



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 1 of 23

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.



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page 4 of 23

	$= 84.29 \text{ W}$ <p>$Q = (T_1 - T_2) / R_1$ where T_2 is the temperature at interface</p> $84.29 = (423 - T_2) / 3.37 \times 10^{-4}$ <p>$T_2 = 422.97 \text{ K}$</p>	1 1
1B- (ii)	<p>Methods of increasing the economy of an evaporator:</p> <ol style="list-style-type: none">Using multiple effect evaporatorVapour recompression <p>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.</p> <p>B. Methods of increasing economy by vapour recompression methods are:</p> <ol style="list-style-type: none">Mechanical recompressionThermal recompression <p>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.</p>	2 2

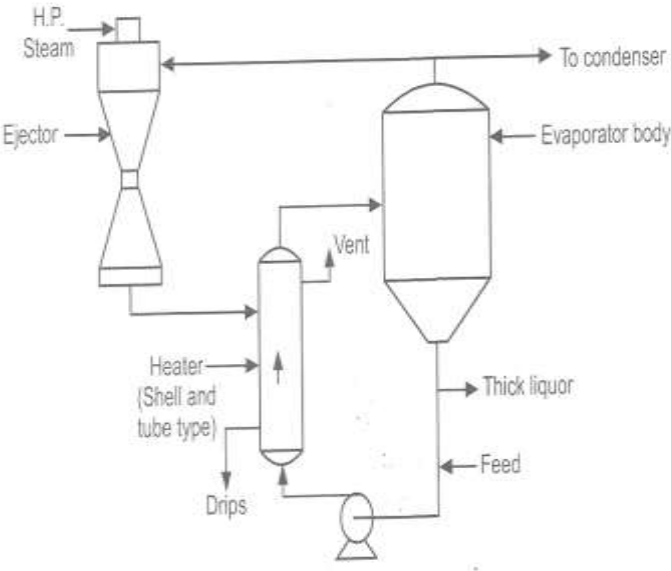


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 5 of 23

		2
2	Any four	16
2-a	<p>Optimum thickness of insulation:</p> <p>The optimum thickness of an insulation is the one at which the total annual cost of the insulation is minimum</p> <p>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.</p> <p>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</p>	1 2

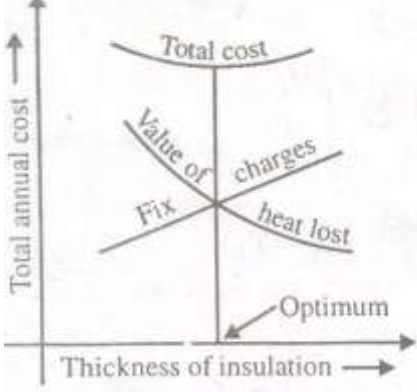


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 6 of 23

	 <p style="text-align: center;">Optimum Thickness Of Insulation</p>	1
2-b	<p>Fourier's law of conduction:</p> <p>It states that the rate of heat flow across an isothermal surface is proportional to the temperature gradient at the surface.</p> $\frac{dQ}{dA} = -k \frac{\delta T}{\delta n}$ <p>Q- rate of heat transfer A- Area perpendicular to heat flow k- Thermal conductivity T- Temperature</p>	2 1 1
2-c	<p>Kirchhoff's Law :</p> <p>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 the non-black body.</p> <p>Let the area of non-black body be A₁ and A₂ respectively. Let 'I' be the rate at</p>	2



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page 7 of 23

	<p>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.</p> <p>At thermal equilibrium, absorption and emission rates are equal, thus,</p> $I_{a_1} A_1 = A_1 E_1 \quad \dots\dots\dots(1.1)$ $\therefore I_{a_1} = E_1 \quad \dots\dots\dots(1.2)$ <p>And $I_{a_b} A_2 = A_2 E_b \quad \dots\dots\dots(1.3)$</p> $I_{a_b} = E_b \quad \dots\dots\dots(1.4)$ <p>From equation (1.1) and (1.4).we get</p> $\frac{E_1}{a_1} = \frac{E_b}{a_b} \quad \dots\dots\dots(1.5)$ <p>Where $a_1, a_b =$ absorptivity of non-black & black bodies respectively.</p> <p>If we introduce a second body (non-black) then for the second non-black body,we have :</p> $I A_3 a_2 = E_2 A_3 \quad \dots\dots\dots(1.6)$ $\therefore I_{a_2} = E_2 \quad \dots\dots\dots(1.7)$ <p>Where $a_1 = E_2$ are the absorptivity and emissive power of the second non-black body.</p> <p>Combining equations (1.2),(1.4) and(1.7) we get,</p> $\frac{E_1}{a_1} = \frac{E_2}{a_2} = \frac{E_3}{a_3} = E_b \quad \dots\dots\dots(1.8)$	2
2-d	<p>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</p>	2

