IPRO 302
CO2 Mitigation: A Techno-Economic Assessment
Problem

- CO$_2$ emissions may be contributing to global warming.
- Future governmental regulations are expected.
- Power plants will require CO$_2$ capture technology.
- Alternate destination for CO$_2$ must be found
Our Sponsor:

• Full service provider to public utilities and independent power producers

• Provides global consulting services for:
  – Renewable power
  – Nuclear power
  – Fossil power
  – Design of environmental control systems
Objectives

• **Analysis of CO$_2$ removal system**
  – Computer models of power, steam and flue gas cycles

• **Economic analysis**
  – Capital and operation costs.
  – Sequestration costs.
Steam Team Purpose and Goals

- Analysis of steam cycle and flue gas
- Find values via Matlab simulation and hand calculations
- Determine Flue chemical composition, total mass flow rate, and temperature
**FIGURE 9-19**

Schematic and T-s diagram for Example 9-6.
Steam Calculations (MATLAB)

- **Gross power**
  - Power produced at generator

- **Net power**
  - Power delivered to transmission lines
    - (Gross power – power consumed in plant)

- **Generator and turbine efficiencies**
  - Used to determine the steam flow rate at the turbines (gross power known)

- **Heat transfer requirements for intermediate stages.**

- **Boiler specifications given**
Steam/Flue Gas Flow

STEAM SIDE OF BOILER

FLAME AREA → WATER WALLS → SECONDARY SUPERHEATER → REHEATER → PRIMARY SUPERHEATER → ECONOMIZER

FANS → BAG HOUSE → DRY FLUE GAS DE-SULFURIZER (DFGD) → AIR HEATER → SELECTIVE CATALYTIC REDUCER (SCR)

CO2 REMOVAL 175 F → FLAME AREA 300 F

FLAME AREA 160 F → 350 F

STEAM

FLUE GAS
Pollution Control Devices

- **CO2 REMOVAL** (175°F)
- **FANS**
- **BAG HOUSE** (160°F)
- **DRY FLUE GAS DE-SULFURIZER (DFGD)** (350°F)
- **AIR HEATER**
- **SELECTIVE CATALYTIC REDUCER (SCR)**

**Flow Diagram:**
- **STEAM**
- **FLUE GAS**
- **AMBIENT AIR** (300°F)
- **FLAME AREA** (300°F)
Assumptions

- Ideal Heat transfer
- Pollution Control Devices energy losses are negligible
- Baghouse removes all additional components
Results

- 76 kg/sec of coal
- 708 kg/sec air into furnace
- 730 kg/sec out of flue
- 152 kg/sec of CO2 out of flue
- 82.7 Degrees C
Resulting Power Losses

- 30 MW loss for steam removal prior to entering intermediate turbine for use by CO2 removal process

- 30 / 53 MW loss depending on 100 F or 35 F temp requirement respectively
• **Process Schematic**

![CO₂ Capture Process Diagram](image)

**Flue Gas**

**Absorber**

**Wash Section**

**Structured Packing**

**DCC Section**

**MEA Heat Integration**

**Stripper**

**Reflux Drum**

**Flue Gas**

**CO₂-Amm MIX**

**Regenerated Solvent**

**Steam: heat source**
• **Absorber**
  – Absorption: Operation when liquid & gas phases contact
  – **Diffusion or mass transfer** of solute to Solution
  – Solute: $CO_2$ – absorbed from flue gas into stagnant liquid

• **Stripper**
  – Separate and regenerate $CO_2$ from solution
  – Separation Property: **Relative Volatility** --- 30 times volatility difference

• **Reaction**

\[
(NH_4)_2CO_3 + H_2O + CO_2 \rightleftharpoons 2 NH_4HCO_3
\]

Ammonia Carbonate \(\text{absorber}\)

Ammonia Bicarbonate \(\text{stripper}\)
• **Counter-Current packed Absorber**
  - The highest *theoretical* efficiency.
  - Driving force: concentration difference
  - Pressure Drop

\[
f_p = \frac{150}{\text{Re}_p} + 1.75 \Rightarrow f_p = \frac{\Delta P}{L} \frac{D_p}{\rho V^2_s} \frac{\varepsilon^3}{1 - \varepsilon}
\]

