Question:-

Methanol vapor at saturation temperature and 1 atm pressure is to be condensed and sub-cooled to 40oC at a rate of 100 g/s. Water at 20oC and 3 kg/s is available as a coolant flowing through 2 mm thick AISI 302 stainless steel tubes of 20 mm outer diameter. Design a shell and tube heat exchanger for this purpose.

Solution:-

Assumptions

1) Steady operating conditions exist.
2) The heat exchanger is well insulated so that heat loss to the surroundings is negligible.
3) Changes in the kinetic and potential energies of fluid streams are negligible.
4) Fluids' properties are constant.

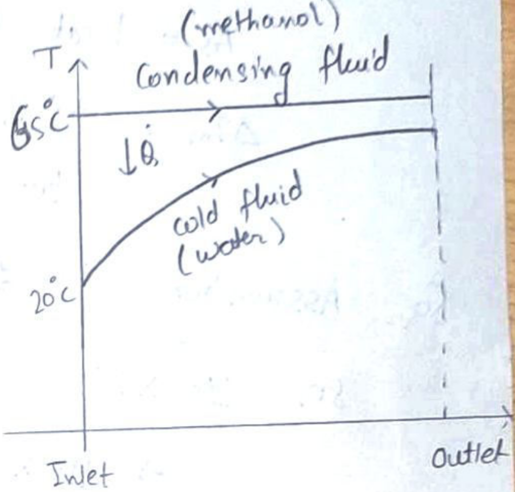
& along with the solution

Group - 1

Since methanol vapor is condensing and also sub-cooled So we divide the heat exchanger in to two parts

: firstly we solve/calculate the length of tube that involves condensation of methanol vapor

: Secondly, we calculate the length of tube that involving the subcooling of methanol to 40°C.



Part - A : Condensation

At saturation temperature and 1 atm pressure ; $T_{sat} = 65°C$

Water is at 20°C

∵ methanol is undergoing phase change.

So, rate of heat transfer : $\dot{Q} = \dot{m}\, h_{fg}$

where, $\dot{m}$ = rate of condensation of fluid

h_{fg} = enthalpy of vaporization of fluid at specified temperature.

Now, in the problem : $\dot{m} = 100\ g/s = 0.1\ kg/s$

and h_{fg} (at 65°C) = 35.21 kJ/mol

Now, molar mass of methanol (CH_3OH) = 32 g/mol $= 32 \times 10^{-3}$ kg/mol

Hence $h_{fg} = \frac{35.21}{32 \times 10^{-3}}$ kJ/kg

$\Rightarrow h_{fg} = 1.1 \times 10^3$ kJ/kg ≈ 1100 kJ/kg

So, $\dot{Q} = 0.1 \times 1100$ kJ/s

$\Rightarrow \dot{Q} = 110$ kJ/s

from Newton's law of cooling, rate of heat transfer in a heat exchanger,

$$\dot{Q} = U A_s \Delta T_m$$

where U = Overall heat transfer coefficient ($\cancel{800 - 1700}$ 250 - 700 for ~~water - water~~ Alcohol condensor)

A_s = heat transfer surface area

ΔT_m = mean temperature difference between the two fluids.

So, Assuming $U = \cancel{1250}\ 475$

So, $110 \times 10^3 = \cancel{1250}\ 475 \times (\pi \times D_o \times L) \times (65 - 20)$

$\cancel{110 \times 10^3 = 1250 \times \pi \times 20 \times 10^{-3} \times L \times 45}$

$\cancel{\Rightarrow L = 31 \text{ m}}$

$\Rightarrow 110 \times 10^3 = 475 \times \pi \times 20 \times 10^{-3} \times L \times 45 \Rightarrow \boxed{L \approxeq 81.57 \text{ m}}$

Part - B : Subcooling of methanol

Since the outlet temperature ~~of~~ coolant (water) is not known, so we will take the limiting case.

for methanol: $T_{avg} = \frac{65 + 40}{2} = 52.5°C$

at T_{avg}, $C_{ph} = 2738$ J/kg-k (using interpolation between 50°C & 60°C)

