The 9th International Supercritical CO_2 Power Cycles Symposium
March 2 – 5, 2026, Pittsburgh, PA
Paper #067

Steady State Model Update for the 10 MWe sCO_2 Test Facility Program

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Abstract

This paper describes improvements to the steady state cycle model of the 10 MWe sCO_2 Brayton Cycle test facility that have been implemented. The model which was built using Flownex for simple cycle operation was validated and verified using experimental test data recorded in late 2024. Significant deviations from the original model were observed due to variations in as-built discoveries including compressor maps derived from mapping exercises, equipment and shaft efficiencies, and an updated turbine stop and control valve (TSV/TCV) flow curves. The Flownex model was updated to match equipment as-builts, including revised piping geometries from isometric drawings (lengths, bends, elevations, diameters), and corrected insulation specifications. These updates improved model agreement with measured performance parameters. This paper describes the 10 MWe sCO2 system, key test results from the Data Acquisition System, and the Flownex model. It details the methods of incorporating site test data into the Flownex model and presents a quantitative comparison between the current model predictions and STEP simple cycle test results.

Introduction

The 10 MWe Supercritical Transformational Electric Power (STEP) pilot plant, located at Southwest Research Institute (SwRI) in San Antonio, Texas, represents the first integrated demonstration of a large scale supercritical carbon dioxide (sCO_2) Brayton power cycle in the United States. The facility has successfully completed its first phase of testing that operates in a simple recuperated Brayton cycle configuration and has demonstrated the operability and efficiency of sCO_2 power conversion at multi-megawatt scale. This achievement marks a significant step toward commercial readiness of sCO_2 power systems, which are expected to deliver cleaner, more compact, and lower cost electricity production compared to traditional steam Rankine cycles.

The STEP program is led by GTI Energy in partnership with Southwest Research Institute (SwRI) and General Electric Vernova Advanced Research (GEVAR), with funding support from the U.S. Department of Energy. During the first operational phase, the pilot facility was configured in a simple cycle mode, which uses a main compressor and a high temperature heat recuperator to recover waste heat from the turbine exhaust. The simple cycle tests, conducted during September and October 2024, achieved turbine inlet temperatures up to 500 °C and generated a gross turbine power of 8.25 MWe, and a net electric power of 3.93 MWe with grid connection. These tests successfully demonstrated the fundamental control, operability, and stability of a recuperated sCO_2 Brayton system and provided critical component and system level data. The results form the foundation for future testing in the recompression closed Brayton cycle (RCBC) configuration, which will add a second compressor and a low temperature recuperator to improve efficiency and power output.

Accurate modeling of the sCO_2 cycle near the critical point presents a number of challenges due to the significant thermophysical property variations of CO_2 and their impact on turbomachinery performance, heat exchanger effectiveness, and system controllability. The sensitivity of density, enthalpy, and specific heat to small temperature or pressure perturbations can lead to large deviations between predicted and measured performance. To improve predictive accuracy between model simulation and test performance, the steady state Flownex model of the STEP simple cycle configuration was updated using data obtained during the 2024 test campaign. The updated model incorporates compressor performance maps derived from measured test data, an improved turbine stop valve (TSV) Cv curve, refined piping geometries based on isometric drawings, and corrected insulation specifications. These updates enhance the model’s ability to reproduce measured pressures, temperatures, and mass flows across the cycle to yield a more representative comparison between predicted and actual facility performance. The results are reflected in comparison plots where model predictions align closely with measured test data. The updated model predicts turbine, compressor, and overall cycle performance within a few percent of measured values which confirms improved consistency and accuracy in representing the facility’s actual operation. This work supports ongoing model validation efforts and provides a solid foundation for future recompression cycle (RCBC) modeling and transient analysis.

Modeling Methods

The simple cycle Flownex model represents the configuration of the 10 MWe sCO_2 Brayton power cycle at the STEP facility. The model captures the thermodynamic path of the working fluid through five major subsystems: the heater, main compressor, recuperator, turbine, and precooler. This configuration provides the simplest closed-loop form of an sCO_2 Brayton cycle. As illustrated in Figure 1, the model serves as the baseline framework for validating the integrated plant performance under simple cycle operating conditions. The Flownex environment allows component customization with built-in compressible flow solvers while also allowing user defined parameters and external spreadsheets to capture performance calculations not directly modeled by standard elements.

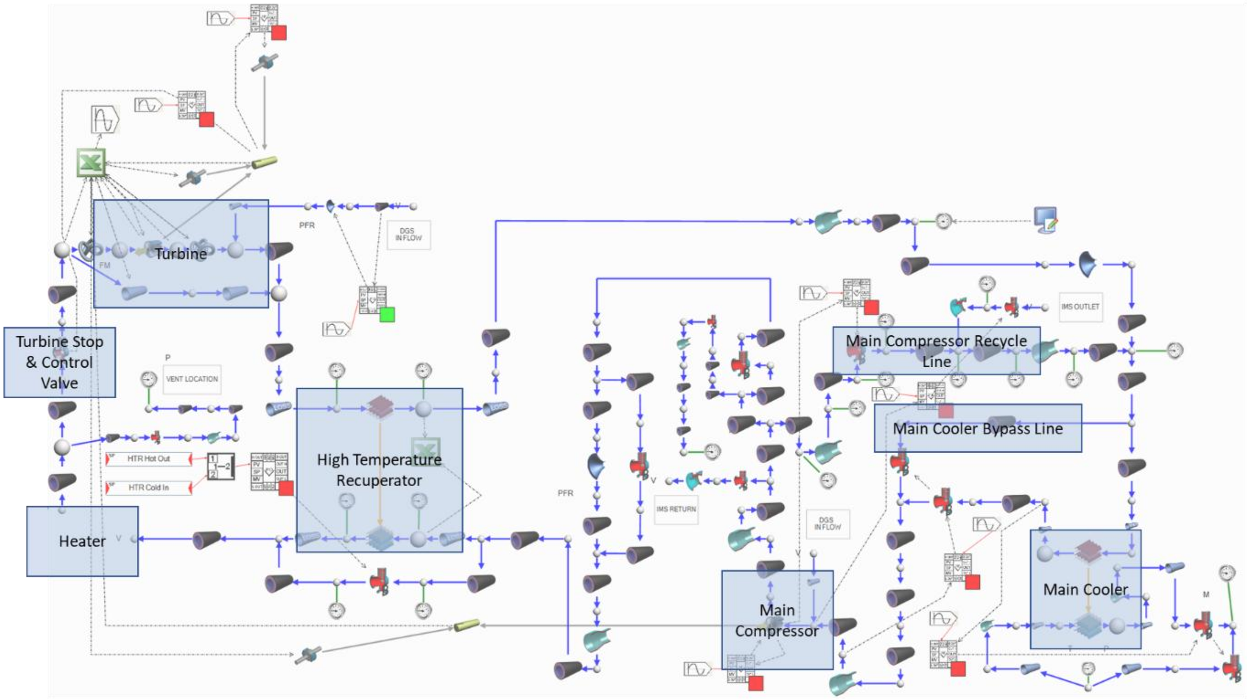


Figure 1: Steady state Flownex model of the STEP simple cycle configuration [1]

The STEP turbine is represented through a combination of Flownex turbine elements linked to an external spreadsheet developed to capture non-ideal mechanical and leakage effects. The supporting spreadsheet includes embedded calculations for the turbine flow function, shaft efficiency, gearbox efficiency, generator efficiency, balance-piston leakage, and inlet and outlet pressure losses. In addition, dry gas seal flows from the inventory management system (IMS) are modeled explicitly to account for bypassed mass flows.

