RESEARCH ON THE DEVELOPMENT OF A SMALL-SCALE SUPERCRITICAL CARBON DIOXIDE POWER CYCLE EXPERIMENTAL TEST LOOP

Junhyun Cho
Korea Institute of Energy Research
Daejeon, South Korea
jhcho@kier.re.kr

Hyungki Shin
Korea Institute of Energy Research
Daejeon, South Korea
hkeewind@kier.re.kr

Ho-Sang Ra
Korea Institute of Energy Research
Daejeon, South Korea
hsra@kier.re.kr

Gilbong Lee
Korea Institute of Energy Research
Daejeon, South Korea
giblee@kier.re.kr

Chulwoo Roh
Korea Institute of Energy Research
Daejeon, South Korea
chulwoo.roh@kier.re.kr

Beomjoon Lee
Korea Institute of Energy Research
Daejeon, South Korea
beomjoon.lee@kier.re.kr

Young-Jin Baik*
Korea Institute of Energy Research
Daejeon, South Korea
twinjin@kier.re.kr

Junhyun Cho is the senior researcher at Korea Institute of Energy Research (KIER) located in Daejeon city, South Korea. He joined KIER in October 2012. Dr. Cho majored in mechanical engineering and received Ph.D. from Seoul National University in 2012.

ABSTRACT

Three supercritical carbon dioxide power cycle experimental loops have been developed at the Korea Institute of Energy Research (KIER) from 2013. As a first step, a 10 kWe-class simple un-recuperated Brayton power cycle experimental loop was designed and manufactured to test feasibility. A 12.6 kWe hermetic turbine-alternator-compressor unit that is composed of a centrifugal compressor, a radial turbine and gas foil bearings was manufactured. The turbine inlet design temperature and pressure were 180 °C and 13,000 kPa, respectively. Preliminary operation was successful at 30,000 RPM, and all states of the cycle were in the supercritical region. Second, a multi-purpose 1 kWe-class test loop that operates as a transcritical cycle at a temperature of 200 °C was developed to focus on the characteristics of the cycle and control and stability issues associated with the cycle. A high-speed turbo-generator was developed that was composed of a radial turbine with a partial admission nozzle and commercial oil-lubricated angular contact ball bearings. Finally, a 80 kWe-class Brayton cycle is being developed that is composed of two turbines and one compressor to utilize flue-gas waste heat. In the first phase of development, a turbo-generator that is composed of an axial impulse turbine, a mechanical seal and oil-lubricated tilting-pad bearings was designed and manufactured.

INTRODUCTION

The U.S. is currently taking the lead in developing supercritical CO_2 power generation systems. Sandia National Lab (SNL) has been developing a 250 kWe supercritical CO_2 power generation test loop since 2005 [1-4]. The Bechtel Marine Propulsion Corporation (BMPC) has also designed and built a 100 kWe supercritical CO_2 Brayton cycle integrated systems test (IST) experimental apparatus for evaluating the applicability of a supercritical CO_2 power generation system in a nuclear propulsion

Table 1. Descriptions of the supercritical carbon dioxide power cycle experimental loops in KIER

	10 kWe-class (2013-2014)	1 kWe-class (2015)	80 kWe-class (2015-2016)
Purpose	Feasibility test	Control, Operation	Power generation
Status	Tested @ 30,000RPM Modified to the 80 kWe test loop	Manufactured Cold-run test @ 140,000RPM	Designed/1 turbo-generator was manufactured, cold-run test @ 43,000RPM
Design Capacity (kWe)	12	1	80
Cycle type	Simple Un-Recuperated Closed Brayton	Transcritical & Simple recuperated Brayton	Dual
Turbomachinery	1 Turbo-Alternator-Compressor	1 Turbo-generator	1 Turbo-Alternator-Compressor (design) 1 Turbo-generator (manufactured)
Compressor type	Centrifugal, Shrouded	Positive displacement Pump	Centrifugal
Turbine type	Radial, Shrouded	Radial w/ Partial admission nozzle	Axial impulse w/ Partial admission nozzle*
Bearing	Gas foil journal/thrust	Angular contact ball (Oil lubrication)	Tilting-pad* (Oil lubrication)
Rotational speed (RPM)	70,000	200,000	45,000*
Heater	LNG fired Thermal Oil Boiler	Immersion electric heater	LNG fired flue gas heater
Recuperator	none	PCHE	PCHE

* Specifications of the turbo-generator

shipboard [5-7]. Working with the Tokyo Institute of Technology (TIT), the Institute of Applied Energy (IAE) built a 10 kWe test loop for a supercritical CO_2 power generation system and has conducted studies on power generation [8].

