CHEMICAL ENGINEERING (GATE & PSUs)

Postal Correspondence

STUDY MATERIAL (Handwritten Notes)

By Ajay Sir

PROCESS CALCULATION

GATE-2022 Syllabus: Chemical Engineering: PC

Steady and unsteady state mass and energy balances including multiphase, multi-component, reacting and non-reacting systems. Use of tie components; recycle, bypass and purge calculations, Gibb's phase rule and degree of freedom analysis.

PROCESS CALCULATION COURSE CONTENT

Note for Student:

1. Full GATE Syllabus covers in Notes.

2. Total number of pages in PC Notes = 145 Pages

3. No. of Questions solved in PC Notes = 90+ Questions (GATE PYQs & other good quality question)

PROCESS CALCULATION

Units and Dimensions :-

Chemical engineering

- unit operations (Physical changes)
  - FM
  - HT
  - MT
  - Drying
  - Distillation
  - Crystallization
  - Extraction
  - Adsorption
  - MO
  - Evaporation
- unit process (Chemical changes)
  - oxidation
  - Reduction
  - Nitration
  - Sulphonation
  - Halogenation
  - Pyrolysis
  - Hydrolysis

* **unit :-** unit is any measure or amount used as a standard for measurment.

* **Dimensions :-** By dimensions we mean the measurable extent of a physical quantity

Example : 50 kg weight / mass

kg ↓ unit

mass ↓ Dimension

* unit provides standards to measure the quantities called dimensions.
* Each unit is associated with a dimension which is unique.
* A unit refers to one and only one dimension.

Example: The kilogram is a unit used to measure the dimension mass.

Physical quantities :- (fundamental units / dimensions)

1) fundamental units / dimensions (primary)
2) Derived physical unit / dimension (secondary)

(1) fundamental physical quantities :-

Are those that can be measured independently and are sufficient to describe most physical quantities such as length, mass, time and temperature

		S.I unit	
① Length	→	M	(meter)
② Mass	→	kg	(kilogram)
③ Time	→	Sec	(second)
④ Temperature	→	K	(kelvin)
⑤ current	→	Amperes	
⑥ Amount of substance	→	mol	

II) Derived physical quantities :-

Those quantities which are obtained by the combination of base / primary physical quantities.

(I) **Force** :-

$$F = ma$$

$$= kg \times \frac{m}{s^2}$$

F = 1 Newton = 1 N (S.I unit)

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

* Convert 1 N into $1 \frac{g.cm}{s^2}$

$$1N = 1 kg. \frac{m}{s^2} \rightarrow \frac{10^3 g \times 10^2 cm}{s^2} \rightarrow 10^5 \frac{g.cm}{s^2}$$ (cgs unit)

$$\left(1 N = 10^5 \frac{gm\ cm}{s^2}\right) \rightarrow 1N = 10^5 \text{ dynes}$$

$$1 \text{ dynes} = 1 \frac{gm.cm}{s^2}$$

SAMPLE

* FPS :- ~~feet / pound second~~ feet pound second

* **Imp** :-

1 lbm or 1 lb = 0.45 kg

1 feet = 0.3048 m

1 feet = 12 inch

1 inch = 2.54 cm

lb = pound

II) **Weight :-** $\boxed{W = mg}$

$= 1kg \cdot \frac{m}{s^2}$

$= 1N$

III) **Pressure :** $\boxed{P = \frac{F_N}{A}} = \frac{N}{m^2} = \frac{kg \cdot m/s^2}{m^2} = \frac{kg}{m \cdot s^2}$

F_N = Normal / perpendicular force

$\{ P \rightarrow \frac{N}{m^2} = 1 \text{ pascal} = 1 \text{ Pa} \}$

$\boxed{P = \rho g h}$ (Hydrostatic law)

$P \propto h$

* **Imp:**

1 atm	=	101325 Pa
1 atm	=	1.01325 bar
1 bar	=	10^5 Pa
1 atm	=	760 mm Hg
1 mm Hg	=	1 torr
1 atm	=	14.7 psi
1 atm	=	10.33 m of water

* psi = pound per square inch

$= \frac{lbf}{inch^2}$

$P = \rho g h$

1 atm = 101325 Pa = 1000 × 9.81 × h_w

~~1 atm~~ =

h_w = 10.3 m of water

Wet Basis & Dry Basis :- (solvent free Basis)

