

VERIFICATION OF SETTLE OUT CONDITION PREDICTION METHODS FOR SUPERCRITICAL TRANSFORMATIONAL ELECTRIC POWER (STEP) 10 MWE PILOT SCALE POWER PLANT

Jonathan L. Wade
Manager
Southwest Research Institute
San Antonio, TX USA

Kagan Bixler
Engineer
Southwest Research Institute
San Antonio, TX USA

Catherine Potts
Engineer
Southwest Research Institute
San Antonio, TX USA

Darryl Hino
Manager
Gas Technology Institute
Woodland Hills, CA USA

AUTHORS



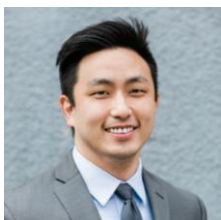
Mr. Wade is the manager of the Power Cycle Machinery section at Southwest Research Institute. His research interests are in the areas of advanced power cycles, turbomachinery, rotordynamics, seals, bearings, foil gas bearings, microturbines, structural dynamics, finite element analysis, and fluid-structure interactions. He is experienced in turbomachinery design, high-vibration (synchronous and sub-synchronous) root cause and corrective action investigations, machine failure investigations, and vibration and performance testing.



Mr. Bixler is an Engineer within the Power Cycle Machinery section at the Southwest Research Institute. He supports power cycle design and energy industry research projects. At the STEP facility, Kagan provides onsite support for commissioning tasks on the compressor systems and other STEP equipment.



Ms. Potts is an engineer in the Power Cycle Machinery section at Southwest Research Institute. She received her B.S. and M.S. in Mechanical Engineering, specializing in thermal fluids, from Florida State University (FSU) in Tallahassee, FL. Her background is largely in research labs where she gained experience in experiment design and operation of high-pressure systems. Since joining the section, she has supported the STEP 10MW sCO₂ Pilot Power Plant and other projects relating to energy storage and advanced power cycles.



Darryl Hino is an R&D Manager, leading the Mechanical Design and Analysis group at GTI Energy, where he has been supporting the U.S. Department of Energy's STEP 10WMe sCO₂ Pilot-Scale Demonstration facility since 2019. His primary responsibility is the Flownex STEP dynamic system model, which includes simulating various transient events and reviewing test data ensuring the model's accuracy. In addition to supporting

the STEP project, Darryl's responsibilities include thermal and structural verification of combustors and reactors for various applications. Prior to joining GTI Energy in 2017, Darryl worked at Aerojet Rocketdyne as a Test Development Engineer and a Structural Analyst from 2010 to 2017. He holds a B.S. in Mechanical Engineering and an M.S. in Engineering with a Certificate in Structural Mechanics from the University of California, Los Angeles (UCLA).

ABSTRACT

Super critical carbon dioxide (sCO₂) power cycles have the potential for high thermodynamic efficiencies. The high cycle efficiencies are achieved by operating with the turbine inlet at high temperatures and pressures and the compressors generally close to the critical point. Each cycle implementation will have different geometries and likely different ratios between the low-pressure and high-pressure sides of the loop. When the cycle is not operating, without other intervention the loop will naturally achieve one pressure throughout the loop. Determining that settle out pressure and the distribution of temperatures if shutting down from an operating condition can drive critical design decisions. It is important to be able to accurately predict the settle out conditions for closed loop sCO₂ systems. Because of the large difference in the sCO₂ conditions at different locations in a power cycle loop, predicting the settle out conditions can be challenging. This paper will discuss a variety of methods that were used to predict the settle out pressure and temperature distribution and compare those predictions to test data collected during commissioning and operation of the simple cycle configuration of the STEP Facility.

INTRODUCTION

Closed loop power cycles when operating have a distribution of different pressures and temperatures at different locations around the loop. Pressure differential is what drives the fluid flow, if there are no pressure differentials in the loop there would be no net mass flow around the loop. Compressors and pumps are used to increase the pressure while turbines and expansion valves are used to decrease the pressure. Additionally, there is pressure loss that naturally occurs due to viscous losses as the working fluid flows through the piping and heat exchangers in the loop. The working fluid temperature is also changing as the working fluid travels around the closed loop.

Supercritical carbon dioxide (sCO₂) has properties that are very sensitive to temperature. Relatively small changes in the temperature of the fluid can drive significant changes to the pressure when the fluid is in a closed volume. Designing components to the maximum conditions that they will be exposed to is critical to proper loop design. During cycle operation the loop will have a large distribution of pressures with the portion between the compressor discharge and the turbine inlet significantly higher pressure than between the turbine discharge and the compressor inlet, see Figure 1. When the system is not flowing the pressure in the loop will assume a settle out pressure, depending on the amount of mass in the loop and the conditions before settle out is achieved will determine the settle out pressure. For the same inventory mass, higher temperature working fluid will result a higher settle out pressure. Accurately predicting both the operating and the settle out conditions is critical to determining the appropriate design conditions for the system components. Heim et. all describe several methods to predict the settle out conditions [1].

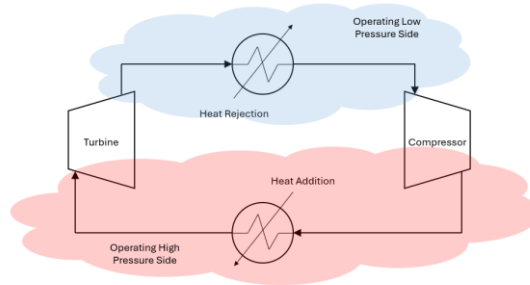


Figure 1: Simplified Closed Loop Cycle

STEP DEMO

The United States Department of Energy (DOE) has funded the Supercritical Transformational Electric Power (STEP) Demo project to design, procure, commission, and operate a 10MWe pilot scale powerplant. An overview of the STEP Demo project is described with additional details by Marion et. all in [2].

