

Supercritical Carbon Dioxide Power Cycle Modeling and Additive Manufactured Turbine Experimentation

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Tony Grotjan is a Graduate Research Assistant working at the University of Wisconsin-Madison's Solar Energy Laboratory and Thermal Hydraulics Laboratory. His research is in supercritical carbon dioxide power cycle simulation, analysis, and development. His work focuses on the integration of turbomachinery loss modeling in the context of cycle design as well as turbomachinery experimentation with the goal of characterizing supercritical carbon dioxide cycles and turbomachinery to inform future generations of heat to power solutions.



Professor Nellis has engaged in research that builds on his expertise in cryogenics, refrigeration, heat transfer, thermodynamics, and energy systems. Professor Nellis received the R.W. Boom Award in 2008 from the Cryogenic Society of America and was elected a Fellow of ASHRAE in 2013. He co-authored the second edition of the book *Cryogenic Heat Transfer* which is widely used in the industry. He has received "Distinguished Professor" awards from the engineering student organizations Polygon and Pi Tau Sigma several times. Professor Nellis, together with his colleague Professor Sanford Klein, have co-authored three undergraduate-level texts and a reference book.



Dr. Mark Anderson is a Professor in the Department of Mechanical Engineering and Director of the University of Wisconsin's Thermal Hydraulic Laboratory. He also manages the UW-Madison Tantalus facility in Stoughton, WI. Dr. Anderson studies the physics, thermal hydraulic performance, and material corrosion issues of several different fluids (salts, liquid metals, SCW, sCO₂). He is also currently the U.S. representative to the International Atomic Energy Agency (IAEA) for the coordinated research project on supercritical fluids and has active research on the sCO₂ Brayton cycle for nuclear, solar, and fossil advanced power generation. He is one of the UW's Co-PIs on the Department of Energy fluoride-cooled nuclear reactor integrated research project and focuses on salt chemistry, purification, and materials compatibility. Dr. Anderson was recently awarded the Young Investigator Engineering Achievement Award from the American Nuclear Society for his work on liquid salts and supercritical fluids. He has been awarded three patents and has published over 150 papers in various areas related to physics, energy science, production, and utilization. Dr. Anderson currently serves as an Associate Editor for the ASME Journal of Nuclear Engineering & Radiation Science.

ABSTRACT

This work presents an integrated study of supercritical carbon dioxide power cycles, combining cycle-level modeling, turbomachinery loss prediction, and preparation for experimental validation. A detailed modeling framework incorporating empirical aerodynamic, windage, and leakage loss correlations enables accurate system-level performance predictions across a range of power scales without relying on computationally intense methods. Multi-objective optimization and parametric studies reveal trade-offs between cycle efficiency and system compactness, showing how turbomachinery losses influence small-scale system performance and push optimal compressor inlet pressures below the critical point. Complementing the modeling, a test facility was designed and constructed to be capable of 800°C and 11 MPa operation, including management of complex auxiliary cooling flows. This facility was validated and will be used to test a 30 kW turbine-generator system additively manufactured from Haynes 282 to characterize and validate loss modeling predictions. This integrated approach provides pathways toward higher-efficiency, scalable cycles.

INTRODUCTION

The supercritical carbon dioxide (sCO₂) power cycle has the potential to achieve higher heat to electrical power conversion efficiencies in combined heat and power applications compared to traditional steam power cycle technology. To reach the Department of Energy's 65% cycle efficiency target, turbine inlet temperatures approaching 1300°C are necessary. These extreme temperatures surpass current turbine capabilities, making detailed modeling and performance prediction essential to understand cycle behavior and identify practical near-term improvements. Additionally, practical advancements in materials and turbine-generator cooling systems are required to meet these goals. The present work presents a comprehensive research effort that spans cycle-level modeling and experimental validation to advance the development of sCO₂ power cycles.

To support this effort, a detailed modeling framework for the sCO₂ recompressed closed Brayton cycle (RCBC) was developed, incorporating empirical loss models for turbomachinery. The model accounts for aerodynamic, windage, and leakage losses, improving upon conventional constant-efficiency approaches without requiring input from machine-specific or high-fidelity computational fluid dynamic simulations. This enables system-level exploration across a range of power scales, with an emphasis on small-scale applications such as microreactors and extraterrestrial power systems, where cycle performance is sensitive to scale. Parametric studies and multi-objective optimization reveal trade-offs between cycle efficiency and system compactness, with Pareto fronts highlighting how turbomachinery loss mechanisms dominate at lower power scales. This pushes the Pareto-optimal compressor inlet pressure below the critical point for small power scales. Design recommendations are provided for recompression split ratio, generator cavity pressure, and other key parameters.