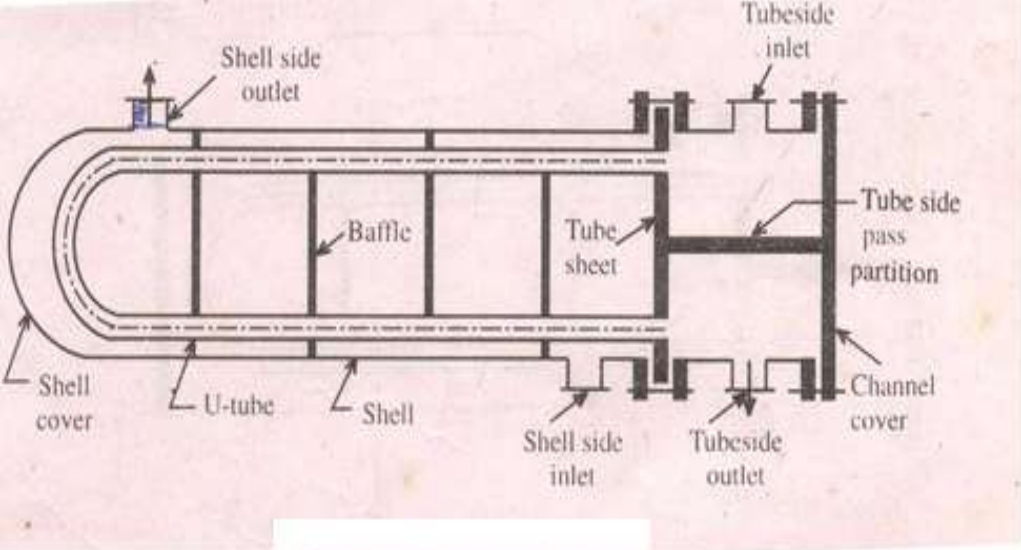


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page **8** of **23**

	<p>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.</p> <p>Used in: Automobile radiator, air cooled steam condensers for turbine and engine works, economiser</p>	1 mark each for any 2
2-e	<p>U tube heat exchanger:</p> 	4
3	Any two	16
3-a	<p>Heat given out by thermic fluid = $20 \times 4.187(360-340)$</p> <p>$Q = 1674.8 \text{ KJ/s} = 1674.8 \times 10^3 \text{ W}$</p> <p>For counter current flow</p> <p>$LMTD = 44 - 40 / \ln(44/40)$</p> <p>$= 41.97$</p> <p>$Q = U \cdot A \cdot LMTD$</p> <p>$U = 2000 \text{ W/m}^2\text{K}$</p> <p>$1674.8 \times 10^3 = 2000 \cdot A \cdot 41.97$</p>	1 2 2 1 1



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page 9 of 23

	A = 19.95 m²	1															
3-b	Dropwise and filmwise condensation:	2 marks each for any 4															
	<table border="1"><thead><tr><th>Points</th><th>Dropwise condensation</th><th>Filmwise condensation</th></tr></thead><tbody><tr><td>mechanism</td><td>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.</td><td>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</td></tr><tr><td>Heat transfer coefficient</td><td>Heat transfer coefficient are very high in case of drop-wise condensation since the heat does not have to flow through film by conduction</td><td>Heat transfer coefficients are relatively very low in case of film-wise condensation since the heat does have to flow through film by conduction</td></tr><tr><td>Surface type</td><td>Oily or greasy surfaces seem to tend towards drop-wise condensation</td><td>Smooth, clean surfaces seem to tend towards film-wise condensation</td></tr><tr><td>Stability</td><td>Drop-wise condensation is very</td><td>Film-wise</td></tr></tbody></table>	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	
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SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 10 of 23

