CHEMISTRY

Stage 6

Module 8: Applying Chemical Ideas

Chemical Synthesis and Design

Teacher: Samantha Wong

Exam Equivalent Time: 37.5 minutes *(based on allocation of 1.5 minutes per mark)*

Questions

1. CHEMISTRY, M5 2023 HSC 12 MC

The industrial production of ammonia is represented by the Haber process reaction shown.

$$\mathrm{N_2\,(g) + 3H_2\,(g) \rightleftharpoons 2\,NH_3\,(g)} \quad \Delta H = -91.8\ \mathrm{kJ\ mol^{-1}}$$

Factors such as temperature and pressure need to be considered in order to maximise yield.

Which of the following is correct?

A. A lower pressure would result in a higher yield.

B. A higher pressure would result in a higher yield.

C. A lower temperature would result in a lower yield.

D. A higher temperature would result in a higher yield.

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2. CHEMISTRY, M8 EQ-Bank 5

A chemical reaction occurs at a constant temperature.

Describe the effect on the yield if

a. the value of the equilibrium expression is higher. ***(2 marks)***

b. the activation energy of the reaction is decreased. ***(2 marks)***

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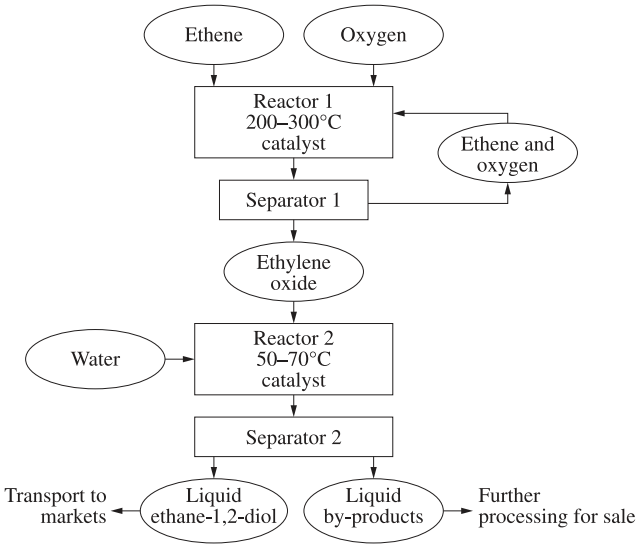
3. CHEMISTRY, M8 2020 HSC 23

The flow chart summarises an industrial process for the synthesis of ethane-1,2-diol.

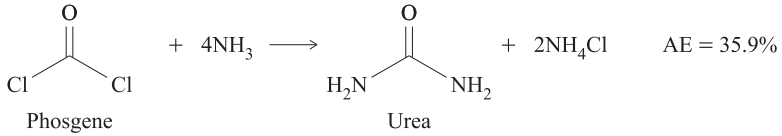


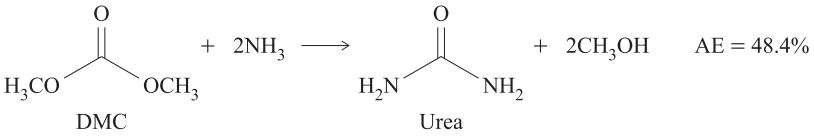
Explain THREE factors that may have been considered in the design of this industrial process. Make specific reference to the flow chart. ***(4 marks)***

4. CHEMISTRY, M8 2024 HSC 31

The atom economy (AE) of a reaction is a measure of the mass of atoms in the starting materials that are incorporated into the desired product. Higher AE means lower mass of waste products.

Urea can be produced in a variety of ways. One way is to react ammonia (high toxicity) with phosgene (high toxicity). Another way is to react ammonia with dimethyl carbonate (DMC, low toxicity). The chemical equations and AE for these two processes are provided.

