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GATE 2022

CHEMICAL ENGINEERING

Exam held on 06/02/2022

Questions & Solutions

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SECTION - A GENERAL APTITUDE

Q.1 Inhaling the smoke from a burning ________ could ________ you quickly.

(a) tire / tier (b) tire / tyre
(c) tyre / tire (d) tyre / tier

Ans. (c)

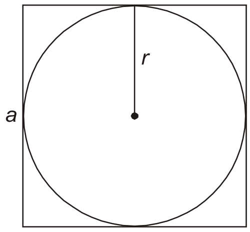
End of Solution

Q.2 A sphere of radius *r* cm is packed in a box of cubical shape.

What should be the minimum volume (in cm^3) of the box that can enclose the sphere?

(a) $\frac{r^3}{8}$ (b) r^3
(c) $2r^3$ (d) $8r^3$

Ans. (d)



$$\begin{aligned}\text{Diameter of sphere} &= \text{Side of cube}\\ a &= 2r\\ \text{Volume of cube} &= (2r)^3\\ &= 8r^3\end{aligned}$$

End of Solution

Q.3 Pipes P and Q can fill a storage tank in full with water in 10 and 6 minutes, respectively. Pipe R draws the water out from the storage tank at a rate of 34 litres per minute. P, Q and R operate at a constant rate.
If it takes one hour to completely empty a full storage tank with all the pipes operating simultaneously, what is the capacity of the storage tank (in litres)?

(a) 26.8 (b) 60.0
(c) 120.0 (d) 127.5

Ans. (c)
Let the capacity of storage tank is x liters. Amount of water drawn only by pipe *R* is in one minute.

$$\frac{x}{60}+\left(\frac{x}{6}+\frac{x}{10}\right) = +\frac{17x}{60}$$

Total time taken *R* to draw a storage tank

$$= \frac{x}{\frac{17x}{60}} = \frac{60}{17}\text{min}$$

$$\text{Capacity of tank} = \frac{60}{17} \times 34 = 120 \text{ liters}$$

End of Solution

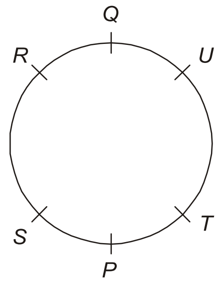
Q.4 Six persons P, Q, R, S, T and U are sitting around a circular table facing the center not necessarily in the same order. Consider the following statements:

- P sits next to S and T.
- Q sits diametrically opposite to P.
- The shortest distance between S and R is equal to the shortest distance between T and U.

Based on the above statements, Q is a neighbor of

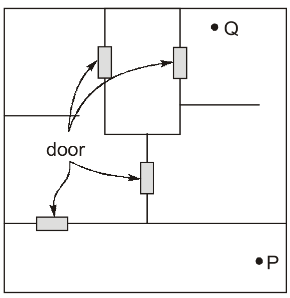
(a) U and S (b) R and T
(c) R and U (d) P and S

Ans. (c)



End of Solution

Q.5 A building has several rooms and doors as shown in the top view of the building given below. The doors are closed initially.
What is the minimum number of doors that need to be opened in order to go from the point P to the point Q?



(a) 4 (b) 3
(c) 2 (d) 1

Ans. (c)

End of Solution

Q.6 Rice, a versatile and inexpensive source of carbohydrate, is a critical component of diet worldwide. Climate change, causing extreme weather, poses a threat to sustained availability of rice. Scientists are working on developing Green Super Rice (GSR), which is resilient under extreme weather conditions yet gives higher yields sustainably.

Which one of the following is the CORRECT logical inference based on the information given in the above passage?

(a) GSR is an alternative to regular rice, but it grows only in an extreme weather.
(b) GSR may be used in future in response to adverse effects of climate change.
(c) GSR grows in an extreme weather, but the quantity of produce is lesser than regular rice.
(d) Regular rice will continue to provide good yields even in extreme weather.

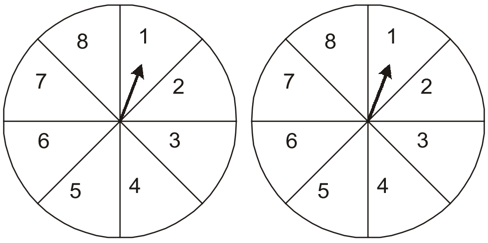
Ans. (b)

GSR may be used in future in response to adverse effects of climate change.

End of Solution

Q.7 A game consists of spinning an arrow around a stationary disk as shown below. When the arrow comes to rest, there are eight equally likely outcomes. It could come to rest in any one of the sectors numbered 1, 2, 3, 4, 5, 6, 7 or 8 as shown. Two such disks are used in a game where their arrows are independently spun.

What is the probability that the sum of the numbers on the resulting sectors upon spinning the two disks is equal to 8 after the arrows come to rest?



(a) $\frac{1}{16}$ (b) $\frac{5}{64}$

(c) $\frac{3}{32}$ (d) $\frac{7}{64}$

Ans. (d)

Probability of getting only one number $= \frac{1}{8}$

As they are independent spins probability of getting one number for each disc is

$$P = \frac{1}{8} \times \frac{1}{8}$$

Possible outcomes to the sum of 8

$= (1, 7), (2, 6), (3, 5), (4, 4), (5, 3), (6, 2), (7, 1)$

Required probability $= \frac{7}{64}$

End of Solution

Q.8 Consider the following inequalities.

(i) $3p - q < 4$

(ii) $3q - p < 12$

Which one of the following expressions below satisfies the above two inequalities?

(a) $p + q < 8$ (b) $p + q = 8$

(c) $8 \leq p + q < 16$ (d) $p + q \geq 16$

Ans. (a)

Adding both equation

$$2p + 2q < 16$$
$$p + q < 8$$

End of Solution

Q.9 Given below are three statements and four conclusions drawn based on the statements.

Statement 1: Some engineers are writers.

Statement 2: No writer is an actor.

Statement 3: All actors are engineers.

Conclusion I: Some writers are engineers.

Conclusion II: All engineers are actors.

Conclusion III: No actor is a writer.

Conclusion IV: Some actors are writers.

Which one of the following options can be logically inferred?

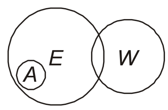
(a) Only conclusion I is correct

(b) Only conclusion II and conclusion III are correct

(c) Only conclusion I and conclusion III are correct

(d) Either conclusion III or conclusion IV is correct

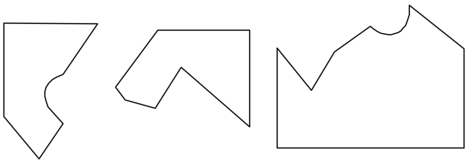
Ans. (c)



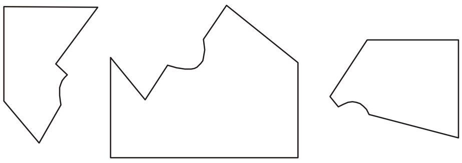
End of Solution

Q.10 Which one of the following sets of pieces can be assembled to form a square with a single round hole near the center? Pieces cannot overlap.

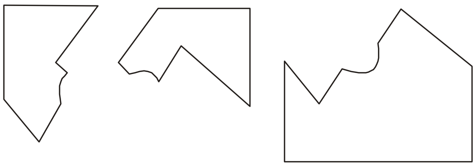
(a)



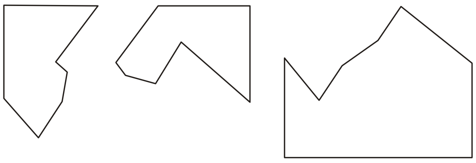
(b)



(c)



(d)



Ans. (c)

End of Solution

■■■■

SECTION - B TECHNICAL

Q.11 The value of $(1 + i)^{12}$, where $i = \sqrt{-1}$, is

(a) $-4\,i$
(b) $64i$
(c) 64
(d) -64

Ans. (d)

$$\begin{aligned}(1 + i)^{12} &= [(1 + i)^2]^6 \\ &= [1^2 + i^2 + 2i]^6 \\ &= [1 - 1 + 2i]^6 \\ &= 2^6 \times i^6 \\ &= 64 \times i^2 \times i^4 \\ &= 64 \times (-1) \times 1 \\ &= -64\end{aligned}$$

End of Solution

Q.12 Given matrix $\begin{bmatrix} x & 1 & 3 \\ y & 2 & 6 \\ 3 & 5 & 7 \end{bmatrix}$ the ordered pair (x, y) for which $\det(A) = 0$ is

(a) (1, 1)
(b) (1, 2)
(c) (2, 2)
(d) (2, 1)

Ans. (b)

$$A = \begin{bmatrix} x & 1 & 3 \\ y & 2 & 6 \\ 3 & 5 & 7 \end{bmatrix}; \; |A| = 0$$

For, $|A| = 0$

Row 2 element is 2 times of Row 1

$\Rightarrow$ $y = 2x$

So, option (b) satisfies this equation.

End of Solution

Q.13 Let $f(x) = e^{-|x|}$, where x is real. The value of $\frac{df}{dx}$ = at $x = -1$ is

(a) $-e$

(b) e

(c) $\frac{1}{e}$

(d) $-\frac{1}{e}$

Ans. (c)

$$f(x) = e^{-|x|} = \begin{Bmatrix} e^{x} & x < 0 \\ e^{-x} & x \geq 0 \end{Bmatrix}$$

$$f'(x)\Big| = \frac{d f(x)}{dx}\Big| = +\frac{1}{e^{|x|}}$$

$$f'(x)_{x=-1}\Big| = \frac{1}{e}$$

End of Solution

Q.14 The value of the real variable $x \geq 0$, which maximizes the function

$f(x) = x^{e}\ e^{-x}$ is

(a) e

(b) 0

(c) $\frac{1}{e}$

(d) 1

Ans. (a)

End of Solution

Q.15 For a single component system at vapor-liquid equilibrium, the extensive variables A, V, S and N denote the Helmholtz free energy, volume, entropy, and number of moles, respectively, in a given phase. If superscripts (v) and (l) denote the vapor and liquid phase, respectively, the relation that is NOT CORRECT is

(a) $\left(\frac{\partial A^{(l)}}{\partial V^{(l)}}\right)_{T,N^{(l)}} = \left(\frac{\partial A^{(v)}}{\partial V^{(v)}}\right)_{T,N^{(v)}}$

(b) $\left(\frac{\partial A^{(l)}}{\partial N^{(l)}}\right)_{T,N^{(l)}} = \left(\frac{\partial A^{(v)}}{\partial N^{(v)}}\right)_{T,N^{(v)}}$

(c) $\left(\frac{A+PV}{N}\right)^{(l)} = \left(\frac{A+PV}{N}\right)^{(v)}$

(d) $\left(\frac{A+TS}{N}\right)^{(l)} = \left(\frac{A+TS}{N}\right)^{(v)}$

Ans. (d)

At equilibrium of vapor and liquid phases

$$G^L = G^V$$
$$T^L = T^V$$
$$P^L = P^V$$

We know, $A = U - TS$

$$A + TS = U$$

So internal energy is not equal at equilibrium condition.

