Chemical Engineering
GATE 2016

Time:	3 hrs			
	Questions	Marks	Total	Negative marking (for each wrong answer)
General Aptitude	Q1-Q5	1×5 = 5	5	-⅓
	Q6-Q10	2×5 = 10	10	-⅔
Chemical -CH				
	Q1-Q25	1 ×25 = 25	25	-⅓
	Q26-Q55	2 ×30 = 60	60	-⅔
	Total :		100	

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Q. 1 – Q. 5 Carry one mark each.

Q. 1 The volume of a sphere of diameter 1 unit is ___ than the volume of a cube of side 1 unit.

(A) least (B) less (C) lesser (D) low

1 $d = 1$ unit say 1 cm

$$V_{sphere} = \frac{\pi d^3}{6} = \frac{\pi (1)^3}{6} = \frac{\pi}{6} = 0.5236$$

$$V_{cube} = 1^3 = 1$$

$\therefore V_{sphere} < V_{cube}$ $\Rightarrow$ B correct answer

(dia = 1 unit) (side of 1 unit)

Q. 2 The unruly crowd demanded that the accused be __________ without trial.

(A) hanged (B) hanging (C) hankering (D) hung

Q. 3 Choose the statement(s) where the underlined word is used correctly:

(i) A prone is a dried plum.
(ii) He was lying prone on the floor.
(iii) People who eat a lot of fat are prone to heart disease.

(A) (i) and (iii) only
(B) (iii) only,
(C) (i) and (ii) only
(D) (ii) and (ii) only

Q. 4 Fact: If it rains, then the field is wet.

Read the following statements:
(i) It rains
(ii) The field is not wet
(iii) The field is wet
(iv) It did not rain.

Which one of the options given below is NOT logically possible, based on the given fact?

(A) If (iii), then (iv)
(B) If (i), then (iii)

(C) If (i), then (ii)

(D) If (ii), then (iv)

Q. 5 A window is made up of a square portion and an equilateral triangle portion above it. The base of the triangular portion coincides with the upper side of the square. If the perimeter of the window is 6 m, the area of the window in m^2 is ___________

(A) 1.43

(B) 2.06

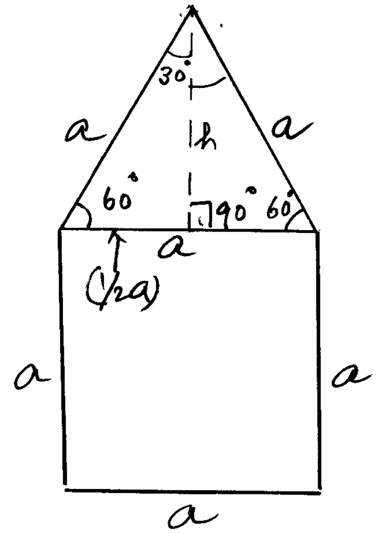
(C) 2.68

(D) 2.88

5. Perimeter $\Rightarrow 5a = 6\,m$

$$a = \frac{6}{5}\,m \Leftarrow$$

h (height of equilater triangle)



$$a^2 = h^2 + \left(\frac{1}{2}a\right)^2$$

$$\text{or } h^2 = a^2 - \frac{1}{4}a^2 = \frac{3}{4}a^2$$

$$h = \frac{\sqrt{3}}{2}a$$

$$\therefore \text{Area of window} = \underbrace{a^2}_{\text{Square}} + \underbrace{\left[\frac{1}{2}\left(\frac{\sqrt{3}}{2}a\right)a\right]}_{\text{Triangle}}$$

$$= a^2 + \frac{\sqrt{3}}{4}a^2 = a^2\left(1 + \frac{\sqrt{3}}{4}\right)$$

$$= a^2(1.433)$$

$$= \left(\frac{6}{5}\right)^2(1.433) = 2.063\ m$$

(B) correct answer

Q. 6 – Q. 10 carry two marks each.

Q. 6 Students taking an exam are divided into two groups. P and Q such that each group has the same number of students. The performance of each of the students in a test was evaluated out of 200 marks. It was observed that the mean of group P was 105, while that of group Q was 85. The standard deviation of group P was 25, while that of group Q was 5. Assuming that the marks were distributed on a normal distribution, which of the following statements will have the highest probability of being TRUE ?

(A) No student in group Q scored less marks than any student in group P.

(B) No student in group P scored less marks than any student in group Q.

(C) Most students of group Q scored marks in a narrower range than students in group P.

(D) The median of the marks of group P is 100.

Q6.

	P	Q
μ (mean)	105	85
σ (standard deviation)	25	5

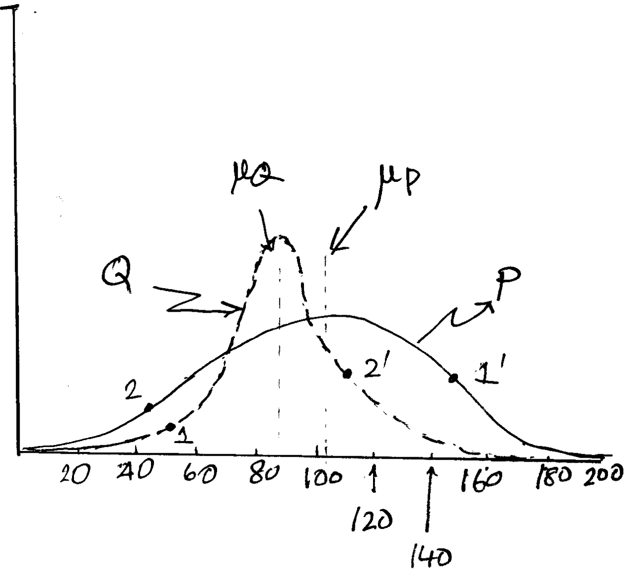
⇒ Same no of Students
Total 200 marks

Lower σ ⇒ sharper peak

(A) ⇒ 1 (Gr. Q) got less marks than 1' (Gr. P) ⇒ FALSE

(B) ⇒ 2 (Gr. P) got less marks than 2' (Gr. Q) ⇒ FALSE

(C) True ⇒ Narrower peak (lower σ)



(D) Mean, Median and Mode of a normal distribution are equal $\left[f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \right]$

∴ Mode of P = 105
Mode of Q = 85

$\Big\}$ option (D) is FALSE

∴ (C) ⇒ Correct answer.

Q. 7 **A smart city integrates all modes of transport, uses clean energy and promotes sustainable use of resources. It also uses technology to ensure safety and security of the city, something which critics argue, will lead to a surveillance state.**

Which of the following can be logically inferred from the above paragraph?

(i) **All smart cities encourage the formation of surveillance states.**
(ii) **Surveillance is an integral part of a smart city.**
(iii) **Sustainability and surveillance go hand in hand in a smart city.**
(iv) **There is a perception that smart cities promote surveillance.**

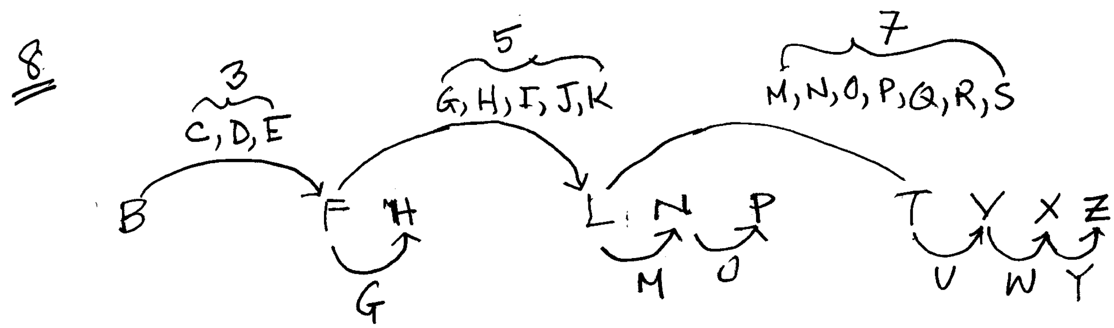
(A) (i) and (iv) only (B) (i) and (iv) only

(C) (iv) only (D) (i) only

Q. 8 **Find the missing sequence in the letter series.**

B, FH, LNP,

(A) SUWY (B) TUVW (C) TVXZ (D) TWXZ



(C) ⇒ correct answer

Q. 9 **The binary operation □ is defined as a □ b = ab + (a + b), where a and be are any two real numbers. The value of the identity element of this operation, defined as the number x such that a □ x = a, for any a, is ____ .**

(A) 0 (B) 1 (C) 2 (D) 10

9.

$$a \square b = ab + (a+b)$$

Identity element $\Rightarrow$ an identity element of a set that if combined with another element by a specific binary operation $(a \square x)$ leaves the other element unchanged. $(\therefore \underbrace{a}_{\text{other element}} \square \underbrace{x}_{\text{Identity element}} = a)$

$$\therefore a \square x = ax + (a+x)$$

$$\cancel{a} = ax + (\cancel{a}+x)$$

$$\therefore x(1+a) = 0$$

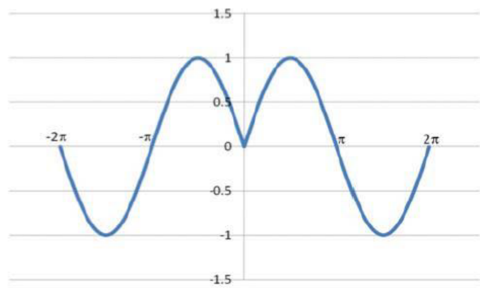
For any value of a, $x = 0$

(A) $\Rightarrow$ Correct answer ✓

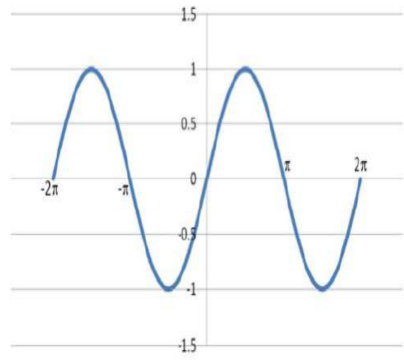
$a \square 0 = a \cdot 0 + (a+0) = a$

Q. 10 Which of the following curves represents the function
y = ln (|e [|sin (|x|)|] |) for |x| < 2π? Here, x represents the abscissa and y represents the ordinate.

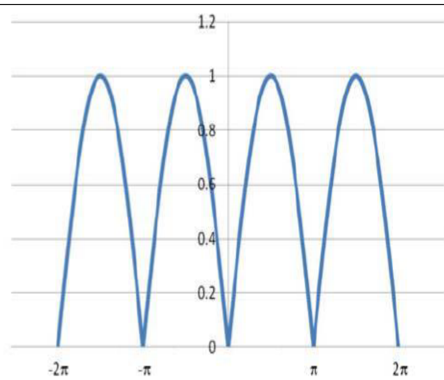
(A)


1.5
1
0.5
0
-0.5
-1
-1.5
-2π
-π
π
2π

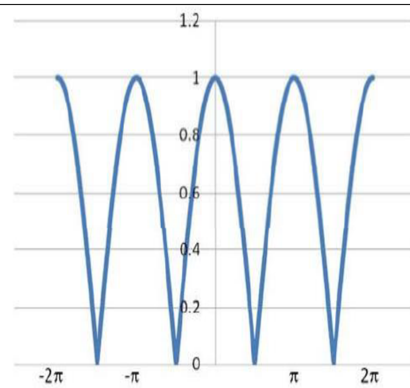
(B)


1.5
1
0.5
0
-0.5
-1
-1.5
-2π
-π
π
2π

(C)


1.2
1
0.8
0.6
0.4
0.2
0
-2π
-π
π
2π

(D)


1.2
1
0.8
0.6
0.4
0.2
0
-2π
-π
π
2π

10. $y = \ln\left(\left|e^{[|\sin(|x|)]}\right|\right)$ for $x < 2\pi$

Sine function $f(x) = \sin x$ ✓

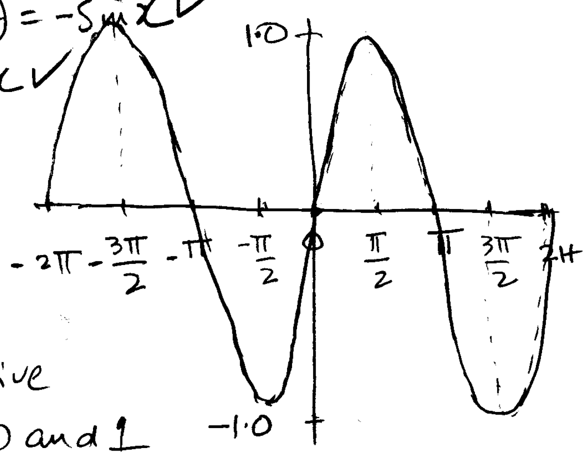
and $\sin(-x) = -\sin x$ ✓

$\ln(e^x) = x$ ✓

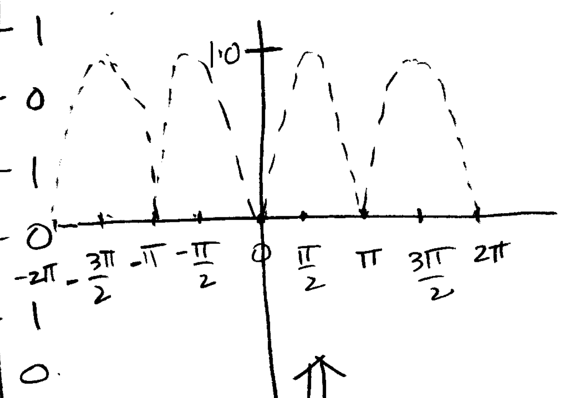
$\ln\left|e^{[|\sin|x|]}\right|$

$-2\pi \quad -2\pi$

will always be positive oscillating between 0 and 1



x	$\lvert x \rvert$	$\sin\lvert x \rvert$	$\lvert \sin\lvert x \rvert \rvert$	$y = \ln\left(\left\lvert e^{[\lvert\sin(\lvert x \rvert)\rvert]}\right\rvert\right) = \lvert\sin\lvert x \rvert\rvert$
-2π	2π	0	0	0
$-\frac{3\pi}{2}$	$3\pi/2$	1	1	1
$-\pi$	π	0	0	0
$-\frac{\pi}{2}$	$\pi/2$	1	1	1
0	0	0	0	0
$\frac{\pi}{2}$	$\pi/2$	1	1	1
π	π	0	0	0
$\frac{3\pi}{2}$	$3\pi/2$	1	1	1
2π	2π	0	0	0



(c) correct answer

Q. 1 – Q. 25 Carry one mark each.

Q. 1 Which one of the following is an iterative for solving a system of simultaneous linear algebraic equations?

(A) Gauss elimination (B) Gauss-Jordan
(C) Gauss-Seidel (D) LU decomposition

Q1

A & B → Gauss Elimination and Gauss-Jordan use row / or reduced row form to solve explicitly / for each variable (addition, substraction, multiplication by a constant value etc.) ⇒ variables are solved explicitely

(C) Gauss-Siedel ⇒ Iterative technique. Initial value $[X_0]$ ⇒ updated to set $[X_1]$ → so on to converged solution vector

correct answer

(D) ⇒ LUD (Lower, upper Decomposition) method ⇒ forms Lower / upper triangular matrices using Gaussian elimination method.