The main compressor is modeled using the Flownex compressor element, which employs compressor map inputs. The compressor map defines volumetric flow, compressor head, and efficiency at designated rotational speed and operating conditions. Initially, vendor supplied compressor maps were implemented to define the performance. Following the simple cycle test campaign, these vendor maps were replaced with measured compressor maps derived directly from the most recent site data to improve accuracy as shown in Figure 2. Figure 2 illustrates the comparison between the vendor supplied map and the measured test-derived map. The lines correspond to increasing volumetric flow rate from left to right and represent inlet guide vane (IGV) angles ranging from –70° to +10°. Both the vendor and measured maps were generated at the same nominal compressor speed of 27,000 rpm with inlet conditions of 84 bar and 35 °C. The compressor head values shown in the plot are derived from the total pressure and temperature measurements at the compressor inlet and discharge locations. The comparison highlights the differences between the vendor predicted and as-tested compressor maps.

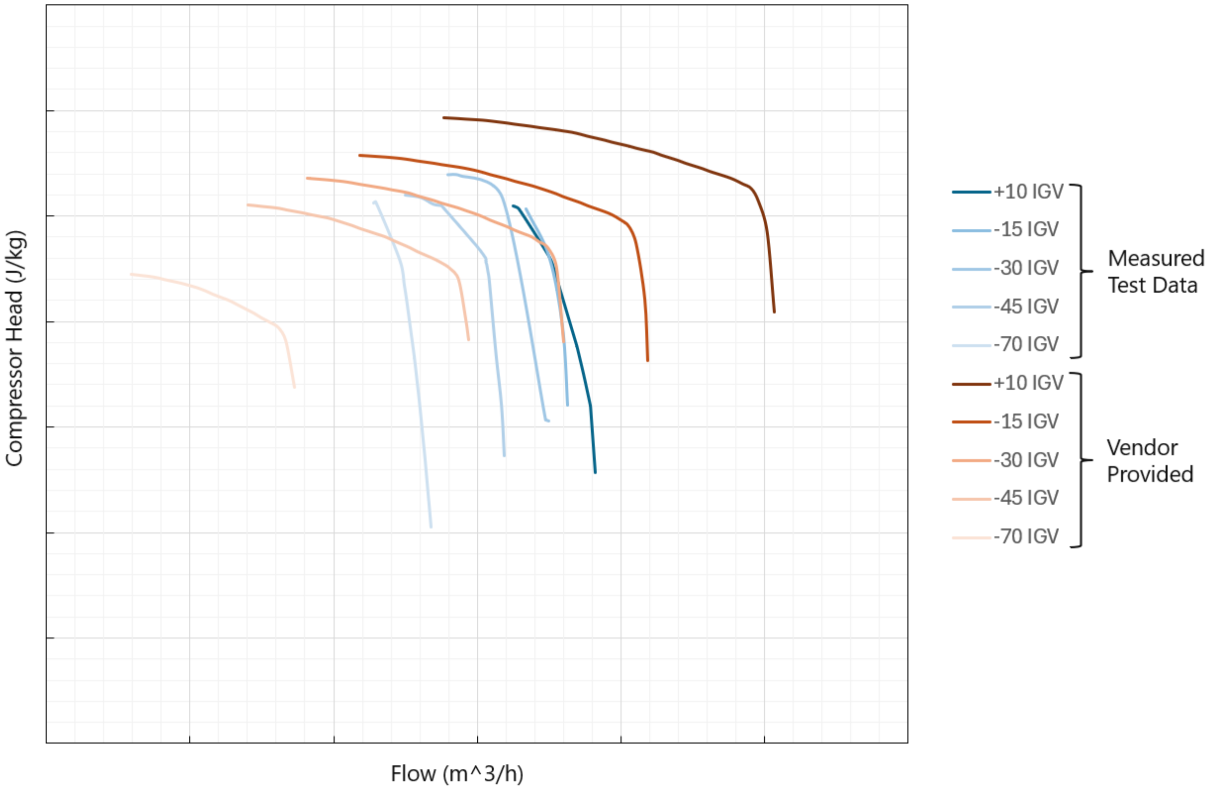


Figure 2: Compressor maps showing comparison of expected (vendor) vs. measured (test derived), Head vs. Flow

Temperature measurements at the compressor inlet, which are often relatively close to the critical point, are prone to increased uncertainty due to the rapid swings in thermodynamic properties that can occur in that region. In the near-critical region of CO_2, very small deviations in measured temperature produce disproportionately large changes in calculated density, specific heat, and compressibility. For example, small changes in inlet temperature can result in large changes in density, which directly affects the volumetric flow rate and can lead operators or performance analysts to believe the compressor is operating in a different region of its map than is the actual case. The thermocouples used for compressor inlet temperature measurement were end-to-end calibrated which resulted in an average uncertainty of approximately 0.2 ºC. Measured compressor inlet temperature averaged closer to 37 ºC for most test points, which is 2 ºC higher than the 35 ºC at which the maps were generated. Some amount of model discrepancy can likely be explained by this difference, but further testing or analysis is needed to quantify.

The turbine stop valve (TSV) and turbine control valve (TCV) are modeled using a Flownex control valve element, where the effective flow area varies according to a user defined Cv versus % open curve. New vendor provided valve data were implemented in the current model to replace the earlier approximation used in the initial baseline as shown in Figure 3. The Cv curve displayed in Figure 3 is the composite Cv curve of the TSV and TCV.