Option (d) is incorrect.

$$dA = -SdT - PdV$$

$$\left.\frac{\partial A}{\partial V}\right|_{T,N} = -P \text{ at equilibrium it is equal in both phase}$$

$$\left.\frac{\partial A}{\partial N}\right|_{T,V} = u \text{ (chemical potential also equal in both phase at equilibrium)}$$

End of Solution

Q.16 Consider turbulent flow in a pipe under isothermal conditions. Let r denote the radial coordinate and z denote the axial flow direction. On moving away from the wall towards the center of the pipe, the rz-component of the Reynolds stress

(a) Increases and then decreases
(b) Decreases and then increases
(c) Remains unchanged
(d) Only increases

Ans. (c)

End of Solution

Q.17 Consider two stationary spherical pure water droplets of diameters d_1 and $2d_2$. CO_2 diffuses into the droplets from the surroundings. If the rate of diffusion of CO_2 into the smaller droplet is W_1 mol s^{-1}, the rate of diffusion of CO_2 into the larger droplet is

(a) $2W_1$
(b) $4W_1$
(c) W_1
(d) $0.5W_1$

Ans. (b)

We know mass transfer rate,

$$W = \text{Flux} \times \text{Area}$$

For spherical pure water droplets of d_1, rate of diffusion of CO_2 is W_1 mol/s

For droplet of diameter $2d_1$, rate of diffusion of CO_2 is W_2 mol/s

So, $$\frac{w_1}{w_2} \propto \frac{A_1}{A_2}$$

$$\frac{w_1}{w_2} = \left(\frac{d_1}{2d_1}\right)^2$$

$$w_2 = 4w_1$$

End of Solution

Q.18 In soap manufacturing, the triglycerides present in oils and fats are hydrolyzed to mainly produce

(a) Fatty acids and glycerol
(b) Glycerol only
(c) Fatty acids only
(d) Glycerol and paraffins

Ans. (a)

End of Solution

Q.19 The chemical formula of Glauber's salt, used in the Kraft process, is

(a) $Na_2CO_3.10H_2O$
(b) $Na_2S_2O_4.2H_2O$
(c) $Na_2HPO_4.2H_2O$
(d) $Na_2SO_4.10H_2O$

Ans. (d)

End of Solution

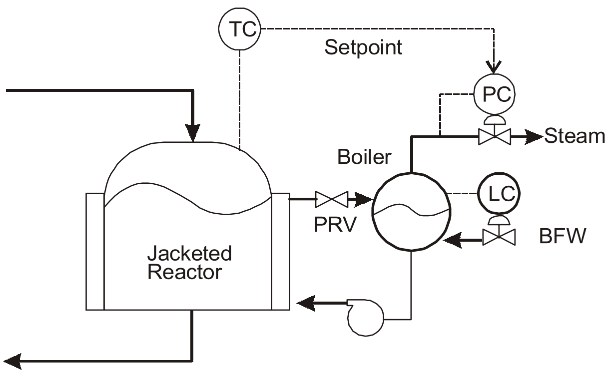
Q.20 Catalytic reforming is commonly used in the petroleum industry to improve fuel quality. The undesirable reaction in the catalytic reforming of naphtha is

(a) Hydrocracking of paraffins
(b) Dehydrogenation of naphthenes
(c) Isomerization of naphthenes
(d) Cyclization of paraffins

Ans. (a)

End of Solution

Q.21 A control system on the jacket side of a reactor is shown in the figure. Pressurized water flows through the jacket to cool the reactor. The heated water flashes in the boiler. The exothermic reaction heat thus generates steam. Fresh boiler feed water (BFW) is added to make-up for the loss of water as steam. Assume that all control valves are air-to-open. The controller action, 'direct' or 'reverse', is defined with respect to the controller. Select the option that correctly specifies the action of the controllers.



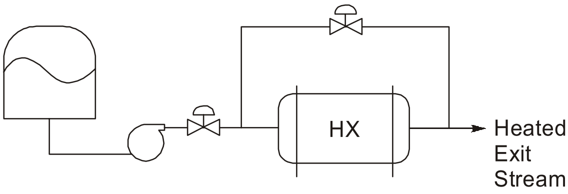
LC : Level Controller
PC : Pressure Controller
TC : Temperature Controller
PRV : Pressure Reducing Valve

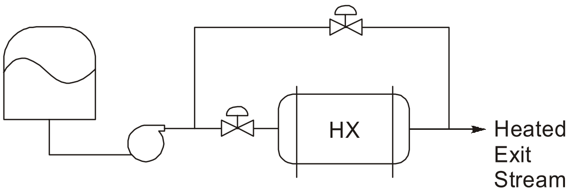
(a) PC: Reverse, LC: Direct, TC: Reverse
(b) PC: Direct, LC: Reverse, TC: Direct
(c) PC: Direct, LC: Reverse, TC: Reverse
(d) PC: Reverse, LC: Direct, TC: Direct

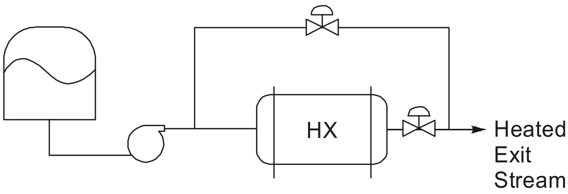
Ans. (b)

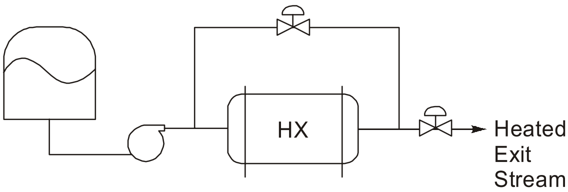
End of Solution

Q.22 Liquid flowing through a heat exchanger (HX) is heated. A bypass stream is provided to control the temperature of the heated exit stream. From the given plumbing options, the one that provides the most effective temperature control for large disturbances while avoiding vaporization in the heat exchanger

(a)


(b)


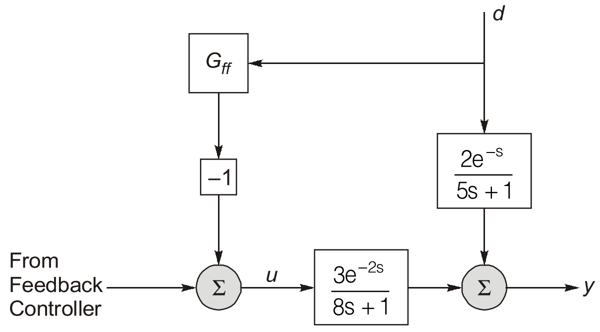
(c)


(d)


Ans. (b)

End of Solution

Q.23 The appropriate feedforward compensator, G_{ff}, in the shown block diagram is



(a) $G_{ff} = \dfrac{2(8s+1)}{3(5s+1)}$

(b) $G_{ff} = -\dfrac{2(8s+1)}{3(5s+1)}$

(c) $G_{ff} = \dfrac{3(5s+1)}{2(8s+1)}e^{-s}$

(d) $G_{ff} = -\dfrac{3(5s+1)}{2(8s+1)}e^{-s}$

Ans. (a)

$$[-G_{ff}\,d(s) + C]\frac{3e^{-2s}}{8s+1} + \frac{2e^{-s}}{5s+1}d(s) = y(s)$$

For feed forward controller $\quad y(s) = 0$

$$-G_{ff}\frac{3e^{-2s}}{8s+1}d(s) + \frac{2e^{-s}}{5s+1}d(s) = 0$$

$$d(s)\left[-G_{ff}\left(\frac{3e^{-2s}}{8s+1}\right) + \frac{2e^{-s}}{5s+1}\right] = 0$$

$$G_{ff} = \frac{2}{3}\left[\frac{8s+1}{5s+1}\right]$$

End of Solution

Q.24 Choose the option that correctly pairs the given measurement devices with the quantities they measure.

S No	Measurement Device
I	Bourdon Gauge
II	Orifice Plate meter
III	Pyrometer
IV	Colorimeter
V	Pirani Gauge

S No	Measured Quantity
A	Temperature
B	Concentration
C	Pressure
D	Flow rate
E	Liquid level

(a) I-E II-C III-D IV-B V-A
(b) I-C II-D III-A IV-B V-C
(c) I-C II-D III-E IV-A V-D
(d) I-D II-C III-A IV-E V-C

Ans. (b)

End of Solution

Q.25 A simple distillation column is designed to separate an ideal binary mixture to specified distillate and bottoms purities at a given column pressure. If RR_{min} is the minimum reflux ratio for this separation, select the statement that is NOT CORRECT with regard to the variation in the total annualized cost (TAC) of the column with reflux ratio (RR).

