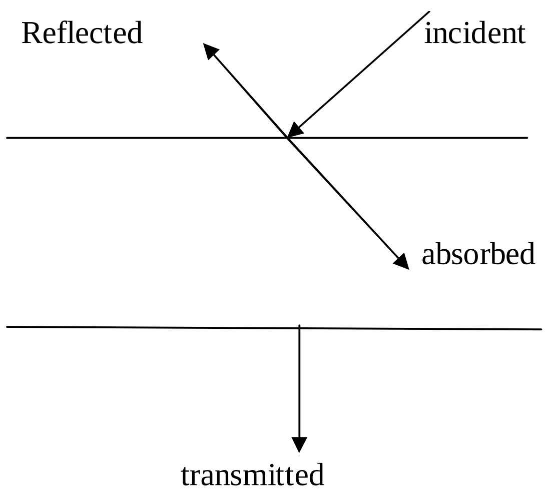
WINTER-15 EXAMINATION

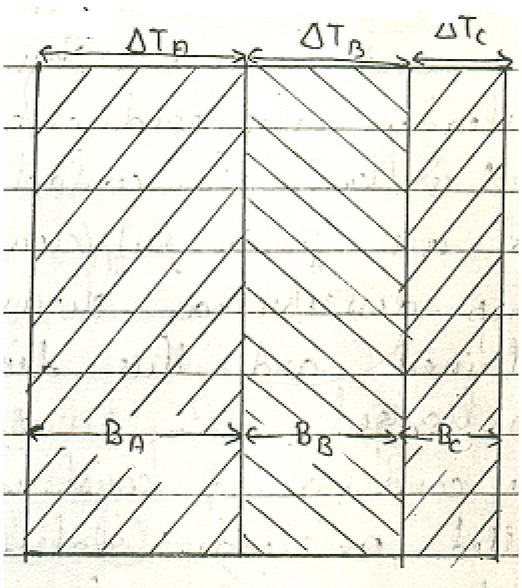
Model Answer

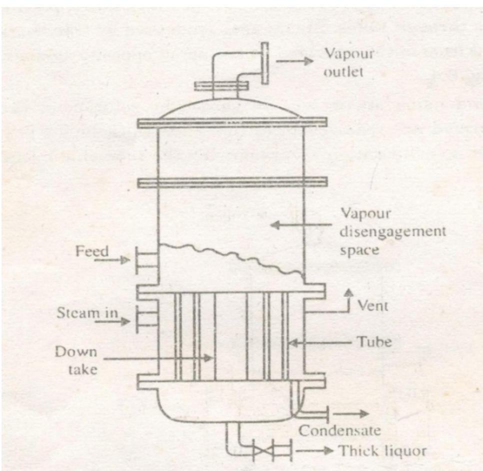
Important Instructions to examiners:

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.

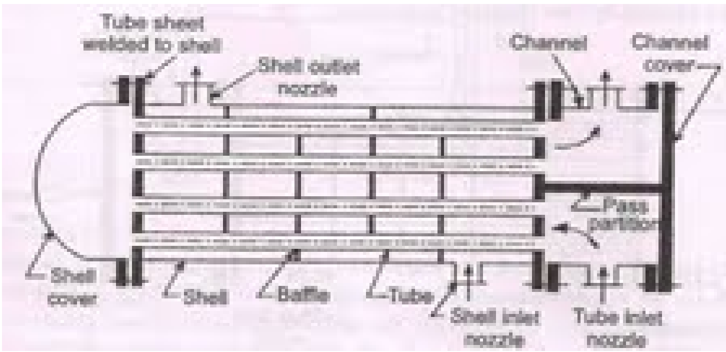
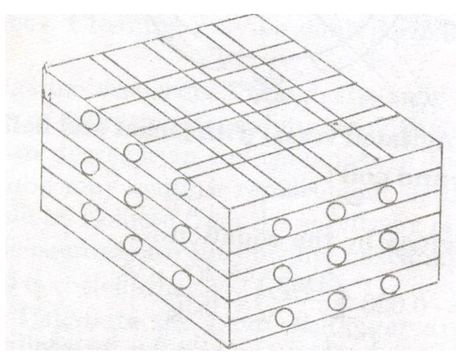
Q No.	Answer	marks	Total marks
1 A	Any three		12
1A-a	**Modes of heat transfer are:** **1. Conduction** **2. Convection** **3. Radiation** 1) **Conduction :** If a temperature gradient exist in a continuous substance, heat can flow unaccompanied by any observable motion of mater. Heat flow of this kind is called conduction. 2) **Convection** : When a macroscopic particle of fluid crosses a specific surface, it carries with it a definite quantity of enthalpy. Such a flow of enthalpy is called convection. 3) **Radiation** : Radiation is transfer of energy through space by electromagnetic waves.	1 1 1 1	4
1A-b	**Absorptivity (α):** It is defined as the fraction of radiation falling on a body which is getting absorbed. **Reflectivity (ρ) :** It is defined as the fraction of radiation falling on a body which is getting reflected. **Transmissivity (τ) :** It is defined as the fraction of radiation falling on a body which is getting transmitted. **The relation between the three are** : $(\alpha)+(\rho)+(\tau) = 1$	1 1 1	4

