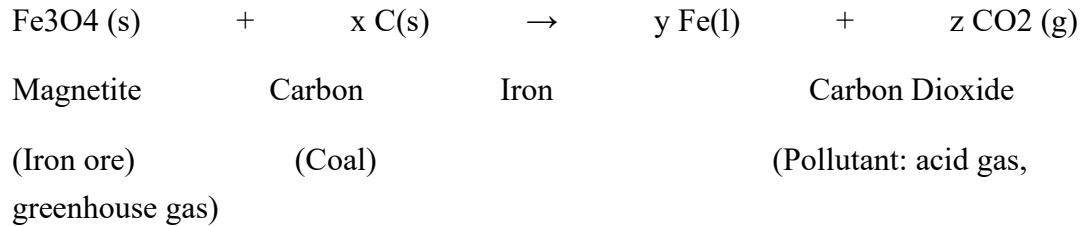


### Q1.1

1.1: Added to a stone furnace entity

Reaction Stoichiometry: Iron ore smelting

Iron can be smelted (extracted from its ore) by reacting magnetite (an iron ore) with coal (carbon) at high temperature in a stone furnace or a blast furnace:



To optimize the input mixture and increase the yield of iron, the reaction stoichiometry must be solved to determine x, y and z.

Answer for 1.1

$$x = [2]$$

$$y = [3]$$

$$z = [2]$$

#### 1. Write down the balanced chemical reaction:

The reaction involves magnetite ( $\text{Fe}_3\text{O}_4$ ), carbon (C), iron (Fe), and carbon dioxide ( $\text{CO}_2$ ). We need to balance the reaction to find the correct coefficients x, y, and z.

#### 2. Balance the number of iron atoms (Fe):

On the left side, we have 3 iron atoms in  $\text{Fe}_3\text{O}_4$ . On the right side, if we assume y iron atoms are produced as elemental iron (Fe), then:  $y=3$ .

#### 3. Balance the number of oxygen atoms (O):

On the left side,  $\text{Fe}_3\text{O}_4$  contains 4 oxygen atoms. On the right side, oxygen atoms are only present in carbon dioxide ( $\text{CO}_2$ ). Each  $\text{CO}_2$  molecule contains 2 oxygen atoms, so

if there are  $z$   $\text{CO}_2$  molecules, we must have:  $z=2$ .

#### 4. Balance the number of carbon atoms (C):

On the right side, there are  $z=2$   $\text{CO}_2$  molecules, which require 2 carbon atoms. Therefore, the number of carbon atoms on the left side must also be 2

#### Final Balanced Reaction:

##### Explanation:

- **Iron (Fe):** The number of iron atoms is balanced by having 3 atoms of iron on both sides of the reaction.
- **Oxygen (O):** The oxygen atoms are balanced by having 4 atoms of oxygen on the left (in  $\text{Fe}_3\text{O}_4$ ) and 4 atoms on the right (in 2 molecules of  $\text{CO}_2$ ).
- **Carbon (C):** The carbon atoms are balanced by using 2 atoms of carbon to produce 2 molecules of  $\text{CO}_2$ .

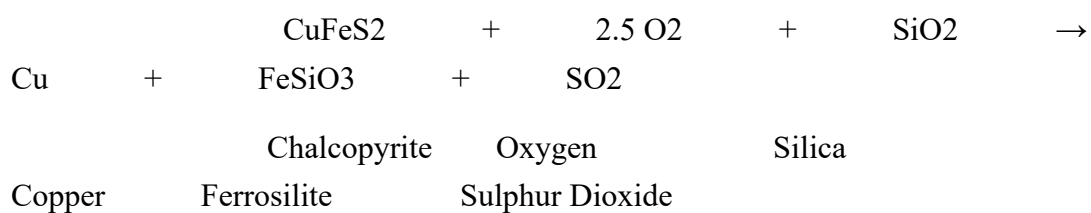
Thus, the reaction is correctly balanced with  $x=2$ ,  $y=3$ , and  $z=2$ .

## Q2.1

2.1: Added to a stone furnace Entity

Molecular Weight: Copper ore smelting

Copper can be smelted from chalcopyrite (a copper ore) according to the reaction stoichiometry:



	(Copper Ore)	(In air)	(Sand)
(Waste)	(Pollutant: acid gas)		
Molar	183.54	32	60.09
113.94		64.07	63.55
mass			
(g/mol)			

Adding the correct ratio of sand to chalcopyrite will minimize waste slag production. Using the molar mass, the amount of pure silica sand can be calculated per kilogram of chalcopyrite feed (for a stoichiometric mixture).

Answer for Q 2.1

Mass of silica per kilogram of chalcopyrite = [0.346] kg silica

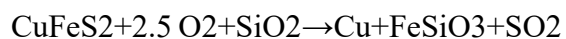
**Molar masses (g/mol):**

- CuFeS<sub>2</sub>: 183.54
- O<sub>2</sub>: 32
- SiO<sub>2</sub>: 60.09
- Cu: 63.55
- FeSiO<sub>3</sub>: 113.94
- SO<sub>2</sub>: 64.07

**Steps to Solve:**

1. **Write down the reaction:**

The balanced chemical reaction is:



**Determine the molar ratios from the balanced equation:**

The reaction indicates that 1 mole of CuFeS<sub>2</sub> reacts with 1 mole of SiO<sub>2</sub>.

**2. Calculate the mass of 1 mole of each substance:**

- Molar mass of  $\text{CuFeS}_2 = 183.54 \text{ g/mol}$
- Molar mass of  $\text{SiO}_2 = 60.09 \text{ g/mol}$

**3. Determine the mass ratio:**

Since 1 mole of  $\text{CuFeS}_2$  reacts with 1 mole of  $\text{SiO}_2$ , the mass ratio of  $\text{SiO}_2$  to  $\text{CuFeS}_2$  is:

Mass of  $\text{SiO}_2$  required = Molar mass of  $\text{SiO}_2$  / Molar mass of  $\text{CuFeS}_2 = 60.09 / 183.54$

Molar mass of  $\text{SiO}_2 = 183.54 \times 60.09$

**4. Calculate the amount of  $\text{SiO}_2$  required per kilogram of  $\text{CuFeS}_2$ :**

Convert the ratio to a per-kilogram basis:

Amount of  $\text{SiO}_2$  per 1 kg of  $\text{CuFeS}_2 = (60.09 / 183.54) \times 1000 \text{ g} = 327.32 \text{ g of SiO}_2$

**Final Answer:**

To minimize waste slag production, **327.32 grams of pure silica ( $\text{SiO}_2$ ) sand** is required per kilogram of chalcopyrite ( $\text{CuFeS}_2$ ) feed.

## Q 2.2

Carnot Cycle: Maximum efficiency

The combustion of coal produces a high temperature flame in the boiler's furnace ( $T_H = 700^\circ\text{C}$ ). Some of this thermal energy has been extracted to produce useful work to generate electricity. If the ambient conditions are assumed to be  $15^\circ\text{C}$  ( $T_L$ ) the system can be modelled as a thermodynamic cycle and the Carnot cycle can be used to determine the maximum possible system efficiency.

Answer for Q2.2

Carnot cycle efficiency = [70.4] %

The efficiency of heat engine is  $e = \frac{\text{work done by engine}}{Q_{\text{hot, which is the heat add into the engine}}}$

$$\text{Work} = Q_{\text{hot}} - Q_{\text{cold}}$$

$$E = \frac{Q_{\text{hot}} - Q_{\text{cold}}}{Q_{\text{hot}}} = 1 - \frac{Q_{\text{cold}}}{Q_{\text{hot}}}$$

Then use  $PV = nRT$

	Heat	Work
Stage 1	$Q_{\text{hot}} = -nR T_{\text{hot}} \ln\left(\frac{V_n}{V_m}\right)$	$\text{Work} = nR T_{\text{hot}} \ln\left(\frac{V_n}{V_m}\right)$
Stage 2	0	$C_v(T_{\text{cold}} - T_{\text{hot}})$
Stage 3	$Q_{\text{cold}} = -nR T_{\text{cold}} \ln\left(\frac{V_o}{V_p}\right)$	$\text{Work} = nR T_{\text{cold}} \ln\left(\frac{V_o}{V_p}\right)$
Stage 4	0	$C_v(T_{\text{hot}} - T_{\text{cold}})$

Using the adiabatic expansion and compression Stage 2 and 4

$$\frac{V_o}{V_n} = \left(\frac{T_{\text{hot}}}{T_{\text{cold}}}\right)^{\frac{C_v}{R}} \quad \text{and} \quad \frac{V_p}{V_m} = \left(\frac{T_{\text{cold}}}{T_{\text{hot}}}\right)^{\frac{C_v}{R}}$$

$$\frac{v_o}{v_n} = \frac{v_p}{v_m}$$

A simple rearrangement shows that

$$\frac{v_o}{v_p} = \frac{v_n}{v_m}$$

$$E = 1 - \frac{Q_{cold}}{Q_{hot}} = 1 - \frac{-nRT_{cold} \ln\left(\frac{v_o}{v_p}\right)}{-nRT_{hot} \ln\left(\frac{v_n}{v_m}\right)} = 1 - \frac{T_{cold}}{T_{hot}} = 1 - \frac{15k + 273k}{700k + 273k} = 1 - 0.296 = 0.704$$

The efficiency is 70.4%

## Q2.3

2.3: Added to a boiler entity

### Energy Balance: Boiler Design

The combustion of coal produces a huge amount of energy: 20 MJ/kg coal. This released energy has been harnessed to produce low-pressure steam, which can be used to drive a turbine for mechanization or to generate electricity.