So, $C_h = \dot{m}_h C_{ph} = 0.1 \frac{kg}{s} \times 2738 \frac{J}{kg\text{-}k} = 273.8 \frac{J}{s\text{-}k}$

for water: Assuming, ~~[illegible]~~ $C_{pw} = 4182 \ J/kg\text{-}K$

then, $C_w = \dot{m}_w C_{pw} = 3 \frac{kg}{s} \times 4182 \frac{J}{kg\text{-}K} = 12546 \frac{J}{s\text{-}K}$

Therefore $C_{min} = C_h = 273.8 \ J/s\text{-}K$

$\therefore$ maximum heat transfer rate

$$\dot{Q}_{max} = C_{min} (T_{h,in} - T_{w,in})$$
$$= 273.8 (65 - 20)$$
$$= 273.8 \times 45 = 12321 \ J/s \simeq 12.321 \ kJ/s$$

maximum temperature difference in this heat exchanger is

$\Delta T_{max} = T_{h\,in} - T_{w\,in} = 45°C$

The outlet temperature of the cold stream (water)

in this limiting case:

$\dot{Q}_{max} = C_w (T_{w,out} - T_{w,in}) \Rightarrow T_{w,out} = T_{w,in} + \frac{\dot{Q}_{max}}{C_w}$

$\Rightarrow T_{w,out} = 20 + \frac{12321}{12546} \simeq 20.98 \simeq 21°C$

So, $Q = UA \, \Delta T_m$ (without fouling)

where U = overall heat transfer coefficient ; A = surface area

$\Delta T_m = \Delta T_{lm}$ = Logarithmic mean difference

So, $\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)}$ with $\Delta T_1 = T_{h,in} - T_{w,out}$

$\Delta T_2 = T_{h\,out} - T_{w,in}$

So, $\Delta T_1 = 65 - 21 = 44°C$; $\Delta T_2 = 40 - 20 = 20°C$

So, $\Delta T_{lm} = \frac{44 - 20}{\ln\left(\frac{44}{20}\right)} = \frac{24}{0.788} = 30.45°C$

Also, $Q = C_h \Delta T = 273.8 \times (65 - 40) \Rightarrow Q = 6845 \ J/s$

For Calculating U

cold fluid → water ; Hot fluid → methanol

So, $U = 50 - 150$ Btu/hr-ft²-F

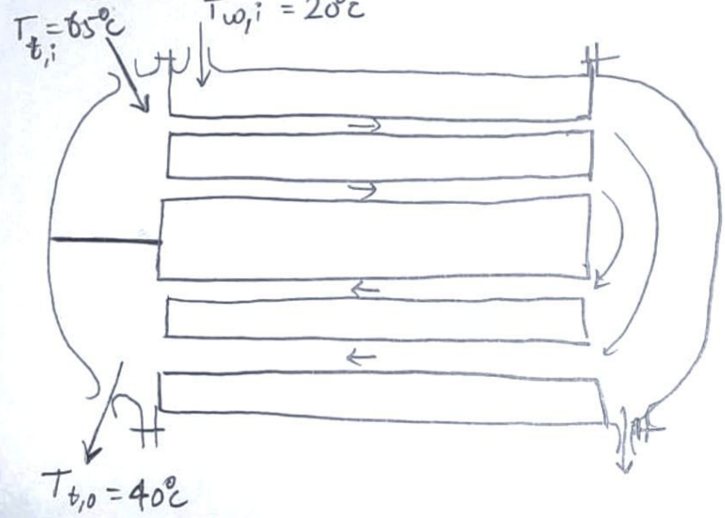
So, $U_{avg} = 100$ Btu/hr-ft²-F $= 567.826$ J/s-m²-K

So, $Q = U A_s \Delta T_{lm}$

$\Rightarrow 6845 = 567.826 \times \pi (D_o - 2 \times 2 \times 10^{-3}) L \times 30.45$

$\Rightarrow \boxed{L \cong 7.87 \text{ m}}$

Hence the total length of Shell & tube heat Exchanger would be $81.57 + 7.87 = \underline{89.44 \text{ m}}$



Outer surface area $= \pi D_o (89.44)$

$= \underline{5.6168 \text{ m}^2}$