		1	
1A-c	**Types of convection:** 1. **Natural convection** : If the currents are the result of buoyancy forces generated by differences in density and the differences in density are in turn caused by temperature gradient the action is called natural convection. **Example**: heating of water by hot surface **2. Forced convection** : If the currents are set in motion by the action of a mechanical device such as a pump or agitator, the flow is called forced convection. **Example:** heat flow to a fluid pumped through a heated pipe	1 1 1 1	4
1A-d	**Heat Exchanger:** It is an equipment that allows exchange of heat between hot and cold process streams. **Heat transfer equipments:** 1. Cooler: To cool process fluid by means of water or atmospheric air. 2. Condenser: To condense a vapour or mixture of vapours. 3. Chiller: To cool a process fluid to a temperature below that can be obtained by using water as a cooling media	1 1 mark each for any 3	4

	4. Heater: Which imparts sensible heat to process fluid. 5. Vaporiser: Which vaporizes part of liquid. 6. Reboiler: Employed to meet latent heat requirement at the bottom of distillation column. 7. Evaporator: To concentrate a solution by evaporating water.		
1.B	**Any one**		6
1B-a	**Heat loss through a composite wall:**  Consider a flat wall constructed of a series of layers of thickness x1, x2, x3 respectively. Let the thermal conductivities of layers be K_1, K_2, K_3 . Let ΔT1, ΔT2, ΔT3 be the temperature drop across the layers. Let ΔT be the total temperature drop across the entire wall. $\Delta T = \Delta T_A + \Delta T_B + \Delta T_C$ $\Delta T_A = q_1 * B_A / K_1 * A$ $\Delta T_B = q_2 * B_B / K_2 * A$ $\Delta T_C = q_3 * B_C / K_3 * A$ Where A is the area of the wall at right angle to the plane Then $\Delta T = q_1 * B_A / K_1 * A + q_2 * B_B / K_2 * A + q_3 * B_C / K_3 * A$	2 2	6

	In steady state conduction, all the heat passes through the first resistance should pass through second and third. So $q_1 = q_2 = q_3$ $\Delta T = q[B_A/K_1*A + B_B/K_2*A + B_C/K_3*A]$ $= q[R_1+R_2+R_3]$ OR $q = \Delta T/[R_1+R_2+R_3]$ But $q = \Delta T/R$ Therefore : $R = R_1+R_2+R_3$ In heat flow through a series of layers the overall resistance is equal to the sum of individual resistances.	2	
1B-b	**Short tube evaporator:**  **Construction:** It consists of vertical cylindrical shell incorporating short vertical tube bundle with horizontal tube sheet. Vapour inlet is provided at top cover while thick liquor discharge is provided at bottom. Downtake is provided at centre of tube bundle for circulating cooler liquid back to the bottom of the tubes. Solution to be evaporated is inside the tubes and steam flows outside the tubes in the steam chest. Baffles are incorporated in steam chest to promote uniform distribution of steam. The condensate is withdrawn at a point near lower tube sheet, while non condensable gas is vented to atmosphere from point	2 2	6