(a) TAC has a minimum with respect to RR
(b) The sharpest rise in TAC occurs as RR approaches RR_{min} from above
(c) The sharpest decrease in TAC occurs as RR approaches RR_{min} from above
(d) TAC increases with RR for RR >> RR_{min}

Ans. (c)

End of Solution

Q.26 The reaction $A \rightarrow B$ is carried out isothermally on a porous catalyst. The intrinsic reaction rate is kC_A^2, where k is the rate constant and C_A is the concentration of A. If the reaction is strongly pore-diffusion controlled, the observed order of the reaction is

(a) 1
(b) 2
(c) $\frac{3}{2}$
(d) $\sqrt{2}$

Ans. (c)

For strong pore resistance regime, observed order is given by,

$$n_{obs} = \frac{n_{actual}+1}{2}$$

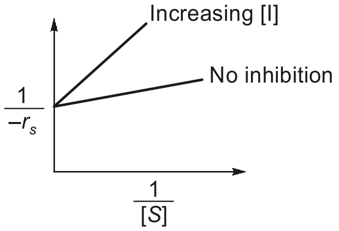
$$n_{obs} = \frac{2+1}{2} = \frac{3}{2}$$

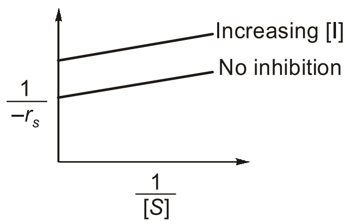
End of Solution

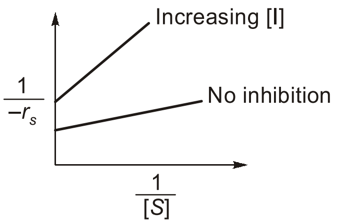
Q.27 In an enzymatic reaction, an inhibitor (I) competes with the substrate (S) to bind with the enzyme (E), thereby reducing the rate of product (P) formation. The competitive inhibition follows the reaction mechanism shown below. Let $[S]$ and $[I]$ be the concentration of S and I, respectively, and r_s be the rate of consumption of S. Assuming pseudo-steady state, the correct plot of $\frac{1}{-r_s}$ vs $\frac{1}{[S]}$ is

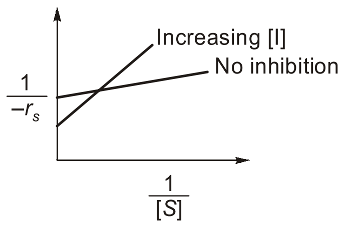
$$E + S \underset{k_2}{\overset{k_1}{\rightleftharpoons}} E.S \xrightarrow{k_3} E + P$$

$$E + I \underset{k_2}{\overset{k_1}{\rightleftharpoons}} E.I$$

(a)


(b)


(c)


(d)


Ans. (c)

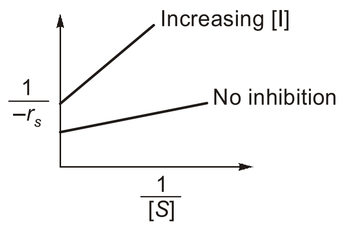
With inhibition, $-r_s = \dfrac{k_3 C_{E0} C_s}{C_M(1 + LC_{B0}) + C_S}$

Without inhibition, $-r_s = \dfrac{k_3 C_{E0} C_s}{C_M + C_S}$

Now C_S high, $-r_s = k_3 C_{E0}$

$-r_s = k_3 C_{E0}$

$-\dfrac{1}{r_s}$ V/s $\dfrac{1}{C_S}$ same



C_S low $\therefore$ with $-r_s = \dfrac{k_3 C_{E0} C_S}{C_M(1 + L_{CB0})}$

with inhibition slope $\dfrac{C_M(1 + LC_{B0})}{k_3 C_{E0}}$

without inhibition slope $\dfrac{C_M}{k_3 C_{E0}}$

that it, with slope > without slope.

End of Solution

Q.28 The area of a circular field is 25 m^2. The radius, *r*, is to be determined using the Newton-Raphson iterative method. For an initial guess of r = 2.500 m, the revised estimate of *r* after one iteration is ________ m (rounded off to three decimal places).

Ans. **(2.841) (2.831 to 2.851)**

$$\text{Area of circle} = 25 \text{ m}^2$$
$$\pi R^2 = 25$$
$$f(R) = \pi R^2 - 25 = 0$$
$$\Rightarrow \quad f'(R) = 2\pi R$$
$$\text{Initial guess, } R = 2.5 \text{ m}$$

So, by Newton Raphson's method,

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)}$$

$$R_1 = 2.5 - \frac{f(R)}{f'(R)} = 2.5 - \frac{\pi \times 2.5^2 - 25}{2\pi \times 2.5}$$
$$= 2.5 + 0.341 = 2.841$$

End of Solution

Q.29 5 moles of liquid benzene, 8 moles of liquid toluene and 7 moles of liquid xylene are mixed at 25 °C and 1 bar. Assuming the formation of an ideal solution and using the universal gas constant R = 8.314 J mol^{-1} K^{-1}, the total entropy change is ________ J K^{-1} (rounded off to one decimal place).

Ans. **(179.67) (178.5 to 180.5)**

5 mol (A) benzene, 7 mol (B) xylene, 8 mol (C) toluene at 25°C and 1 bar are mixed.

$$\Delta S_{mix}^{id} = -nR \sum x_i \ln x_i$$

$$x_A = \frac{5}{20} = 0.25$$
$$x_B = \frac{7}{20} = 0.35$$
$$x_C = \frac{8}{20} = 0.4$$

$$\Delta S_{mix}^{id} = -20 \times 8.314 \, (0.25 \ln 0.25 + 0.35 \ln 0.35 + 0.4 \ln 0.4)$$
$$= 179.67 \text{ (J/K)}$$

End of Solution

Q.30 A perfectly insulated double pipe heat exchanger is operating at steady state. Saturated steam enters the inner pipe at 100 °C and leaves as saturated water at 100 °C. Cooling water enters the outer pipe at 75 °C and exits at 95 °C. The overall heat transfer coefficient is 1 kW m^{-2} K^{-1} and the heat transfer area is 1 m^2. The average specific heat capacity of water at constant pressure is 4.2 kJ kg^{-1} K^{-1}. The required cooling water flow rate is ________ kg s^{-1} (rounded off to two decimal places).

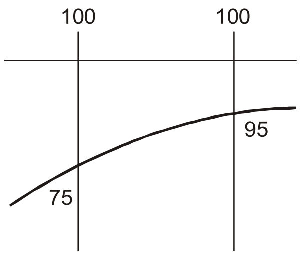
Ans. (0.148) (0.13 to 0.16)

Data given: $U = 1$ kW/m^2 K

$A = 1$ m^2

$t_{c_1} = 75°C$, $C_p = 4.2$ KJ/kg K

$t_{c2} = 95°C$, $\dot{m}_c = ?$



Here hot fluid is saturated water at 100°C.

$$Q = U \cdot A\,(\Delta T)_{lmtd} = \dot{m}_c C_{pc}(95 - 75)$$

$$\Delta T_{lmtd} = \frac{25-5}{\ln\left|\frac{25}{5}\right|} = 12.43$$

$$Q = U \cdot A\,(\Delta T)_{lmtd} = 1 \times 1 \times 12.43 = 12.43 \text{ kW}$$

$$1 \times 1 \times 12.43 = m \times 4.2 \times 20$$

$$\dot{m}_c = 0.148 \text{ kg/sec}$$

End of Solution

Q.31 Consider steady-state diffusion in a binary A-B liquid at constant temperature and pressure. The mole-fraction of A at two different locations is 0.8 and 0.1. Let N_{A1} be the diffusive flux of A calculated assuming B to be non-diffusing, and N_{A2} be the diffusive flux of A calculated assuming equimolar counter-diffusion. The quantity $\frac{(N_{A1} - N_{A2})}{N_{A1}} \times 100$ is ___________ (rounded off to one decimal place).

Ans. (53.5) (53.2 to 53.8)

For A diffusing in non-diffusing B

$$N_{A_1} = \frac{D_{AB} P_T}{RT\,Z\,P_{Bl\,m}}\left(P_{A_1} - P_{A_2}\right)$$

For equimolar diffusion

$$N_{A_2} = \frac{D_{AB}}{RT\,Z}\left(P_{A_1} - P_{A_2}\right)$$

$$\frac{N_{A_1}}{N_{A_2}} = \frac{P_T}{P_{Bl\,m}} = \frac{1}{y_{Bl\,m}}$$

Given, $y_{A_1} = 0.8$, $y_{A_2} = 0.1$

$y_{B_1} = 1 - y_{A_1} = 0.2$

$y_{B_2} = 1 - y_{A_2} = 0.9$

$$y_{Bl\,m} = \frac{0.9 - 0.2}{\ln\left(\frac{9}{2}\right)} = \frac{0.7}{\ln(4.5)} = 0.465$$

$$\frac{N_{A_2}}{N_{A_1}} = y_{Bl\,m}$$

$$\frac{N_{A_1} - N_{A_2}}{N_{A_1}} \times 100 = 53.45$$

End of Solution

Q.32 Consider interphase mass transfer of a species *S* between two immiscible liquids *A* and *B*. The interfacial mass transfer coefficient of *S* in liquid *A* is twice of that in liquid *B*. The equilibrium distribution of *S* between the liquids is given by $y_S^A = 0.5\, y_S^B$, where y_S^A and y_S^B are the mole-fractions of *S* in *A* and *B*, respectively. The bulk phase mole-fraction of *S* in *A* and *B* is 0.10 and 0.02, respectively. If the steady-state flux of *S* is estimated to be 10 kmol h^{-1} m^{-2}, the mass transfer coefficient of *S* in *A* is ________ kmol h^{-1} m^{-2} (rounded off to one decimal place).

Ans. **(222.22) (221.2 to 223.2)**

Liquid (A)	Liquid (B)
k_a	k_b
$(y_{Ag})0.10$	$0.02(y_{Bl})$

Given: $k_a = 2k_b$

$$N_A = k_A(y_{Ag} - y_S^A) = k_B(y_S^B - y_{Bl})$$
$$2k_B(0.10 - y_S^A) = k_b(y_S^B - 0.02)$$
$$0.20 - 2y_S^A = y_S^B - 0.02$$

Equilibrium relation is

$$y_S^A = 0.5y_S^B$$
$$0.20 - y_S^B = y_S^B - 0.02$$
$$0.22 = 2y_S^B$$
$$y_S^B = 0.11$$

So, $$N_A = k_b(0.11 - 0.02)$$

$$k_b = \frac{10}{0.11-0.02} = 111.11$$

$$k_a = 2 \times 111.11 = 222.22 \text{ kmol/m}^2\text{.hr}$$

End of Solution

Q.33 A wet solid containing 20% (w/w) moisture (based on mass of bone-dry solid) is dried in a tray-dryer. The critical moisture content of the solid is 10% (w/w). The drying rate (kg m^{-2} s^{-1}) is constant for the first 4 hours, and then decreases linearly to half the initial value in the next 1 hour. At the end of 5 hours of drying, the percentage moisture content of the solid is _________% (w/w) (rounded off to one decimal place).

