Integrated Transient Modeling of Gas Turbine and sCO_2 Power Cycle for Exhaust Heat Recovery Application

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Project Objective and Key Partners

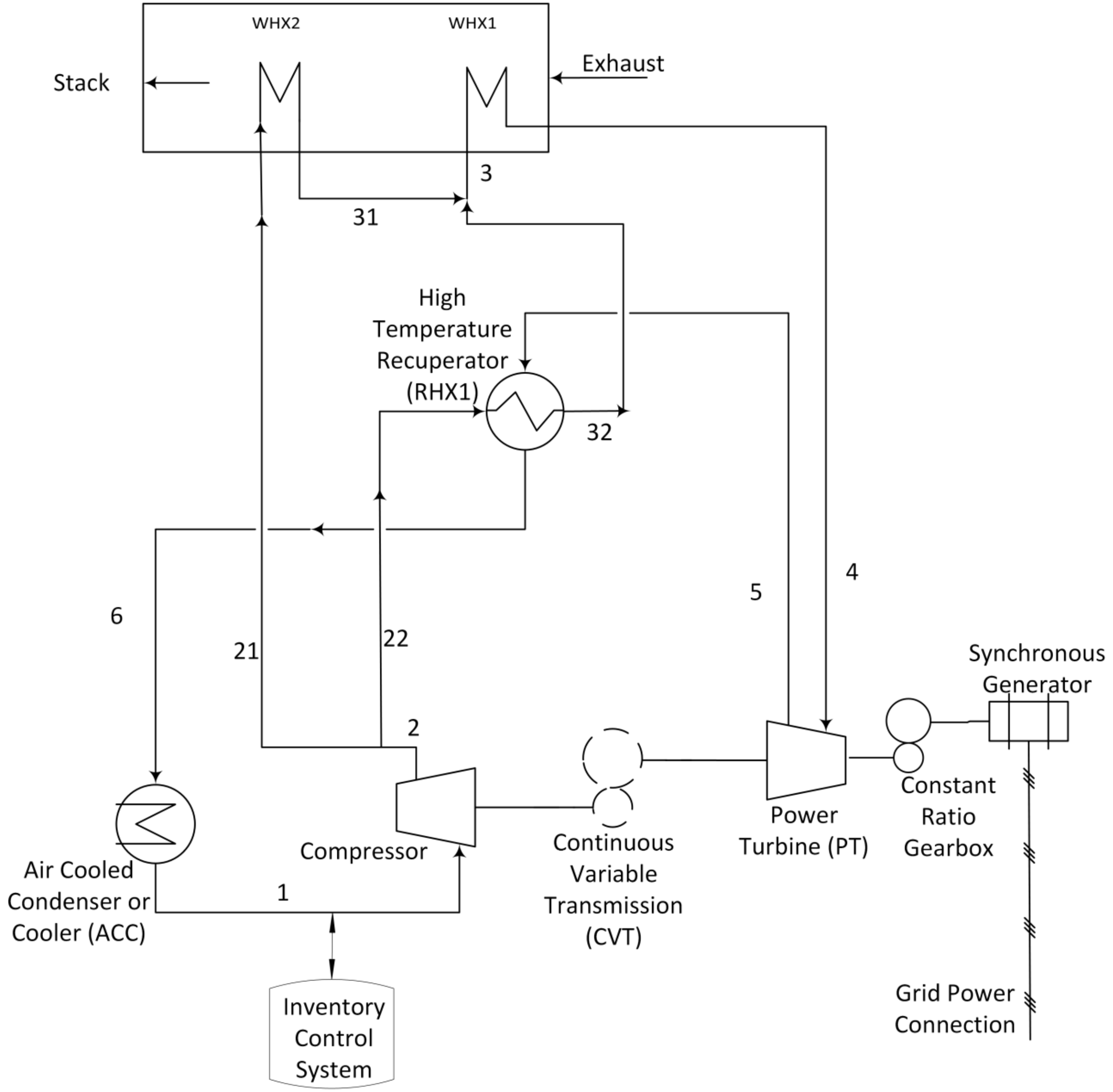
Objective: Integration of SGT-750 gas turbine transient model with sCO_2 power cycle transient model for exhaust heat recovery study and run simulations on the integrated model using representative micro-grid load profile.

- **Echogen Power Systems:** Acted as prime partner in (i) development of sCO_2 power cycle transient model in GT-Suite (ii) integration of gas turbine transient model with sCO_2 power cycle (iii) Controls development and simulation of integrated gas turbine/sCO_2 power cycle transient model using micro-grid load profile.
- **Siemens Industrial Turbomachinery in Finspang, Sweden:** Provided SGT-750 gas turbine transient model as a Functional Mock-up Unit (FMU) (basically a 'black-box' model) for integration with sCO_2 power cycle transient model.
- **Siemens PTI Group:** Provided micro-grid load profile for simulation of integrated gas turbine/sCO_2 power cycle transient model.

Key Design Point Considerations

- SGT-750 is a twin-shaft gas turbine with about 40MWe capacity with efficiency of about 40% at ISO conditions.
- At 100% gas turbine throttle (load), the SGT-750 has average exhaust conditions of 114.6 kg/s and 469.8*C.
- 15*C ambient temperature.
- sCO_2 flow circuit has single-shaft turbomachinery with net 11.5MWe power output at design conditions.

sCO_2 Power Cycle Architecture

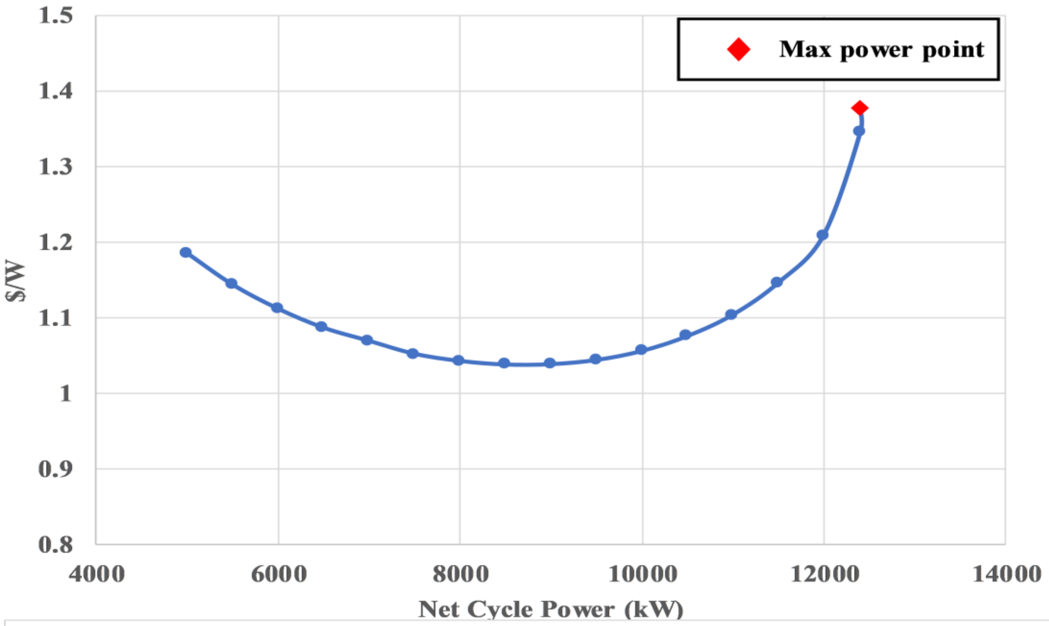


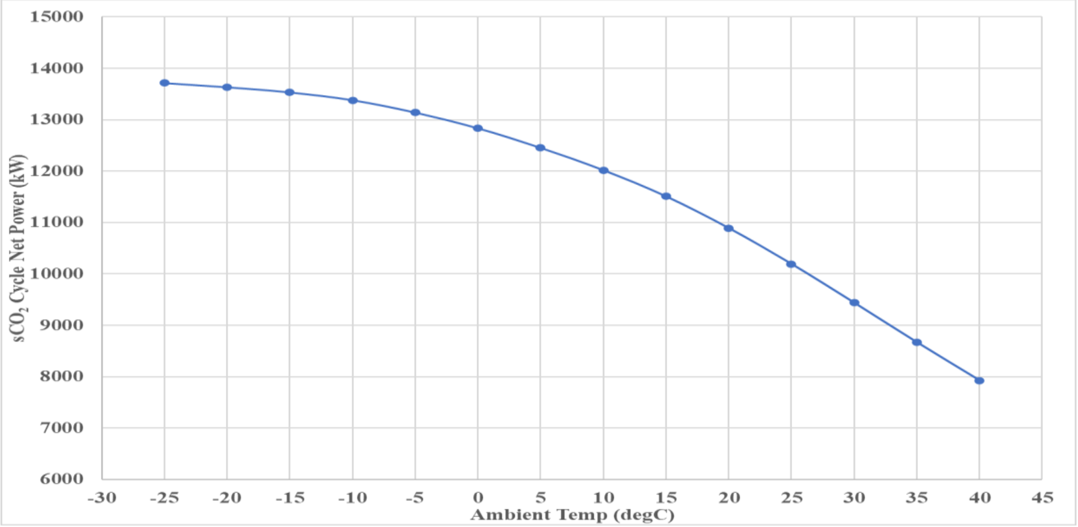
sCO_2 Power Cycle Sizing

sCO_2 cycle design point boundary conditions				sCO_2 cycle constraints		
Exhaust flow (kg/s)	Exhaust temperature (°C)	Ambient temperature (°C)		Minimum exhaust stack temperature (°C)	Maximum sCO_2 cycle pressure (MPa)	Minimum allowable power cycle temperature (°C)
114.6	469.8	15.00		85.00	25.00	5

- In-house written Matlab Techno-Economic Optimization Code (or simply 'optimizer' code) was used to size the sCO_2 power cycle.
- Optimizer code was used in three step process:

1. Power Optimization: to maximize net sCO_2 cycle power
2. Cost Optimization: For a given load optimize power cycle cost which helps in selecting the sCO_2 power cycle size.
3. Ambient 'sweep': Fixing the equipment sizes from step-2, run power optimization over ambient range (-25*C to 40*C). <u>This data is used to size and validate components in transient model.</u>





sCO_2 Power Cycle Transient Model in GT-Suite

- The transient model for sCO_2 power cycle was developed in GT-SUITE 1D system simulation software platform. In flow simulations (of present work), GT-SUITE solves 1D Navier-Stokes equations along flow components and solution convergence is checked using pressure, continuity and energy residuals.
- Component templates can take manufacturer data or test data or purely based on empirical correlations to size the component.
- Individual components can then be simulated using subsystem boundary conditions before being incorporated into full system model. – Switch to GTS window to show an example

sCO_2 Cycle Transient Model: Heat Exchangers

WHX1, WHX2 and ACC physical parameters

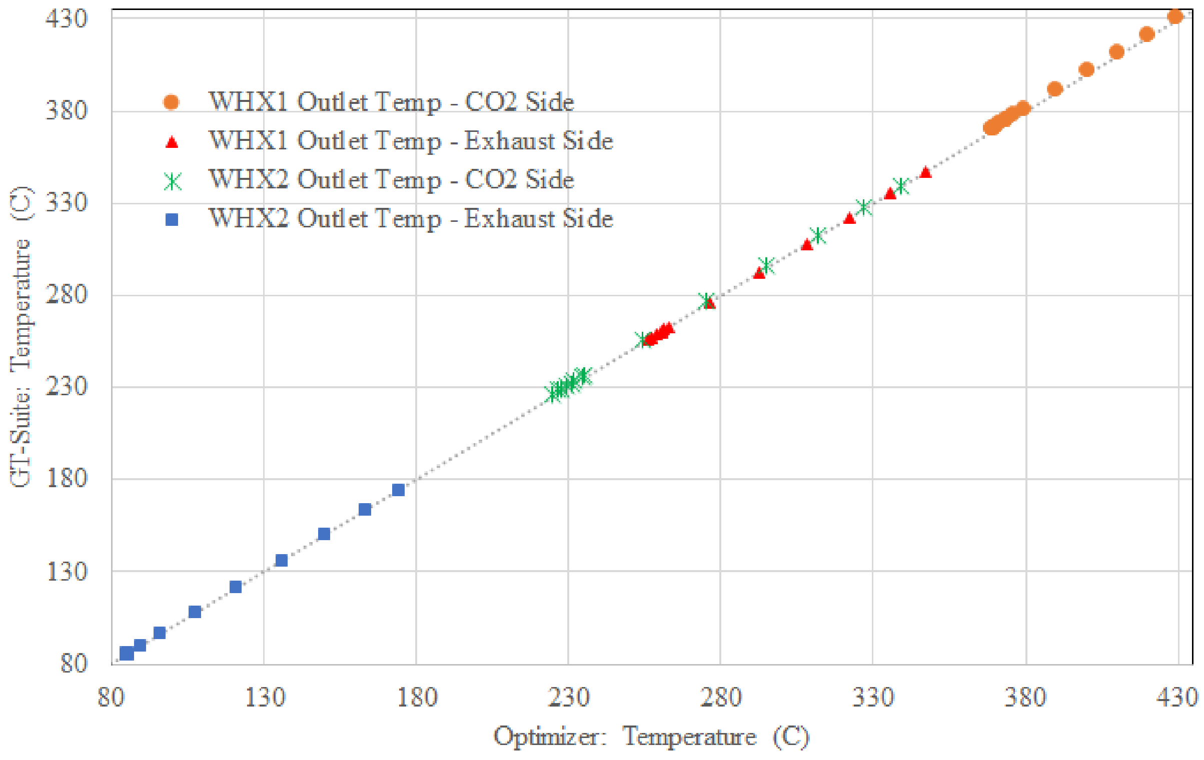
	WHX1	WHX2	ACC: single-bay
Dry mass, kg	92,532.8	174,179	20,030.6
Height(m) x Width(m) x Depth(m)	11 x 6.5 x 3.6	11 x 6.5 x 3.6	4.3 x 15.8 x 0.33
Inlet connection diameter, cm (in)	28.4 (11.2)	17.3 (6.8)	29.2 (11.5)
Outlet connection diameter, cm (in)	32.5 (12.8)	17.3 (6.8)	29.2 (11.5)
Circular channel diameter, cm (in)	3.81 (1.5)	3.81 (1.5)	2.2 (0.87)
Fin density, 1/m (1/in)	236 (6)	236 (6)	394 (10)
Number of tubes in the direction of exhaust (or air) flow	5	10	6
Number of tubes perpendicular to the direction of exhaust (or air) flow	64	64	67
Total number of bays	-	-	6
Fans per bay (total fans)	-	-	3 (18)

