Simulation of IST Turbomachinery Power-Neutral Tests with the ANL Plant Dynamics Code

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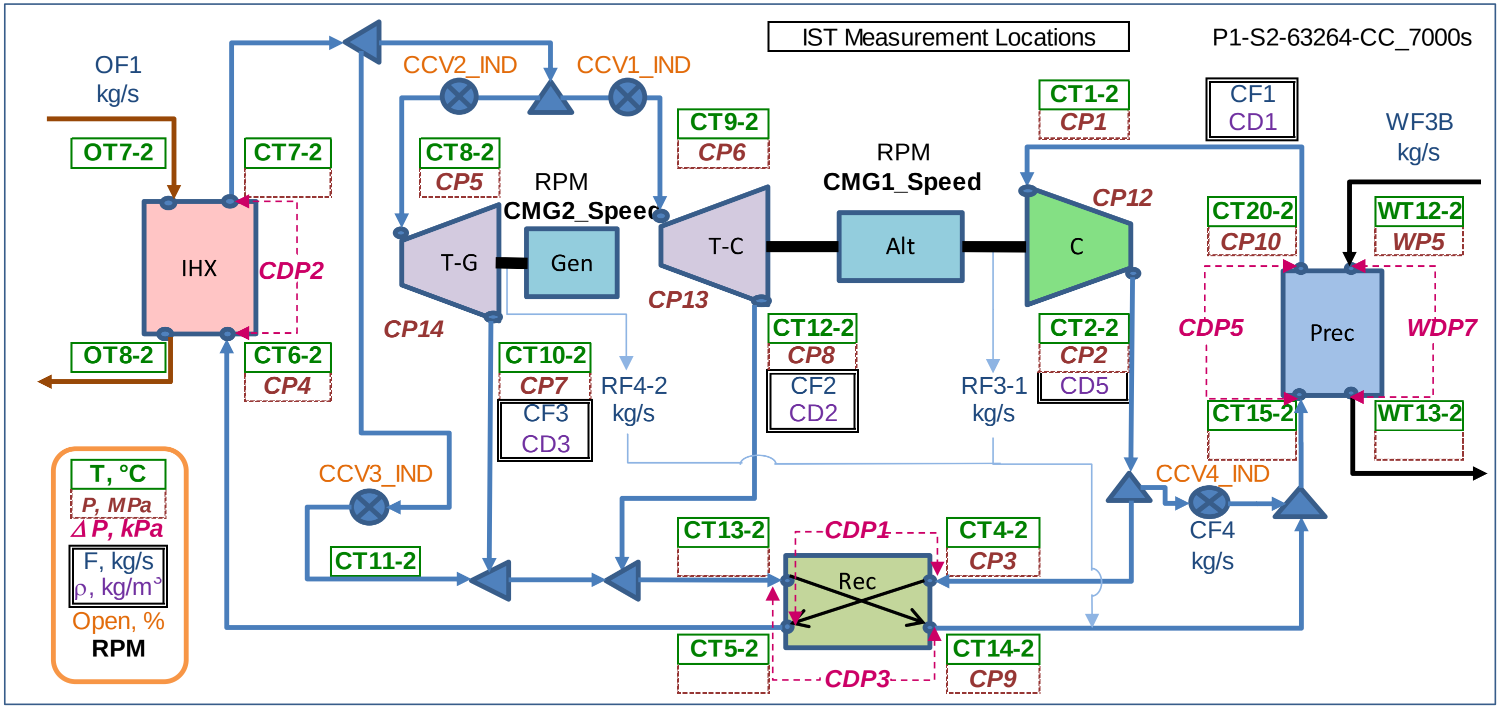
ANL Plant Dynamics Code (PDC)

- **Specifically developed for analysis of sCO_2 cycles**
  - One-dimensional system level transient analysis code
  - Targets the specific features of the cycle
    - Operation close to the critical point
    - Recompression cycle (if needed)
  - Real CO_2 properties
    - Property variations in HX's and turbomachinery
    - No simplifying ideal gas assumptions
    - Compressibility effects
- **Incorporates sCO_2 cycle control mechanisms and logic**
- **Incorporates steady-state design code to determine cycle initial conditions**
- **Design and performance subroutines for both turbine and compressor**

- **This presentation describes validation work with Naval Nuclear Laboratory IST data**

Naval Nuclear Laboratory's Integrated System Test

- ≈1 MWt heat input through oil-to-CO_2 HX
- Simple (not recompression) cycle configuration, one recuperator
- Two turbines, one drives compressor
- Turbomachinery leakage collection system