Solution = solute + solvent

Ex:- Dry solid + H_2O

Mole fraction or wet basis = $\dfrac{n_{H_2O}}{n_{dry\,solid} + n_{H_2O}}$ = $\dfrac{\text{kg moisture}}{\text{kg wet solid}}$

Mole Ratio or Dry basis = $\dfrac{n_{H_2O}}{n_{dry\,solid}}$ = $\dfrac{\text{kg moisture}}{\text{kg dry solid}}$

Mole fraction : $x_{H_2O} = \dfrac{X_{H_2O}}{1 + X_{H_2O}}$

Mole Ratio $X_{H_2O} = \dfrac{x_{H_2O}}{1 - x_{H_2O}}$

Ideal Gas calculation :-

$$\boxed{PV = nRT}$$

* At STP for Ideal gas: { 0°C or 273.15 K, 1 atm
  - 1 mol ⟶ 22.4 L
  - 1 kmol ⟶ 22.4 m^3 }

($1 m^3 = 1000 L$)

R = Gas constant

$PV = nRT$

$$R = \frac{PV}{nT} = \frac{1\ \text{atm} \times 22.4\ L}{1\ \text{mol} \times 273.15\ K} \Rightarrow \boxed{R = 0.0821\ \frac{\text{atm-L}}{\text{mol-K}}}$$

1) $R = \frac{PV}{nT} = \frac{1\,atm \times 22.4\,L}{1\,mol \times 273.15\,K} \Rightarrow$ ** $R = 0.0821 \frac{atm - L}{mol - K}$

1 atm = 1.01325 bar

2) $R = \frac{PV}{nT} = \frac{1.01325\,bar \times 22.4\,L}{1\,mol \times 273.15\,K} \Rightarrow$ $R = 0.0831 \frac{bar - L}{mol - K}$

1 atm = 101325 Pa, $V = 22.4\,m^3$ R → gas constant

1 kmol = 1000 mol,

3) $R = \frac{PV}{nT} = \frac{101325\,Pa \times 22.4\,m^3}{1000\,mol \times 273.15\,K} \Rightarrow$ ** $R = 8.314 \frac{J}{mol - K}$

($Pa \to N/m^2$) (N-m)

$R = 8.314 \frac{Pa - m^3}{mol - K}$

$R = 8314 \frac{J}{kmol - K}$

4) 1 cal → 4.1868 J

$R = 8.314 \frac{J}{mol - K} = \frac{8.314}{4.1868} \frac{cal}{mol - K} \Rightarrow$ $R = 1.987 \frac{cal}{mol - K}$

Ex. 13) find the value of Gas constant R in $\frac{mmHg - m^3}{mol - K}$

Sol → $R = \frac{PV}{nT} = \frac{760\,mmHg \times 22.4\,m^3}{1\,kmol \times 273.15\,K}$

$R = \frac{760 \times 22.4}{1000 \times 273.15} \frac{mmHg \times m^3}{mol - K}$

$\left(R = 0.062 \frac{mmHg - m^3}{mol - K}\right)$

* **Total material balance :-**

[Rate of mass In − Rate of mass out = Rate of Accumulation of mass]

* Mass balance for a component which is taking part in a reaction, then there will be generation (in case of product) and consumption (in case of reactant).

* For steady-state process, set accumulation = 0

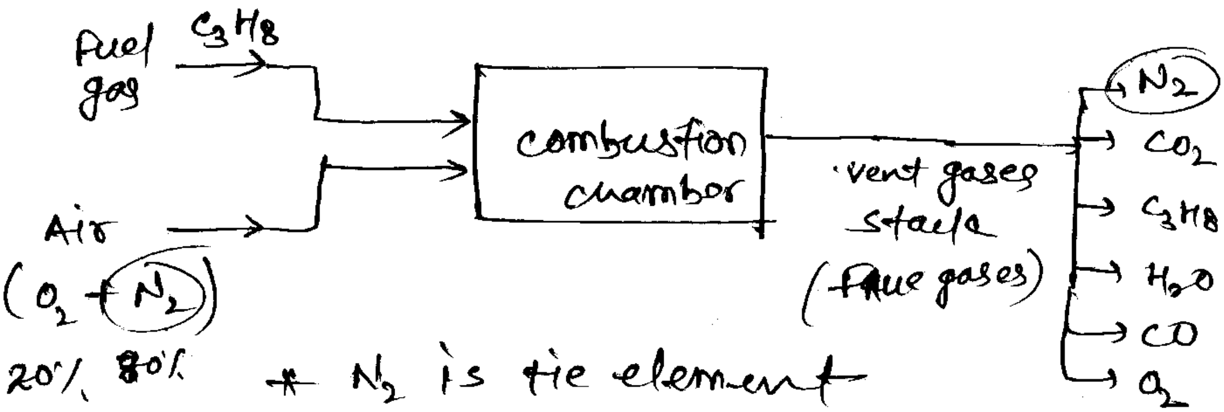
* For inert material, set generation and consumption is zero.