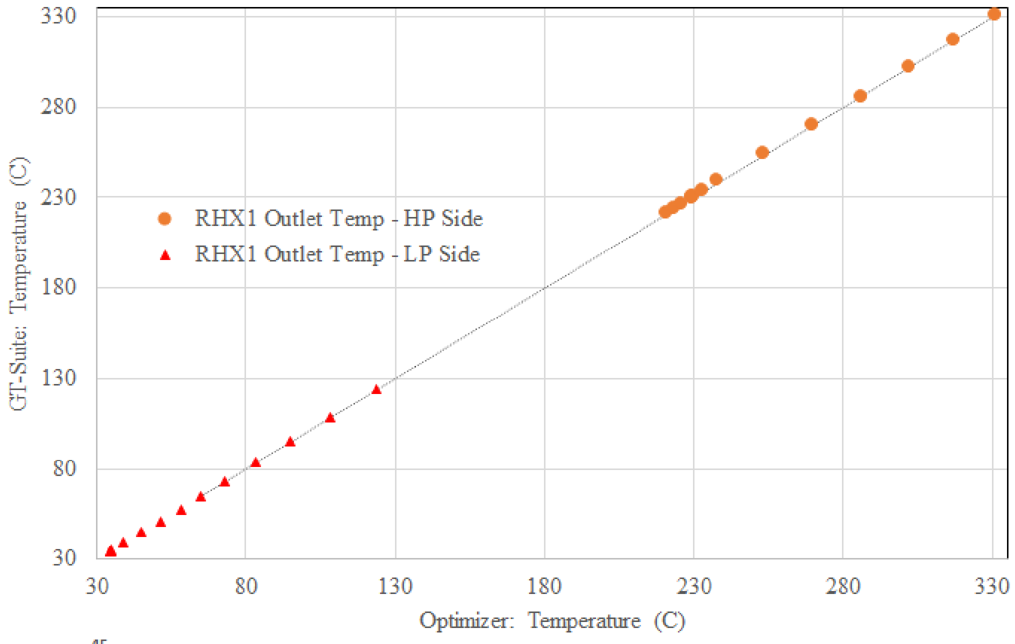
RHX1 physical parameters

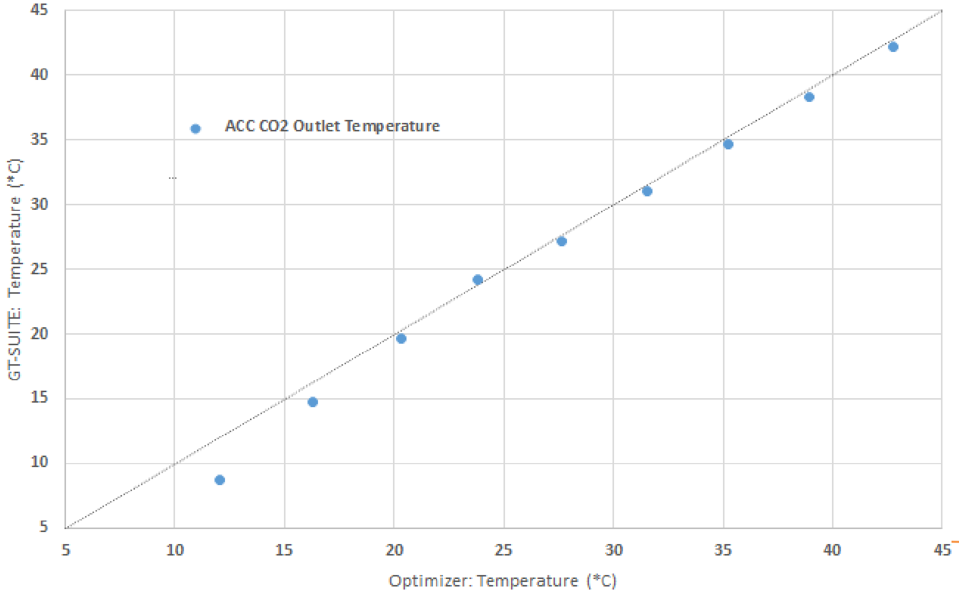
Dry mass, kg	10,400
Plate length (cm)	156.2
Plate width (cm)	59.6
Plate wall thickness (mm)	4
High pressure side connection diameter, cm (in)	21.6 (8.5)
Low pressure connection diameter, cm (in)	54.7 (21.5)
Number of plates of high and low pressure side	300
Heat transfer area multiplier	6

- WHX1, WHX2 and ACC were modeled as finned-tube heat exchangers.
- Recuperator is modeled as plate heat exchanger.

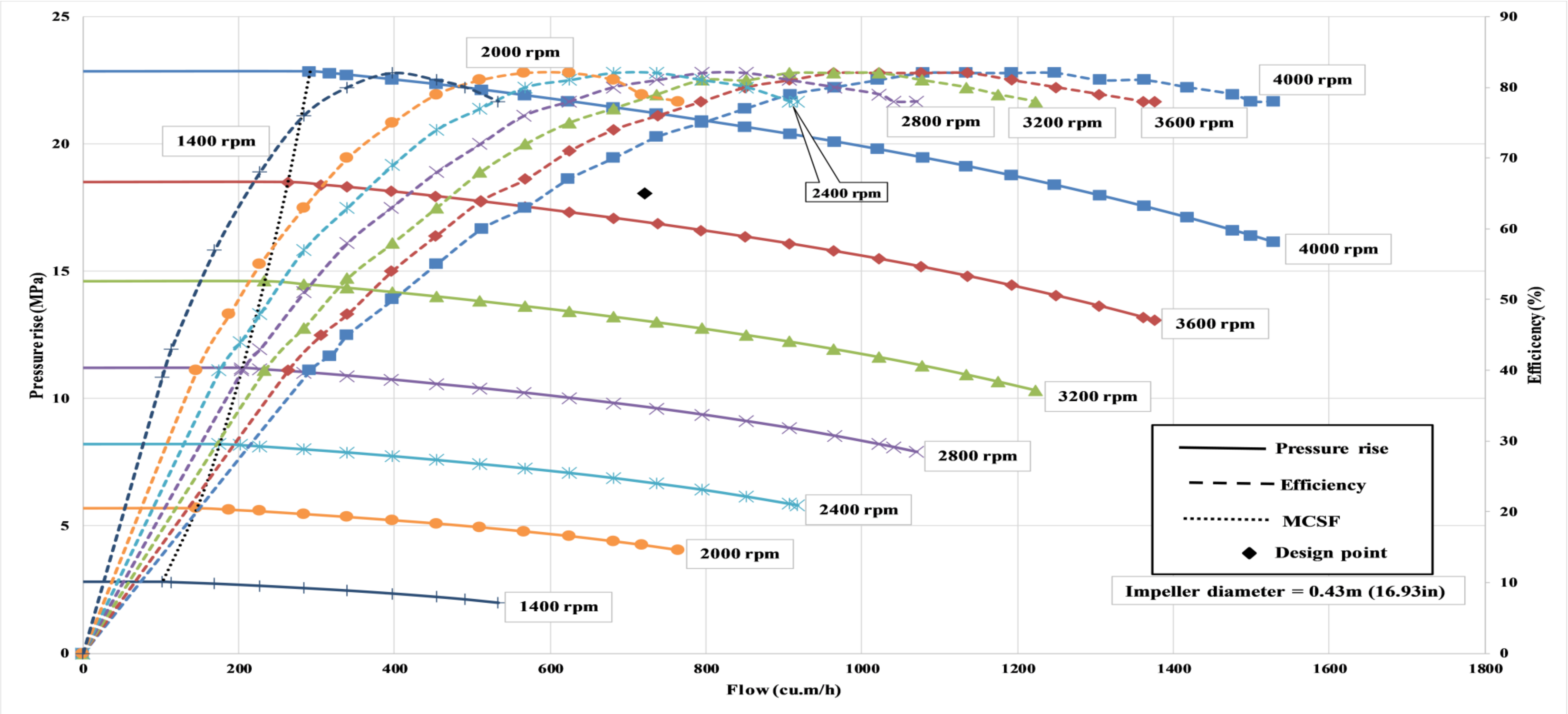
sCO_2 Cycle Transient Model: Heat Exchangers





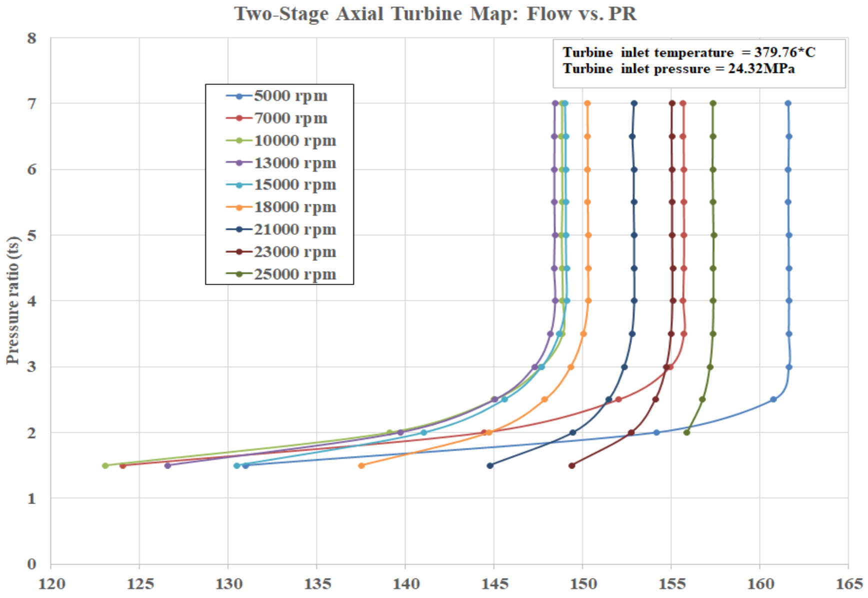


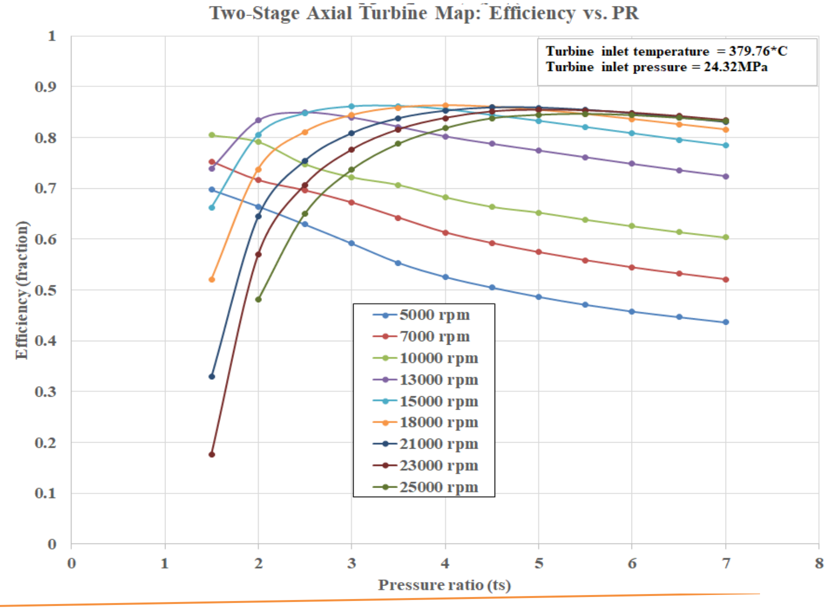
sCO_2 Cycle Transient Model: Compressor



- Multistage (8) CO_2 compressor curve was selected from Sulzer pump catalog.
- Design point: Flow= 722m^3/h; Pressure rise= 18.06MPa; Efficiency=75%.
- Compressor map was directly supplied to GTS pump template.