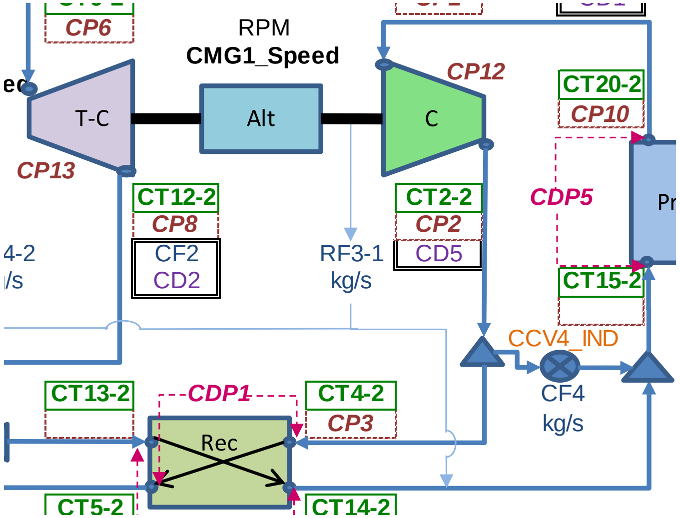
Simulated Tests

- **First PDC validation results with IST data were reported at the 5th sCO_2 Symposium in San Antonio in 2016**

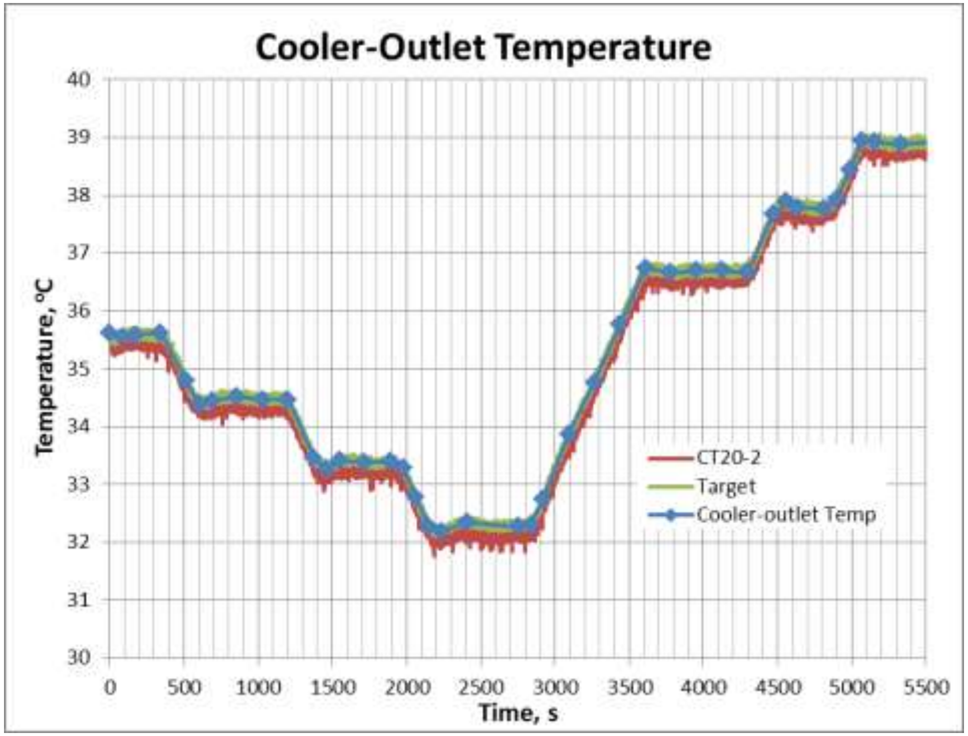
- **Recently, new IST test data was provided to ANL**
  - Same test configuration and equipment

- **Power-neutral operation of the turbine-compressor unit**
  - No power in alternator
  - TAC is free to change speed
  - Speed is controlled by Recirculation Valve

- **Benefits for PDC validation**
  - Shaft dynamics
  - Equivalent to turbine bypass control and compressor surge control



Test 64661: Compressor-Inlet Temperature Sensitivity



- **CIT was commanded to change**
  - By means of water flow control
- **Turbine-Compressor speed of 48,675 rpm is requested**
  - Controlled by CR valve
- **Test duration: 5,500 seconds (1.5 hours)**
- **All other inputs are basically fixed**
  - Turbine-Generator speed, Turbine-inlet temperature, oil flow rate
  - No turbine bypass or throttling
- **Expected outcome: Lower CIT -> Decreased compressor work -> TC tends to increase speed -> Need to open CRv to maintain speed**

PDC Simulation of Test 64661

- **Three stages**
  1. Steady-state for conditions prior to the test
     - Good agreement, except:
     - Larger than before discrepancy in flow split between turbines
     - Attributed to the recent change in turbine materials, which might affect clearances at operation
  2. Transient with given TC speed and CR valve position
     - Same mode as previous PDC simulation of IST tests
     - To validate cycle response
  3. Full simulation with TC speed control
     - To validate the shaft speed control