Figure 2 shows the STEP facility high bay with the compressor on the right side of the image and the turbine on the left side. Figure 3 shows a plan view of the facility layout, in addition to the piping and equipment seen in Figure 2 the process heater is shown that is located outside of the facility.



Figure 2: Step facility picture

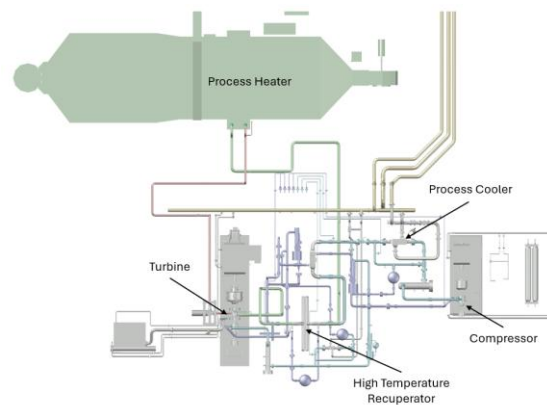


Figure 3: STEP facility layout

Figure 4 shows the simple cycle configuration Process and Instrumentation Diagram (P&ID) of the STEP Demo facility with three key areas identified. The areas are the piping between

compressor discharge (CBA-001) to the check valve (NRV-248) in yellow, the piping from the check valve (NRV-248) to the turbine stop valve (CV-470A) in green, and from the turbine stop valve (CV-470A) to the compressor inlet (CBA-001) in blue. The colors used for the three piping sections in Figure 4 match the colors of the pressure plots for those same locations in Figure 5. Figure 5 shows the pressures versus time of those three pipe volumes plus the rotor speeds for the turbine and the compressor. As can be seen, the turbine speed increases slightly before the turbine stop valve tripped, causing the turbine speed to rapidly decrease. When the turbine tripped the compressor continued to operate in full recycle before the compressor tripped less than one minute after the turbine trip occurred.

As can be seen in the pressure plots of Figure 5, when the turbine stop valve (CV-470A) closes and the flow stops, the check valve (NRV-248) closes and bottles up the pressure. The loop has two zones for settle out with different pressures. This strategy was used to ensure that the low pressure side of the loop, between the turbine discharge and the compressor inlet maintained a relatively low settle out pressure condition. Additionally, this strategy controls the distribution of the post heater high temperature CO₂ ensuring that it doesn't backflow through the system to piping and equipment not designed for the highest temperatures in the loop.

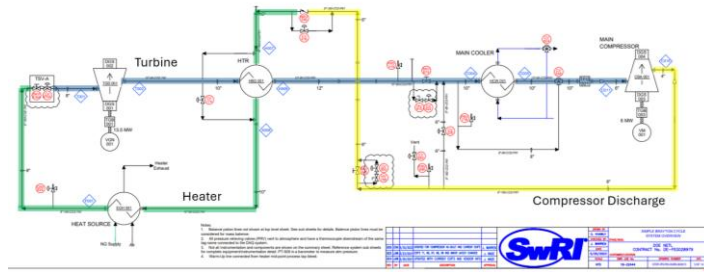


Figure 4: Key pressure locations map

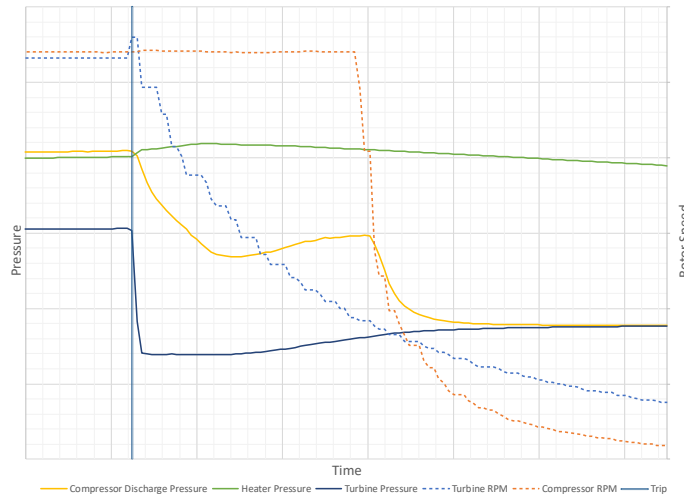


Figure 5: Key location pressures during a system trip

CONCLUSIONS

The settle out conditions for an sCO₂ closed loop system are very dynamic and a detailed transient model is required to accurately predict the behavior. Bulk models can be used to get approximate values but the behaviors observed, specifically the increase in the heater pressure

(Figure 5) after the trip will not be predicted without a transient model. The pressure increase observed in the heater section is due to heat addition from the heater even though the combustion is tripped off with the process trip.

The two zone settle out strategy was successful as can be observed by the heater pressure zone maintaining a pressure approximately 100 bar above the compressor discharge and turbine sections.

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ACKNOWLEDGEMENTS

The authors would like to thank the U.S. Department of Energy, Office of Fossil Energy and the National Energy Technology Laboratory, under Award Number DE-FE0028979 that supports this work, as well as Supercritical Transformational Electric Power (STEP) project prime, GTI Energy, and the STEP project partners, Southwest Research Institute and General Electric Vernova.

DISCLAIMER

This information, data or work presented herein was funded in part by the National Energy Technology Laboratory (NETL), U.S. Department of Energy, under Award Number DE-FE0028979.

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