sCO_2 Cycle Transient Model: Power turbine





Two-stage axial turbine design constraints considered and achieved values

	Design Constraint		Design Achieved Values
Parameter	Min	Max	
Shaft Power (kW)	17000	-	17326.2
Stress (MPa)	-	360	132.679
(AN)^2 (m^2*rpm^2)	-	2.80E+07	6.20E+06
Zweifel factor in Rotors	-	1.15	0.645735
Zweifel factor in Stators	-	1.15	0.655249
Seal tip clearance (mm)	0.1	1	0.3
Blade height (m)	0.007	-	0.0128691
Hub separation between blades (m)	0.0025	-	0.0103891
Pressure reaction in rotors (ReactionPts)	0.05	0.6	0.537491
Hub speed (m/s)	-	320	231.055

- Concepts NREC meanline code was used to develop two-stage axial turbine.
- Design point: Speed= 15000rpm; PR= 3.6; Efficiency=86.2%
- Map generation: Speed:5000 rpm to 25000 rpm increments of 1000 rpm; PR: 1.5 to 7.0 increments of 0.5; and turbine inlet temperature 287.9 C to 429.7 C
- PT map was directly supplied to GTS turbine template.

sCO_2 Cycle Transient Model: Control System

Four major control parameters have been considered

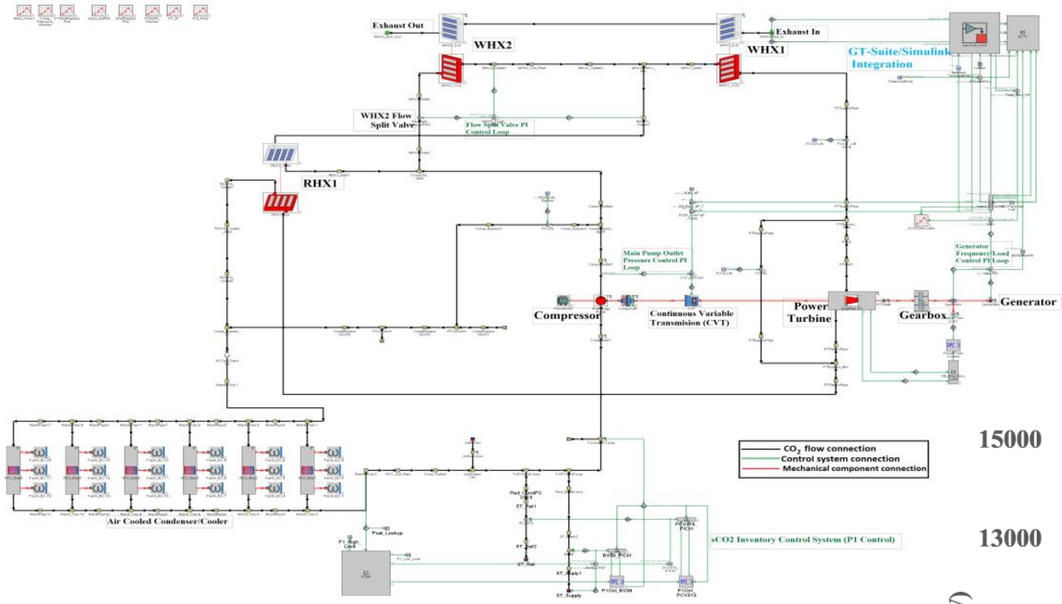
1. Compressor inlet pressure (designated as P1) using inventory control system (ICS).
2. Continuous variable transmission (CVT) maintains compressor outlet pressure (designated as P2) at a setpoint. A 2D table, generated using optimizer (TEOC) data, is supplied to the model.

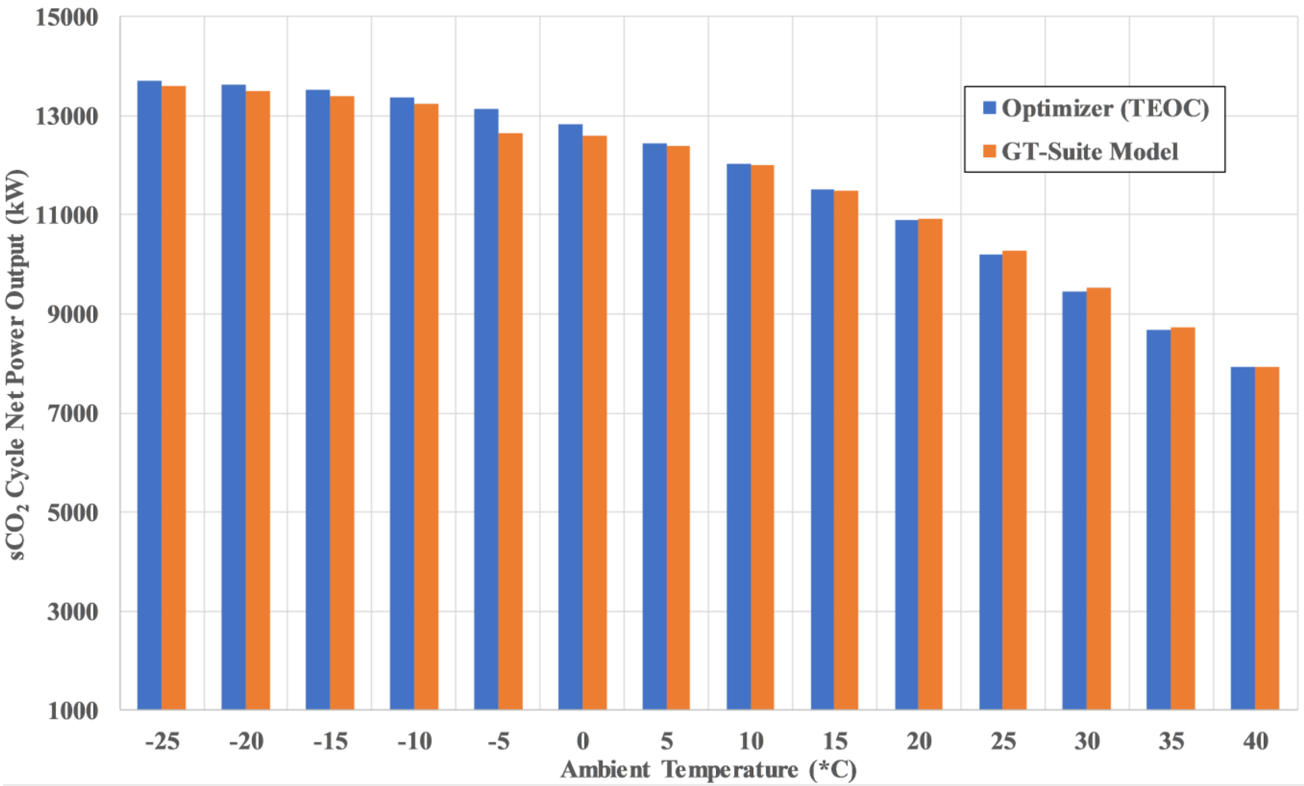
$$P2 = f(T_{exht}, dP_{exht})$$

3. Generator speed is controlled to synchronous speed of 1800 rpm (4-pole generator) by varying generator load.
4. CO_2 flow to WHX2 coil is varied by controlling lift on a flow split valve to match WHX2 and RHX1 outlet temperatures.

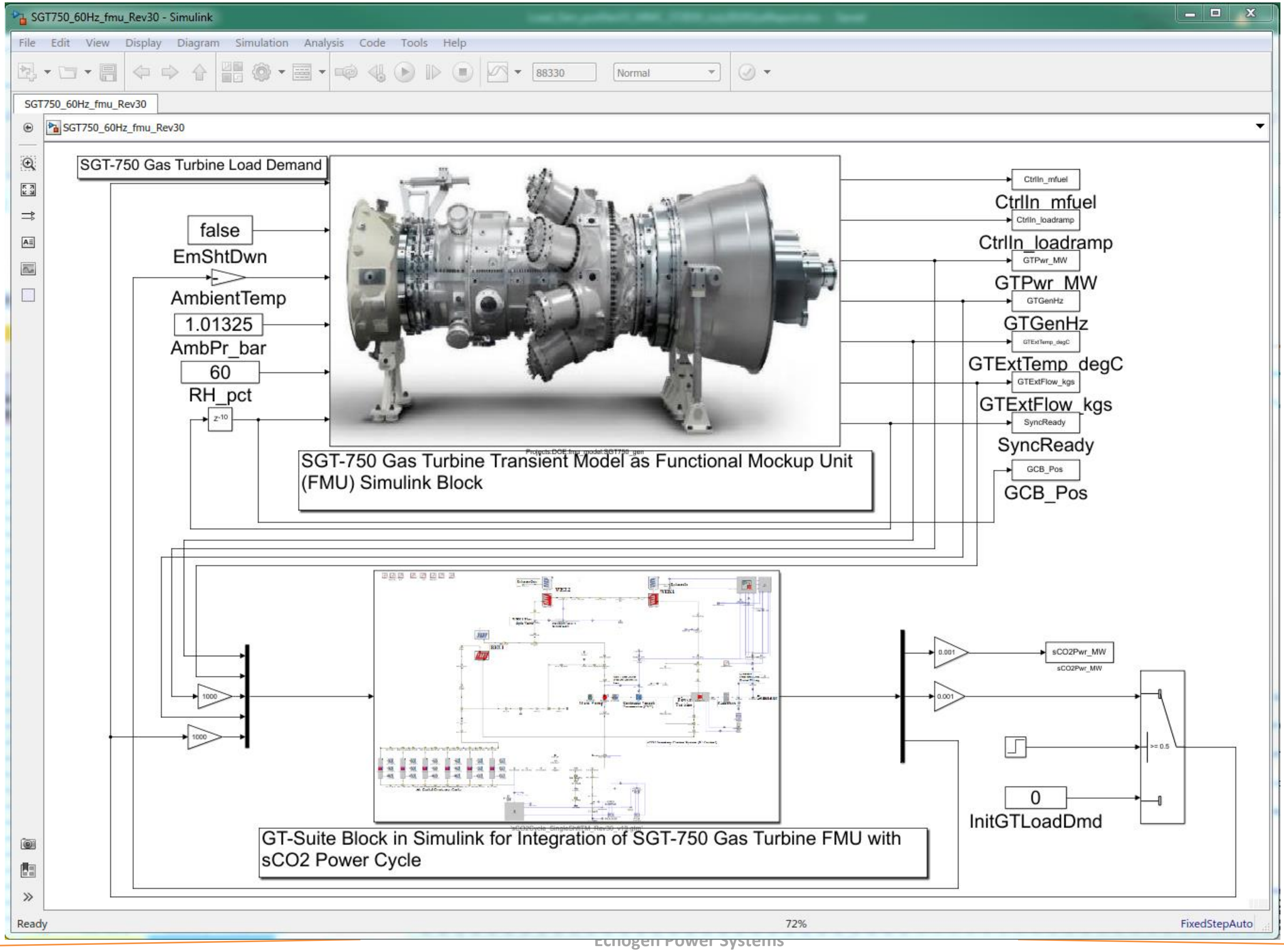
- Classical proportional-integral (PI) formulations, with the proportional gain and integral times were used.

