National Aeronautics and Space Administration

Sabatier Subsystem Thermal Management

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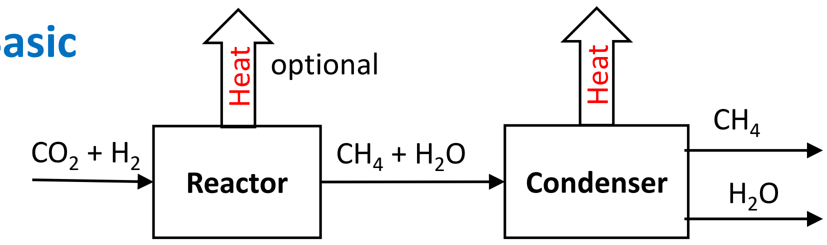
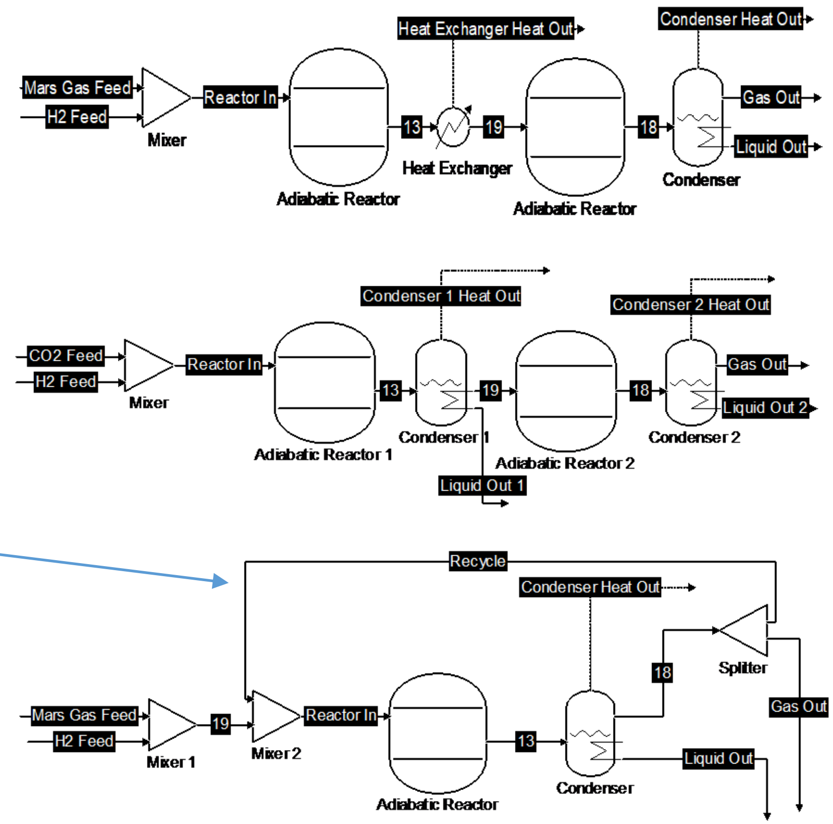
Sabatier Subsystem Overview

- **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**
    - $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
    - **Exothermic, ΔH = -165.4 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

