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Designing Steps for a Heat Exchanger

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ABSTRACT

Distillation is a common method for removing dissolved solids and to obtain pure water for drinking and for the purpose like battery water, electroplating etc. Distillation of water have certain problems and operational issues and too like as it is an energy consuming process.

Multiple – effect distillation is a distillation process generally used for sea water distillation. It consists of stages (effect). In first stage feed water is heated by steam in tubes. Some of the water evaporates and this fresh steam flows into the tube of the next stage. But for better heat transfer, it is necessary to design a heat exchanger which fulfills the requirements of MED unit.

The most common problems in heat exchanger design are rating and sizing. The rating problem is concerned with the determination of the heat transfer rate, fluid outlet temperature, inlet temperature, heat transfer area and the sizing problem involves determination of the dimension of the heat exchanger. An heat exchanger (shell and tube type) is being designed here with proper dimension for 45 Kg/hr steam. This method is also used for other temperature range and increased mass flow rate of steam. Using this design procedure of heat exchanger we can also increases the boiler efficiency which produces steam for multi effect distillation unit.

Related input data for the design of heat exchanger, which is used for multiple distillation unit is given below-

Input steam pressure = 4 bar gauge

Standard atmospheric pressure = 1.013 bar

Absolute pressure = Atmospheric pressure + gauge Pressure

Therefore Input steam pressure = 1.013 + 4 = 5.013 bar

Inlet Temperature of Steam, T_{hi} = 152.7 °C at 5.013 bar

Outlet Temperature of Steam, T_{ho} = 117 ° C

Inlet Temperature of Water, T_{ci} = 110 ° C

Specific Heat for Steam, C_{ph} = 2.5 kJ/kg K

Specific Heat for Water, C_{pc} = 4.18 kJ/kg K

Mass –flow rate of Steam, m_h = 45 kg/h

= 45/3600

= 0.0125 kg/s

Mass –flow rate of Water, m_c = 250 kg/h

= 250/3600

= 0.0694 kg/s

1. Energy Balance Eq.,

$m_c * C_{ph} * (T_{co} – T_{ci}) = m_h * C_{ph} * (T_{hi} – T_{ho})$

$0.0694 * 4.18 * (T_{co} – 110) = 0.0125 * 2.5 * (152.7 – 117)$

$0.290092 * T_{co} – 31.91012 = 1.1156$

$0.290092 * T_{co} = 33.025745$

$T_{co} = 113.85$ °C

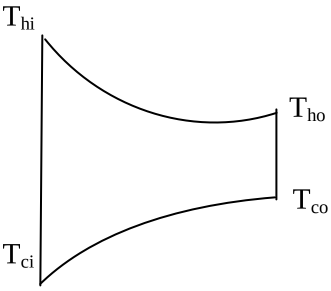
Outlet Temperature of Water, $T_{co} = 113.85\ °C$

2. Heat Transfer Rate,

$$Q = m_c * C_{ph} * (T_{co} - T_{ci})$$
$$= 0.0694 * 4.18 * (113.85 - 110)$$
$$= 1.17\ kW$$

3. Log Mean Temperature Difference, LMTD for Parallel Flow,

$$\Delta T_1 = T_{hi} - T_{ci}$$
$$= 152.7 - 110 = 42.7°C$$
$$\Delta T_2 = T_{ho} - T_{co}$$
$$= 117 - 113.85 = 3.15°C$$



$$\text{LMTD, } \Delta Tm = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} = \frac{42.7 - 3.15}{\ln\left(\frac{42.7}{3.15}\right)}$$

$$\Delta T_m = 39.55 / 2.6067 = 15.17°C$$

4. Temperature Correction Factor,

The selection of parameters R and P should be such that the value of correction factor, F_t is more than 0.75

$$\text{Capacity Ratio, R} = \frac{T_{ci} - T_{co}}{T_{ho} - T_{hi}}$$
$$= (110 - 113.85) / (117 - 152.7)$$
$$= 0.12$$

$$\text{Temperature Ratio, P} = \frac{T_{ho} - T_{hi}}{T_{ci} - T_{hi}}$$
$$= (117 - 152.7) / (110 - 152.7)$$
$$= 0.84$$