Additive manufacturing of turbine systems using advanced nickel-based super-alloys like Haynes 282 could enable higher temperature operation and offer design flexibility, addressing the practical metallurgical and cooling system design challenges. The development of test facilities to characterize and validate novel turbine-generator system designs enabled by additive manufacturing is crucial for the advancement of sCO₂ technology. A turbine test facility capable of achieving turbine inlet conditions of 800°C, 11 MPa, and 0.43 kg/s with functionality to manage complex auxiliary cooling flow requirements has been designed and constructed to test a Haynes 282 additive manufactured 30 kW turbine-generator system with advanced cooling channel designs. This facility was experimentally validated using a placeholder expansion device, and will be used to characterize aerodynamic performance as well as leakage and windage losses in small-scale sCO₂ turbomachinery, paving the way for higher-efficiency cycles. Operational data will be used to evaluate turbine performance and refine design recommendations through comparison with modeling results.

RESULTS AND DISCUSSION

Cycle Modeling

The cycle model used in this work is built as a modular, object-oriented MATLAB framework designed to represent the key components of an RCBC. The framework is comprised of dedicated class objects for the turbine, compressors, heat exchangers, and generator, each of which contains methods for standard thermodynamic evaluation as well as advanced loss-prediction capabilities. Unlike conventional $s\text{CO}_2$ cycle models that rely on fixed isentropic efficiencies, this framework integrates empirical aerodynamic, leakage, and windage loss correlations directly into each turbomachinery class, enabling scale-sensitive performance prediction. The full implementation of the RCBC class hierarchy is available in open-access form at [1], and is more fully discussed in [2]. Figure 1 shows the modeled cycle.

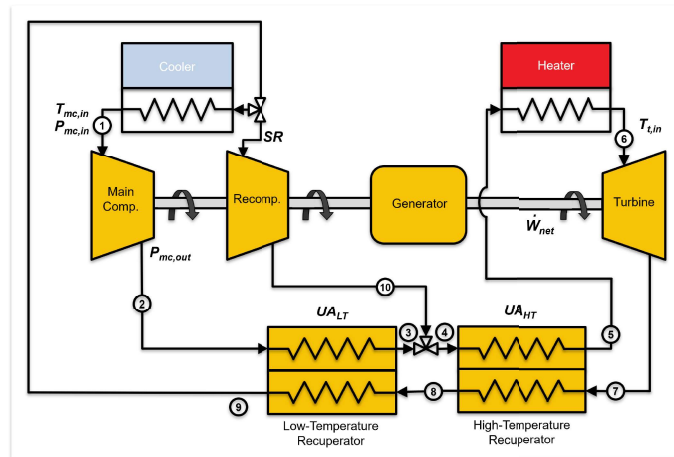


Figure 1: Schematic of RCBC with model inputs. Gold components integrate more sophisticated loss modeling than typical RCBC models in the literature.

The loss models integrated into this framework are summarized below:

- Heat exchanger performance: discretized effectiveness-NTU model [3], [4]
- Heat exchanger sizing: analytical/empirical model [2] based on Blasius [5] and Dittus-Boelter [6] correlations
- Turbomachine aerodynamic losses: specific speed and specific diameter curves compiled by Balje [7] and digitized by Sondelski [8]
- Radial turbomachine leakage: Curve fit function of geometric clearances proposed by Qi [9] based on data from Futral and Holeski [10]
- Radial turbomachine windage: analytical model given by Vilim [11] with coefficients from Daily and Nece [12]
- Labyrinth seal leakage: empirical model developed by Egli [13] and Aungier [14],[15], and modified by Grotjan [2]
- Generator windage: empirical model developed by Aungier [14],[15]

Cycle performance was evaluated using a parametric sweep over compressor inlet pressures at multiple power scales. Figures 2 and 3 show results for the 500 kW and 50 kW scales, respectively, with conventional baseline efficiency overlaid for reference.