Q. 2 The Laplace transform of $e^{at} \sin(bt)$ is ,

(A) $\dfrac{b}{(s-a)^2+b^2}$

(B) $\dfrac{(s-a)}{(s-a)^2+b^2}$

(C) $\dfrac{(s-a)}{(s-a)^2-b^2}$

(D) $\dfrac{b}{(s-a)^2-b^2}$

Q2:- (A) is the correct answer ✓

$$\mathcal{L}\left[e^{at}\sin(bt)\right] = \frac{b}{(s-a)^2+b^2}$$

[See any book on Process Control
Seborg, p 42

Q. 3 What are the modulus (r) and argument (θ) of the complex number 3 + 4i ?

(A) $r = \sqrt{7},\quad \theta = \tan^{-1}\left(\dfrac{4}{3}\right)$

(B) $r = \sqrt{7},\quad \theta = \tan^{-1}\left(\dfrac{3}{4}\right)$

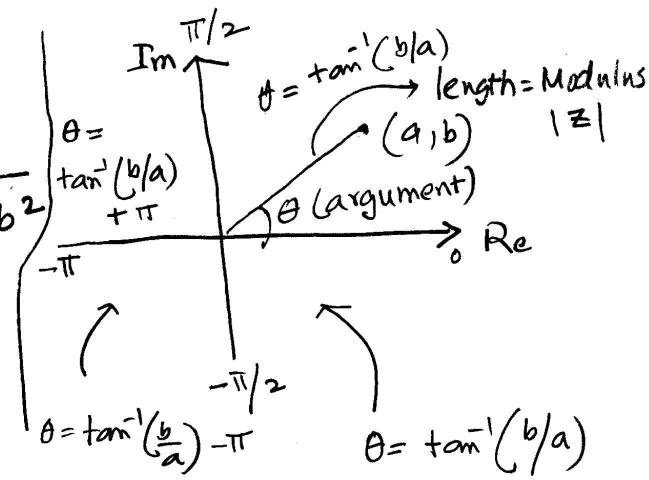
(C) $r = 5,\quad \theta = \tan^{-1}\left(\dfrac{3}{4}\right)$

(D) $r = 5,\quad \theta = \tan^{-1}\left(\dfrac{4}{3}\right)$

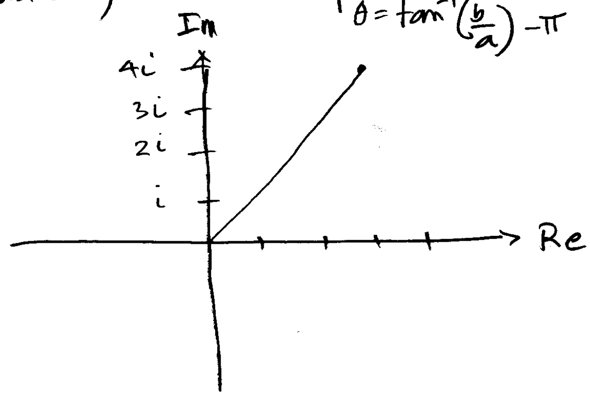
Q3

complex no
$z = a + bi$

$\text{Modulus} = |z| = \sqrt{a^2+b^2}$



$z = 3 + 4i$
(1st quadrant)



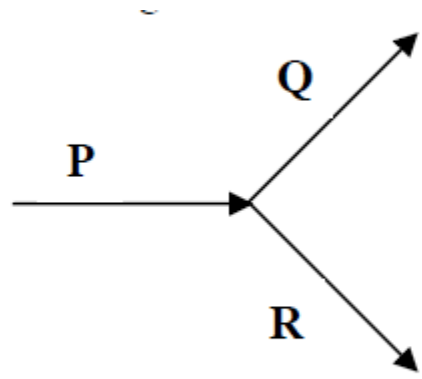
$\underset{|z|}{\text{Modulus}} = \sqrt{3^2+4^2} = \sqrt{25} = 5$

$\text{Argument}(z) = \tan^{-1}\left(\frac{4}{3}\right) = 0.927$ radians
(1st quadrant)

[π (3.1417) radian = $180°$]

(D) ⇒ correct answer

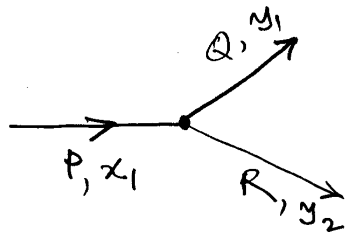
Q. 4 A liquid mixture of ethanol and water is flowing as inlet stream P into a stream splitter. It is split into two streams, Q and R, as shown in the figure below.



The flow rate of P, containing 30 mass% of ethanol, is 100 kg/h. What is the least number of additional specification (s) required to determine the mass flow rates and compositions (mass%) of the two exit steams ?

(A) 0 (B) 1 (C) 2 (D) 3

4.



Independent equs

1) Overall material balance

$P = Q + R$

2) Component material balance

$P x_1 = Q y_1 + R y_2$

Degree of freedom ($n_{df} = n_{unknowns} - n_{indep.\ equs} - n_{constraints}$)

$n_{unknowns} = 6$ (P, Q, R, x_1, y_1, y_2)

$n_{indep.\ equs} = 2$

$n_{constraints} = 1$ (stream splitting ⇒ all mass fractions are equal. $x_1 = y_1 = y_2$)

[See Felder & Rousseau p99]

$\therefore n_{df} = 6 - 2 - 1 = 3$

(Two variable values are already known)

$P = 100$ kg/h

$x_1 = 0.3$

$\therefore n_{df} = (3-2) = 1$

$\therefore$ To make $n_{df} = 0$ (for a completely defined problem $n_{df} = 0$) ⇒ we need to define one more variable. This variable is f (fraction of P going to Q)

⇒ (B) is the correct answer

$\therefore Q = fP$

$R = (1-f)P$

Q. 5 **The partial molar enthalpy (in kJ/mol) of species 1 in a binary mixture is given by $\bar{h}_1 = 2 - 60x_2^2 + 100x_1x_2^2$, where x_1 and x_2 are the mole fractions of species 1 and 2, respectively. The partial molar enthalpy (in kJ/mol, rounded off to the first decimal place) of species 1 at infinite dilution is ______.**

Q5

$$\bar{h}_1 = 2 - 60x_2^2 + 100x_1x_2^2$$

$\bar{h}_1 = 2 - 60(1)^2$

$= -58$ kJ/mol

Answer

Infinite dilution

$x_1 \to 0, \; x_2 \to 1$

(See Sandler, p286)

Q. 6 **For a flow through a smooth pipe, the Fanning friction factor (f) is given by f = mRe$^{-0.2}$ in the turbulent flow regime, where Re is the Reynolds number and m is a constant. Water flowing through a section of this pipe with a velocity 1 m/s results in a frictional pressure drop of 10 kPa. What will be the pressure drop across this section (in kPa), when the velocity of water is 2 m/s ?**

(A) 11.5 (B) 20 (C) 34.8 (D) 40

Q6.

$$\Delta P_f = 4 f \rho \left(\frac{\Delta L}{D}\right) \frac{v^2}{2}$$ [See Geankoplis p 89]

$$\Delta P_f = \underbrace{\left(4 \rho \frac{\Delta L}{D} \frac{1}{2}\right)}_{K} \left(f v^2\right) = K f v^2$$

$$= K (m Re)^{-0.2} v^2 = K' Re^{-0.2} v^2 \quad [K' = mK]$$

$$= K' \left[\frac{D u \rho}{\mu}\right]^{-0.2} v^2 = \left\{K' \left[\frac{D \rho}{\mu}\right]^{-0.2}\right\} u^{(2-0.2)}$$

$$= K'' u^{1.8} \quad \left[K'' = K' \left(\frac{D\rho}{\mu}\right)^{-0.2}\right]$$

$\Delta P_{f1} = 10$ kPa, $u_1 = 1$ m/s

$\Delta P_{f2} = ?$ $\quad u_2 = 2$ m/s

$$\therefore \frac{\Delta P_{f2}}{\Delta P_{f1}} = \left(\frac{u_2}{u_1}\right)^{1.8} = \left(\frac{2}{1}\right)^{1.8} = 3.482$$

$$\therefore \Delta P_{f2} = 3.482 \times 10 \text{ kPa} = 34.82 \text{ kPa}$$

(c) correct answer

Q. 7 In a cyclone separator used for separation of solid particles from a dust laden gas, the separation factor is defined as the ratio of the centrifugal force to the gravitational force acting on the particle. S_r denotes the separation factor at a location (near the wall) that

is at a radial distance r from the centre of the cyclone. Which one of the following statements is INCORRECT ?

(A) S_r depends on mass of the particle
(B) S_r depends on the acceleration due to gravity.
(C) S_r depends on tangential velocity of the particle.
(D) S_r depends on the radial location (r) of the particle.

Q7

For a cyclone separator

$$S_r = \frac{\text{Centrifugal force}}{\text{gravitational force}}$$

$$= \frac{(\cancel{m} u^2_{tangential}/r)}{\cancel{m} g}$$

$$= \frac{u^2_{tan}}{r g}$$

$u^2_{tan} \rightarrow$ option c (true)

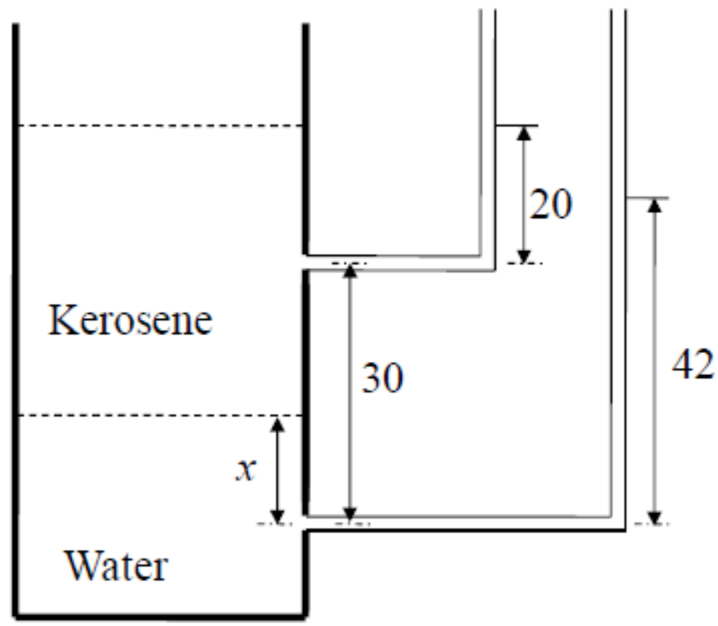
$g \leftarrow$ option B (true)

$r \leftarrow$ option D (true)

$S_r \neq f(m) \Rightarrow$ separation factor does not depend on mass of particle

OPTION (A) is INCORRECT ✓

Q, 8 A vertical cylindrical vessel has a layer of kerosene (of density 800 kg/m3) over a layer of water (of density 1000 kg/m^3). L-shaped glass tubes are connected to the column 30 cm apart. The interface between the two layers lies between the two points at which the L-tubes are connected. The levels (in cm) to which the liquids rise in the respective tubes are shown in the figure below.

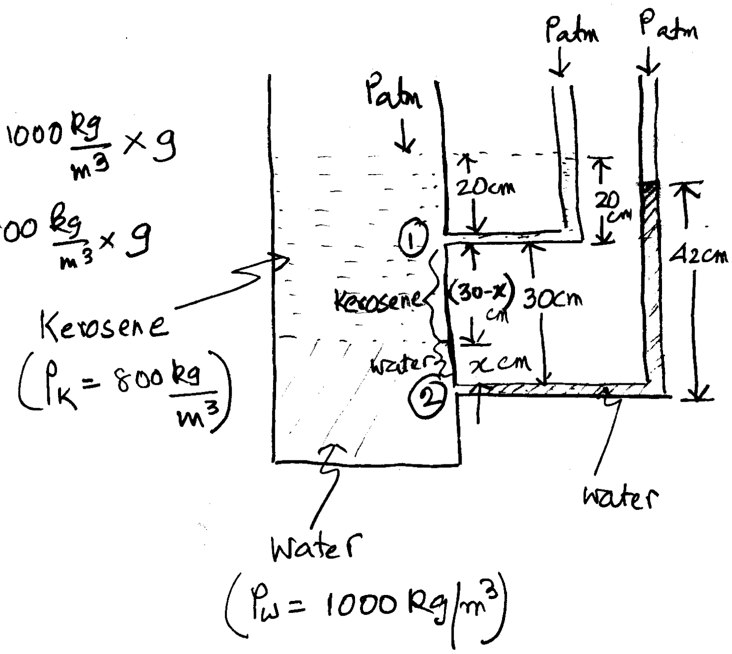


The distance (x in cm, rounded off to the first decimal place) of the interface from the point at which the lower L-tube is connected is _______

Q8

$$P_2 = \left(42\,cm \times \frac{1\,m}{100\,cm}\right) \times 1000\,\frac{kg}{m^3} \times g$$

$$P_1 = \left(20\,cm \times \frac{1}{100}\right) \times 800\,\frac{kg}{m^3} \times g$$



$$P_2 = P_1 + \underbrace{\left[(30-x)\,cm \times \frac{1}{100}\right] \times 800 \times g}_{\text{Kerosene}} + \underbrace{x \times \frac{1}{100} \times 1000 \times g}_{\text{water}}$$

$$\therefore \underbrace{42 \times \frac{1}{\cancel{100}} \times 10\cancel{00} \times \cancel{g}}_{P_2} = \overbrace{\left(20 \times \frac{1}{\cancel{100}}\right) \times 8\cancel{00} \times \cancel{g}}^{P_1} + \left[(30-x) \times \frac{1}{\cancel{100}}\right] \times 8\cancel{00} \times \cancel{g} + x \times \frac{1}{\cancel{100}} \times 10\cancel{00} \times \cancel{g}$$

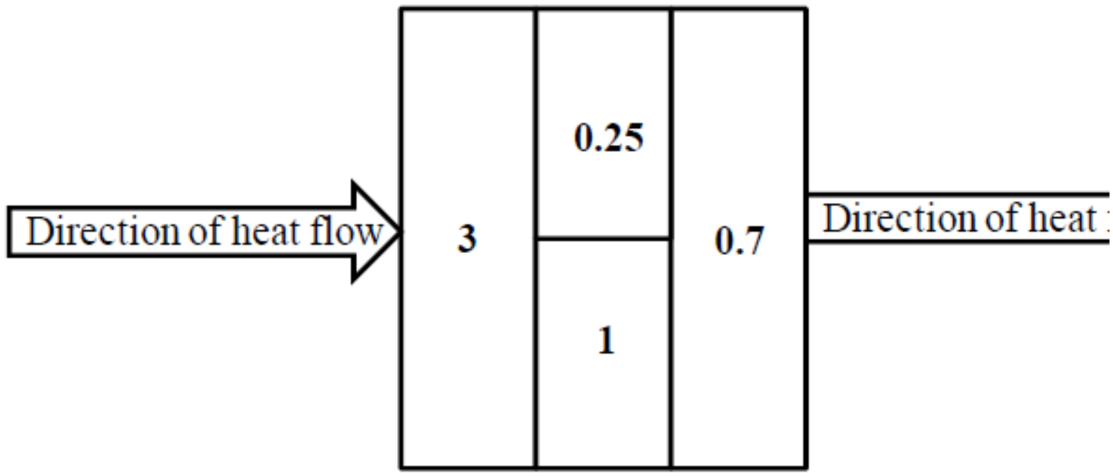
$$42 \times 10 = 20 \times 8 + (30-x) \times 8 + x \times 10$$

$$420 = 160 + 240 - 8x + 10x$$

$$2x = (420 - 240 - 160) = 20$$

$$\therefore x = 10\,cm \Rightarrow \text{Answer}$$

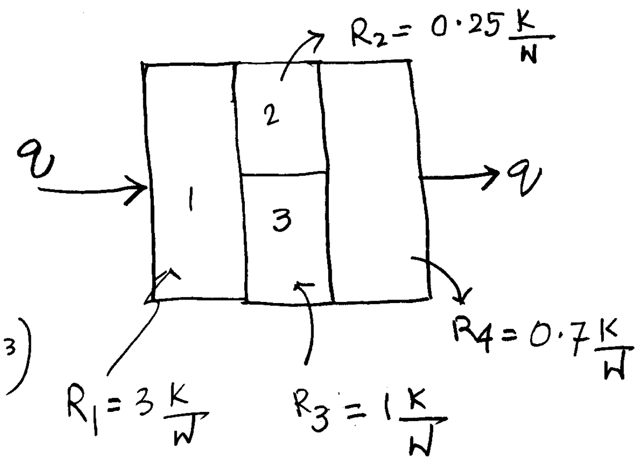
Q. 9 **A composite wall is made of four different materials of construction in the fashion shown below. The resistance (in K/W) of each of the section of the wall is indicated in the diagram.**