Assuming the system is operating at steady state, a mass and energy balance can be performed to determine the amount of steam produced per kilogram of coal feed, to optimize the boiler production rate and operation of downstream units.

Answer for Q2.3

Mass of steam produced per kg of coal = [5.96] kg of steam

#### **Given Data:**

- **Energy content of coal:** 20 MJ/kg (20,000 kJ/kg)
- **Boiler efficiency:** Assume 100% for this calculation.
- **Specific enthalpy of steam:** 2704 kJ/kg (at 7 bars, 165°C)
- **Specific enthalpy of feedwater:** 419 kJ/kg
- **Mass of air required:** 12 kg
- **Mass of flue gas produced:** 13 kg
- **Specific enthalpy of flue gas:** 295 kJ/kg
- **Mass of steam produced:** x
- **The datum is 15C at 1atm**

#### **Energy Balance on the Boiler:**

The total energy input from the coal is used to generate steam and is partly lost as flue gas energy. The energy balance equation can be written as:

Energy input from coal=Energy used to produce steam+Energy lost in flue gases

Write in number

$$1\text{kg} \times 20000 = 13\text{kg} \times 295\text{kJ/kg} + x \times 2704\text{kJ/kg}$$

$$X = 5.96\text{kg}$$

Q3.1

3.1 Equations of Motion: Flame turret nozzle.

The barrel tip of this flame turret has melted and needs a replacement nozzle.

Ignoring wind resistance and setting a range of 30 m, the equations of motion can be used to determine the required exit velocity ( $v_1$ ) for the nozzle design. The time of flight to target will be 2.47 sec and the peak arc height will be 7.47 m.

$$(dv_{\text{vertical}})/dt = -9.8 \text{ m/s}^2$$

$$(dv_{\text{horizon}})/dt = 0 \text{ m/s}^2 \quad (\text{negligible air friction})$$

Answer for Q3.1

Exit velocity of crude oil: [17.14] m/s

**Problem Statement:**

To design a replacement nozzle for a flame turret, we need to determine the required exit velocity ( $v_1$ ) for a range of 30 meters, given:

- **Time of flight:** 2.47 seconds



- **Peak arc height:** 7.47 meters
- **Vertical acceleration:**  $dv/dt = -9.8 \text{ m/s}^2$  (due to gravity)
- **Horizontal acceleration:**  $dv/dt = 0 \text{ m/s}^2$  (negligible air resistance)

**Steps to Solve:**

1. **Break down the problem into horizontal and vertical components:**

- Horizontal motion:

Range =  $v_{\text{horizontal}} \times \text{time of flight} = v_{\text{horizontal}} \times \text{time of flight}$   $30 \text{ m} = v_{\text{horizontal}} \times 2.47 \text{ s}$   $v_{\text{horizontal}} = 30 / 2.47 \approx 12.15 \text{ m/s}$

- Vertical motion: Use the fact that at the peak height, the vertical velocity is zero. The time to reach the peak height is half of the total time of flight:

$$t_{\text{up}} = 2.47 \text{ s} / 2 = 1.235 \text{ s}$$

Using the equation for vertical motion:

$$v_{\text{vertical}} = v_{1y} - g \times t_{\text{up}}$$

At the peak height,  $v_{\text{vertical}} = 0$ , so:

$$v_{1y} = 9.8 \times 1.235 \approx 12.11 \text{ m/s}$$

2. **Determine the initial velocity  $v_1$ :**

The exit velocity ( $v_1$ ) is the vector sum of the horizontal and vertical components of the velocity:

$$v_1 = \sqrt{v_{\text{horizontal}}^2 + v_{\text{vertical}}^2} = \sqrt{12.15^2 + 12.11^2} = 17.14 \text{ m/s}$$

**Final Answer:**

The required exit velocity ( $v_1$ ) for the nozzle design to achieve the specified range, time of flight, and peak arc height is approximately **17.14 m/s**.

Q3.2

3.2 Distillation Column

This fractional distillation tower separates crude oil into 4 streams: an aqueous water phase (waste), petroleum gas (volatile gases like methane), light oil (C8-C16) and heavy oil (>C17).

But the outlets have all been disconnected.

A downstream unit converts the light oil into RP-1 (rocket fuel). The heavy oil would make a high energy density feed to the flame turret.

The lines must be identified and reconnected to restart the unit, but any mismatch could damage downstream equipment. The density of the crude oil is 850 kg/m<sup>3</sup> so less than water (1000 kg/m<sup>3</sup>).

Answer for Q3.2

Aqueous phase: Steam [4]

Petroleum Gas: Stream [1]

Light Oil: Stream [2]

Heavy Oil: Steam [3]

The 3 phase separator can separate liquid using density the most light gas come to the top which is the petroleum gas the most heavy will come to the bottom which is the stream of aqueous phase. The rest of them come to the distillation column the thing that left is light oil and heavy oil. the distillation column helps to separate the light and heavy oil the light oil will come to the top the heavy will goes to the bottom of the distillation tower.

So Answer is Aqueous phase: Steam [4]

Petroleum Gas: Stream [1]

Light Oil: Stream [2]

Heavy Oil: Steam [3]

Q3.3

This crude oil storage tank is currently shutdown: the valves V-01, V-02 and V-03 are all closed, and V-02 has corroded shut.

If V-01 remains closed, but V-03 is opened, the tank contents will begin to free drain out and draw a vacuum inside the tank, which may cause an implosion. The pressure indicator (PI-101) currently reads 0 atm gauge (see Absolute vs Gauge pressure) and the level indicator (LI-102) shows 6m at the maximum. The crude oil density is 850 kg/m<sup>3</sup> and the tank has a pressure rating from -40 kPa to 200 kPa (gauge pressure).

Bernoulli's principle may be used to determine the vacuum pressure during free draining, to know if there's a risk of implosion and if V-02 needs to be repaired.

Answer for Q3.3

Free draining vacuum pressure inside tank = [-50 ] kPa gauge

To determine whether there's a risk of implosion when V-03 is opened, we can use Bernoulli's principle to estimate the vacuum pressure inside the tank during free draining. We need to assess if this vacuum pressure will drop below the tank's minimum pressure rating of -40 kPa gauge (which is -40 kPa below atmospheric pressure).

**Given Data:**

- **Tank Pressure Rating:** -40 kPa to 200 kPa (gauge pressure)
- **Current Pressure (PI-101):** 0 atm gauge (which equals 1 atm absolute, or 101.325 kPa absolute)
- **Crude Oil Density:** 850 kg/m<sup>3</sup>
- **Height of Liquid (LI-102):** 6 m
- **Valve Status:** V-01 closed, V-02 corroded shut, V-03 will be opened

**Key Concepts:**

- **Bernoulli's Principle:** Relates the pressure, velocity, and height at two points in a fluid flow.
- **Gauge Pressure:** Pressure relative to atmospheric pressure (absolute pressure minus atmospheric pressure).

**Steps to Solve:**

1. **Bernoulli's Equation for Free Draining:**

For a fluid at rest, Bernoulli's equation can be simplified to:

$$P_1 + \rho gh_1 + 0.5\rho v_1^2 = P_2 + \rho gh_2 + 0.5\rho v_2^2$$

Where:

- P1 and P2 are the pressures at points 1 and 2.
- $\rho$  is the fluid density.
- g is the acceleration due to gravity.
- h1 and h2 are the heights of the fluid at points 1 and 2.
- v1 and v2 are the fluid velocities at points 1 and 2.

2. **Simplification:**

For free draining, assume that the fluid exits at a point where height h2 is 0 (at the tank outlet) and pressure P2 is atmospheric pressure (since the fluid is draining into the atmosphere).

The equation simplifies to:

$$P_1 + \rho gh_1 = P_{\text{atm}} + 0.5 \rho v_2^2$$

Rearranging to solve for  $P_1$  (the vacuum pressure inside the tank):

$$P_1 = P_{\text{atm}} - \rho gh_1 + 1/2 \rho v_2^2$$

### 3. Initial Consideration:

Assume that initially, the velocity  $v_2$  is zero (just as the draining begins), so:

$$P_1 = P_{\text{atm}} - \rho gh_1$$

Substitute the given values:

- $P_{\text{atm}} = 101.325 \text{ kPa}$  (absolute)
- $\rho = 850 \text{ kg/m}^3$
- $g = 9.81 \text{ m/s}^2$
- $h_1 = 6 \text{ m}$

$$P_1 = 101.325 \text{ kPa} - (850 \text{ kg/m}^3) \times (9.81 \text{ m/s}^2) \times (6 \text{ m}) = 51.258 \text{ kPa (absolute)}$$

### 4. Compare with Tank Pressure Rating:

The tank's minimum pressure rating is  $-40 \text{ kPa}$  gauge. The calculated pressure of  $-50.067 \text{ kPa}$  gauge is lower than the tank's minimum pressure rating.