Tie Element :- (key component)

A component in a material balance, which enters and leaves the system in a single stream or one which enters and leaves without any change

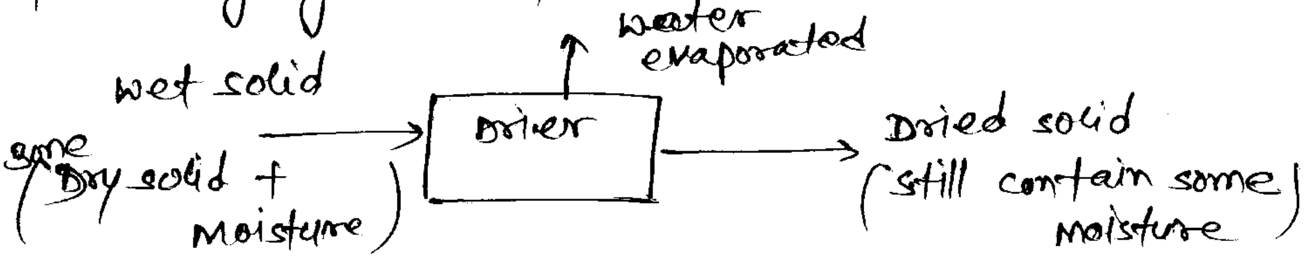
For example :

1) combustion chamber



* N_2 is tie element

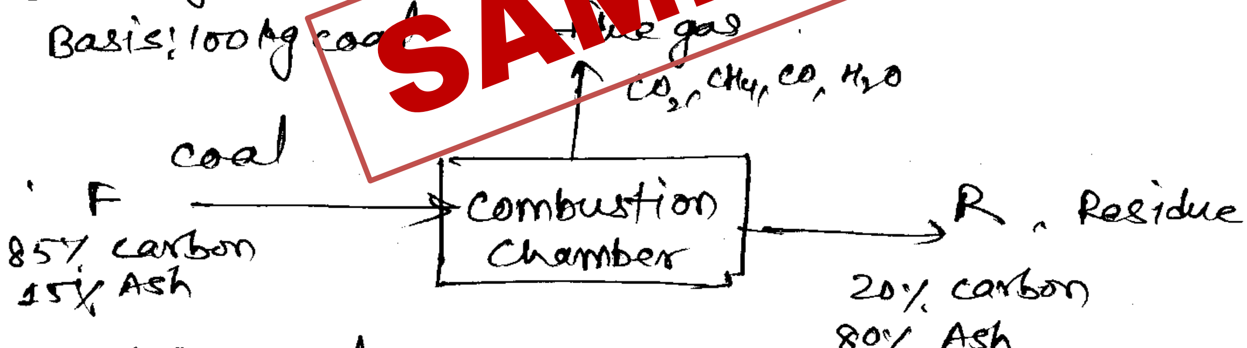
Example. Drying assembly



– Tie element is bone dry solid.

Ques 16) Coal contains 85% carbon and 15% ash. Carbon is burnt in a combustion chamber and residue found to contain 80% ash and 20% carbon. Determine the amount of residue form for 100 kg of coal and % of amount of flue gas leaving