sCO_2 Power Cycle Transient Model in GT-Suite

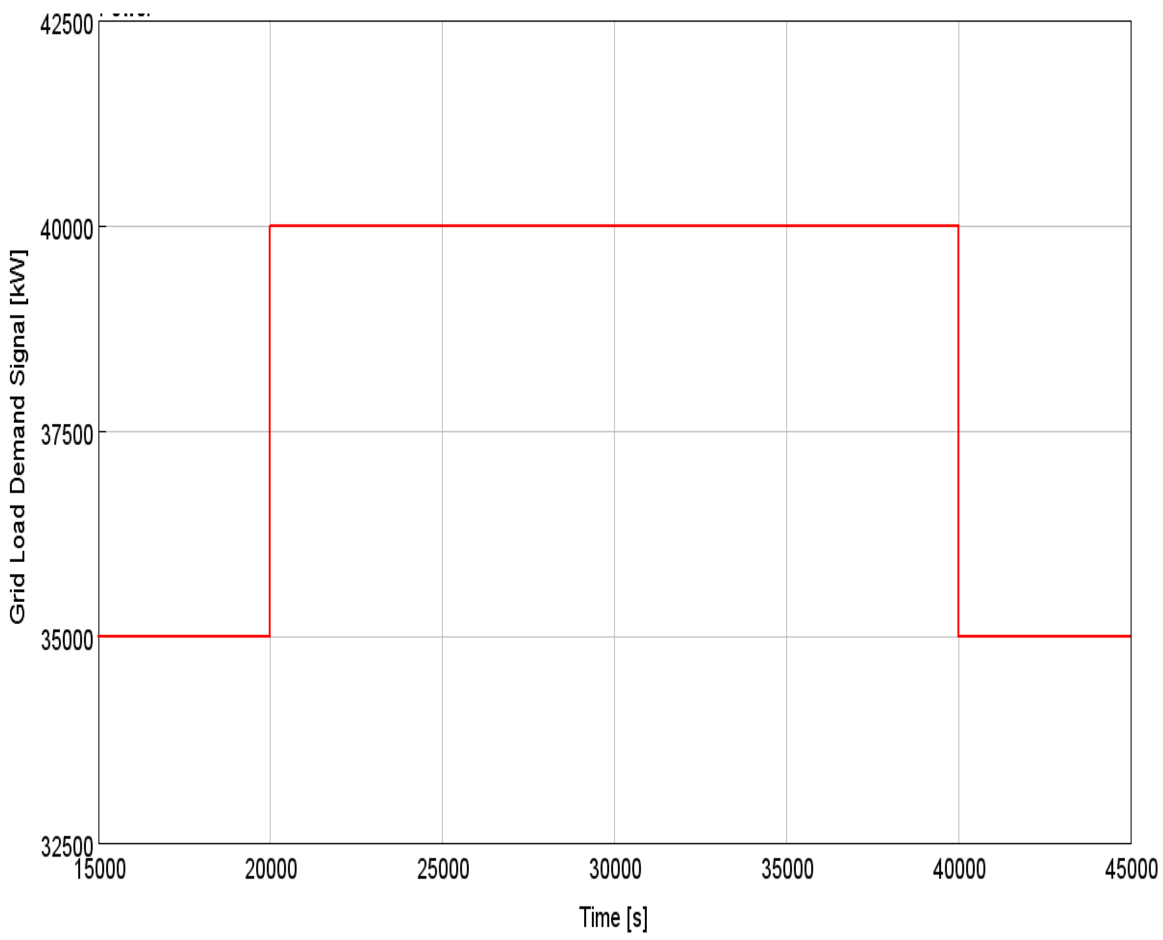


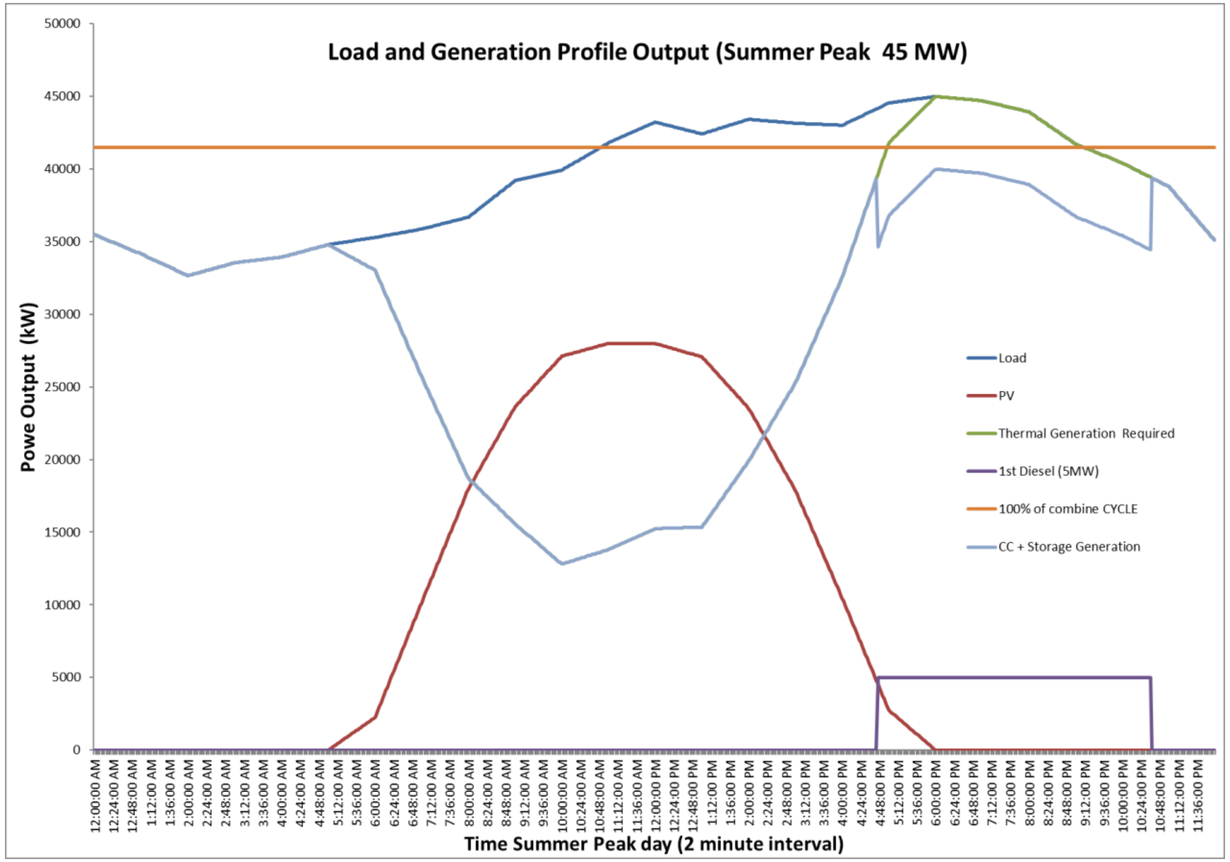


SGT-750 FMU and Integrated GT/sCO_2 Model



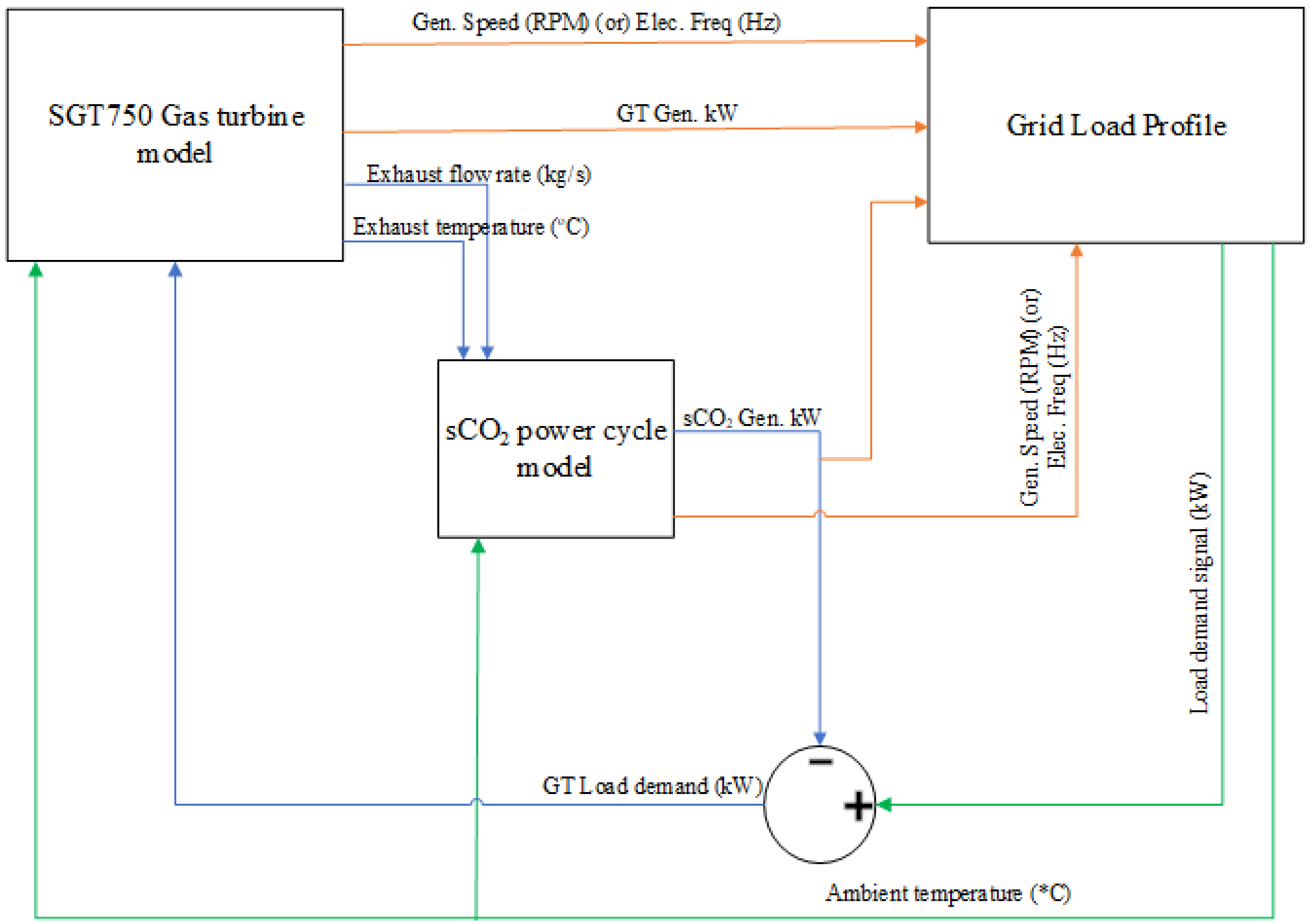
Grid Load Profile



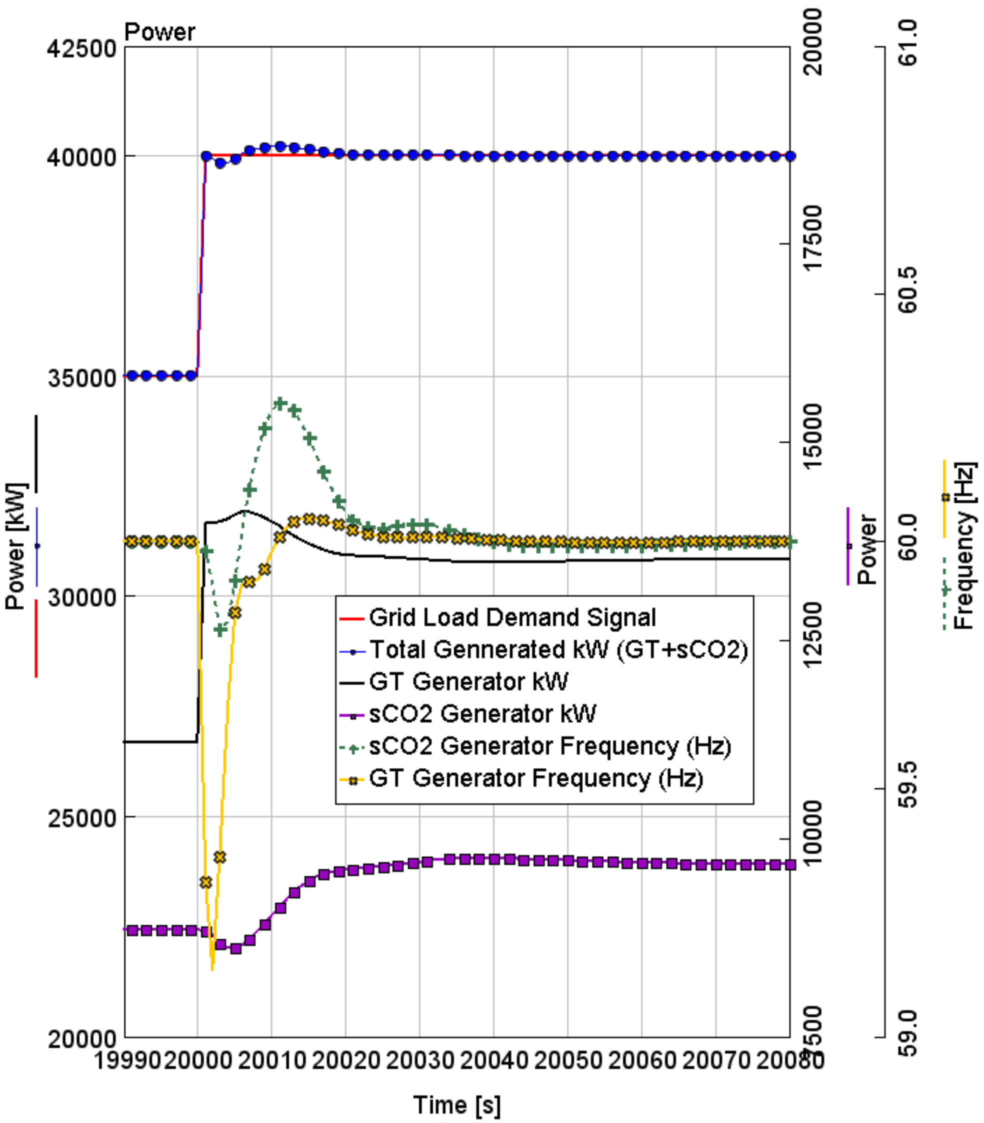


Interface Points for Integrated Model