Through the review of previous studies conducted by several research groups, the operation of a supercritical CO_2 Brayton power cycle at the design point has been found to be difficult. Korea Institute of Energy Research (KIER) became the first organization in Korea to develop a turbine-alternator-compressor (TAC) unit for the supercritical CO_2 Brayton cycle. KIER has developed a 10 kWe and a 1 kWe test loops beginning 2013 to evaluate the feasibility and to develop operation/control strategy, respectively. A new 80 kWe-class test loop was designed and partially manufactured in 2015 with a 60 kW axial impulse type turbo-generator by modifying previous 10 kWe-class test loop manufactured in 2013. Table 1 shows specifications of the KIER's test loops.

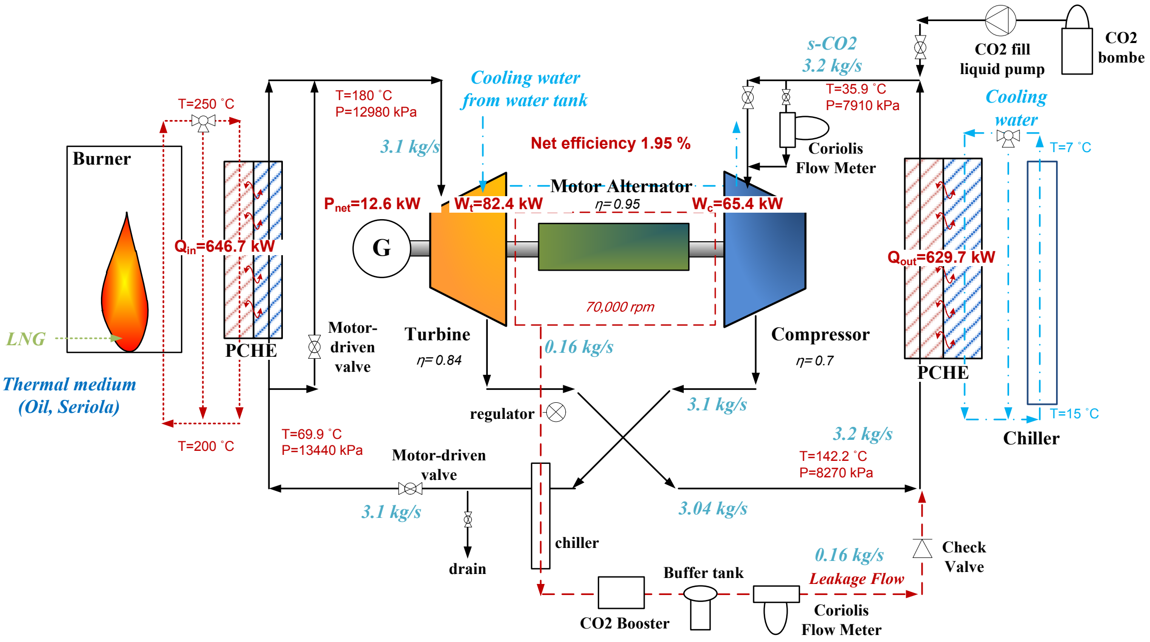

Figure 1. Schematic of the KIER 10 kWe-class simple un-recuperated supercritical CO2 Brayton cycle test loop [9]

10 kWe-CLASS TEST LOOP

KIER built a simple un-recuperated supercritical CO_2 Brayton cycle test loop, as shown in Fig. 1 and 2 [9]. The test loop was composed of a turbine-alternator-compressor (TAC) unit which has a design capacity of 12.6 kWe with a compressor and a turbine inlet design temperature/pressure of 35.9°C/7,900 kPa and 180°C/13,000 kPa, respectively. A shrouded compressor impeller and a turbine wheel with labyrinth seals were designed to overcome the thrust balancing problems associated with