Ans. **(8.75) (8.4 to 8.9)**

Initial moisture content $(x_i) = 0.2$
Critical moisture content $(x_c) = 0.1$
Time taking in constant rate period,

$$t_c = \frac{W_s}{AN_{C_1}}(x_i - x_c)$$

Given: $t_c = 4$ hr

$$4 = \frac{W_s}{AN_{C_1}}(0.2 - 0.1)$$

$$\frac{W_s}{AN_{C_1}} = 40$$

So, $$\frac{W_s}{A} = 40\,N_{C_1}$$

In **case II^nd^:** Falling rate period is linear and rate of drying in falling period is half of rate of drying in constant rate period.

$$N_{C_2} = \frac{N_{C_1}}{2}$$

$$N_{C_2} = -\frac{W_s}{A} \times \frac{dx}{dt}$$

$$\int_o^t dt = -\frac{W_s}{A}\int_{0.1}^{x_f} \frac{dx}{N_{C2}}$$

$$t = -\frac{2 \times 40 N_{C_1}}{N_{C_1}}[x_f - 0.1] \qquad \text{[Given: } t = 1 \text{ hr]}$$

$$1 = -80\,[x_f - 0.1]$$

$$x_f = -\frac{1}{80} + 0.1 = 0.0875$$

$$x_f = 0.0875 = 8.75\%$$

End of Solution

Q.34 A process described by the transfer function

$$G_p(s) = \frac{(10s+1)}{(5s+1)}$$

is forced by a unit step input at time $t = 0$. The output value immediately after the step input (at $t = 0^+$) is ________ (rounded off to the nearest integer).

Ans. (2) (2 to 2)

$$G_p(s) = \frac{(10s+1)}{(5s+1)}$$

From initial value theorem:

$$\frac{y(s)}{x(s)} = \frac{(10s+1)}{(5s+1)}$$

$$y(s) = \frac{(10s+1)}{s(5s+1)}$$

$$y(t)\big|_{t\to 0} = \lim_{s\to\infty} s.y(s)$$
$$= \lim_{s\to\infty}\left(\frac{10s+1}{5s+1}\right)$$
$$= \lim_{s\to\infty}\left(\frac{10s+1/s}{5s+1/s}\right) = 2$$

End of Solution

Q.35 A compressor with a life of 10 years costs Rs 10 lakhs. Its yearly operating cost is Rs 0.5 lakh. If the annual compound interest rate is 8%, the amount needed at present to fund perpetual operation of the compressor is Rs ________ lakhs (rounded to first decimal place).

Ans. **(6.25) (6.1 to 6.3)**

Given: $V_o = 10$ lakh, $n = 10$ year

Yearly operating cost = 0.5 lakh

$i = 8\%$

Amount for perpetual operation $= \frac{M}{i} = \frac{0.5}{0.08} = 6.25$

End of Solution

Q.36 The partial differential equation

$$\frac{\partial u}{\partial t} = \frac{1}{\pi^2}\frac{\partial^2 u}{\partial x^2}$$

where, $t \geq 0$ and $x \in [0, 1]$, is subjected to the following initial and boundary conditions.

$$u(x, 0) = \sin(\pi x)$$
$$u(0, t) = 0$$
$$u(1, t) = 0$$

The value of t at which $\frac{u(0.5,t)}{u(0.5,0)} = \frac{1}{e}$ is

(a) 1
(b) e
(c) π
(d) $\frac{1}{e}$

Ans. **(a)**

$$u(x, t) = X(x), T(t)$$
$$u(x, 0) = \sin(\pi, x)$$
$$\Rightarrow \quad X(x) = \sin(\pi, x)$$
$$u = \sin \pi X T(t)$$

$$u_T = \frac{1}{\pi^2} u_{xx}$$

$$X(x)\ T'(t) = \frac{1}{\pi^2}\left[-\sin(\pi\ x)\right]\pi^2 . T(t)$$

$$\frac{T'(t)}{T(t)} = -1$$

$$\ln\ T(t) = -t + c$$

$$T(t) = e^{-t+c}$$

$$u(x,\ t) = \sin(\pi,\ x)\ .\ e^{-t+c}$$

$$u(x,\ 0) = \sin\ \pi\ x\ .\ e^{-c} = \sin\ (\pi\ x)$$

$$e^{-c} = 1$$

$$c = 0$$

$$\therefore \quad u = \sin(\pi\ x)\ .\ e^{-t}$$

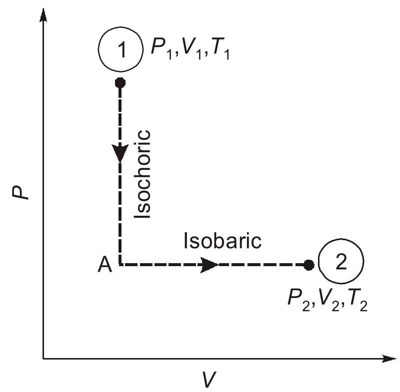
$$\because \quad \frac{u(0.5,t)}{u(0.5,0)} = \frac{1}{e}$$

$$\frac{\sin\left(\frac{\pi}{2}\right)e^{-t}}{\sin\left(\frac{\pi}{2}\right)1} = \frac{1}{e}$$

$$t = 1$$

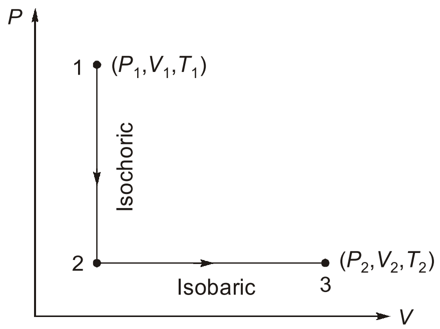
End of Solution

Q.37 N moles of an ideal gas undergo a two-step process as shown in the figure. Let P, V and T denote the pressure, volume and temperature of the gas, respectively. The gas, initially at state-1 (P_1, V_1, T_1), undergoes an isochoric (constant volume) process to reach state-A, and then undergoes an isobaric (constant pressure) expansion to reach state-2 (P_2, V_2, T_2). For an ideal gas, $C_P - C_V = NR$, where C_P and C_V are the heat capacities at constant pressure and constant volume, respectively, and assumed to be temperature independent. The heat gained by the gas in the two-step process is given by



(a) $P_2(V_2 - V_1) + C_V(T_2 - T_1)$
(b) $P_2(V_2 - V_1) + C_P(T_2 - T_1)$
(c) $C_P(T_2 - T_1) + C_V(T_2 - T_1)$
(d) $P_2V_2 - P_1V_1$

Ans. (a)



Assume at point '2' temperature is T.

In process 1 to 2 volume is constant so

$$du = dQ - dw$$
$$du_1 = dQ_1$$
$$du_1 = C_v (T - T_1)$$

In process 2-3 pressure is constant so

$$du_2 = dQ_2 - dw$$

Here, $$dw = P_2 (V_2 - V_1)$$
$$du_2 = C_v (T_2 - T)$$

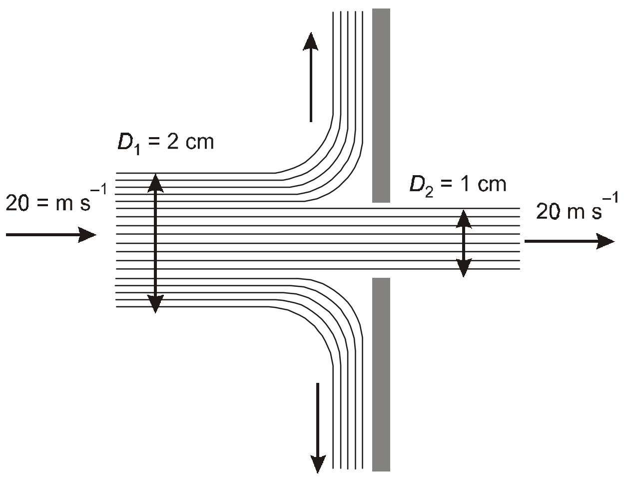
So, heat gained by process

$$dQ_1 + dQ_2 = du_1 + du_2 + dw$$
$$= P_2 (V_2 - V_1) + C_v (T_2 - T) + C_v (T - T_1)$$
$$P_2 (V_2 - V_1) + C_v (T_2 - T_1)$$

Correct option is (a).

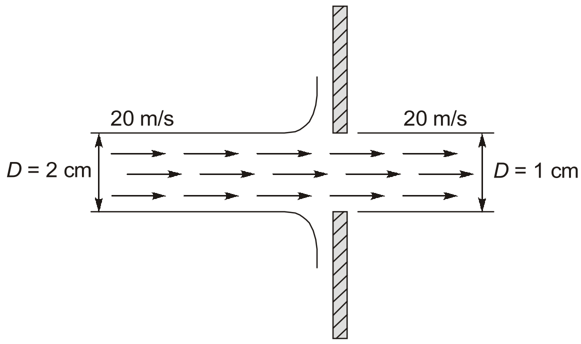
End of Solution

Q.38 A horizontal cylindrical water jet of diameter D_1 = 2 cm strikes a vertical solid plate with a hole of diameter D_2 = 1 cm, as shown in the figure. A part of the jet passes through the hole and the rest is deflected along the plate. The density of water is 1000 kg m^{-3}. If the speed of the jet is 20 m s^{-1}, the magnitude of the horizontal force, in N, required to hold the plate stationary is



(a) 30 π
(b) 10 π
(c) 20 π
(d) 5 π

Ans. (a)



Applying momentum balance, we get

$$\Sigma F_x = \dot{m}v|_{out} - \dot{m}v|_{in}$$

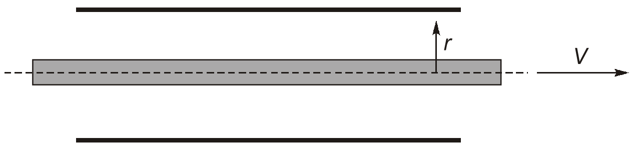
$$= \rho Q_{out} V_{out} - \rho Q_{gn} \; V_{gh}$$

$$= 1000\left[\frac{\pi}{4}(0.01)^2 \times 400 - \frac{\pi}{4}(0.02)^2 \times 400\right]$$

$$= \frac{1000 \times 400 \times \pi}{4}\left[(0.01)^2 - (0.02)^2\right] = 30\pi$$

End of Solution

Q.39 Consider a horizontal rod of radius aR ($a < 1$) in a stationary pipe of radius R. The rod is pulled coaxially at a constant velocity V as shown in the figure. The annular region is filled with a Newtonian incompressible fluid of viscosity μ. The steady state fully developed axial velocity profile in the fluid is given by $u(r) = V\frac{\ln(r/R)}{\ln(a)}$, where r is the radial coordinate. Ignoring end effects, the magnitude of the pulling force per unit rod length is



(a) $\pi\mu V$

(b) $-\frac{2\pi\mu V}{\ln(a)}$

(c) 0

(d) $-\frac{\pi\mu V}{\ln(a)}$

Ans. (b)

From Newton law of viscosity, we have

$$\tau = -\mu \frac{du}{dr}$$

$$F = -A \cdot \mu \cdot \frac{du}{dr}$$

$$u(r) = V\frac{\ln(r/R)}{\ln a} \qquad \because \quad r = aR$$

$$A = 2\pi aR \cdot 1$$

$$\frac{du}{dr} = \frac{V}{r \ln a}$$

$$F = -2\pi aR \cdot \mu \frac{V}{r \ln a} = -2\pi aR\mu \frac{V}{aR \cdot \ln a}$$

$$F = \frac{-2\pi\mu V}{\ln(a)}$$

End of Solution

Q.40 Consider a bare long copper wire of 1 mm diameter. Its surface temperature is T_s and the ambient temperature is $T_a (T_s > T_a)$. The wire is to be coated with a 2 mm thick insulation. The convective heat transfer coefficient is 20 W m^{-2} K^{-1}. Assume that T_s and T_s remain unchanged. To reduce heat loss from the wire, the maximum allowed thermal conductivity of the insulating material, in W m^{-1} K^{-1}, rounded off to two decimal places, is

(a) 0.02
(b) 0.04
(c) 0.10
(d) 0.01

Ans. (d)

Given copper wire diameter = 1 mm

To reduce heat less from rate of heat transfer without insulation

$$r_c \le R_0$$

$$\frac{k_{ins}}{h} \le R_0$$

$$k_{ins} \le 0.5 \times 10^{-3} \times 20$$

$$k_{ins} \le 0.01 \text{ w/m-k}$$

Correct option is (d).