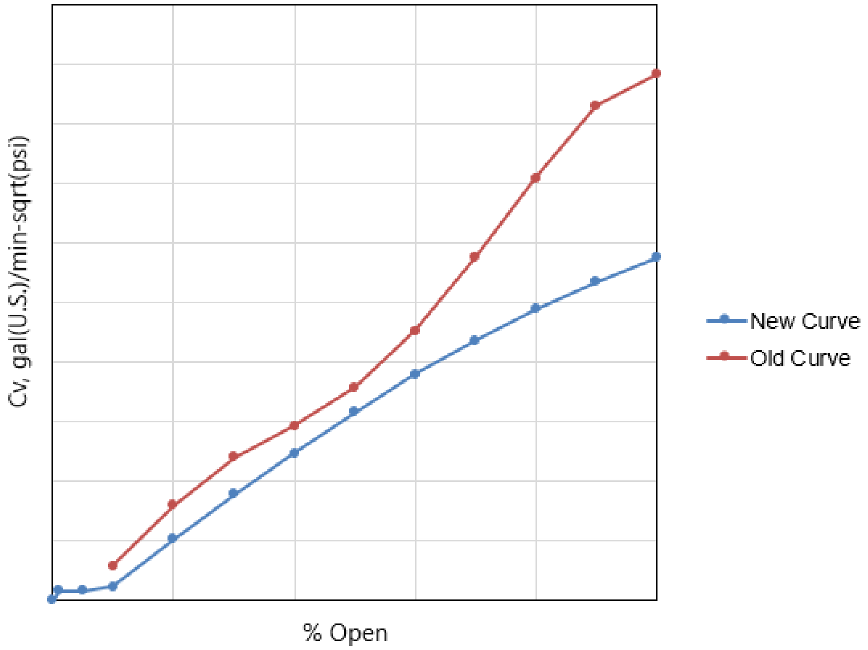
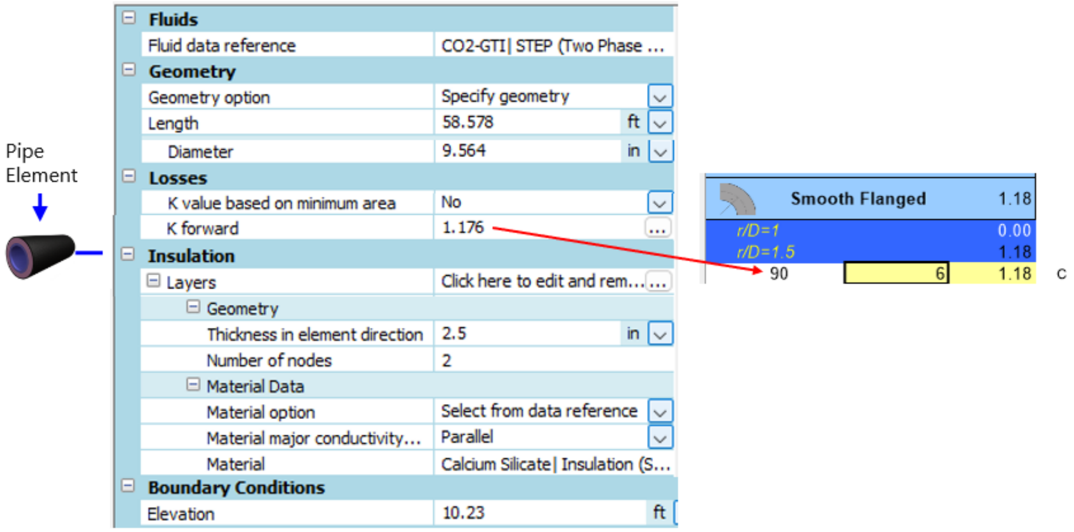


Figure 3: Updated TSV flow characteristic (Cv vs. % open) compared with previous vendor curve

The piping and insulation in the model are represented using Flownex insulated pipe elements. Each pipe segment specifies its length, inner diameter, number of bends, bend angles, elevation changes, insulation thickness, and insulation material, as shown in Figure 4. The total hydraulic resistance of each segment is computed through the specified resistance coefficient K, which accounts for frictional losses due to the number of bends and bend angles. To improve model fidelity, all pipe geometries were updated based on the most recent isometric drawings to ensure that the Flownex representation accurately reflects the current facility configuration. Elevation data were extracted from the same isometric sources and included in the model.



Fluids		
Fluid data reference	CO2-GTI| STEP (Two Phase ...	
Geometry		
Geometry option	Specify geometry	
Length	58.578	ft
Diameter	9.564	in
Losses		
K value based on minimum area	No	
K forward	1.176	
Insulation		
Layers	Click here to edit and rem...	
Geometry		
Thickness in element direction	2.5	in
Number of nodes	2	
Material Data		
Material option	Select from data reference	
Material major conductivity...	Parallel	
Material	Calcium Silicate| Insulation (S...	
Boundary Conditions		
Elevation	10.23	ft

	Smooth Flanged	1.18
r/D=1		0.00
r/D=1.5		1.18
90	6	1.18

Figure 4: Example of a Flownex insulated pipe element setup showing geometry, bend loss specification, insulation properties, and elevation inputs.

The turbine-generator shaft train was updated to incorporate the latest measured efficiencies. The generator efficiency was updated from 0.993 to 0.966, the gearbox efficiency from 0.976 to 0.957, and the shaft efficiency from 0.99 to 0.98 that resulted in a more realistic overall mechanical-to-electrical conversion. For the main compressor (MC) train, a gearbox efficiency of 0.987 and a motor efficiency of 0.968 at full load were applied. These modifications corrected previous overestimations of system mechanical output and improved the model's agreement with measured electrical power. The adjustments were derived from commissioning data obtained during operation, where measured shaft power, gearbox losses, and generator output allowed the extraction of component level efficiencies. The main compressor map was also re-updated using the most recent test data (Figure 2). Similarly, the turbine stop valve (TSV) model was refined by implementing a new Cv versus % opening curve (Figure 3) obtained from vendor's latest specification sheet. Additionally, a measured lube-oil heat loss of 0.42 MW was introduced into the model. This loss represents the energy transferred to the lubricating oil from the turbine and gearbox based on the observed temperature rise between oil inlet and drain during simple cycle operation. Accounting for this parasitic loss reduced the model's overprediction of thermal efficiency. Finally, the piping parameters in the model were updated using the as-built isometric drawings provided by SwRI. Insulation specifications, including material type, thickness, and coverage, were also cross checked against SwRI facility documentation to confirm consistency with the installed configuration.

In summary, significant updates were implemented in the current Flownex simple cycle model to improve correlation with the STEP facility's 2024 test data and to better reflect the as-built system configuration. The most notable improvements include updates to component efficiencies, revised turbomachinery performance data, refined valve characteristics, and verified piping geometries and heat-loss parameters.

Model Validation Results

The steady state model validation was performed (prior to the detailed updates mentioned in the Methods section) by comparing model predictions with measured data from steady state and ramp-up operating periods defined as Data Acquisition Periods (DAPs) as shown in Table 1. Each DAP represents a distinct operating window of approximately 1,000 seconds during which all major system parameters (pressure, temperature, and flow rates) remained within steady or slowly varying conditions suitable for model comparison. Ten DAPs were selected to evaluate the model performance across a range of system loads. The Flownex model was run under close boundary conditions for each DAP, including compressor inlet temperature and pressure, turbine inlet temperature, and measured rotational speed. Among the selected validation points, DAP 8 and DAP 9 correspond to simple cycle maximum conditions and could potentially deliver higher overall cycle efficiencies. However, during these runs, the cooling tower reached its maximum capacity due to elevated ambient temperatures. DAP 6 and DAP 10 represent simple cycle minimum load conditions, operated with more closed IGV positions of –45° and –70°, respectively. Only the conditions at simple cycle maximum or minimum can be classified as steady state operations. The remaining DAPs correspond to intermediate ramp-up intervals and transitional conditions.