	near top tube sheet. **Working:** Thin liquor is introduced to the tube side and steam into steam chest . The liquor covers top of tubes. Heat transfer to boiling liquid inside the tubes take place from condensing steam on outside of tubes. Vapours formed will rise through the tubes, come to the liquid surface from which they are disengaged into the vapour space and removed from the vapour outlet. Thick liquor is removed from the bottom of the evaporator.	2	
2	Any four		16
2-a	**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 **Thermal conductivity** : It is a physical property of substance through which heat flows. It is defined as amount of heat flows per unit time through unit area when temperature difference is unity.	2 2	4
2-b	r1= 20 mm = 0.02 m r2= 70 mm = 0.07 m T1-T2 = 570-300 = 270 K K= 17.5 W/(mK) Heat transferred Q= 4Πk r1r2(T1-T2)/ (r2-r1) = 4Π*17.5*0.02*0.07(270)/(0.07-0.02)	 2 1	4

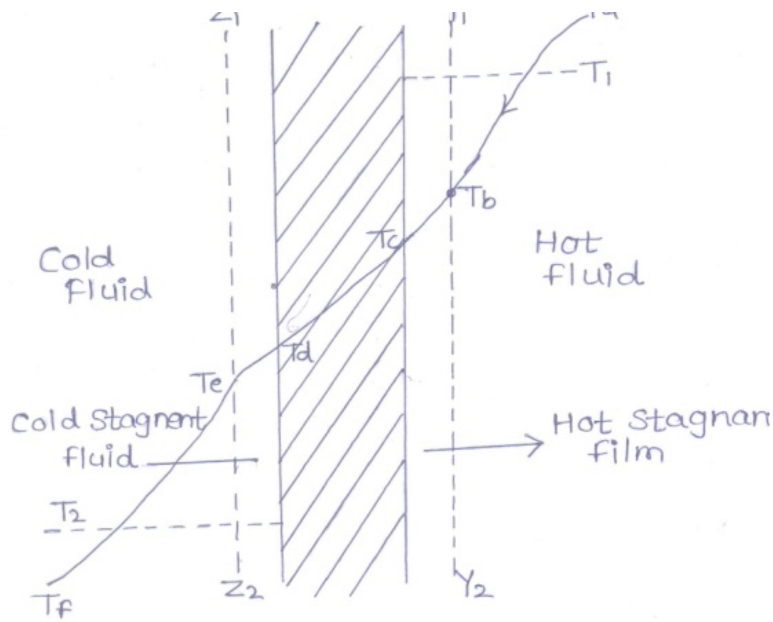
	= **1661.69 W**	1	
2-c	**1-2 shell and tube heat exchanger:**  	4	4
2-d	**Graphite block heat exchanger:** Graphite heat exchangers are well suited for handling corrosive fluids. Graphite is inert towards most corrosive fluids and has very high thermal conductivity. Graphite being soft, these exchangers 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. 	3	4

	Applications of graphite block h.e. i) It is used for very explosive liquid. ii) ii) It can be used for Corrosive Fluid.	1	
2-e	**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 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.	2	4

	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	
3	**Any two**		16
3-a	**Relationship between overall and individual heat transfer coefficients**: Consider a hot fluid flowing through a circular pipe & a cold fluid flowing on the outside of the pipe. Heat is flowing from the hot fluid to the bulk of cold fluid through a Series of resistances. (i) When heat is flowing from bulk of hot fluid to the metal wall , although heat transfer in bulk fluid takes by convection current ,there is a very small layer of fluid near the pipe in which heat transfer takes place by conduction. This is because flow in this layer is laminar & there is no mixing of molecules. This layer is known as viscous sublayer. This thin film of fluid flowing in Laminar flow is of great importance in determining the rate of heat transfer. The Thermal conductivity of fluid is very low so that resistance offered by this film is very large through the film is thin. (ii) When heat across metal wall resistance is comparatively low.	2	8

(iii) When heat transfer takes place from metal to the bulk of fluid there exists a thin film of cold fluid which has a high resistance.

(iv) Heat then flows from this thin film to bulk of cold fluid by convection.The process of heat transfer from bulk of hot fluid to bulk of cold fluid is represented by fig.



2

Y1, y2 represents thin film on hot side in which liquid is flowing in Laminar flow.

Ta – Tb –Tc is temperature drop from bulk of hot fluid to metal wall on hot side.

