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10MW-CLASS sCO2 COMPRESSOR TEST FACILITY AT UNIVERSITY OF NOTRE DAME

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ABSTRACT

The compressor is a key component in closed-loop Brayton Cycles and advanced electrothermal energy storage systems. The use of sCO2 as the primary working fluid had many advantages for these systems. However, due to the unique operating conditions and fluid properties, there remains significant challenges for the development of high efficiency compression systems with sCO2. Detailed experimental measurements from sCO2 compressors are extremely difficult to obtain, given the small size and very high power requirements. This has limited the majority of current experimental results to very small scale, single stage, centrifugal compressors. Larger, multi-stage axial compressors are of significant interest for sCO2 systems, but have not been subject to experimental investigations.

The present communication describes the design and salient characteristics of a new, 10MW-class closed-loop sCO2 or CO2 compressor test facility. The 10MW drive system allows for a physical scale that allows testing of both axial and centrifugal compressor types with flow passages large enough to enable detailed experimental measurements., including surveys through the flow passage, steady and unsteady performance measurements, and aeromechanical measurements on vanes or blades.

INTRODUCTION

The use of supercritical CO2 as the working fluid in closed-loop Brayton Cycles and advanced electrothermal energy storage systems has shown great promise in delivering electricity with high efficiency, flexibility of heat source, and reduced power-plant size and cost [1, 2]. However, a number of new technology advancements must be realized in order to make sCO2 cycles commercially viable. One of the major components is the compressor, which provides the pressure increase needed in the cycle. Some characteristics of sCO2 in regard to its application in a compressor differ from those seen with air or gas which is widely used for turbo compressors. Higher density inside the compressor, overall higher operating pressure ranges, and drastic change of fluid properties near the critical point each present unique challenges for compressor design.

Recent experimental studies of sCO2 compressor in compressor test loops [3-8] or in power cycle loops [9-15] have successfully demonstrated the operation of sCO2 compressors in closed loops test environment. However, due to the small demonstration scale or due to limited available driving power, all of them were designed with a centrifugal type compressor with small scale where efficiency must be sacrificed resulting in low overall cycle efficiency. Also studies on detail flow

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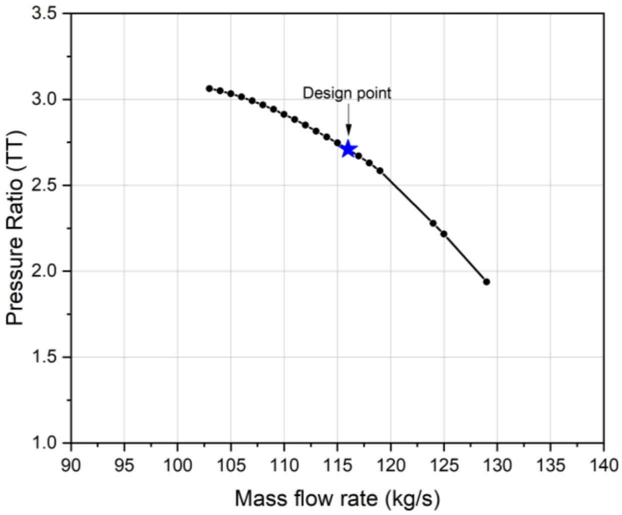

Figure 1: Predicted map of a 3-stage axial compressor @ design point

measurement were not suitable due to the very small flow passages through the compressor.

With this background, Notre Dame Turbomachinery Laboratory and Echogen Power Systems has designed a 10 MW-class sCO2 compressor test facility to be built at the University of Notre Dame. The test compressor is driven by a 10 MW variable speed motor with a speed increasing gear box. A water/Glycol cooled heat exchanger absorbs added energy from the test compressor. The closed loop is designed to reach steady operation where the addition of energy through the drive motor and the absorption of energy through cooling flow are equal. A CO2 inventory management system with CO2 tank and supply system was designed to supply CO2 from initial operation to test operation.

The choice of a 10 MW size sCO2 compressor test facility has various merits in terms of scale. It allows use of commercial hardware for many of the components of the test compressor and facility [16]. Also it enables the facility to test the multi-stage axial compressor as well as centrifugal compressors with flow passages wide enough to allow a detailed flow field investigation through various flow measurement technologies. The experiments will include detailed measurements that will significantly advance our understanding of the design, performance, efficiency, and operability of sCO2 compressors for advanced power systems.