PDC Simulation of Test 64661: Transient

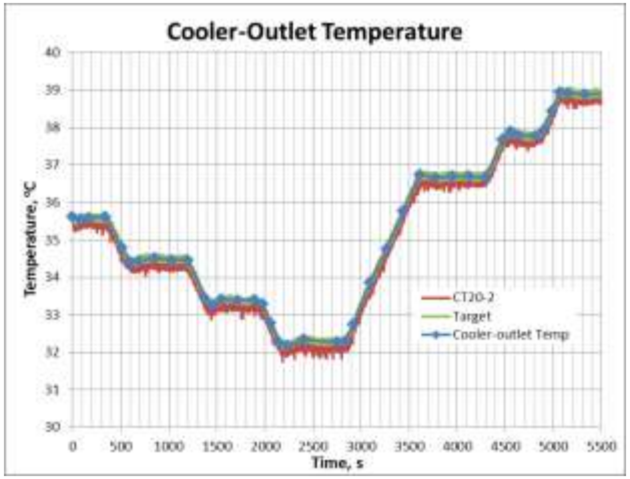
- **First transient results showed much slower cooler response in PDC**
  - Resulting in much larger oscillations of water flow rate

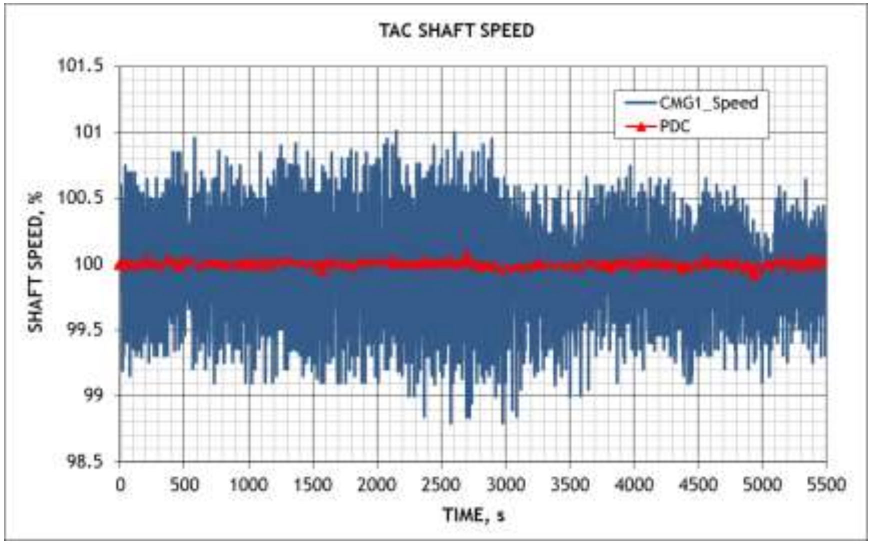
- **Error in the shell-and-tube heat exchanger tube mass was discovered and corrected**
  - Both SNL RCBC and all recent sCO_2 control analysis used PCHE
    - Shell-and-tube HX tube mass error neither affected those results nor could be identified from previous validation

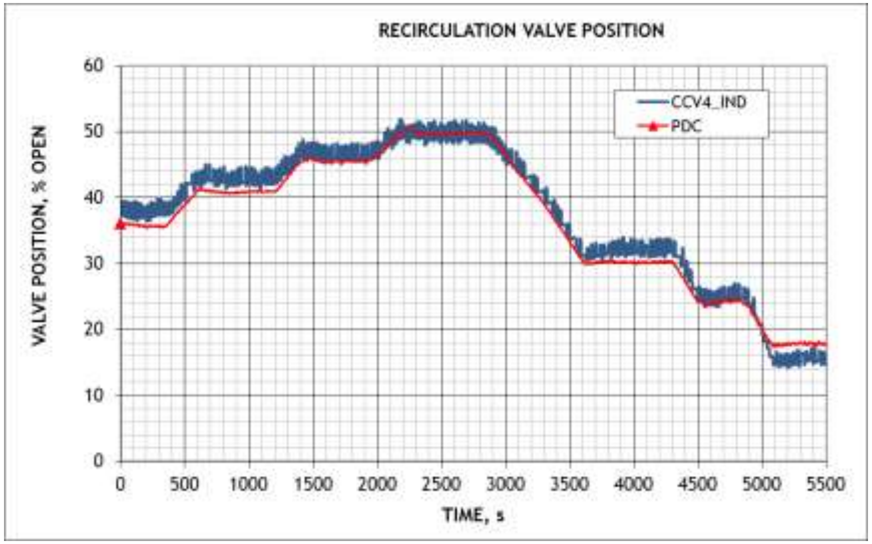
PDC Simulation of Test 64661: Full Transient

- **PDC maintains TC speed**
  - Even better than the actual test
    - Not including dead bands, electronic delays, etc.

