Rate of Reaction

Unit 36  An introduction to rate of reaction
Unit 37  Factors affecting the rate of a reaction
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An introduction to rate of reaction
• Average rate and instantaneous rate
• Following the progress of a reaction

Factors affecting the rate of a reaction
• Concentration, surface area, temperature and catalyst
• Relationship between reaction rate and effective collisions
• Applications of catalysts and enzymes

Gas volume calculations
• Calculations involving the mass, number of moles and volume of a gas
• Calculations involving gas volumes and chemical equations
An introduction to rate of reaction

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36.2 The rate of a reaction
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36.4 How are different expressions for reaction rates related?
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### Summary

1. Rate of a reaction = \( \frac{\text{change in concentration (or amount) of a reactant or a product}}{\text{time}} \)
2. The instantaneous rate at time \( t \) is equal to the slope of the tangent to a concentration-time curve at that particular time \( t \). The steeper the slope, the higher the rate.

3. The following table summarizes the methods used to follow the progress of different reactions.

<table>
<thead>
<tr>
<th>Method</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring the volume of a gaseous product</td>
<td>( \text{Mg(s)} + 2\text{HCl(aq)} \rightarrow \text{MgCl}_2(aq) + \text{H}_2(g) )</td>
</tr>
<tr>
<td></td>
<td>( \text{CaCO}_3(s) + 2\text{HCl(aq)} \rightarrow \text{CaCl}_2(aq) + \text{H}_2\text{O(l)} + \text{CO}_2(g) )</td>
</tr>
<tr>
<td>Measuring the loss in mass of the reaction mixture</td>
<td>( \text{CaCO}_3(s) + 2\text{HCl(aq)} \rightarrow \text{CaCl}_2(aq) + \text{H}_2\text{O(l)} + \text{CO}_2(g) )</td>
</tr>
<tr>
<td>Measuring the pressure of the reaction mixture</td>
<td>( \text{2H}_2\text{O}_2(aq) \rightarrow \text{2H}_2\text{O(l)} + \text{O}_2(g) )</td>
</tr>
<tr>
<td></td>
<td>( \text{2H}_2(g) + 2\text{NO(g)} \rightarrow \text{2H}_2\text{O(g)} + \text{N}_2(g) )</td>
</tr>
<tr>
<td>Measuring the colour intensity of the reaction mixture</td>
<td>( \text{2MnO}_4^{-}(aq) + 5\text{C}_2\text{O}_4^{2-}(aq) + 16\text{H}^{+}(aq) \rightarrow \text{2Mn}^{2+}(aq) + 10\text{CO}_2(g) + 8\text{H}_2\text{O(l)} )</td>
</tr>
<tr>
<td></td>
<td>( \text{Br}_2(aq) + \text{HCOOH}(aq) \rightarrow \text{2Br}^{-}(aq) + 2\text{H}^{+}(aq) + \text{CO}_2(g) )</td>
</tr>
<tr>
<td></td>
<td>( \text{CH}_3\text{COCH}_2(aq) + \text{I}(aq) \rightarrow \text{CH}_3\text{COCH}_2(aq) + \text{H}^{+}(aq) + \text{I}^{-}(aq) )</td>
</tr>
<tr>
<td>Measuring the light transmittance of the reaction mixture</td>
<td>( \text{Na}_2\text{S}_2\text{O}_3(aq) + \text{H}_2\text{SO}_4(aq) \rightarrow \text{Na}_2\text{SO}_4(aq) + \text{SO}_2(g) + \text{H}_2\text{O(l)} + \text{S(l)} )</td>
</tr>
<tr>
<td>Titrimetric analysis</td>
<td>( \text{CH}_3\text{COOC}_2\text{H}_5(l) + \text{OH}^{-}(aq) \rightarrow \text{CH}_3\text{COO}^{-}(aq) + \text{C}_2\text{H}_5\text{OH(aq)} )</td>
</tr>
</tbody>
</table>
Example

In an experiment, a data-logger with a pressure sensor was used to study the rate of decomposition of sodium hypochlorite solution (NaOCl(aq)). The relation between the pressure and time measured is shown in the curve below.

Examination Tips

- To determine the initial rate of reaction, draw a tangent to the concentration-time curve at $t = 0$ and calculate the slope of the tangent.

- Questions may show the basic components of a colorimeter and ask students to give the name of the instrument and the property of the reaction mixture measured by it.