Interface Points for Gas turbine-sCO_2 Power Cycle-Grid models



Integrated Transient Model Results – Step Response



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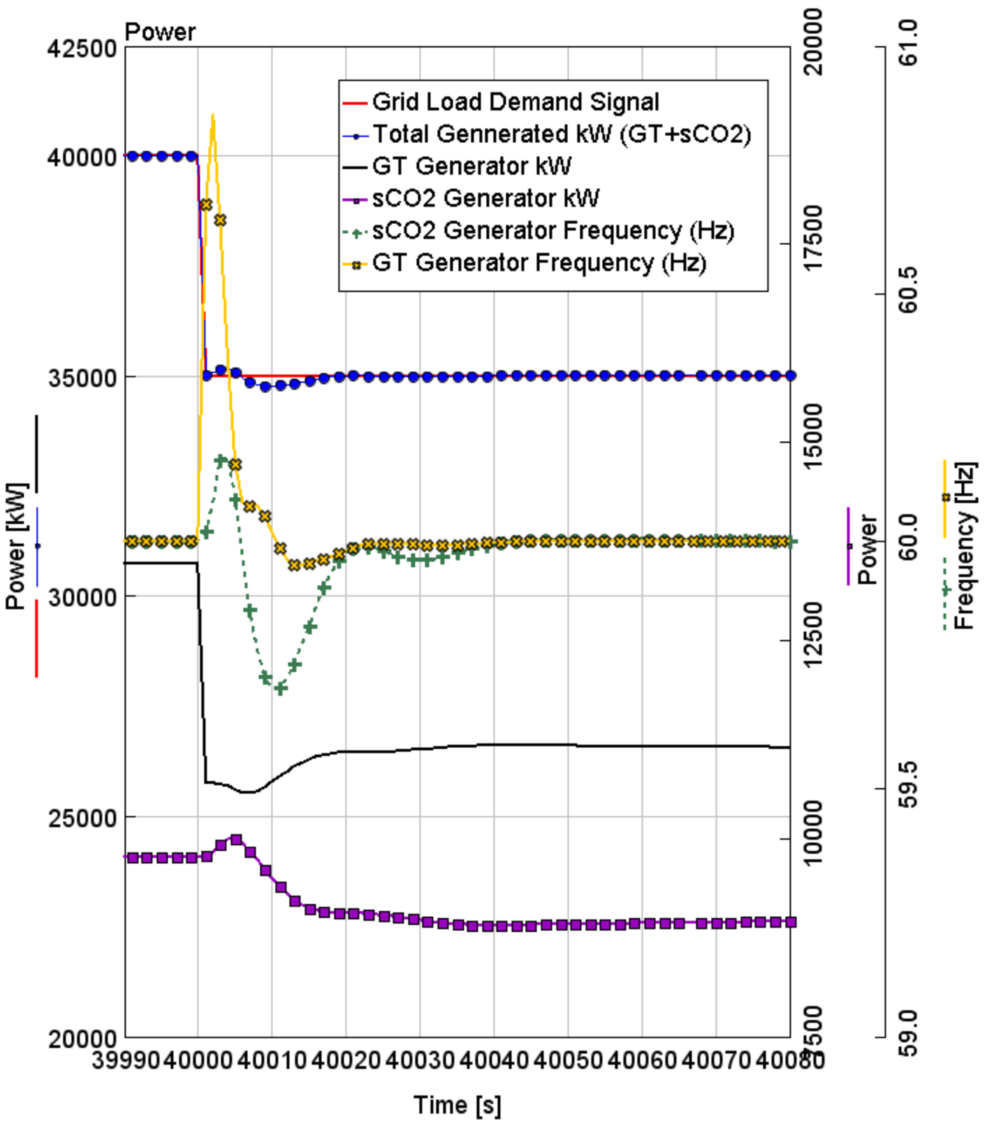
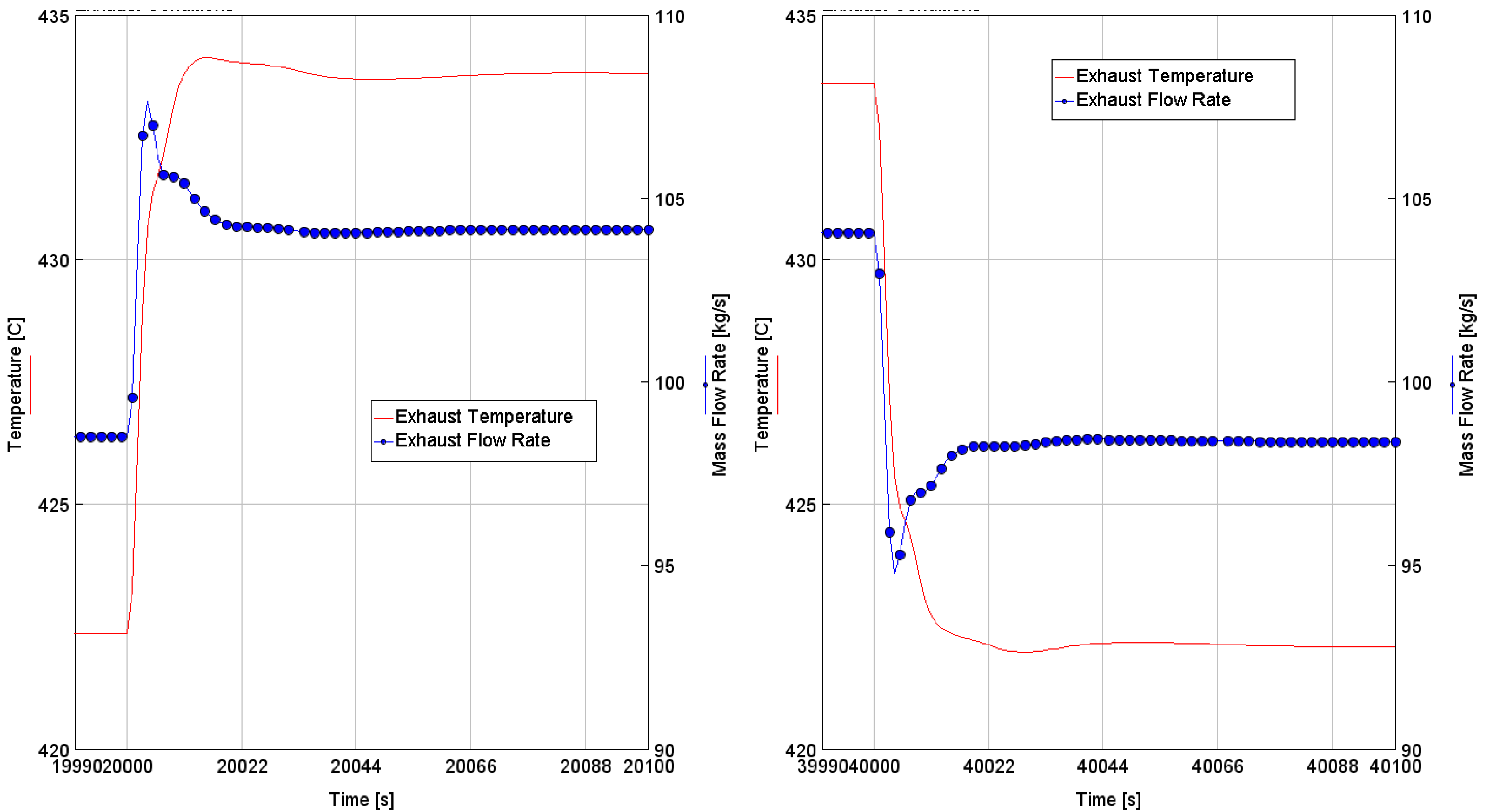


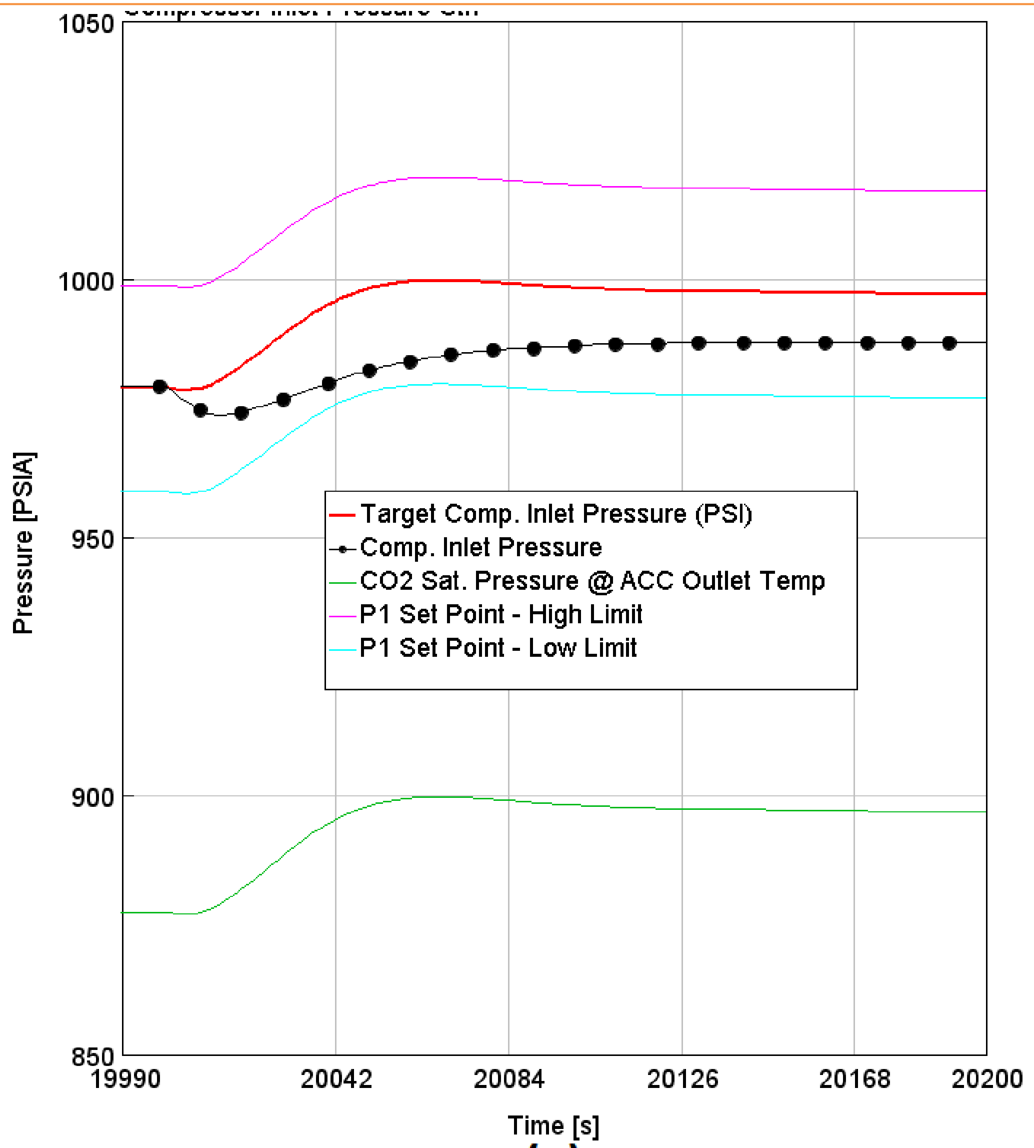
(b)

Integrated Transient Model Results – Step Response



(a) (b)