The value may taken from the chart:-

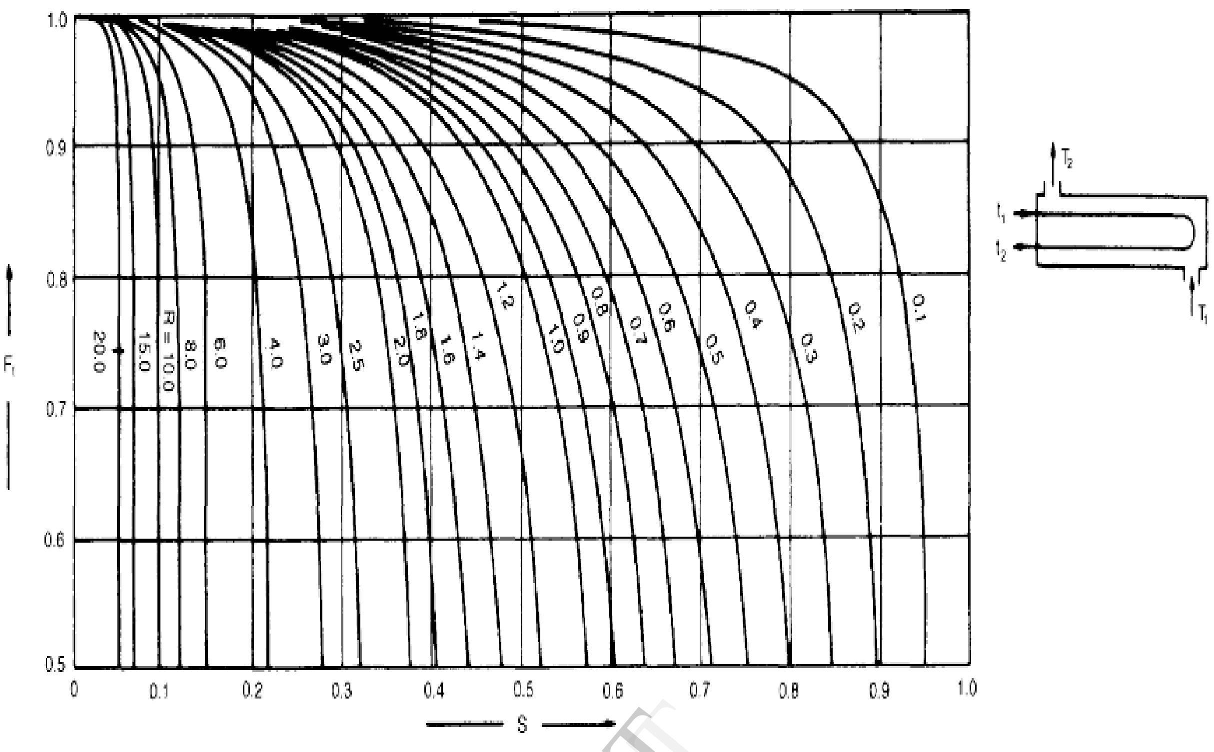


Fig.1: Relation between R, P and F_t

$$F_t = \frac{\sqrt{R^2+1}}{(R-1)} * \frac{ln\frac{(1-P)}{(1-P*R)}}{ln\frac{\left[2-P\left(R+1-\sqrt{R^2+1}\right)\right]}{\left[2-P\left(R+1+\sqrt{R^2+1}\right)\right]}}$$

$$F_t = \frac{\sqrt{0.12^2+1}}{(0.12-1)} * \frac{ln\frac{(1-0.84)}{(1-0.84*0.12)}}{ln\frac{\left[2-0.84\left(0.12+1-\sqrt{0.12^2+1}\right)\right]}{\left[2-0.84\left(0.12+1+\sqrt{0.12^2+1}\right)\right]}}$$

F_t = 0.904

Both result are same, therefore F_t = 0.904

5. Mean Temperature Difference,

DT_m = F_t * LMTD

= 0.904 * 15.17

DT_m = 13.71°C

6. Overall Heat Transfer Co-efficient,

Study based on, Steps for design of Heat Exchanger by Dr. Reyad Shewabkeh, Dept. of Chemical Engineering, King Fahd University of Petroleum & Minerals, The range of overall heat transfer co-efficient for water is 800 – 1500 w/m^2 °C.