- Students should know the different quenching methods.
  
e.g. Adding NaHCO$_3$(aq) to remove the acid catalyst in the following reaction:
  \[ \text{I}_2(aq) + \text{CH}_3\text{COCH}_3(aq) \xrightarrow{H^+(aq)} \text{CH}_3\text{COCH}_2\text{I}(aq) + H^+(aq) + I^-(aq) \]

Answer

a) i) $2\text{NaOCl}(aq) \rightarrow 2\text{NaCl}(aq) + \text{O}_2(g)$

ii) A gas is evolved in the decomposition.

b) At A, the rate of decomposition is high because the concentration of NaOCl(aq) is high.
At B, the rate of decomposition decreases because the concentration of NaOCl(aq) decreases during the reaction.
At C, the decomposition stops because all the NaOCl(aq) has been used up.

Remarks

- Besides the above method, the decomposition of NaOCl(aq) can also be followed by measuring the volume of oxygen gas evolved.
Unit 37 Factors affecting the rate of a reaction

37.1 Factors affecting the rate of a reaction
37.2 Studying the effect of change in concentration of a reactant on the rate of a reaction
37.3 Studying the effect of change in surface area of a solid reactant on the rate of a reaction
37.4 Studying the effect of change in temperature on the rate of a reaction
37.5 Studying how the presence of a catalyst affects the rate of a reaction
37.6 Reaction rate and effective collisions
37.7 Applications of catalysts
37.8 Enzymes

Summary

1. In most cases, the rate of a reaction increases when the concentration of a reactant is increased.

   The following graph shows the results of reactions between equal masses of magnesium and excess hydrochloric acid of different concentrations.

2. The rate of a reaction increases when the surface area of a solid reactant is increased.

   The following graph shows the results of reactions between equal masses of calcium carbonate of different particle sizes with dilute hydrochloric acid.
3 In most cases, the rate of a reaction increases when the temperature is increased.

The following graph shows the results of reactions between equal quantities of magnesium and hydrochloric acid at different temperatures.

![Graph showing volume of hydrogen produced vs. time for higher and lower temperatures.]

4 A catalyst is a substance which alters the rate of a reaction without itself undergoing any permanent chemical changes.

5 The rate of a reaction depends on how many effective collisions there are in a unit volume per unit of time. To determine whether a collision is effective, two factors must be considered:
   • whether the particles collide in the right orientation;
   • whether the colliding particles have energy equal to or greater than the activation energy.

6 Enzymes are protein-based catalysts found in living things.

**Example**

The diagram below shows the essential components of an instrument for studying the kinetics of the following reaction.

\[ \text{S}_2\text{O}_8^{2-}(aq) + 2\text{I}^-(aq) \rightarrow 2\text{SO}_4^{2-}(aq) + \text{I}_2(aq) \]

![Diagram of instrument with light source, filter, reaction mixture, detector, recorder.]

a) What is this instrument? (1 mark)

b) What physical parameter of the reaction mixture is measured by this instrument? (1 mark)

c) In an experiment to investigate the reaction between \( \text{I}^-(aq) \) and excess \( \text{S}_2\text{O}_8^{2-}(aq) \), the concentration of iodine was determined at different times. Curve A shown below was obtained.

![Graph showing concentration of iodine vs. time with curve A highlighted.]

i) Suggest how the concentration of iodine can be obtained from the readings of the instrument. (2 marks)

ii) The experiment was repeated using half the original concentration of iodide ions while keeping other conditions the same.

Sketch, on the same graph, the change of concentration of iodine with time during this experiment. (1 mark)

d) Outline how you can show that the reaction is catalyzed by \( \text{Fe}^{2+}(aq) \) ions. (3 marks)

**Answer**

a) Colorimeter (1)

b) Absorbance (1)

c) i) Record the absorbance of iodine samples of known concentrations. Prepare a calibration curve by plotting the absorbance against the concentration of iodine. (1)

From the calibration curve, read off the concentration of iodine according to the absorbance recorded. (1)
ii) Time

Concentration
of solution

curve A

curve B

(0.5 mark for curve with a smaller slope; 0.5 mark for curve leveling off at about half of the final level of curve A)

(d) Mix known volumes of \( \text{S}_2\text{O}_8^{2-}(aq) \) and \( \Gamma^-(aq) \). Record the absorbance of the reaction mixture using a colorimeter for a certain time period. (1)

Repeat the experiment using the same reagents but with a few drops of \( \text{Fe}^{3+}(aq) \). (1)

Compare the two absorbance curves obtained. The absorbance of the reaction mixture increases more rapidly in the presence of \( \text{Fe}^{3+}(aq) \) ions. (1)

It can be concluded that the rate of reaction increases in the presence of \( \text{Fe}^{3+}(aq) \) ions.