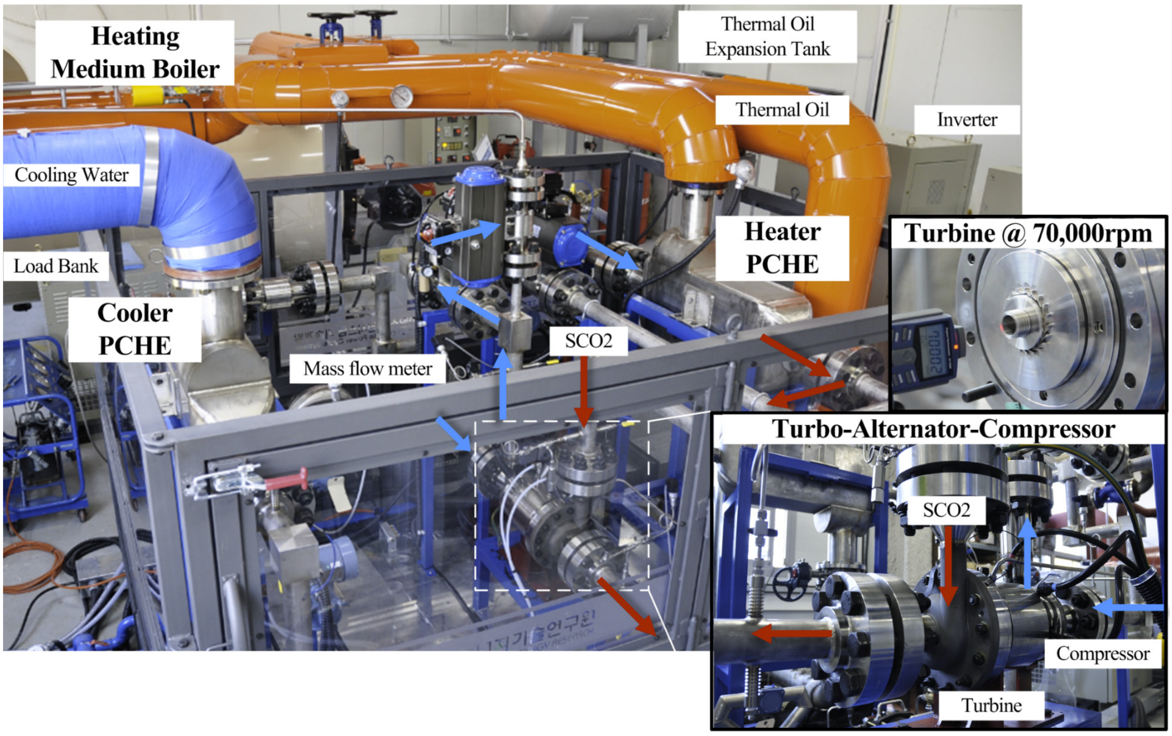

Figure 2. KIER 10 kWe-class simple un-recuperated supercritical CO_2 Brayton cycle test loop [9]

the high-pressure fluid turbomachinery. A gas-foil journal and thrust bearings were used, as shown in Fig. 3. The diameter of the compressor and the turbine wheel were approximately 50 mm, and the motor was designed to meet 60 kW and 70,000 RPM conditions.

The preliminary performance test was conducted to experience supercritical state of the carbon dioxide power cycle. After testing of the rotating parts and all balance of plants, the inverter drove the turbomachinery at 15,000 RPM which is a minimum rotational speed to lift up the shaft in the gas foil bearing. Simultaneously, hot thermal oil heated the carbon dioxide through the heater PCHE. A compressor inlet pressure was increased as a temperature of the carbon dioxide was increased. After several operation check, a rotational speed was maintained at 30,000 RPM. Figure 4 shows temperature and pressure data of the inlet and outlet of the compressor and the turbine at 30,000 RPM, respectively. The critical temperature and pressure of the carbon dioxide was described as a dash line inside the figure. During 0 to 100 seconds, the cooling water supply control valve was tested, therefore steep decrease of temperature was shown when the cooling water was suddenly supplied to the cooler PCHE. As a compressor inlet temperature decreased a compressor inlet pressure also decreased because the carbon dioxide was changed to the liquid state at that condition. At 130 seconds, the highest turbine inlet temperature of 83 °C and pressure of 8,500 kPa were obtained. The compression ratio at the compressor was about 1.10 and expansion ratio at the turbine was about 1.08. This result is preliminary start up test data to check safe operation of all components such as turbomachinery, inverter, heat exchangers, boiler, chiller, secondary loop, pipes, valves and data acquisition. Detailed adjustments are necessary to obtain stable operational data. Although simple initial test was conducted, several operation results showed that all states of inlet and outlet of the compressor and the turbine existed at supercritical state. Figure 4(c) shows representative operation points which existed at supercritical region. Details have been described in our publication [9].

