High Efficiency Power Production from Coal with Carbon Capture

Chemical Engineering 4N04

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Process Overview

- Generate electricity from coal with zero emissions and 100% carbon capture
- Consists of air separation, gasification, cleaning, shifting, fuel impurity, power generation, heat recovery, CO$_2$ recovery and CO$_2$ compression

CO$_2$ Recovery
- Fuel exhaust is cooled to 21°C and flashed in Drum1
- Liquid phase is further depressurized and separated in cascading flash drums
- Vapor products are recycled to Drum 1, enabling nearly 100% CO$_2$ capture

CO$_2$ Compression
- CO$_2$ stream recovered from Flash Drum 1 is compressed to about 74 bar
### Pressure of flash drum

<table>
<thead>
<tr>
<th>Guide Words</th>
<th>Deviation</th>
<th>Causes</th>
<th>Consequences</th>
<th>Actions</th>
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Drum 1
## Pressure of flash drum

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<td>- Higher liquid level</td>
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<td>- Low CO2 vapor recovered at the top of the flash drum</td>
<td>Install pressure indicator on the flash drum and replace the drum if required</td>
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<td><strong>High</strong></td>
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<td>1. Higher feed temperature</td>
<td>- Lower liquid level, less CO₂ purity recovered</td>
<td>Install pressure and temperature controller for the drum</td>
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<tr>
<td></td>
<td></td>
<td>2. Blockage in the vapor stream</td>
<td>- Less CO₂ recovered and risk of drum explosion</td>
<td>Install pressure alarm</td>
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HAZOP

- Level of flash drum

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**HAZOP**

- **Level of flash drum**

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| High       | High level of liquid in flash drum | 2.Inlet stream too cold        | -Less vapor fraction product resulting in possible compressor damage | -Install temperature controller on the feed stream  
- Install SIS on the compressor |
| Low        | 2.Blockage in the liquid stream  | -Less liquid water leaving at the bottom | -Install level indicator  
- High level alarm should be installed | |
# HAZOP

## Level of flash drum

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- Install SIS on the compressor |
|            |                                   | 2. Blockage in the liquid    | - Less liquid water leaving at the bottom                                   | - Install level indicator  
- High level alarm should be installed |
| Low        | Low level of liquid in flash drum  | 1. Blockage in the inlet     | - No separation occurs                                                      | - Install pressure sensor on the feed stream  
- Low level alarm                         |
|            |                                   | stream                       | - Damage to pump                                                            |                                              |
|            |                                   | 2. The inlet stream is too   | - No separation occurs                                                      | - Install temperature controller on the feed stream  
- Low level alarm                           |
|            |                                   | hot                          | - Damage to pump                                                            |                                              |
HAZOP

Drum 1

- TIC
- PS
- PIC
- LALH
- LI
HAZOP

- **What is Operability?**
  - Any fluctuation in procedure that could lead to violation of health, safety, and environmental regulations
  - Negative impact on product yield

- **Operating window**
  - -50%-200%

- **Reliability**
  - Safety issues: Pressure build-up
  - Equipment damage: valves and pipes
  - Environmental: with base case (throughput) no emission of CO₂ takes place.
    - Increased throughput may lead to emission of CO₂ to the surrounding
  - Increase and/or decrease in throughput will lead to less production yield
Class Activity
Formaldehyde Synthesis from Methanol

CHEM ENG 4N04 2012

Thursday, November 29th, 2012

Group Members:
Angel Li
Fizza Anwar
Heather Van
Tolulope Fadiya
Xin Yuan
Introduction

• What is Formaldehyde?
• Silver catalyst vs. Metal oxide catalyst
Process overview

Deionized Water

Methanol

Air

Absorber

Fixed-bed reactor with heat exchanger

Distillation column

Off-Gas

Formalin

\[ C\text{H}_3\text{OH} + \frac{1}{2} O_2 \rightarrow HCHO + H_2O \quad \Delta H = -37.3 \text{ kcal/mol} \]

\[ C\text{H}_3\text{OH} \rightarrow HCHO + H_2 \quad \Delta H = 20.3 \text{ kcal/mol} \]
**NRTL fluid package**