Integrated Transient Model Results – Step Response



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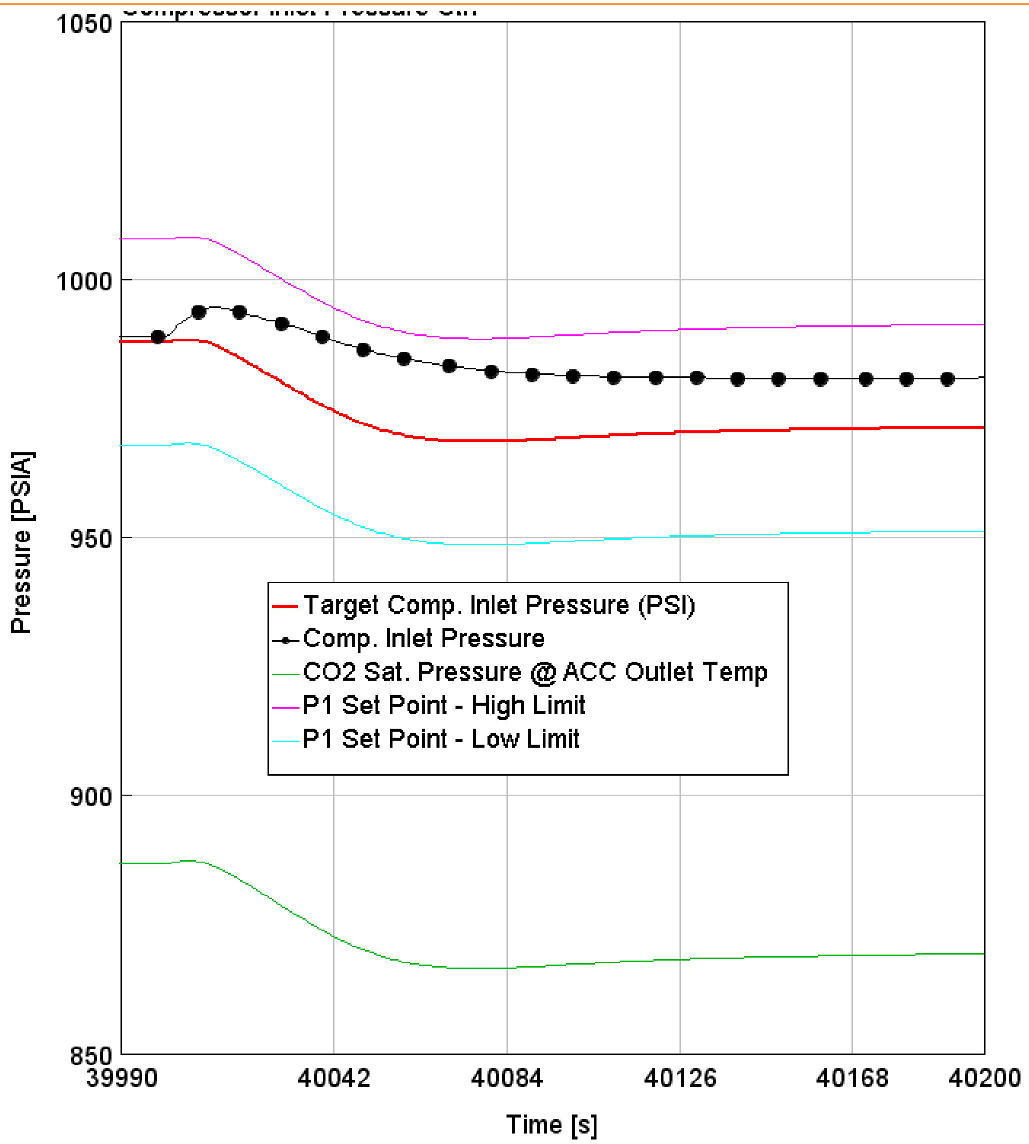
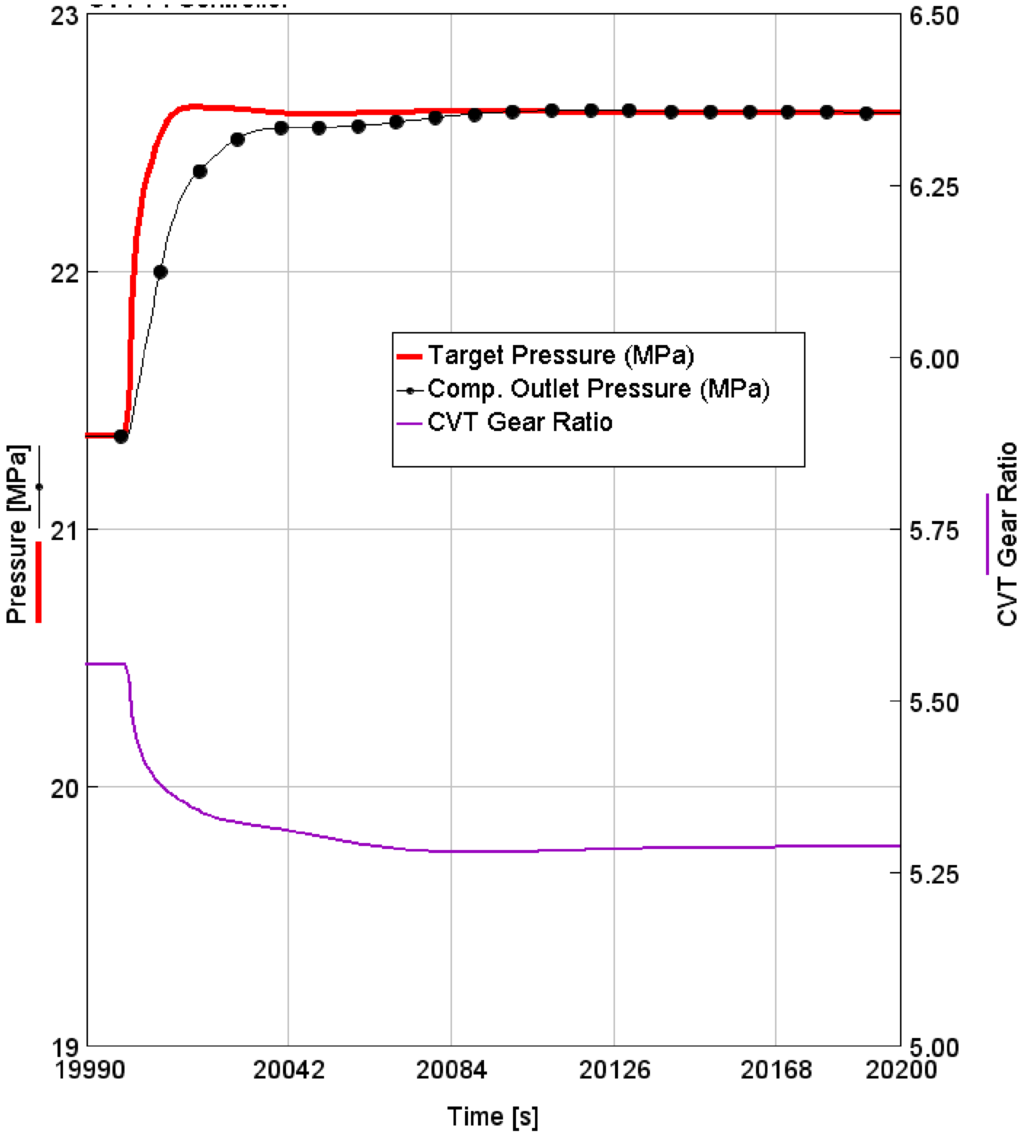


(b)

Integrated Transient Model Results – Step Response



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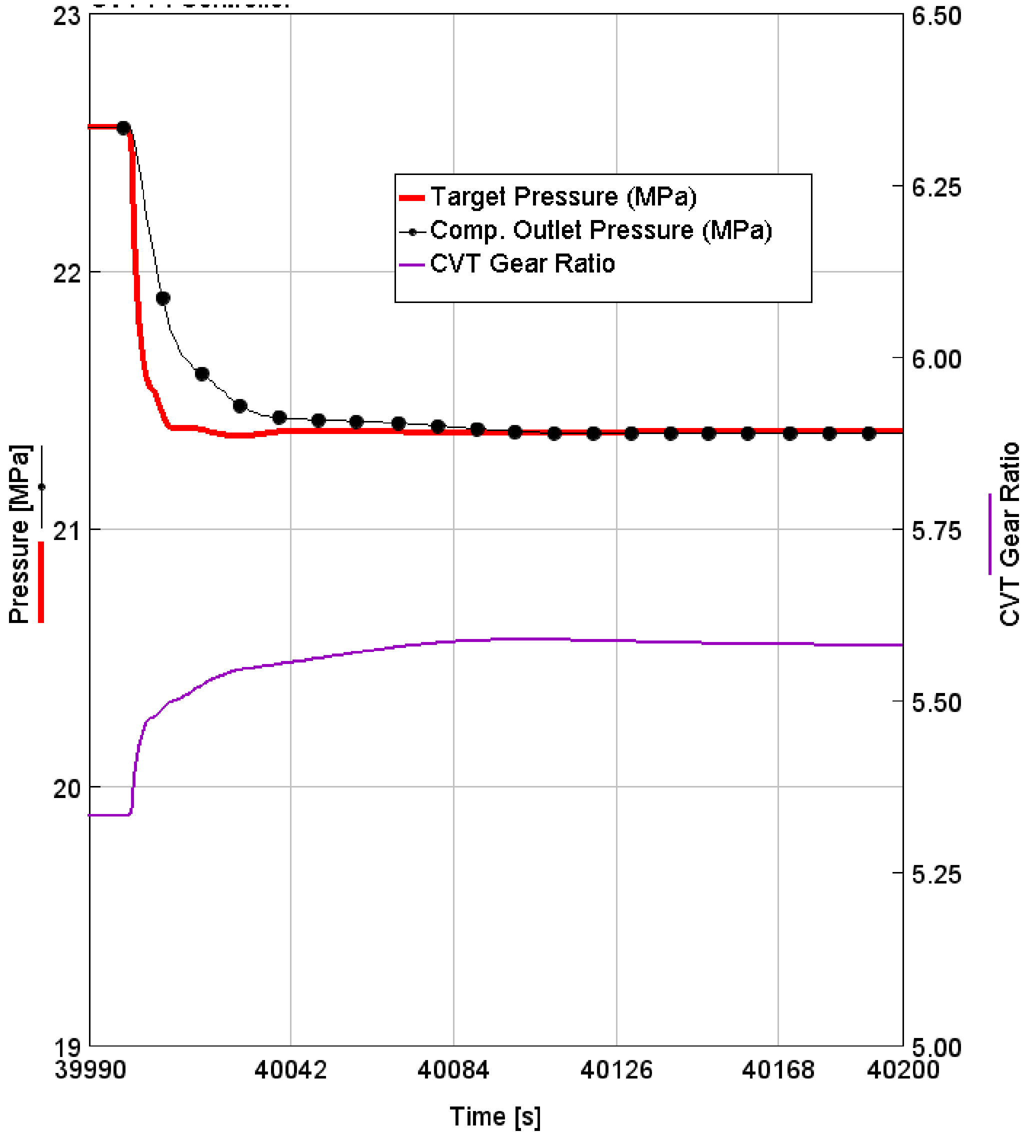

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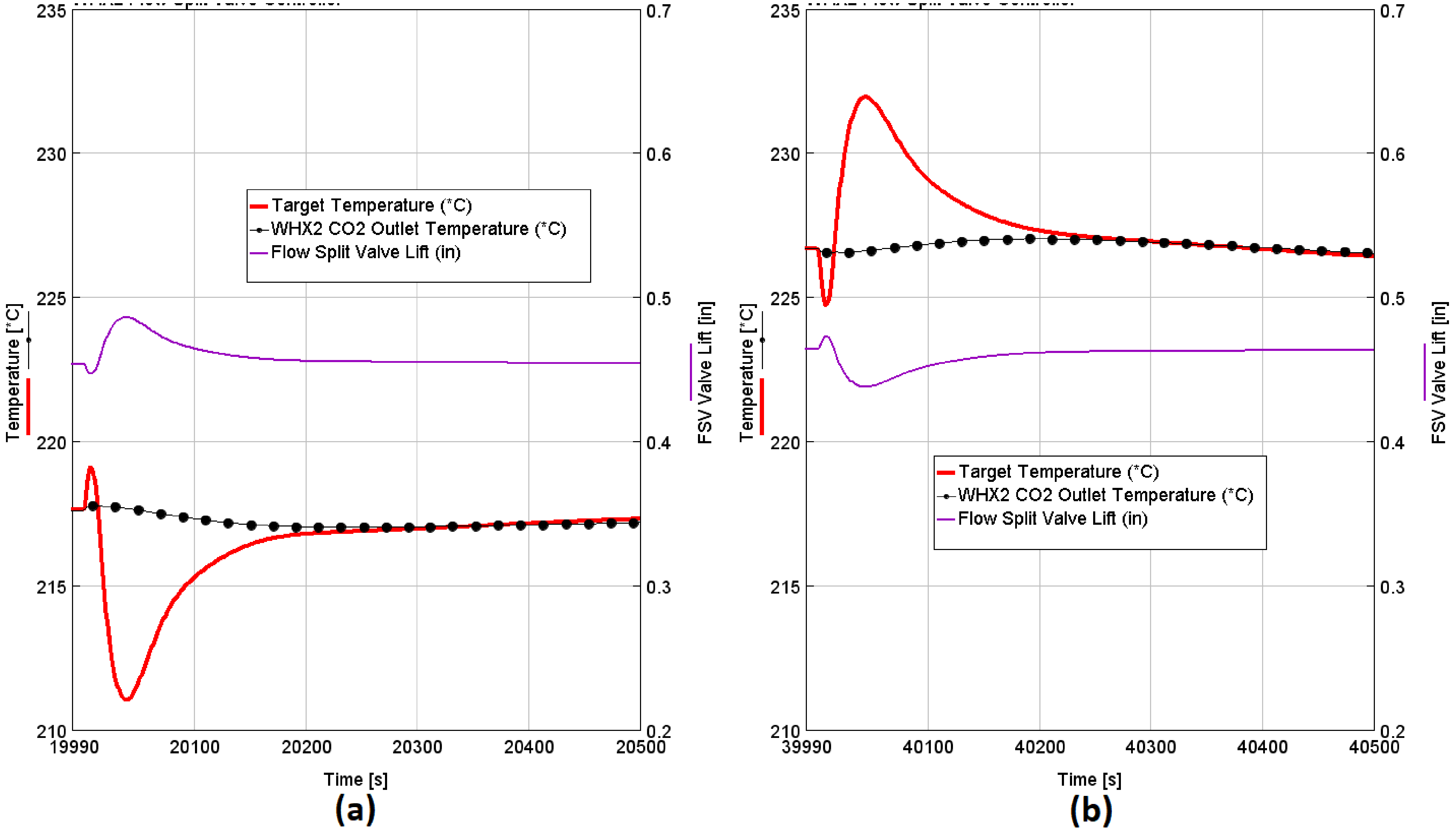

