Sabatier Subsystem
Thermal Management

Paul Hintze (KSC) & Hector Guardado (JSC)

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Sabatier Subsystem Overview

• Basic system consist of the Sabatier reactor, condenser, and thermal control system

• Reactor is used to convert carbon dioxide and hydrogen into methane and water
  • \( \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \)
  • Exothermic, \( \Delta H = -165.4 \text{ kJ/mole} \)

• Condenser is used to separate the methane and water

• Single or multiple Reactors, each can be Adiabatic or Isothermal
  • Single reactor can have both adiabatic and isothermal zones or a thermal gradient along length

• Adiabatic Reactor
  • Operates at higher temperature for faster kinetics (smaller reactor)
  • Recycled product gas can be used to control reactor temperature

• Isothermal Reactor
  • Operates at lower temperatures for higher CO2 conversion efficiency
  • Thermal control system required to removed heat from reactor
Basic Thermal Control System (TCS)

- Cold reactant feed is typically preheated directly by reactor
- Isothermal reactor operates at ~400°C, adiabatic reactor temperature must kept < 600°C
- Reactor coolant loop removes up to 50% of total heat load

- Condenser temperature is maintained just above H₂O freezing point
- Condenser coolant loop removes up to 100% of total heat load (adiabatic reactor)
  - Radiator at reactor exit would likely be used to help cool the reactor products before entering the condenser
Thermal Challenges

- Reactor and condenser operate at significantly different temperatures
  - The reactor at around 400 °C and the condenser at ~5°C
  - A single coolant loop is desired to minimize TCS mass and increase reliability

- High interdependence between reactor and thermal control system designs
  - Reactor temperature has a significantly impact on performance
  - Certain reactors have unique requirements that have advantages or disadvantages that do not become apparent until considered as a system
    - Example: Is it better to drive the Sabatier reactor to high conversion with thermal management or use gas recycling and lower conversion with no thermal management?

- Reactor is capable of generating a significant amount of heat per unit area
  - TCS must minimize risk of hot spots (catalyst deactivation) or reaction quenching

- Continuous Operation
  - TCS must adjust to fluctuations in feed gas temperature and ambient temperature
  - Large ambient temperature range -112 to 5°C

- Condenser must produce liquid water near freezing temperature
  - 2-5°C desired to minimize partial pressure of water vapor in product gases
  - Low temperature delta between condenser and environment for several hours per day, active cooling will likely be required to reject heat during the hottest part of the day

- Low passive heat transfer due to low atmospheric pressure and gravity
Potential Solutions – System Level

1) Adiabatic Reactor

- Larger Reactor
- Condenser
- Recycle Pump

No Reactor TCS

2) Independent TCS

- Isothermal Reactor
- Condenser

Separate coolants and components

3) Partially Integrated TCS

- Isothermal Reactor
- Condenser

Heat exchanged between coolants, some shared components (e.g. radiator)

4) Integrated TCS

- Isothermal Reactor
- Condenser

Single coolant & shared components
Potential Solutions: Isothermal Reactor

- **Main Features**: High heat exchange efficiency (i.e. reduce weight and size) and controllability (e.g. self-sustainability) of the catalyst temperature.

- **Possible Reactor Designs**: Packed bed (traditional), microchannel, monolith, microlith, etc.

- **Reactor Heat Exchanger Designs**:
  - Single cooling jacket (shell)
  - Multiple cooling channels (tubes)
  - Cocurrent or countercurrent flow

- **Reactor Temperature Profile**:
  - **Uniform**: requires liquid coolant boiling at high pressure or high coolant flow rate
  - **Variable**: more difficult to control

- **Heat Exchange Fluid**:
  - **Gas**: CO2, Hydrogen, Methane, etc.
    - high flow rates required (larger HEX)
  - **Liquid**: Water, Dowtherm, Oil, Molten Salt, etc.
    - Lower flow rate, isothermal boiling possible

- **Heat can be rejected to ambient by flowing coolant thru a radiator**
  - Refrigeration cycle is not required due to high temperature delta
  - Direct air cooling may not be possible
Potential Solutions: Condenser

- **Main Features:** High heat exchange efficiency (i.e. reduce weight and size) and controllability. Minimal power input.

Cooling Options

- **Direct air cooling or Liquid (e.g. antifreeze) cooling loop**
  - Pros: Very low energy input, high simplicity/reliability
  - Cons: Very low control, likely not feasible due to low dT between max ambient & condenser target temperature

- **Thermoelectric cooler (TEC)**
  - Pros: High simplicity/reliability, high temperature control
  - Cons: Poor power efficiency (6x higher power input relative to conventional vapor-compression), Low temperature delta (large radiator or multistage coolers required)

- **Vapor-Compression cycle**
  - Pros: Good efficiency and temperature control. Saturated CO2 can be used isothermally cool condenser. Same system could also be used to cool an isothermal reactor.
  - Cons: Less reliable than TEC. Will require higher pressure condenser and radiator.

- **Vapor-Absorption cycle**
  - Pros: Low electrical power input, utilizes waste heat from reactor and other systems
  - Cons: Complex, ammonia refrigerant required. May not be feasible.
Potential Solutions: Condenser

Heat Exchanger Design Options

• **Plate HEX**
  • Thin metal plates used to transfer heat between fluids
  • High heat transfer efficiency, small size
  • Higher pressure drop than shell-and-tube

• **Shell and Tube**
  • Most commonly used heat exchanger
  • Suited for high-pressure applications
  • Lower efficiency than plate heat exchangers

• **Submerged Coil**
  • Products cooled by flowing through a coil submerged in a stagnant heat transfer liquid; similar to shell and tube except heat is extracted at the condenser outer wall
  • This design is many applicable to thermoelectric cooling

• **Direct Contact (low potential)**
  • Reactor gases cooled by mixing with coolant. Coolant must be the same as product (CH4) to avoid contamination
  • Very high heat transfer, simplest condenser design
  • May not be feasible due to high methane flow rate. Very cold coolant required, high risk of H2O freezing.
Backup