**Remarks**

- Questions often ask about using a colorimeter to follow the progress of a reaction.
- Spell the term ‘colorimeter’ correctly, NOT ‘calorimeter’.
- Students should know the concept of ‘fair test’ when asked to make comparison. For example, to find how the change in the concentration of a certain reactant affects the rate of a reaction, keep all other conditions the same except the concentration of that reactant.
1. Avogadro's law states that equal volumes of gases at the same temperature and pressure contain equal numbers of particles.

2. The molar volume of a gas is the volume occupied by one mole of the gas.

3. At room temperature and pressure (25°C and 1 atmospheric pressure), the molar volume of any gas is 24.0 dm³ mol⁻¹ (or 24,000 cm³ mol⁻¹).

4. Under the same temperature and pressure, the relationship involving the mass, number of moles and volume of a gas is as follows:

\[
\frac{\text{mass of gas (in g)}}{\text{molar mass (g/mol)}} \times \frac{\text{molar mass (g/mol)}}{\text{number of moles of gas}} \times 24.0 \text{ dm}^3 \text{ mol}^{-1} \div 24.0 \text{ dm}^3 \text{ mol}^{-1} = \text{volume of gas at room temperature and pressure (in dm}^3)\]

Example

An oxide of metal M reacts completely with carbon to give 12.6 g of metal M and 2.38 dm³ of carbon dioxide measured at room temperature and pressure. What is the chemical formula of the oxide? (4 marks)

(Relative atomic masses: O = 16.0, M = 65.5)

Answer

1. Number of moles of CO₂ = 2.38 dm³ \div 24.0 dm³ mol⁻¹ = 0.0992 mol
2. Number of moles of O = 0.0992 mol \times 2 \text{ (from CO₂)} = 0.1984 mol
3. Number of moles of M = 12.6 g \div 65.5 g mol⁻¹ = 0.1918 mol
4. Number of moles of O : number of moles of M = 0.1984 : 0.1918

\(\therefore\) the chemical formula of the oxide is MO.

Remarks

Such questions may also give the volume of oxygen obtained from the decomposition of an oxide of M. Deduce the chemical formula of the oxide in a similar way.
17.5 g of calcium carbonate are added to 100.0 cm$^3$ of 2.00 mol dm$^{-3}$ hydrochloric acid. What is the volume of carbon dioxide liberated at room temperature and pressure? (4 marks)

(Relative atomic masses: C = 12.0, O = 16.0, Ca = 40.1; molar volume of gas at room temperature and pressure = 24.0 dm$^3$ mol$^{-1}$)

\[
\text{CaCO}_3(s) + 2\text{HCl}(aq) \rightarrow \text{CaCl}_2(aq) + \text{CO}_2(g) + \text{H}_2\text{O}(l)
\]

\[17.5 \text{ g} \quad 2.00 \text{ mol dm}^{-3} \quad ? \text{ cm}^3 \]

**Answer**

Number of moles of CaCO$_3$ present = \( \frac{17.5 \text{ g}}{100.1 \text{ g mol}^{-1}} \) = 0.175 mol \hspace{1cm} (1)

Number of moles of HCl present = 2.00 mol dm$^{-3} \times \frac{100.0 \text{ cm}^3}{1000 \text{ cm}^3} = 0.200 \text{ mol} \hspace{1cm} (1)

According to the equation, 1 mole of CaCO$_3$ reacts with 2 moles of HCl to produce 1 mole of CO$_2$. CaCO$_3$ is in excess in this case. The amount of hydrochloric acid limits the amount of CO$_2$ liberated.

Number of moles of CO$_2$ liberated = \( \frac{0.200}{2} \) mol = 0.100 mol \hspace{1cm} (1)

Volume of CO$_2$ liberated (at room temperature and pressure) = 0.100 mol $\times$ 24.0 dm$^3$ mol$^{-1}$ = 2.40 dm$^3$ \hspace{1cm} (1)

**Remarks**

- Question may NOT inform students when a limiting reagent is present. Be careful when the question gives the quantities of both reagents in a reaction.