Operational Transients in Supercritical CO_2 Systems: A Case Study on a 10 MWe Cycle

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Paper #61

Supercritical Transformational Electric Power (STEP) Demo Project

- **Objectives:**
  - Advance sCO_2 power from TRL3 to TRL7
  - Demonstrate pathway to net plant efficiency > 50%
  - Demonstrate control and operability at **500°C** and **715°C** turbine inlet temperature with **10 MWe** power generation
- **Accomplished:**
  - Simple Cycle (SC) operation – 4 MWe to grid
  - Reconfiguration to RCBC – Final stages of installation
- **Project Partners:**

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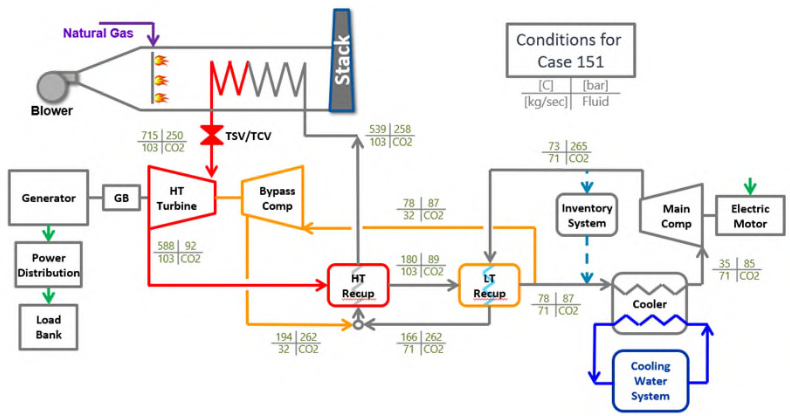
sCO_2 Power Cycle: 10 MWe Case Study

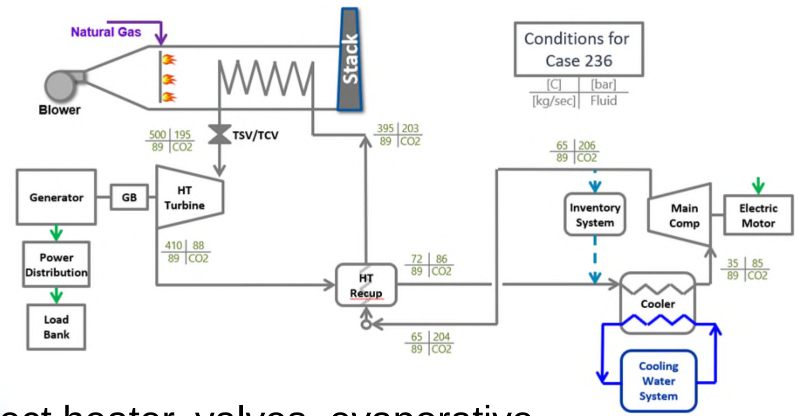


Recompression Closed Brayton Cycle (RCBC)

- 10 MWe net
- 2 Compressors
- 2 Recuperators
- 2 Coolers (cooler for bypass comp. not shown)

