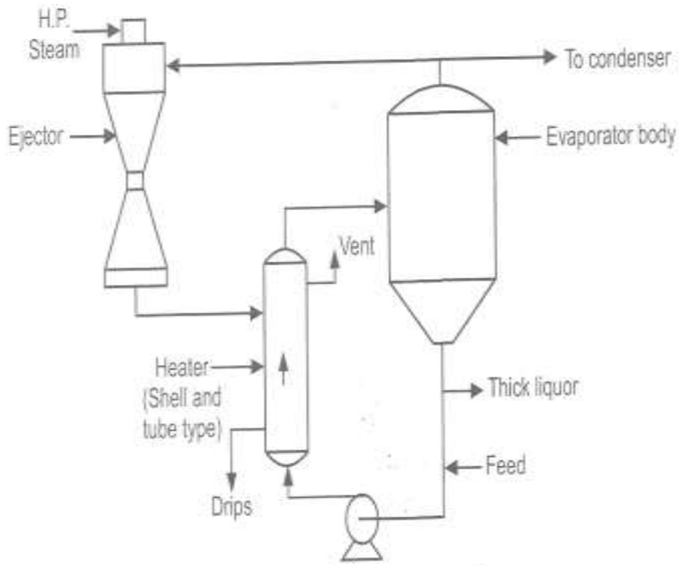
Important Instructions to examiners:

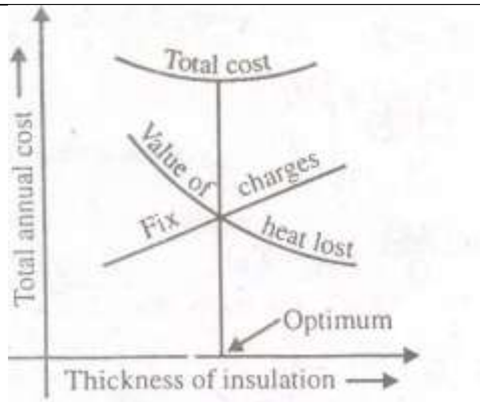
1) The answers should be examined by key words and not as word-to-word as given in the model answer scheme.
2) The model answer and the answer written by candidate may vary but the examiner may try to assess the understanding level of the candidate.
3) The language errors such as grammatical, spelling errors should not be given more Importance (Not applicable for subject English and Communication Skills.
4) While assessing figures, examiner may give credit for principal components indicated in the figure. The figures drawn by candidate and model answer may vary. The examiner may give credit for any equivalent figure drawn.
5) Credits may be given step wise for numerical problems. In some cases, the assumed constant values may vary and there may be some difference in the candidate's answers and model answer.
6) In case of some questions credit may be given by judgement on part of examiner of relevant answer based on candidate's understanding.
7) For programming language papers, credit may be given to any other program based on equivalent concept.

Q No.	Answer	marks
1 A	Any three	12
1A-(i)	**Thermal conductivity**: It is the ability of measure of the substance to conduct heat. It is the quantity of heat passing through a material of a unit thickness with a unit heat flow area in unit time when a unit temperature difference is maintained across the opposite faces of the material.	2
	From Fourier's law	
	Q= -kA(dT/dx)	1
	Or k= Q.dx/(A.dT)	
	Substituting the units	
	k = W.m/(m^2.K)	1
	= W/mK or J/(s.m.K)	
1A-(ii)	**Film heat transfer coefficient:** Film heat transfer coefficient h is defined as the quantity of heat transferred in unit time through unit area at a temperature difference of 1^0 between the surface and surrounding.	2
	$1/U_o = 1/h_o + 1/h_i(D_o/D_i) + x_w/k(D_o/D_w)+R_d$	2
	$1/U_i = 1/h_i + 1/h_o(D_i/D_o) + x_w/k(D_i/D_w)+R_d$	
1A-(iii)	**Stefan- Boltzman law:**	
	It states that the total energy emitted (emissive power) per unit area per unit time by a black body is proportional to fourth power of its absolute temperature.	2
	$W_b \alpha T^4$	
	Or $W_b = \sigma T^4$	1
	Where W_b = total energy emitted (emissive power) by a black body	
	σ = Stefan Boltzman constant= $5.67*10^{-8}$ W/m^2 K	1