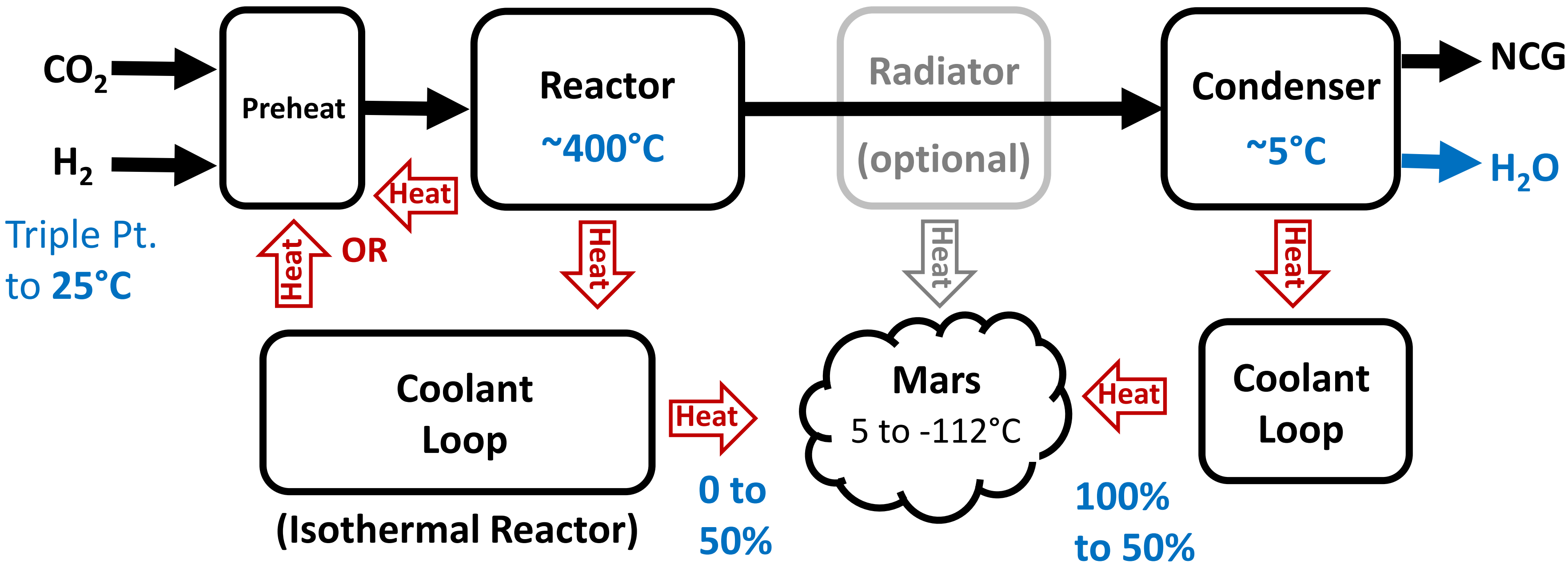
Basic



Advanced Designs



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

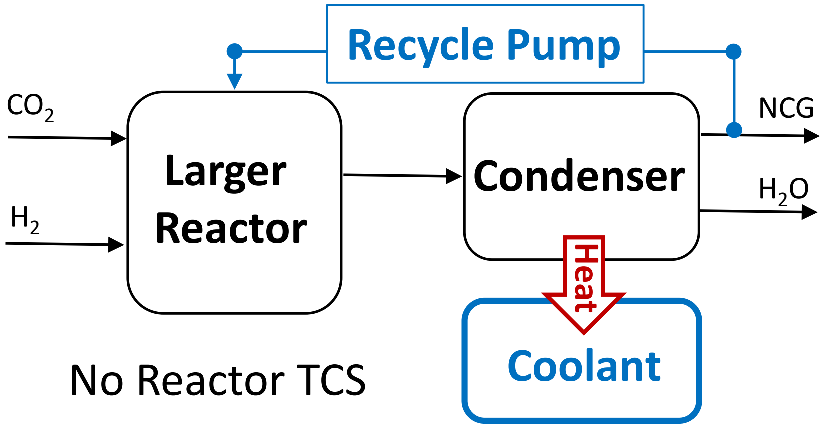
- Condenser temperature is maintained just above H_2O freezing point
- Condenser coolant loop removes up to 100% of total heat load (adiabatic reactor)
  - Radiator at reactor exit would likely be used to help cool the reactor products before entering the condenser

