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PRACTICAL ASPECTS OF SUPERCRITICAL CARBON DIOXIDE BRAYTON SYSTEM TESTING

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ABSTRACT

The supercritical carbon dioxide (S-CO_2) Brayton cycle has been gaining interest in recent years due to its high efficiency and compact components. Bechtel Marine Propulsion Corporation (BMPC) is testing an S-CO_2 Brayton system at the Bettis Atomic Power Laboratory. The Integrated System Test (IST) is a two shaft recuperated closed Brayton cycle with a variable speed turbine driven compressor and a constant speed turbine driven generator using S-CO_2 as the working fluid designed to output 100 kWe. This paper presents practical aspects of S-CO_2 Brayton cycle operation including loop purge and fill operations and system leakage as well as design considerations including thermal stresses, material quality and loop cleanliness, and instrumentation. Additionally, operational test data for CO_2 temperature, pressure, and density are presented and comparisons made on the ability to accurately calculate CO_2 density using REFPROP for an operating Brayton loop.

INTRODUCTION

The S-CO_2 Brayton cycle is being actively developed for potential use in a wide range of energy conversion applications. S-CO_2 power cycles offer the potential for improved plant economics based on high power conversion efficiency at moderate temperatures, compact component size, and standard materials of construction [1]. Based on the potential benefits, BMPC has constructed and operated the IST to demonstrate operability and controllability of the S-CO_2 Brayton power cycle [2-6].

The IST is a simple recuperated closed loop S-CO_2 Brayton system with a variable speed turbine-compressor and a constant speed turbine-generator. The IST is designed to generate nominally 100 kWe at a relatively modest turbine inlet temperature of 570°F (299°C). The physical arrangement of the IST is shown in Figure 1. The heat source for the IST is a 1 MW electrically-heated organic heat transfer fluid system which transfers heat to the CO_2 through a counter-flow shell-and-tube heat exchanger. The heat sink is a chilled water system which rejects heat from the precooler and other heat loads to a refrigerated chiller. This chilled water system is broken into two loops so that cooling flow can always be provided to auxiliary heat loads throughout the system while the precooler can either be cooled from this chilled loop or heated during startup through a separate water loop to achieve supercritical conditions in the CO_2 loop.

PRACTICAL ASPECTS OF LOOP DESIGN AND OPERATION

As of May 2014, the IST Brayton loop has been operated for approximately 165 hours. There are many aspects of how the IST is operated that are driven by the small scale of the equipment and use of technologies that are not prototypic of what would be used in larger scale systems. A full description of system startup and operation is provided in [5] and [6]. This paper focuses on design and operational considerations from the IST which are likely to apply to S-CO_2 Brayton power systems independent of size.