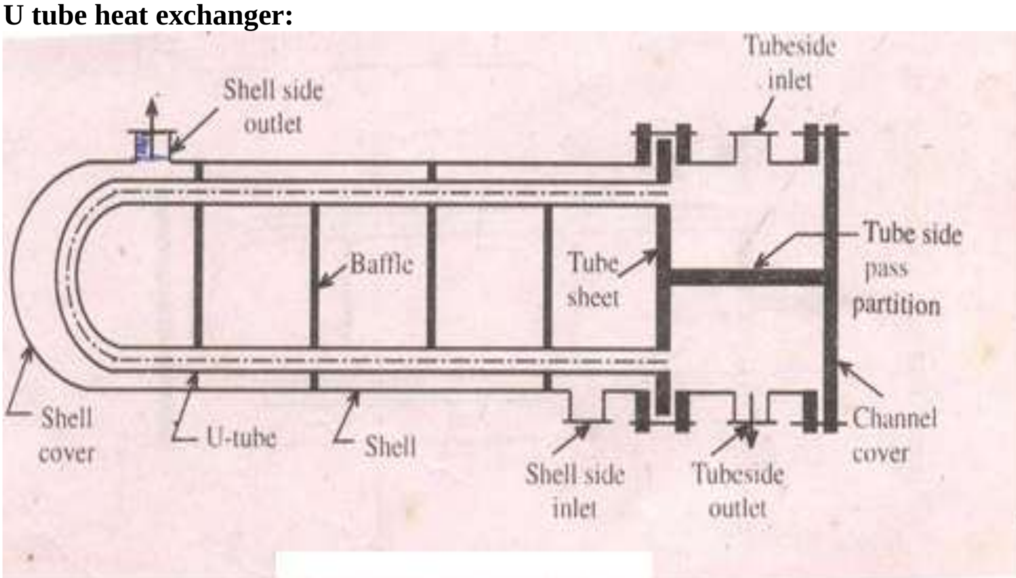
	T = absolute temperature	
1A-(iv)	**Classification of shell and tube heat exchanger:** 1. Fixed tube heat exchanger 2. Floating head heat exchanger 3. U- tube type heat exchanger 4. Kettle/ Reboiler type heat exchanger	1 mark each
1.B	**Any one**	6
1B-(i)	Basis: 1 m length $r_1 = 0.0525m$ $r_2 = 0.0575m$ $r_L = (r_2-r_1) / \ln(r_2/r_1) = 0.055m$ $A_{L1} = 2\pi r_L L = 0.3452\ m^2$ $K_1 = 43.03$ W/mK $R_1 = B_1 / K_1 A_{L1}$ $= 0.005/43.03 * 0.3452$ $= 3.37*10^{-4}$ K/W $r_2 = 0.0575m$ $r_3 = 0.1075m$ $r_L = (r_3-r_2) / \ln(r_3/r_2) = 0.08m$ $A_{L2} = 2\pi r_L L = 0.5018\ m^2$ $K_2 = 0.07$ W/mK $R_2 = B_2 / K_2 A_{L2}$ $= 0.05/0.07 * 0.5018$ $= 1.423$ K/W $R = R_1 + R_2$ $= 1.4237$ K/W Temp.drop $\Delta T = 120$ K Heat loss $Q = \Delta T / R$ $= 120 / 1.4237$	 1 1 1 1

	= **84.29 W** $Q = (T_1-T_2) / R_1$ where T_2 is the temperature at interface $84.29 = (423- T_2) / 3.37*10^{-4}$ **T_2 = 422.97 K**	 1 1
1B-(ii)	**Methods of increasing the economy of an evaporator:** 1. Using multiple effect evaporator 2. Vapour recompression **A. Multiple effect evaporation:** In this system, evaporators are arranged in series so that the vapour produced in first effect is fed to the steam chest of second effect as heating medium in which boiling takes place at low pressure and temperature and so on. **B. Methods of increasing economy by vapour recompression methods are:** **1.** Mechanical recompression **2.** Thermal recompression **Thermal recompression:** To increase the economy of single effect evaporator, the principle of thermal recompression is used. Here the vapour from the evaporator is compressed to increase its temperature so that it will condense at a temperature higher enough to permit its use as heating media in the same evaporator. In this method, vapour is compressed by means of jet ejectors. Here the high pressure steam is used to draw and compress the major part of vapours from the evaporator, while the remaining part of vapours is separately condensed for compensating motive steam added.	2 2