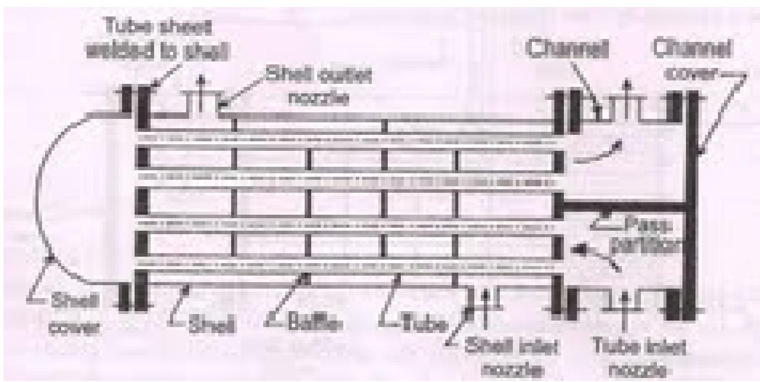
T_1 = is Avarage temperature on hot side

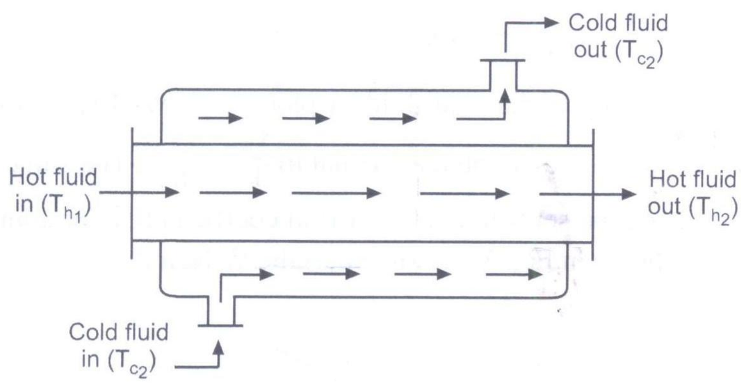
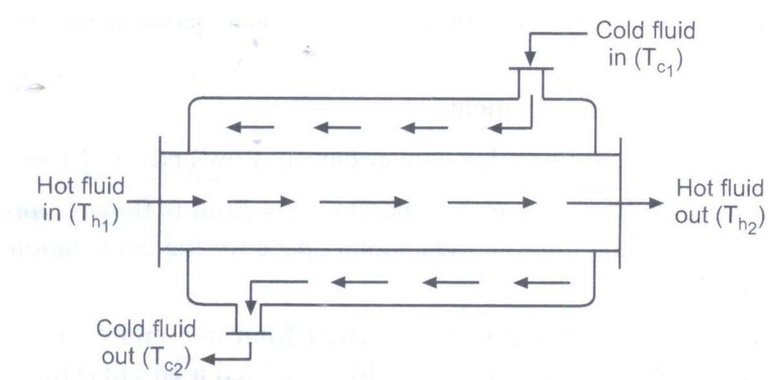
Z_1 Z_2 represents thin film on cold side in which liquid is flowing in Laminar flow.

Td –Te – Tf is temperature drop from metal wall to the bulk of cold fluid.

	T2 is average temperature on cold side. The rate of heat tranfer on hot side liquid is given by $Q = k_i A_i (Ta - Tc)/x_1$ ……..(i) The effective thickness x_1 depends on nature of flow , nature of surface and is generally not known. Therefore an indirect method of calculating heat transfer rate is by use of inside heat transfer coefficient represented by hi. Rate equation is usually written as Q =hi Ai (Ta – Tc) ……..(ii) Comparing equation (i) & (ii), $hi = k_1/x_1$ Resistance for heat tranfer is given as $R = x/k_A = 1/K/x(A) = 1/hiAi$ Resistance offered by film on hot side= 1/hiAo = Resistance of metal wall = L/KmAm = Resistance of thin film on cold fluid =1/hoAo So effectively heat tranfer is across this there is Q1 +Q2 +Q3 films. At Steady State, Q1 = Q2 = Q3= Q=Constant . ..Q =Δt/R1+R2+R3 Q = T1 –T2/[(1/hiAi)+(Lm/R Am)+(1/hoAo)] …….(i) We multiply N & D by Ai=area of heat transfer on hot side,we get Q = (T1-T2)Ai / [(1/hiAi)+(Lm/Km.Am + (1/ho.Ao)] Ai	1 1 1	