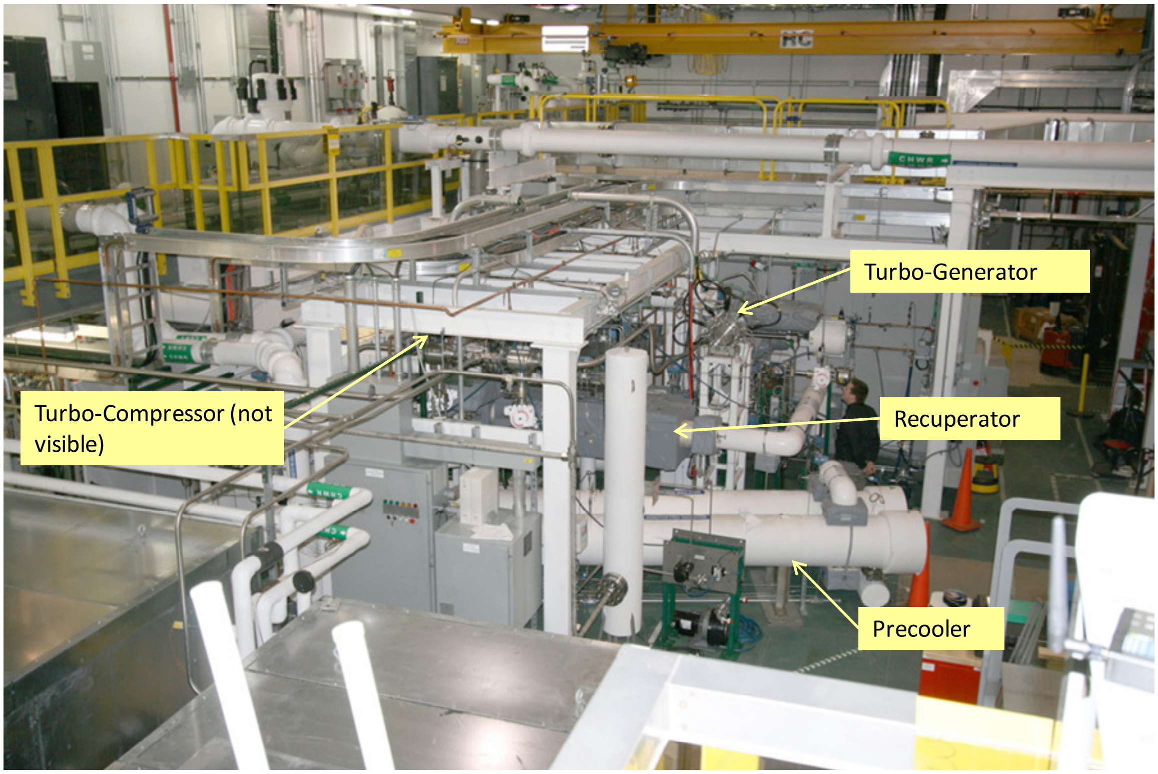

Figure 1. IST Physical Layout

Design Considerations

The main purpose of the IST is to demonstrate the operability and controllability of an S-CO_2 Brayton system. For this reason, the design of the loop was affected by the predictions of the transient model that was used to develop the control strategies. Pipe size, valve resistance, valve stroke time, and support equipment were selected based on optimizing the controllability of the system via model predictions. Additionally, the use of the transient model allowed design decisions to be made which would improve the ability to startup the system and operate at off-design conditions reliably. This approach has proven valuable to the success of the IST as startup strategies could be developed and tested in the model before using them on test equipment thereby reducing the risk of damage to the equipment. The model is also used to develop the operating procedures and control strategies for the loop reducing the burden on the operations staff in determining the best way to operate the system over a range of conditions. IST test data is used to update the model and improve its accuracy.

A number of design choices were made for the IST based on BMPC's envisioned end application of the S-CO_2 Brayton cycle. A simple recuperated Brayton cycle was selected for the IST to reduce the operational complexity and cost of the loop compared to a recompression or other configuration. A two-shaft arrangement with a variable speed turbine-compressor and a separate constant speed turbine-generator was chosen to simplify the electric distribution system of the generator by operating at a constant frequency at all power levels. The maximum operating temperature of 570°F (299°C) was selected to be compatible with a pressurized water reactor (PWR) and allow for use of stainless steel throughout the loop. The 100 kWe rating of the system was selected as this was the lowest power level that would give representative system turbomachinery while minimizing size and cost. The precooler has water on the tube-side and CO_2 on the shell side of the heat exchanger to simulate a condenser and the ability to clean the water tubes. The compressor inlet conditions were chosen to be away from the critical point to reduce the effect of variations in temperature and pressure on density as the system operates through difference transients. Cumulatively these decisions result in a system that does not have the high efficiency of the many envisioned applications of the cycle but has improved controllability and operational reliability in support of the test objectives.

The IST CO_2 loops are assembled using a combination of Grayloc fittings, Swagelok fittings, and ANSI flanges. Brayton loop piping-to-component connections are all made using Grayloc flanges while instrumentation connections are made using ¼" Swagelok fittings which are welded onto the piping. Larger Swagelok fittings and ANSI flanges are used in support systems which typically operate at pressures below the critical pressure of CO_2. The fittings have all proven to be leak-tight in an S-CO_2 environment when properly installed. Bolt selection should consider not only the design operating conditions but also the heatup and cooldown rate of the system as well as the temperature that would be expected to impinge on the bolts if a leak occurred. Due to the large temperature difference between ambient temperature and normal operating temperature and the potential for very low temperatures caused by the expansion of CO_2 through a leaking fitting, high material grade bolts are used in Grayloc fittings and ANSI flanges in the IST CO_2 systems.