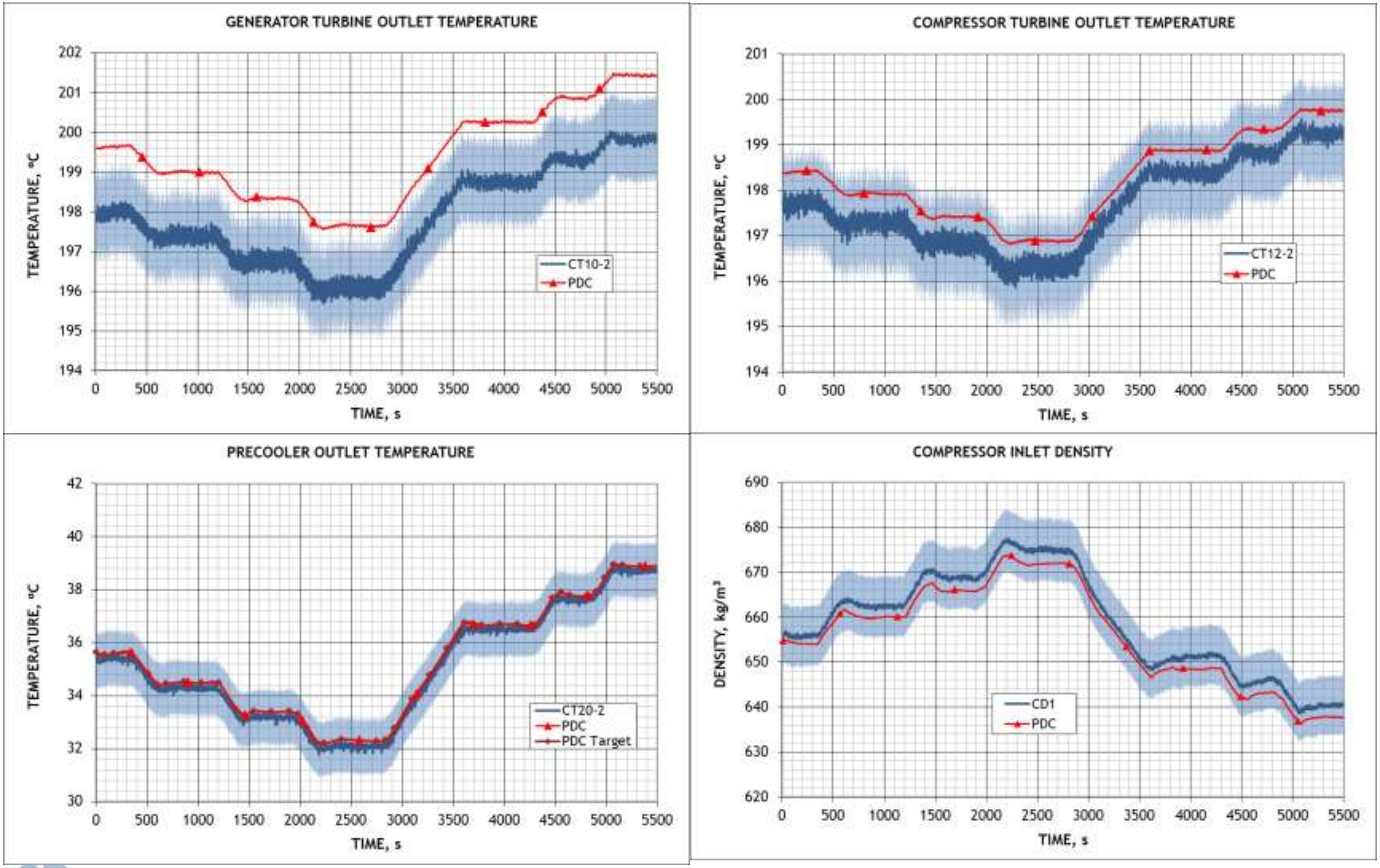
- **Very good agreement on the CRv position**