$$U = 945 \text{ w/m}^2 \text{ °C}$$

Shell and tube exchangers

Hot fluid	Cold fluid	U (W/m^2°C)
Heat exchangers		
Water	Water	800–1500
Organic solvents	Organic solvents	100–300
Light oils	Light oils	100–400
Heavy oils	Heavy oils	50–300
Gases	Gases	10–50
Coolers		
Organic solvents	Water	250–750
Light oils	Water	350–900
Heavy oils	Water	60–300
Gases	Water	20–300
Organic solvents	Brine	150–500
Water	Brine	600–1200
Gases	Brine	15–250
Heaters		
Steam	Water	1500–4000
Steam	Organic solvents	500–1000
Steam	Light oils	300–900
Steam	Heavy oils	60–450
Steam	Gases	30–300
Dowtherm	Heavy oils	50–300
Dowtherm	Gases	20–200
Flue gases	Steam	30–100
Flue	Hydrocarbon vapours	30–100
Condensers		
Aqueous vapours	Water	1000–1500
Organic vapours	Water	700–1000
Organics (some non-condensables)	Water	500–700
Vacuum condensers	Water	200–500
Vaporisers		
Steam	Aqueous solutions	1000–1500
Steam	Light organics	900–1200
Steam	Heavy organics	600–900

Table 1: Overall heat transfer coefficient for different combination

7. Provisional Area,

$$A = \frac{Q}{U * \Delta T} = \frac{1170}{945 * 13.71}$$

$$= 0.090 \ m^2 = 900 \ cm^2$$

8. Tube Outer Diameter,

<u>Case I-</u> Number of Tubes, N_t = 7

Length of Tubes, L = 100 cm

d_o = 900 / (3.14*7*100) = 0.41 cm

= 4.1 mm

<u>Case II-</u> Number of Tubes, N_t = 5

Length of Tubes, L = 100 cm

d_o = 900 / (3.14*5*100) = 0.57 cm

= 5.7mm

<u>Case III-</u> Number of Tubes, N_t = 7

Length of Tubes, L = 50 cm

d_o = 900 / (3.14*7*50) = 0.82 cm

= 8.2 mm

<u>Case IV-</u> Number of Tubes, N_t = 5

Length of Tubes, L = 50 cm

d_o = 900 / (3.14*5*50) = 1.15 cm

= 11.5 mm

Above design calculation are not feasible because calculations are based on LMTD 13.71°C. MED Unit will provide best result when condensation of steam will take place with minimum temperature difference.

Study based on paper – Porteous,A. (1975), Saline water distillation Process (1st Ed) Longman UK, London, 150p, it is clear that condensation can take place with a temperature difference of 2°C.

Therefore our design calculation will be based on 4°C.

$DT_m = 4°C$

$$A = \frac{Q}{U * DT_m} = \frac{1170}{945*4}$$

$$= 0.309523 \text{ m}^2$$

$$= 3095.23 \text{ cm}^2$$

Case I- Number of Tubes, N_t = 7

Length of Tubes, L = 100 cm

d_o = 3095.23 / (3.14*7*100) = 1.408 cm

= 14.08 mm

Case II- Number of Tubes, N_t = 5

Length of Tubes, L = 100 cm

d_o = 3095.23 / (3.14*5*100) = 1.8207 cm

= 18.21 mm

Case III- Number of Tubes, N_t = 7

Length of Tubes, L = 50 cm

d_o = 3095.25 / (3.14*7*50) = 2.816 cm

= 28.16 mm

Case IV- Number of Tubes, N_t = 5

Length of Tubes, L = 50 cm

d_o = 3095.25 / (3.14*5*50) = 3.942 cm

= 39.42 mm

<u>Case V-</u> Number of Tubes, N_t = 5

Length of Tubes, L = 75 cm

d_o = 3095.25 / (3.14*5*75) = 2.628 cm

= 26.28 mm

<u>Case IV-</u> Number of Tubes, N_t = 7

Length of Tubes, L = 75 cm

d_o = 3095.25 / (3.14*7*75) = 1.877 cm

= 18.77 mm

Sr. No.	NUMBER OF TUBES, N_t	LENGTH OF TUBES, L (mm)	OUTER DIAMETER, d_o (mm)
1.	7	1000	14.08
2.	5	1000	18.21
3.	**7**	**500**	**28.16**
4.	5	500	39.42
5.	5	750	26.28
6.	7	750	18.77