A benefit of the S-CO_2 Brayton cycle is the small size of the components which allows for compact system arrangement. The high operating temperatures and pressures require thick-walled piping. Additionally, maximum system efficiency occurs when piping pressure drop is minimized which results in short pipe runs and larger pipe sizes than would be used if pressure drop was not a concern. These factors combined can make thermal stresses in the piping system difficult to accommodate. The IST component arrangement and piping system design were performed in parallel with thermal stress analyses being performed to influence the design. Thermal stress analysis indicated that four thermal expansion loops needed to be incorporated into the loop (Figure 2). By performing this analysis in parallel with the loop arrangement, the locations of the expansion loops could be selected while space was available in the optimum locations and the loop piping could be procured with the thermal expansion loops in place. By comparison, the relief valve inlet piping was designed without considering thermal expansion, which resulted in the need to redesign one relief line after the original relief piping was procured and installed, resulting in added costs associated with buying, installing, and insulating the second pipe.

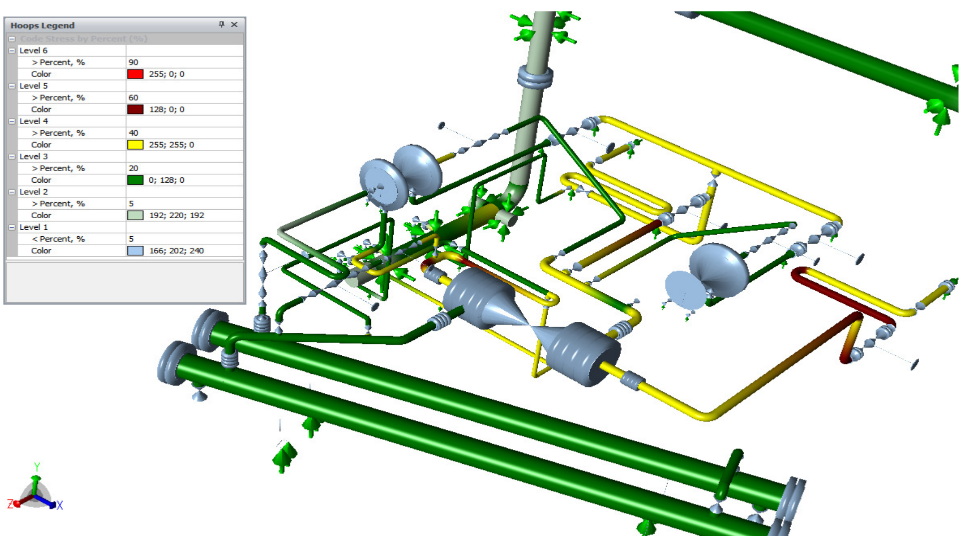

Figure 2. Thermal Stress Analysis of Brayton Loop Piping

Loop Cleanliness

S-CO_2 is an effective solvent which has the potential to absorb loose oils and other organic matter and can redeposit it in other parts of the system where solubility is decreased, primarily downstream of large pressure reductions. IST components, piping, and tubing were procured with material quality and cleanliness controls to reduce the potential for contaminants which could be absorbed by the S-CO_2 and transported throughout the loop. Additionally, all hydro-tested piping and tubing was wiped down with a clean rag after drying to remove contaminants that were in the water used for the test. During maintenance evolutions, all open sections of the loop are capped to prevent dust and debris that could cause cleanliness issues from entering the loop. With these actions in place, minimal oils and other contaminants have been found in the IST during loop and component disassembly and inspection.

In addition to absorbing impurities, materials testing performed at BMPC [7] and loop operating experience has shown that some common polymer materials are incompatible with the S-CO_2 environment through either material degradation or CO_2 impregnation. Based on results of materials testing, the IST uses EPDM o-rings in locations exposed to S-CO_2 and has not seen any issues with S-CO_2 and EPDM interaction. Conversely, CO_2 impregnation and explosive decompression have been experienced with Viton o-rings. The IST has also experienced sporadic degradation of Teflon tape used on threaded fittings on instrument lines which are exposed to operating pressure and ambient temperature.

The IST has experienced turbine nozzle and shroud wear and erosion similar to that seen in the turbomachinery at Sandia National Laboratories [8].. It is believed that this damage is cause by fine particulate material in the loop which passes through the turbine nozzles where it is struck by the turbine blades and batted into the back side of the nozzles causing wear and erosion, as shown in Figure 3. This causes the turbine nozzles to weaken and bend into the flow path thereby creating a restriction which results in reduced turbine flow and performance. As the nozzles and shroud erode, more particulate material is created which causes further wear of the nozzles. The recuperator and precooler provide areas of low flow velocity and material impingement zones which serve as good system filters as indicated by a high density of material on the pipe walls at the outlet of the turbines but little to no debris found at the turbine inlets and no damage from material impingement noticed at the compressor.