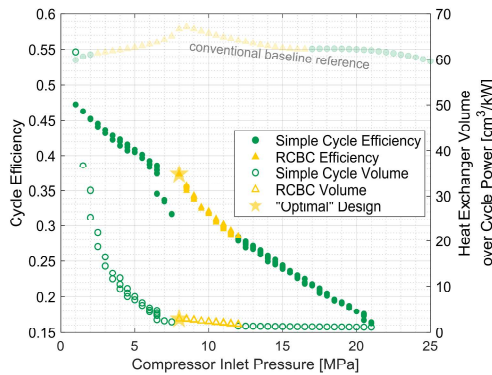


Figure 2: 500 kW power scale: Efficiency and normalized volume with loss models. Conventional baseline efficiency for constant turbomachine efficiency model is overlaid.

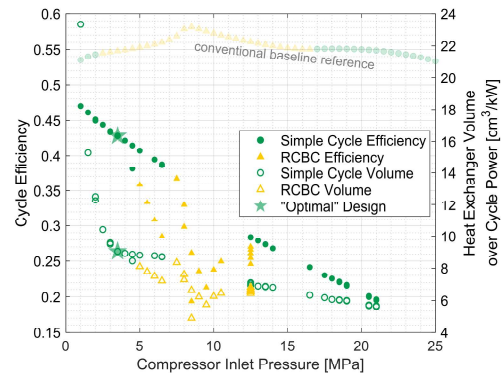


Figure 3: 50 kW power scale: Efficiency and normalized volume with loss models. Conventional baseline efficiency for constant turbomachine efficiency model is overlaid.

Efficiency alone favors low compressor inlet pressures, but the corresponding increase in heat exchanger size reduces system compactness. To capture these trade-offs, efficiency and normalized system volume were combined to construct Pareto fronts. A down-selection of options that reside on the Pareto fronts are shown as a function of the compressor inlet pressure. Optimal designs were selected near the Pareto knee to avoid sharp increases in volume for marginal efficiency gains.

Across power scales, the optimal compressor inlet pressure rises slightly above the critical point at larger scales, while cavity pressures follow consistent trends (Fig. 4). This approach highlights how turbomachinery losses and component sizing interact, providing guidance for design choices that balance efficiency and compactness.

Across the power scales considered, optimal RCBC design trends shift with scale due to turbomachinery losses. At large power scales (generally above 350 kW), designs favor conventional recompressed configurations with moderate split ratios (22–29%). At smaller scales, aerodynamic and leakage losses dominate, pushing optimal designs toward subcritical compressor inlet pressures and simple recuperated configurations. Generator cavity pressure shows a trade-off between windage and leakage losses, with higher cavity pressures (normalized to compressor inlet pressure) favored at large scales and lower values at small scales. Figure 4 summarizes these trends.

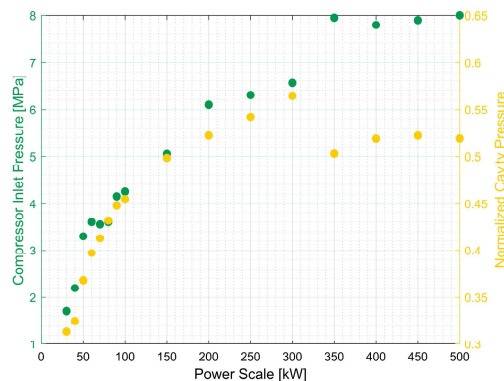


Figure 4: Optimal compressor inlet pressure and normalized cavity pressures as a function of power scale, derived from Pareto-optimal designs.

Experimental Facility Validation

A detailed description of the original facility design is provided in the authors' prior work [16]. Since that publication, the system has been fully constructed, commissioned, and operated in preparation for upcoming turbine experiments. Figure 5 shows an updated schematic of the facility, reproduced from the authors' recent ASME journal article [17].

