}$ FOR EACH SECTION

(3) CALCULATE U_o FOR EACH SECTION (FROM GIVEN INDIVIDUAL COEFFICIENTS)

(4) CALCULATE AREA FOR EACH SECTION: $A_{sect.} = \frac{q_{sect.}}{U_{o,sect.} (\Delta T)_{lm,sect.}}$

(5) CALCULATE LENGTH OF EACH SECTION, $L_{sect} = \frac{A_{sect}}{N_{TUBES} \pi D_o}$

$$q_{\substack{\text{DESUPERHEAT}\\\text{SECTION}}} = w_c c_{pc}(T_{c2} - T_{c3}) = 352{,}500 \ \frac{\text{BTU}}{\text{HR}}$$

$$T_{c2} - T_{c3} = \frac{q_{\text{DESUPERHEAT}}}{w_c c_{pc}} = \frac{352{,}500 \ \frac{\text{BTU}}{\text{HR}}}{24{,}409 \ \frac{\text{lb}}{\text{HR}} \cdot 1.00 \ \frac{\text{BTU}}{\text{lb-°F}}} = 14.4 \text{ °F}$$

$$T_{c3} = T_{c2} - 14.4\text{°F} = (160 - 14.4)\text{°F} = \underline{145.6} \text{ °F}$$

$$q_{\substack{\text{SUBCOOLING}\\\text{SECTION}}} = w_c c_{pc}(T_{c4} - T_{c1}) = 360{,}000 \ \text{BTU/HR}$$

$$T_{c4} - T_{c1} = \frac{q_{\text{SUBCOOL}}}{w_c c_{pc}} = \frac{360{,}000 \ \text{BTU/HR}}{24{,}409 \ \text{lb/HR} \cdot 1.00 \ \frac{\text{BTU}}{\text{lb-°F}}} = 14.7 \text{ °F}$$

$$T_{c4} = T_{c1} + 14.7\text{°F} = 50 + 14.7\text{°F} = \underline{64.7} \text{ °F}$$

$$(\Delta T_{lm})_{\text{DESUPERHEAT}} = \frac{(250-160) - (150-145.6)}{\ln\left(\frac{250-160}{150-145.6}\right)} = \frac{85.6}{\ln 20.45} = \underline{28.36} \text{ °F}$$

$$(\Delta T_{lm})_{\text{CONDENSING}} = \frac{(150-64.7) - (150-145.6)}{\ln\left(\frac{150-64.7}{150-145.6}\right)} = \frac{80.9}{\ln 19.39} = \underline{27.29} \text{ °F}$$

$$(\Delta T_{lm})_{\text{SUBCOOLING}} = \frac{(150-64.7) - (70-50)}{\ln\left(\frac{150-64.7}{70-50}\right)} = \frac{65.3}{\ln 4.265} = \underline{45.02} \text{ °F}$$

BASE U ON OUTSIDE AREA OF TUBES (NEGLECT R_{WALL})

FOR ALL 3 SECTIONS:

$$U_o = \frac{1}{\frac{1}{h_o} + \frac{A_o}{A_i h_i}} = \frac{1}{\frac{1}{h_o} + \frac{\pi(0.5\text{ in})L}{\pi(0.282\text{ in})L\left(180 \ \frac{\text{BTU}}{\text{HR-FT}^2\text{-°F}}\right)}} = \frac{1}{\frac{1}{h_o} + 0.00985}$$

$\therefore$

$$U_{o\,\text{DESUPERHEAT}} = \frac{1}{\frac{1}{30} + 0.00985} = \frac{1}{0.04318} = \underline{23.16} \ \frac{\text{BTU}}{\text{HR-FT}^2\text{-°F}}$$

$$U_{o\,\text{CONDENSING}} = \frac{1}{\frac{1}{300} + 0.00985} = \frac{1}{0.01318} = \underline{75.85} \ \frac{\text{BTU}}{\text{HR-FT}^2\text{-°F}}$$

$$U_{o\,\text{SUBCOOL}} = \frac{1}{\frac{1}{20} + 0.00985} = \frac{1}{0.05985} = \underline{16.71} \ \frac{\text{BTU}}{\text{HR-FT}^2\text{-°F}}$$