• **Stripper**

![Diagram of a packed tower with liquid sprays and ammonia streams](image)
• Operating Condition for Chilled Ammonia Process
  – Reagent composition: **25% Ammonia, 75% Water**
  – CO2 Removal Efficiency: **1.29 lb CO₂ / lb Reagent**
  – Heat of Reaction: 260 Btu/lb
  – Absorption Temp.: 35~60°F (2 ~ 16 °C)
  – Absorption Pressure: Atmospheric
  – Regeneration Temp.: 200 ~ 250°F
  – Regeneration Pressure: 300 ~ 600 psia
  – Pressure Drop: 0.1 psia / tray
• **Absorber Design with Matlab**

**Berl Saddles**

- 20 meter diameter
  chosen as best compromise of cost and efficiency.

**Raschig Rings**

- Higher cost
- Lower Void fraction
- Higher Surface Area
• Stripper Design with Matlab
• **Heat integration Design**
  – HYSYS simulation
  – Obstacle: system does not have ammonium carbonate (AC) and ammonium bicarbonate (BC)
  – Assumptions
    • majority of streams between Stripper and Absorber consists of Ammonia and Water.
    • HYSYS design model with $\text{H}_2\text{O}$, $\text{NH}_3$, $\text{CO}_2$ estimates the most similar heat integration process including heat exchangers and compressors.
• Economical Analysis
  – Assumptions: interest rate, labor fee, Land cost, etc.
Challenges with CO$_2$ Compression

- Corrosive – water + CO$_2$
- Iron Carbonyl formation – water + CO
Centrifugal Compressors

• Superior efficiency
• Oil-free compression
• Less maintenance-intensive
• Higher speed, commonly used in the 10-40MW range
MOST VIALBE COMPRESSOR

• Specifications:
  • Model = Man Turbo
  • Type = RG
  • Stages = 2-8
  • Max. Pressure Ratio = 225
  • Inter-stage Coolers = 1-4
  • Power = 4,500KW
  • Flow Rate = 2000-500,000 m³/hr
Power vs. Inlet Pressure @ Different Flow Rates

- 100% CO2
- 90% CO2
- 50% CO2
- 25% CO2

Power (Mega Watt) vs. Inlet Pressure (Psi)
PRESSURE
Basis - $0.067/kW
CO$_2$ Uses and Destinations

- Food Industry

- Enhanced-Oil Recovery

- Sequestration
  - Oceanic
  - Terrestrial
  - Geological
Iowa Options

• Saline Aquifer Storage
• Enhanced Oil Recovery
• Coal-Bed Methane Recovery
Recommendation
Coal-Bed Methane (CBM) Recovery!

- Relatively close proximity to power plant
- Offers value-added benefit of fuel extraction

THE ECBM PROCESS

- CO₂ from power plant
  - Compressor
  - 100-150km pipeline
    - 16” diameter
    - 152 bars, 38°C
  - CBM Production Wells
    - Coalbed methane is dewatered and compressed to 25.1 bars before being piped away for selling
  - CBM displaced
  - CO₂ stored underground
  - Saline water
  - To aquifers
  - CO₂ Injection Wells
    - CO₂ Injection Wells
    - CO₂ Pipeline Terminal
    - CO₂ from power plant
Economics

- CBM benefits from sale of CO₂
Ethical Challenges

- Degeneration and loss of ammonia (~3500kg/yr)
- Ensuring reliable CO$_2$ storage
- Software Licensing (Law)
- Proprietary Information (Professional Codes)
Overall Conclusions

– 30MW Average Energy Penalty from Steam Cycle
– Only CO₂ capture with 25% feasible
– 158 bar compression to liquid CO₂ follows
– Coal-Bed Methane Recovery/Sequestration
Thank You

Special Thanks: Charles Guilfoyle
Lily Popadopoulos

Questions