Table 2: Different configuration for tubes

We get best result in case III, therefore outer diameter of tube is 28.16 mm, And the configuration of the tube is-

d_o = 28.16 mm

= 0.02816 m

N_t = 7

L = 50 mm

9. Tube Pitch,

P_t = 1.25 * d_o

= 1.25 * 28.16

= 35.2 mm

10. Bundle Diameter,

D_b = d_o [N_t / K_1]$^{1/n}$

Triangular pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, $p_t = 1.25d_o$					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

Table 3: Relation between constant K_1 and n_1

For Square pitch,

P_t = 1.25 * d_o

K_1 = 0.0366

N = 2.63

D_b = 28.16 * [7 / 0.0366]$^{1/2.63}$

= 207.57 mm

= 0.207 m

11. Bundle diameter clearance,

For fixed floating head, BDC = 10 mm

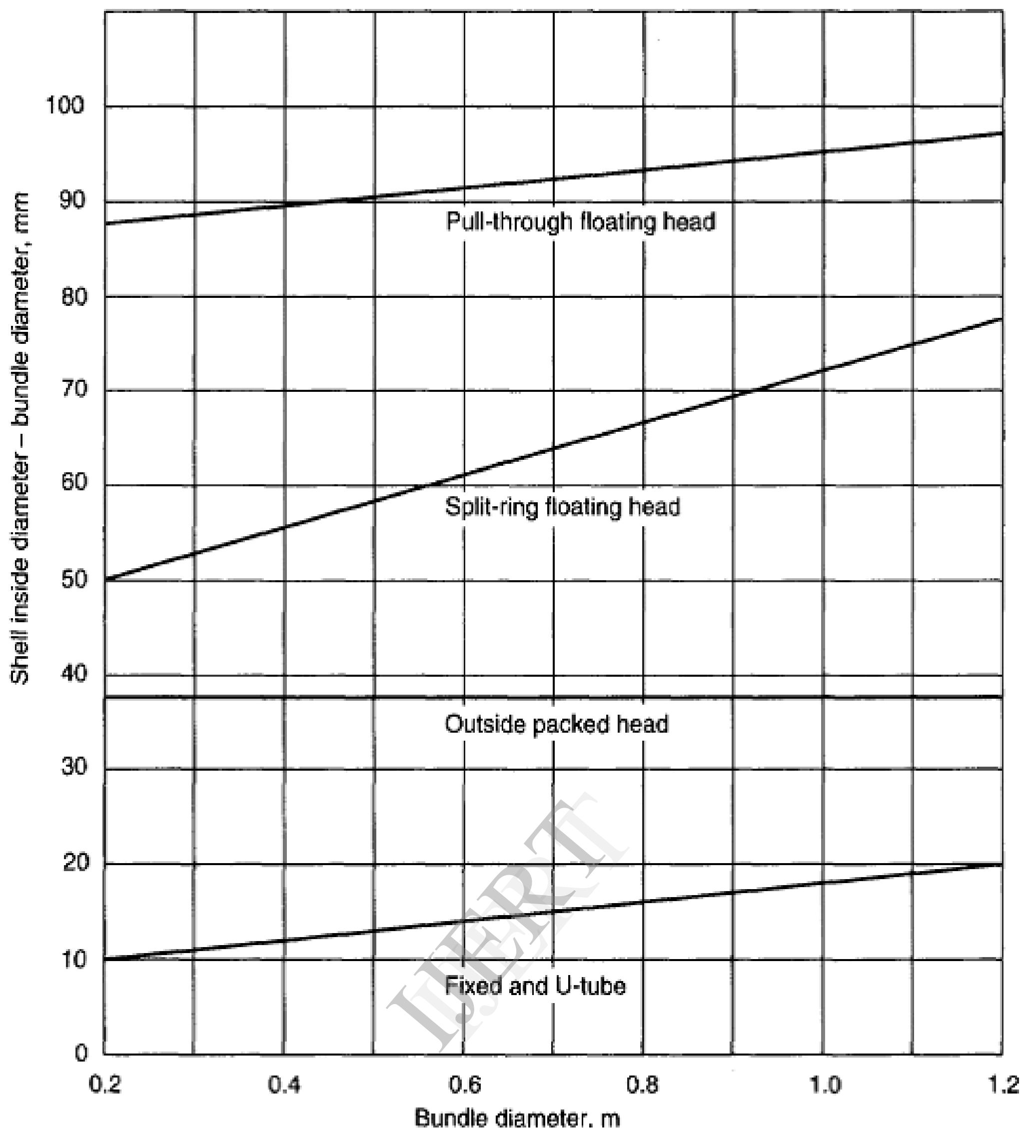


Fig. 2: Bundle diameter clearance

12. Shell Diameter,

$$D_s = D_b + BDC = 207.57 + 10$$

$$= 217.57 \text{ mm}$$

13. Baffle Spacing,

$$B_s = 0.4 * D_s$$

$$= 0.4 * 217.57$$

$$= 87.03 \text{ mm}$$

14. Area for cross – flow,

$$As = \frac{(P_t - d_o) * D_s * B_s}{P_t}$$

$$= \frac{(35.2-28.6)*217.57*87.03}{35.2}$$

$= 3550.33\ mm^2$

$= 3.55 * 10^{-3}\ m^2$

15. Shell – side mass velocity,

$$Gs = \frac{\text{Shell Side flow rate [kg/s]}}{A_s}$$

Shell – side flow rate = 0.0694 kg/s

$$Gs = \frac{0.0694}{3.55 * 10^{-3}} = 19.55\ kg/m2 - s$$

$= 1.955 * 10^{-5}\ kg/mm^2\text{-s}$