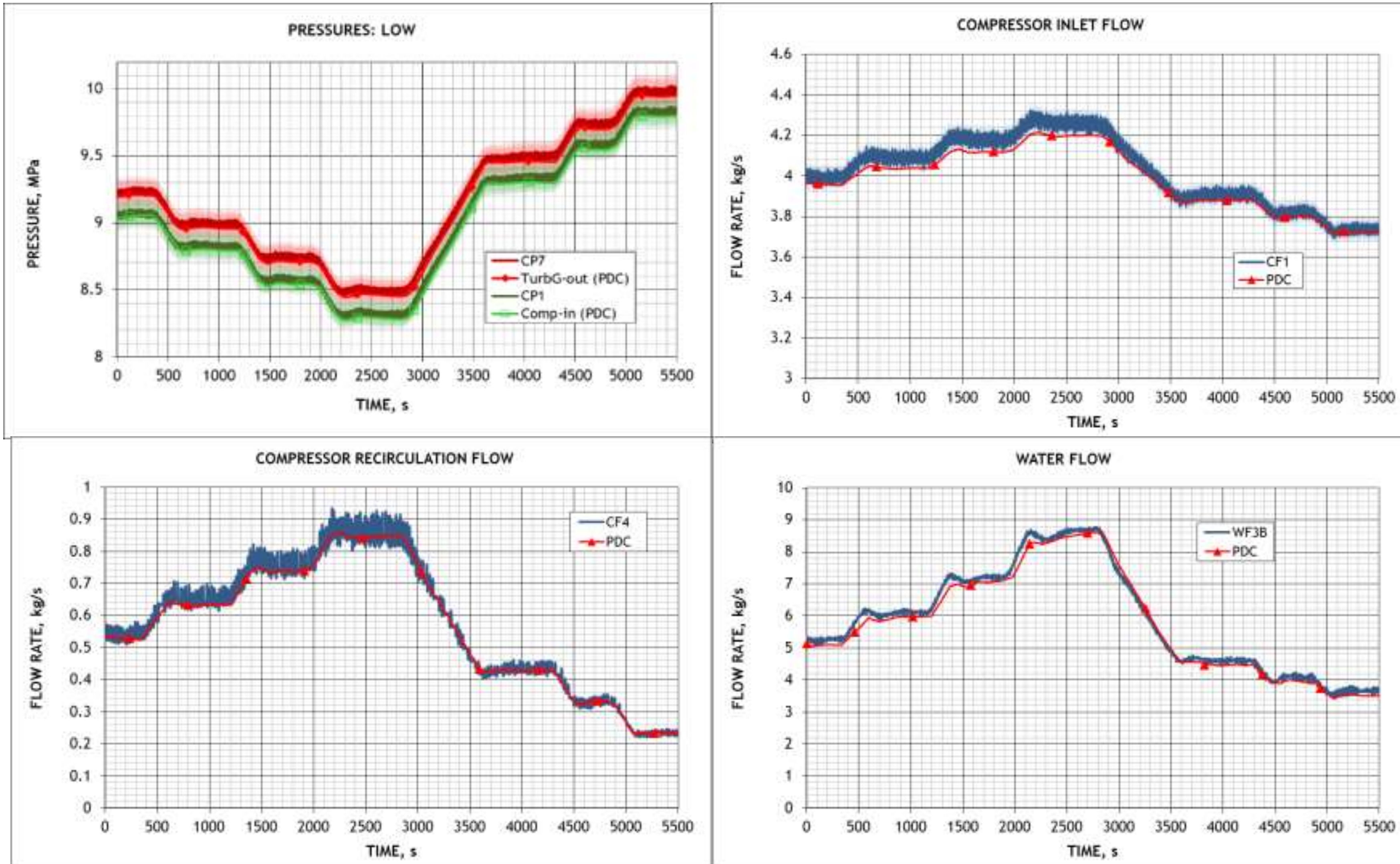




PDC Simulation of Test 64661: Full Transient

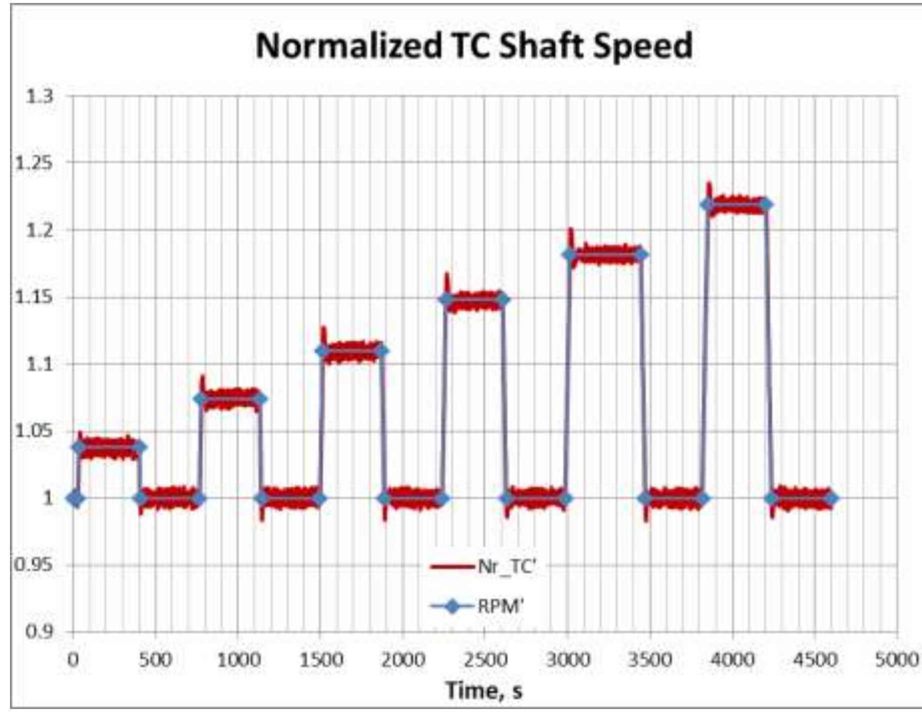


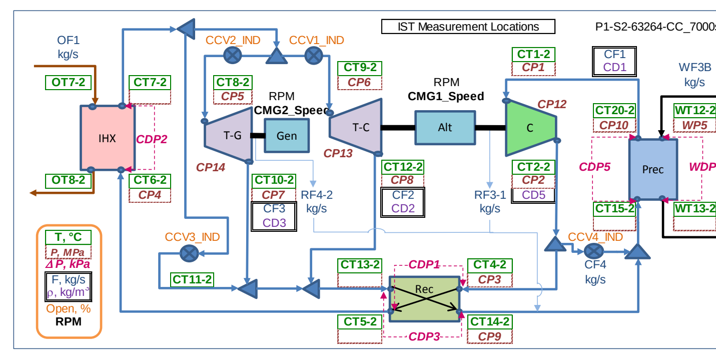
PDC Simulation of Test 64661: Full Transient



Test 65261-P: Varying Power Test

- **TC speed was commanded to change**
  - Between 42,000 and 52,000 rpm
- **Corresponds to pre-calculated TG power**
  - Between 5% and 35%
  - Higher TC speeds increases CO_2 flow rate in TG
- **Test duration: 4,600 seconds (1.3 hours)**
- **All other inputs are basically fixed**