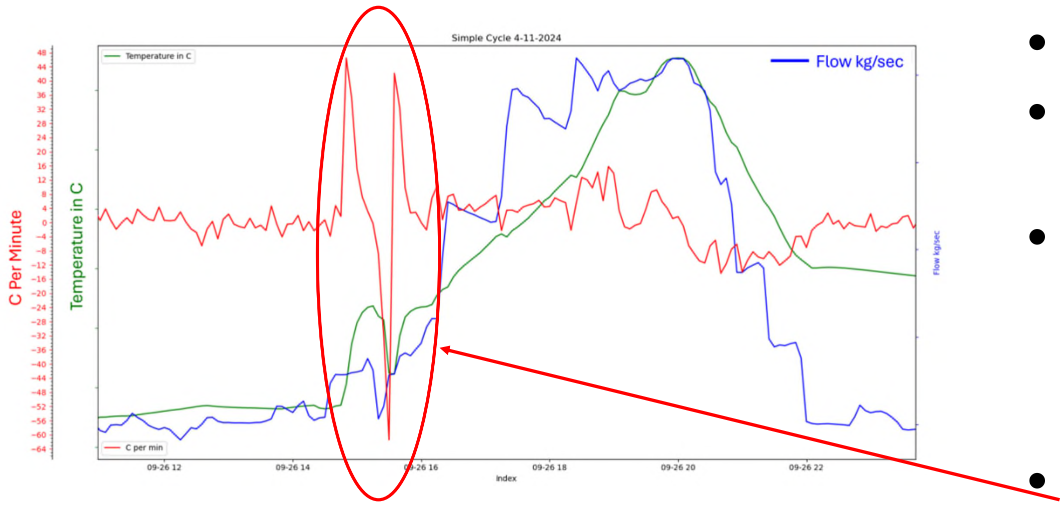
Simple Recuperated Brayton Cycle (SC)

- 5 MWe net
- 1 Compressor
- 1 Recuperator
- 1 Cooler



Common equipment: Turbine, Natural Gas fired indirect heater, valves, evaporative cooling tower, Inventory system, electrical distribution equipment

Transient Operation Challenges



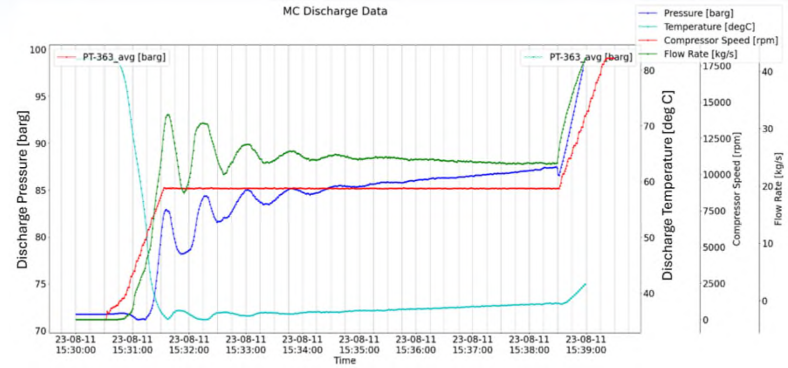
Heater outlet temperature during hot startup followed by a normal shutdown

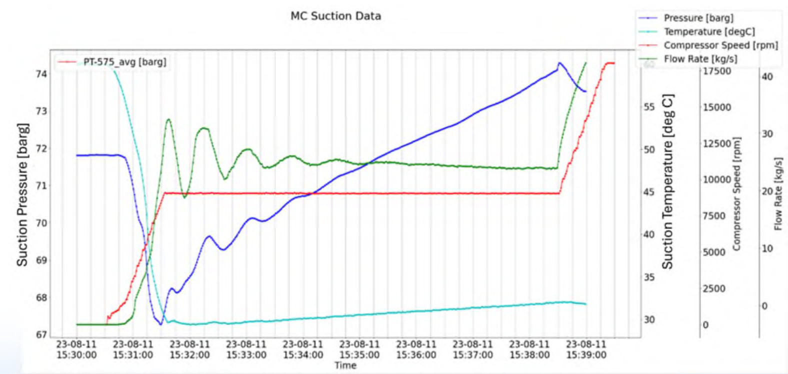
Natural gas, indirectly fired sCO_2 heater

- Must comply with NFPA codes
- Leads to fast cooling during shutdown/trip
- Slow ramp when increasing heater outlet temp:
  - 55°C/hr (0.9°C/min) below 260°C
  - 110°C/hr (1.8°C/min) above 260°C
- Rapid transient during hot startup
  - +40°C/min followed by -60°C/min