Table 1: Data acquisition summary [3]

DAP #	Test ID	Day	Turbine Inlet Temp TC-325avg [C]	Turbine Speed N-550 [rpm]	Compressor Inlet Temp TC-473avg [C]	Compressor Speed KT-3351 [rpm]	Time Slice Start [GMT]	Time Slice [sec]
1	T-8	9/10/2024	286	19998	49	27026	254/17:46:43	64000-65000
2	T-11	9/11/2024	389.6	19999	49.5	27022	255/12:26:47	44800-45800
3	T-12	9/11/2024	394.4	26612	49.5	27025	255/15:00:07	54000-55000
4	T-12	9/11/2024	492.1	26616	49.6	27027	255/16:36:57	59810-60810
5	T-13	9/12/2024	496.4	26615	34	20729	256/17:51:19	64275-65275
6	T-17	9/13/2024	502	26602	35.3	20728	257/15:22:00	55320-56320
7*	T-15	9/26/2024	319	26614	49	27024	270/19:53:25	71600-72400*
8	T-16	9/27/2024	500.5	26622	36.7	27026	271/20:25:04	73500-74500
9	T-19	10/2/2024	500.7	26617	37.3	27025	276/13:03:21	47000-48000
10	T-19	10/2/2024	498.8	26620	35	20727	276/14:10:01	51000-52000
* 800 sec avg. All others 1000 sec								

The data acquisition (DAQ) system for the physical STEP Demo plant utilizes a distributed network of NI cRIO chassis and modules to monitor and record signals from process instrumentation. Each chassis is located in a junction box to which cables from neighboring instrumentation are routed. The network of cRIOs communicate on an isolated network with a PC running the “primary” LabVIEW data processing code. This code collects the data from each chassis and post-processes it in order to record and display live performance data for the plant. Figure 5 shows the DAQ network configuration.

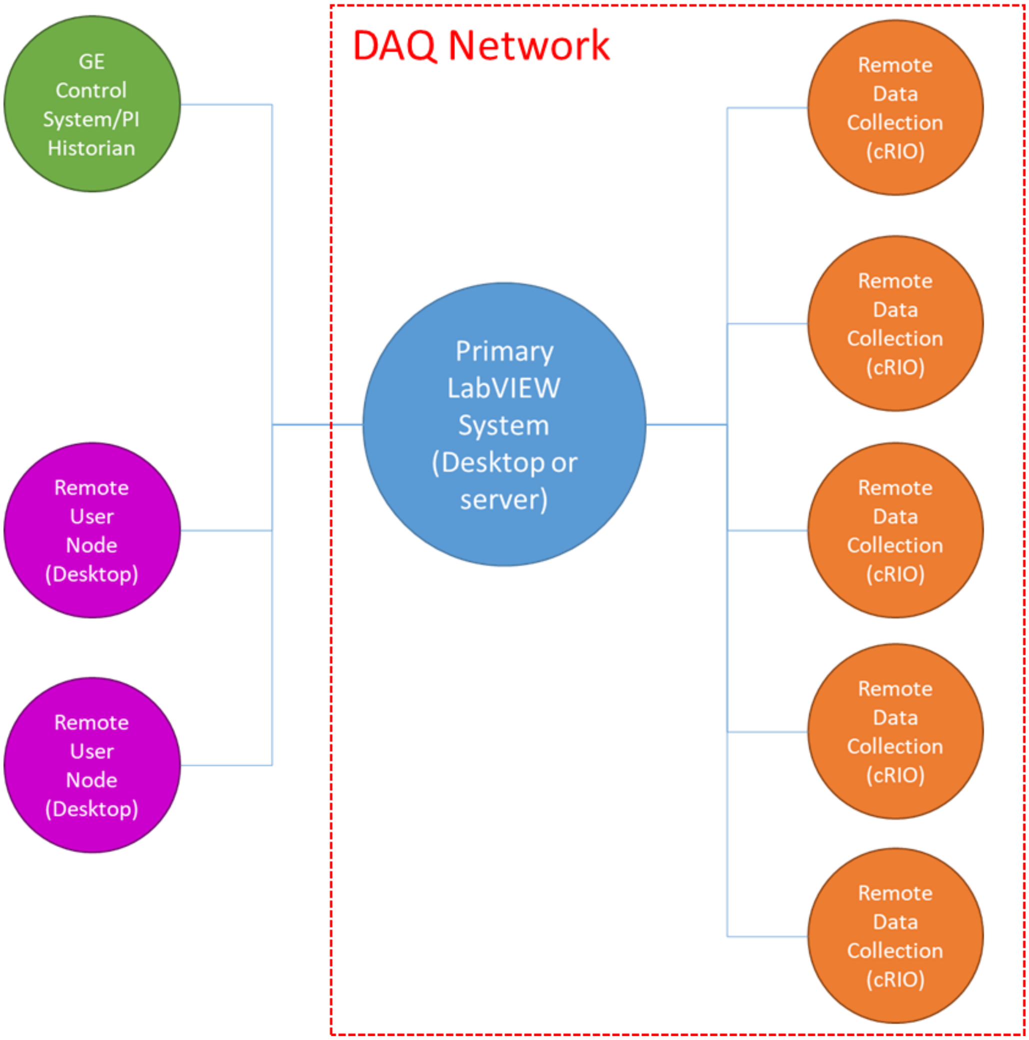


Figure 5: DAQ network schematic [2]

Multiple different types of sensors are used for process measurement. Temperature measurements were made using thermocouples (T-type or K-type depending on process temperature). Static and differential pressure measurements were made using piezoresistive pressure transmitters. In total, the plant includes over 600 pressure and temperature measurements, with double, triple, or quadruple redundancy implemented at key locations, and separate instrumentation dedicated to the DAQ and the distributed control system (DCS).

The DAQ instrumentation locations are focused on the inlet and outlet of major equipment to understand and quantify the equipment's effects on the process, to monitor the equipment's health, and to provide data for model validation and overall cycle performance evaluation.

Measured cycle performance was compared to the predicted cycle performance using 45-degree charts as shown in 6 through 13. The DAPs representing the simple max and simple min conditions are located in the positive region of the plots, whereas the DAPs selected from intermediate ramp-up time slices yield negative net power outputs and efficiencies due to the main components not reaching their designated setpoints. Measured cycle net electric power outputs and efficiencies for simple max and simple min conditions are up to 13% lower than their predicted values mainly due to the discrepancies in the turbine efficiencies and main compressor map issues. After the improvements of the model using the Simple Max data set, the predicted cycle net power output was able to match the power output measured during simple cycle testing of 3.93 MW labeled as a green square point (Simple Max) in Figure 6. The discrepancy between the measured and predicted cycle aero efficiency also falls within 1% as shown in Figure 7. It is worth noting that the points exhibiting the largest deviations correspond to intermediate or non-steady operating conditions obtained during ramp-up or transition periods rather than true steady state. The current Flownex model is only updated for steady state operation, as a result, model prediction error will increase for these off-design points.