  - TG speed, Turbine-inlet temperature, compressor-inlet temperature, oil flow rate
  - No turbine bypass or throttling



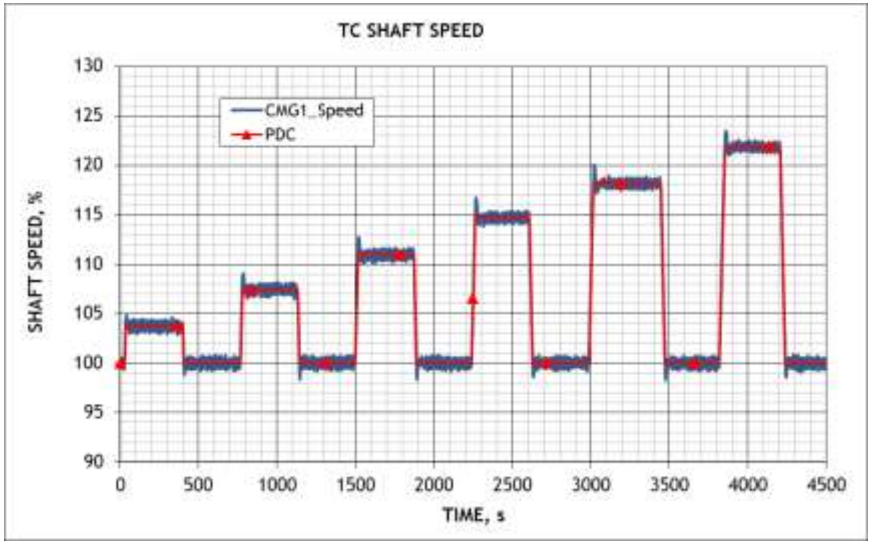


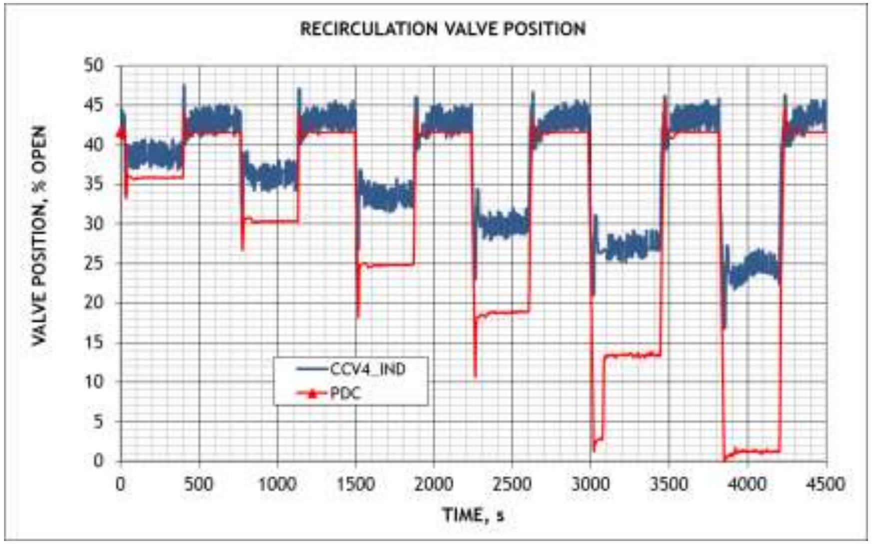
PDC Simulation of Test 65261-P

- **Same three stages**
  1. Steady-state for conditions prior to the test
  2. Transient with given TC speed and CR valve position
  3. Full simulation with TC speed control
- **Level of agreement for Steady-state and Stage 2 are similar to the Test 64661**
  - Largest discrepancies are generator turbine outlet temperature and flow split between the turbines