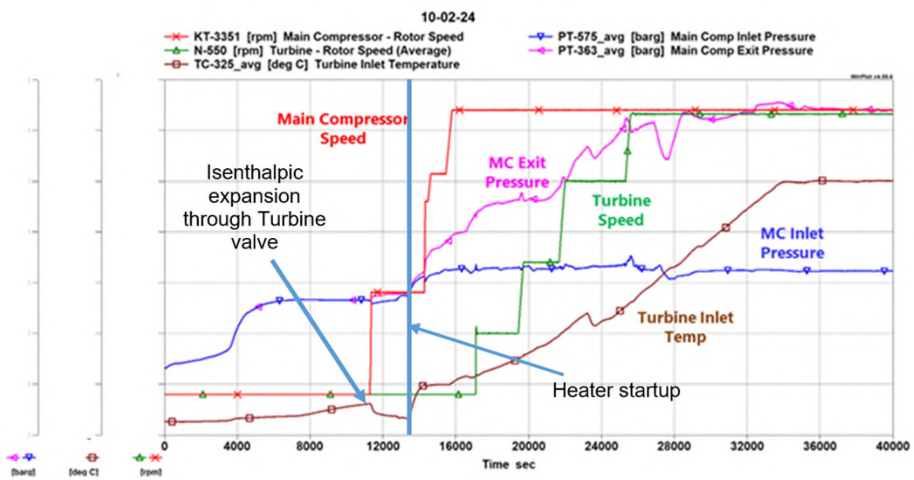
Startup Dynamics: Liquid Stagnation

- During overnight shutdowns, ambient cooling allows liquid to form in “cold” section piping
- As compressor begins rotation, liquid “slug” moves around loop and creates oscillations in pressure and temperature
- Low-speed roll implemented to allow removal of liquid (and thereby 2-phase flow) by heat addition
- Period of oscillation pattern follows approximated circulation cycle



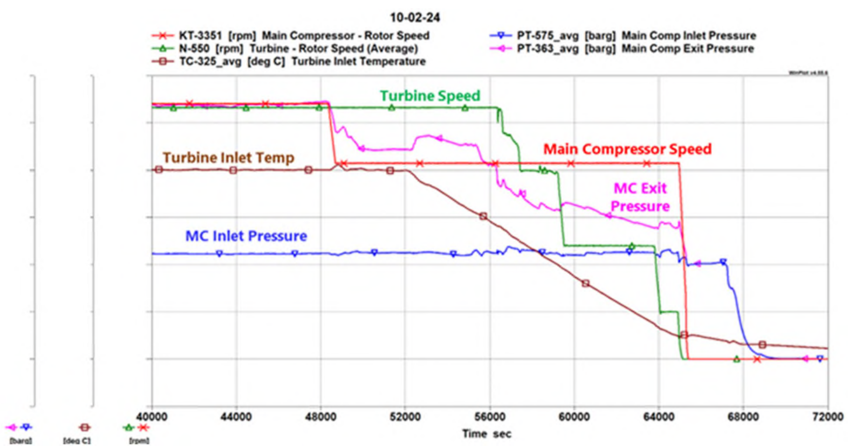


Startup Dynamics: Isenthalpic Expansion



- Compressor provides pressure build prior to flow through the turbine
- Initial flow through turbine is cooled due to isenthalpic expansion
  - Can produce liquid CO_2
- Firing the heater helps eliminate this risk however, heater controls require minimum CO_2 flow prior to firing