The overall resistance (in K/W, rounded off to the first decimal place) of the composite wall, in the direction of heat flow, is __________

9.

$$q = \frac{\Delta T}{\sum \frac{L}{kA}} = \frac{\Delta T}{\sum R}$$

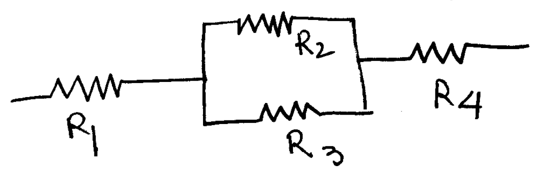


(See Geankoplis p 223)

$$W = \frac{K \rightarrow \Delta T}{\left(\frac{m \rightarrow L}{\frac{W}{mK} \cdot m^2}\right)} \Rightarrow \text{Resistance unit} \Rightarrow \frac{K}{W}$$

$W \leftarrow q$, $\frac{W}{mK} \leftarrow k$, $m^2 \leftarrow A$

Resistances can be calculated taking equivalent electrical resistance circuit



equiv. resistance of R_2 and R_3 (Parallel)

$$\frac{1}{R_{23}} = \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{0.25} + \frac{1}{1} = 5 \Rightarrow R_{23} = \frac{1}{5} = 0.2\ \frac{K}{W}$$

$\therefore$ Overall resistance of composite wall $= R_1 + R_{23} + R_4$

$$= 3 + 0.2 + 0.7 = 3.9\ K/W \Rightarrow \text{Answer.}$$

Q. 10 Steam at 100°C is condensing on a vertical steel plate. The condensate flow is laminar. The average Nusselt numbers are Nu_1 and Nu_2, when the plate temperatures are 10°C and 55°C, respectively. Assume the physical properties of the fluid and steel to remain

constant within the temperature range of interest. Using Nusselt equations for film-type condensation, what is the value of the ratio $\frac{Nu_2}{Nu_1}$?

(A) 0.5 (B) 0.84 (C) 1.19 (D) 1.41

Q10 For condensation on a vertical plate and laminar flow of condensate

$$Nu = 1.13\left[\frac{\rho_L(\rho_L-\rho_v)\,g\,h_{fg}\,L^3}{\mu_L\,k_L\,\Delta T}\right]^{1/4}$$

[See Geankoplis Eq. 4.8-20 p265]

Physical properties remaining same $(\rho_L, \rho_v, h_{fg}, \mu_L, k_L)$

$$\therefore Nu = K\frac{1}{(\Delta T)^{1/4}} \qquad K = \left[\frac{\rho_L(\rho_L-\rho_v)\,g\,h_{fg}\,L^3}{\mu_L\,k_L}\right]$$

$Nu_1 \Rightarrow \Delta T_1 = 100 - 10 = 90^\circ C$ $\quad \Delta T = T_{sat} - T_{wall}$

$Nu_2 \Rightarrow \Delta T_2 = 100 - 55 = 45^\circ C$

$$\frac{Nu_2}{Nu_1} = \left(\frac{\Delta T_1}{\Delta T_2}\right)^{1/4} = \left(\frac{90}{45}\right)^{1/4} = 2^{1/4} = 1.189$$

(C) correct answer

Q. 11 A binary liquid mixture of benzene and toluene contains 20 mol% of benzene. At 350 K the vapour pressures of pure benzene and pure toluene are 92 kPa and 35 kPa, respectively. The mixture follows Raoult's law. The equilibrium vapor phase mole

fraction (rounded off to the second decimal place) of benzene in contact with this liquid mixture at 350 K is _______

Q11

$p_B = x_B P_B^{vap}$ | $p_T = x_T P_T^{vap}$

(Mixture follows Raoult's Law)

$P = p_B + p_T$

p = partial pressure

P = Total pressure

$$y_B = \frac{p_B}{P}$$

$$= \frac{x_B P^B_{vap}}{x_B p^B_{vap} + x_T p_T^{vap}}$$

$x_B = 0.2$

$x_T = (1-0.2) = 0.8$

$p_B^{vap} = 92\,kPa$

$p_T^{vap} = 35\,kPa$

$$= \frac{0.2 \times 92}{(0.2 \times 92 + 0.8 \times 35)}$$

$$= \frac{18.4}{46.4} = 0.396 \simeq 0.40$$

$\therefore$ vap. phase mol. fraction of benzene = 0.40
" Toluene = 0.60

$\}$ Answer.

Q. 12 Match the dimensionless numbers in Group-1 with the ratios in Group-2

	Group-1		Group-2
P	Biot number	I	$\frac{\text{buoyancy force}}{\text{viscous force}}$
Q	Schmidt number	II	$\frac{\text{internal thermal resistance of a solid}}{\text{boundary layer thermal resistance}}$
R	Grashof number	III	$\frac{\text{momentum diffusivity}}{\text{mass diffusivity}}$

(A) P-II, Q-I, R-III (B) P-I, Q-III, R-II
(C) P-III, Q-I, R-II (D) P-II, Q-III, R-I

Q. 13 For what value of Lewis number, the wet-bulb temperature and adiabatic saturation temperature are nearly equal ?

(A) 0.33 (B) 0.5 (C) 1 (D) 2

Q13 Eqn for adiabatic saturation temperature

$$\frac{H - H_S}{T - T_S} = -\frac{C_S}{\lambda_S} \quad (1)$$

(Geankoplis p530, Eqn. 9.3-11)

S ⇒ adiabatic satn temp.

C_S = humid heat
= 1.005 + 1.88 H
(Geankoplis p527)
(kJ/kg dry air)

λ_S = latent heat of vapn. for water at T_S (kJ/kg)

Eqn for wet bulb temperature

$$\frac{H - H_W}{T - T_W} = -\frac{(h/M_B k_y)}{\lambda_W} \quad (2)$$

(Geankoplis p532, Eq- 9.3-18)

W ⇒ wet bulb temp

h = heat tr. coeft (kW/m²K)

M_B = Mol. wt of air (kg/kmol)

k_y = Mass tr. Coeff water- air (kmol/s.m²)

$$\text{Lewis No } (Le) = \frac{Sc}{Pr} = \left[\frac{(h/M_B k_y)}{C_s}\right]$$

Ratio of R.H.S of Eq.(2) and (1)

∴ For water vap- Air system
Le ≈ 1 (see proof and details given below)

$$\therefore \frac{\left[\frac{H - H_W}{T - T_W}\right]}{\left[\frac{H - H_S}{T - T_S}\right]} \approx Le \approx 1$$

(True only for air-water system)

$\boxed{\text{C is CORRECT ANSWER}}$

∴ In psychrometric chart the adiabatic saturation line may be used to estimate "Wet bulb temperature.

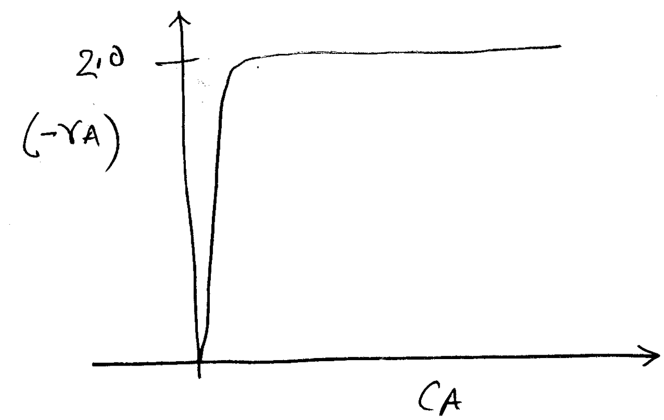
Q. 14 For a non-catalytic homogeneous reaction A → B, the rate expression at 300 K is $-r_A\,(mol\,m^{-3}s^{-1}) = \frac{10C_A}{1+5C_A}$, where C_A is the concentration of A (in mol/m^3). Theoretically, the upper limit for the magnitude of the reaction rate ($-r_A$ in mol $m^{-3}s^{-1}$, rounded off to the first decimal place) at 300 K is _______

Q14

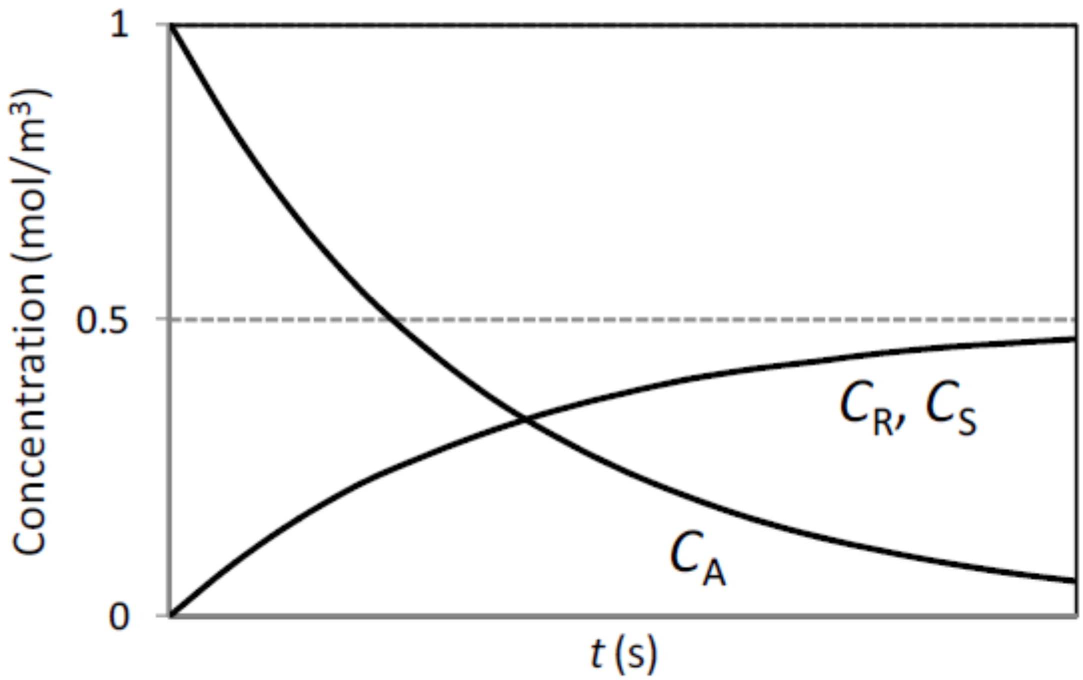
$$-r_A = \frac{10\,C_A}{1+5\,C_A}$$

At high values of C_A (initial and intermediate concns) $5C_A \gg 1$, $-r_A = \frac{10\,C_{A0}}{5\,C_{A0}} = 2$ (Answer)

at low concns ($10\,C_A \ll 1+5C_A$), the value of $-r_A$ drops close to zero

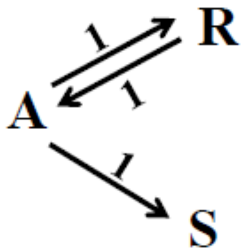


Q. 15 The variations of the concentrations (C_A, C_R and C_S) for three species (A, R and S) with time, in an isothermal homogeneous batch reactor are shown in the figure below.

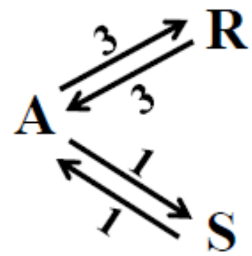


Select the reaction scheme that correctly represents the above plot. The numbers in the reaction schemes shown below, represent the first order rate constants in unit of s^{-1}.

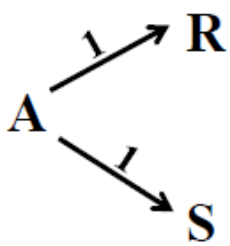
(A)



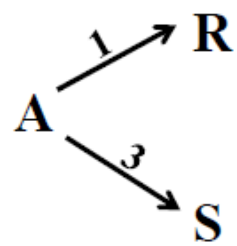
(B)



(C)



(D)



Q15

OPTION A

$$A \underset{k_2=1\,s^{-1}}{\overset{k_1=1\,s^{-1}}{\rightleftharpoons}} R \qquad A \xrightarrow{k_3=1\,s^{-1}} S$$

$$\frac{dC_A}{dt} = -k_1 C_A + k_2 C_R - k_3 C_A$$
$$= -C_A + C_R - C_A$$
$$\frac{dC_A}{dt} = C_R - 2C_A \checkmark$$
$$\frac{dC_R}{dt} = k_1 C_A - k_2 C_R$$
$$= C_A - C_R \checkmark$$
$$\frac{dC_S}{dt} = k_3 C_A = C_A$$

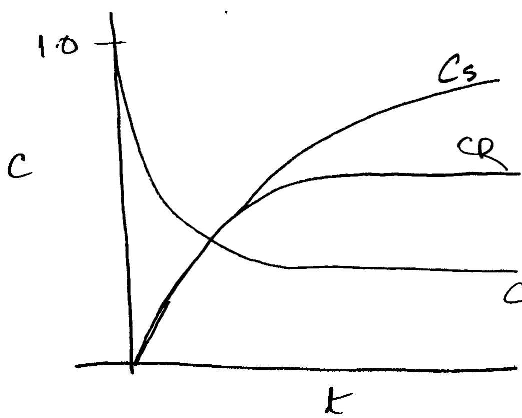
at $t=0$, $C_A = 1\ mol/m^3$
$C_R = 0$, $C_S = 0$

$$\left.\frac{dC_A}{dt}\right|_{t=0} = 0 - 2C_A^0 = -2$$
$$\frac{dC_R}{dt} = 1$$
$$\frac{dC_S}{dt} = 1$$

After some time, $C_A\downarrow$, $C_R\uparrow$, $C_S\uparrow$

a) when $C_R = 2C_A$, $\frac{dC_A}{dt} = 0$
$\downarrow$
C_A = Constant

b) when $C_A = C_R$, $\frac{dC_R}{dt} = 0$
$\downarrow$
C_R = Constant



c) C_S increases exponentially with time (although rate decreases)

$\Uparrow$

C_A, C_R, C_S profiles do not match the profiles shown in Q-15 $\Rightarrow$ OPTION A is FALSE ✓