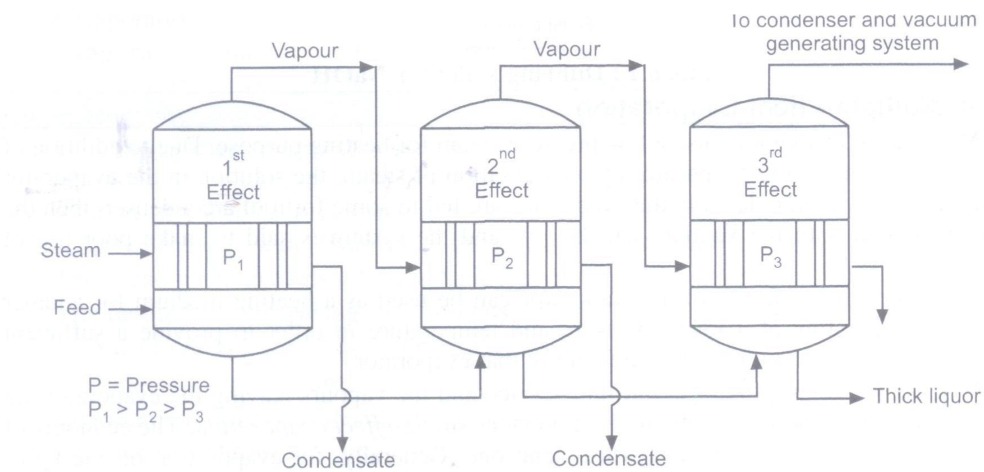
	=(T1-T2) Ai [(1/hi)+(Lm/Km.Ai/Am)+(1/ho.Ai/Ao)] Since pipes are circular, $A = 2\pi rl$ = (T1-T2)Ai[(1/hi)+(Lm/Km.2πri L/2πrm L)+(1/ho.2πri /2πro)] = (T1-T2)Ai[(1/hi)+(Lm/Km. ri/ rm)+(1/ho. . ri/ ro)] We assume a new parameter, Ui = Overall heat transfer coefficient on inside liquid. ... 1/Ui =1/hi + Lm/Km.ri/rm +1/ho ri/ro ……(i)	1	
3-b	Heat load=λ m =7*286 =2002KW =2002000Watt The heat balance over the condenser yields Heat removed from vapours = Heat gained by water $Q = m_1\lambda = m_2Cp_2 (t_2 - t_1)$ $t_2 = 318$ K $t_2 = 303$ K $Cp_2 = 4.187$ KJ/(Kg.K) $2002 = m_2 * 4.187 *(318 - 303)$ $m_2 = 31.879$ kg/s **Mass flow rate of cooling water = 31.87 kg/s**	2 2 2 2	8