Sol→ Basis: 100 kg coal



100 kg coal

(a) → Ash is tie component

Apply mass balance on tie-component

In = out

$$0.15 \times 100 = 0.80 \times R$$

$$R = \frac{0.15 \times 100}{0.8} = 18.75 \text{ kg} \quad \text{Answer}$$

(b) F = flue gas + Residue

$100 = \text{flue gas} + 18.75$

Flue gas = 81.25 kg

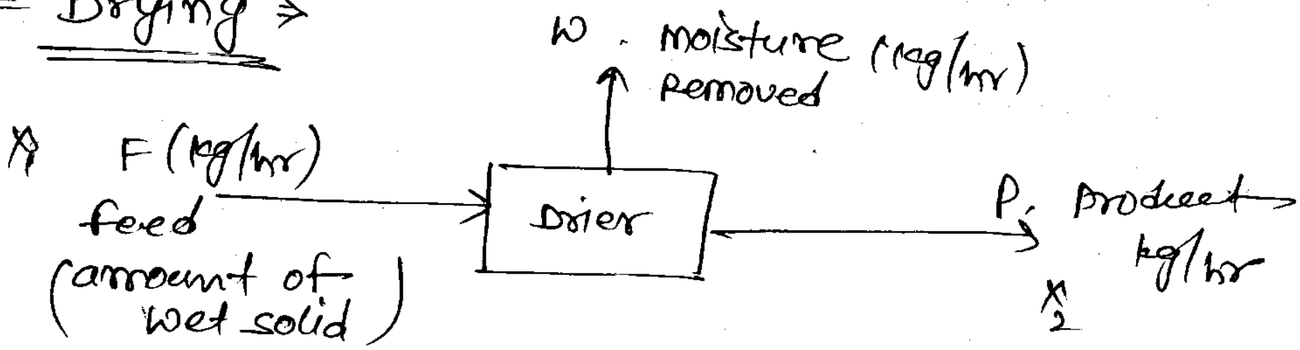
% amount of flue gas

$$= \frac{\text{flue gas}}{\text{feed}} \times 100$$

$$= \frac{81.25}{100} \times 100 = 81.25\%$$

Answer

Drying ⇒



Basis: 1 h, ✓ overall material balance

$$F = P + W \quad \leftarrow (1)$$

✓ component material balance

$x \left(\frac{\text{kg moisture}}{\text{kg wet solid}}\right)$ = moisture entering in feed

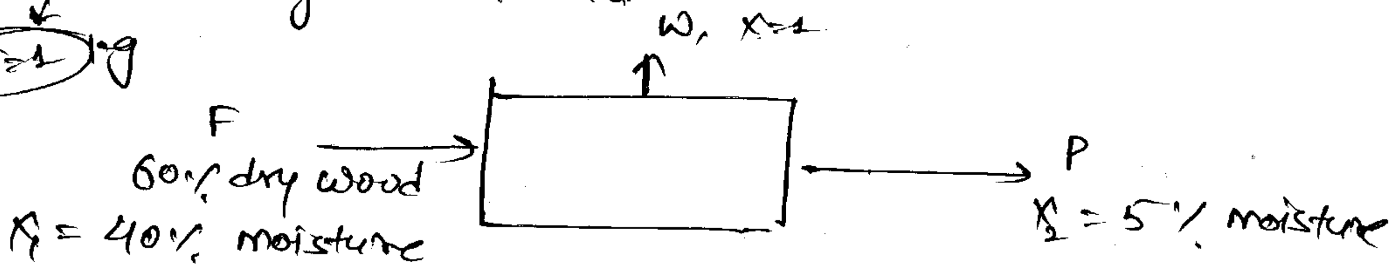
$$F \cdot x_1 = P \cdot x_2 + w \cdot 1$$

* Note: → (For a system) we have to write no. of independent equation for a system equal to no. of variable. (only valid for non-reacting system)

Que 17) A wood containing 40% moisture is dried upto 5% moisture. What mass of water is evaporated per kg of dry wood.

Sol → Basis: 1 kg of wet solid

(F = 1) kg



OMB: $F = P + w$

$1 = P + w \quad \text{--- } (1)$

Component (moisture) mass balance $\quad 1 = P + W$ —— (1)

$$F x_1 = P x_2 + W \cdot 1$$

$$1 \times 0.4 = P(0.05) + W \quad \text{—— (2)}$$

By solving eq^n (1) & (2), we get $P = 0.632$ kg, $W = 0.368$ kg

* mass of water evaporated per kg wet solid = 0.368 kg

Dry solid in feed = 1 kg − (0.4 × F) ⟶ moisture fraction

= 1 − (0.4 × 1)