OPTION B

$$A \underset{k_2 = 3\,s^{-1}}{\overset{k_1 = 3\,s^{-1}}{\rightleftharpoons}} R \qquad A \underset{k_4 = 1\,s^{-1}}{\overset{k_3 = 1\,s^{-1}}{\rightleftharpoons}} S$$

$$\frac{dC_A}{dt} = -k_1 C_A - k_3 C_A + k_2 C_R + k_4 C_S$$

$$= -3C_A - C_A + 3C_R + C_S$$

$$\frac{dC_A}{dt} = 3C_R + C_S - 4C_A$$

$$\frac{dC_R}{dt} = k_1 C_A - k_2 C_R = 3C_A - 3C_R$$

$$\frac{dC_S}{dt} = k_3 C_A - k_4 C_S = C_A - C_S$$

at $t = 0$, $C_A = C_A^0 = 1\ mol/m^3$, $C_R^0 = 0$, $C_S^0 = 0$

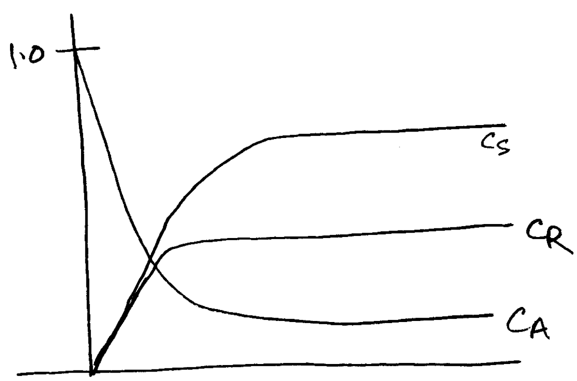
$$\frac{dC_A}{dt} = -4(1) = -4$$

$$\frac{dC_R}{dt} = 3(1) - 3(0) = 3$$

$$\frac{dC_S}{dt} = 1 - (0) = 1$$

after certain time

$C_A \downarrow$, $C_R \uparrow$, $C_S \uparrow$



$\frac{dC_A}{dt} = 0$ when $3C_R + C_S = 4C_A$

C_A = constant

$\frac{dC_R}{dt} = 0$, when $C_A = C_R$

C_R = Constant

$\frac{dC_S}{dt} = 0$, when $C_A = C_S$

C_S = Constant

C_A, C_R, C_S profiles do not match the profiles shown in Q-15 $\Rightarrow$ OPTION B is FALSE ✓

OPTION. C

$$A \xrightarrow{k_1 = 1 s^{-1}} R$$
$$A \xrightarrow{k_2 = 1 s^{-1}} S$$

$$\frac{dC_A}{dt} = -k_1 C_A - k_2 C_A$$
$$= -C_A - C_A = -2C_A$$

$$\frac{dC_A}{dt} = -2C_A$$

$$\therefore \ln C_A = -2t + C$$

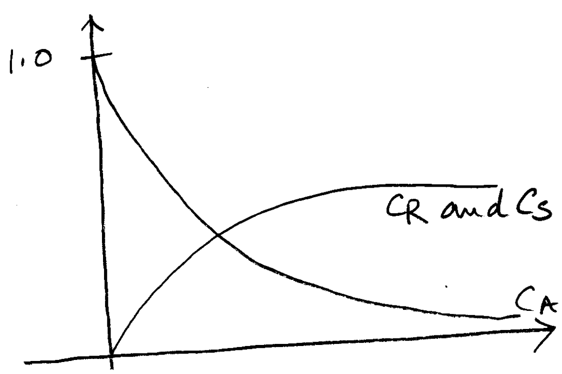
$$C_A = C_A^0 e^{-2t}$$

$C_A \Rightarrow$ will decrease exponentially

$C_R \Rightarrow$ will increase exponentially

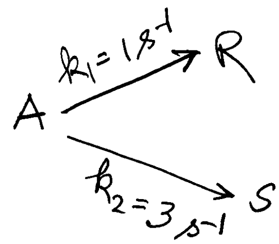
$C_S \Rightarrow$ will increase exponentially (and at the same rate as C_R) ✓

$$\left.\begin{aligned} \frac{dC_R}{dt} &= k_1 C_A = C_A \\ \frac{dC_S}{dt} &= k_2 C_A = C_A \end{aligned}\right\} \quad C_A^0 = C_A + C_R + C_S$$



C_A, C_R and C_S profiles match exactly with the profile given in Q-15 $\Rightarrow$ OPTION C is correct ✓

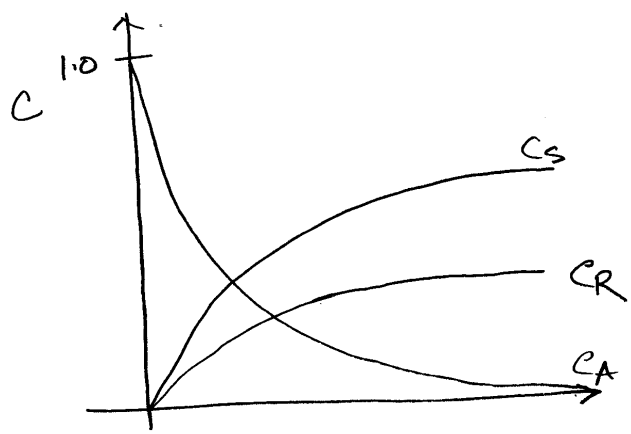
OPTION D



$$\frac{dC_A}{dt} = -k_1 C_A - k_2 C_A$$
$$= -C_A - 3C_A = -4C_A$$
$$C_A = C_{A0} e^{-4t}$$

$$\frac{dC_R}{dt} = k_1 C_A = C_A$$
$$\frac{dC_S}{dt} = k_2 C_A = 3C_A$$

$C_A \Rightarrow$ will decrease exponentially
$C_R \Rightarrow$ will increase exponentially
$C_S \Rightarrow$ will increase exponentially (but 3 times faster than R)



C_A, C_R and C_S profiles do not match with the profiles given in Q-15. $\Rightarrow$ **FALSE**

Q. 16 **Hydrogen iodide decomposes through the reaction 2HI** **$H_2 + I_2$. The value of the universal gas constant R is 8.314 J mol^{-1} K^{-1}. The activation energy for the forward reaction is 184000 J mol^{-1}. The ratio (rounded off to the first decimal place) of the forward reaction rate at 600 K to that at 550 K is ______.**

Q.16

$$\ln\left(\frac{r_{@600K}}{r_{@550K}}\right) = \frac{E}{R}\left[\frac{1}{550} - \frac{1}{600}\right]$$

[See Levenspiel p27]

$$= 184000 \frac{J}{mol} \times \frac{1 \quad mol \cdot K}{8.314 \, J}$$

$$\times \left[1.8181 \times 10^{-3} - 1.667 \times 10^{-3}\right]$$

$$= 3.3514$$

$$\therefore \frac{r_{@600K}}{r_{@500K}} = e^{3.3514} = 28.543$$

Answer

Q. 17 **Match the instruments in Group-1 with process variables in Group-2.**

	Group-1		Group-2
P	**Conductivity meter**	**I**	**Flow**
Q	**Turbine meter**	**II**	**Pressure**

R	**Piezoresistivity element**	**III**	**Composition**

(A) P-II, Q-I, R-III　　(B) P-II, Q-III, R-I
(C) P-III, Q-II, R-I　　(D) P-III, Q-I, R-II

Q. 18 What is the order of response exhibited by; a U-tube manometer?

(A) Zero order　　(B) First order
(C) Second order　　(D) Third order

Q. 19 A system exhibits inverse response for a unit step change in the input. Which one of the following statement must necessarily be satisfied ?

(A) The transfer function of the system has at least one negative pole.

(B) The transfer function of the system has at least one positive pole.

(C) The transfer function of the system has at least one negative zero.

(C) The transfer function of the system has at least one positive zero.

Q. 20 Two design options for a distillation system are being compared based on the total annual cost. Information available is as follows:

	Option P	**Option Q**
Installed cost of the system (Rs. In lakhs)	**150**	**120**
Cost of cooling water for condenser (Rs. In lakhs/year)	**6**	**8**
Cost of steam for reboiler (Rs. In lakhs/year)	**16**	**20**

The annual fixed charge amounts to 12% of the installed cost. Based on the above information, what is the total annual cost (Rs. In lakhs/year) of the better option?

(A) 40　　(B) 42.4　　(C) 92　　(D) 128

Q 20

	Option P	Option Q
Installed cost (₹, lakh)	150	120
Cooling water (₹, lakh)	6	8
Steam (₹, lakh)	16	20
Annual fixed charges (12% installed cost) (₹, lakh)	18 (150×0.12)	14.4 (120×0.12)
Total annual cost (₹, lakh) (Annual fixed cost + variable cost)	$(6+16+18) = 40$	$(8+20+14.4) = 42.4$

Lower total annual cost (Better option) ⇑ Option P

Answer ✓

Q. 21 Standard pipes of different schedule numbers and standard tubes of different BWG numbers are available in the market. For pipe / tube of a given nominal diameter, which one of the following statements is TRUE?

(A) Wall thickness increases with increase in both the schedule number and the BWG number.

(B) Wall thickness increases with increase in the schedule number and decreases with increase in the BWG number.

(C) Wall thickness decreases with increase in both the schedule number and the BWG number.

(D) Neither the schedule number, nor the BWG number has any relation to wall thickness

Q 21: B ->> Correct answer

For details on Schedule no, see: https://en.wikipedia.org/wiki/Nominal_Pipe_Size
For details on BWG: https see ://it.wikipedia.org/wiki/Birmingham_Wire_Gauge
Ref: http://engineeringoperations.blogspot.my/2011/11/what-are-differences-between-pipe-and.html

Pipes:

- **Heavy walled**
- **Relatively large in diameter**
- **comes in moderate lengths (20 to 40 ft)**
- **Threading is not possible**
- **Pipe walls are rough**
- **Lengths of pipes are joined by screwed, flanged and welded fittings**
- **Made by welding , casting, or piercing a billet in a piercing mill**
- **The wall thickness of the pipe is indicated using schedule number**
- **Size of the pipe is indicated as nominal diameter**

Tubes:

- **Thin walled**
- **Less diameter**
- **available in the form of coils also, several hundred meters**
- **Can be threaded**
- **Tube walls are smooth**
- **These are joined by compression fittings, flare fittings, or soldered fittings**
- **These can be cold drawn**
- **Tube thickness is indicated using BWG (Birmingham wire gauge)**
- **Size of the tube is indicated as outside diameter**

Q. 22 Terms used in engineering economics have standard definitions and interpretations. Which one of the following statements is INCORRECT?

(A) The profitability measure ‘return on investment’ does not consider the time value of money.

(B) A cost index is an index value for a given time showing the cost at that time relative to a certain base time.

(C) The six-tenths factor rule’ is used to estimate the cost of an equipment from the cost of a similar equipment with a different capacity.

(D) Payback period is calculated based on the payback time for the sum of the fixed and the working capital investment.

Q 22 - options A, B and C are true
- option D is Incorrect because payback period is calculated based on fixed capital investment ONLY, NOT (fixed + working capital investment)

Q. 23 India has no elemental sulphur deposits that can be economically exploited. In India, which one of the following industries produces elemental sulphur as a by-product?

(A) Cost carbonization plants

(B) Petroleum refineries.

(C) Paper and pulp industries

(D) Iron and steel making plants

Q. 24 Two paper pulp plants P and Q use the same quality of bamboo as a raw material. The chemicals used in their digester are as follows :

	Plant P	**Plant Q**
NaOH	**Yes**	**No**
Na_2S	**Yes**	**No**
Na_2CO_3	**Yes**	**Yes**
$NaHCO_3$	**No**	**Yes**
Na_2SO_3	**No**	**Yes**

Which one of the following statements is CORRECT ?

(A) Plant P and Plant Q both use the Sulfite process
(B) Plant P and Plant Q both use the Kraft process
(C) Plant P uses Sulfite process
(D) Plant P uses Kraft process

Q. 25 Match the industrial Process in Group-1 with the catalyst materials in Group-2.

Group-1 **Group-2**

P	**Ethylene polymerisation**	**I**	**Nickel**
Q	**Petroleu;m feedstock cracking**	**II**	**Vanadium pentoxide**
R	**Oxidation of SO2 to SO3**	**III**	**Zeolite**
S	**Hydrogenation of oil**	**IV**	**Aluminium triethyl with titanium chloride promoter**

(A) P-IV, Q-III, R-II, S-I
(B) P-I, Q-IV, R-III, S-II
(C) P-I, Q-II, R-III, S-IV
(D) P-II, Q-III, R-IV, S-I

Q. 26 – Q. 55 carry two marks each.

Q. 26 A set of simultaneous linear algebraic equations is represented in a matrix form as shown below.

$$\begin{bmatrix} 0 & 0 & 0 & 4 & 13 \\ 2 & 5 & 5 & 2 & 10 \\ 0 & 0 & 2 & 5 & 3 \\ 0 & 0 & 0 & 4 & 5 \\ 2 & 3 & 2 & 1 & 5 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} 46 \\ 161 \\ 61 \\ 30 \\ 81 \end{bmatrix}$$

The value (rounded off to the nearest integer) of x_3 is ______

Q26

$$\begin{bmatrix} 0 & 0 & 0 & 4 & 13 \\ 2 & 5 & 5 & 2 & 10 \\ 0 & 0 & 2 & 5 & 3 \\ 0 & 0 & 0 & 4 & 5 \\ 2 & 3 & 2 & 1 & 5 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} 46 \\ 161 \\ 61 \\ 30 \\ 81 \end{bmatrix}$$

(Only value of x_3 is required (acc to question)

$$0 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 4x_4 + 13x_5 = 46$$

$$4x_4 + 13x_5 = 46 \checkmark \; \ldots\ldots (1)$$

$$0 \cdot x_1 + 0 \cdot x_2 + 2x_3 + 5x_4 + 3x_5 = 61$$

or, $2x_3 + 5x_4 + 3x_5 = 61 \checkmark \; \ldots (2)$

$$0 \cdot x_1 + 0 \cdot x_2 + 0 \cdot x_3 + 4x_4 + 5x_5 = 30$$

$$4x_4 + 5x_5 = 30 \; \ldots\ldots (3)$$

(1) − (3)

$$(13-5)x_5 = 46-30 = 16$$

$$x_5 = 16/8 = 2 \checkmark \; \ldots\ldots (4)$$

Substitute in (1)

$$4x_4 = 46 - 13(2) = 46 - 26 = 20$$

$$\therefore x_4 = 5 \checkmark \; \ldots\ldots (5)$$

use (2)

$$2x_3 = 61 - 5(5) - 3(2) = 61 - 25 - 6$$

$$= 30$$

$$\therefore x_3 = 15 \checkmark \Rightarrow \text{Answer} \checkmark$$

Q. 27 What is the solution for the second order differential equation $\frac{d^2y}{dx^2} + y = 0$, with the initial conditions $y|_{x=0} = 5$ and $\frac{dy}{dx}\Big|_{x=0} = 10$?

(A) y = 5 + 10 sin x

(B) y = 5 cos x – 5 sin x

(C) y = 5 cos x + 10 x

(D) y = 5 cos x + 10 sin x

Q 27 $\frac{d^2y}{dx^2} + y = 0$ $y\big|_{x=0} = 5$, $\frac{dy}{dx}\Big|_{x=0} = 10$

Homogeneous differential equ.

Auxiliary equ $m^2+1=0$

$m = \sqrt{-1} = \pm i$

For complex roots $\alpha \pm j\beta$

$y = e^{\alpha x}(A\cos\beta x + B\sin\beta x)$

Here $\alpha = 0$, $\beta = 1$

$\therefore y = e^{(0 \cdot x)}(A\cos x + B\sin x) = A\cos x + B\sin x$

$\underline{\underline{y = A\cos x + B\sin x}}$

B.C.1 $y\big|_{x=0} = 5$

$5 = A\cos 0 + B\cancelto{0}{\sin 0} = A \Rightarrow \underline{\underline{A=5}}$

B.C.2 $\frac{dy}{dx} = -A\sin x + B\cos x$

$\frac{dy}{dx}\Big|_{x=0} = 10 = -A\cancelto{0}{\sin 0} + B\cos 0 = B$

$\Rightarrow B = 10$

$\therefore y = 5\cos x + 10\sin x \Rightarrow$ (D) correct answer.