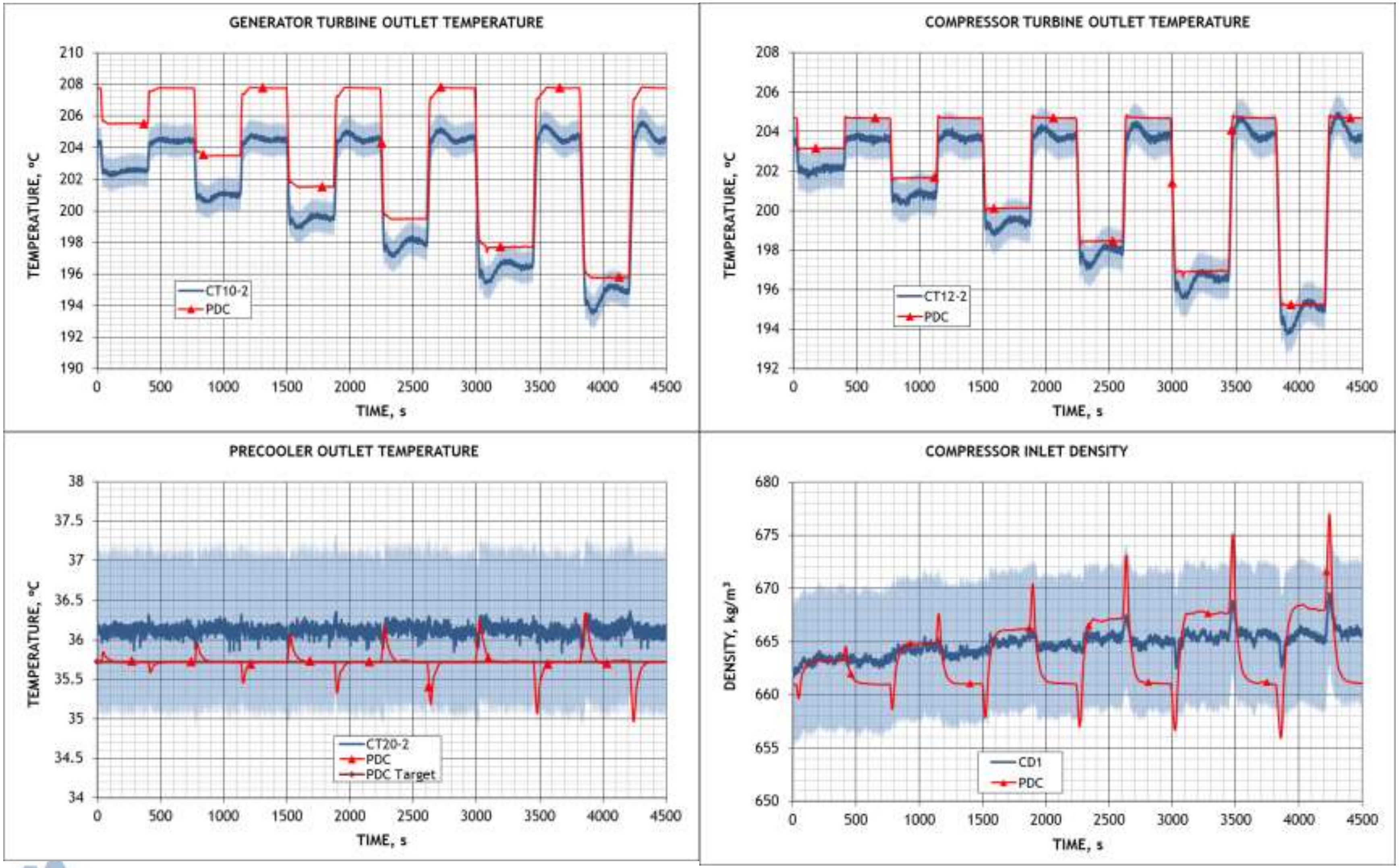
PDC Simulation of Test 65261-P : Full Transient

- **PDC matches TC speed**
  - Validates control setup
- **Predicted CRv position progressively deviates from test data, as speed increases**
  - Issue with scaling shaft windage losses with speed only
    - Neglecting cavity pressure and fluid density effect (not modeled)