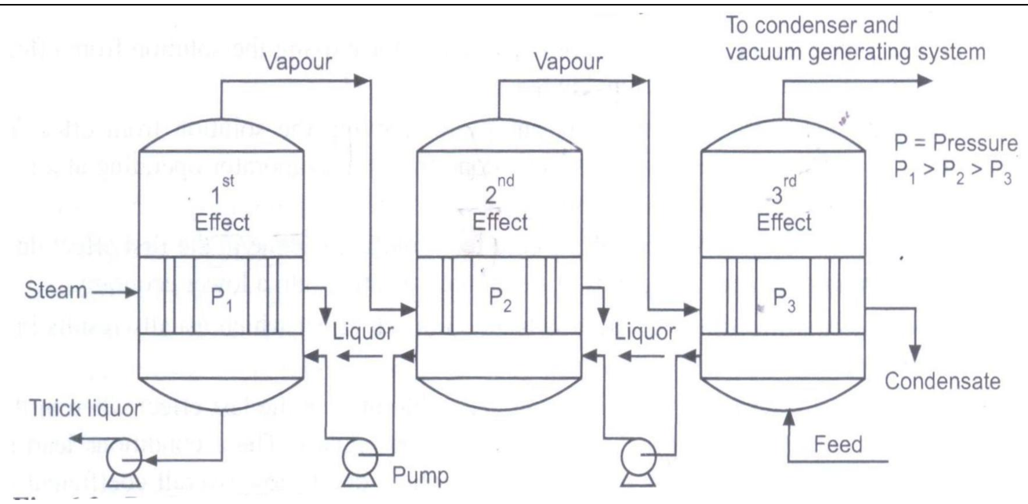
3-c			8
	 	2	
	Construction: In 1-2 Shell and tube heat exchanger the tubes are fixed into two tube sheets and the tube sheets are welded to the shell which also serve as flanges for atttachment of channel and the cover. On one side fo shell, the channel is employed with pass partition to permit the entry and exit of tube side fluid through it. On the other side of shell the cover is clamped to the tube sheet with the help of nuts and bolts to permit the tube side fluid to cross from the first to second pass.The outside of tubes are not accessible for inspection and mechanical cleaning.The shell is provide with nozels for entry and exit of the shell side fluid.	3	
	Working: In this type of heat exchanger the shell side fluid flows once through the exchanger and tube side fluid flows twice to the exchanger.In this exchanger the tube side fluid flows in co current as well as counter cureent fashion with respect to the shell side fluid.	2	
		1	

	Application: For a variety of industrial services where large heat transfer surfaces are required, shell and tube heat exchangers are commonly used.		
4 A	Any three		12
4A-a	 **Co- current/Parallel flow in heat exchanger**  **Counter- current flow in heat exchanger**	2 2	4
4A-b	Basis: 4 m length of pipe Inner radius r1= 20 mm= 0.002 m Outer radius r2= 30 mm=0.003m T_i = 375 K T2 =310 K	1 1	4

	K= 0.300 W/mK		
	r_m= (r2-r1) / ln(r2/r1) = 0.0123	1	
	Heat loss Q = [2π r_m Lk(T1-T2)] / (r_2-r_1)		
	= **1205.61W**	1	
4A-c	The heat loss by radiation per unit area is given by		4
	e = 0.90	1	
	$\sigma = 5.67*10^{-8}$ W/($m^2.K^4$)		
	T_1 = 415 K		
	T_2 = 290K		
	$Q_r/A = e* \sigma * (T_1^4 - T_2^4)$	1	
	$Q_r/A = 0.90*5.67*10^{-8} [(415)^4 - (290)^4]$		
	Q_r/A = 1152.69 W/m^2	2	
4A-d			4
	Evaporation | Drying	1 mark each	

		1	It is an operation in which a weak solution/liquor is concentrated by vaporising a portion of the solvent	It is an operation in which the moisture of a substance is removed by thermal means.			
		2	It is a heat transfer operation.	It is a mass and heat transfer operation.			
		3	Evaporation involves the removal of water as a vapour at its boiling point.	Drying involves the removal of water at a temperature below its boiling point.			
		4	In evaporation operation, the product obtained is a liquid.	In drying operation, the product obtained is a solid.			
4 B	**Any one**						6
4B-a	Fourier's law for heat conduction is $Q = -kA \frac{dT}{dX}$ $Q\ dx = -kA\ dT$ $K = k_0 (1 + aT)$ $Q \int dx = -k_0 A \int (1 + aT) dT$ The limits of integration are At, $x = 0$, $T = T_1$ At, $x = x$, $T = T_2$ $\int_0^x dx = -k_0 A \int_{T_1}^{T_2} (1 + aT) dT$ $Q . x = k_0 A \int_{T_2}^{T_1} (1 + aT) dT$ Integrating, we get					1 1 1	6

	$Q = \frac{AK_0}{X}[(T_1 - T_2) + \frac{a}{2}(T_1^2 - T_2^2)]$ $Q = \frac{AK_0}{X}[(T_1 - T_2) + \frac{a}{2}(T_1 + T_2)(T_1 - T_2)]$ $\mathbf{Q = \frac{AK_0}{X}[1 + \frac{a}{2}(T_1 + T_2)](T_1 - T_2)]}$	1 1 1	
4B-b	 **Forward feed arrangement**	3 3	6