= 0.6 kg

* mass of water evaporated on dried wood base

⇒ 1 kg wet solid ⟶ 0.368 kg water evaporated

↳ 0.6 kg dry solid ⟶ 0.368 kg —— " ——

then for 1 kg dry solid = $\frac{0.368}{0.6}$ kg water evaporated

Answer ⇒ 0.613 $\frac{\text{kg water evaporated}}{\text{kg dry solid}}$

(II) method :- Basis 1 kg wet solid

Tie-component :- Solid $\quad$ In = out

$F = P + W$

$$0.6 \times F = 0.95 \times P$$

$$0.6 \times 1 = 0.95 \times P \Rightarrow P = 0.631 \text{ kg}$$

$W = F - P$

$W = (1 - 0.631)$

$W = 0.368$ kg based on wet solid

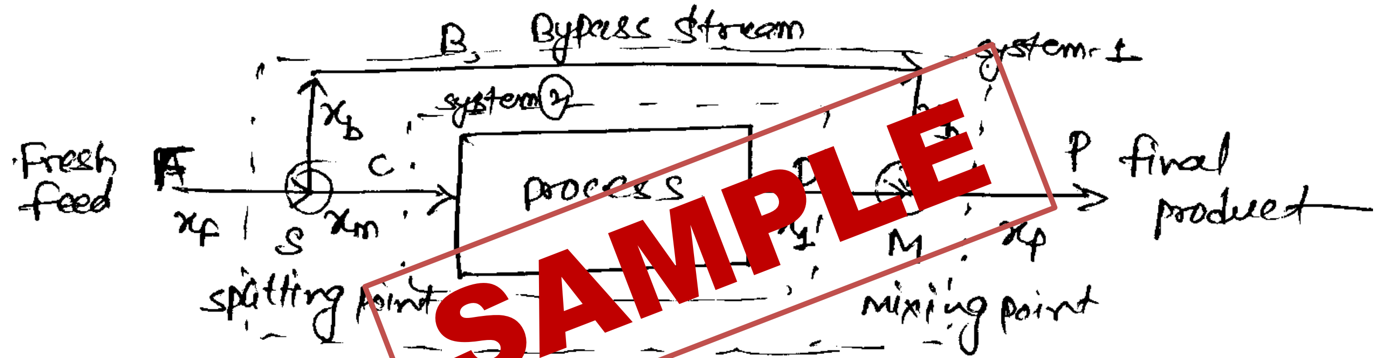
* Based on dry solid = $\frac{0.368}{0.6}$ = 0.613 kg Answer

BYPASS, RECYCLE AND PURGING →

* BYPASS : (Bypassing)

In bypassing a fraction of feed to a process unit is diverted around the unit and combined with product stream from the unit.

- Bypassing is use to control the compositions and properties of final product



* Bypass operation *

(Note) At splitting point $x_f = x_b = x_m$

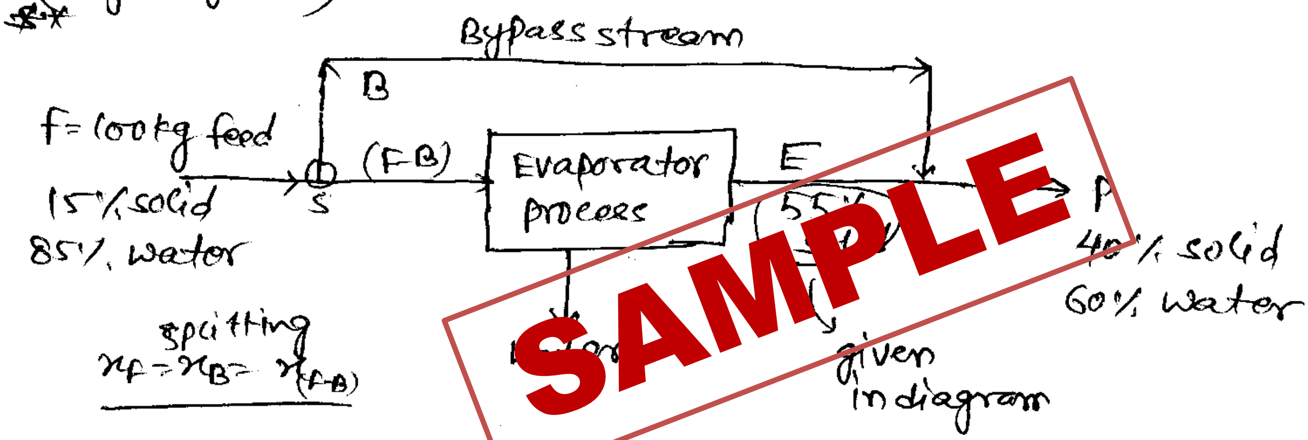
at mixing point
$x_1 \neq x_b \neq x_p$

At system 1: write two equation
① overall mass Balance
② component mass Balance

At system 2: write two equation
① overall mass Balance
② component mass Balance

Ques 28) (GATE) fresh juice contains 15% solids and 85% water is to be concentrated upto 40% solid in a single evaporator system. It is found to have bad taste. so to make it proper, a part of fresh juice is by passed the evaporator and added to the product stream. calculate the fraction of juice that is byproduct and the concentrated juice produced per 100 kg of fresh juice.