End of Solution

Q.41 Two large parallel planar walls are maintained at 1000 K and 500 K. Parallel radiation shields are to be installed between the two walls. Assume that the emissivities of the walls and the shields are equal. If the melting temperature of the shields is 900 K, the maximum number of shield(s) that can be installed between the walls is (are)

(a) 1
(b) 0
(c) 2
(d) 3

Ans. (a)

Data given:

Emissivities of walls and the shield are equal.

Now, melting point of shield is given as 900 K.

$$q_{\text{without}} = \frac{A\sigma\left[1000^4 - 500^4\right]}{\frac{2}{\epsilon} - 1} \quad \text{...(i)}$$

$$q_{\text{with shield}} = \frac{A\sigma\left[1000^4 - 900^4\right]}{\frac{2}{\epsilon} - 1}$$

Now,
$$\frac{q_{\text{with}}}{q_{\text{without}}} = \frac{1}{n+1}$$

$$n + 1 = 2.72$$

$$n = 1.72$$

Now, the maximum number of shield will be 1.72 so, its integer value will be one.

$$n = 1$$

End of Solution

Q.42 Saturated steam condenses on a vertical plate maintained at a constant wall temperature. If x is the vertical distance from the top edge of the plate, then the local heat transfer coefficient $h(x) \propto \Gamma(x)^{-1/3}$, where $\Gamma(x)$ is the local mass flow rate of the condensate per unit plate width. The ratio of the average heat transfer coefficient over the entire plate to the heat transfer coefficient at the bottom of the plate is

(a) 4
(b) 4/3
(c) 3/4
(d) 3

Ans. (b)

From Nusselt theory, we have

$$h_x \propto (\dot{m})^{-1/3}$$

$$\dot{m} \propto \delta^3$$

$$h_x \propto \delta^{-1} \propto \frac{1}{\delta}$$

$$h_x \propto (x)^{-0.25}$$

$$h_{avg} = \frac{\int_0^L k\,x^{-0.25}}{L} = \frac{4}{3}h_x$$

$$\frac{h_{avg}}{h_x} = \frac{4}{3}$$

End of Solution

Q.43 Match the product in Group-1 with the manufacturing process in Group-2. The correct combination is

	Group-1		Group-2
P	Nitric acid	I	Trona process
Q	Phosphoric acid	II	Twitchell process
R	Potassium chloride	III	Ostwald's process
S	Stearic acid	IV	Haifa process

(a) P-III, Q-I, R-IV, S-II
(b) P-IV, Q-I, R-II, S-III
(c) P-III, Q-IV, R-I, S-II
(d) P-I, Q-IV, R-II, S-III

Ans. (c)

End of Solution

Q.44 The directional derivative of $f(x, y, z) = 4x^2 + 2y^2 + z^2$ at the point (1,1,1) in the direction of the vector $\vec{v} = \hat{i} - \hat{k}$ is ________ (rounded off to two decimal places).

Ans. (4.24) (4.11 to 4.31)

$$f = 4x^2 + 2y^2 + z^2 \text{ at } (1, 1, 1)$$

$$\vec{V} = (\hat{i} - \hat{k})$$

$$\hat{V} = \frac{\hat{i} - \hat{k}}{\sqrt{1^2 + 1^2}} = \frac{1}{\sqrt{2}}(\hat{i} - \hat{k})$$

$$\text{Directional derivative} = \text{grad}(f)_{at(1,1,1)} \cdot \vec{V}$$

$$= \frac{\left[(8x\hat{i} + 4y\hat{j} + 2z\hat{k}) \cdot (\hat{i} - \hat{k})\right]_{(1,1,1)}}{\sqrt{2}}$$

$$= \frac{(8x - 2z)_{at}\,(1,1,1)}{\sqrt{2}}$$

$$= \frac{8-2}{\sqrt{2}} = \frac{6}{\sqrt{2}} = 3\sqrt{2}$$

End of Solution

Q.45 Consider a sphere of radius 4, centered at the origin, with outward unit normal $\hat{n}$ on its surface S. The value of the surface integral $\iint_s \left(\frac{2x\hat{i} + 3y\hat{j} + 4z\hat{k}}{4\pi}\right)\hat{n}\,dA$ is _____ (rounded off to one decimal place)

Ans. (192) (192 to 192)

$$\iint_S \left(\frac{2x\hat{i} + 3y\hat{j} + 4z\hat{k}}{4\pi}\right)\cdot\hat{n}\,dS$$

By gauss divergence theorem

$$= \frac{1}{4\pi}\iiint_v \text{div}(\vec{A})\,dV$$

$$= \frac{1}{4\pi}\iiint_v \nabla\cdot\vec{A}\,dV$$

$$= \frac{1}{4\pi}\iint_v \left(\frac{\partial}{\partial x}(2x) + \frac{\partial}{\partial y}(3y) + \frac{\partial}{\partial z}(4z)\right)dv$$

$$= \frac{1}{4\pi}\int_v (2+3+4)\,dv$$

$$= \frac{1}{4\pi}\times 9 \times \text{Volume of sphere}$$

$$= \frac{9}{4\pi}\times\frac{4}{3}\times\pi\times(4)^3$$

$$= 3 \times 4^3 = 192$$

End of Solution

Q.46 The equation $\frac{dy}{dx} = xy^2 + 2y + x - 4.5$ with the initial condition $y(x = 0) = 1$ is to be solved using a predictor-corrector approach. Use a predictor based on the implicit Euler's method and a corrector based on the trapezoidal rule of integration, each with a full-step size of 0.5. Considering only positive values of y, the value of y at $x = 0.5$ is ___________ (rounded off to three decimal places).

Ans. (0.875) (0.845 to 0.895)

$$\frac{dy}{dx} = xy^2 + 2y + x - 4.5$$

$$y(0) = 1$$

Given $h = 0.5$

$\Rightarrow$ $x_1 = x_0 + h = 0 + 0.5 = 0.5$

by Implicit Euler formula

$$y_1 = y_0 + h\,f(x_1, y_1)$$

$$dy = (xy^2 + 2y + x - 4.5)\,dx$$

$$\int_0^{0.5} dy = \int_0^{0.5} (x^2 + 2y + x - 4.5)dx \text{ by trapezoidal}$$

$$\Rightarrow \qquad y(0.5) - y(0) = \int_0^{0.5} (xy^2 + 2y + x - 4.5)dx$$

x	0	0.5
$f(x,y)$	–2.5	2

By trapezoidal rule,

$$y(0.5) = y(0) + \frac{h}{2}[f(x_0, y_0) + f(x_1, y_1)]$$

$$= 1 + \frac{0.5}{2}[-2.5 + 2]$$

$$= 1 + \frac{0.5}{2}(-0.5)$$

$$= 1 - \frac{0.25}{2} = \frac{7}{8} = 0.875$$

End of Solution

Q.47 A substance at 4 °C has thermal expansion coefficient $\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P = 0\ K^{-1}$, an isothermal compressibility, $\kappa_T = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T$ = 5 × 10^{-4} Pa^{-1} and a molar volume v = 18 × 10^{-6} m^3 mol^{-1}. If s is the molar entropy, then at 4°C, the quantity $\left[v\left(\frac{\partial s}{\partial v}\right)_T\right]$ evaluated for the substance is _____ J mol^{-1} K^{-1} (rounded off to the nearest integer).

Ans. (0)

Given at 4°C,

β = 0 K^{-1}

α = 5 × 10^{-4} Pa^{-1}

κ_T = 18 × 10^{-6} m^3/mol

Form Maxwell equation

$$\left.\frac{\partial S}{\partial V}\right|_T = \left.\frac{\partial P}{\partial T}\right|_V$$

Given:

$$\beta = \left.\frac{dv}{vdT}\right|_P, \quad \kappa_T = -\left.\frac{dv}{vdP}\right|_T$$

$$\frac{dv}{v} = \beta dT - \kappa_T dP \quad \text{(at constant volume)}$$

$$\left.\frac{\partial P}{\partial T}\right|_V = 0$$

So value of $v\left(\frac{\partial S}{\partial V}\right)_T = v\left(\frac{\partial P}{\partial T}\right)_V = 0$

End of Solution

Q.48 The molar excess Gibbs free energy (g^E) of a liquid mixture of A and B is given by

$$\frac{g^E}{RT} = x_A x_B\,[C_1 + C_2\,(x_A - x_V)]$$

where x_A and x_B are the mole fraction of A and B, respectively, the universal gas constant, $R = 8.314$ J K^{-1} mol^{-1}, T is the temperature in K, and C_1, C_2 are temperature-dependent parameters. At 300 K, $C_1 = 0.45$ and $C_2 = -0.018$. If γ_A and γ_B are the activity coefficients of A and B, respectively, the value of

$$\int_0^1 \ln\left(\frac{\gamma_A}{\gamma_B}\right) dx_A$$

at 300 K and 1 bar is _____ (rounded off to the nearest integer).