At the time of this writing, the construction of the drive train with a variable speed motor, a gear box, a torquemeter and relevant control systems is complete and has been fully commissioned. Also, a unique data acquisition/control system was developed and tested. This includes the ability to conduct real-time post processing and control with 100s or 1000s of steady and unsteady acquisition channels. The design of the closed CO2 test loop is funded by the U.S. Department of Energy and will be complete in mid-2021. Initial sCO2 axial compressor tests will begin in 2021.

TEST COMPRESSOR : 3-STAGE AXIAL COMPRESSOR

The first compressor to be tested at the facility is a three stage axial compressor. Its design condition is in Table 1 and its predicted map is shown in figure 1.

Table 1: Design point of 3-stage axial compressor

# of compressor stages	-	3
Inlet total pressure	MPa	2.77
Inlet total temperature	˚C	97.94
Mass flow rate	kg/s	116
Pressure ratio	-	2.706
Design point aero power	MW	9.09
Design speed	rpm	19,800

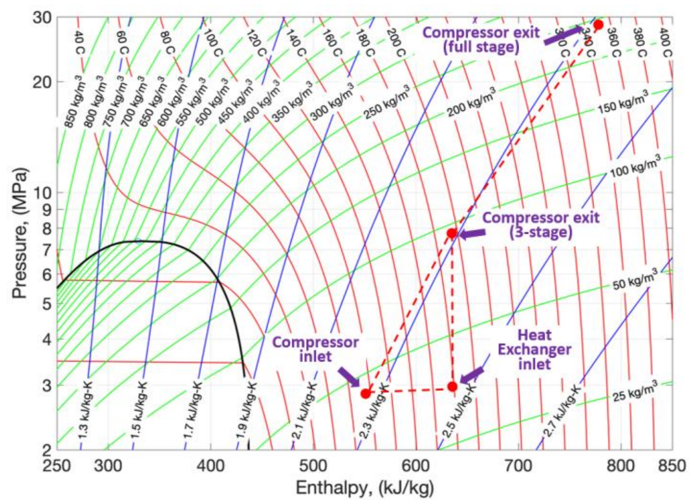

Figure 2: *p-h* diagram of the 3 stage test compressor in test loop vs full stage compressor operating point.

The 3-stage test compressor is a scaled version of first 3 stages of a 100 MW class multi-stage axial compressor designed for a sCO2-based energy storage system. The objective of the program is to study and ultimately demonstrate a high efficiency, multi-stage, axial sCO2 compressor. Pressure ratio of the full stage compressor is 10.27. The first three stages of the full machine will be tested in the designed test facility with a design-point pressure ratio and mass flow rate of approximately 2.6 and 116 kg/s, respectively.

CLOSED TESP LOOP

The specification of the CO2 compressor test loop is shown in table 2 and a schematic diagram of the test facility is shown