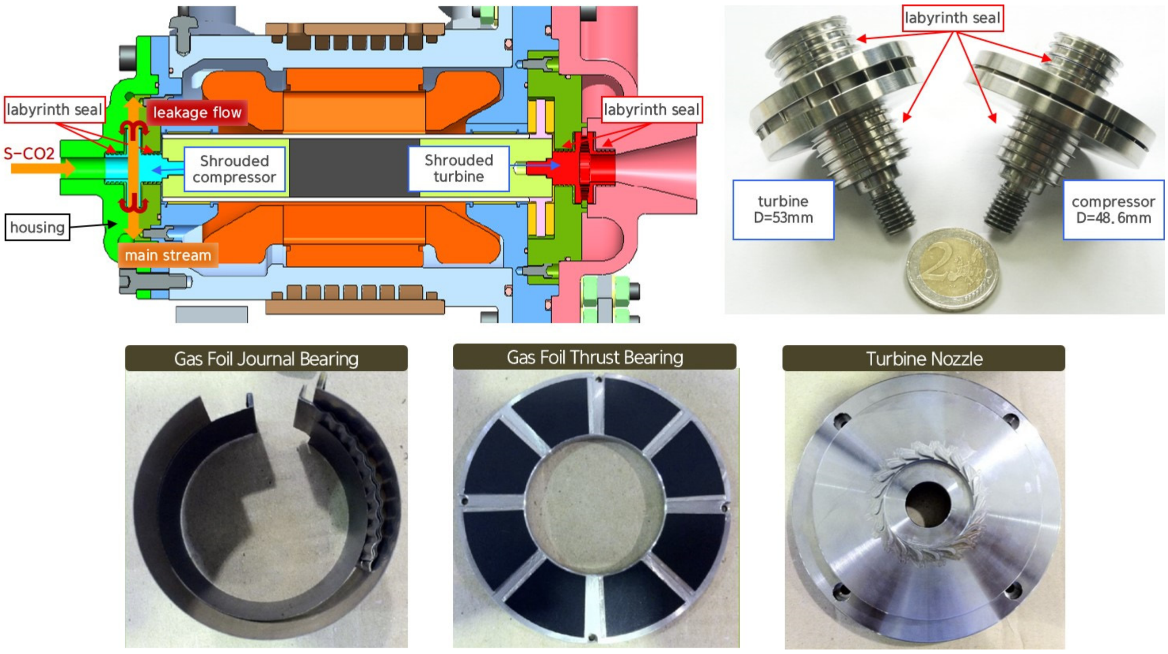

Figure 3. The turbomachinery of a 10 kWe-class test loop [9]