		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) <table border="1" style="width: 100%; border-collapse: collapse; margin-top: 5px;"> <thead> <tr> <th style="width: 50%; text-align: center;">Square pitch</th> <th style="width: 50%; text-align: center;">Triangular pitch</th> </tr> </thead> <tbody> <tr> <td>Permits external cleaning of the tubes</td> <td>Difficult to clean</td> </tr> <tr> <td>Causes low pressure drop on the shell side fluid</td> <td>Causes more pressure drop</td> </tr> <tr> <td>Less no. of tubes can be accommodated than with triangular pitch</td> <td>Larger no. of tubes can be accommodated in a given shell diameter</td> </tr> <tr> <td>Creates comparatively less turbulence</td> <td>Creates large turbulence in the shell side fluid</td> </tr> <tr> <td>Can be used for dirty fluids also</td> <td>Used for clean fluid</td> </tr> </tbody> </table> <p>Use of baffle:</p> <ol style="list-style-type: none"> 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. 			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	1.5 mark each
Square pitch	Triangular pitch															
Permits external cleaning of the tubes	Difficult to clean															
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Creates comparatively less turbulence	Creates large turbulence in the shell side fluid															
Can be used for dirty fluids also	Used for clean fluid															
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												



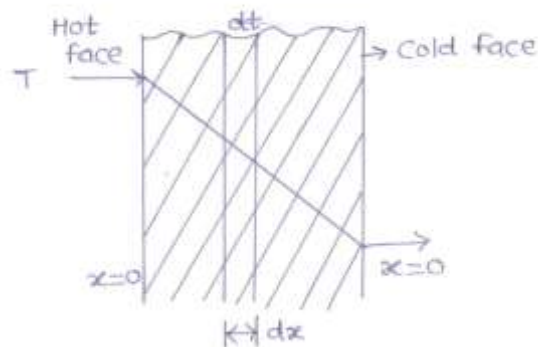
SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 11 of 23

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 $x = 0, x = x$.

$$\therefore Q = -K A dT/dx$$

$$Q dx = -K A dT$$

OR

$$Q \int_0^x dx = -K A \int_{T_1}^{T_2} dt$$

$$Q \cdot x = -K A (T_2 - T_1)$$

OR

$$Q = K A (T_2 - T_1) / x$$

2

4A-
(ii)

Forward feed and backward feed arrangements: (any 4)

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.

1 mark
each



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page **12** of **23**

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

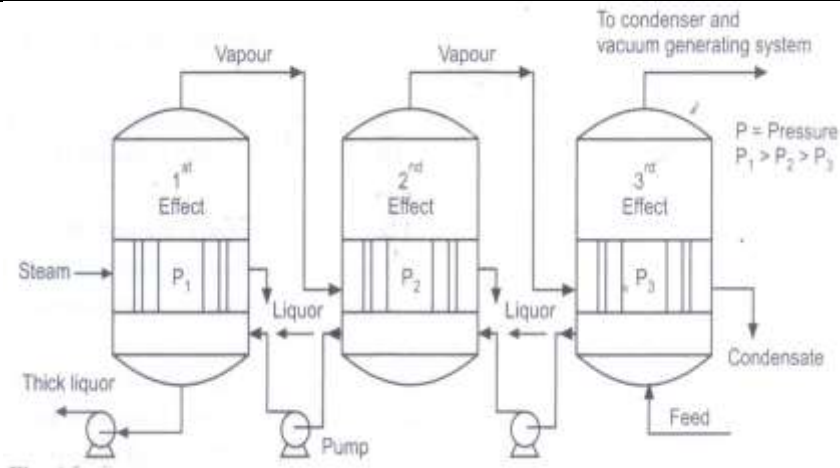


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 13 of 23



Backward feed arrangement

4A-
(iii)

Solution:

$$Q/A = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{e_1} + \left(\frac{1}{e_2} - 1\right)}$$

$$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{k}^4$$

$$e_1 = 0.85, e_2 = 0.75$$

$$T_1 = 703 \text{ k}$$

$$T_2 = 513 \text{ k}$$

$$(Q/A)_r = \frac{5.67 \times 10^{-8} \times (703^4 - 513^4)}{\frac{1}{0.85} + \left(\frac{1}{0.75} - 1\right)}$$