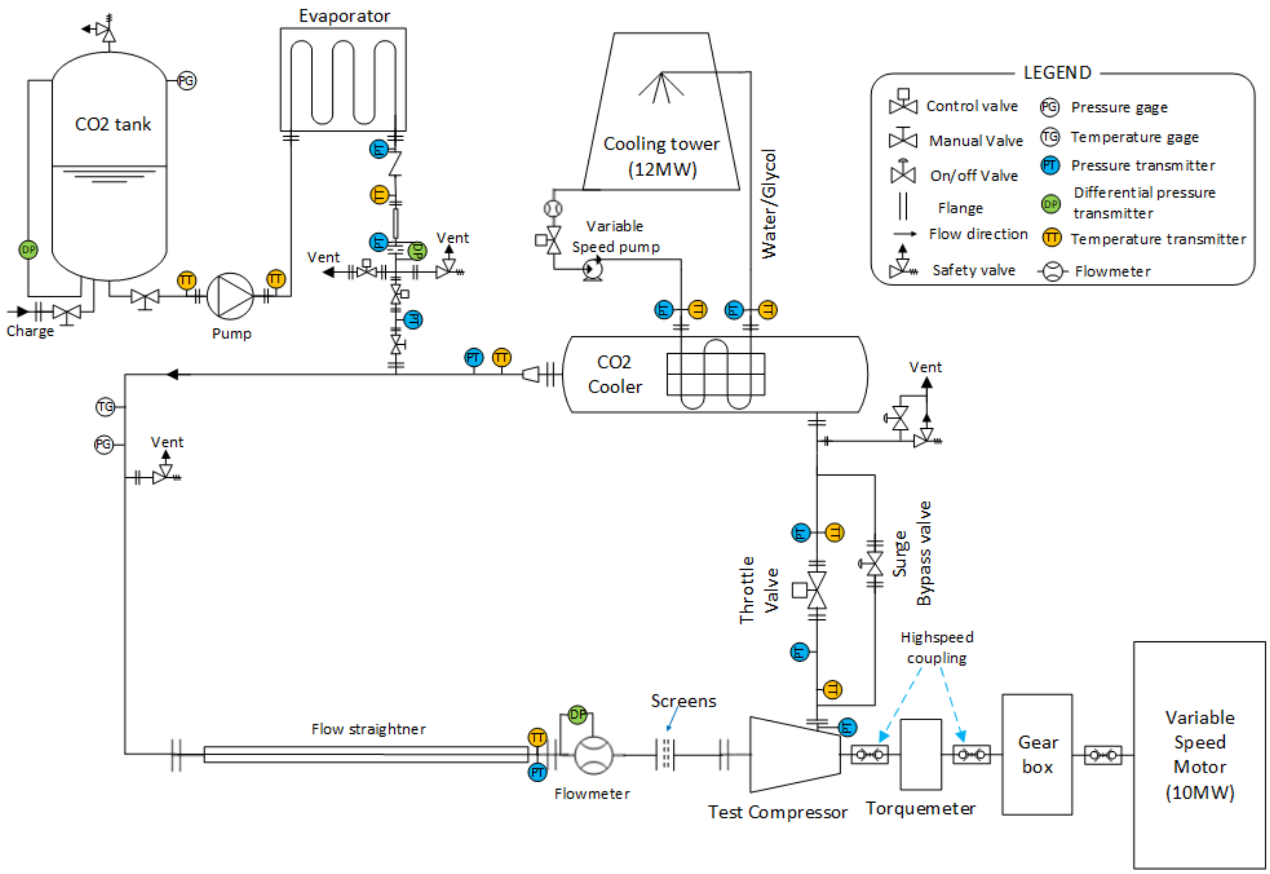

Figure 3: Schematic diagram of sCO2 compressor test facility.

in figure 3. Images of the design implementation showing the overall scale and layout of the equipment is shown in figure 4. The CO2 compressor test loop can be divided into the main closed loop and the CO2 inventory system. The closed test loop is where CO2 gas recirculates to feed the test compressor continuously with CO2. The back-pressure to the compressor is provided and controlled by a throttle valve. Heat is then removed through a CO2/Water heat exchanger. The return flow then moves through a long straight piping section prior to entering a mass flow meter. The inventory system stores CO2 in a CO2 tank and supplies CO2 for testing. This system includes a CO2 tank, an evaporator, a feed pump, a flowmeter, and associated valves.

Table 2: Design specifications of compressor test loop

Max inlet pressure	MPa	10
Max exit pressure	MPa	30
Max heat exchanger heat rejection rate	MW	12

The pressure resistance of the closed loop was calculated using an in-house code where all the components in the closed loop are divided into 20 nodes and each node is modeled with its performance characteristics. Figure 5 shows pressure resistance of each components in the main CO2 test loop in single stage and two stage compressor configurations. The main interest in the single stage configuration is the maximum combined pressure loss at the maximum compressor flow rate condition to confirm the operability of the test facility with a wide range of flowrates. Losses from the components were found to be small enough to allow mapping the test in full flowrate range in a single stage configuration. Most of the pressure resistance to balance the pressure increase by the compressor is to be generated through throttling at the compressor exit.

The CO2 inventory system supplies CO2 gas before and during the testing. Before testing, the inventory system fills the closed test loop with CO2 at the desired compressor inlet pressure. The inventory system operates continuously during testing to make up for the small leakage flow through the compressor seal and to account for the changes of the total mass of CO2 gas present in the closed loop with compressor operating conditions due to pressure and temperature changes in the loop.