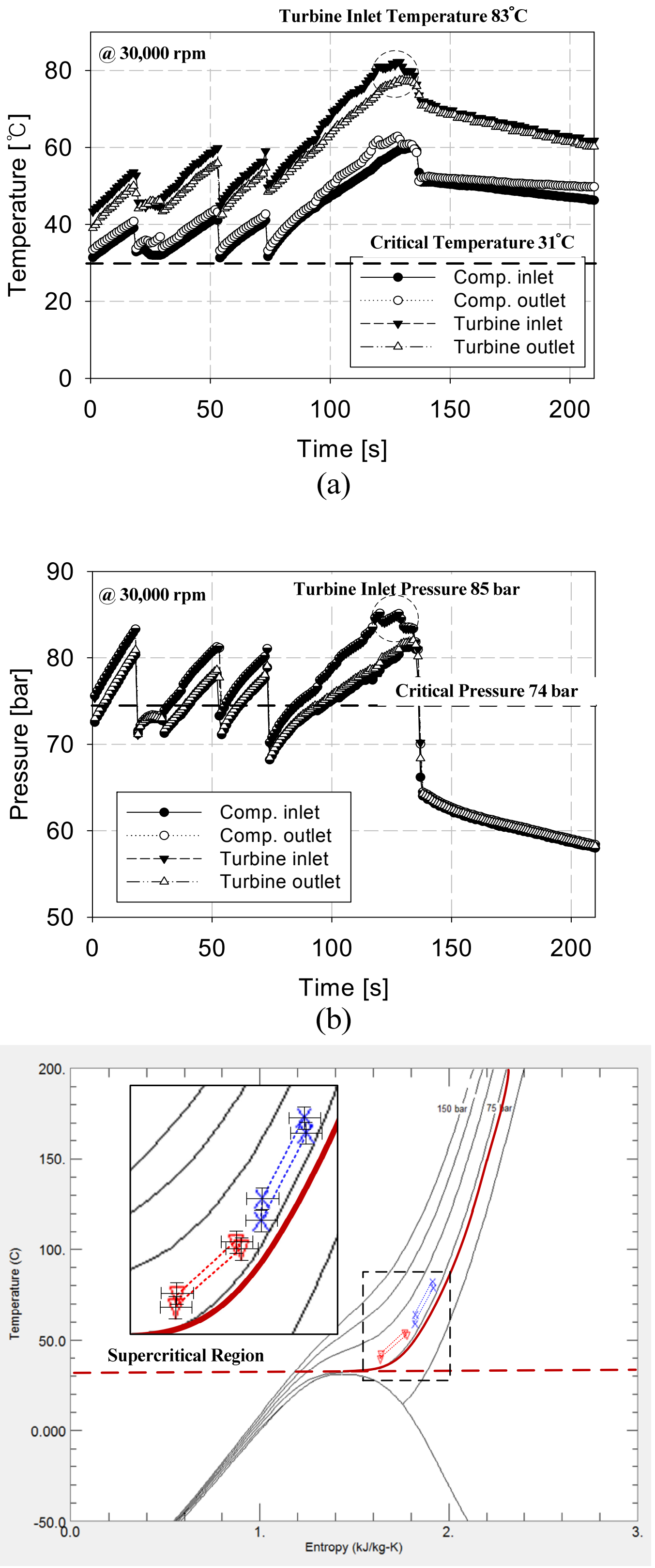

Figure. 4 Experimental (a) temperature and (b) pressure data for each state of the compressor and turbine, (c) T-s diagram [9]

1 kWe-CLASS TEST LOOP

A turbo-alternator-compressor unit (TAC) using a radial compressor was used in a several published 10-100 kWe-class supercritical carbon dioxide power cycle test loops to configure the Brayton power cycle. Due to a high energy density near the critical point, the size of the TAC unit becomes very small in a lab-scale test loop.

Therefore, the TAC unit has a minimum size to obtain the proper efficiency and manufacturability. Next, the system components, such as a heater, the heat exchangers, a chiller, valves, pipes and other parts, have to be large to build the test loop; thus, it is difficult to build, control and handle the system. In large test loop, large amount of the carbon dioxide, thermal oil, coolant are necessary. Then thermal parts such as heat exchangers had a large thermal inertia, so response of the system is slow and then control is difficult. Many resources such as operating persons, electricity, gases are also needed. All pipes and valves have to be assembled by big flanges with metal gaskets or welding, then maintenance and modification is difficult.

At KIER, using a small piston-type carbon dioxide pump, a multi-purpose 1 kWe-class supercritical carbon dioxide power cycle test loop that operates as a simple recuperated Brayton cycle at a temperature of 500°C and at a pressure of 13,000 kPa and as a transcritical cycle at a temperature of 200°C was designed to focus on the characteristics of the cycle and the control and stability issues of a supercritical carbon dioxide power cycle.

Figure 5 and 6 shows an experimental test loop and its transcritical operating conditions, and the turbine inlet temperature is 200°C. Because it is difficult to achieve 500°C of turbine inlet temperature directly without any experience of the supercritical carbon dioxide cycle, we manufactured a prototype turbo-generator operating under 200°C condition which is considered mild condition as a first step.

Two piston-type carbon dioxide pumps (Catpump, USA) which mass flow rates of 0.023 kg/s and 0.046 kg/s were used to pressurize liquid carbon dioxide at a temperature of 20°C and at a pressure of 5,729 kPa up to 13,000 kPa, which is a supercritical state. An immersion type electric heater heats the supercritical carbon dioxide up to 200°C, and then, hot CO_2 drives a radial-type turbine. After expansion at the turbine, a supercritical carbon dioxide is cooled to a liquid state using coolant water and a brazing plate heat exchanger (BPHE). In this operation, a printed circuit heat exchanger (PCHE) type recuperator was not used. When the system is operated as a simple recuperated Brayton cycle, the turbine inlet temperature goes up to 500°C, and the recuperator is used to preheat a working fluid using the heat remaining after the turbine outlet. Instead of a BPHE, a PCHE-type cooler is used because the pressure of the carbon dioxide is still high during the cooling process (greater than 7,400 kPa). By controlling temperature and mass flow rates of the coolant, lowest temperature of the cycle will be controlled to make the Brayton cycle. Using several valves and a bypass loop, these two cycles are configured using one test loop facility.