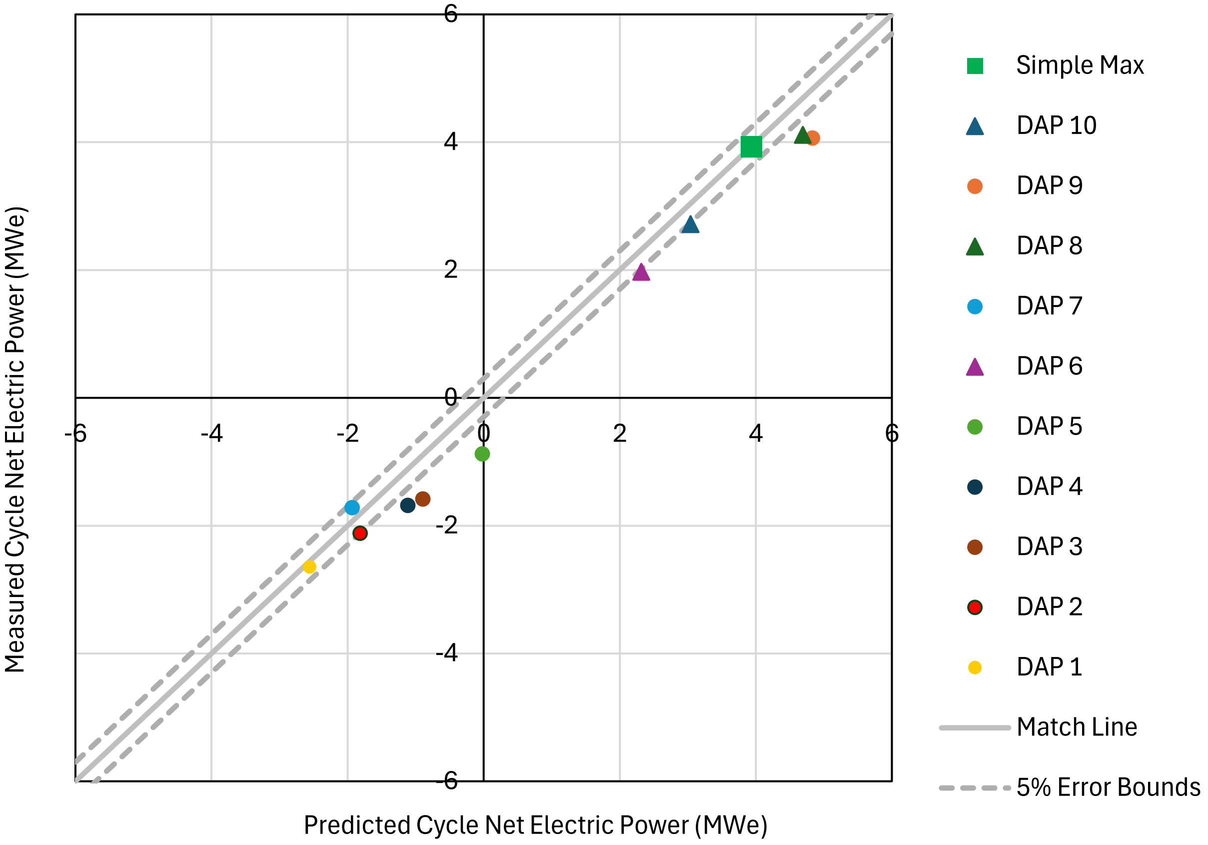


Figure 6: Simple cycle net electric power output (Measured vs. Predicted)

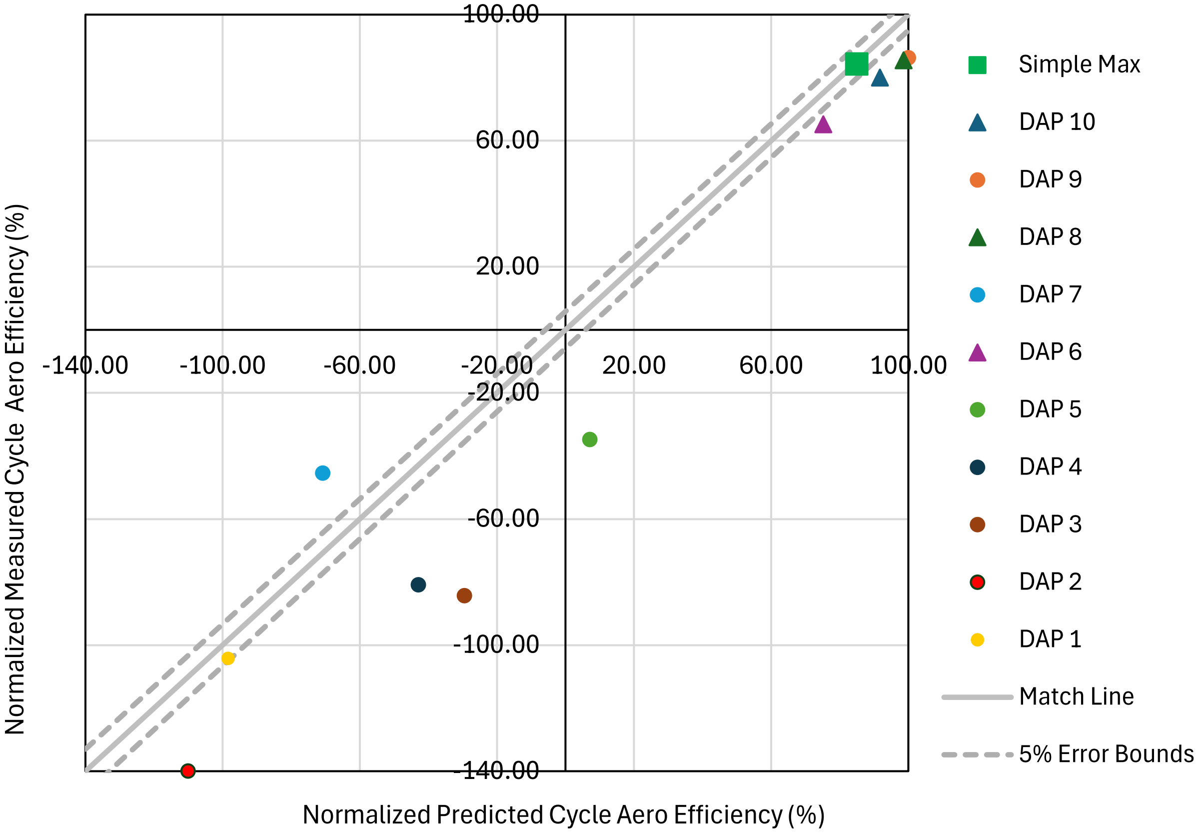


Figure 7: Simple cycle normalized aero efficiency (Measured vs. Predicted)

Measured turbine performance was compared with model-predicted results using 45-degree parity plot as illustrated in Figure 8. For the DAPs corresponding to stable steady state operation (upper right quadrant), the measured turbine shaft power and efficiency values were within 5% lower than model predictions. The model shows slightly higher deviations during transitional or intermediate system operation. These discrepancies arise from transient effects that are not captured in the steady state solver. After all model updates, the discrepancy between measured and simulated turbine power output remains consistently within the 1 – 5% range which confirms the good prediction of the turbine performance in the Flownex model at steady state operation as shown in Figure 8 and Figure 9.