An important aspect of the mechanical design of the facility is the thermal growth of the materials due to the coefficient of thermal expansion. The overall piping length of the facility as

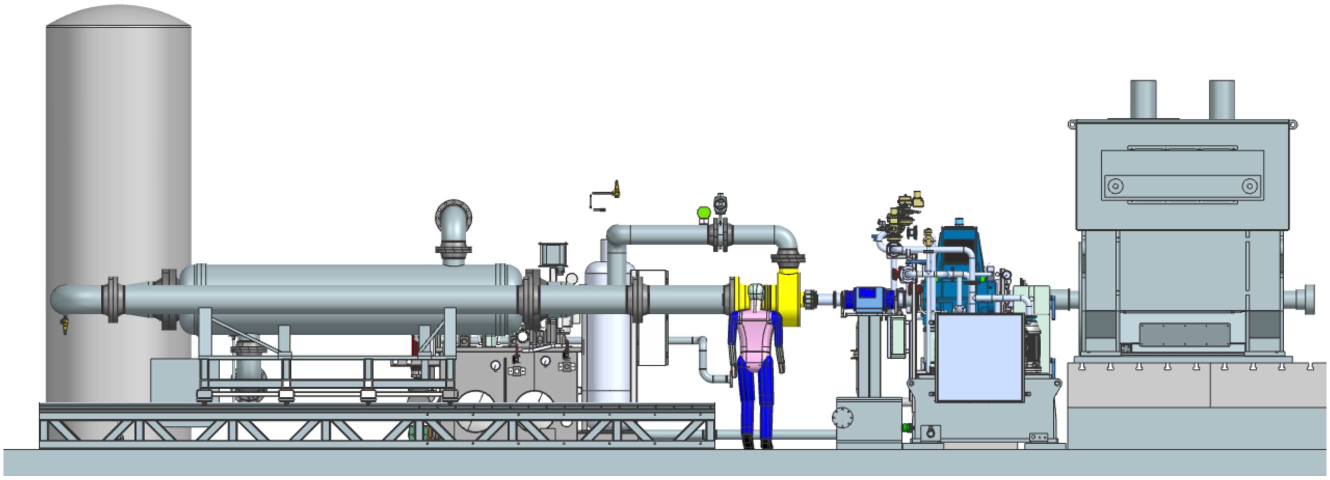

Figure 4a: Layout of CO2 compressor test facility.