$$= 6571.48 \text{ W}$$

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

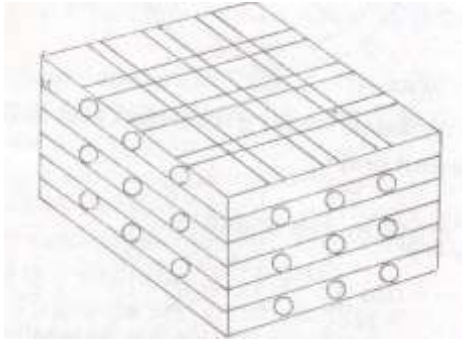


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page **14** of **23**

	<p>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.</p> 	2
4 B	Any one	6
4B-(i)	<p>let area = 1 m²</p> <p>Thermal resistance o fire brick = $x_1/k_1 A$</p> <p>$R_1 = 0.23/1.21 \times 1 = \mathbf{0.190 \text{ k/w}}$</p> <p>Similarly $R_2 = x_2/k_2 A = 0.075/0.121 \times 1 = \mathbf{0.62 \text{ k/w}}$</p> <p>$R_3 = x_3/k_3 A = 0.089/0.865 \times 1 = \mathbf{0.103 \text{ k/w}}$</p> <p>$R = R_1 + R_2 + R_3$</p> <p>$R = \mathbf{0.913 \text{ k/w}}$</p> <p>The heat loss per unit area is $Q = \Delta T/R$</p> <p>$\Delta T = (1073 - 333) = 740 \text{ k}$</p> <p>$Q = 740/0.913 = \mathbf{810.51W}$</p> <p>$Q = (T_1 - T_2) / R_1$ where T_2 is the temp at interface between fire brick and insulating brick</p>	1 2 1

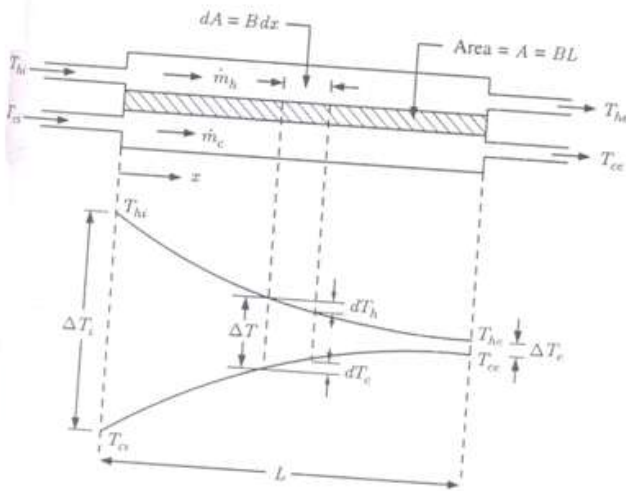


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 17 of 23



1

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

$$dq = U (T_h - T_c) B dx \text{ -----(1)}$$

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,

$$dq = -\dot{m}_h C_{ph} dT_h \text{ -----(2)}$$

$$= \dot{m}_c C_{pc} dT_c \text{ -----(3)}$$

$$\text{Now } \Delta T = T_h - T_c \text{ -----(4)}$$

On differentiating

$$d(\Delta T) = dT_h - dT_c \text{ -----(5)}$$

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

1

1

$$\frac{d(\Delta T)}{\Delta T} = - \left(\frac{1}{\dot{m}_h C_{ph}} + \frac{1}{\dot{m}_c C_{pc}} \right) U B dx$$

ΔT_e



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page **18** of **23**

	<p>$\int_{\Delta T_i} d(\Delta T) / \Delta T = - (1/(m_h C_{ph}) + 1/(m_c C_{pc})) U B \int_0^L dx$</p> <p>$\ln (\Delta T_e / \Delta T_i) = - (1/(m_h C_{ph}) + 1/(m_c C_{pc})) U A \text{ -----(6)}$</p> <p>where $\Delta T_e = T_{he} - T_{ce}$</p> <p>$\Delta T_i = T_{hi} - T_{ci}$</p> <p>Now if q is the total rate of heat transfer in the heat exchanger, then</p> <p>$q = m_h C_{ph} (T_{hi} - T_{he}) \text{ -----(7)}$</p> <p>$= m_c C_{pc} (T_{ce} - T_{ci}) \text{ -----(8)}$</p> <p>Substituting equations (7) and (8) into equation (6),</p> <p>$\ln (\Delta T_e / \Delta T_i) = -1/q [(T_{hi} - T_{he}) + (T_{ce} - T_{ci})] U A$</p> <p>$q = U A (\Delta T_i - \Delta T_e) / \ln (\Delta T_i / \Delta T_e) \text{ -----(9)}$</p> <p>Equation (9) is the performance equation for a parallel-flow heat exchanger.</p> <p>Q = U A ΔT_{lm}</p> <p>Where $\Delta T_{lm} = (\Delta T_i - \Delta T_e) / \ln (\Delta T_i / \Delta T_e)$</p>	<p>1</p> <p>1</p> <p>1</p>
5-b	<p>Material balance equation for single effect evaporator:</p> <p>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 :</p>	1