	 **Backward feed arrangement**		
5	Any two		16
5-a	Basis: 30000kg/h feed to the evaporator. Let mf ,m', mv be the mass flow rate of feed, thick liquor and water vapour respectively. **Material balance of solid**: Solids in the feed= solids in the thick liquor 0.10 x 30000=0.05m' m' = 6000kg/h. **overall material balance**: kg/h feed = kg/h water evaporated + kg/h thick liquor water evaporated = mv = 30000-6000 = 24000kg/h. **Feed at 293 k** ms =mass flow rate of steam in kg/h mf = 30000kg/h, mv = 24000kg/h Cpf = 3.98kj/kg.k	1 1 1	8

	Ts= saturation temperature of steam = 393 k T = boiling point of solution = 323K Λs = latent heat of condensation of steam at 0.20 MPa = 2202kj/kg Λ = latent of vaporisation of water at 323 K = 2383 kJ/kg Enthalpy balance over evaporator Q = msΛs = mf Cpf (T-Tf) + mv Λ ms x 2202 = 30000 x 3.98 x (323-293) + 24000x 2383 ms = 27599.5 kg/h. **Steam consumption = 27599.5 kg/h** **Steam economy = 24000/27599.5 = 0.87**	 2 1 2 \	
5-b	At steady state : Heat gained by cold water = Heat removed from hot water Q = mc Cpc (t2-t1) = mhCph (T1-T2) mc = mass flow rate of cold water = 30 kg/s mh = mass flow rate of hot water = 24 kg/s Cpc = Cph = 4.187 kJ/kg k t2 =313 K, t1=298 k ,T1 = 353 K, T2 =? Q= 30 x 4.187 x (313-298) = 1884.15 kJ/s = 1884.15 x 10^3 J/s= 1884.15 x 10^3 w Q= heat gained by cold fluid = Heat lost by hot fluid 1884.15 = 24 X 4.187 (353 – T2) T2 = 334.2 K Δ T1=353-313 =40K, ΔT2= 334.2-298 = 36.2 k Δ Tlm= (40-36.2)/ln(40/36.2) = 38.1 K A= Q/ (U Δ Tlm) = 1884.15 X 10^3/ (1220 x 38.1) =40.53 m^2 **HEAT TRANSFER AREA REQUIRED = 40.53 m^2**	 1 2 2 1 2	8

5-c	The **logarithmic mean temperature difference** (also known as **log mean temperature difference** or simply by its initialism**LMTD**) is used to determine the temperature driving force for heat transfer in flow systems, most notably in heat exchangers. The LMTD is a logarithmic average of the temperature difference between the hot and cold feeds at each end of the double pipe exchanger. The larger the LMTD, the more heat is transferred. The use of the LMTD arises straightforwardly from the analysis of a heat exchanger with constant flow rate and fluid thermal properties. Understanding the concept of log mean temperature difference or LMTD is very important for heat exchanger design especially for the heat exchangers with no phase change. The LMTD is the driven force for the heat exchange between the two fluids. As the LMTD value increases, the amounts of heat transfer between the two fluids also increase. The LMTD value is used for calculating the heat duty of the heat exchanger. The formula is: **Q = U * A * LMTD** Where, Q – Heat duty of the heat exchanger (in *watts*) U – Heat transfer co-efficient (in *watts/Kelvin/Meter square*) A – Heat transfer area (in meter square)	3	8
	Assume heat transfer is occurring in a heat exchanger along an axis *z*, from generic coordinate *A* to *B*, between two fluids, identified as *1* and *2*, whose temperatures along *z* are $T_1(z)$ and $T_2(z)$. The local exchanged heat flux at *z* is proportional to the temperature difference:	5	

$$q(z) = U(T_2(z) - T_1(z))/D = U(\Delta T(z))/D,$$

where D is the distance between the two fluids.

The heat that leaves the fluids causes a temperature gradient according to Fourier's law:

$$\frac{dT_1}{dz} = k_a(T_1(z) - T_2(z)) = -k_a\,\Delta T(z)$$

$$\frac{dT_2}{dz} = k_b(T_2(z) - T_1(z)) = k_b\,\Delta T(z)$$

Summed together, this becomes

$$\frac{d\,\Delta T}{dz} = \frac{d\,(T_2 - T_1)}{dz} = \frac{dT_2}{dz} - \frac{dT_1}{dz} = K\Delta T(z)$$

where $K=k_a+k_b$.