### Conclusion:

Since the calculated vacuum pressure ( $-50.067 \text{ kPa}$  gauge) is lower than the tank's minimum pressure rating of  $-40 \text{ kPa}$  gauge, there **is a risk of implosion** if V-03 is opened while V-01 remains closed and V-02 is corroded shut.

**Recommendation:** V-02 needs to be repaired before V-03 is opened, or another method to equalize pressure (such as opening V-01) should be implemented to avoid creating a vacuum that could cause the tank to implode.

### Q3.4

For a maximum range of  $15 \text{ m}$ , the flame thrower needs an exit velocity of  $12.1 \text{ m/s}$ . Bernoulli's principle may be used to calculate the required tank pressure (gauge pressure) of the flamethrower ammo, given the crude oil fuel density is  $850 \text{ kg/m}^3$ .

Answer for Q3.4

Tank gauge pressure:  $[62.2] \text{ kPa}$

To calculate the required tank pressure (gauge pressure) for the flamethrower ammo to achieve a maximum range of  $15 \text{ meters}$  with an exit velocity of  $12.1 \text{ m/s}$ , we can apply Bernoulli's principle.

### Given Data:

- **Exit velocity ( $v_1$ ):**  $12.1 \text{ m/s}$
- **Range:**  $15 \text{ meters}$
- **Crude oil fuel density ( $\rho$ ):**  $850 \text{ kg/m}^3$
- **Assumption:** The fluid is incompressible, and the exit point is open to the atmosphere, so the pressure at the exit ( $P_2$ ) is atmospheric pressure.

**Bernoulli's Equation:**

Bernoulli's equation relates the pressure, velocity, and height at two points in a fluid flow. Assuming the height difference is negligible (i.e., the height of the fluid in the tank is the same as at the nozzle exit), the equation simplifies to:

$$P_1 + 0.5\rho v_1^2 = P_2 + 0.5\rho v_2^2$$

Where:

- $P_1$ : Pressure inside the tank (what we want to find).
- $v_1$ : Exit velocity of the fluid (12.1 m/s).
- $P_2$ : Atmospheric pressure (since the fluid exits to the atmosphere,  $P_2$  is 101.325 kPa absolute).
- $v_2$ : Velocity inside the tank, which we assume is negligible (close to zero).

The equation simplifies to:

$$P_1 = P_2 + \frac{1}{2}\rho v_1^2$$

**Substitute the Known Values:**

$$P_1 = 101.325 \text{ kPa} + \frac{1}{2} \times 850 \text{ kg/m}^3 \times (12.1 \text{ m/s})^2$$

Calculate the dynamic pressure component:

$$\frac{1}{2} \times 850 \times (12.1)^2 = \frac{1}{2} \times 850 \times 146.41 = 62174.25 \text{ Pa} = 62.174 \text{ kPa}$$

So, the total pressure  $P_1$  inside the tank is:

$$P_1 = 101.325 \text{ kPa} + 62.174 \text{ kPa} = 163.499 \text{ kPa (absolute)}$$

**Convert to Gauge Pressure:**

Gauge pressure is the pressure relative to atmospheric pressure, so:

$$P_{\text{gauge}} = P_1 - P_{\text{atm}} = 163.499 \text{ kPa} - 101.325 \text{ kPa} = 62.174 \text{ kPa}$$

**Final Answer:**

The required tank pressure (gauge pressure) to achieve the desired exit velocity of 12.1 m/s is **62.174 kPa**.

**Q3.5****3.5 RESEARCH Solar powered Car**

Could a car be built that is continually powered by sunlight (from the photoelectric effect)? (There are currently no resources to make a reliable battery, so the car would only run during daylight). Assuming a 100% efficient solar cell and peak solar irradiance of 1.0 kW/m<sup>2</sup>, what solar panel collection area would be required to provide an engine output power of 150 kW?

Answer for Q3.5

Solar car minimum collection area = [150] m<sup>2</sup>

To determine the required solar panel collection area for a car powered by sunlight using the photoelectric effect, we can use the given parameters and perform the necessary calculations.

**Given Data:**

- **Engine Output Power Required:** 150 kW
- **Peak Solar Irradiance:** 1.0 kW/m<sup>2</sup>
- **Solar Cell Efficiency:** 100% (hypothetical)

**Steps to Calculate the Required Solar Panel Area:**

1. **Calculate the power output per unit area:**
  - Since the solar cell is 100% efficient, the power output per square meter of solar panel is equal to the solar irradiance.
  - Given the solar irradiance of 1.0 kW/m<sup>2</sup>, each square meter of the solar panel can generate 1.0 kW of power.
2. **Determine the total power required:**
  - The engine requires 150 kW of power to operate.
3. **Calculate the required solar panel area:**
  - To find the area required to generate 150 kW of power, divide the total power required by the power generated per square meter:
  - Required Area =  $\frac{\text{Total Power Required}}{\text{Power per unit area}} = \frac{150 \text{ kW}}{\frac{1 \text{ kW}}{\text{m}^2}} = 150 \text{ m}^2$

**Final Answer:**

- **Required Solar Panel Area:** 150 m<sup>2</sup>

**Conclusion:**

Yes, a car could be built that is continually powered by sunlight using the photoelectric effect, provided it operates only during daylight and under optimal conditions. To achieve an engine output power of 150 kW, a solar panel collection area of **150 m<sup>2</sup>** would be required, assuming a hypothetical 100% efficient solar cell and peak solar irradiance of 1.0 kW/m<sup>2</sup>.

In reality, because actual solar cells are less than 100% efficient (typically around 15-22%), the required area would be significantly larger.

### Q3.6

#### 3.6 RESEARCH Internal combustion Engine

A spark-ignition internal combustion engine can be modelled as an Otto thermodynamic cycle (plotted below). The car will carry a lot of weight (armour and supplies) and must traverse rough terrain, so needs at least 150 kW of power. What maximum output power could the design specs below deliver?

Design specs:

Engine volume: 2.4 L

Maximum cylinder pressure: 120 bar

Exhaust pressure: 1.1 bar (just above atmosphere)

RPM: 6000 (maximum)

Compression Ratio: 10

4 stroke engine

6 cylinder engine

The exhaust gases have a polytropic index of 1.4.

Answer for Q3.6

Maximum output power = [166.2] kW

#### Given Data:

- **Engine Volume ( $V_{\text{total}}$ ):** 2.4 L (total for 6 cylinders)
- **Compression Ratio:** 10
- **Maximum RPM:** 6000
- **Number of Cylinders:** 6
- **Pressure 1 ( $P_1$ ):** 4.8 bar = 480 kPa
- **Pressure 2 ( $P_2$ ):** 27.6 bar = 2760 kPa
- **Exhaust Pressure ( $P_{\text{exhaust}}$ ):** 1.1 bar = 110 kPa
- **Polytropic Index ( $\gamma$ ):** 1.4 (for exhaust gases)
- **4-stroke engine**

#### Steps to Calculate Maximum Output Power:

1. **Calculate the Displacement Volume Per Cylinder:**

$$V_{\text{cylinder}} = \frac{V_{\text{total}}}{\text{Number of cylinders}} = \frac{2.4 \text{ L}}{6} = 0.4 \text{ L} = 0.0004 \text{ m}^3$$

2. **Calculate the Mean Effective Pressure (MEP):** The work done per cycle for each cylinder can be approximated using the pressure difference between  $P_2$  and  $P_1$ . The Mean Effective Pressure (MEP) can be calculated as:

$$\text{MEP} = P_{\text{max}} \times [1 - (P_{\text{exhaust}}/P_{\text{max}})^{\gamma - 1}]$$

Substituting the values:

$$\text{MEP} = 2760 \text{ kPa} \times [1 - (110 \text{ kPa} / 2760 \text{ kPa})^{(1.4 - 1/1.4)}]$$

3. **Calculate the Work Done Per Cycle:** The work done per cycle per cylinder is:  
 $W_{\text{cycle}} = \text{MEP} \times V_{\text{swept}} = 1330.32 \text{ kPa} \times 0.0004 \text{ m}^3 = 0.53213 \text{ kJ (per cylinder)}$

4. **Calculate Power Output Per Cylinder:**

- Each cylinder undergoes power strokes at half the engine's RPM (since it's a 4-stroke engine), so:  
 $\text{Power strokes per minute} = 6000 / 2 = 3000 \text{ strokes/min}$
- The power output per cylinder:  
 $P_{\text{cylinder}} = W_{\text{cycle}} \times \text{Power strokes per minute} = 0.53213 \text{ kJ} \times 3000 \text{ strokes/min} = 1596.4 \text{ kJ/min}$
- $P_{\text{cylinder}} = 1596.4 \text{ kJ/min} \times 1/60 \approx 26.61 \text{ kW}$

5. **Total Power Output for 6 Cylinders:**

$$P_{\text{total}} = 26.61 \text{ kW} \times 6 \approx 159.66 \text{ kW}$$

### Q3.7

Pumps are usually designed to move a single liquid phase. If the suction pressure is too low, it will cause cavitation: gas bubbles will enter the pump, which can damage the centrifugal pump vane. The pump suction pressure is 0.5 bar (absolute pressure) so the Antoine equation can be used to calculate the liquid vapour pressure to know if it's safe to run (for a maximum temperature of 40°C).