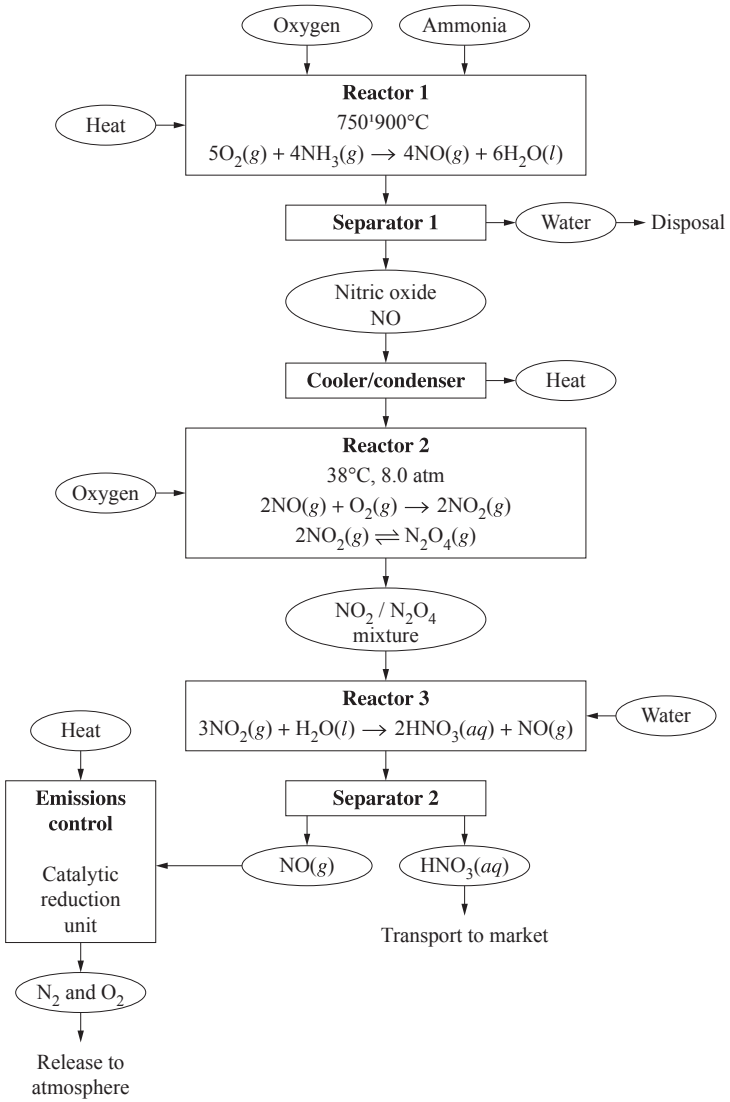




Which of these two processes is preferable for urea production? Justify your answer with reference to the information provided. ***(3 marks)***

5. CHEMISTRY, M8 2023 HSC 26

Nitric acid can be produced industrially using the process shown.



a. A mixture of NO_2 and N_2O_4 enters Reactor 3 , where only NO_2 is consumed by the reaction with water.

Explain, with respect to Le Chatelier's principle, what happens to the N_2O_4. ***(2 marks)***

b. Explain TWO improvements that can be made to the design of the process shown. ***(3 marks)***

6. CHEMISTRY, M8 2022 HSC 33

Analyse how a student could design a chemical synthesis process to be undertaken in the school laboratory. In your response, use a specific process relating to the synthesis of an organic compound, including a chemical equation, and refer to:

- selection of reagent(s)
- reaction conditions
- any potential hazards and any safety precautions to minimise the risk
- yield and purity of the product(s). ***(8 marks)***

Worked Solutions

1. CHEMISTRY, M5 2023 HSC 12 MC

→ Increasing the pressure would shift the position of equilibrium to the side of the equation with less moles (as per Le Chatelier's principle).

→ This would increase the yield of $\mathrm{NH_3}$

$\Rightarrow B$

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2. CHEMISTRY, M8 EQ-Bank 5

a. Equilibrium expression is higher:

→ The equilibrium expression shows the ratio of reactants to products in a chemical equation.

→ A higher value for the equilibrium expression suggests a higher proportion of products / increased product concentration compared to reactants, and hence a higher yield.

b. The activation energy is decreased:

→ A decrease in activation energy increases the reaction rate and allows the system to get to equilibrium faster.

→ This has no effect on the equilibrium yield which remains the same.

Worked Solutions

3. CHEMISTRY, M8 2020 HSC 23

→ A catalyst is utilised in reactions 1 and 2 to increase the rate of reaction by lowering the activation energy.

→ Additionally, moderate temperatures are utilised to increase the average kinetic energy of the molecules, increasing the likelihood of successful collisions.

→ These factors reduce energy consumption and make the process more economically viable.

→ Separators were used to separate and recycle the unused reactant gases. Ensuring that the resources were not wasted again increases the efficiency and economic sustainability of the design.

→ The availability of reagents should be taken into account by locating the process close to a pretrochemical or industrial plant, where ethylene and oxygen gases are readily available.