		2
2	Any four	16
2-a	**Optimum thickness of insulation:** The optimum thickness of an insulation is the one at which the total annual cost of the insulation is minimum The optimum thickness of an insulation is obtained by purely economic approach. The greater the thickness, the lower the heat loss & the greater the initial cost of insulation & the greater the annual fixed charges. It is obtained by purely economic approach. Increasing the thickness of an insulation reduces the loss of heat & thus gives saving in operating costs but at the same time cost of insulation will increase with thickness. The optimum thickness of an insulation is the one at which the total annual cost (the sum values of heat lost and annual fixed charges) of the insulation is minimum	1 2

	 **Optimum Thickness Of Insulation**	1
2-b	**Fourier's law of conduction:** It states that the rate of heat flow across an isothermal surface is proportional to the temperature gradient at the surface. $\frac{dQ}{dA} = - k\frac{\partial T}{\partial n}$ Q- rate of heat transfer A- Area perpendicular to heat flow k- Thermal conductivity T- Temperature	2 1 1
2-c	**Kirchhoff's Law :** Consider that the two bodies are kept into a furnace held at constant temperature of T K. Assume that, of the two bodies one is a black body& the other is a non-black body i.e. the body having 'a' value less than one. Both the bodies will eventually attain the temperature of T K & the bodies neither become hotter nor cooler than the furnace. At this condition of thermal equilibrium, each body absorbs and emits thermal radiation at the same rate. The rate of absorption & emission for the black body will be different from that of he non-black body. Let the area of non-black body be A_1 and A_2 respectively. Let 'I' be the rate at	2

	which radiation falling on bodies per unit area and E_1 and E_2 be the emissive powers (emissive power is the total quantity of radiant energy emitted by a body per unit area per unit time)of non-black & black body respectively. At thermal equilibrium, absorption and emission rates are equal, thus, $Ia_1 A_1 = A_1 E_1$ ………………..(1.1) $\therefore\ Ia_1 = E_1$ …………….(1.2) And $Ia_b A_2 = A_2 E_b$ ……………..(1.3) $Ia_b = E_b$ ………….(1.4) From equation (1.1) and (1.4).we get $\frac{E1}{a1} = \frac{Eb}{ab}$ ………….(1.5) Where $a_{1,}a_b$ = absorptivity of non-black & black bodies respectively. If we introduce a second body (non-black) then for the second non-black body,we have : $I A_3 a_2 = E_2 A_3$ ………….(1.6) $\therefore\ Ia_2 = E_2$ …………..(1.7) Where $a_1 = E_2$ are the absorptivity and emissive power of the second non-black body. Combining equations (1.2),(1.4) and(1.7) we get, $\frac{E1}{a1} = \frac{E2}{a2} = \frac{E3}{a3} = E_b$ ………..(1.8)	2
2-d	**Application of finned tube heat exchanger:** When the heat transfer coefficient of one of the process fluids is very low as compared to the other, the overall heat transfer coefficient becomes approximately equal to the lower coefficient. This reduces the capacity per unit area of the heat transfer surface	2

	and thus make it necessary to provide very large heat transfer area. The heat transfer area of a pipe or or tube is increased by attaching metal pieces called fins. **Used in:** Automobile radiator, air cooled steam condensers for turbine and engine works, economiser	1 mark each for any2
2-e	**U tube heat exchanger:**  	4
3	**Any two**	16
3-a	Heat given out by thermic fluid = 20*4.187(360-340) Q= 1674.8 KJ/s = 1674.8*10 ^{3} W For counter current flow LMTD = 44 - 40/ln(44/40) = 41.97 Q=U.A.LMTD U = 2000 W/m^{2}K 1674.8*10 ^{3} = 2000*A*41.97	1 2 2 1 1

	A = 19.95 m^2	1
3-b	**Dropwise and filmwise condensation:**	2 marks each for any 4