For the pressure in bar, the light oil Antoine Equation constants are:

A: 4.003

B: 1171 K

C: -48.784 K

Answer for Q3.7

$$\text{Vapour Pressure (maximum)} = [0.372] \text{ Bar (Absolute)}$$

To determine if it's safe to run the pump, we need to calculate the vapor pressure of the light oil at the maximum temperature of 40°C using the Antoine equation. If the vapor pressure of the light oil at this temperature is lower than the suction pressure of 0.5 bar, the pump can be operated safely without the risk of cavitation.



**Given Data:**

- **Suction pressure:** 0.5 bar (absolute)
- **Maximum temperature:** 40°C
- **Antoine equation constants for light oil:**
  - $A = 4.003$
  - $B = 1171 \text{ K}$
  - $C = -48.784 \text{ K}$

**Antoine Equation:**

The Antoine equation is used to calculate the vapor pressure of a substance as a function of temperature:

$$\log_{10}(P) = A - \frac{B}{T+C}$$

Where:

- P is the vapor pressure in bar.
- T is the temperature in degrees Celsius.

**Steps to Calculate Vapor Pressure:**

1. **Convert the temperature to Kelvin:**

$$TK = 40 + 273.15 = 313.15 \text{ K}$$

2. **Substitute the values into the Antoine equation:**

$$\log_{10}(P) = 4.003 - 1171 / (313.15 - 48.784) = -0.426$$

3. **Calculate the vapor pressure:**

$$P = 10^{-0.426} \approx 0.375 \text{ bar}$$

**Conclusion:**

The calculated vapor pressure of the light oil at 40°C is approximately **0.375 bar**.

**Safety Check:**

- **Suction pressure:** 0.5 bar (absolute)
- **Vapor pressure of light oil:** 0.375 bar

Since the vapor pressure of the light oil (0.375 bar) is less than the suction pressure of 0.5 bar, **it is safe to run the pump**. There is a low risk of cavitation under these conditions because the suction pressure is sufficient to keep the light oil in the liquid phase.

**Q3.8****3.8 Level 3 Red Science: Thermodynamics Pack**

Use a mass balance (see mass and energy balance) to determine the mass of carbon dioxide produced at steady state from the boiler furnace below, if coal is fed in at a rate of 100 kg/hr. Incombustible solids in the thermal coal leaves as a residual ash from the bottom of the furnace.

Answer for Q3.8

Mass flowrate of carbon dioxide = [330] kg/hr

Given that the coal is 100% pure carbon, let's simplify the calculation for the mass of carbon dioxide (CO<sub>2</sub>) produced at steady state.

**Given Data:**

- **Coal feed rate:** 100 kg/hr (pure carbon)
- **Oxygen inlet:** 240 kg/hr
- **Ash production:** 10 kg/hr (assuming this is unburned carbon, which will be subtracted from the total carbon mass)

**Steps to Solve:**

1. **Determine the mass of carbon that is combusted:**
  - Since the ash production is 10 kg/hr, this implies that 10 kg/hr of the carbon does not combust and is left as residual ash.
  - The mass of carbon that combusts:  
 $\text{Mass of C combusted} = 100 \text{ kg/hr} - 10 \text{ kg/hr} = 90 \text{ kg/hr}$
2. **Combustion Reaction:** The combustion reaction for pure carbon is:  
 $\text{C} + \text{O}_2 = \text{CO}_2$

The molar masses are:

- Carbon (C): 12 g/mol
- Oxygen (O<sub>2</sub>): 32 g/mol
- Carbon dioxide (CO<sub>2</sub>): 44 g/mol

From the stoichiometry of the reaction, 1 mole of carbon produces 1 mole of carbon dioxide.

3. **Calculate the moles of carbon combusted:**

Moles of C =  $90 \text{ kg/hr} / 12 \text{ g/mol} = 90000 \text{ g/hr} / 12 \text{ g/mol} = 7500 \text{ mol/hr}$

4. **Determine the moles of CO<sub>2</sub> produced:** Since 1 mole of carbon produces 1 mole of carbon dioxide:

Moles of CO<sub>2</sub> = Moles of C = 7500 mol/hr

5. **Calculate the mass of CO<sub>2</sub> produced:**

Mass of CO<sub>2</sub> = Moles of CO<sub>2</sub> × Molar mass of CO<sub>2</sub> =  $7500 \text{ mol/hr} \times 44 \text{ g/mol} = 330000 \text{ g/hr} = 330 \text{ kg/hr}$

**Final Answer:**

The mass of carbon dioxide (CO<sub>2</sub>) produced at steady state from the boiler furnace, when pure carbon coal is fed at a rate of 100 kg/hr and 10 kg/hr of residual ash is left, is **330 kg/hr**.

Q4.0

#### 4.0 Steam Engine

##### Thermal Efficiency: Steam Engine

This steam engine has been designed like the first locomotives: steam drives a piston but then vents directly to the atmosphere, as an open system. So a lot of energy (enthalpy) is emitted with the steam and the boiler water must be continuously replenished.

The thermal efficiency of this design can be determined by completing a mass and energy balance around the steam engine to determine the useful work extracted by the turbine, relative to the input energy from the coal (1kg of coal releases 20 MJ of thermal energy).

Answer for Q4.0

Thermal Efficiency = [1.4] %

The thermal efficiency = useful work / heat supplied (20 MJ)

Total work =  $2714 * 5.96 - 2616 * 5.96 - 50 * 5.96 = 286.08 \text{ kJ}$

Efficiency =  $286.08 / 20000 = 0.014$

Times 100% is 1.4%

Q4.1

#### 4.1 RESEARCH Steam Engine level 2

Open-system steam engines have a very low thermal efficiency as a lot of energy is lost with the steam outlet (1.4% thermal efficiency for the level 1 steam engine).

Condensing the steam in a heat exchanger and recycling it back to the boiler (a closed system) can increase the electricity generated per kilogram of coal feed (and also reduce water consumption). Condensing the steam can also reduce the pressure at the steam engine outlet, which can further improve efficiency. Determine the thermal efficiency of the closed system heat engine. One kg of coal produces 20 MJ of energy.

Answer for Q4.1

Thermal Efficiency = [2.96] %

Same as Q4.0 The thermal efficiency = useful work / heat supplied (20 MJ)

Total waste work =  $50 * 6.58 + 13 * 295 + 2319 * 6.58 = 19423.02 \text{ kJ}$

Efficiency =  $19423.02 \text{ kJ} / 20000 = 0.9711$

Useful work efficiency=1-0.9711=0.0288. which is 2.88%

#### Q4.2

##### 4.2 RESEARCH Boiler Level 2: Economizer

In the current boiler design, flue gas leaves the system at 300°C, which wastes a lot of energy. The thermal efficiency could be boosted by using this stream to pre-heat the boiler feed water with an economizer, a type of heat exchanger. This would lower the flue gas outlet temperature and produce more steam, to generate more power.

Cooling the flue gas below 150°C causes acid gases to condense, which corrodes the carbon steel piping. So the flue gas must be kept above a minimum of 160°C as a safety margin. This boosts steam production from 6.58 to 7.36 kg steam / kg coal feed and improves the overall thermal efficiency from 2.96% to 3.31% (a 10%+ boost).

To design the economizer the heat transfer area must be determined (to size the economizer) which can be calculated from Fourier's law. Assume a counter-current flow profile (to optimize performance) and an overall heat transfer coefficient of 0.1 kW/m<sup>2</sup>K, for a coal feed rate of 1kg/s.

Answer for Q4.2

Economizer heat transfer area = [165.5] m<sup>2</sup>

Fourier's law,  $Q = U A \text{LMTD}$ . Log-mean temperature difference

$$Q = 255.8 \times 7.36 = 1882.688 \text{ kJ}$$

$$\text{fluid difference at inlet} = 300 - 141.1 = 158$$

$$\text{fluid difference at outlet} = 160 - 78.08 = 81.92$$

$$\text{LMTD} = \frac{\Delta T_A - \Delta T_B}{\ln(\Delta T_A / \Delta T_B)} = \frac{158 - 81.92}{\ln 158 - \ln 81.92} = 116.2$$

$$A = Q / (U \times \text{LMTD}) = 1882.688 / (0.1 \times 116.2) = 162.02 \text{ m}^2$$

#### Q4.3

##### 4.3 RESEARCH: Atmospheric carbon dioxide scrubber

A scrubber is a unit that captures carbon dioxide from air or flue gas. It can then concentrate the carbon dioxide for sequestration (underground storage) to remove it from the atmosphere.

Could the atmospheric air be scrubbed to remove carbon dioxide?

Air contains 79 vol% nitrogen, 21 vol% oxygen and 0.041 vol% carbon dioxide (and other trace gases). This makes the mass concentration of carbon dioxide in air: 0.806 g CO<sub>2</sub> / m<sup>3</sup> air. What is the minimum volume of bulk air that must be processed to collect 1kg of carbon dioxide (equivalent to burning about 0.25 kg coal)?