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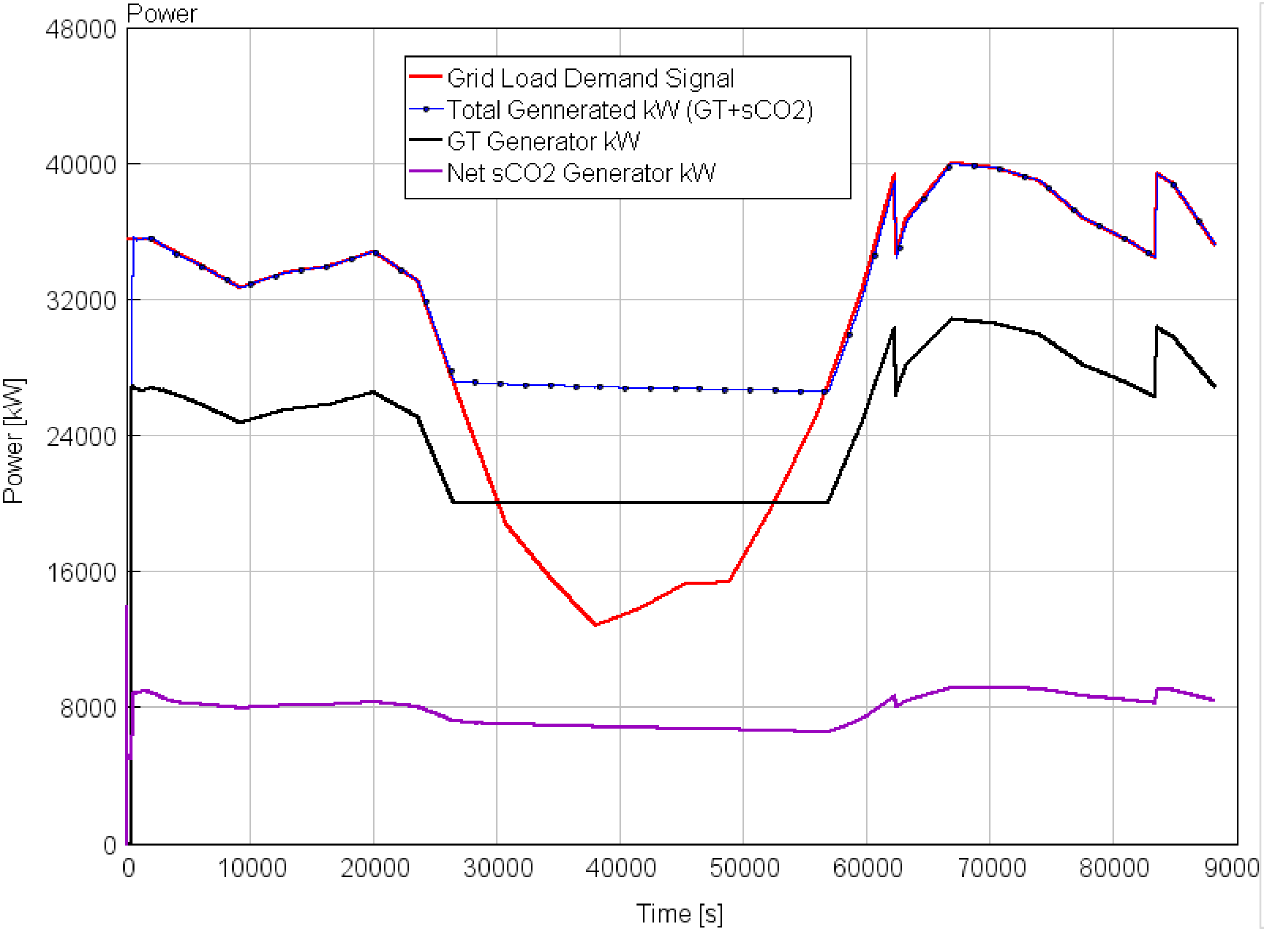
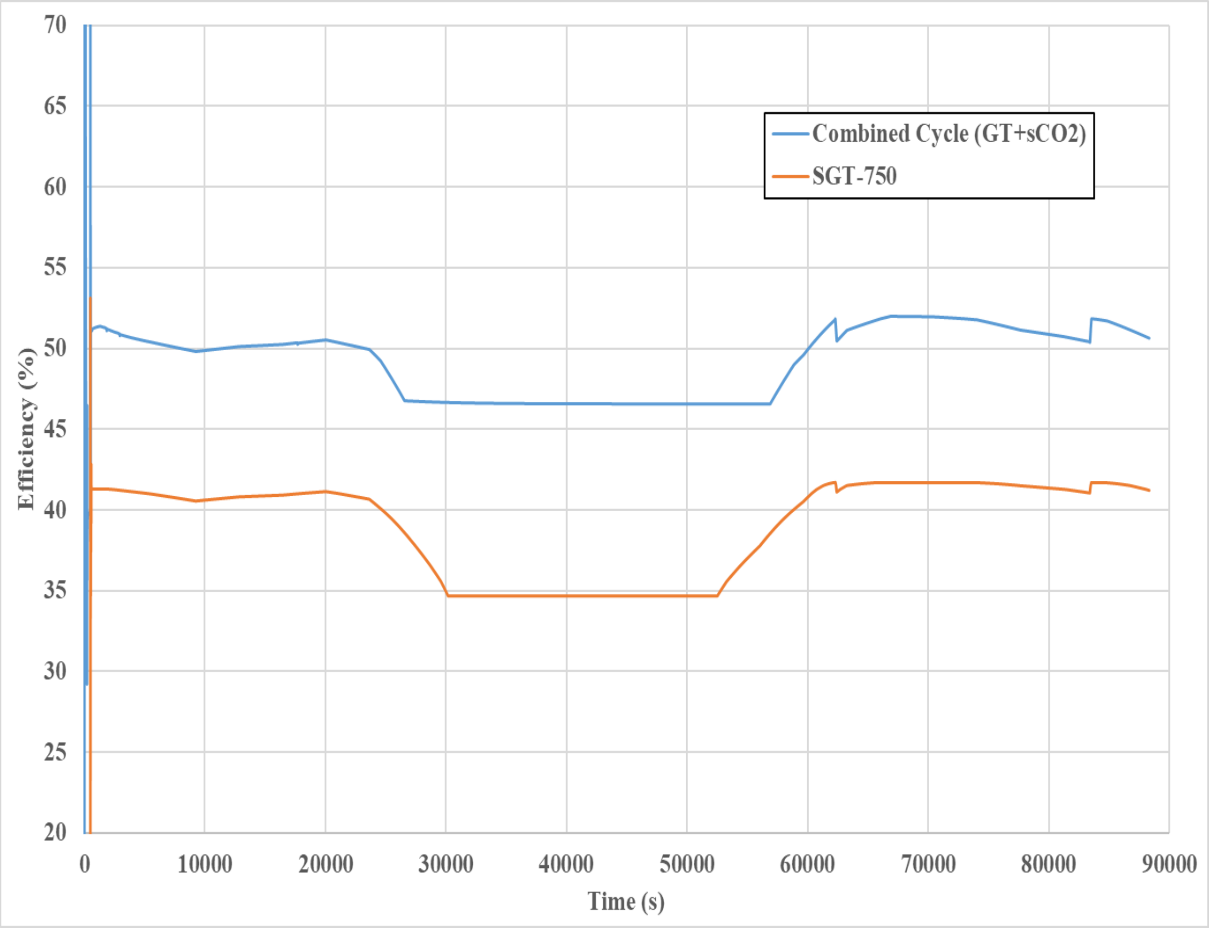
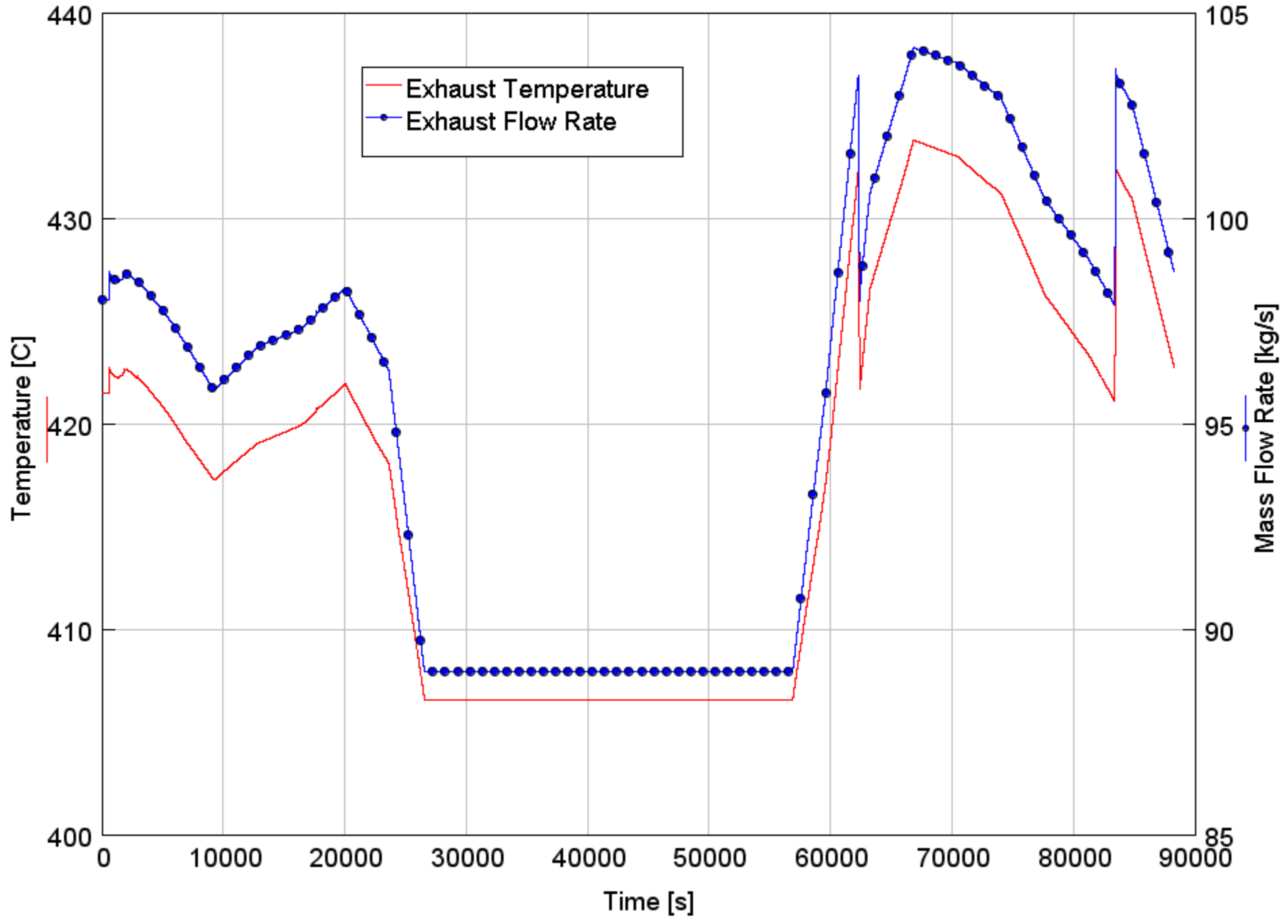




