Development of control strategies for a 10MWe supercritical CO2 recompression Brayton cycle

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Sensors an Controls FWP Task 5.1 - Systems Engineering & Analysis Support

Development of Control Strategies for the Dynamic Operation 10MWe Supercritical CO_2 Recompression Brayton Cycle

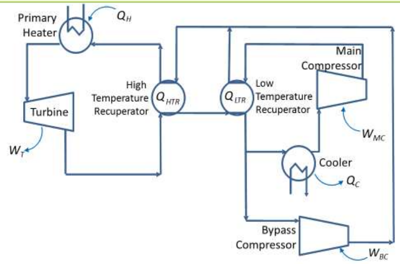
- **Objective**
  - Develop operational and control strategies for the dynamic operation of a 10MWe supercritical CO_2 recompression Brayton cycle. Load following, startup, shutdown, plant trips
- **Challenges**
  - Cope with highly nonlinear fluid property changes, especially near the critical point
  - Cope with high degree of heat recuperation and pressure interactions
  - Maintain operation with CO_2 working fluid in supercritical region
  - Operate commercial cycles with coupled, constant-speed turbomachinery
- **Approach**
  - Use Aspen Dynamics® and Aspen Custom Modeler® to develop dynamic system model. Other software (such as Matlab/Simulink®) may be used for advanced control implementation.
- **FWP M1 Milestone (M1.17.5.A)**
  - Complete off-design studies of 10 MW system model that includes "inventory control" method. Basic P&ID system control implemented for slow load/heat input ramping. Document with an internal report or technical paper. (5/30/2017).

Background - U.S. DOE's Supercritical Transformational Electric Power (STEP) Program

- **DOE sCO_2 Crosscutting Initiative (CCI) to demonstrate sCO_2 Brayton technologies at commercial scale**
- **DOE announced project award to develop sCO_2 test facility (10/17/2016)**
  - $80M federal contribution, 20% industry cost share, and 6-year duration
  - Managed by team led by GTI, SwRI, and GE Global Research
  - Design, build, and operate 10 MWe sCO2 Pilot Plant Test Facility in San Antonio, TX
    - Closed, indirect, sCO_2 recompression Brayton cycle
    - Turbine inlet operating temperature of 973.15 K (700 °C)
    - Demonstrate steady-state, dynamic, load-following, startup, and shutdown operations
- **DOE-Industry workshop at Argonne National Laboratory (11/1-2/2016)**
  - Explored status of interests and needs on technology applications
  - Discussed potential development of collaboration consortium for sCO_2 RD&D work

Closed Indirect sCO_2 Recompression Brayton Cycle

Simplified Block Flow Diagram

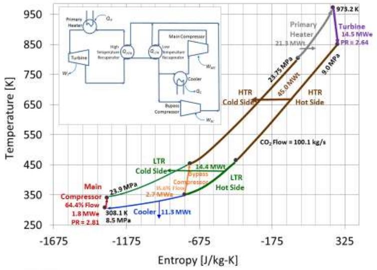


Key Features

- **Closed cycle**
- **Indirect heat source**
- **Two stages of recuperation**
- **Cooler to reject unused heat**
- **Parallel compressors**
- **Decoupled turbomachinery**

10 MW sCO_2 Recompression Brayton Cycle

Simulation Results: Steady-state Design Point



- **Net power is 10 MWe.**
  - $W_{NET} = W_T - W_{MC} - W_{BC}$
- **Heat input is 21.3 MWt.**
- **Cooler rejects 11.3 MWt.**
- **Efficiency is 46.9%.**
- **Low pressure ratio (PR)**
  - Turbine PR = 2.64 (23.75 MPa/ 9.0 Mpa)
- **Cycle is highly recuperated.**
  - $(Q_{HTR}+Q_{LTR})/Q_H = 2.8$
  - $Q_{HTR}/Q_{LTR} = 3.1$
- **Bypass compressor flow is ~1/3 of total CO_2 flow.**

Property Method: NIST REFPROP

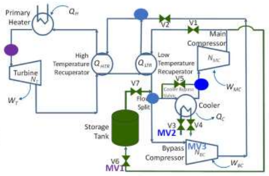
Transient Study: Part-Load Operation

Heat Input Turndown

- **Goal: Maintain high cycle efficiency during turndown in heat input ($Q = MC_p \Delta T$)**
- **To transfer less heat (Q), the cycle ΔT or mass flow rate (M), must decrease**
- **When considering ΔT, recall that Carnot cycle efficiency ($\eta = 1 - T_{low}/T_{high}$)**
  - T_{high} = Turbine Inlet Temperature (TIT)
    - Design point, 973.2 K (material constraint)
  - T_{low} = Main compressor inlet T (or Cooler Outlet T)
    - Design point, 308.1 K (4 K above critical T to avoid two-phase dome)
- **Thus to achieve highest efficiency, reduce cycle mass flowrate ($M = \rho A V$)**
  - Speed Control: If cycle is not grid connected, turbomachinery speeds can be decreased
    - Decoupled turbomachinery offers more operational flexibility and speed control options
  - Inventory Control ($M_{inventory} = \Sigma \rho_i V_i$): At fixed turbomachinery speeds, mass can be removed from the cycle
    - As mass is removed, cycle pressure decreases resulting in different changes in volumetric flow rate for each turbomachine since each turbomachine operates at a different temperature and pressure.
    - Thus, other control measures are required to maintain high efficiency operation while satisfying process constraints.

Heat Input Turndown - Decoupled Turbomachinery

Temperature, Flow Split, and Inventory Control



- **Objective**
  - Maximize cycle efficiency (net power/heat input)
- **Operating Constraints**
  - **TIT ≤ Upper bound** [MV1, MV2, MV3,]
    - ● **Design point, 973.2 K** (material constraint)
  - Main compressor inlet T for CO_2 ≥ Lower bound [MV2]
    - ● Design point, 308.1 K (4 K above critical T to avoid two-phase dome)
  - LTR Cold Side Exit T = Bypass Compressor Exit T [MV3]
    - ● Surge limit for bypass compressor
- **Manipulated Variables (MV)**

MV1: Storage valve (V6) | Inventory Control
MV2: Cooling water flow (V3) | Temperature Control
MV3: Bypass compressor speed (N_{BC}) | Flow Split Control

Future Work

10MWe sCO_2 Recompression Brayton Cycle

- **Dynamic Modeling**
  - Multistage compressors
  - Enhance turbine design and performance maps
  - Compact heat exchangers
- **Control**
  - Regulatory PID
  - Advanced process control, including model predictive control
- **Transient Operations**
  - Load-following operation (while maintaining maximum efficiency)
  - Startup and shutdown
  - Plant trips
- **Sensors**
  - Optimal sensor network design
  - Disturbance rejection, state estimation, condition monitoring, fault diagnosis, …
- **Validation**
  - Exploit data from STEP pilot plant test facility
  - Validate dynamic models, controls, and sensor network