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**

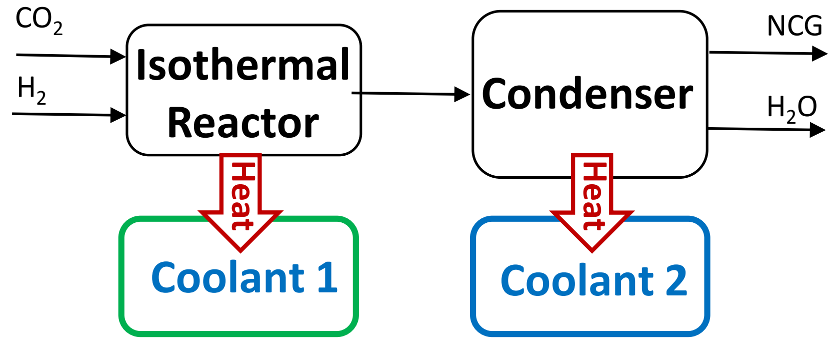
Potential Solutions – System Level

1) Adiabatic Reactor



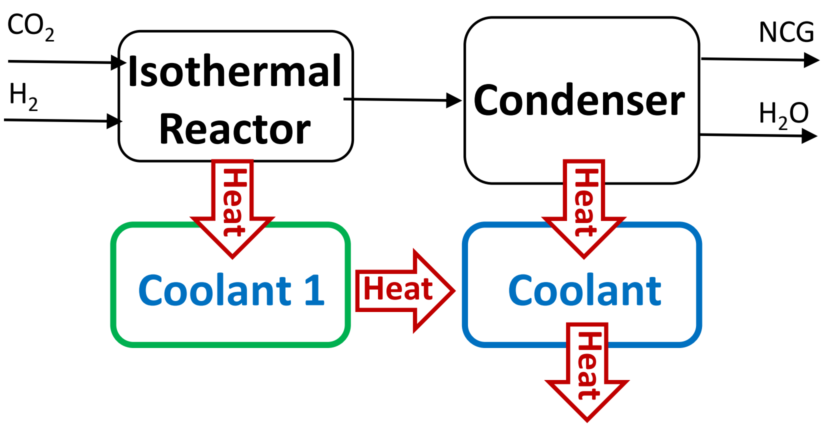
No Reactor TCS

2) Independent TCS



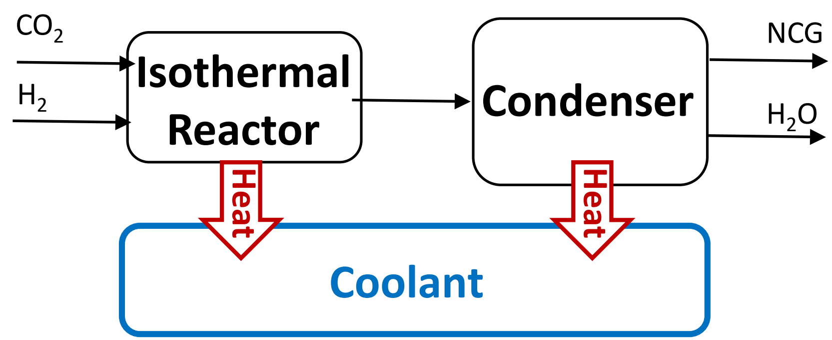
Separate coolants and components

3) Partially Integrated TCS



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

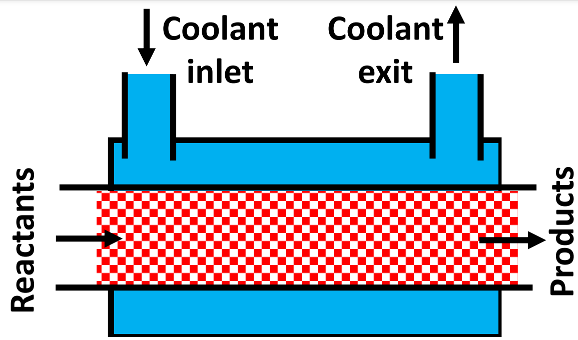
4) Integrated TCS

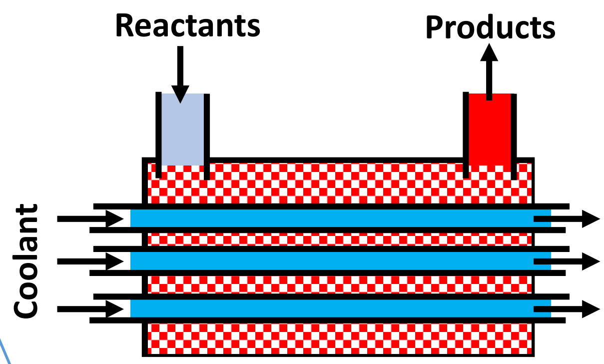


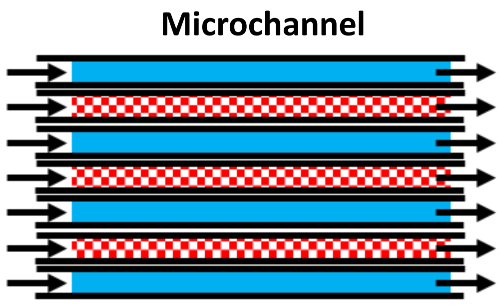
Single coolant & shared components

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: CO_2, 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





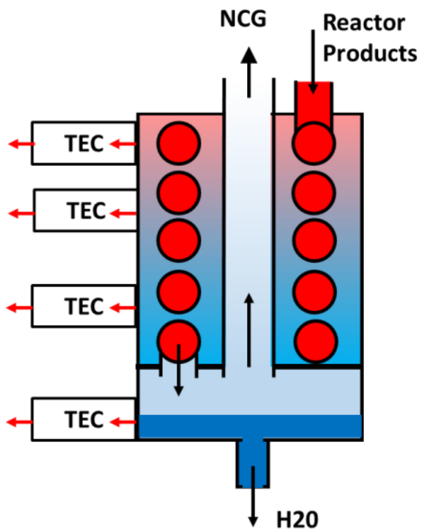


Potential Solutions: Condenser

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

Cooling Options

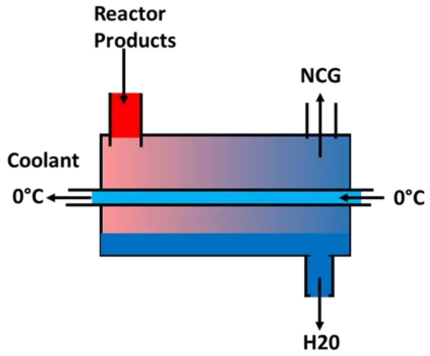
- **Direct air cooling or Liquid (e.g. antifreeze) cooling loop**
  - Pros: Very low energy input, high simplicity/reliability
  - Cons: Very low control, likely not feasible due to low dT between max ambient & condenser target temperature
- **Thermoelectric cooler (TEC)**
  - Pros: High simplicity/reliability,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



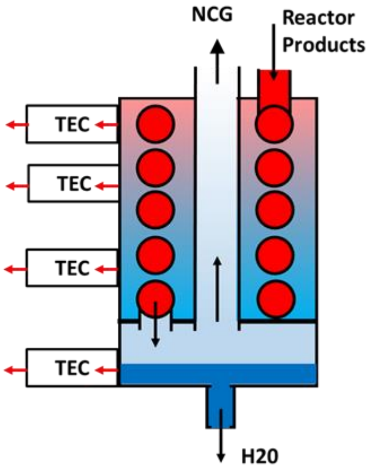
Potential Solutions: Condenser

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