*Fuel low heating value = 46808.7kJ/kg

Integrated Transient Model Results



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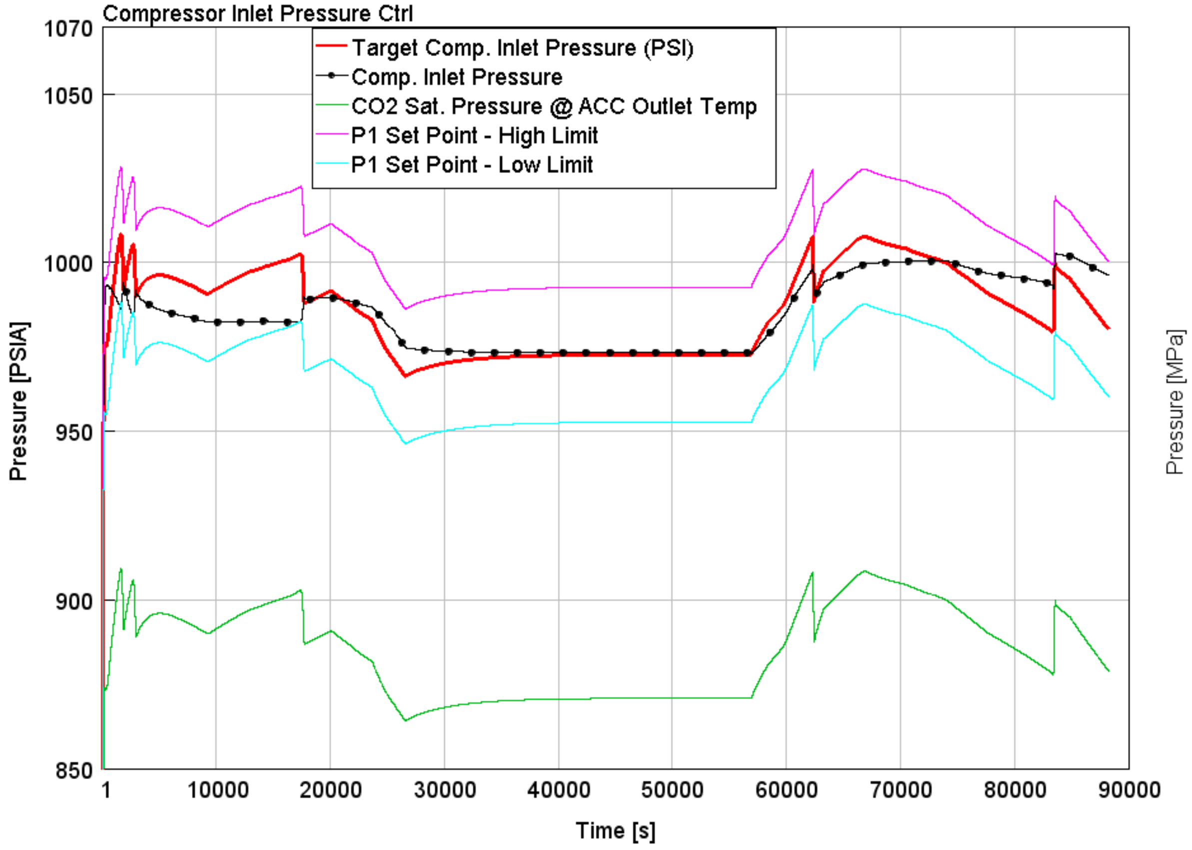

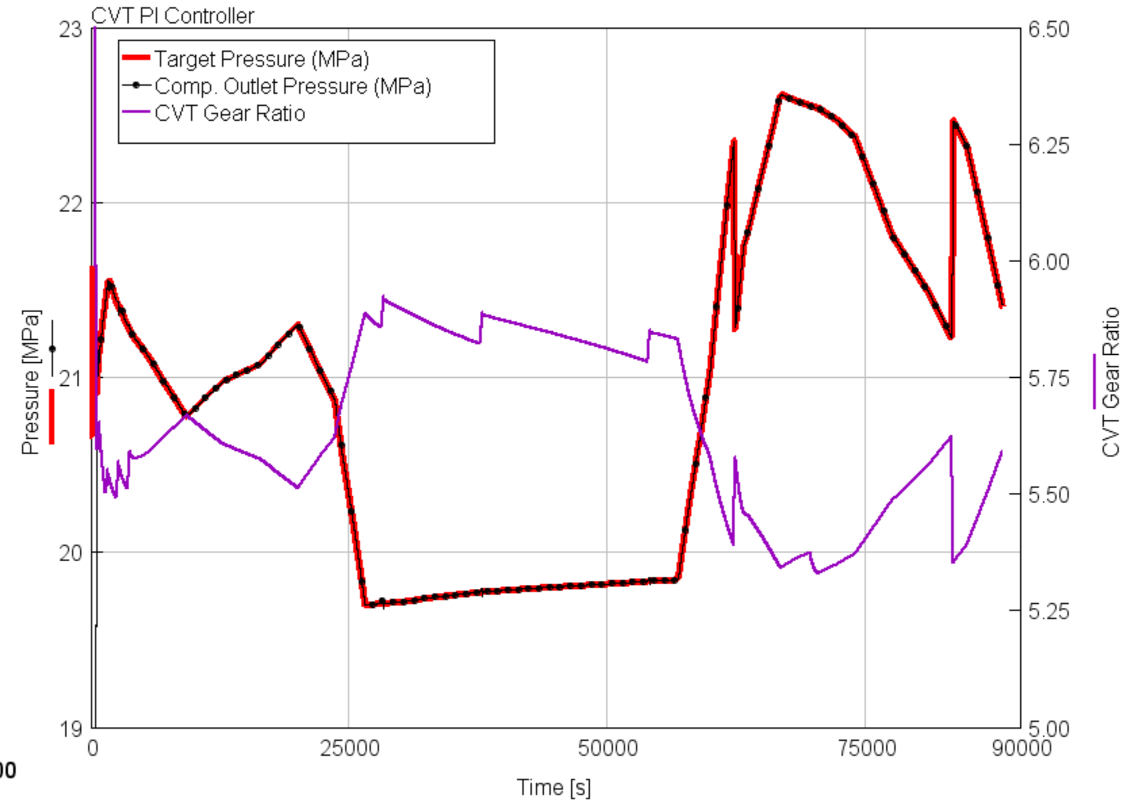

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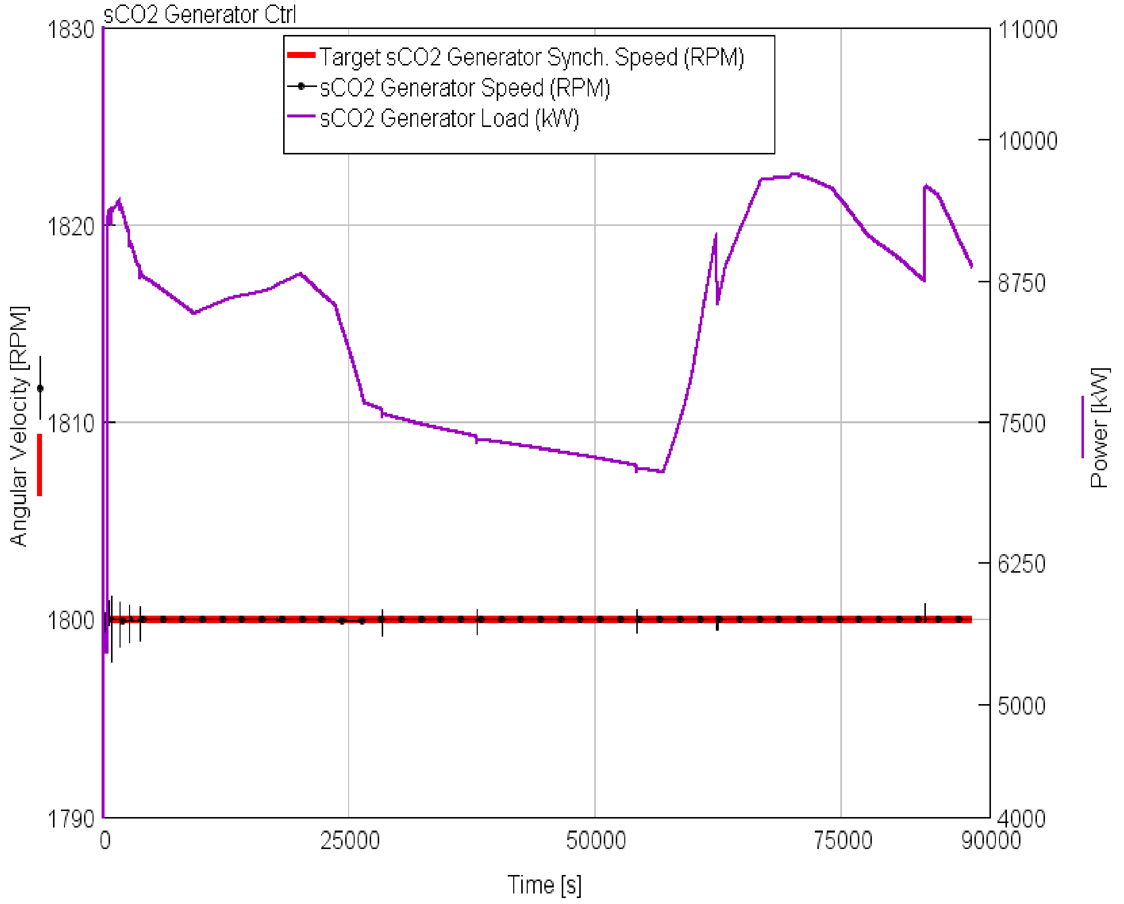

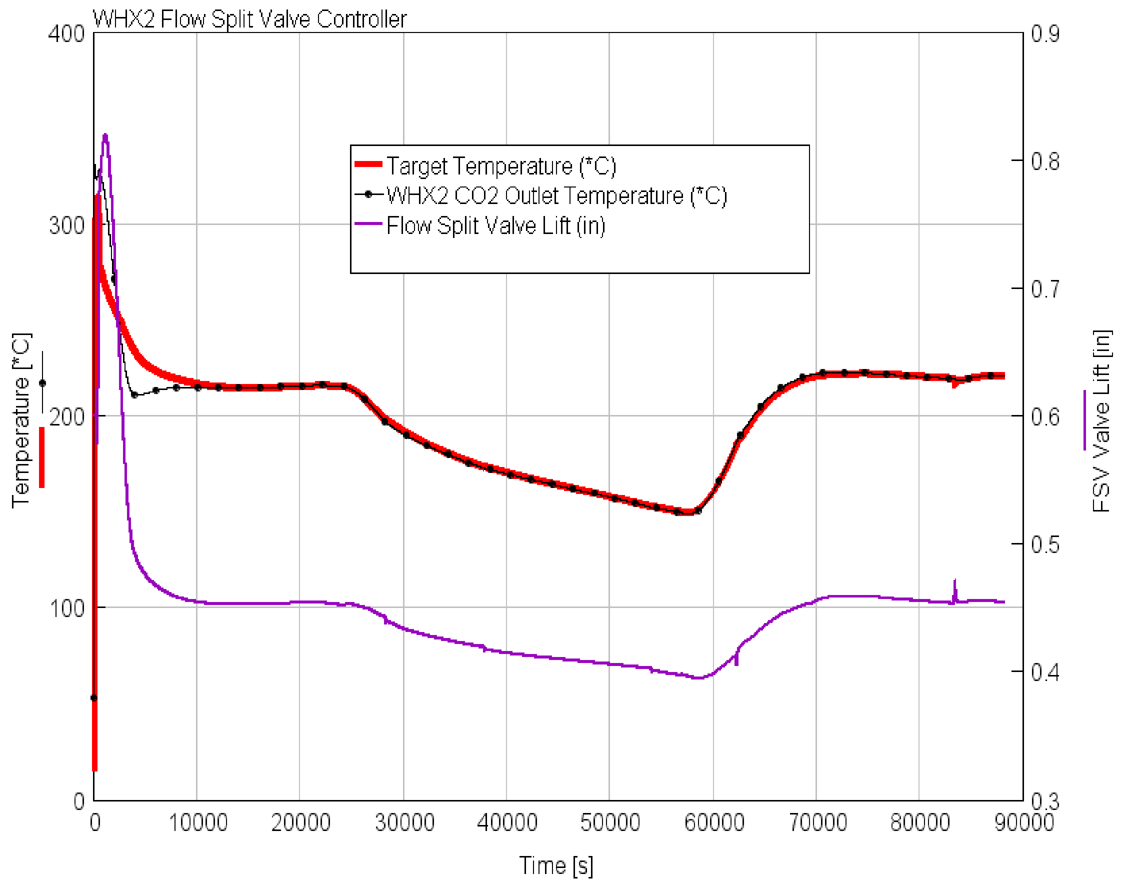

Integrated Transient Modeling Summary

- sCO_2 power cycle transient model was developed in GT-Suite system simulation software platform.
- Developed sCO_2 model was integrated with SGT-750 gas turbine transient model for exhaust heat recovery bottoming cycle.
- Integrated model was simulated with micro-grid load profile.
- The control system performance to track the setpoint values was as expected.
- Project future direction: (i) Control system performance can be improved so that the model tracks for optimal system power output (supervisory controls and model predictive controls). (ii) Control system development in industrial control platforms (such as Rockwell Automation, Siemens Controls etc.) for Software-in-Loop (SiL) and later Hardware-in-Loop (HiL) studies.

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- Authors would also acknowledge and thank Siemens Finspang (Sweden) for providing SGT-750 gas turbine transient model and Siemens PTI Group for providing representative grid load profile.