Ans. **(0)**

Given $\frac{g^E}{RT} = x_A x_B\left[C_1 + C_2\left(x_A - x_B\right)\right]$

where, $C_1 = 0.45$ and $C_2 = -0.018$

$$\frac{g^E}{RT} = x_A x_B\left[0.45 - 0.018\left(x_A - x_B\right)\right]$$

$$\frac{g^E}{RT} = x_A x_B\left[0.45 - 0.018 x_A + 0.018 x_B\right]$$

$$\frac{d}{dx_A}\left[\frac{g^E}{RT}\right] = \ln\left[\frac{\gamma_A}{\gamma_B}\right]$$

$$\frac{g^E}{RT} = x_A(1 - x_A)\,[0.45 - 0.018x_A + 0.018 - 0.018x_A]$$

$$(x_A - x_A^2)\,[0.468 - 0.036x_A]$$

$$= 0.468x_A - 0.036x_A^2 - 0.468x_A^2 + 0.036x_A^3$$

$$\frac{d\left(\frac{g^E}{RT}\right)}{dx_A} = 0.468 - 0.072x_A - 0.936x_A + 0.108x_A^2$$

$$\ln\left(\frac{\gamma_A}{\gamma_B}\right) = 0.108x_A^2 - 1.008x_A + 0.468$$

$$\int_0^1 \ln\left(\frac{\gamma_A}{\gamma_B}\right)dx_A = \int_0^1 \left(0.108x_A^2 - 1.008x_A + 0.468\right)dx_A$$

$$= \left[\frac{0.108x_A^3}{3} - \frac{1.008x_A^2}{2} + 0.468x_A\right]_0^1$$

$$= [0.036 - 0.504 + 0.468] = 0$$

End of Solution

Q.49 For a pure substance, the following data at saturated conditions are given:

ln P^{sat} (bar)	T (K)
0.693	350
1.386	370

Assume that the vapor phase behaves ideally, the molar volume of the liquid is negligible, and the latent heat of vaporization is constant over the given temperature range. The universal gas constant, R = 8.314 J K^{-1} mol^{-1}. From the above data, the estimated latent heat of vaporization at 360 K is ___________ kJ/mol (rounded off to one decimal place).

Ans. (37.306) (36.1 to 38.1)

$$\ln\left(\frac{P_2^{sat}}{P_1^{sat}}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

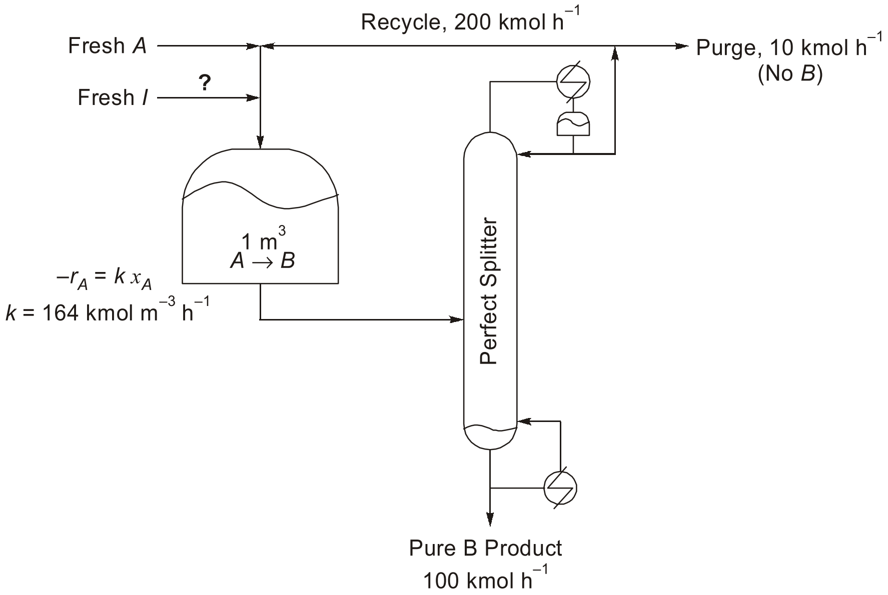
$$\ln P_2^{sat} - \ln P_1^{sat} = \frac{\Delta H_{vap}}{R}\left[\frac{1}{350} - \frac{1}{370}\right]$$

$$1.386 - 0.693 = \frac{\Delta H_{vap}}{R}\left[\frac{1}{350} - \frac{1}{370}\right]$$

$$\Delta H_{vap} = \frac{0.693 \times 8.314 \times 350 \times 370}{20} = 37.306 \text{ kJ/mol}$$

End of Solution

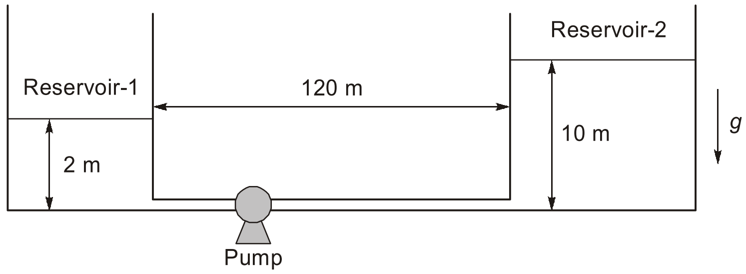
Q.50 Consider the process flowsheet in the figure. An irreversible liquid-phase reaction $A \rightarrow B$ (reaction rate $-r_A$ = 164 x_A kmol m^{-3} h^{-1}) occurs in a 1 m^3 continuous stirred tank reactor (CSTR), where x_A is the mole fraction of A. A small amount of inert, I, is added to the reactor. The reactor effluent is separated in a perfect splitter to recover pure B product down the bottoms and a B-free distillate. A fraction of the distillate is purged and the rest is recycled back to the reactor. At a particular steady state, the product rate is 100 kmol h^{-1}, the recycle rate is 200 kmol h^{-1} and the purge rate is 10 kmol h^{-1}. Given the above information, the inert feed rate into the process is ___________ kmol h^{-1} (rounded off to two decimal places).



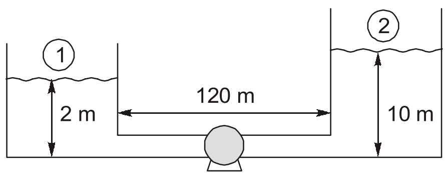
Ans. (3.99) (3.51 to 4.10)

End of Solution

Q.51 Two reservoirs located at the same altitude are connected by a straight horizontal pipe of length 120 m and inner diameter 0.5 m, as shown in the figure. A pump transfers the liquid of density 800 kg m^{-3} at a flow rate of 1 m^3 s^{-1} from Reservoir-1 to Reservoir-2. The liquid levels in Reservoir-1 and Reservoir-2 are 2 m and 10 m, respectively. Assume that the reservoirs' cross-section areas are large enough to neglect the liquid velocity at the top of the reservoirs. All minor losses can be ignored. The acceleration due to gravity is 9.8 m s^{-2}. If the friction factor for the pipe-flow is 0.01, the required power of the pump is _________ kW (rounded off to one decimal place).



Ans. (87.75) (85.7 to 89.7)



Given data: d = 0.5 m

$4f$ = F (friction factor) = 0.01

ρ = 800 kg/m^3

$$Q = 1 \text{ m}^3/\text{s}$$

Now (neglecting minor losses) apply Bernoulli's equation (between 1 and 2), we get

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 + H_P = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + h_f$$

As open to atmosphere and having large surface area of tank, so $[v_1 = v_2 = 0]$; $p_1 = p_2$

$$2 + h_p = 10 + h_f$$

$$h_f = \frac{4flv^2}{2gd} = \frac{0.01 \times 120 \times v^2}{2 \times 9.81 \times 0.5} \qquad \left\{ \begin{array}{l} 1 = \frac{\pi}{4}(0.25)V \\ V = 5.1 \text{ m/s} \end{array} \right\}$$

$$h_f = 3.18 \text{ m}$$

$$H_P = 8 + 3.18 = 11.18 \text{ m}$$

$$\text{Power} = 800 \times 9.81 \times 11.18 \times 1 = 87.75 \text{ kW}$$

End of Solution

Q.52 A venturi meter (venturi coefficient, $C_v = 0.98$) is connected to a pipe of inner diameter 50 mm. Water (density 1000 kg m^{-3}) is flowing through the pipe. The pressure-drop measured across the venturi meter is 50 kPa. If the venturi throat diameter is 20 mm, the estimated flow rate of water is _______ $\times 10^{-3}$ m^3 s^{-1} (rounded off to two decimal places).

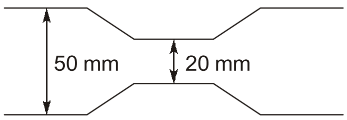
Ans. **(3.12) (3.10 to 3.15)**

Data given: $C_d = 0.98$

Pipe diameter, $D_o = 50$ mm, $d_o = 20$ mm (throat diameter)

$\Delta P = 50$ kPa

$\rho_w = 1000$ kg/m^3



For venturimeter, the flow rate is given by

$$Q = C_d A_2 \sqrt{\frac{2\Delta P}{\rho_f(1-\beta^4)}}$$

$$\beta = \frac{d_2}{d_1} = \frac{20}{50} = 0.4, \; A_2 = \frac{\pi}{4}(0.0.2)^2 = 0.000314$$

$$Q = 0.98 \times 0.000314 \sqrt{\frac{2 \times 50 \times 1000}{1000\left(1-(0.4)^4\right)}}$$

$$Q = 3.12 \times 10^{-3} \text{ m}^3/\text{s}$$

End of Solution

Q.53 In a constant-rate cake filtration operation, the collected filtrate volumes are 120 m^3 and 240 m^3 at 1 min and 2 min, respectively. Assume the cake resistance to be constant and the filter medium resistance to be negligible. If the pressure-drop across the cake is 10 kPa at 1 min, its value at 2 min is ________ kPa (rounded off to the nearest integer).

Ans. (20) (20 to 20)

Data given:

$$t = 1\text{ min},\ V_1 = 120\text{ m}^3,\ \Delta P_1 = 10\text{ kPa}$$

$$t = 2\text{ min},\ V_2 = 240\text{ m}^3,\ \Delta P_2 = ?$$

$$\propto = \text{Constant},\ R_m \cong 0$$

For constant rate filtration, we have

$$\frac{dt}{dV} = \frac{t}{V} = k_c V,\ \text{where } k_c = \frac{\mu \propto c}{A_1^2 \Delta P}$$

$$k_c = \frac{t}{V^2} \quad \because\ k_c \propto \frac{1}{\Delta P}$$

Thus,

$$\Delta P \propto \frac{V^2}{t} \rightarrow \frac{\Delta P_1}{\Delta P_2} = \frac{V_1^2}{t_1}\frac{t_2}{V_2^2}$$

$$\frac{\Delta P_1}{\Delta P_2} = \frac{(120)^2 2}{1(240)^2} = \frac{1}{2}$$

$$\frac{10}{\Delta P_2} = \frac{1}{2} \rightarrow \Delta P_2 = 20\text{ kPa}$$

End of Solution

Q.54 A cylindrical fin of diameter 24 mm is attached horizontally to a vertical planar wall. The heat transfer rate from the fin to the surrounding air is 60% of the heat transfer rate if the entire fin were at the wall temperature. If the fin effectiveness is 10, its length is __________ mm (rounded off to the nearest integer).