Points	**Dropwise condensation**	**Filmwise condensation**
mechanism	In case of drop-wise condensation the condensate (condensed liquid) does not wet the surface and collects to grow for a while and then fall from the surface, leaving bare metal surface for further condensation.	In case of film-wise condensation the condensed liquid wets the surface and forms a continuous film of condensate through which heat transfer takes place. This condensate flows down due to action of gravity
Heat transfer coefficient	Heat transfer coefficient are very high in case of drop-wise condensation since the heat does not have to flow through film by conduction	Heat transfer coefficients are relatively very low in case of film-wise condensation since the heat does have to flow through film by conduction
Surface type	Oily or greasy surfaces seem to tend towards drop-wise condensation	Smooth, clean surfaces seem to tend towards film-wise condensation
Stability	Drop-wise condensation is very	Film-wise

		difficult to achieve and unstable	condensation is easily obtainable and stable	
	equations	If the students write equations for film coefficients on vertical and horizontal surfaces marks should be given	If the students write equations for film coefficients on vertical and horizontal surfaces marks should be given	

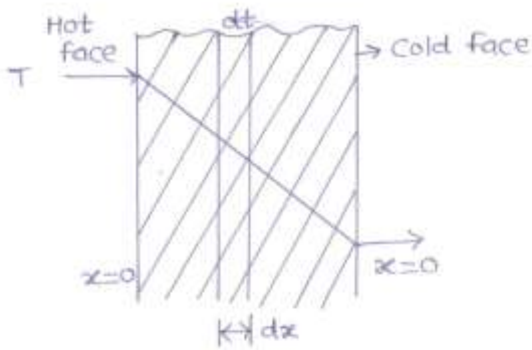
3-c **Comparison of square pitch and triangular pitch(any 4)** — 1.5 mark each

Square pitch	Triangular pitch
Permits external cleaning of the tubes	Difficult to clean
Causes low pressure drop on the shell side fluid	Causes more pressure drop
Less no. of tubes can be accommodated than with triangular pitch	Larger no. of tubes can be accommodated in a given shell diameter
Creates comparatively less turbulence	Creates large turbulence in the shell side fluid
Can be used for dirty fluids also	Used for clean fluid

Use of baffle: — 1 mark each

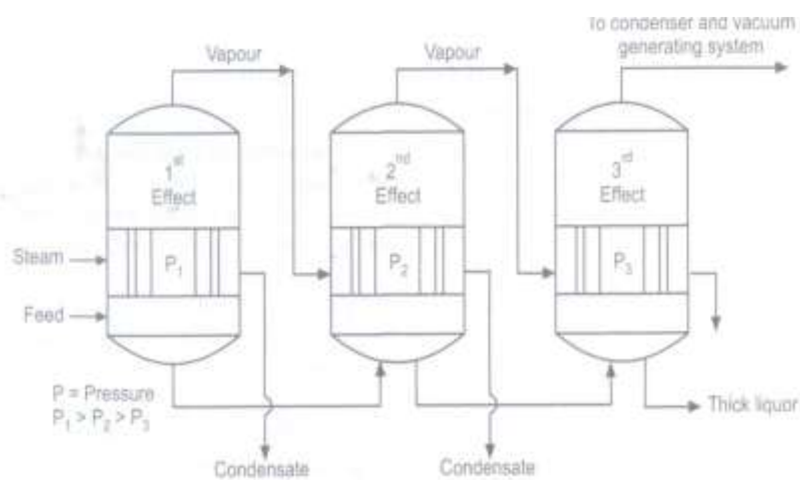
1. To increase the rate of heat transfer by increasing the velocity and turbulence of the shell side fluid.
2. Structural support for the tubes and dampers against vibration.

4 A	Any three	12
4A-(i)	**Heat transfer through single flat furnace wall :** Consider that a wall is made of material of thermal conductivity K & is of uniform thickness (x) & constant cross sectional area (A) .Assume K is	2