Answer for Q4.3

Minimum volume of air required = [1240] m<sup>3</sup>

To determine the minimum volume of atmospheric air that must be processed to collect 1 kg of carbon dioxide (CO<sub>2</sub>), we can use the given mass concentration of CO<sub>2</sub> in air.

**Given Data:**

- **Mass concentration of CO<sub>2</sub> in air:** 0.806 g CO<sub>2</sub>/m<sup>3</sup> air
- **Target mass of CO<sub>2</sub> to collect:** 1 kg = 1000 g

**Calculation Steps:**

1. **Determine the volume of air needed to collect 1 kg of CO<sub>2</sub>:**
  - We need to find the volume of air (V<sub>air</sub>) that contains 1000 g of CO<sub>2</sub>.
  - Use the mass concentration of CO<sub>2</sub> to set up the equation:
  - $V_{\text{air}} = \text{Mass of CO}_2 / \text{Mass concentration of CO}_2 \text{ in air}$

2. **Calculate the volume of air required:**

$$V_{\text{air}} = 1000\text{g} / 0.806\text{g/cm}^3 = 1240.2\text{m}^3$$

**Final Answer:**

The minimum volume of bulk air that must be processed to collect 1 kg of carbon dioxide is approximately **1240.2 cubic meters** of air.

This means that to capture 1 kg of CO<sub>2</sub> from the atmosphere, a scrubber would need to process at least 1240.2 m<sup>3</sup> of air.

#### Q4.4

#### 4.4 RESEARCH Amine Scrubber

Carbon dioxide is highly soluble in alkylamine solutions (amines) where other flue gases are not (nitrogen, oxygen, water) so amines can be used in a scrubber. The blast furnace could be redesigned with amine gas treatment unit but it would need to be sized.

The mass transfer is gas phase limited, so Fick's first law can be used to determine the unit's volume. I could calculate the mass transfer flux at the inlet (the maximum flux) and then use that to size a minimum required volume for the unit.

Key parameters to determine the mass flux are:

- ☐ Inlet flue gas concentration of CO<sub>2</sub>: 260 g CO<sub>2</sub>/m<sup>3</sup> flue gas
- ☐ Diffusivity of carbon dioxide in the flue gas: 16 mm<sup>2</sup>/sec
- ☐ Gas phase boundary layer thickness: 0.5 mm

For this this mass flux, the key parameters to size the scrubber (determine the required active volume) are:

- ☐ Flowrate of flue gas: 15 m<sup>3</sup>/sec (constant)
- ☐ 90% removal CO<sub>2</sub>
- ☐ Specific surface area packing: 100 m<sup>2</sup>/m<sup>3</sup>

(The CO<sub>2</sub> concentration will drop as it moves through the scrubber so this represents a minimum size).

Answer for Q4.4

Mass transfer flux = [8.32] g/m<sup>2</sup> sec

Active volume of Amine Unit = [4.2] m<sup>3</sup>

To determine the required volume of the scrubber using Fick's first law and the provided data, we'll proceed step by step.

#### **Step 1: Calculate the Mass Transfer Flux**

Fick's first law describes the mass transfer flux  $J$  as:

$$J = -D * \frac{dC}{dx}$$

Where:

- J is the mass transfer flux (in kg/m<sup>2</sup>·s).
- D is the diffusivity of the gas (in m<sup>2</sup>/s).
- dC/dx is the concentration gradient across the boundary layer.

Given Data:

- **Inlet CO<sub>2</sub> concentration:** C<sub>in</sub>=260 g/m<sup>3</sup>=260g/m<sup>3</sup> = 0.26 kg/m<sup>3</sup>
- **Diffusivity of CO<sub>2</sub> in flue gas:** D=16 mm<sup>2</sup>/s=16×10<sup>-6</sup>m<sup>2</sup>/s
- **Gas phase boundary layer thickness:** dx=0.5 mm=0.5×10<sup>-3</sup>m

The concentration gradient dC/dx=0.26kg/m<sup>3</sup>/0.5×10<sup>-3</sup>m =520kg/m<sup>4</sup>

Now, calculate the mass transfer flux J:

$$J = -D \cdot dC/dx = -16 \times 10^{-6} \text{ m}^2/\text{s} \times 520 \text{ kg/m}^4 = -8.32 \times 10^{-3} \text{ kg/m}^2 \cdot \text{s}$$

The negative sign indicates the direction of the mass transfer (from high concentration to low concentration), but for sizing purposes, we use the magnitude.

#### Step 2: Determine the Required Active Volume of the Scrubber

The total mass of CO<sub>2</sub> that needs to be removed per second (m<sup>3</sup>·CO<sub>2</sub>) can be calculated based on the flow rate of flue gas and the desired 90% removal efficiency:

**Initial mass flow rate of CO<sub>2</sub>=C<sub>in</sub>×Flow rate of flue gas**

$$m^{\circ}\text{CO}_2, \text{in} = 0.26 \text{ kg/m}^3 \times 15 \text{ m}^3/\text{s} = 3.9 \text{ kg/s}$$

Since 90% of the CO<sub>2</sub> needs to be removed:

$$m^{\circ}\text{CO}_2, \text{removed} = 0.9 \times 3.9 \text{ kg/s} = 3.51 \text{ kg/s}$$

#### Step 3: Calculate the Surface Area Required

The surface area required for the mass transfer can be calculated as:

$$A = m^{\circ}\text{CO}_2, \text{removed} / J = 3.51 \text{ kg/s} / 8.32 \times 10^{-3} \text{ kg/m}^2 \cdot \text{s} \approx 421.03 \text{ m}^2$$

#### Step 4: Calculate the Required Volume of the Scrubber

The required volume V of the scrubber can be determined using the specific surface area packing:

$$V = A / \text{Specific surface area packing} = 421.03 \text{ m}^2 / 100 \text{ m}^2/\text{m}^3 = 4.21 \text{ m}^3$$

#### Final Answer:

Mass transfer flux = [8.32] g/m<sup>2</sup> sec

Active volume of Amine Unit = [4.2] m<sup>3</sup>

#### Q4.5

##### 4.5 RESEARCH Activated Carbon Scrubber

Carbon based molecules (like carbon dioxide) tend to adsorb (stick) to solid carbon while other flue gas molecules do not. Coal/charcoal that has been activated (increased surface area) provides a lot of sites for adsorption and can be used as a scrubber. The boiler could be redesigned with an activated carbon filter on the flue gas line.

The pore size in the activated carbon is 50nm (smaller than the mean free path of carbon dioxide) so Knudsen diffusion can describe the diffusivity. Fick's first law could then be used to size the unit, assuming the flue gas flowrate is constant (conservative assumption) with the following information:

Determine the Knudsen diffusivity (in mm<sup>2</sup>/sec)

- ☐ Flue gas temperature: 150°C
- ☐ Molar mass carbon dioxide: 0.044 kg/mol
- ☐ Activated carbon pore size: 50 nm

Answer for Q4.5

Knudsen Diffusivity = [7.5] mm<sup>2</sup>/sec

To determine the Knudsen diffusivity, we need to use the formula for Knudsen diffusion. Knudsen diffusivity is significant when the pore size of the medium is smaller than the mean free path of the gas molecules. The formula for Knudsen diffusivity  $D_K$  is given by:

$$D_K = \frac{2}{3} * \frac{r_{pore} * \sqrt{\frac{8RT}{\pi M}}}{1000}$$

Where:

- $r_{pore}$  is the pore radius in meters (half the pore size).
- $R$  is the universal gas constant ( $R=8.314$  J/molK).
- $T$  is the absolute temperature in Kelvin.
- $M$  is the molar mass of the gas in kg/mol.
- The factor of 1000 converts the diffusivity from m<sup>2</sup>/s to mm<sup>2</sup>/s.

#### Step 1: Convert and Calculate Parameters

##### 1. Pore Radius:

- Given pore size = 50 nm =  $50 \times 10^{-9}$  m.
- Therefore, pore radius  $r_{pore} = 50 \times 10^{-9} / 2 = 25 \times 10^{-9}$  m.

##### 2. Temperature:

- Given temperature  $T = 150^\circ\text{C}$ .
- Convert to Kelvin:  $T = 150 + 273.15 = 423.15$  K.

##### 3. Molar Mass of CO<sub>2</sub>:

- Given molar mass  $M = 0.044$  kg/mol.

#### Step 2: Calculate the Knudsen Diffusivity

Substitute the values into the Knudsen diffusivity equation:

$$D_K = \frac{2}{3} * \frac{25 * 10^{-9} * \sqrt{\frac{8 * 8.314 * 423.15}{\pi * 0.044}}}{1000} = \frac{7.52 \text{ mm}^2}{\text{s}}$$

**Final Answer:**



The Knudsen diffusivity  $DK$  of carbon dioxide through the activated carbon pores is approximately **7.52 mm<sup>2</sup>/s**.