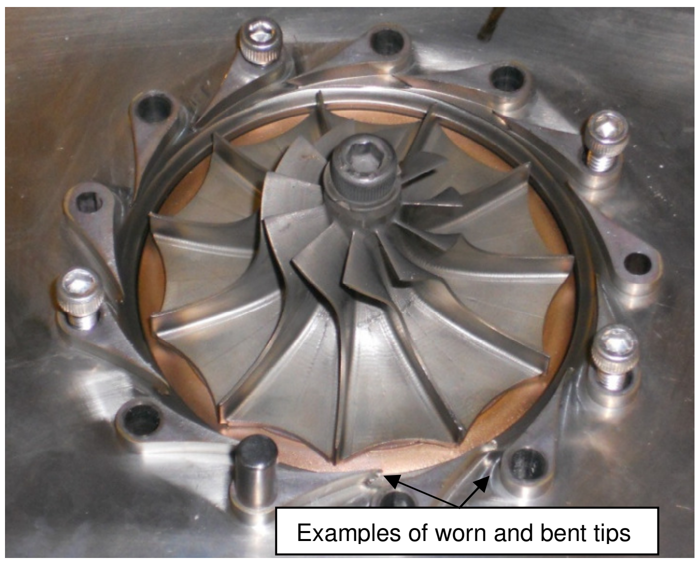

Figure 3. Turbine Nozzle Wear

System Fill and Leakage

The IST is filled with Coleman Instrument grade (99.99%) CO_2. When a system fill operation is performed, a rough vacuum is pulled to less than 0.5 psia (25 torr) to evacuate the loop of air and other impurities. The loop is then filled with CO_2 until pressure is just above atmospheric pressure. This procedure is repeated twice more before adding additional CO_2 up to the normal fill mass. This process reduces the concentration of contaminants to less than 0.01%, or comparable to the purity of the supply gas. Alternate approaches to draw a high vacuum to a lower pressure could be used to accomplish the same level of purity but would require an additional high-vacuum pump.

System fill is accomplished by initially allowing the pressure difference between the CO_2 cylinders and the loop to force CO_2 into the system. As the pressure differential is decreased, a reciprocating compressor is used to pump the CO_2 out of the cylinders. For a large mass addition such as filling an empty loop, CO_2 cylinders with eductor tubes are used to pull liquid from the bottom of the cylinders. This approach reduces the cylinder cooling associated with the heat of vaporization compared to what would be seen by filling with gas from the top of the cylinders. This approach also keeps the supply pressure elevated longer and, therefore, more mass is pulled out of the cylinders before reaching the minimum inlet pressure for the compressor. The liquid CO_2 is expanded in an electrically heated vaporizer to ensure single-phase vapor flows through the coriolis mass flow meter and reciprocating compressor. For small mass additions, standard gas service cylinders are used.

The IST experiences low levels of CO_2 leakage from the system. While the mechanical fittings discussed above are leak tight, the valve stem packing on the 3" Brayton loop valves and 2" shaft seals on the reciprocating compressor have exhibited low leakage rates. During a typical loop startup, 0 to 70 lbm (0 to 32 kg) of CO_2 needs to be added to the system to get to the target loop operating pressure which corresponds to a system mass of approximately 450 lbm (204 kg). The amount of mass added at startup varies from test to test depending on factors including length of time since last mass adjustment, length of system operation since last mass adjustment, and whether the loop was shutdown via the normal procedure where the system is cooled down gradually or by a protective action with the loop at elevated temperature which results in non-uniform cooling.

Instrumentation

The IST uses standard commercial instrumentation to determine the conditions of the CO_2 in the loop. Temperatures are measured using Marlin Type T Special Limit of Error (SLE) thermocouples inserted approximately into the center of the piping. Pressure is typically measured coincident to the temperature using Rosemount 3051S Scalable Pressure Transmitters with the pressure connection located 180° from where the thermocouple is inserted into the pipe. Mass flow and density are measured using Micro Motion Elite Coriolis Flow and Density Meters located in-line with the loop flow in low pressure sections of the loop. This instrumentation has worked well in the IST. The only exception is that the Coriolis flow meters in the support systems provide invalid readings during loop startup as the orientation of the meters allows for collection of liquid in the U-tubes which is believed to affect the sensor readings until the system is heated to the point that the liquid evaporates. Consideration should be given to U-tube orientation to prevent this potential collection point when laying out systems with Coriolis flow meters.