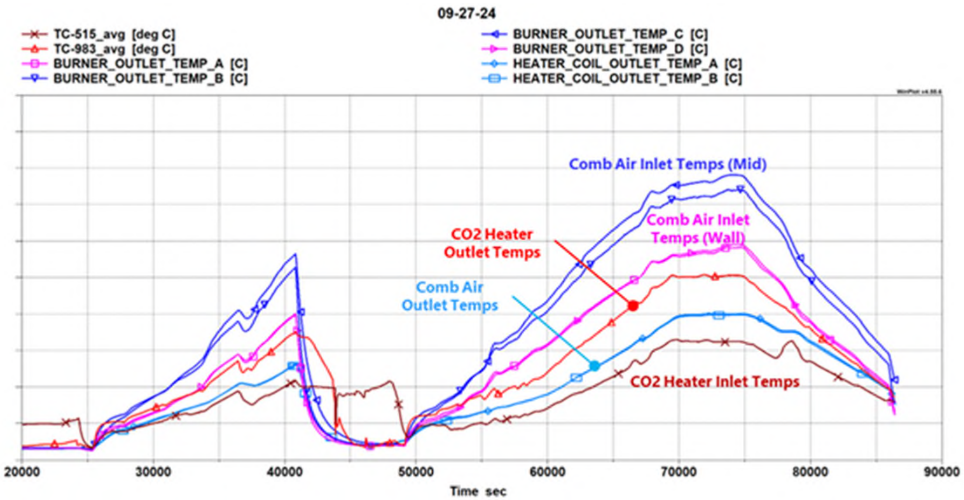
Shutdown Dynamics



Normal shutdown sequence at the STEP Demo facility in San Antonio

- Normal shutdown sequence allows for slow cooling of equipment and depressurization
- Emergency stops add much more complexity due to fast reaction requirements
  - Anti-surge controls
  - Potential PSV actuation
  - Machinery protection (like DGS's)
- Recommend to add minimum wait time for certain E-stops to prevent thermal shocks

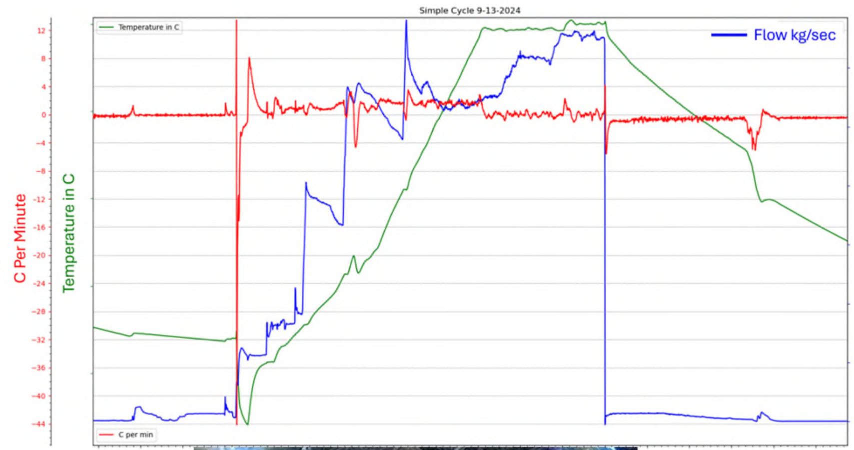
Component Design Implications



- Operating profile and expectations should be determined at an early stage of design
  - Fast start capability
  - Rapid load transients
  - Code requirements impact (such as NFPA)
- Modeling should be employed to estimate design life due to rapid transients
  - See ~41000s in figure peaks at ~300°C and comes back below 50°C at following start

Component Design Implications

- Identify localized system requirements, not only most restrictive equipment
- Turbine control valve outlet temp experienced several fast-cooling events similar to data shown
  - Led to premature cracking and loss of sealing at valve seat
  - More details in paper #69



Summary

- Identify operating scenarios early
  - Code compliance
  - Expected transients
    - Startup
    - Shutdown
    - Emergency stops
- Safety considerations

- Verify physics and thermodynamic processes
  - Closed or open system
  - Phase change phenomenon
  - Joule-Thomson effects
  - Compressibility effects

Cycle configurations must be considered independently

Gratefully Acknowledging the Support from U.S. DOE-NETL and Project Partners

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Questions?

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