Q4.6

#### 4.6 RESEARCH: Solar Panel

A solar cell converts the energy of light into electricity via the photoelectric effect. To know if the solar panel can provide sufficient power, it's necessary to calculate the peak electrical output for these design specs:

Each solar cell is a monocrystalline silicone square with side length of 3.54 m

A solar panel will contain 24 solar cells (4 rows of 6 cells)

Efficiency: 20%

Performance Ratio: 0.95

Tilt correction: 1.0 (panel is perpendicular to light incident angle at peak output)

Peak solar irradiance (energy flux) at planet surface on cloudless day: 1.0 kW/m<sup>2</sup>

Answer for Q4.6

Peak output power = [60.2] kW

To calculate the peak electrical output of the solar panel given the design specifications, we can follow these steps:

##### **Given Data:**

- **Side length of each solar cell:** 3.54 m
- **Number of solar cells in the panel:** 24 (4 rows of 6 cells)
- **Efficiency of solar cells:** 20% (0.20)
- **Performance Ratio:** 0.95
- **Tilt correction:** 1.0
- **Peak solar irradiance:** 1.0 kW/m<sup>2</sup>

##### **Step 1: Calculate the Area of a Single Solar Cell**

Each solar cell is a square with a side length of 3.54 m. The area  $A_{\text{cell}}$  of one solar cell is:

$$A_{\text{cell}} = \text{side length}^2 = 3.54 \text{ m} \times 3.54 \text{ m} = 12.5316 \text{ m}^2$$

##### **Step 2: Calculate the Total Area of the Solar Panel**

Since the panel contains 24 solar cells, the total area  $A_{\text{total}}$  of the solar panel is:

$$A_{\text{total}} = 24 \times A_{\text{cell}} = 24 \times 12.5316 \text{ m}^2 = 300.7584 \text{ m}^2$$

### Step 3: Calculate the Raw Power Output

The raw power output  $P_{\text{raw}}$  from the solar panel, based on the peak solar irradiance, is:

$$P_{\text{raw}} = A_{\text{total}} \times \text{Solar irradiance} = 300.7584 \text{ m}^2 \times 1.0 \text{ kW/m}^2 = 300.7584 \text{ kW}$$

### Step 4: Adjust for Efficiency and Performance Ratio

The actual power output  $P_{\text{output}}$  is the raw power output adjusted for the efficiency of the solar cells and the performance ratio:

$$P_{\text{output}} = P_{\text{raw}} \times \text{Efficiency} \times \text{Performance Ratio} \times \text{Tilt Correction}$$

Substitute the values:

$$P_{\text{output}} = 300.7584 \text{ kW} \times 0.20 \times 0.95 \times 1.0 = 57.144 \text{ kW}$$

### Final Answer:

The peak electrical output of the solar panel is **57.144 kW**.

Q4.7

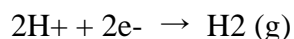
4.7 RESEARCH: Hydrogen green steel

Iron ore can be reduced using hydrogen (instead of carbon from coal) so it produces water as a byproduct (rather than carbon dioxide). It occurs in a 2 step process:

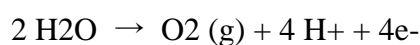
Step 1 Electrolysis of Water:

Water is electrolyzed to produce hydrogen and oxygen.

At the negatively charged cathode, the half reaction is:



At the positively charged anode the half reaction is:

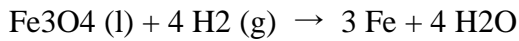


Giving an overall reaction of:



Step 2 Reduction of Iron ore:

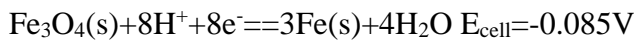
The hydrogen is then used to directly reduce the iron ore according to the overall reaction:



Assuming standard conditions for the electrolysis (so the standard electrode potentials are appropriate) and the reaction stoichiometry is optimized for hydrogen and iron ore, the Gibbs free energy can be used to calculate the theoretical electricity requirements for the 2 step process to produce 458 kg/hr of iron. The molar mass of iron is 55.84 g/mol.

Answer for Q4.7

Theoretical energy requirement = [180.3] kW



$$\Delta G = - n_{\text{electrons}} F_o E_{\text{cell}}$$

E is know by looking with the electrical potential which is -0.085v

$$F = 96485\text{C/mol}$$

Mole number of electrons can be calculated by using iron

$$458\text{kg/hr} / 55.84\text{kg/kmol} = 8.2\text{kmol/hr} = 8200\text{mol/hr (pure iron)}$$

$$\text{Number of electron is } 8200 / 3 * 8 = 21866\text{mole}$$

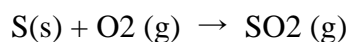
$$\Delta G = - n_{\text{electrons}} F_o E_{\text{cell}} = 21866 * 96485 * -0.085 = 179333453\text{J} = 180\text{MJ}$$

Q4.8

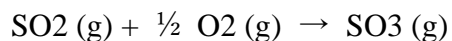
#### 4.8 RESEARCH: Sulphuric Acid

Sulphuric acid can be produced via the wet sulphuric acid process in 3 steps:

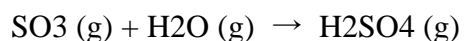
##### 1. Sulphur Combustion:



##### 2. Sulphur dioxide oxidation (over a vanadium oxide catalyst):



##### 3. Hydration:



The sulphuric acid is then cooled and condensed into a liquid phase.

This reactor has a shortage of the vanadium oxide catalyst and so the second reaction has become the rate limiting step (sulphur dioxide oxidation). The overall reaction speed is limited by the fixed number of active sites on the catalyst surface and so the reaction rate collapses to zero order (independent of reactant concentrations):

$$-\frac{dC_{\text{SO}_2}}{dt} = 51.2 \text{ mol/(m}^3 \text{ s)}$$

The reactor is in an isothermal plug flow configuration with a reactor volume of 3.04 m<sup>3</sup>. The molar mass of SO<sub>2</sub> is 64.1 g/mol and for sulphur (S) is 32.1 g/mol.

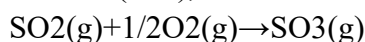
The reaction kinetics and reaction stoichiometry can be used to determine the maximum feed rate of sulphur, assuming 100% conversion all reactions.

Answer for Q4.8

Feed rate of sulphur = [5] kg/s

### Step 1: Understanding the Rate-Limiting Step

The rate-limiting step in this process is the oxidation of sulfur dioxide (SO<sub>2</sub>) to sulfur trioxide (SO<sub>3</sub>), which is described by the reaction:



Given that the reaction rate is zero-order with respect to the reactant concentrations due to the shortage of the vanadium oxide catalyst, the rate of the reaction is constant:

$$-d\text{CSO}_2/dt = 51.2 \text{ mol/m}^3 \cdot \text{s}$$

### Step 2: Reactor Configuration

The reactor is a plug flow reactor with a volume of 3.04 m<sup>3</sup>. In a plug flow reactor with a zero-order reaction, the rate of consumption of the reactant (SO<sub>2</sub>) is constant throughout the reactor.

### Step 3: Calculate the Rate of Sulfur Dioxide Consumption

The rate of SO<sub>2</sub> consumption is given by:

$$\text{Rate of SO}_2 \text{ consumption} = 51.2 \text{ mol/m}^3 \cdot \text{s}$$

The total consumption of SO<sub>2</sub> in the reactor (given by the product of the reaction rate and the reactor volume) is:

$$\text{Total SO}_2 \text{ consumption per second} = 51.2 \times 3.04 \text{ mol/s} = 155.648 \text{ mol/s}$$

### Step 4: Determine the Stoichiometry of the Process

From the reaction stoichiometry:

- $\text{S} + \text{O}_2 \rightarrow \text{SO}_2$
- $\text{SO}_2 + 1/2\text{O}_2 \rightarrow \text{SO}_3$
- $\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4$

For every 1 mole of sulfur (S) fed into the system, 1 mole of SO<sub>2</sub> is produced, which in turn leads to the production of 1 mole of SO<sub>3</sub>, and subsequently 1 mole of H<sub>2</sub>SO<sub>4</sub>.

### Step 5: Maximum Sulfur Feed Rate

Since the rate of SO<sub>2</sub> consumption is 155.648 mol/s, and 1 mole of sulfur produces 1 mole of SO<sub>2</sub>:

$$\text{Maximum sulfur feed rate} = 155.648 \text{ mol/s}$$

### Step 6: Convert Moles of Sulfur to Mass

The molar mass of sulfur (S) is 32.1 g/mol, so:

$$\text{Maximum sulfur feed rate (in grams per second)} = 155.648 \times 32.1 \text{ g/s} = 4992.29 \text{ g/s} = 4.992 \text{ kg/s}$$

Q4.9

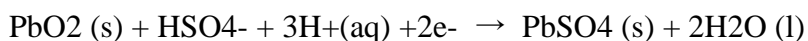
#### 4.9 RESEARCH Galvanic cell

Sulphuric acid and lead(IV) oxide can be used to make an electrochemical cell (a component for a rechargeable battery/accumulator). In a lead-acid battery, the two half-reactions can be written as:

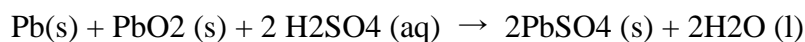
Negative plate (anode) half reaction:



Positive plate (cathode) half reaction:



So the overall reaction can be written as:



The standard electrode potential list can be used to determine the theoretical output voltage from a single cell at standard conditions.