The total exchanged energy is found by integrating the local heat transfer q from A to B:

$$Q = \int_A^B q(z)dz = \frac{U}{D}\int_A^B \Delta T(z)dz = \frac{U}{D}\int_A^B \Delta T\,dz$$

Use the fact that the heat exchanger area Ar is the pipe length A-B multiplied by the interpipe distance D:

$$Q = \frac{UAr}{(B-A)}\int_A^B \Delta T\,dz = \frac{UAr\int_A^B \Delta T\,dz}{\int_A^B dz}$$

In both integrals, make a change of variables from z to ΔT:

	$$Q=\frac{U\,Ar\int_{\Delta T(A)}^{\Delta T(B)}\Delta T\frac{dz}{d\Delta T}\,d(\Delta T)}{\int_{\Delta T(A)}^{\Delta T(B)}\frac{dz}{d\Delta T}\,d(\Delta T)}$$ With the relation for ΔT found above, this becomes $$Q=\frac{U\,Ar\int_{\Delta T(A)}^{\Delta T(B)}\frac{1}{K}\,d(\Delta T)}{\int_{\Delta T(A)}^{\Delta T(B)}\frac{1}{K\Delta T}\,d(\Delta T)}$$ Integration is at this point trivial, and finally gives: $$Q=U\times Ar\times\frac{\Delta T(B)-\Delta T(A)}{\ln[\Delta T(B)/\Delta T(A)]},$$ from which the definition of LMTD follows.		
6	Any two		16
6-a	**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 x $(15745)^{0.8}(36)^{1/3}$ x $((550 \times 10^{-6})/(900 \times 10^{-6}))^{0.14}$ 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**	 3 2 3	8
6-b	**Condensation** is the change of the physical state of matter from gas phase into liquid phase, and is the reverse of evaporation. **Boiling** is the rapid vaporization of a liquid, which occurs when a liquid is	1 1	8

	heated to its boiling point, the temperature at which thevapour pressure of the liquid is equal to the pressure exerted on the liquid by the surrounding environmental pressure. There are two idealized models of condensation (i.e., filmwise and dropwise). The former occurs on a cooled surface which is easily wetted. The vapor condenses in drops which grow by further condensation and coalesce to form a film over the surface, if the surface-fluid combination is wettable; if the surface is non-wetting rivulets of liquid flow away and new drops then begin to form. Difference between **filmwise** and **dropwise condensation** Vapour may condense onto a cooled surface in two distinct modes known as **filmwise** and **dropwise**. For the same temperature difference between the vapour and the surface, dropwise condensation is several more times effective than filmwise. However it involves special surface finishes or treatment in order to maintain dropwise condensation and for this reason, though desirable, it seldom occurs in real plant operation. The process of dropwise condensation is enhanced by the special water cooled condenser surface finish that prevents wetting of the surface. Condensation then occurs in droplets which grow and fall under gravity. These falling droplets wipe the surface clean ready for more droplets to form. This continuous cleaning puts the water cooled surface in direct contact with the vapour.	2 1 mark each for any 4	
6-c	The **capacity** of an evaporator is defined as the number of kilogram of water evaporated per hour.	2	8

	The **economy** of an evaporator is defined as the number of kilogram of water evaporated per kilogram of stem fed to the evaporator. **Methods of increasing economy by vapour recompression methods are:** **1.** Mechanical recompression **2.** Thermal recompression **Vapor-recompression evaporation** is the evaporation method by which a blower, compressor or jet ejector is used to compress, and thus, increase the pressure of the vapor produced. Since the pressure increase of the vapor also generates an increase in the condensation temperature, the same vapor can serve as the heating medium for its "mother" liquid or solution being concentrated, from which the vapor was generated to begin with. If no compression was provided, the vapor would be at the same temperature as the boiling liquid/solution, and no heat transfer could take place. If compression is performed by a mechanically driven compressor or blower, this evaporation process is usually referred to as **MVR** (**Mechanical Vapor Recompression**). In case of compression performed by high pressure motive steam ejectors, the process is usually called **Thermocompression** or **Steam Compression**.	2 4	