**Conversion reactor:**
- 40% exothermic reaction
- 35% endothermic reaction

**Tray absorber & distillation column:**
- Absorber - 20 trays
- Distillation tower - 31 trays, feed on tray 18

<table>
<thead>
<tr>
<th>Component</th>
<th>Flowrate (kgmol/hr)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol Feed</td>
<td>80</td>
<td>Production capacity</td>
</tr>
<tr>
<td>Air Feed</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td>DI Water Feed</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Formaldehyde concentration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Methanol concentration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>180</td>
</tr>
<tr>
<td></td>
<td></td>
<td>47 wt %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 1 wt %</td>
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</table>
Operability - Methanol flammability

UFL - 36 mol%    LFL - 6 mol%

Need to operate outside the flammable range
Operability - Formalin concentration

Commercial grade formalin - 37 wt% formaldehyde
Product needs higher concentration to allow flexibility
By adding water vapour to feed methanol, distillation is not necessary if lower formalin concentration is acceptable.
Economic impact of water ballast

- Equipment cost with distillation column vs. without distillation

- Total Equipment cost: $5,253,755 vs. $1,6801,109
- 70% reduction in equipment cost without distillation column
PFD for water ballast process

Deionized Water

Methanol

Air

Formalin

Off-Gas

Absorber

Fixed-bed reactor with heat exchanger
Reactor P&ID for safety, flexibility, reliability & start-up
Let's play JJJJJeopardy

- Process Safety
  - 100 Points
  - 200 Points
  - 300 Points

- Process Overview
  - 100 Points
  - 200 Points
  - 300 Points

- Operability & Economics
  - 100 Points
  - 200 Points
  - 300 Points
Agenda

• Process Overview
• Economics
• Operability
• Interactive Activity
## Process Overview

<table>
<thead>
<tr>
<th>Turbine</th>
<th>Inlet Pressure (psig)</th>
<th>Outlet Pressure (psig)</th>
</tr>
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<tbody>
<tr>
<td>HP-Turbine</td>
<td>319.08</td>
<td>29.01</td>
</tr>
<tr>
<td>LP-Turbine</td>
<td>29.01</td>
<td>1.45</td>
</tr>
</tbody>
</table>
Economics
Electricity Costs

- Pumps require electricity
  - Total power required: $25\, kW$
  - Costs: $7.4\, \text{¢/kW-hr}$
  - Annual cost: approx. $191,000

- Power generated by turbines:
  - Worst case: $1.19\, MW$
  - Best case: $2.26\, MW$
Selling Back to Grid

- Can sell back at rate of $13.1 \$/kW-hr.
- In worst case, profit from selling all generated electricity would be approx. $1.9 million.
- In best case, profit would be approx. $3.7 million.
- It is most profitable to sell all the energy generated and buy back the energy required for the pumps at the lower rate.
Operability
Efficiency

\[ EFF_{FERC} = \frac{(P+Q/2)}{F} \]

- Overall efficiency calculation
- Recommended by the Federal Energy Regulatory Commission (US)
Flexibility

- 24/7 operation with varying demands
- Main control loops:

<table>
<thead>
<tr>
<th>Controller</th>
<th>Measured/ Controlled Variable(s)</th>
<th>Manipulated Variable(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boiler outlet (stream 1) temperature</td>
<td>Natural gas flow rate</td>
</tr>
<tr>
<td></td>
<td>Boiler outlet (stream 1) pressure</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Boiler inlet (stream 8) flow rate</td>
<td>Make-up water flow rate</td>
</tr>
<tr>
<td>3</td>
<td>Condenser outlet temperature</td>
<td>Chilled water flow rate</td>
</tr>
<tr>
<td>4</td>
<td>Energy client demand</td>
<td>Recycle ratio</td>
</tr>
</tbody>
</table>
Start-up & Shut-down

- Steam turbines have thick casing
  - Large thermal inertia
- Large temperature differential

Therefore, must be warmed up & cooled down slowly

- Moisture in turbine results in stress corrosion cracking and corrosion fatigue

Therefore, must eliminate moisture during shut-down using purge gas
Interactive Activity
Group Activity
Build your own Co-Generation Steam Plant

- Two teams will compete to correctly assemble a co-generation steam plant
- Components Include: HP/LP Turbine, Boiler, Energy Client and Condenser