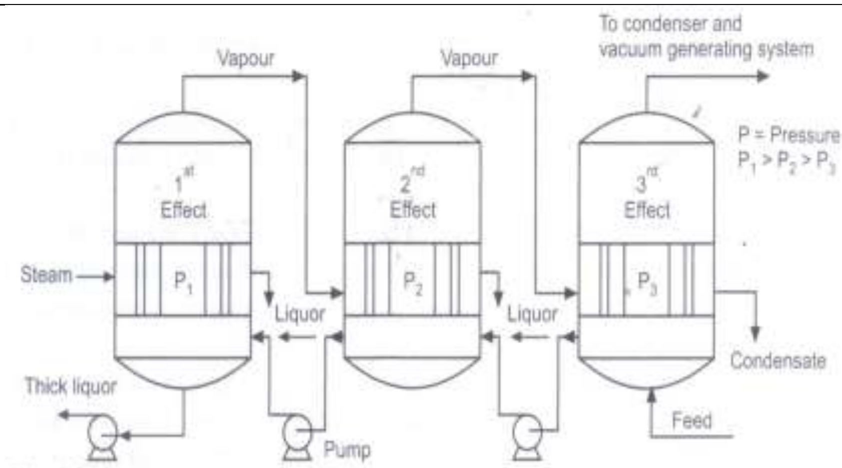
	independent of temperature & heat losses to atmosphere is negligible. Hot face is at a temperature T_1 & cold face is at a temperature T_2. The direction of heat flow is perpendicular to the wall & T varies in direction of X-axis.  At Steady State, there can be neither accumulation nor depletion of heat within a plane wall &Q is constant along heat flow. The ordinary use of Fourier's Law requires that the differential eqn is integrated over entire path from x = 0,x = x. $\therefore Q = -K\, AdT/dx$ $Q\, dx = -K\, A\, dT$ OR $Q \int_0^x dx = -K\, A \int_{T1}^{T2} .dt$ $Q.x = -K\, A\, (T_2 - T_1)$ OR $Q = K\, A\, (T_2 - T_1) / x$	2
4A-(ii)	**Forward feed and backward feed arrangements: (any 4)**	1 mark each

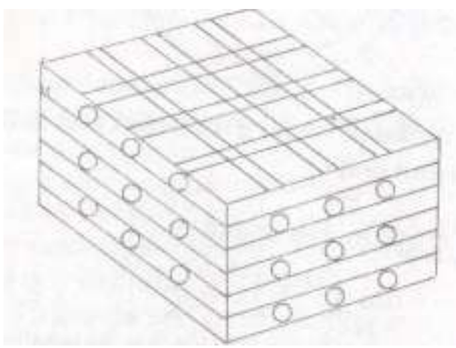
Forward feed	**Backward feed**
Flow of solution to be concentrated is parallel to steam flow.	Flow of solution to be concentrated is in opposite direction to steam flow.

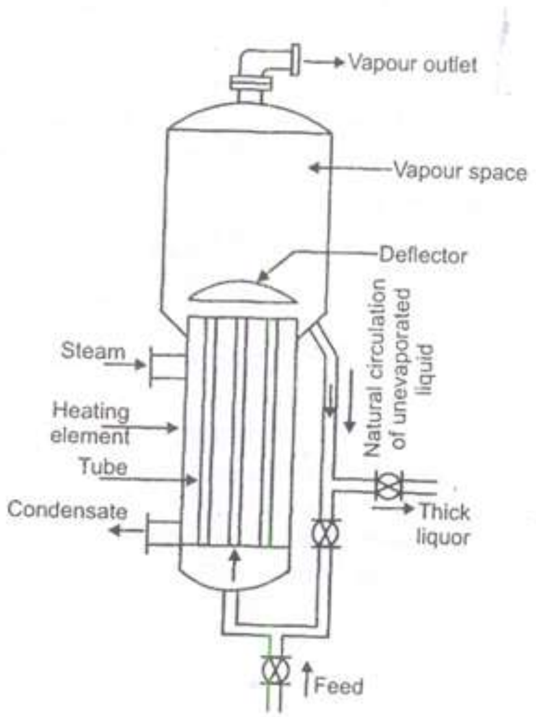
Does not need pump for moving the solution from effect to effect.	Need pump for moving the solution from effect to effect.
As all heating of cold feed solution is done in first effect, less vapour is produced , so lower economy.	Solution is heated in each effect , result in better economy.
The most concentrated liquor is in the last effect where temperature is lowest and viscosity is highest , leads to reduction in capacity.	The most concentrated liquor is in the first effect where temperature is highest and viscosity is lowest , Thus high overall coefficient.
Maintenance charges and power cost are low	Maintenance charges and power cost are more.
Most common as it is simple to operate	Not very common as it need pump.
More economical in steam.	At low values of feed temperature higher economy.