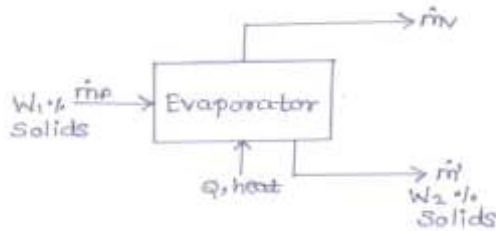


SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: 17560

Page 19 of 23



Overall material balance :

$$m_f = m_v + m \dots (i)$$

Material balance of solute :

Solute in feed = Solute in thick liquor

$$W_1 \times m_f / 100 = W_2 \times m' / 100$$

$$W_1 \times m_f = W_2 \times m' \dots (ii)$$

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 T_f , T and T_s be the temperatures of feed entering the evaporator, solutions in the evaporators and condensing steam respectively.

Let ' λ_s ' 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 :

$$Q_s = m_s \lambda_s \dots (iii)$$

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.

Enthalpy balance can be written in terms of specific heats & temperatures of solutions, in case of solutions having negligible heats of dilution.



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page **20** of **23**

	<p>Heat transfer to solution in evaporator by condensing steam (in absence of heat losses) is utilised to heat the feed solution from T_f to T and for vaporisation of water from solution.</p> $Q_s = Q$ $= m_f C_{pf} (T - T_f) + (m_f - m') \lambda_v \dots \dots (vii)$ $m_s \cdot \lambda_s = m_f C_{pf} (T - T_f) + (m_f - m') \lambda_v \dots \dots (viii)$ <p>where C_{pf} = specific heat of feed solution λ_v = latent heat of evaporation from thick liquor</p> <p>For negligible boiling point rise $\lambda_v = \lambda$</p> <p>Where λ = latent heat of vaporisation of water at pressure in the Vapour space & can be read from steam tables.</p> <p>Above equation (viii) becomes :</p> $m_s \lambda_s = m_f C_{pf} (T - T_f) + (m_f - m') \lambda \dots \dots (ix)$ $m_s \lambda_s = m_f C_{pf} (T - T_f) + m_v \lambda \dots \dots (x)$	<p>1</p> <p>1</p>
5-c	<p>The Sieder –Tate equation is</p> $h_i D_i/k = 0.023 (NRe)^{0.8} (Npr)^{1/3} (\mu/\mu_w)^{0.14}$ <p>Substituting all the values in the equation we get</p> $h_i (0.02)/0.25 = 0.023 \times (15745)^{0.8} (36)^{1/3} \times ((550 \times 10^{-6})/(900 \times 10^{-6}))^{0.14}$ $h_i (0.02)/0.25 = 0.023 \times 2278.84 \times 3.3 \times 0.933$ $h_i (0.02)/0.25 = 161.37$ $h_i = 2017$ <p>Inside heat transfer coefficient = 2017 W/m² .K</p>	<p>2</p> <p>2</p> <p>2</p> <p>2</p>
6	Any two	16
6-a	<p>Dimensional Analysis :</p> <p>It is a method of correlating a number of variables into a single equation expressing an effect.</p>	2



SUMMER-18 EXAMINATION
Model Answer

Subject: Heat Transfer Operation

Subject code: **17560**

Page **21** of **23**

<p>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".</p>	
<p>Dittus – Bolter equation: $hD/k = 0.023[(Du\rho/\mu)^{0.8}(C_p\mu/k)^a]$ where a= 0.4 for heating a= 0.3 for cooling. where h= film heat transfer coefficient D= diameter of pipe line</p>	<p>1</p>
<p>μ= viscosity of the liquid μ_w= 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</p>	<p>2</p>
<p>The Sider –Tate equation is $h_i D_i/k = 0.023 (NRe)^{0.8} (Npr)^{1/3} (\mu/\mu_w)^{0.14}$ where h= film heat transfer coefficient D= diameter of pipe line μ= viscosity of the liquid μ_w= viscosity of the liquid at the wall surface temp</p>	<p>1</p>
<p>Cp= specific heat of the liquid L= length of pipe. k= thermal conductivity u= velocity of flow</p>	<p>2</p>