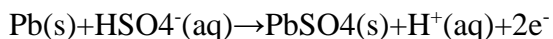
Answer for Q4.9

Standard theoretical output voltage,  $E_{\text{cell}} = [2.05] \text{ V}$

#### Step 1: Identify the Half-Reactions and Their Standard Electrode Potentials

For the lead-acid battery, the half-reactions and their standard electrode potentials ( $E^\ominus$ ) are:

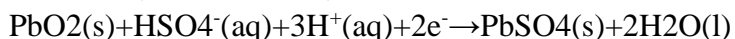
##### Anode (Negative Plate) Half-Reaction:



The standard electrode potential for this half-reaction is typically around:

$$E_{\text{anode}} = -0.356 \text{ V}$$

##### Cathode (Positive Plate) Half-Reaction:



The standard electrode potential for this half-reaction is typically around:

$$E_{\text{cathode}} = +1.685 \text{ V}$$

**Step 2: Calculate the Cell Potential**

The standard cell potential ( $E_{\text{cell}}$ ) is calculated using the following formula:

$$E_{\text{cell}} = E_{\text{cathode}} - E_{\text{anode}}$$

Substituting the values:

$$E_{\text{cell}} = 1.685 \text{ V} - (-0.356 \text{ V}) = 1.685 \text{ V} + 0.356 \text{ V} = 2.041 \text{ V}$$

Q4.10

4.10 RESEARCH Battery

Multiple galvanic cells can be connected together to make a battery/accumulator. Each cell delivers 2.05 V but the battery needs an arrangement that can create a 12V potential (car battery voltage) and then maximizes the capacity of the arrangement. Utilizing 12 galvanic cells, there are a number of possible configurations:

Answer for Q4.10

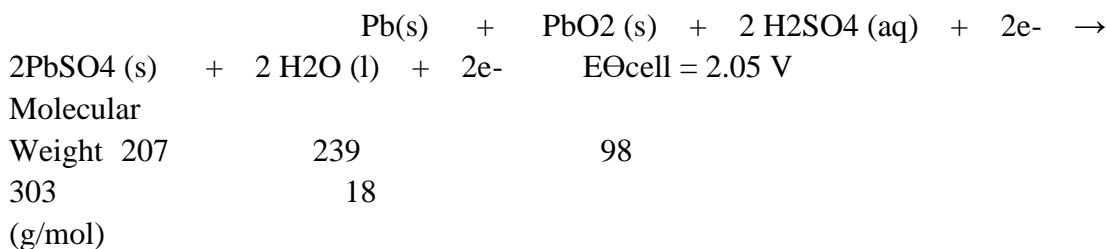
Arrangement that delivers 12+ V and maximizes capacity = configuration [2]

In a parallel circuit, the voltage across each electrical appliance is equal, which is one of the basic characteristics of a parallel circuit. In a parallel circuit, the total voltage is equal to the voltage of each parallel branch, because the two ends of the parallel branch are directly connected to the two poles of the power supply, so each branch is subjected to the same voltage. In a series circuit, the total voltage is equal to the sum of the voltages of the individual components. So Configuration 2 create  $6 \times 2.05 = 12V$  the most related one.



#### 4.11 RESEARCH Accumulator

To build a large battery/accumulator for energy storage the mass of constituent materials must be known (lead, lead oxide and sulphuric acid). For a battery with a storage capacity of 5MJ, the Gibbs Free Energy can be calculated to estimate the minimum mass of reactant required (Pb, PbO<sub>2</sub> and H<sub>2</sub>SO<sub>4</sub>).



Answer for Q4.11

Theoretical reactant mass = [8.1] kg

#### Step 1: Calculate the Number of Moles of Electrons

First, calculate the amount of energy stored per mole of electrons transferred in the cell reaction using the Gibbs free energy change ( $\Delta G$ ) formula:

$$\Delta G = -nFE_{\text{cell}}$$

Where:

- $\Delta G$  is the Gibbs free energy change
- $n$  is the number of moles of electrons transferred (which is 2 for this reaction)
- $F$  is the Faraday constant (96,485 C/mole)
- $E_{\text{cell}}$  is the cell potential (2.05 V)

Calculate the Gibbs free energy change per mole of electrons:

$$\Delta G = -2 \times 96,485 \text{ C/mol} \times 2.05 \text{ V} = -395,586.5 \text{ J/mol}$$

This is the energy associated with one mole of the cell reaction.

#### Step 2: Calculate the Total Number of Moles of Electrons Required

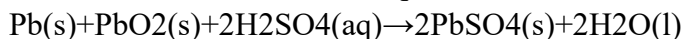
Given that the battery's total storage capacity is 5 MJ (5,000,000 J):

$$\text{Total number of moles of electrons} = \text{Total energy} / \Delta G$$

$$\text{Total number of moles of electrons} = 5,000,000 \text{ J} / 395,586.5 \text{ J/mol} = 12.64 \text{ mol}$$

#### Step 3: Relate the Number of Moles to the Mass of Reactants

From the balanced chemical equation:



For every 2 moles of electrons (12.64 mol in total), the following reactant amounts are required:

- 1 mole of Pb
- 1 mole of PbO<sub>2</sub>
- 2 moles of H<sub>2</sub>SO<sub>4</sub>

For 12.64 moles of electrons, the corresponding moles of reactants are:

- 12.64 moles of Pb

- 12.64 moles of PbO<sub>2</sub>
- 25.28 moles of H<sub>2</sub>SO<sub>4</sub>

#### Step 4: Calculate the Mass of Each Reactant

Now calculate the mass of each reactant using their molar masses:

Mass of Pb = 12.64 mol × 207 g/mol = 2616.48 g = 2.62 kg

Mass of PbO<sub>2</sub> = 12.64 mol × 239 g/mol = 3,019.36 g = 3.02 kg

Mass of H<sub>2</sub>SO<sub>4</sub> = 25.28 mol × 98 g/mol = 2,477.44 g = 2.48 kg

**By add the together we get the number of 8.12kg**

Q4.12

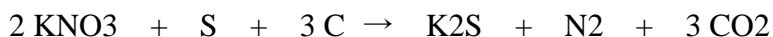
#### 4.12 RESEARCH Explosives

Gunpowder is a mixture of sulphur, carbon (coal or charcoal) and potassium nitrate.

When ignited, it will deflagrate (burn at a very high rate) and so act like an explosive

charge: the potassium nitrate acts as an oxidant, so the reaction speed isn't limited by an oxygen supply rate.

The reaction stoichiometry for the combustion of gunpowder can be simplified to:



To set appropriate charge sizes, the standard enthalpy of reaction should be calculated to determine the energy released per kilogram at standard conditions (assuming stoichiometric ratios for the gunpowder).

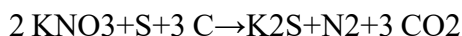
Formula	Name	Standard heat of formation kJ/mol	Molecular Weight g/mol
KNO <sub>3</sub>	Potassium Nitrate	-490	101.1
S	Sulphur	0	32.1
C	Carbon (Coal/Charcoal)	0	12.01
K <sub>2</sub> S	Potassium sulphide	-406	110.26
N <sub>2</sub>	Nitrogen	0	28
CO <sub>2</sub>	Carbon dioxide	-393.5	44

Answer for Q4.12

Energy released (at standard conditions) = [2.25] MJ per kg of gunpowder (correct if - 2.25 as well)

### Step 1: Write the Balanced Reaction

The balanced reaction for the combustion of gunpowder is:



### Step 2: Determine the Standard Enthalpy of Reaction ( $\Delta H_{\text{rxn}}$ )

The standard enthalpy of reaction can be calculated using the heats of formation ( $\Delta H_f^\circ$ ) of the reactants and products:

$$\Delta H_{\text{rxn}}^\circ = \sum \Delta H_f^\circ(\text{products}) - \sum \Delta H_f^\circ(\text{reactants})$$

Given the heats of formation:

- $\Delta H_f^\circ$  of  $\text{KNO}_3 = -490 \text{ kJ/mol}$
- $\Delta H_f^\circ$  of  $\text{S} = 0 \text{ kJ/mol}$  (element in its standard state)
- $\Delta H_f^\circ$  of  $\text{C} = 0 \text{ kJ/mol}$  (element in its standard state)
- $\Delta H_f^\circ$  of  $\text{K}_2\text{S} = -406 \text{ kJ/mol}$
- $\Delta H_f^\circ$  of  $\text{N}_2 = 0 \text{ kJ/mol}$  (element in its standard state)
- $\Delta H_f^\circ$  of  $\text{CO}_2 = -393.5 \text{ kJ/mol}$

### Step 3: Calculate the Standard Enthalpy of Reaction

$$\Delta H_{\text{rxn}}^\circ = [\Delta H_f^\circ(\text{K}_2\text{S}) + \Delta H_f^\circ(\text{N}_2) + 3 \times \Delta H_f^\circ(\text{CO}_2)] - [2 \times \Delta H_f^\circ(\text{KNO}_3) + \Delta H_f^\circ(\text{S}) + 3 \times \Delta H_f^\circ(\text{C})]$$

Substitute the values:

$$\Delta H_{\text{rxn}}^\circ = [(-406 \text{ kJ/mol}) + (0 \text{ kJ/mol}) + 3 \times (-393.5 \text{ kJ/mol})] - [2 \times (-490 \text{ kJ/mol}) + (0 \text{ kJ/mol}) + 3 \times (0 \text{ kJ/mol})] = [-406 - 1180.5] - [-980] = -1586.5 + 980 = -606.5 \text{ kJ/mol}$$

This value represents the energy released per mole of the reaction.