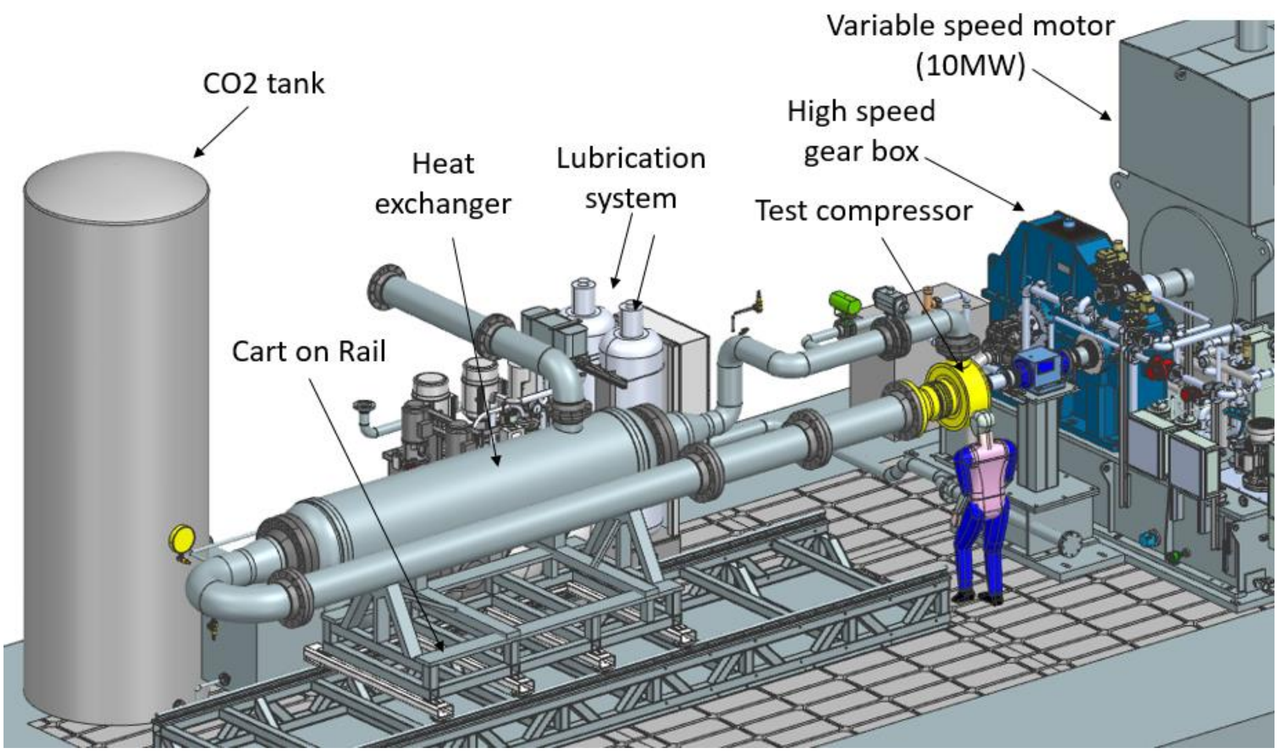

Figure 4b: CAD model of CO2 compressor test facility. A main CO2 closed loop, a CO2 tank and inventory system, test rig lubrication system, and drive train (a motor, a gear box, and a torquemeter) is shown in the model.

shown in figure 4 can grow up to 25 mm at the design operating temperature. To maintain the alignment of the compressor inlet duct along the axis of shaft rotation and to allow large thermal growth in the axial direction, linear roller bearings and rails are designed between the test loop cart and the base structure to allow thermal growth in axial direction. And the center line of main pipe is fixed to align with the test rig while allowing the thermal growth of pipes in horizontal direction.

DRIVE TRAIN

The test facility is equipped with a 10 MW variable speed motor which drives the test compressor through a speed increasing gear box and a torquemeter. The specification of the motor, gear box and torquemeter is shown in table 3. All the components in the drive system are designed to be bi-directional to accommodate test compressors with any rotational direction. The drive system is also designed to be capable of absorbing power up to 10 MW which means it can be converted to a turbine test facility if necessary. In that case the motor works as a generator and dynamometer. Generated electricity can be fed to electric grid to be used for any purpose.

Table 3: Specification of compressor drive system

Motor	Max. power	MW	10
	Full load speed	kg/s	116
Gear Box	Max. output speed	rpm	19,945
	Rated power	MW	10
Torquemeter	Nominal torque	Nm	7,000
	Nominal speed	rpm	21,000

DATA ACQUISITION SYSTEM

The data acquisition system was designed to meet the requirements of the expected test instrumentation and real-time data processing requirements. The low speed data acquisition system can measure 2,000 channels of pressure, thermocouples, RTDs, voltage signals, and current signals with and acquisition frequency up to 1 kHz. The high speed data acquisition system can measure hundreds of channels of dynamic pressure, proximity signals, vibration, blade tip clearance signals, and strain gages up to 200 kHz per channel. A telemetry system and 16 channels of light probe system for blade vibration was integrated with the main data acquisition system.

CONCLUSION

A 10 MW-class sCO2 compressor test facility has been designed. The 10MW scale allows sCO2 compressor testing of both axial and centrifugal compressor types with flow passages large enough to enable advanced experimental studies of CO2 compressors, including detailed flow survey, steady and unsteady performance measurement, and aeromechanical research on vanes or blades including blade vibrations and flutter. The facility is to be built at the University of Notre Dame in 2021 with a schedule to test the first CO2 axial compressor in 2021.