The local temperature and pressure were used with the NIST REFPROP property database to calculate the density of CO_2 during IST operations and compared to measured density from the Coriolis meters. Comparison shows that the difference between calculated and measured density is within the instrument uncertainty when pressure is greater than 100 psi above the critical pressure [9]. Figure 4 shows the difference in the density measured using the Coriolis flow meters and the density calculated using temperature and pressure measurements and REFPROP for 25 operating points for the IST. Data points with the largest difference between measured and calculated density and points where the uncertainty bands on the two densities do not overlap tend to be near the critical pressure of CO_2.

CONCLUSIONS

IST operation has not identified any inherent issues with S-CO_2 Brayton power cycle operation. However, this small scale test has identified areas such as modeling of off-design operations, thermal stress analysis, instrument orientation, cleanliness, and material compatibility that should be considered when designing and operating these cycles. Factoring this practical experience early in the design of future systems early will minimize rework and operational issues S-CO_2 test loops and power cycle applications.

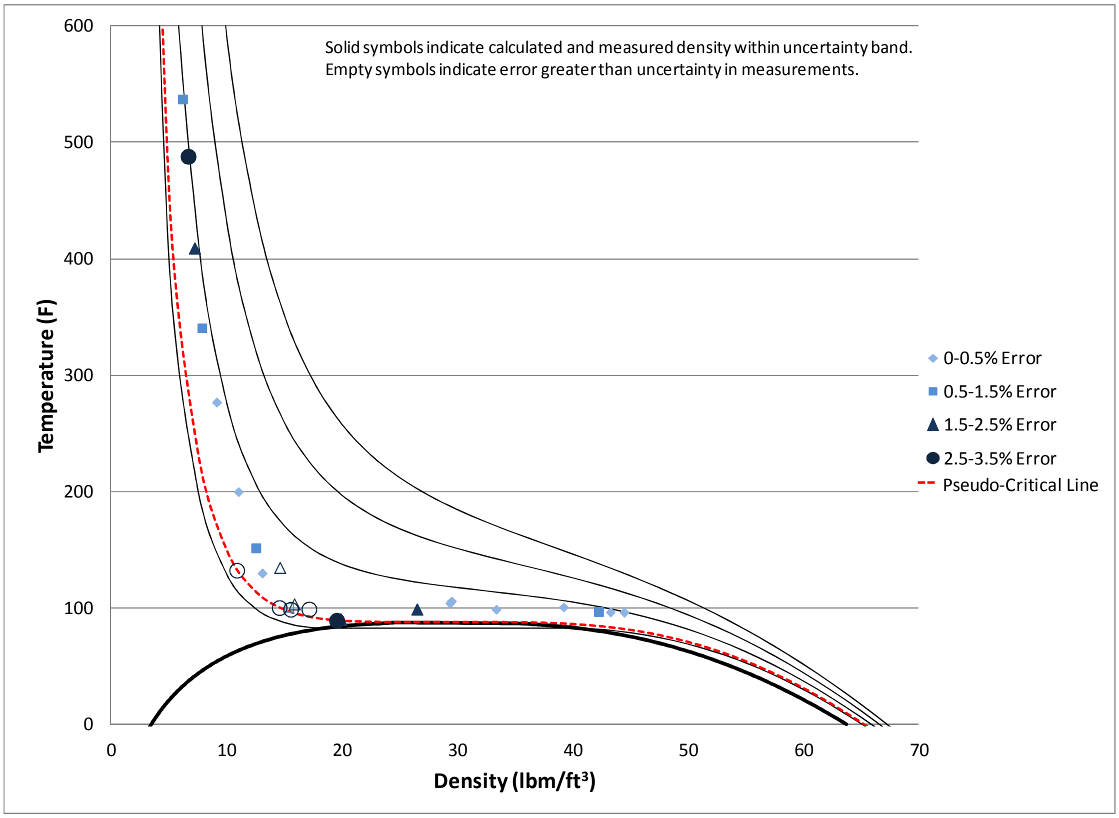

Figure 4. Difference in Measured and Calculated Density During IST Operation

NOMENCLATURE

BMPC	=	Bechtel Marine Propulsion Corporation
IST	=	Integrated System Test
PWR	=	Pressurized Water Reactor
S-CO_2	=	Supercritical Carbon Dioxide
SLE	=	Special Limit of Error

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