FOR EACH SECTION: $A_{SECTION} = \dfrac{q_{SECTION}}{U_{o\,SECTION}\,(\Delta T_{lm})_{SECTION}}$

DESUPERHEATING: $A_{DESUPERHEAT} = \dfrac{352{,}500\ \frac{BTU}{HR}}{\left(23.16\ \frac{BTU}{HR\text{-}FT^2\text{-}°F}\right)(28.36°F)} = 536.7\ FT^2$

CONDENSING: $A_{CONDENSING} = \dfrac{1{,}972{,}500\ \frac{BTU}{HR}}{\left(75.85\ \frac{BTU}{HR\text{-}FT^2\text{-}°F}\right)(27.29\ °F)} = 952.9\ FT^2$

SUBCOOLING: $A_{SUBCOOLING} = \dfrac{360{,}000\ \frac{BTU}{HR}}{\left(16.71\ \frac{BTU}{HR\text{-}FT^2\text{-}°F}\right)(45.02°F)} = 478.5\ FT^2$

$$L_{SECTION} = \frac{A_{SECTION}}{\pi D_o N} = \frac{A_{SECTION}}{\pi\left(\frac{0.5}{12}\ FT\right)(800)} = \frac{A_{SECTION}}{104.72\ FT}$$

$$L_{DESUPERHEAT} = \frac{536.7\ FT^2}{104.72\ FT} = 5.125\ FT$$

$$L_{CONDENSE} = \frac{952.9\ FT^2}{104.72\ FT} = 9.100\ FT$$

$$L_{SUBCOOL} = \frac{478.5\ FT^2}{104.72\ FT} = 4.569\ FT$$

$$L_{TOTAL} = 18.794\ FT$$

WOULD PROBABLY USE 20-FT TUBES (STANDARD LENGTH)

WHAT ABOUT THE ENGINEER'S SUGGESTION? WE WOULD HAVE TO INCREASE THE AREA TO COMPENSATE FOR A SMALLER ΔT_{lm}, BUT HOW MUCH??

NEED TO FIND NEW T_{c3}, T_{c4}

WITH 180° OUTLET TEMPERATURE FOR COOLING WATER:

$$w_c = \frac{q_{TOTAL}}{C_{pc}(T_{c2} - T_{c1})} = \frac{2{,}685{,}000\ BTU/HR}{1.00\ \frac{BTU}{lb\text{-}°F}\ (180-50)°F} = 20{,}654\ \frac{lb}{HR}$$

SAVES $(24{,}409 - 20{,}654) = 3755\ \frac{lb}{HR}$ OF COOLING WATER

LOOKS GOOD SO FAR!

BALANCE ON DESUPERHEATING SECTION

$$T_{C2} - T_{C3} = \frac{q_{\text{DESUPERHEAT}}}{w_c\, c_{pc}} = \frac{352{,}500\ \frac{\text{BTU}}{\text{HR}}}{20{,}654\ \frac{\text{lb}}{\text{HR}} \cdot 1.00\ \frac{\text{BTU}}{\text{lb}-°\text{F}}} = \underline{17.1}\ °\text{F}$$

$$T_{C3} = T_{C2} - 17.1°\text{F} = (180 - 17.1)°\text{F} = \underline{162.9}\ °\text{F}$$

BALANCE ON SUBCOOLING SECTION

$$T_{C4} - T_{C1} = \frac{q_{\text{SUBCOOLING}}}{w_c\, c_{pc}} = \frac{360{,}000\ \frac{\text{BTU}}{\text{HR}}}{20{,}654\ \frac{\text{lb}}{\text{HR}} \cdot 1.00\ \frac{\text{BTU}}{\text{lb}-°\text{F}}} = 17.4°\text{F}$$

$$T_{C4} = T_{C1} + 17.4°\text{F} = (50 + 17.4) = \underline{67.4}\ °\text{F}$$

BUT OOPS! T_{C3} IS > 150°F,

CAN'T TRANSFER HEAT FROM 150°F TO 162.9°F!