Other possible answers:

→ It is critical that the market for the major end product, ethane-1,2-diol, is assessed beforehand. This would involve researching demand for the product, expected market price, and the associated methods and costs of transport of the product to the end customers.

→ The usage and demand for the by-products of this process is another key factor that addresses the wastage and economics of production.

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4. CHEMISTRY, M8 2024 HSC 31

→ The atom economy for the reaction utilising dimethyl carbonate (DMC) is 48.4%, which is significantly higher to the 35.9% achieved in the phosgene reaction.

→ Consequently, the process involving DMC generates a lower mass of waste products and relies on a less hazardous starting material.

→ Additionally, the DMC-based synthesis requires only 2 moles of ammonia, compared to the 4 moles needed for the phosgene process.

→ These factors highlight the synthesis of urea via DMC as the preferable method for urea production as it offers advantages in terms of atom economy, reduced toxicity of reactants, and minimised use of harmful chemicals.

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5. CHEMISTRY, M8 2023 HSC 26

a. Consider the equilibrium system in reactor 2:

♦♦ Mean mark (a) 37%.

$$2\,NO_2\,(g) \rightleftharpoons N_2O_4\,(g)$$

→ NO_2 is a reactant in Reactor 3 and is consumed by the reaction in Reactor 3, disrupting the equilibrium.

→ Le Chatelier's Principle states that the position of equilibrium will shift to the left (as per the equilibrium equation above) to counter the depletion of NO_2.

→ This shift results in the further depletion of N_2O_4. This process will eventually see all of the N_2O_4 decomposing to form NO_2.

b. Design improvements:

♦ Mean mark (b) 49%.

→ A catalyst could be used in Reactor 1 to lower the activation energy required for the reaction to occur. This would decrease the required temperature, making the process more energy efficient.

→ Water is disposed of in Separator 3 and is required as a reactant in Reactor 3. A design improvement would be to recycle (rather than dispose) this water for use in Reactor 3.

Other answers could include:

→ Capture the heat energy released from the cooler/condenser step between the processes in Reactor 1 and Reactor 2. This should be engineered so it can then be used in the Emissions control step, thus reducing the energy consumption of the overall nitric acid production.

→ The NO produced in Reactor 3 that is then further processed for safe release into the atmosphere as $N_2\,(g)$ and $O_2\,(g)$ could be recycled and used as a reactant in Reactor 2, helping conserve resources.

6. CHEMISTRY, M8 2022 HSC 33

♦♦ Mean mark 52%.

Selecting reagents

→ The student could synthesise ethyl ethanoate through esterification between acetic acid and ethanol.

→ Both readily available in the school laboratory and are relatively safe.

Acetic acid + ethanol $\rightleftharpoons$ Ethyl ethanoate + water

→ Concentrated sulfuric acid should be used as the acid catalyst as it is a strong acid that is also readily available.

Reaction conditions

→ Increasing the temperature of the system increases the reaction rate because it increases the average kinetic energy of the reactant molecules, and thus increases the likelihood of successful collisions, producing more product.

→ Additionally, the addition of reactants would increase the likelihood of successful collisions, thus increasing the reaction rate.

→ The reaction should also be undertaken under reflux allowing vaporised molecules to condense and return back to the reaction vessel, increasing the amount of reactants, and thus increasing the rate of reaction.

→ Concentrated sulfuric acid should also be utilised as a catalyst in order to speed up the reaction and lower the activation energy.

Potential hazards and safety precautions

→ The acetic acid and sulfuric acid used is corrosive and may cause skin and eye burns, therefore, appropriate lab coat and safety glasses should be utilised.

→ The organic reactants are highly flammable and may cause fires. The reaction mixture should be heated on a hot plate or heating mantle instead of a bunsen burner.

→ Refluxing may cause pressure build-up, therefore, ensure the reflux condenser is open.

→ Superheating and bumping may occur in apparatus. Boiling chips should be utilised to provide nucleation sites allowing

liquids to boil smoothly.

Yield and purity

→ Concentrated sulfuric acid, used as a catalyst, also acts as a dehydrating agent that removes water from the system and improves yield.

→ When the reaction reaches equilibrium, the ester can be separated from the mixture by adding excess sodium carbonate solution in order to neutralise the acid.

→ Transfer to a separation funnel to separate the organic layer (containing the ester) from the aqueous layer.

→ Then use fractional distillation to separate the ester from the organic layer.