Q. 28 The model $y = mx^2$ is to be fit to the data gives below,

x	1	√3	√2
y	2	8	5

Using linear regression, the value (rounded off to the second decimal place) of m is ______ .

28

$$y = mx^2 = mX \quad [X = x^2]$$

$$Q = \sum_{i=1}^{n} (y_i - mX_i)^2 \qquad \Big| \; Q = \text{sum of square of errors}$$

We have to find out the value of m for which Q is minimum (see any standard text book on Linear regression)

$$\frac{\partial Q}{\partial m} = 0$$

$$\therefore \frac{\partial Q}{\partial m} = 2 \sum_{i=1}^{n} (y_i - mX_i)(-X_i) = 0$$

$$(-2)\left\{ \sum_{i=1}^{n} y_i X_i - m \sum_{i=1}^{n} X_i^2 \right\} = 0$$

$$\text{or, } m = \frac{\sum_{i=1}^{n} y_i X_i}{\sum_{i=1}^{n} X_i^2} = \frac{36}{14} = 2.571$$

Answer

x_i	$X_i (= x_i^2)$	X_i^2	y_i	$y_i X_i$
1	1	1	2	2 $(= 2\times1)$
$\sqrt{2}$	2	4	5	10 $(= 2\times5)$
$\sqrt{3}$	3	9	8	24 $(= 3\times8)$
given		$\sum X_i^2 = 14$	given	$\sum y_i X_i = 36$

Q. 29 The Lagrange mean-value theorem is satisfied for $f(x) = x^3 + 5$, in the interval (1, 4) at a value (rounded off to the second decimal place) of x equal to _______.

Q 29

Lagrange Mean Value of theorem

If $f(x)$ is a continuous in the open interval $[a, b]$ and if $f'(x)$ is differentiable in the open interval (a, b), then there exists a value c $(a < c < b)$ such that

$$f'(c) = \frac{f(b) - f(a)}{b - a}$$

For this problem $f(x) = x^3 + 5$ and $f'(x) = 3x^2$

$a = 1$

$b = 4$

$$\therefore 3c^2 = \frac{f(4) - f(1)}{(4-1)}$$

$$= \frac{[4^3 + 5] - [1^3 + 5]}{(4-1)}$$

$$= \frac{69 - 6}{3} = \frac{63}{3}$$

$$\therefore c^2 = \frac{63}{9} \Rightarrow c = \pm\sqrt{\frac{63}{9}} = \pm\sqrt{7}$$

$$\therefore c = \pm 2.645$$

Interval $\Rightarrow (1, 4)$

$$\therefore c = 2.645 \Rightarrow \text{Answer}$$

Q. 30 Values of f (x) in the interval [0, 4] are given below,

x	0	1	2	3	4
f(x)	3	10	21	36	55

Using Simpson's 1/3 rule with a step size of 1, the numerical approximation (rounded off to the second decimal place) of is _______ .

Q 30

$f(x) \Rightarrow$ interval $[0,4]$

x	0	1	2	3	4
$f(x)$	3	10	21	36	55
	1st	2nd	3rd	4th	5th

$\rightarrow$ $\boxed{\text{width of interval} = 1}$

$$\int_0^4 f(x)\,dx = ?$$

Simpson's rule

$$\text{Area} = \frac{1}{3}\left(\begin{array}{c}\text{width of}\\ \text{interval}\end{array}\right)\left[\left(\begin{array}{c}\text{first}+\\ \text{last}\\ \text{ordinate}\end{array}\right)+4\left(\begin{array}{c}\text{Sum of}\\ \text{even}\\ \text{ordinates}\end{array}\right)+2\left(\begin{array}{c}\text{Sum of}\\ \text{remaining}\\ \text{odd}\\ \text{ordinates}\end{array}\right)\right]$$

$$= \frac{1}{3}(1)\left[(\underset{\substack{\uparrow\\ 1st}}{3}+\underset{\substack{\uparrow\\ 5th}}{55}) + 4(\underset{\substack{\uparrow\\ 2nd}}{10}+\underset{\substack{\uparrow\\ 4th}}{36}) + 2(\underset{\substack{\uparrow\\ 3rd}}{21})\right]$$

$$= \frac{1}{3}(58 + 184 + 42) = \frac{284}{3} = \underset{\substack{\Uparrow\\ \text{Answer}}}{94.67}$$

Q. 31 **A jacketed stirred tank with a provision for heat removal is used to mix sulphuric acid and water in a steady state flow process. H_2SO_4 (l) enters as a rate of 4 kg/h at 25°C and H_2O (l) enters at a rate of 6 kg/h at 10°C. The following data are available.**

Specific heat capacity of water = 4.2 kJ kg^{-1} K^{-1}.
Specific heat capacity of aqueous solution of 40 mass%0 H_2SO_4
= 2.8 kJ (kg solution)$^{-1}$ K^{-1}.

$$\left.\frac{dy}{dx}\right|_{x=0} = 10$$

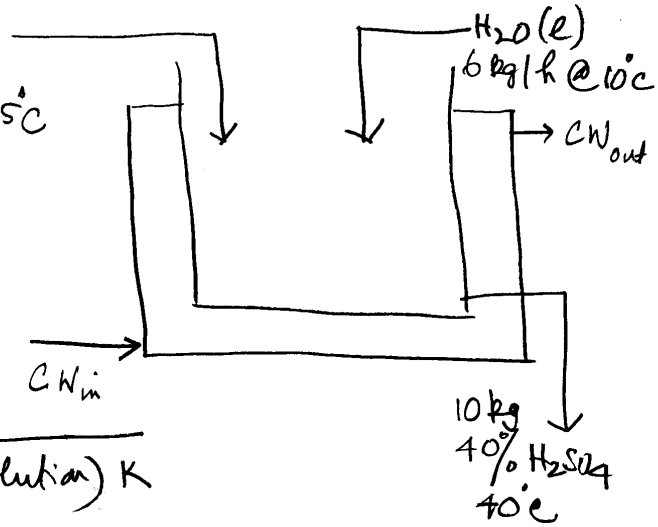
Assume the specific heat capacities to be independent of temperature. Based on reference states of H_2SO_4 (l) and H_2O (l) at 25°C, the heat of mixing for aqueous solution of 40 mass% H_2SO_4 = – 650 kJ (kg H_2SO_4)$^{-1}$.

If the mixed stream leaves at 40°C, what is the rate of heat removal (in kJ/h) ?

(A) 1802 (B) 2558 (C) 5702 (D) 6458

Q31

H_2SO_4 (l)
4 kg/h @ 25°C



Given

$$Cp_{water} = 4.2 \frac{kJ}{kg\,K}$$

$$Cp_{40\%\,H_2SO_4\,soln} = 2.8 \frac{kJ}{(kg\ solution)\,K}$$

Ref. state = 25°C for H_2SO_4 and water

$$\left.\begin{array}{l}\Delta H_{mixing} @ 25°C \\ \text{for } 40\%\ H_2SO_4\ soln\end{array}\right\} = -650 \frac{kJ}{(kg\ H_2SO_4)}$$

Basis = 1 h.

$\Rightarrow$ After mixing H_2SO_4 Concn $= \dfrac{4\ kg\ H_2SO_4}{4\ kg\ H_2SO_4 + 6\ kg\ H_2O}$

$= 40\%$

At steady state (REF TEMP = 25°C)

$$\dot{Q} = \sum_{out} n_i h_i - \sum_{in} n_i h_i + \Delta H_{mixing}$$

See Felder & Rousseau p454

= sum of enthalpy of of all output streams (here it is only one ⇒ 40% H_2SO_4 soln @ 40°C @ 10 kg/h

Enthalpy of inlet streams (Here we have 2 streams)
- Pure H_2SO_4 @ 25°C, 4 kg/h
- Pure H_2O @ 10°C 6 kg/h.

Heat of mixing of 4 kg/h of H_2SO_4 with 6 kg/h of water

$\sum_{in} n_i h_i$ (Ref temp 25°C)

- Enthalpy of 4 kg/h H_2SO_4 stream = 0 (∵ inlet temp = ref temp = 25°C)

- Enthalpy of 6 kg/h of H_2O @ 10°C

$$= 6\,\frac{kg}{h} \times 4.2\,\frac{kJ}{kg\,K} \times \underbrace{(10-25)}_{(T-T_{ref})}\,K$$

(∵ ΔT in °C = ΔT in K)

$$= -378\ kJ/h$$

$$\therefore \sum_{in} n_i h_i = 0 + (-378) = \underline{\underline{-378\ kJ/h}}$$

$$\sum_{out} n_i h_i \text{ (Ref temp } 25^\circ C)$$

$$= 10 \text{ kg } (40\% \ H_2SO_4 \text{ soln}) \times 2.8 \frac{kJ}{(\text{kg soln}) K} \times (40-25)$$

$$\sum_{out} n_i h_i = \underline{\underline{420 \ kJ/h}} \checkmark$$

$$\underline{\Delta H_{mixing} \text{ (Ref temp} = 25^\circ C)}$$

$$\Delta H_{mix} = -650 \frac{kJ}{kg \ H_2SO_4} \times 4 \frac{kg}{h} H_2SO_4 \text{ (in 10 kg 40\% soln)}$$

$$= -2600 \ kJ/h$$

$$\therefore \dot{Q} = \sum_{out} n_i h_i - \sum_{in} n_i h_i + \Delta H_{mix}$$

$$= 420 \left(\frac{kJ}{h}\right) - \left(-378 \frac{kJ}{h}\right) + \left(-2600 \frac{kJ}{h}\right)$$

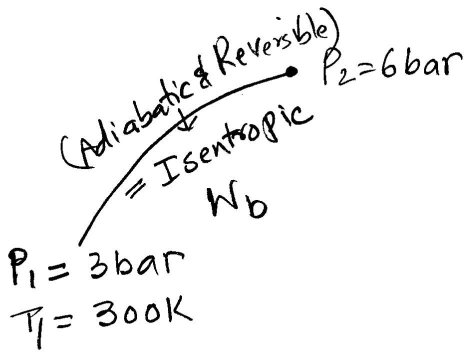
$$Q = -1802 \ kJ/h \Rightarrow \text{A } \underline{\underline{\text{correct answer}}}$$

−ve sign indicates heat to be taken out of the tank.

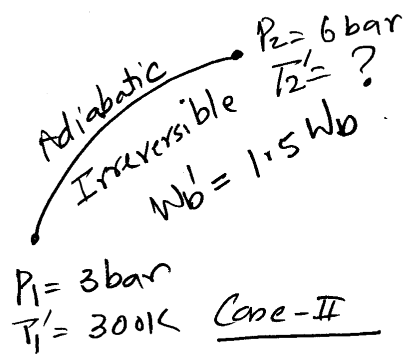
Q. 32 An ideal gas is adiabatically and irreversibly compressed from 3 bar and 300 K to 6 bar in a closed system. The work repaired for the irreversible compression is 1.5 times the work that is required for reversible compression from the same initial temperature and

pressure to the same final pressure. The molar heat capacity of the gas at constant volume is 30 J mol^{-1} K^{-1} (assumed to be independent of temperature), universal gas constant, R is 8.314 J mol^{-1} K^{-1}, ratio of molar heat capacities is 1.277. The temperature (in K, rounded off to the first decimal place) of the gas at the final state in the irreversible compression case is _______ .

Q32



Case I



Case-II

For reversible, adiabatic (= isentropic compression/expansion)

$$W_b = -\frac{P_2V_2 - P_1V_1}{(1-\gamma)} = -\frac{R(T_2-T_1)}{(1-\gamma)}$$

See - Cengel & Boles p168
- Sandler p62

$$= C_v(T_2 - T_1)$$

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} \Rightarrow \text{True only for isentropic process}$$

$$= -\frac{R\left[T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - T_1\right]}{(1-\gamma)}$$

$$= +\frac{RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}{(\gamma-1)}$$

For an adiabatic process (closed system)

$$dE = \delta q^{\,0} - \delta W$$

$$C_v(T_2 - T_1) = -\int P\,dV = W_b$$

True for both reversible and irreversible processes.

Given **Case-I**

$P_1 = 3\ \text{bar},\ T_1 = 300K,\ \gamma = 1.277$

$$\therefore W_b\Big|_{\text{adiab, Rev}} = +8.314\ \frac{kJ}{kmol.K} \times 300K \times \frac{1}{(1.277-1)} \times \left[\left(\frac{6\ \text{bar}}{3\ \text{bar}}\right)^{(1.277-1)/1.277} - 1\right]$$

$$= 9004.33 \times (1.1622 - 1)$$

$$W_b = 1460.50\ \frac{kJ}{kmol}$$

Case-II

$\therefore W_b' = 1.5\,W_b$ (given) [Adiab, Irrev. work (W_b') $= 1.5$ Adiab Rev. work]

$\therefore W_b' = 1.5 \times 1460.50$

$= 2190.754\ \frac{kJ}{kmol}$

$W_b' = C_v(T_2 - T_1)$ $\Rightarrow$ True for both rev/Irrev. work (as long as it is adiabatic)

$$\int dE = \overset{0 \to \text{adiabatic}}{\delta q} - \int \delta W$$

$$C_v(T_2 - T_1) = W_b\ (\text{or } W_b')$$

$\gamma = 1.277$

$\frac{C_p}{C_v} = 1.277$

$\frac{C_v + R}{C_v} = 1.277$ | $\Rightarrow$ Ideal gas

$C_v(1.277 - 1) = R = 8.314$

$$C_v = \frac{8.314}{0.277} = 30.01\ \frac{kJ}{kmol.K} \Leftarrow$$

$$\therefore W_b' = C_V (T_2 - T_1)$$

$$2190.754 \frac{kJ}{kmol} = 30.01 \frac{kJ}{kmol.K} (T_2' - T_1')K$$

$$\therefore T_2' - 300K = \frac{2190.754}{30.01}$$

$$= 72.976$$

[' ⇒ represents Irrev./Adiab. process)

$$\therefore T_2' = 372.976 \simeq 373K$$

⇑ Answer ✓

2nd Method [Easier]

$$W_b' = 1.5 W_b$$

$$\cancel{C_V} (T_2' - T_1') = 1.5 [\cancel{C_V} (T_2 - T_1)]$$

$$T_1' = 300K = T_1$$

$$T_2' - T_1' = 1.5 (T_2 - T_1)$$

$$= 1.5 \left[T_1 \left(\frac{P_2}{P_1}\right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]$$

This relationship is valid only for rev/adiabatic (isentropic) process

$$= 1.5\, T_1 \left[\left(\frac{6}{3}\right)^{(1.277-1)} - 1 \right]$$

$$= 1.5 \times 300 [1.1622 - 1]$$

$$= 73$$

$$\therefore T_2' = T_1' + 73 = 300 + 73$$

$$= 373K$$

⇑ Answer.