16. Shell equivalent diameter for a square pitch arrangement,

$$d_e = \frac{1.27 * [P_t^2 - 0.785 * d_o^2]}{d_o}$$

$$= \frac{1.27 * [35.2^2 - 0.785 * 28.16^2]}{28.16}$$

$= 27.81\ mm = 0.02781\ m$

17. Shell – side Reynolds number,

Properties of water at 110°C temp.

Density , ρ = $951\ kg/m^3$

Kinematic viscosity, υ = $0.273 * 10^{-6}\ m^2/s$

Fluid thermal Conductivity, k_f = 0.62 W/m-K

Specific heat, C_p = 4233 J/kg-K

$$R_e = \frac{G_s * d_e}{\mu} = \frac{G_s * d_e}{\rho \upsilon} = \frac{19.55 * 0.02781}{951 * 0.273 * 10^{-6}}$$

$$= 2094.1$$

R_e > 2000 therefore flow inside shell side is Transition and Turbulent.

18. Prandtle number,

$$P_r = \frac{? * C_p}{k_f} = \frac{\rho * \upsilon * C_p}{k_f} = \frac{951 * 0.273 * 10^{-6} * 4233}{0.62}$$

$$= 1.77$$

19. Nusselt number,

$$N_u = 0.023 * (R_e)^{0.8} * (P_r)^n$$

n = 0.4 for heating.........

= 0.3 for cooling.........

$$N_u = 0.023 * (R_e)^{0.8} * (P_r)^{0.4}$$

$$= 0.023 * (2094.1)^{0.8} * (1.77)^{0.4}$$

$$= 13.11$$

20. Heat transfer coefficient,

$$h_o = \frac{N_u * k_f}{d_e} = \frac{13.11 * 0.62}{0.02781}$$

$$= 292.35 \text{ W/m}^2\text{-K}$$

21. Tube inside diameter,

$$d_i = d_o - t$$

Thickness of tube metal = 6 mm

$$d_i = 28.16 – 6$$

$$= 22.16 \text{ mm}$$

$$= 0.02216 \text{ m}$$

22. Tube – side Reynolds number,

Properties of steam at 152.7°C temp.