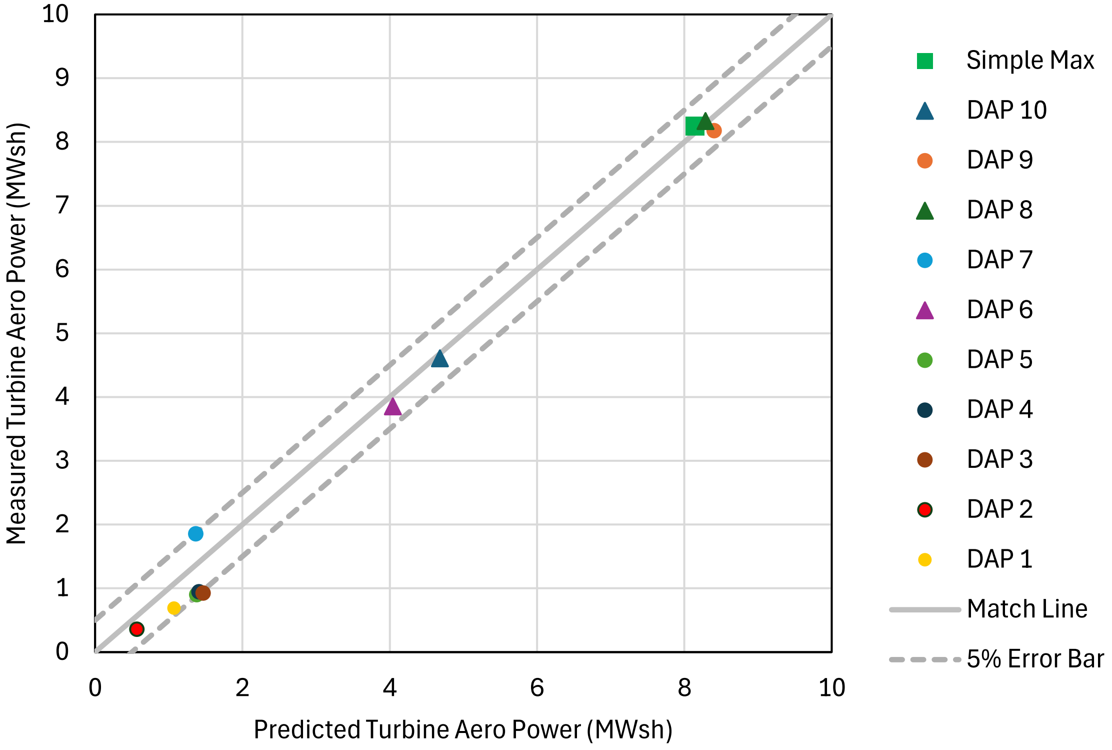


Figure 8: Turbine aero power (Measured vs. Predicted)

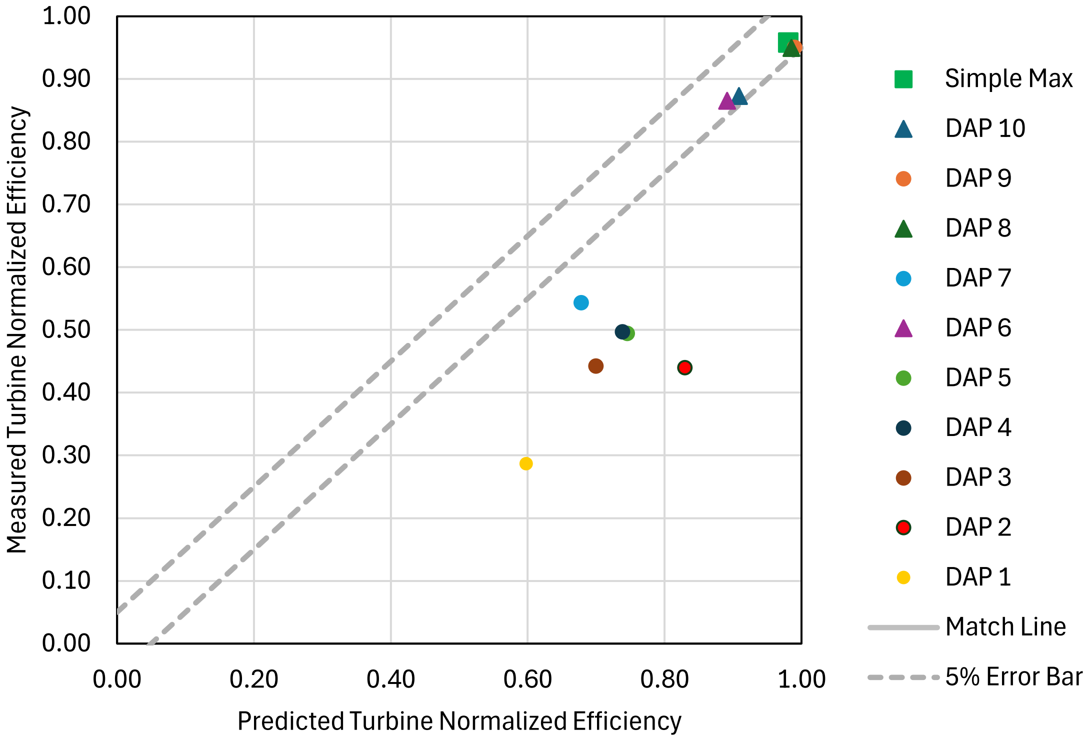


Figure 9: Turbine normalized efficiency (Measured vs. Predicted)

The main compressor was one of the most scrutinized components during the simple cycle test campaign due to its strong influence on the overall cycle. During early component testing in 2023, the as-tested compressor performance exhibited a significant deviation from the predicted operational maps provided by the vendor. To improve model fidelity, the compressor map was first updated after the 2023 component level testing using the as-tested performance data. Following completion of the 2024 simple cycle test campaign, the map was updated a second time using measured system data from the full plant operation. The maps were generated at three specific inlet conditions: 27,000 rpm and 84 bar / 35 °C, 20,700 rpm and 90 bar / 35 °C, and 27,000 rpm and 106 bar / 50 °C.

Measured compressor performance was compared with model-predicted results using 45-degree parity plots for power and efficiency as shown in Figure 10 and Figure 11. Prior to the updates, the model generally underpredicted compressor power (except for DAP 1) and overpredicted efficiency by more than 16% across all selected DAPs. With the new test data derived maps, the difference between measured and predicted compressor power and efficiency was reduced to within approximately 2% under simple cycle operating conditions.