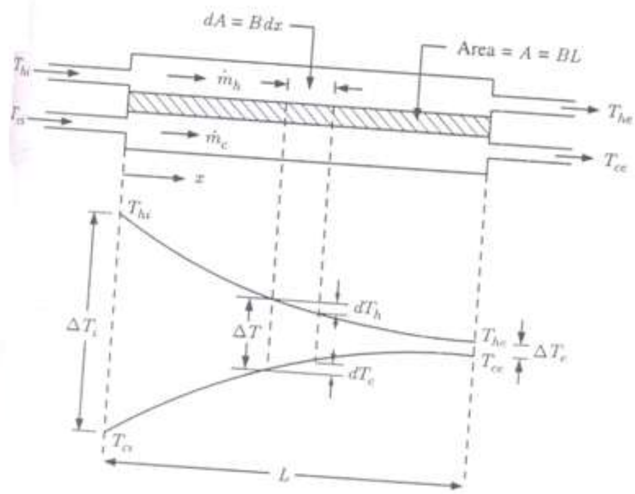
Forward feed arrangement

	 **Backward feed arrangement**	
4A-(iii)	Solution: Q/A = $\frac{\sigma.(T1^4 - T2^4)}{\frac{1}{e1} + (\frac{1}{e2} - 1)}$ σ = 5.67×10^{-8} W/$m^2.k^4$ e_1 = 0.85 , e_2 = 0.75 T_1 = 703 k T_2 = 513k $(Q/A)_r$ = $\frac{5.67\times10^{-8} \times(703^4 - 513^4)}{\frac{1}{0.85} + (\frac{1}{0.75} - 1)}$ = **6571.48 W**	1 1 1 1
4A-(iv)	**Graphite block heat exchanger:** Graphite heat exchangers are well suited for handling corrosive fluids. Graphite is inert towards most corrosive fluids and has very high thermal	2

	conductivity. Graphite being soft, these exchangers are made in cubic or cylindrical blocks. In cubic exchangers, parallel holes are drilled in a solid cube such that parallel holes of a particular row are at right angles to the holes of the row above & below. Headers bolted to the opposite sides of the vertical faces of the cube provide the flow of process fluid through the block. The headers located on the remaining vertical faces direct the service fluid through the exchanger in a cross flow. 	2
4 B	**Any one**	6
4B-(i)	let area = 1 m^2 Thermal resistance o fire brick = x_1/k_1 A R_1 = 0.23/1.21x1 **= 0.190 k/w** Similarly R_2 = x_2/k_2 A = 0.075/0.121x1 = **0.62 k/w** R_3 = x_3/k_3 A = 0.089/0.865x1= **0.103 k/w** R = $R_1 + R_2 + R_3$ R = **0.913 k/w** The heat loss per unit area is Q = ΔT/R ΔT = (1073 – 333) = 740 k Q=740/0.913 = **810.51W** Q= $(T_1-T_2) / R_1$ where T_2 is the temp at interface between fire brick and insulating brick	1 2 1

	810.51 = (1073-T_2) / 0.19 Or **T_2= 919 K** Q= (T_2-T_3) / R_2 where T_3 is the temp at interface between insulating brick and red brick 810.51 = (919-T_3) / 0.62 Or T_3= **416.48 K**	 1 1
4B-(ii)	**Long tube vertical evaporator**  **Construction:** A long tube evaporator consist of a long tubular heating element incorporating tubes 25mm to 50mm in diameter and 4to 8 m in length. The tubular heating element projects into a vapour space for removing entrained liquid from the vapour. The upper tubesheet of tubular exchanger is free and a vapour deflector is incorporated in the vapour space just above it. A return	2

	pipe connecting the vapour space to the bottom of the exchanger is provided for natural circulation of a unvapourised liquid. It is provided with inlet connection for feed, steam and outlet connections for vapour, thick liquor ,condensate etc. **Working:** In this evaporator feed enters the bottom of the tubes,gates heated by the condensing steam, starts to boil part way up the tubes and the mixture of vap. and liquid comes out from the top of the tubes and finally impinges at high velocity on a deflector. The deflector acts both as a primary separator and foam breaker. The separated liquid enters the bottom of the exchanger and parts of this liquid is taken out as a product. This type of evaporator is widely used for handling of foamy, frothy liquids. It is typically used for the production of condensed milk and concentrating black liquor in the pulp and paper industry.	2 2
5	Any two	16
5-a	**To derive Q=UA ΔT_{lm}** **Assumptions:** 1. Overall coefficient U is constant throughout the exchanger 2. Specific heats of hot and cold fluids are constant 3. Heat flow to and from the ambient is negligible 4. Flow is steady and may be parallel or counter current type 5. Temperatures of both the fluids are uniform over a given cross section and may be represented by their bulk temperature.	2