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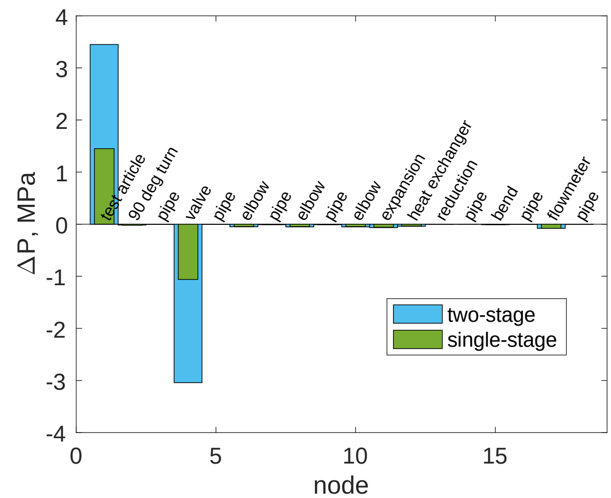

Figure 5: Pressure resistance of the main CO2 test loop in single stage and two stage compressor configurations. Losses from the components are found to be small to allow mapping the test in single stage configuration. Most of the pressure resistance is generated through throttling at compressor exit.

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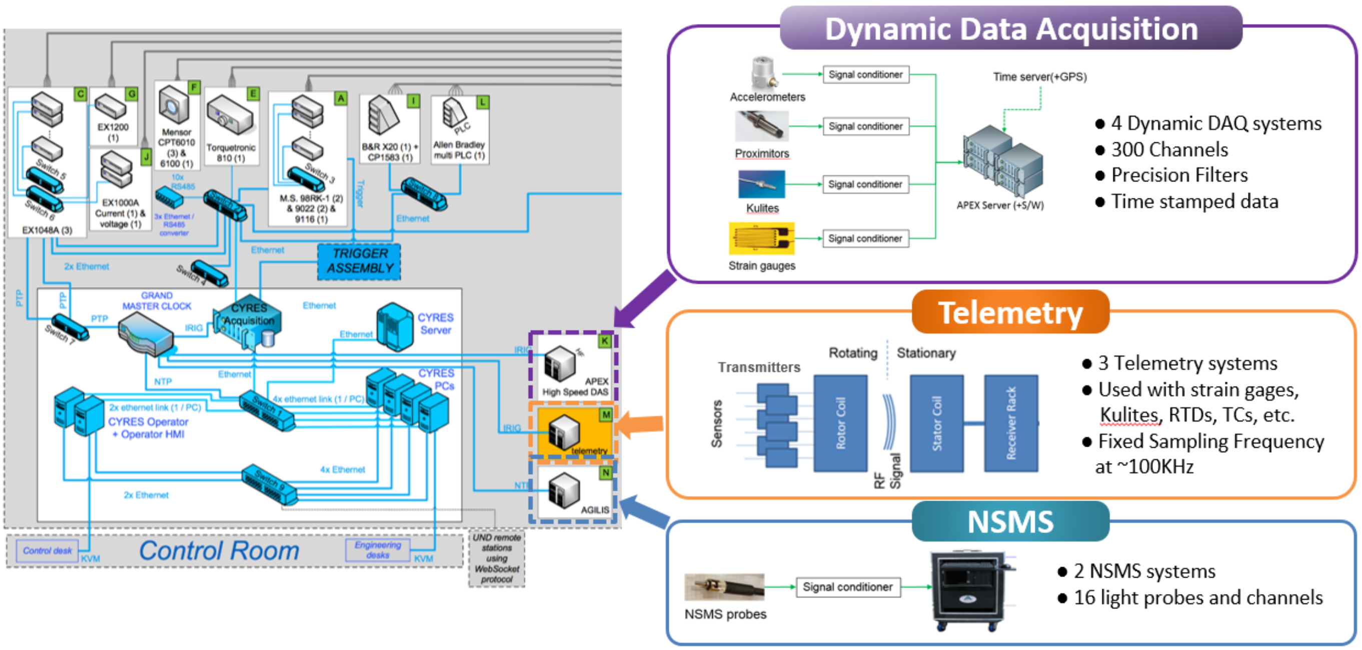

Figure 6: Schematic of the data acquisition system. Low speed data acquisition system for temperatures, pressures, flowrates, etc. and high speed data acquisition system for vibrations, dynamic pressures, strain gages, light probes, and the telemetry system are connected with the main facility control system.

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