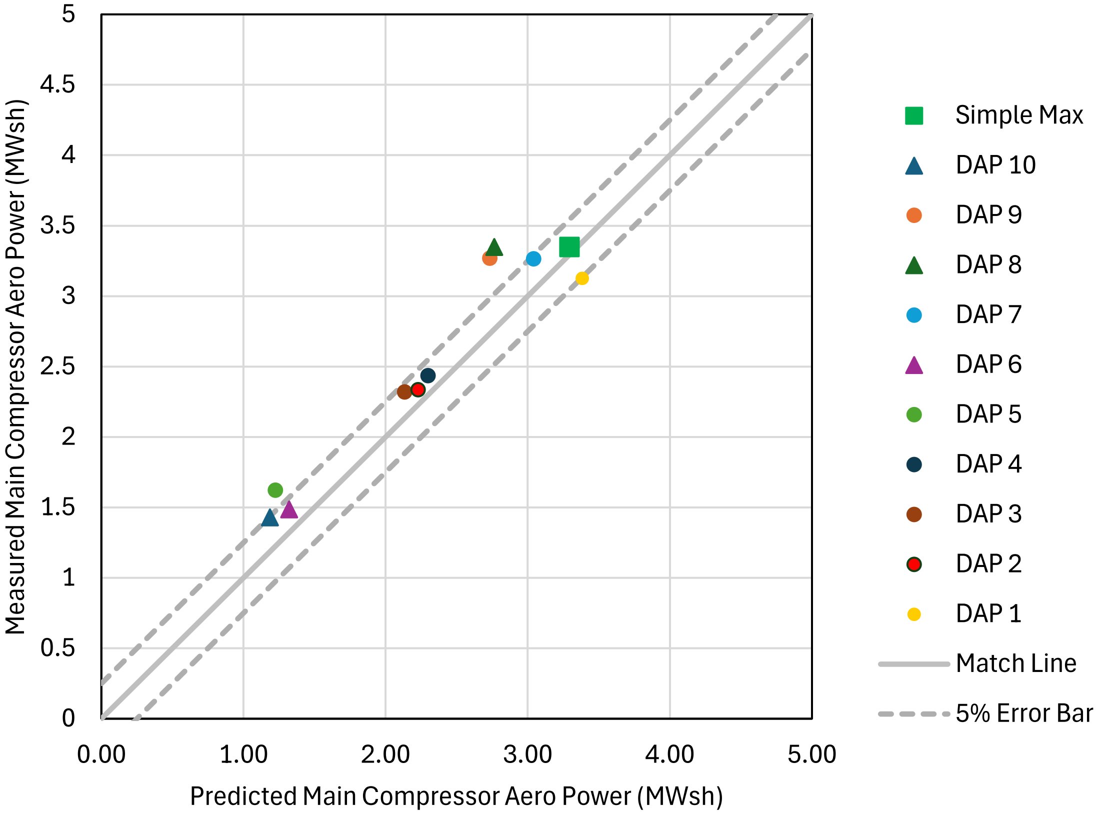


Figure 10: Simple cycle main compressor power (Measured vs. Predicted)

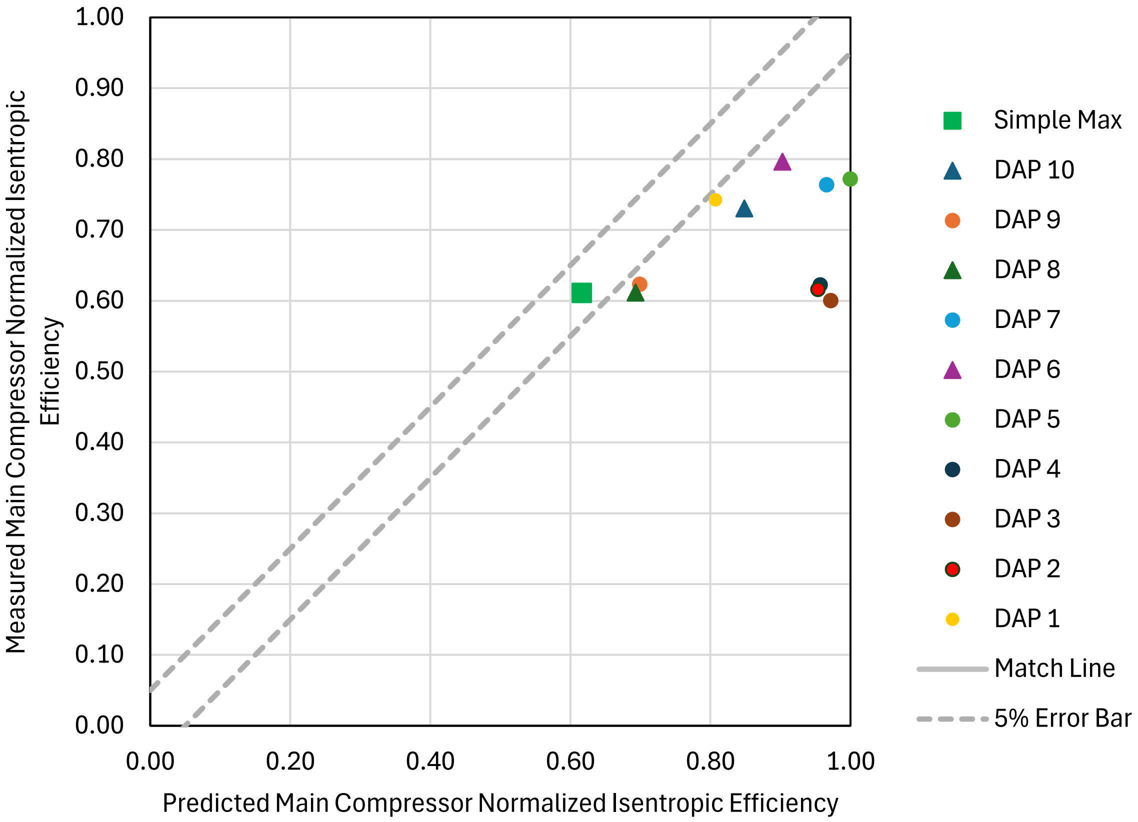


Figure 11: Simple cycle main compressor normalized efficiency (Measured vs. Predicted)

The High Temperature Recuperator (HTR) exhibited stable thermal performance during simple cycle testing. Comparison between measured and model predicted parameter (heat duty) across DAPs is shown in Figure 12. Measured HTR effectiveness values closely matched model predictions both before and after the recent model improvements, with differences remaining within approximately 2%. In this analysis, the LP (low-pressure) side of the HTR refers to the flow path downstream of the turbine outlet before entering the cooling section. Using the LP side to represent HTR duty provides a direct measure of the thermal energy removed from the turbine exhaust prior to entering the cooling system. Attempting to use the HTR high pressure side would be challenging because it introduces additional accuracy concerns due to the HTR bypass flow that mixes into the HTR outlet upstream of the pressure and temperature measurement locations.