1

Consider an elementary area dA(=B.dx). The rate of heat transfer across it is given by

dq= U (Th-Tc) B dx -------------(1)

Since there are no losses to the surroundings, the heat transfer rate is also equal to the rate of change of enthalpy on either side. Therefore,

dq= -mh Cph dTh-------------------(2)

= mc Cpc dTc ----------------------(3)

Now ΔT = Th- Tc -----------------(4) 1

On differentiating

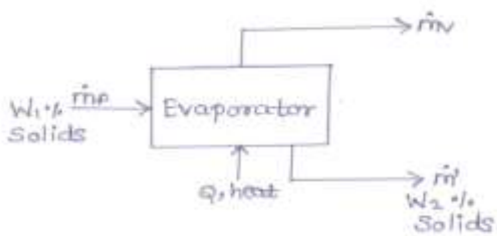
d(ΔT) =dTh- dTc -------------------------------------(5)

substituting for dq, dTh and dTc from equations (1), (2) and (3) into equation (5) , we obtain 1

d(ΔT)/ ΔT= - (1/(mh Cph) + 1/(mc Cpc)) U B dx

ΔTe

	$\int_{\Delta Ti} d(\Delta T)/ \Delta T = - (1/(mh\ Cph) + 1/(mc\ Cpc))\ U\ B\int_0^L dx$ $\ln (\Delta Te/ \Delta Ti) = - (1/(mh\ Cph) + 1/(mc\ Cpc))\ U\ A$ ------------------------------(6) where $\Delta Te = T_{he}-T_{ce}$ $\Delta Ti= T_{hi} - T_{ci}$ Now if q is the total rate of heat transfer in the heat exchanger, then $q = m_hCp_h (T_{hi}-T_{he})$ -----------------------------(7) $= mc\ Cpc\ (T_{ce}- T_{ci})$ --------------------------(8) Substituting equations (7) and (8) into equation (6), $\ln (\Delta Te/ \Delta Ti) = -1/q[(T_{hi}-T_{he}) + (T_{ce}- T_{ci})]U\ A$ $q= U\ A\ (\Delta Ti- \Delta Te)/ \ln (\Delta Ti/ \Delta Te)$ -----------------------------(9) Equation (9) is the performance equation for a parallel-flow heat exchanger. **Q= U A ΔTlm** Where $\Delta Tlm= (\Delta Ti- \Delta Te)/ \ln (\Delta Ti/ \Delta Te)$	1 1 1
5-b	**Material balance equation for single effect evaporator:** Consider that the evaporator is fed with m_f kg/h of weak solution containing w_1 % solute & thick liquor is withdrawn at m' kg/h containing w_2 % solids by weight. Let m_v be the kg/h of water evaporated. Then :	1

		1
	Overall material balance : $m_f = m_v + m$….(i)	1
	Material balance of solute : Solute in feed = Solute in thick liquor $W_1 \times m_f/100 = w_2\, m' / 100$ $W_1 \times m_f = w_2\, m'$……(ii)	1
	Knowing three out of five quantities ,we can find the values of other two with the help of above two equations. **Energy balance equation for single effect evaporator:** Let Tf , T and Ts be the temperatures of feed entering the evaporator , solutions in the evaporators and condensing steam respectively.	1
	Let 'λs' be the latent heat of condensation of steam at saturation temperature and assume that only latent heat of condensation is used. Then, rate of heat transfer through heating surface from steam is : $Q_s = m_s\, \lambda_s$….(iii) Where m_s is mass flowrate of steam to the evaporator in kg/h. Heat transfer rate on steam side = Heat transfer rate on liquor side.	1
	Enthalpy balance can be written in terms of specific heats & temperatures of solutions , in case of solutions having negligible heats of dilution.	