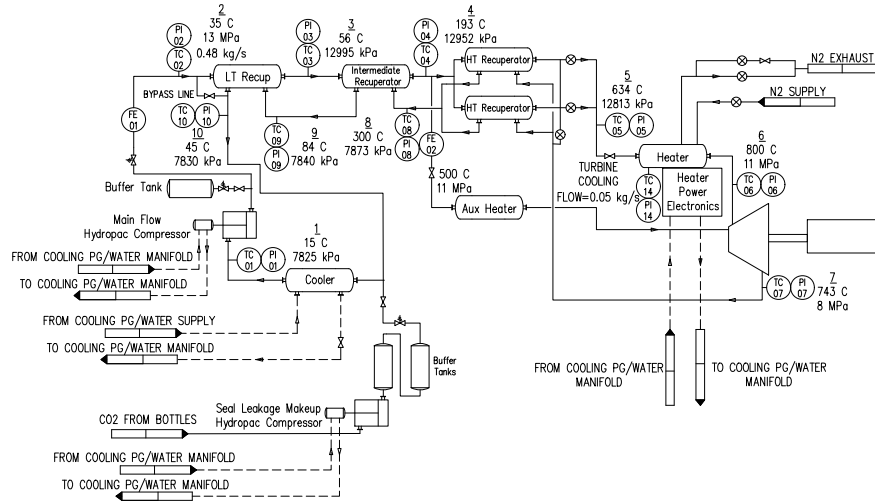


Figure 5: Updated system schematic (reproduced from [17]).

The facility has now been fully constructed. Figure 6 shows the complete test facility layout, and Fig. 7 shows the assembled high-temperature $s\text{CO}_2$ heater. As documented in [17], the system demonstrated turbine inlet temperatures up to 700 °C, pressures up to 9 MPa, and mass flow rates near 0.40 kg/s during initial validation—matching, to the authors' knowledge, the highest reported turbine-inlet temperatures achieved in open-literature $s\text{CO}_2$ test facilities. Once turbine installation is complete, the facility is designed to support future tests at turbine inlet temperatures up to 800 °C.

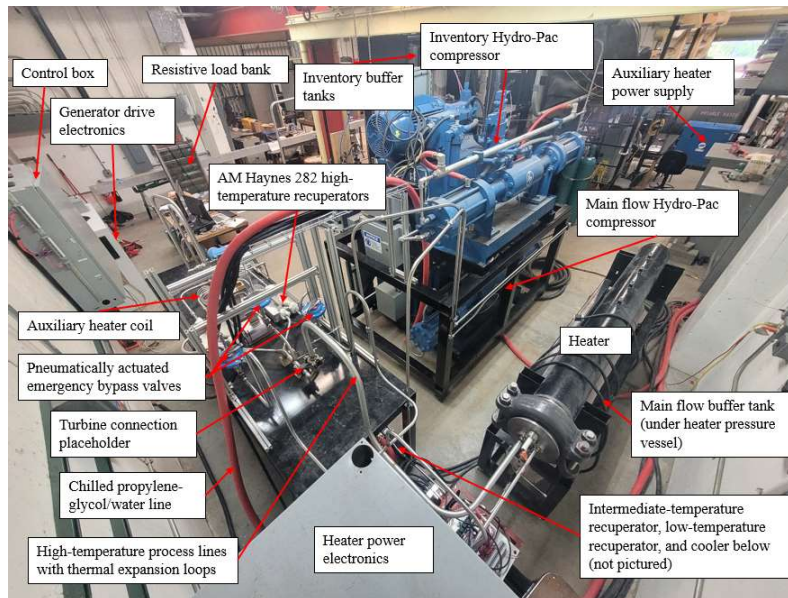


Figure 6: Constructed $s\text{CO}_2$ turbine test facility (reproduced from [17]).

To prepare for future turbine testing, the proposed start-up path (as defined in [17]) was validated experimentally using an orifice as a placeholder expansion device for the turbine. Figure 8 shows a T - ν diagram of the proposed turbine-inlet start-up path in green circle data points. Experimental turbine inlet state data collected during this campaign are overlaid in green. Also shown are full-cycle operating loops corresponding to operating points 4, 7, and 11 to illustrate the progression of the entire cycle through time. Furthermore, Fig. 9 presents the temperature history for all ten cycle states throughout the validation campaign. These data illustrate the evolution of the system as it passes through the planned start-up sequence, including the known instability region near points 6–8 where the CO_2 crosses the top of the vapor dome. As noted in the authors' prior ASME publication, this two-phase sensitivity introduces transient oscillations driven by variations in heat rejection capacity, yet pseudo-steady turbine-inlet conditions remain achievable.