Dynamic viscosity, μ = $1.408 * 10^{-5}$ N-s/m^2

Fluid thermal Conductivity, k_f = 0.0311 W/m-K

Specific heat, C_p = 2335.2 J/kg-K

$$R_e = \frac{G_s * d_i}{\mu} = \frac{19.55 * 0.02216}{1.4085 * 10^{-5}}$$

$$= 100000$$

R_e > 2000 therefore flow inside tube is Transition and Turbulent.

23. Prandtle number,

$$P_r = \frac{\mu * C_p}{k_f} = \frac{1.4085 * 10^{-5} * 2335.2}{0.0311}$$

$$= 1.057$$

24. Nusselt number,

$$N_u = 0.023 * (R_e)^{0.8} * (P_r)^{0.3}$$

$$= 0.023 * (100000)^{0.8} * (1.057)^{0.3}$$

$$= 233.86$$

25. Heat transfer coefficient,

$$h_o = \frac{N_u * k_f}{d_i} = \frac{233.86 * 0.0311}{0.02216}$$

$$= 328.21 \text{ W/m}^2 \text{ - K}$$

26. Overall heat transfer coefficient in Shell and tube heat exchanger,

The heat transfer is in radial direction, firstly the heat is transferred by hot fluid to inner wall of tube by convection . then through the wall of the tube by conduction and finally from the outer wall of tube to cold fluid by convection.

Surface Area of inner tube, $A_i = 2\pi r_i L$

Surface Area of outer tube, $A_o = 2\pi r_o L$

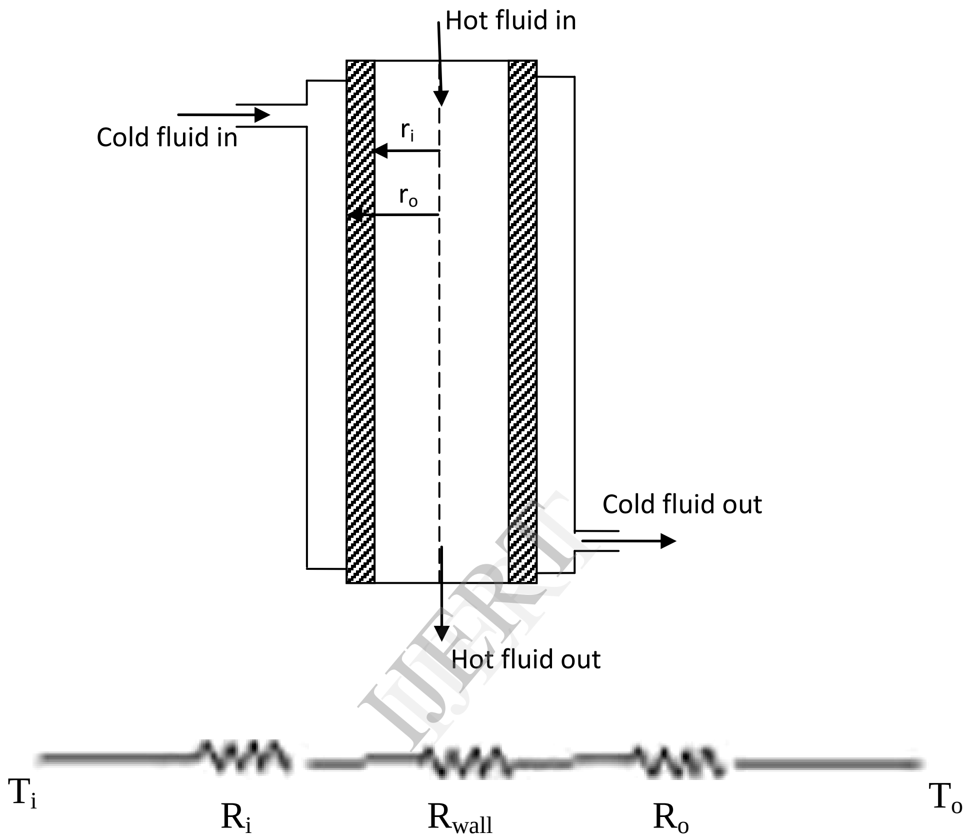


Fig. 3: Heat transfer in shell and tube heat exchanger

Total Thermal resistance,

$$\sum R = R_i + R_{wall} + R_o$$

$$\sum R = \frac{1}{h_i A_i} + \frac{\log\frac{r_o}{r_i}}{2\pi LK} + \frac{1}{h_o A_o}$$

