---Lower Pressure Ammonia Synthesis

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Example: Ethanol production is sustainable and dispersed.

Ammonia is not sustainable and dispersed.

Source: https://www.ers.usda.gov/
A Simplified CH$_4$-Based Process

Requirements for Distributed Production:
1- Cheap Energy/Feed Resources
2- Simpler Process at Moderate Conditions
Wind Offers Sustainable Energy
Stranded Wind Resources Equals Ammonia Need


We are Making Renewable Ammonia Out of Thin Air

Source: UMN.edu/
Absorption (staged) Replaces Condensation (mixed)

Metal Halides with Remarkable Ammonia Uptake Capacity

100 g $\text{MgCl}_2$ block holds 135 $L_{\text{STP}}$ $\text{NH}_3$

$\text{MgCl}_2 + \text{NH}_3 \rightleftharpoons \text{Mg(NH}_3\text{)Cl}_2$

$\text{Mg(NH}_3\text{)Cl}_2 + \text{NH}_3 \rightleftharpoons \text{Mg(NH}_3\text{)}_2\text{Cl}_2$

$\text{Mg(NH}_3\text{)}_2\text{Cl}_2 + 4\text{NH}_3 \rightleftharpoons \text{Mg(NH}_3\text{)}_6\text{Cl}_2$

$\text{Sr(NH}_3\text{)}_8\text{Cl}_2$

$\text{CaCl}_2 + \text{NH}_3 \rightleftharpoons \text{Ca(NH}_3\text{)Cl}_2$

$\text{Ca(NH}_3\text{)Cl}_2 + \text{NH}_3 \rightleftharpoons \text{Ca(NH}_3\text{)}_2\text{Cl}_2$

$\text{Ca(NH}_3\text{)}_2\text{Cl}_2 + 2\text{NH}_3 \rightleftharpoons \text{Ca(NH}_3\text{)}_4\text{Cl}_2$

$\text{Ca(NH}_3\text{)}_4\text{Cl}_2 + 4\text{NH}_3 \rightleftharpoons \text{Ca(NH}_3\text{)}_8\text{Cl}_2$

Strategies to Improve Haber-Bosch Process

1- Better Catalysis *(Not Key Here)*
   Lower Pressure and Lower Temperature

2- Lower Pressure
   - Unraveling Mechanism of Reaction-Absorption Process
   - Implication of a Lower Pressure Process

3- Better Separation/Better Sorbents
Reaction-Absorption Apparatus

In Reaction-Absorption, Reaction Temperature has **Big Little** Effect on the Production Rate

**Production Rate** = \( C^\uparrow - C^\downarrow / (1/k_{\text{R}} M_{\text{R}}) + 1/k_{\text{abs}} A_{\text{abs}} + 1 - C^\uparrow / C / m \)

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**Proof:** Fedbatch at Constant Pressure

Synthesis More Affected by Recycle

\[ \text{Rate} = \frac{C^\uparrow - C^\downarrow}{1/k\downarrow R M\downarrow R} + \frac{1}{k\downarrow \text{abs}} A\downarrow \text{abs} + 1 - \frac{C^\uparrow}{C/m} \]

Strategies to Improve Haber-Bosch Process

1- Better Catalysis – Not Key Here
   Lower Pressure and Lower Temperature

2- Lower Pressure

3- Better Separation/Better Conversion
   Improving the RXN-ABS with Better Absorbents
Bulk Metal Halides Not Stable


Better Absorbent: Improved by 10X

10 g Salt Packed in Column
BET: less than 1 m²/g

10 g Sorbent (5% and 40% loading) Packed in Column
BET: less than 400 m²/g

Proposed Process Flow Diagram (PFD)

- N\(_2\) and H\(_2\) inlet
- Reactor: 400 C, 20 bar
- Absorber 1: uptake 200 C, 20 bar
- Absorber 2: regeneration 400 C
- Absorber 3: regeneration 400 C
- Storage
- Compressor
Conclusions: Distributed Sustainable Ammonia

1. Reactive-Separation Promises Faster Rates
2. Absorption is Promising, we improved absorbents by 10X
3. Distributed Renewable Ammonia Possible with Lower CapEx
4. We want to Test the Reaction-Absorption Benchmark
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