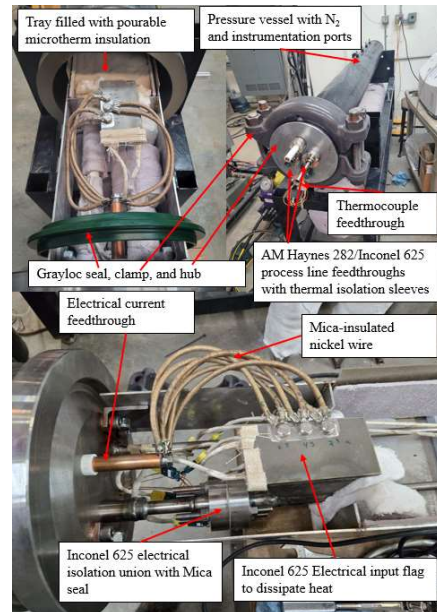


Figure 7: Constructed sCO_2 heater assembly (reproduced from [17]).

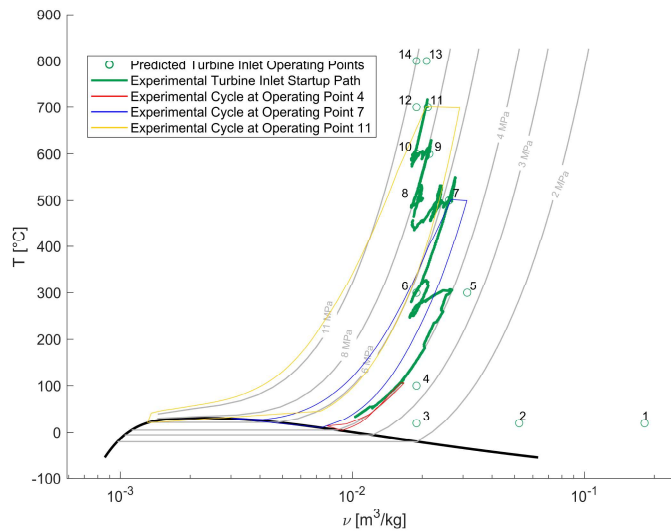


Figure 8: T - ν diagram showing the proposed turbine-inlet start-up path, experimental data obtained using an orifice in place of the turbine, and full-cycle loops at operating points 4, 7, and 11.

With the facility constructed and its start-up path experimentally validated, the next phase of work involves installing the 30 kW additive-manufactured turbine and performing the full aerodynamic, leakage, and windage characterization campaign. These measurements will be used to inform and validate the cycle-level modeling framework presented in this study, enabling a combined computational–experimental assessment of small-scale sCO_2 turbomachinery performance.

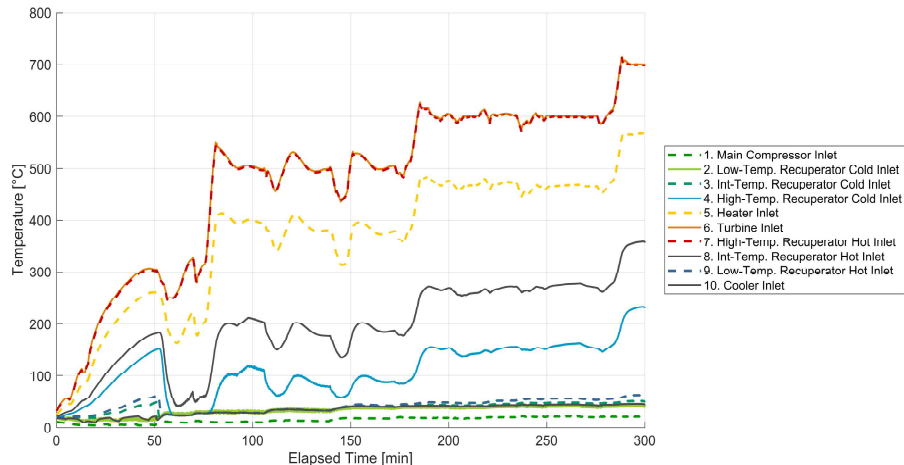


Figure 9: Measured temperature vs. time for all ten thermodynamic states during the validation campaign.

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