Ans. (100) (100 to 100)

Data given:

$$D = 24\text{ mm}$$

$$\eta_{efficiency} = 60\% = 0.60$$

$$\xi = 10\text{ [effectiveness]}$$

Now, we have relation between η and ξ, that is given by

A_s = Surface area

A_c = Cross sectional area

$$\xi = \eta \times \frac{A_s}{A_c}$$

$$\Rightarrow \quad 10 = 0.60 \times \frac{\pi D l}{\frac{\pi}{4}D^2}$$

$$10 = \frac{0.60 \times 4 \times l}{0.024}$$

$$l = 100\text{ mm}$$

End of Solution

Q.55 A single-effect evaporator with a heat transfer area of 70 m^2 concentrates a salt solution using steam. The salt solution feed rate and temperature are 10000 kg h^{-1} and 40°C, respectively. The saturated steam feed rate and temperature are 7500 kg h^{-1} and 150 °C, respectively. The boiling temperature of the solution in the evaporator is 80 °C. The average specific heat of the solution is 0.8 kcal kg^{-1} K^{-1}. The latent heat of vaporization is 500 kcal kg^{-1}. If the steam-economy is 0.8, the overall heat transfer coefficient is ________ kcal h^{-1} m^{-1} K^{-1} (rounded off to the nearest integer).

Ans. **(678) (675 to 679)**

Given, Area = 70 m^2

Latent heat of vaporization (λ_v) = 500 Kcal/kg

Steam economy = 0.8

Feed flow rate = 10000 kg/h at T = 40°C

Steam rate = 7500 kg/h at T = 150°C

Boiling point of solution, T = 80°C,

Applying energy balance,

$$F\,C_P(T - T_F) + V\,\lambda_v = S\lambda_s = u_0 A_0\,(T_S - T)$$

$$\frac{V}{S} = 0.8$$

$$V = 0.8 \times 7500 = 6000 \text{ kg}/n$$

$$10000 \times 0.8\,(80 - 40) + 6000 \times 500 = u_0 \times 70 \times (150 - 80)$$

$$u_0 = 677.55 \text{ Kcal/m}^2\text{.h.k}$$

End of Solution

Q.56 An equimolar binary mixture is to be separated in a simple tray-distillation column. The feed rate is 50 kmol min^{-1}. The mole fractions of the more volatile component in the top and bottom products are 0.90 and 0.01, respectively. The feed as well as the reflux stream are saturated liquids. On application of the McCabe-Thiele method, the operating line for the stripping section is obtained as

$$y = 1.5\,x - 0.005$$

where y and x are the mole fractions of the more volatile component in the vapor and liquid phases, respectively. The reflux ratio is _______ (rounded off to two decimal places).

Ans. **(0.632) (0.60 to 0.65)**

Equimolar binary mixture, x = 0.5

Feed flowrate = 50 kmol/min

$x_D = 0.9,\ x_w = 0.01$

Stripping line equation:

$$y = 1.5x - 0.005$$

and Saturated feed (q) = 1

$$\frac{\bar{L}}{\bar{V}} = 1.5$$

$$Fx_F = Dx_D + Wx_W$$

$$50 \times 0.5 = D \times 0.9 + w \times 0.01$$

$$25 = D \times 0.9 + (50 - D) \times 0.01$$
$$25 - 0.5 = D(0.9 - 0.01)$$
$$D = 27.52,\ w = 22.47$$
$$\frac{W x_W}{\bar{V}} = 0.005$$
$$\frac{22.47 \times 0.01}{0.005} = \bar{V} = 44.94 \text{ kmol/min}$$

For saturated feed

$$V = \bar{V} + F(1-q) = \bar{V} = 44.94 \text{ kmol/min}$$

For enriching section

$$V = L + D$$
$$44.94 - 27.52 = L = 17.42 \text{ kmol/min}$$

So, $$R = \frac{L}{D} = \frac{17.42}{(27.53)} = 0.632$$

End of Solution

Q.57 The dry-bulb temperature of air in a room is 30 °C. The Antoine equation for water is given as

$$\ln P^{sat} = 12.00 - \frac{4000}{T - 40}$$

where T is the temperature in K and P^{sat} is the saturation vapor pressure in bar. The latent heat of vaporization of water is 2000 kJ kg^{-1}, the humid heat is 1.0 kJ kg^{-1} K^{-1}, and the molecular weights of air and water are 28 kg kmol^{-1} and 18 kg kmol^{-1}, respectively. If the absolute humidity of air is Y' kg moisture per kg dry air, then for a wet-bulb depression of 9 °C, $1000 \times Y'$ = _________ (rounded off to one decimal place).

Ans. (22.5) (21.5 to 23.5)

Given: $\ln P^{sat} = 12.00 - \frac{4000}{T-40}$ where T in K.

For water at T = 100°C so, P_T = 1 bar

$$\ln(P^{sat}) = 12.00 - \frac{4000}{303 - 40}$$
$$P^{sat} = 0.0403 \text{ bar}$$
$$T_G - T_W = \frac{\lambda_\omega (Y'_{sat} - Y')}{h_G / k_Y}$$

For air water system,

$$\text{Humid heat } (C_P) = \frac{h_G}{k_Y}$$

Given: T_G = 30°C and $T_G - T_W$ = 9°C

$$\lambda_W = 2000 \text{ kJ/kg and } C_P = 1 \text{ kJ/kg-K}$$
$$Y'_{sat} = \frac{P_A^{sat}}{P_T - P_A^{sat}} \times \frac{18}{28} = 0.027$$

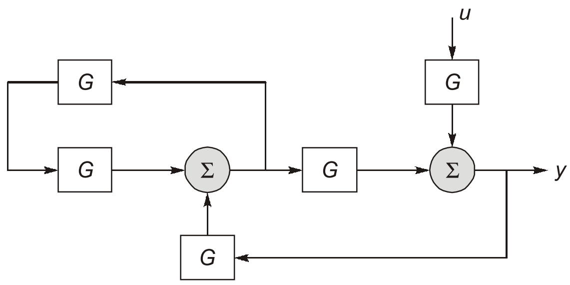
$$9 = \frac{2000 \times (0.027 - Y')}{1}$$

$$Y' = 0.0225$$

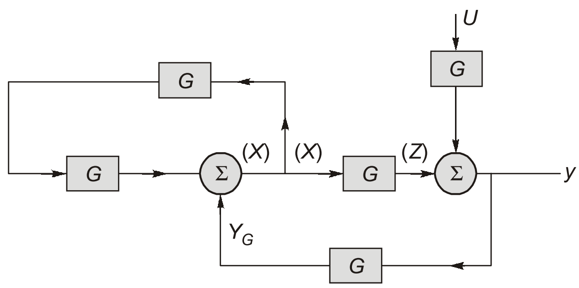
So, $1000 \times Y' = 22.5$

End of Solution

Q.58 In the block diagram shown in the figure, the transfer function $G = \dfrac{K}{(\tau s + 1)}$ with $K > 0$ and $\tau > 0$. The maximum value of K below which the system remains stable is ________ (rounded off to two decimal places).



Ans. **(0.707) (0.70 to 0.72)**



Given: $G = \dfrac{k}{\tau s + 1}$

$$XG^2 + YG = X$$

$\Rightarrow$
$$X = \frac{YG}{1 - G^2}$$

$$Z = XG$$

$$Y = Z + UG$$

$$Y = XG + UG$$

$$Y = \frac{YG^2}{1 - G^2} + UG$$

$$Y\left[1 - \frac{G^2}{1 - G^2}\right] = UG$$

$$\frac{Y}{U} = \frac{G}{\left[1-\frac{G^2}{1-G^2}\right]} = \frac{(1-G^2)G}{1-2G^2}$$

Characteristic equation $= 1 - 2G^2$

$$= 1 - \frac{2k^2}{(\tau s+1)^2}$$

$$(\tau s + 1)^2 - 2k^2 = 0$$

$$\tau^2 s^2 + 2\tau s + 1 - 2k^2 = 0$$

Routh array

s^2	τ^2	$1-2k^2$
s^1	2τ	0
s^0	$1-2k^2$	

For system to be stable, given $\tau > 0$ and $k > 0$

$$1 - 2k^2 \geq 0$$

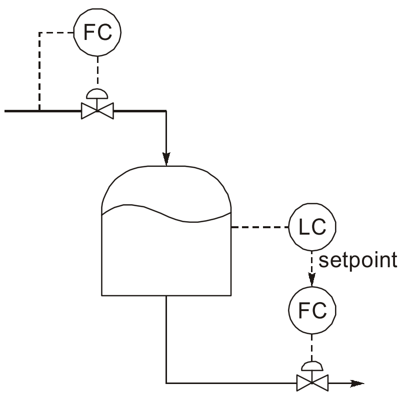
$$2k^2 \leq 1$$

$$k^2 \leq \frac{1}{2}$$

$$k \leq \frac{1}{\sqrt{2}} = 0.707$$

End of Solution

Q.59 Consider the tank level control system shown in the figure, where the cross-section area of the tank is A. Assume perfect flow controllers (FC). The level controller (LC) is proportional-integral (PI). For an integral time, τ_I, the level controller gain, K_c, is tuned for critical damping. The value of $\frac{K_c \tau_I}{A}$ is ________ (rounded off to the nearest integer).



Ans. (1) (1 to 1)

End of Solution

Q.60 Consider a single-input-single-output (SISO) system with the transfer function

$$G_p(s) = \frac{2(s+1)}{\left(\frac{1}{2}s+1\right)\left(\frac{1}{4}s+1\right)}$$

where the time constants are in minutes. The system is forced by a unit step input at time $\tau = 0$. The time at which the output response reaches the maximum is ________ minutes (rounded off to two decimal places).