(figure given)



Sol → OMB:- $F = W + P$ ——— *

$100 = W + P$ ——— (1)

CMB $0.15 \times 100 = 0 + 0.40 P$

$P = 37.5$ kg (Answer), $W = 100 - 37.5$

$W = 62.5$ kg

* At Evaporator!

OMB: $(F-B) = W + E$

$(100-B) = 62.5 + E$

$B + E = 37.5$ ——— (2)

CMB! $0.15(F-B) = W \times 0 + 0.55 E$

$0.15(100-B) = 0.55 E$

$15 - 0.15 B = 0.55 E$ ——— (3)

$0.15B + 0.55E = 15$ ——— (1)

$B + E = 37.5$ ——— (2)

By solving, we get $B = 14.05$ kg

$E = 23.45$ kg

Bypass Ratio $= \frac{B}{F} = \frac{14.05}{100} = 0.14$

(fraction of juice that is byproduct)

Answer

Ques 29) (GATE-2013) A reverse osmosis unit treat feed water (F) containing flouride and its output consist of a permeate stream (P) and a reject stream (R).

C_F, C_P, C_R denotes the flouride ion concentration in F, P and R respectively, under steady-state conditions the volumetric flow rate of the reject stream is 60% of the volumetric flow rate of the inlet stream and $C_F = 2$ mg/L and $C_P = 0.1$ mg/L.

(I) The value of C_R in mg/L is ______ (upto one digit after decimal point)

(II) The fraction (f) of the feed is bypass and mixed with the permeate to obtain treated water. Having a flouride concentration of 1 mg/L. Here also the flow rate of the reject stream is 60% of the flow rate entering the reverse osmosis unit (after the bypass). The value of f upto two digit after the decimal point is ______.

Material Balance with Chemical Reaction ⇒

* General material balance eq^n:

[material in − material out + material generation within the system − material consumption with the system = accumulations of material with the system] —— (1)

* [Input − output = Accumulation] —— (2)
  ↳ In the absence of generation and consumption of material

* under-steady-state, there is no accumulation term.
* for processes with chemical reaction (conversion), eq^n (2) is not universally valid
* eq^n (2) is only valid for the total material balance written on a mass basis, but not valid on a mole basis.
* eq^n (2) is also valid on a mole or mass basis if the balance is written for atomic species, means, the amount of single component entering and leaving the process unit are the same irrespective of wheather the amount is expressed in a mole basis or mass basis.

Ques 40) A combustion chamber is feed with butane and excess air. combustion of butane is complete. After that the composition of combustion on volume basis is given (for flue gas)

$CO_2 = 9.39\%$, $H_2O = 11.73\%$, $O_2 = 4.7\%$, $N_2 = 74.18$.

find the percentage excess air used ?

sol → complete combustion means 100% conversion of butane (C_4H_{10}) { C_nH_{2n+2}

Basis = 100 mol of flue gas

$$C_4H_{10} + \frac{13}{2} O_2 \longrightarrow 4CO_2 + 5H_2O$$

2.3475 mol → $\frac{2.3475 \times 13}{2} = 15.25$ mol

↳ since there is no CO present in product, means there is no side reaction

1 mol C_4H_{10} ⟶ 4 mol CO_2

$\frac{9.39}{4} = 2.3475$ mol ⟵ 9.39 %

→ for 100% conversion

O_2 fed = reacted + unreacted

= 15.25 + 4.7

= 19.95 mol

$$\% \text{ Excess air} = \left(\frac{n_{A\,fed} - n_{A\,theoretical}}{n_{A\,theoretical}}\right) \times 100$$

$$= \left(\frac{19.95 - 15.25}{15.25}\right) \times 100$$

= 30.81 % **Answer**

Note → [% excess air = % excess oxygen]