Q. 33 A gas obeying the Clausius equation of state is isothermally compressed from 5 MPa to 15 MPa in a closed system at 400 K. The Clausius equation of state is $P = \dfrac{RT}{\upsilon - b(T)}$ where P is the pressure, T is the temperature, υ is the molar volume and R is the universal gas constant. The parameter b in the above equation varies with temperature as $b(T) = b_0 + b_1 T$ with $b_0 = 4 \times 10^{-5}$ m^3mol^{-1} and $b_1 = 1.35 \times 10^{-7}$ m^3mol^{-1} K^{-1}. The effect of pressure on the molar enthalpy (h) at a constant temperature is given by $\left(\dfrac{\partial h}{\partial P}\right)_T = \upsilon - T\left(\dfrac{\partial \upsilon}{\partial T}\right)_P$. Let h_i and h_f denote the initial and final molar enthalpies, respectively. The change in the molar enthalpy $h_f - h_i$ (in J mol^{-1}, rounded off to the first decimal place) for this process is _______.

Q33.

$P_1 = 5\,MPa$ $\quad$ $P_2 = 15\,MPa$

$T_1 = 400K$ $\quad$ $T_2 = 400K$

isothermal compression.

$$P = \frac{RT}{v - b(T)} \longrightarrow \text{This means b is a function of temp.}$$

$$P = \frac{RT}{v-b}$$

$$v - b = \frac{RT}{P} \Rightarrow v = \left(\frac{RT}{P} + b\right)$$

$$b = b_0 + b_1 T$$

$b_0 = 4 \times 10^{-5} \frac{m^3}{mol}$

$b_1 = 1.35 \times 10^{-7} \frac{m^3}{mol \cdot K}$

$$v = \frac{RT}{P} + b_0 + b_1 T$$

$$\left(\frac{\partial v}{\partial T}\right)_P = \left(\frac{R}{P} + b_1\right) \checkmark$$

Given

$$\left(\frac{\partial h}{\partial P}\right)_T = v - T\left(\frac{\partial v}{\partial T}\right)_P$$

$$= \left[\left(\frac{RT}{P} + b_0 + b_1 T\right) - T\left(\frac{R}{P} + b_1\right)\right]$$

$$= \left[\cancel{\frac{RT}{P}} + b_0 + \cancel{b_1 T} - \cancel{\frac{RT}{P}} - \cancel{b_1 T}\right]$$

$$\therefore \left(\frac{\partial h}{\partial P}\right)_T = b_0$$

$$\int_{h_1}^{h_2} dh = b_0 \int_{P_1}^{P_2} dP$$

or, $(h_2 - h_1) = b_0 (P_2 - P_1)$

$$= 4 \times 10^{-5} \frac{m^3}{mol} \times (15 \times 10^6 \, Pa - 5 \times 10^6 \, Pa)$$

$$= 400 \frac{m^3 . Pa}{mol}$$

$$Pa \cdot m^3 = J$$

$$\frac{N}{m^2} \cdot m^3 = N \cdot m = J$$

$$(h_2 - h_1) = 400 \frac{J}{mol}$$

$\uparrow$

Answer.

Q. 34 A binary system at a constant pressure with species '1' and '2' is described by the two-suffix Margules equation, $\frac{g^E}{RT} = 3x_1x_2$, where g^E is the molar excess Gibbs free energy, R in the universal gas constant, T is the temperature and x_1, x_2 are the mole fractions of species 1 and 2, respectively. At a temperature T, $\frac{g_1}{RT} = 1$ and $\frac{g_2}{RT} = 2$, where g_1 and g_2 are the molar Gibbs free energies of pure species 1 and 2, respectively. At the same temperature, g represents the molar Gibbs free energy of the mixture. For a binary mixture with 40 mole % of species 1, the value (rounded off to the second decimal place) of $\frac{g}{RT}$ is _______.

Q34

$$g = \underbrace{(x_1 g_1 + x_2 g_2)}_{\text{Total Molar Gibbs free energy of pure components 1 and 2}} + \Delta g_{mix} + g^{ex}$$

g: Molar Gibbs free energy of a non-ideal mixture

Δg_{mix}: Molar Gibbs free energy change due to mixing for an ideal mixture

g^{ex}: molar excess Gibbs free energy (due to non-ideality)

$$\Delta g_{mix} = RT \sum x_i \ln x_i \quad \text{(See Sandler p 313)}$$

$$= RT(x_1 \ln x_1 + x_2 \ln x_2) \Rightarrow \text{for a binary mixture}$$

$$\therefore g = (x_1 g_1 + x_2 g_2) + RT(x_1 \ln x_1 + x_2 \ln x_2) + g^{ex}$$

$$\text{or} \quad \frac{g}{RT} = \left[x_1 \frac{g_1}{RT} + x_2 \frac{g_2}{RT}\right] + (x_1 \ln x_1 + x_2 \ln x_2) + \frac{g^{ex}}{RT}$$

Given $x_1 = 0.4$, $x_2 = 1 - 0.4 = 0.6$

$\frac{g_1}{RT} = 1$, $\frac{g_2}{RT} = 2$, $\frac{g^{ex}}{RT} = 3x_1x_2$

$$\therefore \frac{g}{RT} = [0.4(1) + 0.6(2)] + [0.4 \ln 0.4 + 0.6 \ln 0.6] + 3(0.4)(0.6)$$

$$= 1.6 + [(-0.3665) + (-0.3064)] + 0.72$$

$$= 1.6 - 0.6729 + 0.72 = 1.6471$$

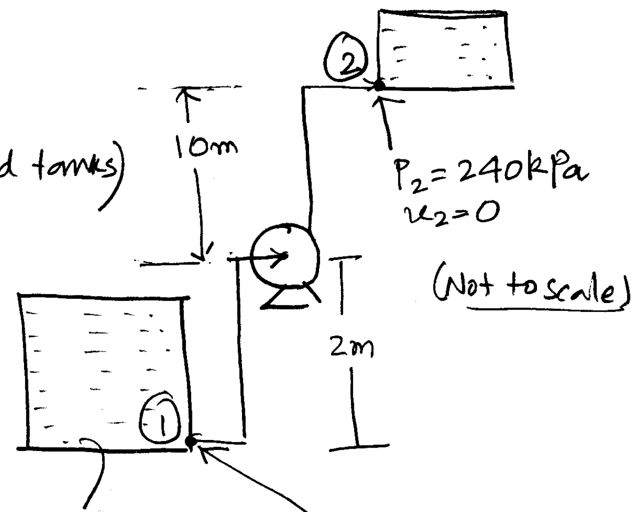
Answer.

Q. 35 **Water (density = 1000 kg m^{-3}) is pumped at a rate of 36 m^3/h, from a tank 2 m below the pump, to an overhead pressurized vessel 10 m above the pump. The pressure values at the point of suction from the bottom tank and at the discharge point to the overhead vessel are 120 kPa and 240 kPa, respectively. All pipes in the system have the same diameter. Take acceleration due to gravity, g = 10 m s^2. Neglecting frictional losses, what is the power (in kW) required to deliver the fluid?**

(A) 1.2 (B) 2.4 (C) 3.6 (D) 4.8

Q35

$u_1 = 0$ and $u_2 = 0$
(Large overhead tanks)



$\rho = 1000\ \frac{kg}{m^3}$ $\quad P_1 = 120\,kPa$

$Q = 36\ m^3/h$ $\quad \underline{u_1 = 0}$ ✓

$g = 10\ m/s^2$

$$\frac{1}{2\alpha}\left(\underbrace{v_{2,av}^2 - v_{1,av}^2}_{=0}\right) + g(z_2 - z_1) + \frac{P_2 - P_1}{\rho} + \underbrace{\sum F}_{0} + W_s = 0$$

$\alpha = 1.0$, turbulent flow

$v_{1,av} = 0$,

$v_{2,av} = 0$ $\qquad$ [See Geankoplis p64, 65)

$(z_2 - z_1) = 12\,m$

$\sum F = 0$ (Friction loss = 0, given)

$$10\ \frac{m}{s^2} \times (10+2)\,m + (240-120)\,kPa \times \frac{1000\,Pa}{kPa} \times \frac{1\ m^3}{1000\,kg} + W_s = 0$$

$$120\ \frac{m^2}{s^2} + 120\ \frac{Pa.m^3}{kg} + W_s = 0$$

$$\frac{m^2}{s^2} \Rightarrow \frac{\left(kg \cdot \frac{m}{s^2}\right)(m)}{kg} = \frac{N \cdot m}{kg} = \frac{J}{kg}$$

$$\frac{Pa \cdot m^3}{kg} = \frac{J}{kg}$$

$$120 \frac{J}{kg} + 120 \frac{J}{kg} + W_s = 0$$

$$\text{or,} \quad W_s = -240 \frac{J}{kg}$$ ✓

[-ve sign indicate energy to be added to fluid]

$$\dot{m} = \frac{36\, m^3}{h} \times \frac{1\, h}{3600\, s} \times 1000 \frac{kg}{m^3}$$

$$= 10 \frac{kg}{s}$$ ✓

Power req'd to deliver the fluid (water)

$$= \dot{m} W_s$$

$$= \left(10 \frac{kg}{s}\right) \times \left(-240 \frac{J}{kg}\right) \times \frac{1\, kJ}{1000\, J}$$

$$= 2.4\, kJ/s = 2.4\, kW$$

(B) correct answer

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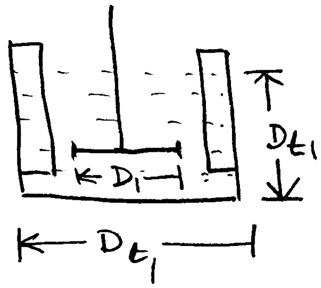
Q. 36 An agitated cylindrical vessel is fitted with baffles and flat place impellers. He power for this system is given by; $N_p = \frac{P}{\rho n^3 D^5}$ where P is the power consumed for the mixing, ρ is the density of the fluid, n is the speed of the impeller and D is the diameter of the impeller. The diameter of the impeller is 1/3rd the diameter of the tank and the height level is equal to the tank diameter. The impeller speed to achieve the desired degree of mixing is 4 rpm. In a scaled up design, the linear dimensions of the equipment are to be doubled, holding the power input per unit volume constant. Assuming the liquid to be Newtonian and Np to be independent of Reynolds number, what is the impeller speed (in rpm) to achieve the same degree of mixing in the scaled up vessel ?

(A) 0.13 (B) 1.26 (C) 2.52 (D) 3.82

Q 36

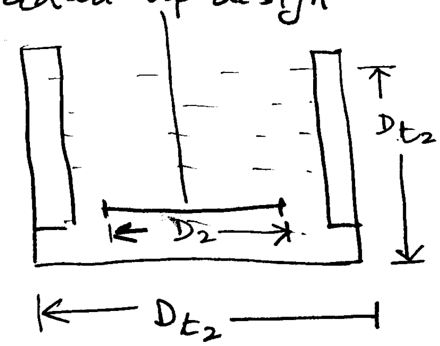
Prototype



$D_1 = \frac{1}{3} D_{t_1}$

$n_1 = 4$ rpm

Scaled-up design



$\left.\begin{aligned} D_{t_2} &= 2 D_{t_1} \\ D_2 &= 2 D_1 \end{aligned}\right\}$ given

$D_2 = \frac{1}{3} D_{t_2}$

$n_2 = ?$

$$N_P = \frac{P}{\rho n^3 D^5}$$

[$N_P \Rightarrow$ Power no becomes constant at high Reynold's no, see Geankoplis p 145]

$$P = N_P \rho n^3 D^5$$

$$= N_P \rho n^3 \left(\frac{1}{3} D_t\right)^5$$

$\rightarrow$ [N_P = constant (given) ; $D = \frac{1}{3} D_t \Rightarrow$ given]

$$= \left[\left(\frac{1}{3}\right)^5 N_P \rho\right] n^3 D_t^5$$

$$= K n^3 D_t^5$$

$$K = \underbrace{\left(\frac{1}{3}\right)^5 N_P \rho}_{\text{constant}}$$

$$V_l \text{ (volume of liquid)} = \left(\frac{\pi D_t^2}{4}\right) D_t = \frac{\pi}{4} D_t^3$$

Scale-up criteria $\Rightarrow$ Power input per unit volume to remain same in prototype and scaled-up unit.
(P/V_l = constant) ✓

$$\frac{P_1}{V_{l_1}} = \frac{K n_1^3 D_{t_1}^5}{\frac{\pi}{4} D_{t_1}^3} = \frac{4K}{\pi} n_1^3 D_{t_1}^2$$

$$\frac{P_2}{V_{l_2}} = \frac{K n_2^3 D_{t_2}^5}{\frac{\pi}{4} D_{t_2}^3} = \frac{4K}{\pi} n_2^3 D_{t_2}^2$$

$$\frac{P_1}{V_{l_1}} = \frac{P_2}{V_{l_2}} \quad (P/V_l = \text{constant} \Rightarrow \text{given})$$

$$\left(\frac{4\cancel{K}}{\cancel{\pi}}\right) n_1^3 D_{t_1}^2 = \left(\frac{4\cancel{K}}{\cancel{\pi}}\right) n_2^3 \cdot D_{t_2}^2$$

$$\left(\frac{n_2}{n_1}\right)^3 = \left(\frac{D_{t_1}}{D_{t_2}}\right)^2$$

$$\frac{n_2}{n_1} = \left(\frac{D_{t_1}}{D_{t_2}}\right)^{2/3}$$

[$D_{t_2} = 2 D_{t_1}$ Linear dimension of equipment doubled]

$$= \left(\frac{1}{2}\right)^{2/3}$$

⇓ (c) correct ✓

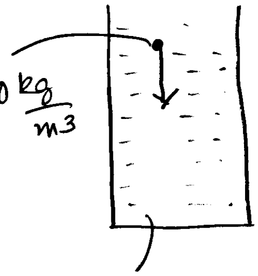
$$\therefore n_2 = 4 \text{ rpm} \left(\frac{1}{2}\right)^{2/3} = \underline{2.52 \text{ rpm}} \Leftarrow \text{Answer}$$

Q. 37 **Consider a rigid solid sphere falling with a constant velocity in a fluid. The following data are known at the conditions of interest: viscosity of the fluid = 0.1 Pa s, acceleration due to gravity = 10 m s^2, density of the particle = 1180 kg m^3 and density of the fluid = 1000 kg m^3. The diameter (in mm, rounded off to the decimal place) of the largest sphere that settles in the Stokes' law regime (Reynolds number ≤ 0.1), is ________.**

37

Stokes' law is valid $Re_p < 0.1$

$\rho_p = 1180 \frac{kg}{m^3}$



$\rho = 1000\ kg/m^3$

$\mu = 0.1\ Pa \cdot s$

$g = 10\ m/s^2$

$$\mu = \frac{2R^2(\rho_s - \rho)g}{9 v_t}$$

(See. Bird- Stewart-Lightfoot) p 60

$$\left[v_t = \frac{2R^2(\rho_s - \rho)g}{9\mu} = \frac{2\left(\frac{D_p}{2}\right)^2(\rho_s - \rho)g}{9\mu} \right.$$

$$v_t = \frac{D_p^2(\rho_s - \rho)g}{18\mu} \quad (1)$$

[Geankoplis p 817]

For the limiting case $\underline{Re = 0.1}$ (largest sphere that settles in stokes' law regime)

$$Re = \frac{D_p v_t \rho}{\mu} = 0.1$$

$$\therefore \quad v_t = 0.1 \frac{\mu}{\rho D_p} \quad \ldots\ldots \quad (2)$$

(1) and (2)

$$0.1 \frac{\mu}{\rho D_p} = \frac{D_p^2(\rho_s - \rho)g}{18\mu}$$

$$\text{or,} \quad D_p^3 = \frac{(18 \times 0.1)\mu^2}{\rho g(\rho_p - \rho)}$$

[writing $\rho_s = \rho_p$]

$$\therefore D_p^3 = 1.8 \times (0.1)^2 (Pa.s)^2 \times \frac{1}{1000}\frac{m^3}{kg} \cdot \frac{1}{10}\frac{s^2}{m} \times \frac{1}{(1180-1000)}\frac{m^3}{kg}$$

$$= \frac{1.8 \times 0.1^2}{1000 \times 10 \times 180} \left[Pa^2.s^2 \cdot \frac{m^3}{kg} \cdot \frac{s^2}{m} \cdot \frac{m^3}{kg} \right]$$

$$\Downarrow$$

$$= 1 \times 10^{-8}\, m^3$$

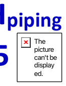
$$Pa.s = \frac{N}{m^2}.s = kg.\frac{m}{s^2}.\frac{1}{m^2}.s \Rightarrow \frac{kg}{m.s}$$

$$\therefore D_p = \sqrt[3]{1 \times 10^{-8}}\, m = 2.15 \times 10^{-3}\, m$$

$$\frac{\cancel{kg^2}}{m^2.\cancel{s^2}} \cdot \frac{m^3}{\cancel{kg}} \cdot \frac{\cancel{s^2}}{m} \cdot \frac{m^3}{\cancel{kg}} = m^3$$

$D_p = 2.15$ mm ⇑ Answer.