### Step 4: Calculate the Molar Mass of the Gunpowder Mixture

Next, calculate the molar mass of the entire mixture:

$$\text{Molar mass of gunpowder} = 2 \times \text{Molar mass of KNO}_3 + \text{Molar mass of S} + 3 \times \text{Molar mass of C}$$
$$\text{Molar mass of gunpowder} = 2 \times 101.1 \text{ g/mol} + 32.1 \text{ g/mol} + 3 \times 12.01 \text{ g/mol}$$

$$\text{Molar mass of gunpowder} = 202.2 + 32.1 + 36.03 = 270.33 \text{ g/mol} = 270.33 \text{ g/mol}$$

### Step 5: Calculate the Energy Released per Kilogram

Convert the energy per mole to energy per kilogram:

$$\text{Energy per kilogram} = -606.5 \text{ kJ/mol} / 270.33 \text{ g/mol} \times 1000 \text{ g/kg} \approx -2243.68 \text{ kJ/kg} = 2.243 \text{ MJ/kg}$$

4.13

#### 4.13 RESEARCH Microprocessor

Microprocessor chips should be kept within 20°C of ambient conditions to improve performance. This microprocessor chip design has an area of 18 cm<sup>2</sup> and generates a maximum of 15 W of heat.

Fourier's law may be used to determine the heat transfer coefficient to know if the chips should be cooled with air (free convection or forced fan) or requires pumped liquid coolant.

Type of cooling    Heat transfer coefficient (U)  
W/m<sup>2</sup> K

Air, free convection    2.5-25

Air, fan forced convection    10-500

Liquid, pumped circulation    100-15,000

Answer for Q4.13

Required heat transfer coefficient = [417] W/m<sup>2</sup>K

#### **Given:**

- Area of the microprocessor chip,  $A = 18 \text{ cm}^2 = 0.0018 \text{ m}^2$
- Maximum heat generation,  $Q = 15 \text{ W}$
- Maximum allowable temperature difference between the chip and ambient conditions,  $\Delta T = 20^\circ\text{C}$

#### **Fourier's Law of Heat Conduction:**

Fourier's law in the context of convective heat transfer is given by:

$$Q = U \cdot A \cdot \Delta T$$

Where:

- $Q$  is the heat transfer rate (15 W)
- $U$  is the heat transfer coefficient (to be determined)
- $A$  is the area of the surface through which heat is being transferred (0.0018 m<sup>2</sup>)

- $\Delta T$  is the temperature difference ( $20^{\circ}\text{C}$ )

### Step 1: Calculate the Required Heat Transfer Coefficient

Rearrange the equation to solve for U:

$$U = Q / (A \cdot \Delta T)$$

Substitute the given values:

$$U = 15 \text{ W} / (0.0018 \text{ m}^2 \times 20 \text{ K}) = 15 / 0.036 \text{ W/m}^2\text{K} = 416.67 \text{ W/m}^2\text{K}$$

### Step 2: Compare with Cooling Methods

Now, compare the calculated heat transfer coefficient with the ranges provided for different cooling methods:

- **Air, free convection:**  $2.5\text{--}25 \text{ W/m}^2\cdot\text{K}$
- **Air, fan forced convection:**  $10\text{--}500 \text{ W/m}^2\cdot\text{K}$
- **Liquid, pumped circulation:**  $100\text{--}15,000 \text{ W/m}^2\cdot\text{K}$

### Conclusion:

The required heat transfer coefficient U is  **$416.67 \text{ W/m}^2\cdot\text{K}$** .

- **Free convection with air:** U is too high, so this method would not be effective.
- **Forced convection with air (using a fan):** The calculated U falls within the range ( $10\text{--}500 \text{ W/m}^2\cdot\text{K}$ ), meaning this method could be suitable for cooling the microprocessor.
- **Pumped liquid coolant:** This method would work, as the heat transfer coefficient range is much higher ( $100\text{--}15,000 \text{ W/m}^2\cdot\text{K}$ ), but it might be over-engineering for this situation.

**Recommendation:** A forced convection cooling system using air (with a fan) would be sufficient to keep the microprocessor within the required temperature limits, given that the required heat transfer coefficient falls within the range for this method.

Q4.14

### 4.14 RESEARCH Landfill

Random loose packing has a void fraction of 0.46 (fraction of space that is empty between stones or other packing like Raschig rings in a scrubber).

Stone has a density of  $2.6 \text{ tonnes/m}^3$ . Determine the mass of stone that would be required to make  $1 \text{ m}^3$  of landfill assuming the stone packing is in a random loose packing structure.

Answer for Q4.14

Mass of stone =  $[1.40] \text{ tonnes}$

### Given:

- Void fraction ( $\epsilon$ ) = 0.46

- Density of stone ( $\rho$ ) = 2.6 tonnes/m<sup>3</sup>
- Volume of the landfill = 1 m<sup>3</sup>

**Step 1: Determine the Solid Fraction**

The solid fraction is the fraction of the volume that is occupied by the stone. It can be calculated as:

$$\text{Solid fraction} = 1 - \text{Void fraction} = 1 - 0.46 = 0.54$$

**Step 2: Calculate the Volume of Stone**

The volume of stone in 1 m<sup>3</sup> of landfill is:

$$\text{Volume of stone} = \text{Solid fraction} \times \text{Total volume} = 0.54 \times 1 \text{ m}^3 = 0.54 \text{ m}^3$$

**Step 3: Calculate the Mass of Stone**

The mass of the stone can be determined by multiplying the volume of the stone by its density:

$$\begin{aligned} \text{Mass of stone} &= \text{Volume of stone} \times \text{Density of stone} \\ &= 0.54 \text{ m}^3 \times 2.6 \text{ tonnes/m}^3 = 1.404 \text{ tonnes} \end{aligned}$$

Q4.15

4.15 RESEARCH Blue Science: Reaction Kinetics Pack

The rate of a reaction may be described by the following reaction stoichiometry and reaction kinetics:



$$-r_{\text{A}} = -\left(\frac{dC_{\text{A}}}{dt}\right) = k(T) \times [C_{\text{A}}]^3 \times [C_{\text{B}}]^1$$

What is the overall order of the reaction?

Answer for Q4.15

Overall Order = [4]

**Step 1: Identify the Orders with Respect to Each Reactant**

- The reaction rate is proportional to  $C_A^3$ , which means the reaction is **third order** with respect to reactant A.
- The reaction rate is proportional to  $C_B^1$ , which means the reaction is **first order** with respect to reactant B.

**Step 2: Determine the Overall Order of the Reaction**

The overall order of the reaction is the sum of the orders with respect to each reactant.

Overall order = 3 (order with respect to A) + 1 (order with respect to B) = 4

Q4.16

4.16 RESEARCH Green Science: Mass Transfer Pack

Mass transfer means the movement of molecules, usually by diffusion or convection. So it can describe phenomena like evaporation, precipitation or drying. It can model the underlying physics of unit operations like membrane filtration, fractional distillation, and absorption in a scrubber. In steady state diffusion is described by Fick's First Law.

A residual mass of 0.5kg of volatile light oil covers the bottom of an open tank. The diffusion coefficient (diffusivity) is 0.2 cm<sup>2</sup>/sec and the steady state concentration gradient to the top of the tank is 150 g/m<sup>3</sup>. The base area of the tank is 20m<sup>2</sup>. Calculate the time for all the light oil to evaporate from the bottom of the tank in minutes.

Answer for Q4.16

Evaporation time = [1.39] mins

**Given:**

- Residual mass of light oil, m=0.5 kg
- Diffusion coefficient (diffusivity), D=0.2 cm<sup>2</sup>/s=0.002 m<sup>2</sup>/s
- Concentration gradient, dC/dx=150 g/m<sup>4</sup>
- Base area of the tank, A=20 m<sup>2</sup>

**Step 1: Calculate the Mass Transfer Rate**

Fick's First Law states that the mass transfer rate  $\dot{m}$  due to diffusion can be described by:

$$\dot{m} = -D \times A \times dC/dx$$

Substituting the values:

$$\dot{m} = -0.002 \text{ m}^2/\text{s} \times 20 \text{ m}^2 \times 150 \text{ g/m}^4 = -6 \text{ g/s}$$

Convert this to kilograms per second:

$$\dot{m} = -6 \text{ g/s} \times 1 \text{ kg} / 1000 \text{ g} = -0.006 \text{ kg/s}$$

**Step 2: Calculate the Time Required for Complete Evaporation**

The total mass of oil to evaporate is 0.5 kg. The time required can be calculated by dividing the total mass by the mass transfer rate:

$$t = m / \dot{m} = 0.5 \text{ kg} / 0.006 \text{ kg/s} = 83.33 \text{ second}$$

**Step 3: Convert the Time to Minutes**

$$t = 83.33 \text{ seconds} / 60 \text{ seconds/minute} = 1.39 \text{ minutes}$$