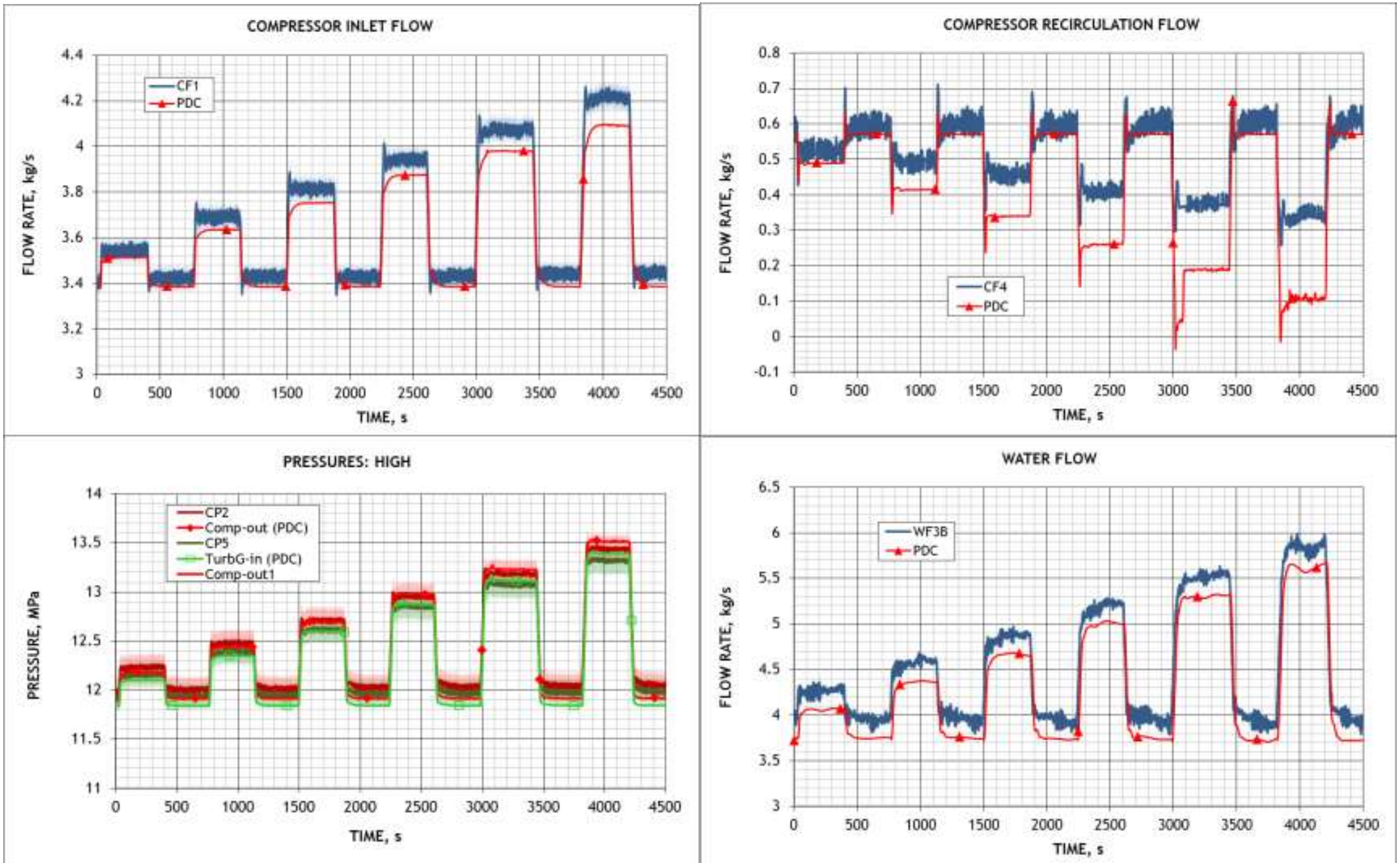




PDC Simulation of Test 65261-P : Full Transient



PDC Simulation of Test 65261-P: Full Transient



Summary

- **Validation of PDC for sCO_2 cycle has been continued**
  - With new test data from IST
  - Test 64661: Compressor-Inlet Temperature Sensitivity
  - Test 65261-P: Varying Power Test
- **Power-neutral operation of turbine-compressor shaft**
  - No external power or control from alternator
  - Shaft speed is determined from shaft power balance
  - Speed controlled by compressor recirculation valve
- **New test data is important for PDC validation**
  - Allows validation of the shaft dynamics equations in asynchronous mode
  - Shaft speed control with the CR valve allows for testing the code control logic
  - Also serves as a good test for validation of both the compressor surge control and the turbine bypass control actions
  - Varying compressor-inlet temperature change test allows validation of the transient response of the precooler

Summary

- **New test data was obtained in the same loop configuration and the same equipment as the previous data analyzed**
  - No changes to the PDC input (except for transient definitions)
  - However, the turbomachinery equipment was rebuilt several times
    - Including a material change
    - Possible effect on the clearances
- **PDC simulation was done in three stages**
  - Steady-state
    - Good agreement, except generator turbine performance
  - Transient with given TC speed and CRv position
    - Same as previous work
    - Helped to identify an error with shell-and-tube HX tube mass
  - Full transient with active control
    - Validates control setup and shaft speed equations
    - Both test results show good agreement
    - TC shaft power balance affected by windage losses approximation