Ans. (0.549) (0.53 to 0.56)

$$G_p = \frac{2(s+1)}{\left(\frac{1}{2}s+1\right)\left(\frac{1}{4}s+1\right)}$$

After step unit, we have

$$y = \frac{1}{s}\frac{2(s+1)\times 8}{(s+2)(s+4)}$$

$$\frac{16(s+1)}{s(s+2)(s+4)} = \frac{A}{s} + \frac{B}{s+2} + \frac{C}{s+4}$$

$$16s + 16 = s^2(A + B + C) + s(6A + 4B + 2C) + 8A$$

Solving,

$$A = 2$$
$$B = 4$$
$$C = -6$$
$$y(t) = 2 + 4e^{-2t} - 6e^{-4t}$$

$$\frac{dy}{dt} = 0 - 8e^{-2t} + 24e^{-4t} = 0 \qquad \left\{\text{for mox } \frac{dy}{dt} = 0\right\}$$

$$e^{-2t} + 4t = 3$$
$$e^{2t} = 3$$

$$t = \frac{\ln 3}{2} = 0.549$$

End of Solution

Q.61 Information for a proposed greenfield project is provided in the table. The discounted cash flow for the fourth year is Rs ________ crores (rounded off to one decimal place).

Fixed capital investment (excluding land)	Rs 250 crores
Salvage value	Rs 0
Yearly revenue from product sales	Rs 120 crores
Yearly manufacturing cost (excluding depreciation)	Rs 30 crores
Interest rate	10% compounded annually
Annual taxation rate	30%
Depreciation method	Double declining balance* over seven years
Plant start-up	2 years after project initiation

* $d_k = \frac{2}{7}BV_{k-1}$ *k*: years post start-up *d*: Depreciation amount *BV*: Book value

Ans. (48.36) (46.5 to 49.5)

Given:

FCI (excluding land) = 250 crores

Salvage value = 0

Yearly revenue from product sales = 120 crores

Yearly Manufacturing cost (excluding depreciation) = 30 crores

Interest rate = 10% compounded annually

Annual taxation rate = 30%

Profit = 120 – 30 = 90 crores

$$\text{Depreciation for } 4^{th} \text{ year} = \frac{2}{7}BV_{k-1} = \frac{2}{7}BV_3$$

From double declining balance method,

$$f = \frac{2}{7} = 0.2857$$

$$BV_3 = V_o(1-f)^3 = 250(1-0.2857)^3$$

$$= 91.107 \text{ crore}$$

$$d = \frac{2}{7} \times 91.107 = 26.03 \text{ crore}$$

Taxable profit = 90 – 26.03 = 63.96 crore

Tax paid = 63.96 × 0.3

Profit after tax = 44.77 crore

Cash flow = PAT + Depreciation = 44.77 + 26.03

= 70.80 crore

Discounted cash flow = Present value at time, $t = 0$

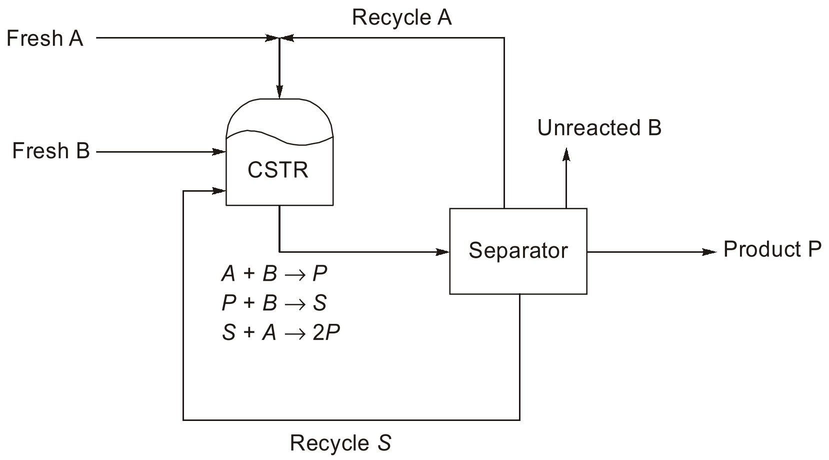
$$\text{Discounted cash flow} = \frac{70.80}{(1+i)^4} = 48.36 \text{ crore}$$

End of Solution

Q.62 Consider the process in the figure. The liquid phase elementary reactions

$$A + B \rightarrow P \quad -r_{B1} = k_1 x_A x_B$$
$$P + B \rightarrow S \quad -r_{B2} = k_2 x_P x_B$$
$$S + A \rightarrow 2P \quad -r_{S3} = k_3 x_S x_A$$

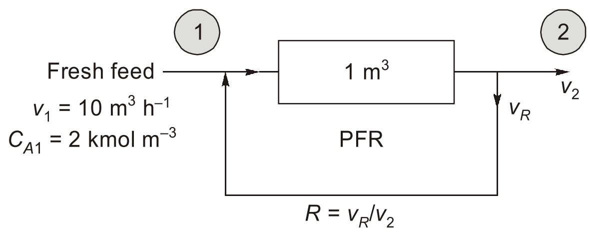
occur in the continuous stirred tank reactor (CSTR), where x_j is the mole fraction of the j^{th} component (j = A, B, P, S) in the CSTR. It is given that $k_2 = k_3$. All process feed, process exit and recycle streams are pure. At steady state, the net generation rate of the undesired product, S, in the CSTR is zero. As $q = x_A/x_B$ is varied at constant reactor temperature, the reactor volume is adjusted to maintain a constant single-pass conversion of B. For a fixed product rate and 90% conversion of B in the reactor, the value of q that minimizes the sum of the molar flow rates of the A and S recycle streams is ________ (round off to one decimal place).



Ans. (2) (2 to 2)

End of Solution

Q.63 An elementary irreversible liquid-phase reaction, $2A \rightarrow B$, is carried out under isothermal conditions in a 1 m^3 ideal plug flow reactor (PFR) as shown in the figure. The volumetric flow rate of fresh A, v_1 = 10 $m^3\ h^{-1}$, and its concentration C_{A1} = 2 kmol m^{-3}. For a recycle ratio R = 0, the conversion of A at location 2 with respect to the fresh feed (location 1) is 50%. For R → ∞, the corresponding conversion of A is ________% (rounded off to one decimal place).



Ans. (38.2%) (37.2 to 39.2)

Now for PFR $\quad \dfrac{X}{1-X} = kC_{AO}t$

$$\frac{0.50}{0.50} = 5\times2\times\frac{1}{10} \Rightarrow k = 5\ \text{m}^3/\text{kmol.hr}$$

Now, $$\frac{1}{10\times C_{A_0}} = \frac{x_A}{5\times C_{A_0}^2(1-x)^2}$$

$$x^2 - 3x + 1 = 0$$

Solving, $$x = 0.382,\ 38.2\%$$

End of Solution

Q.64 An elementary irreversible gas-phase reaction, $A \rightarrow B + C$, is carried out at fixed temperature and pressure in two separate ideal reactors: (i) a 10 m^3 plug flow reactor (PFR), (ii) a 10 m^3 continuous-stirred tank reactor (CSTR). If pure A is fed at 5 $m^3\ h^{-1}$ to the PFR operating at 400 K, the conversion is 80%. If a mixture of 50 mol% of A and 50 mol% of an inert is fed at 5 $m^3\ h^{-1}$ to the CSTR operating at 425 K, the conversion is 80%. The universal gas constant $R = 8.314$ J mol^{-1} K^{-1}. Assuming the Arrhenius rate law, the estimated activation energy is _________ kJ mol^{-1} (rounded off to one decimal place).

Ans. (47.432) (45.5 to 49.5)

PFR:

$A \rightarrow B + C$ $$\varepsilon_A = \left(\frac{2-1}{1}\right) = 1$$

$$\frac{\tau}{C_{A0}} = \int_o^{x_A} \frac{dx_A}{(-r_A)} \Rightarrow \frac{10}{5C_{A0}} = \int_o^{0.80} \frac{dx_A}{\dfrac{k_1C_{A0}(1-x)}{(1+\varepsilon_{x_A})}}$$

$$2k_1 = \int_o^{0.80}\left(\frac{1+x}{1-x}\right)dx = \int\frac{2dx}{1-x} - \int dx = -2\ln|1-x| - x$$

$$-2k_1 = \left[2\ln|1-x| + x\right]_0^{0.80}$$

$$k_1 = 1.21 \text{ at } 400 \text{ K}$$

Now for CSTR,

$$\tau = \frac{10}{5} = \frac{C_{A0}X_A(1+\varepsilon_A\times A)}{k_2C_{A0}(1-x)}$$

$$2 = \frac{0.80(1+0.50\times0.80)}{k_2(0.20)}$$

$$k_2 = 2.8 \text{ at } 425 \text{ K}$$

Using Arrhenius equation,

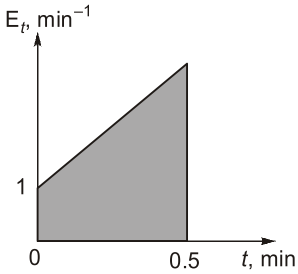
$$\ln\left|\frac{k_2}{k_1}\right| = \frac{E}{8.314}\left(\frac{1}{400}-\frac{1}{425}\right)$$

$$\ln\left|\frac{2.8}{1.21}\right| = \frac{E}{8.314}\left(\frac{1}{400}-\frac{1}{425}\right)$$

$$E = 47.432 \text{ kJ/mol}$$

End of Solution

Q.65 An elementary irreversible liquid-phase reaction, $2P \xrightarrow{k} Q$, where the rate constant k = 2 L mol^{-1} min^{-1}, takes place in an isothermal non-ideal reactor. The E-curve in a tracer experiment is shown in the figure. Pure P(2 mol L^{-1}) is fed to the reactor. Using the segregated model, the percentage conversion of P at the exit of the reactor is ________% (rounded off to the nearest integer).



Ans. (50) (49 to 51)

Using segregation model, the mean conversion is given by

$$\bar{x} = \int_o^\infty x(t)E(t)dt$$

Now for II order, we know

$$\frac{X}{1-X} = kC_{AO}t$$

$$\Rightarrow \quad X = \frac{kC_{AO}t}{1+kC_{AO}t} = \frac{4t}{1+4t}$$

From E-curve, $E = \int_o^\infty E(t)dt = 1$ [Area will be one]

$$1 = \frac{1}{2}[1+x]\times 0.5 \Rightarrow x = 3$$

$$E(t) - 1 = \frac{3-1}{0.5}(t-0)$$

$$\Rightarrow \quad E(t) = 4t + 1$$

Now for, $$(\bar{x}) = \int_o^{0.5}\frac{4t}{1+4t}\times(1+4t)dt = \left[2t^2\right]_0^{0.5}$$

$$\bar{x} = 0.5 = 50\%$$

End of Solution

■■■■