Max^m dia to fall under stokes' regime

Q. 38 The characteristics curve (Head – Capacity relationship) of a centrifugal pump is represented by the equation $\Delta H_{pump} = 43.8 - 0.19Q$, where ΔH_{pump} is the developed by the p8mp (in m) and Q is the flowrate (in m^3/h) through the pump. The pump is to be used for pumping water through a horizontal pipeline. The frictional head loss ΔH_{piping} (in m) is related to the water flowrate QL (in m^3/h) by the equation $\Delta H_{piping} = 0.0135$  + 0.045 Q_L. The flowrate (in m^3/h, rounded off to the first decimal place) of water pumped through the above pipeline, is _________ .

38

$$\Delta H_{pump} = 43.8 - 0.19Q$$

$$\Delta H_{Piping} = 0.0135 Q_L^2 + 0.045 Q_L$$

The pump head to compensate for head loss due to friction.

$$43.8 - 0.19Q = 0.0135Q^2 + 0.045Q$$

$$0.0135Q^2 + (0.045 + 0.19)Q - 43.8 = 0$$

or, $0.0135Q^2 + 0.235Q - 43.8 = 0$

or, $Q^2 + (0.235/0.0135)Q - (43.8/0.0135) = 0$

or $Q^2 + 17.407Q - 3244.44 = 0$

or. $Q = \dfrac{-17.407 \pm \sqrt{(17.407)^2 - 4(1)(-3244.44)}}{2}$

$= \dfrac{-17.407 \pm 115.24}{2}$

$\therefore Q = \dfrac{115.24 - 17.407}{2}$ [Neglecting the −ve root]

$Q = 48.92\ m^3/h$ ⇐ Answer.

Q. 39 **Water flows through a smooth circular pipe under turbulent conditions. In the viscous sub-layer, the velocity varies linearly with the distance from the wall. The Fanning friction factor is defined as,** $f = \dfrac{\tau_w}{\rho \bar{u}^2 / 2}$ **where τ_w is the shear at the wall of the pipe, ρ is the density of the fluid and $\bar{u}$ is the average velocity in the pipe. Water (density = 1000 kg m^3, viscosity = 1 x 10^3 kg $m^1 s^1$) flows at an average velocity of 1 m s^{-1} through the pipe. For this flow condition, the friction factor f is 0.005. At a distance of 0.05 mm from the wall of the pipe (in the viscous sub-layer), the velocity (in m s^1, rounded off to the third decimal place), is _______.**

39

$$v^+ = y^+$$ (in viscous sublayer for turbulent flow ~~through~~ a pipe See Geankoplis p197)

$$v^+ = v\sqrt{\frac{\rho}{\tau_w}}$$

$$y^+ = \frac{\sqrt{\tau_w \rho}}{\mu} y$$

$$v\sqrt{\frac{\rho}{\tau_w}} = \frac{\sqrt{\tau_w \rho}}{\mu} y$$

$$v = \left(\frac{\sqrt{\tau_w \cancel{\rho}}}{\mu}\right)\left(\sqrt{\frac{\tau_w}{\cancel{\rho}}}\right) y$$

$$= \frac{\tau_w y}{\mu} = \frac{\left[(f\rho\bar{u}^2)/2\right] y}{\mu}$$

$$\left[\text{given } f = \frac{\tau_w}{(\rho\bar{u}^2/2)}\right]$$

$$= \frac{f\rho\bar{u}^2 y}{2\mu}$$

$f = 0.005$

$\bar{u} = 1\ \frac{m}{s}$

$y = 0.05\,mm$

$= 0.05\times10^{-3}\,m$

$\mu = 1\times10^{-3}\ \frac{kg}{m\cdot s}$

$\rho = 1000\ \frac{kg}{m^3}$

$$= 0.005 \times 1000\,\cancel{\frac{kg}{m^3}} \times 1^2\,\cancel{\frac{m^2}{s^2}} \times 0.05\times10^{-3}\,\cancel{m} \times \frac{1}{2} \times \frac{1}{1\times10^{-3}}\,\frac{m\cdot \cancel{s}}{\cancel{kg}}$$

$v = 0.125\ \frac{m}{s}$

@ 0.05 mm from wall

Q. 40 In a 1-1 pass shell and tube exchanger, steam is condensing in the shell side at a temperature (T_s) of 135°C and the cold fluid is heated from a temperature (T_1) of 20°C to a temperature (T_2) of 90°C. The energy balance equation for this heat exchanger is

$$\ln \frac{T_s - T_1}{T_s - T_2} = \frac{UA}{mc_p}$$

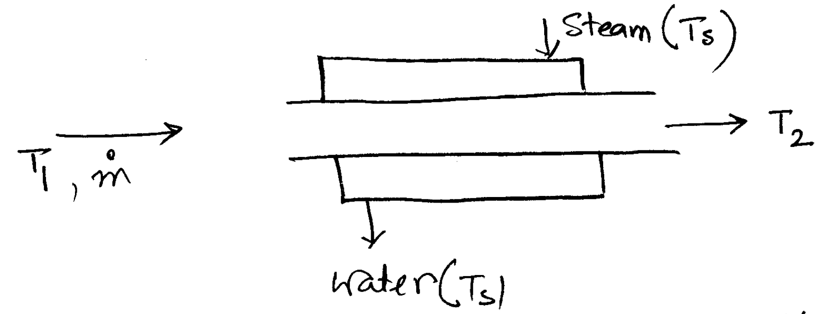
where U is the overall heat transfer coefficient, A is the heat transfer area, m is the mass flow rate of the cold fluid and c_p is its specific hat. Tube side fluid is in a turbulent flow and the heat transfer coefficient can be estimated from the flowing equation:

$$\text{Nu} = 0.023\,(\text{Re})^{0.8}\,(\text{Pr})^{1/3}$$

where Nu is the Nusselt number, Re is the Reynolds number and Pr is the Prandtl number. The condensing heat transfer coefficient in the shell side is significantly higher than the tube side heat transfer coefficient. The resistance of the wall to heat transfer is negligible. If only the mass flow rate of the cold fluid is doubled, what is the outlet temperature (in °C) of the cold fluid at steady state?

(A) 80.2 (B) 84.2 (C) 87.4 (D) 88.6

40



$$\ln\left(\frac{T_s - T_1}{T_s - T_2}\right) = \frac{UA}{\dot{m} C_p} \quad \Big| \quad Nu = 0.023\, Re^{0.8}\, Pr^{1/3}$$

$$U_i = \frac{1}{\dfrac{1}{h_i} + \underbrace{\cancel{\dfrac{(r_0 - r_i) A_i}{k_A A_{A,lm}}}}_{\approx 0 \text{ (given)}} + \underbrace{\dfrac{A_i}{A_0} \cdot \cancel{\dfrac{1}{h_0}}}_{\approx 0\ (h_0 \gg h_i)}}$$

[See Geankoplis p 228]

$$U_i \approx \frac{1}{1/h_i} = h_i \text{ (let's call it } h\text{)}$$

$$Nu\left(= \frac{h d_i}{k}\right) = 0.023 \left(\frac{d_i \bar{u} \rho}{\mu}\right)^{0.8} Pr^{1/3}$$

$$= 0.023 \left(\frac{d_i \dot{m}}{A_i \mu}\right)^{0.8} Pr^{1/3}$$

$$\left[\begin{array}{l} \dfrac{\dot{m}}{A_i} \Rightarrow u\rho \\ \left(\dfrac{\cancel{kg}}{s}\right)\left(\dfrac{1}{m^2}\right) \Rightarrow \dfrac{m}{s} \cdot \dfrac{kg}{m^3} \end{array}\right] \qquad A_i = \frac{\pi d_i^2}{4}$$

$$\therefore \frac{h d_i}{k} = \underbrace{0.023 \left[\left(\frac{d_i}{A_i \mu} \right)^{0.8} Pr^{1/3} \right]}_{\text{Constant}} \dot{m}^{0.8}$$

$$h = \left\{ \underbrace{0.023 \left(\frac{k}{D} \right) \left(\frac{d_i}{A_i \mu} \right)^{0.8} Pr^{1/3}}_{K \text{ (constant)}} \right\} (\dot{m})^{0.8}$$

$$h = K (\dot{m})^{0.8} \checkmark$$

$$U = K (\dot{m})^{0.8} \checkmark \qquad [U_i \approx h_i]$$

$$\therefore \ln \left(\frac{T_S - T_1}{T_S - T_2} \right) = \left(\frac{U}{\dot{m}} \right) \left(\frac{A}{C_p} \right) \qquad [\text{Here } A = A_i]$$

$$= \left[\frac{K \dot{m}^{0.8}}{\dot{m}} \right] \left(\frac{A}{C_p} \right)$$

$$= \left(\frac{KA}{C_p} \right) (\dot{m})^{-0.2}$$

$$\boxed{\ln \left(\frac{T_S - T_1}{T_S - T_2} \right) = K' (\dot{m})^{-0.2}} \quad \cdots \text{(Eq-1)}$$

$$K' = \left(\frac{KA}{C_p} \right)$$

Case - I

$\dot{m}$ = mass flow rate of liquid

$T_1 = 20°C$

$T_2 = 90°C$

$T_S = 135°C$

Case - II

$\dot{m}' = 2\dot{m}$

$T_1' = 20°C$

$T_2' = ?$

$T_S = 135°C$

Taking ratio of eq-1 for Case-I and Case-II

$$\frac{\ln\left[\frac{(T_S - T_1')}{(T_S - T_2')}\right]}{\ln\left[\frac{(T_S - T_1)}{(T_S - T_2)}\right]} = \frac{K'(\dot{m}')^{-0.2}}{K'(\dot{m})^{-0.2}} = \left(\frac{\dot{m}'}{\dot{m}}\right)^{-0.2}$$

$$\frac{\ln\left[\frac{(135-20)}{(135-T_2')}\right]}{\ln\left[\frac{(135-20)}{(135-90)}\right]} = 2^{-0.2} \qquad \left[\dot{m}' = 2\dot{m}\right]$$

$$\frac{\ln\left[\frac{115}{(135-T_2')}\right]}{\ln\left(\frac{115}{45}\right)} = 0.8705$$

$$\ln\left[\frac{115}{(135-T_2')}\right] = 0.8705 \ln(2.556) = 0.8169$$

$$\frac{115}{(135-T_2')} = e^{0.8169} = 2.2634$$

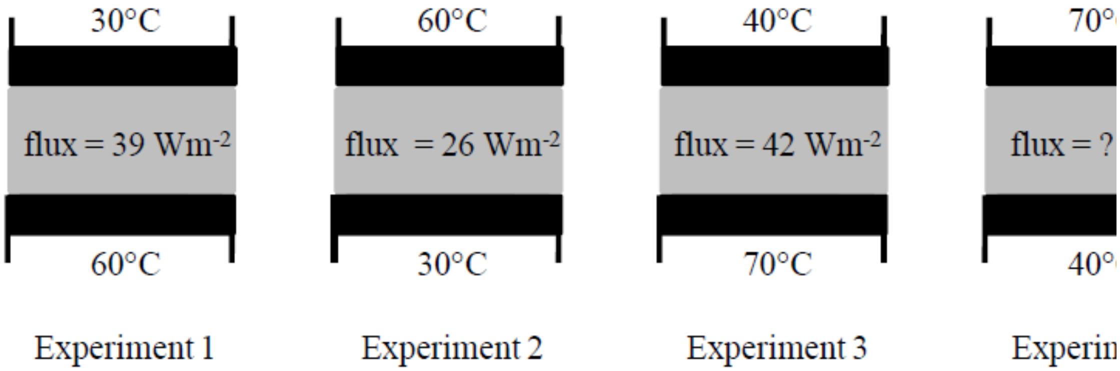
$$\text{or } 135-T_2' = \frac{115}{2.2634} = 50.808$$

$$\text{or } T_2' = 135-50.808 = 84.192$$

(B) correct answer

(E)

Q. 41 **In an experimental setup, mineral oil is filled in between the narrow gap of two horizontal smooth plates. The setup has arrangements to maintain the plates at desired uniform temperature. At these temperatures, ONLY the radiative heat flux is negligible. The thermal conductivity of the oil does not vary perceptibly in this temperature range. Consider four experiments at steady state under different experimental conditions, as shown in the figure below. The figure shows plate temperatures and the heat fluxes in the vertical direction.**



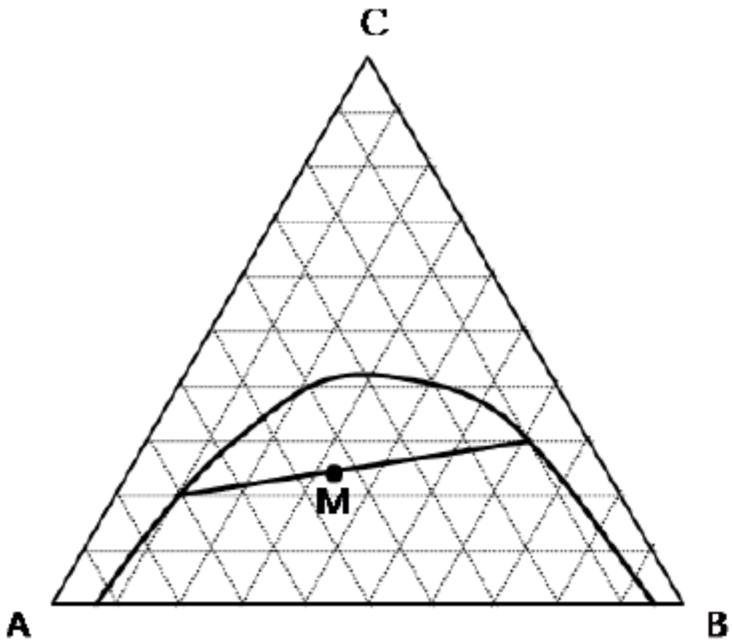
What is the steady state heat flux (in W m^2) with the top plate at 70°C and the bottom plate at 40°C?

(A) 26 (B) 39 (C) 42 (D) 63

Q. 42 The space between two below concentric spheres of radii 0.1 m and 0.2 m is under vacuum. Exchange of radiation (uniform in all directions) occurs only between the outer surface (S_1) of the smaller sphere and the inner surface (S_2) of the larger sphere. The fraction (rounded off to the second decimal place) of the radiation energy leaving S_2, which reaches S_1 is _____.