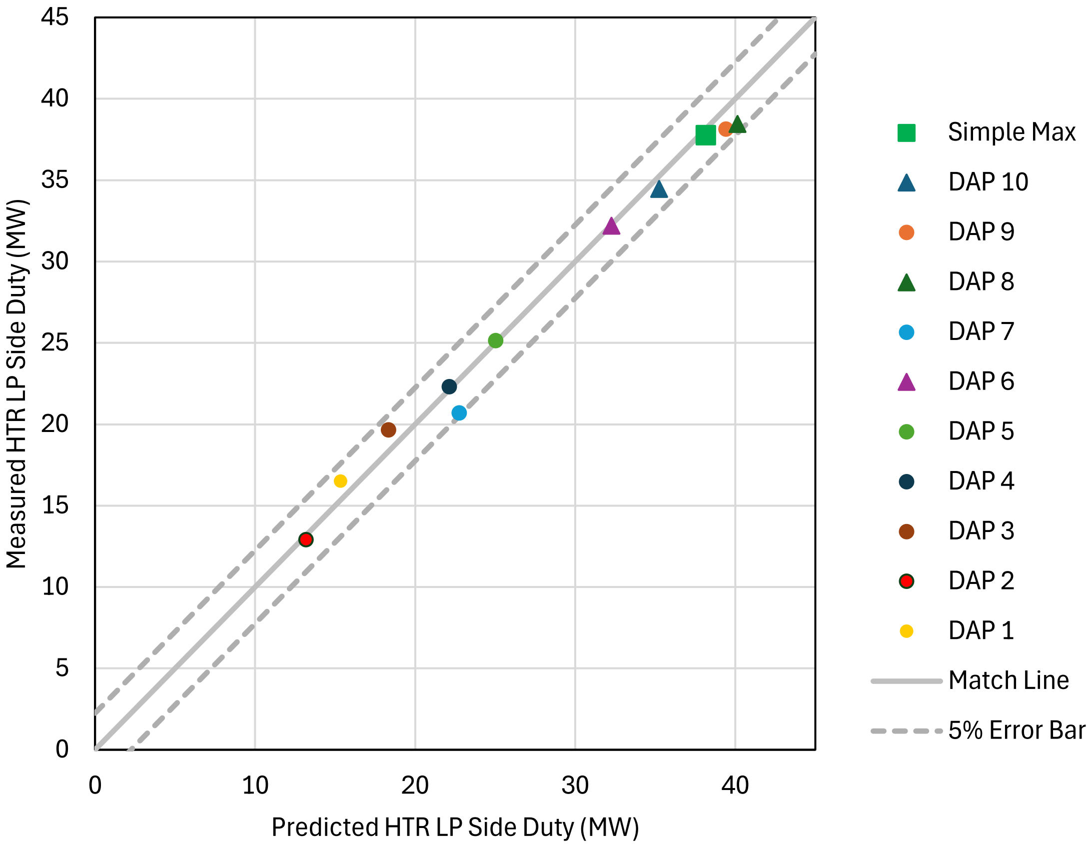


Figure 12: Simple cycle HTR heat duty (LP side, Measured vs. Predicted)

The heater performance during the simple cycle operation also showed strong agreement with model predictions. As illustrated in Figure 13, the measured heater thermal duty closely matched the predicted values from the Flownex model during steady state operation (DAP 6, DAP 8, DAP 9, DAP 10). The heater model aligned well with the test data; thus, no further adjustments were made on the heater section in the Flownex model.

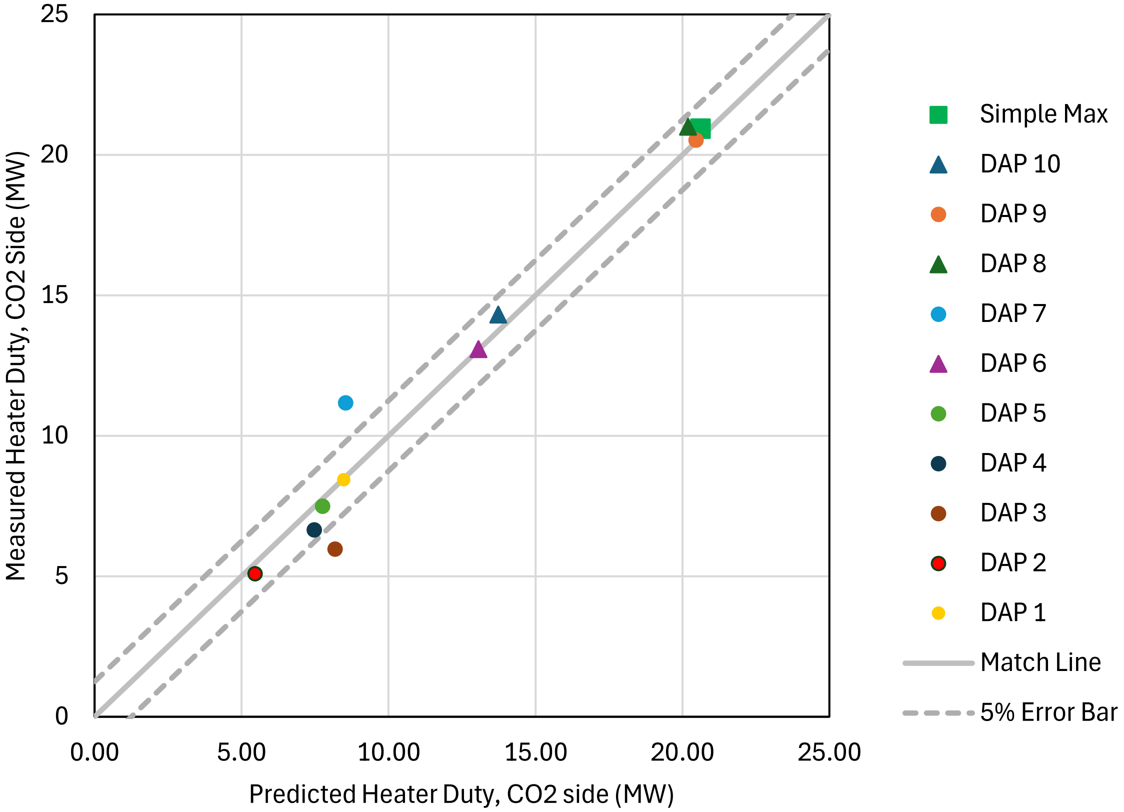


Figure 13: Simple cycle heater duty (CO_2 side, Measured vs. Predicted)

Conclusion

The updated steady state Flownex model for the STEP 10 MWe sCO_2 Brayton Cycle test facility successfully integrates as built geometry, measured component efficiencies, and test derived performance data. Incorporation of the latest compressor maps, revised turbine and shaft train efficiencies, updated turbine stop valve characteristics, and verified piping and insulation specifications significantly improved agreement between the model and the measured test data. These improvements demonstrate the value of iteratively coupling facility data with system modeling tools to achieve more accurate predictions on cycle and component performances. The resulting steady state model provides a validated baseline for ongoing development of the RCBC configuration. Future work will focus on implementing new turbomachinery test data and valve correlations, incorporating a more detailed HTR model in development in collaboration with Carleton University, and extending the system modeling framework to include a cooling tower model with support from Natural Resources Canada (NRCan). These additions will further enhance the model's ability to represent full plant thermal behavior and improve predictive accuracy under variable operating conditions. The STEP steady state model is now a validated tool for analyzing sCO_2 cycle performance. It can be used to as a valuable resource for designing commercial sCO_2 power systems.

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Acknowledgements

The authors would like to acknowledge and thank the hard work of the team members of GTI Energy, SwRI, GE and Joint Industry Program members, and gratefully acknowledge the U.S. Department of Energy, Office of Fossil Energy and the National Energy Technology Laboratory, under Award Number DE-FE0028979.

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