	Heat transfer to solution in evaporator by condensing steam (in absece of heat losses) is utilised to heat the feed solution from Tf to T and for vaporisation of water from solution. $Qs = Q$ $= m_f\ Cpf\ (T - T_f) + (m_f - m')\ \lambda_v$…….(vii) $m_s\ .\ \lambda_s = mf\ Cpf\ (T - T_f) + (m_f - m')\ \lambda_v$…..(viii) where Cp_f = specific heat of feed solution λ_v = latent heat of evaporation from thick liquor For negligible boiling point rise $\lambda v = \lambda$ Where λ =latent heat of vaporisation of water at pressure in the Vapour space & can be read from steam tables. Above equation (viii) becomes : $m_s\ \lambda_s = m_f\ Cp_f\ (T - T_f) + (m_f - m')\ \lambda$……(ix) $m_s\ \lambda_s = m_f\ Cp_f\ (T - T_f) + m_v\ \lambda$…..(x)	1 1
5-c	**The Sider –Tate equation is** $hi\ Di/k = 0.023\ (NRe)^{0.8}\ (Npr)^{1/3}\ (\mu/\mu w)^{0.14}$ Substituting all the values in the equation we get $hi\ (0.02)/0.25 = 0.023 \times (15745)^{0.8}(36)^{1/3} \times ((550 \times 10^{-6})/(900 \times 10^{-6}))^{0.14}$ hi (0.02)/0.25 = 0.023 x 2278.84 x 3.3 x 0.933 hi (0.02)/0.25 = 161.37 hi= 2017 **Inside heat transfer coefficient = 2017 W/m^2 .K**	2 2 2 2
6	Any two	16
6-a	**Dimensional Analysis :** It is a method of correlating a number of variables into a single equation expressing an effect.	2

	Dimensional analysis is a method of reducing the number of variables required to describe a given physical situation by making use of the information implied by the units of the physical quantities involved. It is also known as the "theory of similarity".	
	Dittus – Bolter equation:	
	$hD/k = 0.023[(Du\rho/ \mu)^{0.8}(Cp\ \mu/k)^{a}$	1
	where a= 0.4 for heating a= 0.3 for cooling. where h= film heat transfer coefficient D= diameter of pipe line μ= viscosity of the liquid μw= viscosity of the liquid at the wall surface temp Cp= specific heat of the liquid L= length of pipe. k= thermal conductivity u= velocity of flow	2
	The Sider –Tate equation is	
	$hi\ Di/k = 0.023\ (NRe)^{0.8}\ (Npr)^{1/3}\ (\mu/\mu w)^{0.14}$	1
	where h= film heat transfer coefficient D= diameter of pipe line μ= viscosity of the liquid μw= viscosity of the liquid at the wall surface temp Cp= specific heat of the liquid L= length of pipe. k= thermal conductivity u= velocity of flow	2

6-b	328 K —Cold fluid→ 358 K (t_1) 328 —Cold fluid→ 358 K (t_2) 578 K —Thermic fluid→ 433 K 433 K ←Thermic fluid— 578 K (T_1) Co-current flow Counter current flow **co current flow** $\Delta T_1 = 578 - 328 = 250$ K $\Delta T_2 = 433 - 358 = 75$ K $\text{LMTD} = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T1}{\Delta T2})} = \frac{250-75}{\ln(\frac{250}{75})} = 145.35\text{K}$ Total heat transferred Q = U A LMTD = 700 * 500 * 145.35 = **50873242.14 W or 50873.242 kW** **counter current flow** $\Delta T_1 = 433 - 328 = 105$ K $\Delta T_2 = 578 - 358 = 220$ K $\text{LMTD} = \frac{\Delta T1 - \Delta T2}{\ln(\frac{\Delta T1}{\Delta T2})} = \frac{105-220}{\ln(\frac{105}{220})} = 155.48\text{K}$ Total heat transferred Q = U A LMTD = 700 * 500 * 155.48 = **54416364.83 W or 54416.364 kW**	2 1 1 1 1 1 1
6-c	Basis: 5000 kg/hr feed is fed to the evaporator. Material balance of solids:	

	Solids in feed= solids in the thick liquor	1
	0.01x5000=0.4 x m'	
	m'=1250kg/h.	
	overall Material balance:	
	kg/h feed= kg/h water evaporated + kg/h thick liquor	1
	water evaporated(m_v)=5000-1750=3750kg/h	
	Energy balance is	
	$m_s \lambda_s = m^* c_{pf} *(T-T_f) + m_v \lambda_v$	1
	m_s 2162 = 5000*4.187*(373-313) + 3750 (2676-419)	
	steam fed(m_s)= 4495.77 kg/h	1
	steam economy= kg/h water evaporated/kg/h steam consumed	
	= 3750/4495.77=**0.834**	1
	Q= U*A*****ΔT	1
	4495.77*2162*1000/ 3600 = 1750 * A*(373-313)	
	A = **45.38 m^2**	2