$$= \frac{1}{2\pi r_i h_i} + \frac{\log\frac{r_o}{r_i}}{2\pi LK} + \frac{1}{2\pi r_o h_o}$$

$$Q = \frac{Ti - To}{\sum R} = UA\Delta T = U_i A_i \Delta T = U_o A_o \Delta T$$

Where, U = Overall heat transfer coefficient in W/m^{2}K

$$\sum R = \frac{1}{UA} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o}$$

Overall heat transfer coefficient based on outside surface area of tube can be expressed as:

$$U_o = \frac{1}{\sum R\ A_o} = \frac{1}{\frac{A_o}{h_i A_i} + \frac{A_o}{2\pi L K} log\frac{r_o}{r_i} + \frac{1}{h_o}}$$

$$= \frac{1}{\frac{r_o}{h_i r_i} + \frac{r_o}{K} log\frac{r_o}{r_i} + \frac{1}{h_o}}$$

$$= \frac{1}{\frac{0.01408}{0.01108 * 328.21} + \frac{0.01408}{225} ln\frac{0.01408}{0.01108} + \frac{1}{292.35}}$$

$$= 136.89 \text{ W/m}^2\text{-K}$$

Overall heat transfer coefficient based on inner surface area of tube can be expressed as:

$$U_o = \frac{1}{\sum R\ A_i} = \frac{1}{\frac{A_i}{h_i A_o} + \frac{A_i}{2\pi L K} log\frac{r_o}{r_i} + \frac{1}{h_i}}$$

$$= \frac{1}{\frac{r_i}{h_i r_o} + \frac{r_i}{K} log\frac{r_o}{r_i} + \frac{1}{h_i}}$$

$$= \frac{1}{\frac{0.01108}{0.01408 * 292.35} + \frac{0.01108}{225} ln\frac{0.01408}{0.01108} + \frac{1}{328.21}}$$

$$= 136.89 \text{ W/m}^2\text{-K}$$

After comparing the overall heat transfer coefficient, I obtained from previous step with that I assumed in step 6. It is smaller to what I assumed, then I have a valid assumption, that tabulate my results such as total surface area of tubes, number of tubes, exchanger length and diameter and other design specification.

CONCLUSION AND SCOPE FOR FUTURE WORK

Following conclusion can be made after study:

1. Six different combination of No. of tubes and length of tubes were tried. Above design of heat exchanger was best, because our calculated dimensions are verified very accurately.
2. Due to agronomic consideration of design, the tube of very large diameter is not selected.
3. Smallest diameter is not selected because it is not practically feasible.
4. An appropriate heat exchanger is designed for multiple effect distillation unit to condense 45 Kg/hr steam. Dimension of heat exchanger is given below-

Number of tubes, N_t	=	7
Length of tube, L	=	500 mm
Outer diameter of tube, d_o	=	28.16 mm
Thickness of the tube, t	=	6 mm
Inner diameter of tube, d_i	=	22.16 mm
Overall heat transfer coefficient,U	=	136.89 W/m^2K
Tube pitch, p_t	=	35.2 mm
Bundle diameter, D_b	=	207.57 mm
Bundle diameter clearance, BDC	=	10 mm
Shell Diameter, D_s	=	217.57 mm
Baffle spacing, B_s	=	87.03 mm
Area for cross – flow, A_s	=	3550.33 mm^2
Material selected	=	Aluminum

Following Modification can be done for future work:

1. Other type of heat exchanger can be design.
2. Flow of steam and water can be reverse. That means the feed water may be taken inside tubes and condensing steam outside tubes.
3. Pressure drop inside shell and tube can be calculated.

4. Counter flow arrangement can be tried.
5. Design may done for different types of floating head.
6. We can use some other material than aluminum for better heat transfer.
7. Effect of corrosion can be considered.

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