Q. 43 A binary distillation column is to be designed using McCabe Thiele method. The distillate contains 90 mol% of the more volatile component. The point of intersection of the q-line with the equilibrium curve is (0.5, 0.7). The minimum reflux ratio (rounded off to the first decimal place) for this operation is _______.

Q. 44 Solute C is extracted in a batch process from its homogeneous solution of A and C, using solvent B. The combined composition of the feed and the extracting solvent is shown in the figure below as point M, along with the tie line passing through it. The ends of the tie line are on the equilibrium curve.



What is the selectivity for C ?

(A) 3.5 (B) 7 (C) 10.5 (D) 21

Q. 45 At 30°C, the amounts of acetone adsorbed at partial pressures of 10 and 100 mmHg are 0.1 and 0.4 kg acetone/kg activated carbon, respectively. Assume Langmuir isotherm describes the adsorption of acetone on activated carbon. What is the amount of acetone adsorbed (in kg per kg of activated carbon) at a partial pressure of 50 mmHg and 30°C?

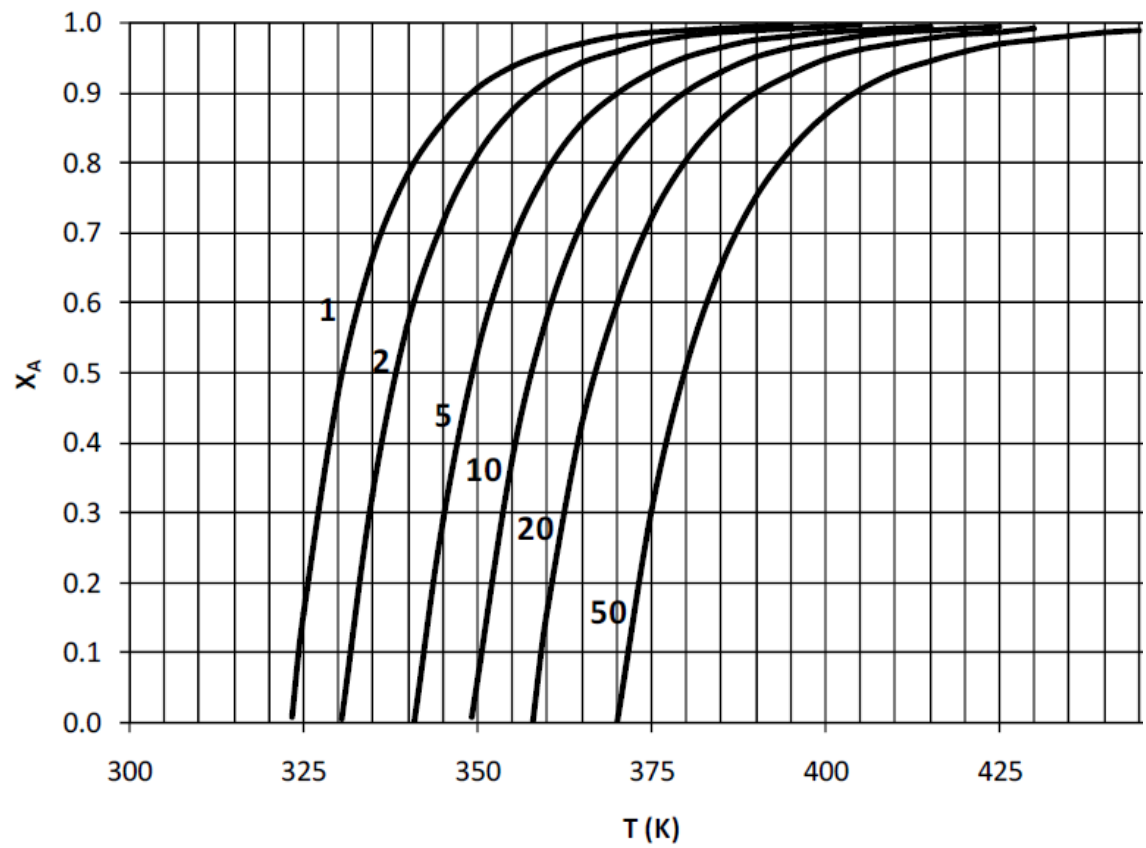
(A) 0.23 (B) 0.25 (C) 0.30 (D) 0.35

Q. 46 Consider the following two cases for a binary mixture of ideal gases A and B under steady state conditions. In Case 1, the diffusion of A occurs through non-diffusing B. In Case 2, equimolal counter diffusion of A and B occurs. In both the cases, the total pressure is 100 kPa and the partial pressures of A at two points separated by a distance of 10 mm are 10 kPa and 5 kPa. Assume that the Fick's first law of diffusion is applicable. What is the ratio of molar flux of A in Case 1 to that in Case 2?

(A) 0.58 (B) 1.08 (C) 1.58 (D) 2.18

Q. 47 **The liquid phase reversible reaction A B is carried out in an isothermal CSTR operating under steady state conditions. The inlet stream does not contain B and the concentration of A in the inlet stream is 10 mol/lit. The concentrations of A at the reactor exit, for residence times of 1 s and 5 s are 8 mol/lit and 5 mol/lit, respectively. Assume the forward and backward reactions are elementary following the first order rate law. Also assume that the system has constant molar density. The rate constant of the forward reaction (in s1, rounded off to the third decimal place) is _______.**

Q. 48 **A liquid phase irreversible reaction A → B is carried out in an adiabatic CSTR operating under steady state conditions. The reaction is elementary and follows the first order rate law. For this reaction, the figure below shows the conversion (X_A) of A as a function of temperature (T) for different values of the rate of reaction ($-r_A$ in mol $m^{-3}s^{-1}$) denoted by the numbers to the left of each curve. This figure can be used to determine the rate of the reaction at a particular temperature, for a given conversion of A.**



The inlet stream does not contain B and the concentration of A in the inlet stream is 5 mol/m^3. The molar feed rate of A is 100 mol/s. A steady state energy balance for this CSTR results in the following relation: $T = 350 + 25 X_A$ where T is the temperature (in K) of the exit stream and X_A is the conversion of A in the CSTR. For an exit conversion of 80% of A, the volume (in m^3, rounded off to the first decimal place) of CSTR required is _______.

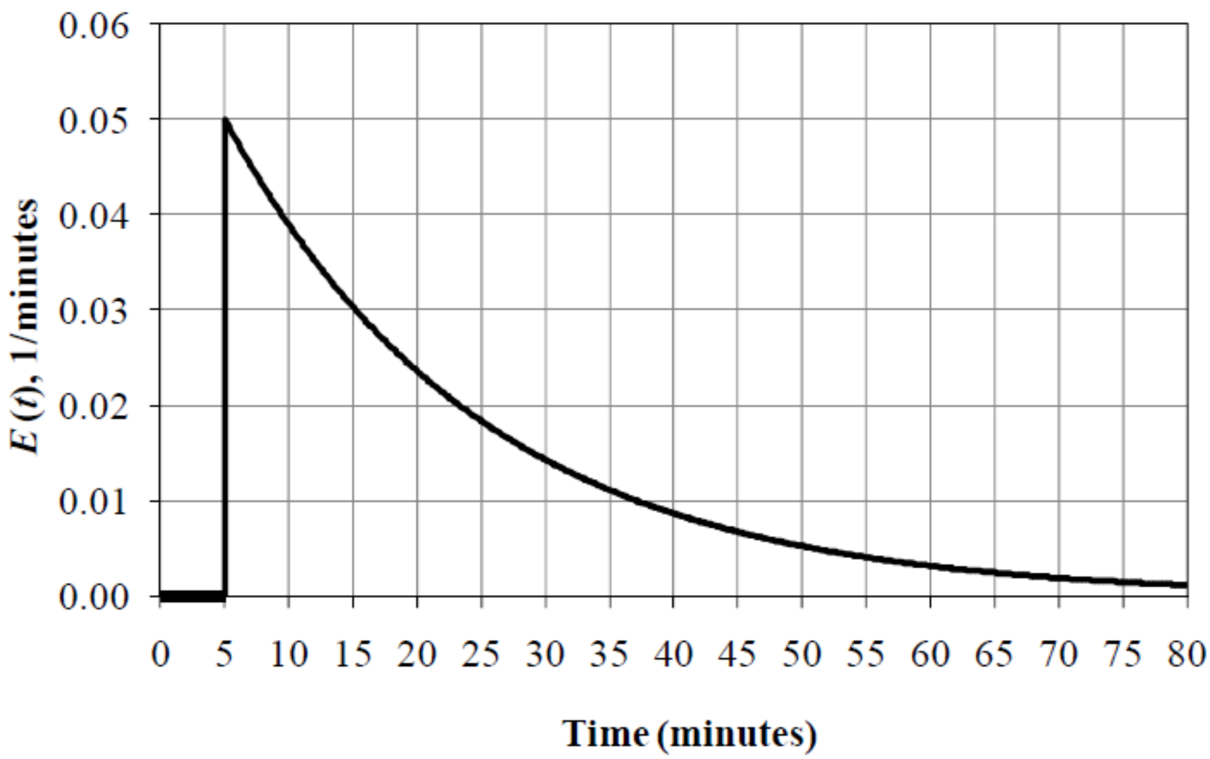
Q. 49 **A porous pellet with Pt dispersed in it is used to carry out a catalytic reaction. Following two scenarios are possible.**

Scenario 1: Pt present throughout the pores of the pellet is used for catalyzing the reaction.
Scenario 2: Pt present only in the immediate vicinity of the external surface of the pellet is used for catalyzing the reaction.

At a large value of Thiele modulus, which one of the following statements is TRUE?

(A) Since the reaction rate is much greater than the diffusion rate, Scenario 1 occurs
(B) Since the reaction rate is much greater than the diffusion rate, Scenario 2 occurs
(C) Since the reaction rate is much lower than the diffusion rate, Scenario 1 occurs
(D) Since the reaction rate is much lower than the diffusion rate, Scenario 2 occurs

Q. 50 **A CSTR has a long inlet pipe. A tracer is injected at the entrance of the pipe. The E-curve obtained at the exit of the CSTR is shown in the figure below.**



Assuming plug flow in the inlet pipe, the ratio (rounded off to the second decimal place) of the volume of the pipe to that of the CSTR is _______

Q. 51 **A liquid flows through an "equal percentage" valve at a rate of 2 m^3/h when the valve is 10% open. When the valve opens to 20% the flowrate increases to 3 m^3/h. Assume that the pressure drop across the valve and the density of the liquid remain constant. When the valve opens to 50%, the flowrate (in m^3/h, rounded off to the second decimal place) is _______**

Q. 52 **A PI controller with integral time constant of 0.1 min is to be designed to control a process with transfer function,**

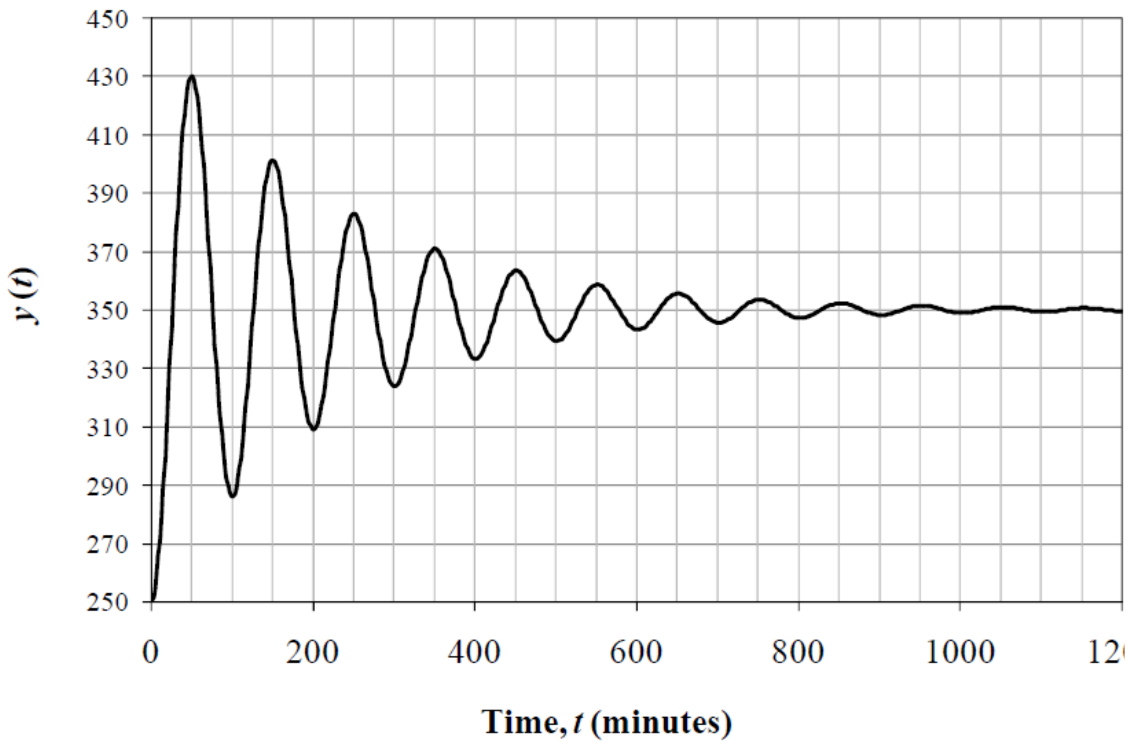
$$G_p(s) = \frac{10}{s^2 + 2s + 100}$$

Assume the transfer functions of the measuring element and the final control element are both unity (G_m = 1, G_f = 1). The gain (rounded off to the first decimal place) of the controller that will constitute the critical condition for stability of the PI feedback control system is _______.

Q. 53 **For a unit step input, the response of a second order system is**

$$y(t) = K_p\left[1 - \frac{1}{\sqrt{1-\zeta^2}} e^{-\frac{\zeta t}{\tau}} \sin\left(\frac{\sqrt{1-\zeta^2}}{\tau} t + \phi\right)\right]$$

where, Kp is the steady state gain, ζ is the damping coefficient, τ is the natural period of oscillation and ϕ is the phase lag. The overshoot of the system is exp $\left(-\frac{\pi\zeta}{\sqrt{1-\zeta^2}}\right)$**. For a unit step input, the response of the system from an initial steady state condition at t = 0 is shown in the figure below.**



What is the natural period of oscillation (in seconds) of the system?

(A) 15.9 (B) 50 (C) 63.2 (D) 100

Q. 54 A vertical cylindrical tank with a flat roof and bottom is to be constructed for storing 150 m^3 of ethylene glycol. The cost of material and fabrication for the tank wall is Rs. 6000 per m^2 and the same for the roof and the tank bottom are Rs. 2000 and Rs. 4000 per m^2, respectively. The cost of accessories, piping and instruments can be taken as 100% of the cost of the wall. 10% of the volume of the tank needs to be kept free as vapour space above the liquid storage. What is the optimum diameter (in m) for the tank?

(A) 3.5 (B) 3.9 (C) 7.5 (D) 7.8

Q. 55 A catalytic reforming plant produces hydrogen and benzene from cyclohexane by de-hydroaromatization. In order to increase the production of hydrogen, the owner plans to change the process to steam reforming of the same feedstock that produces

hydrogen and carbon dioxide. Stoichiometrically, what is the maximum ratio of pure hydrogen produced in the proposed process to that in the existing process?

(A) 1 (B) 2 (C) 5 (D) 6

END OF THE QUESTION PAPER