As a first step, a transcritical carbon dioxide power cycle is designed with a turbine inlet temperature of 200°C. Because the mass flow rate is so small (0.07 kg/s), it is difficult to design a radial-type turbine. Given our operating conditions, an optimal radial turbine has a diameter of 22.6 mm and a rotating speed of 800,000 rpm. Because it is nearly impossible to achieve 800,000 RPM turbine, a partial admission nozzle is adopted to manufacture and operate the turbo-generator in an experimental test loop. By using only one channel of the nozzle, a rotating speed condition of 200,000 rpm is designed, as shown in Fig. 7.

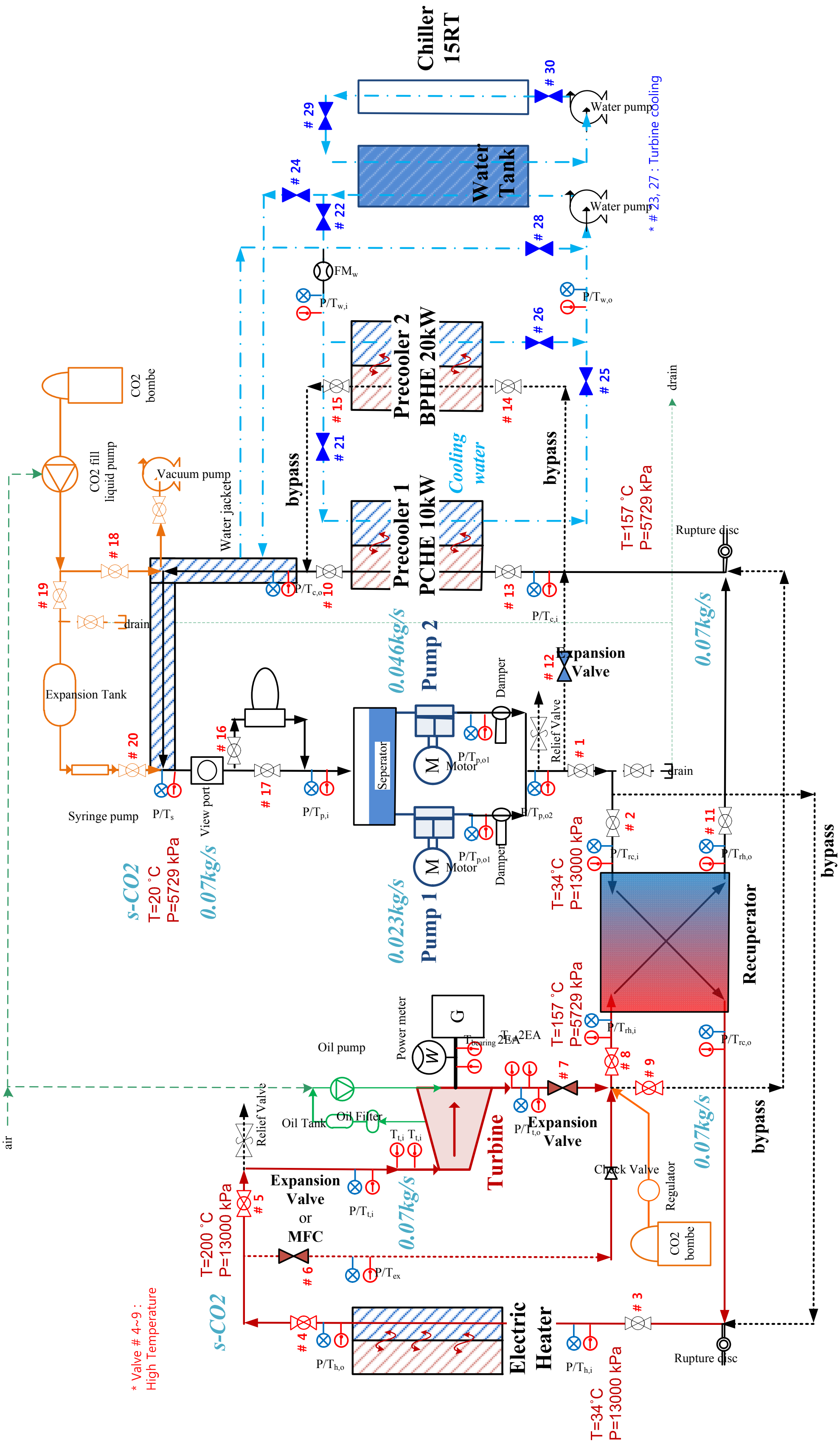

Figure 5. Schematic of KIER 1 kWe-class supercritical CO2 power cycle test loop

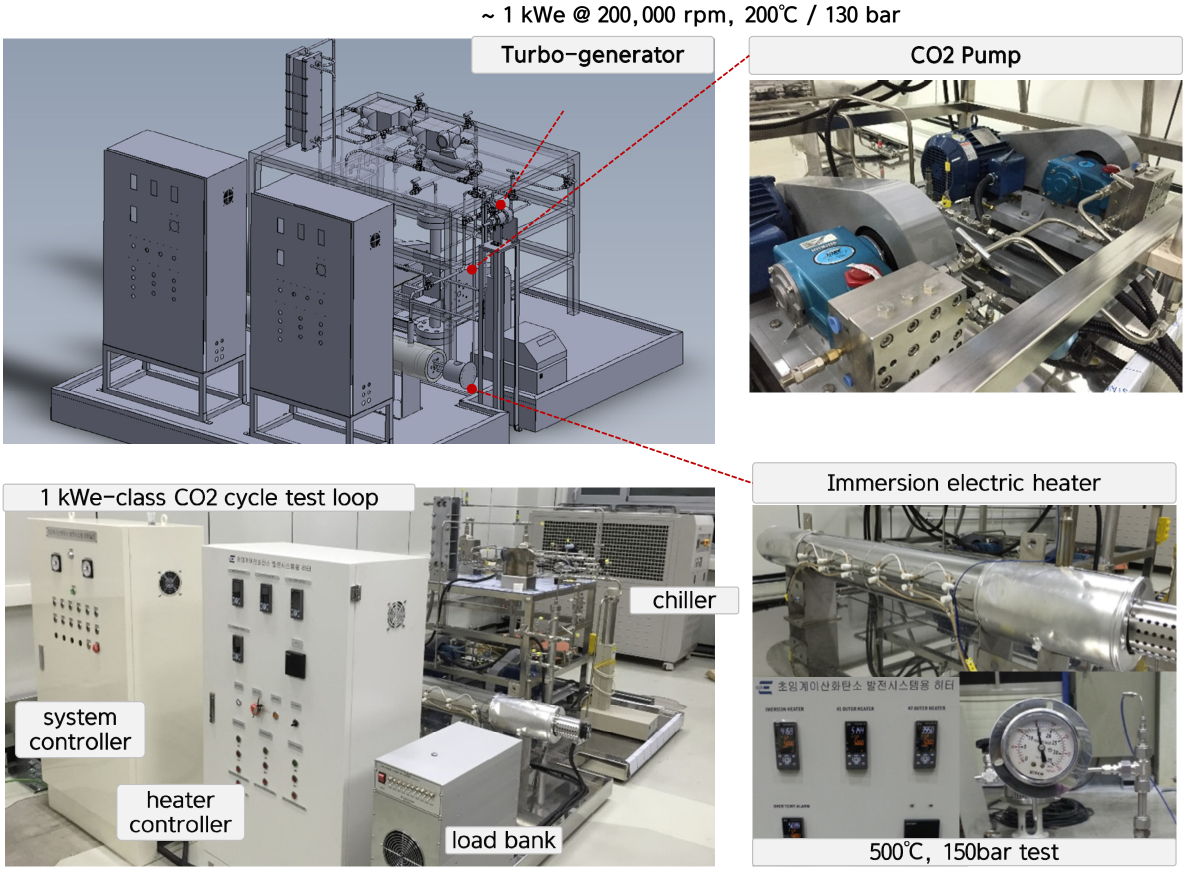

Figure 6. KIER 1 kWe-class supercritical CO2 power cycle test loop

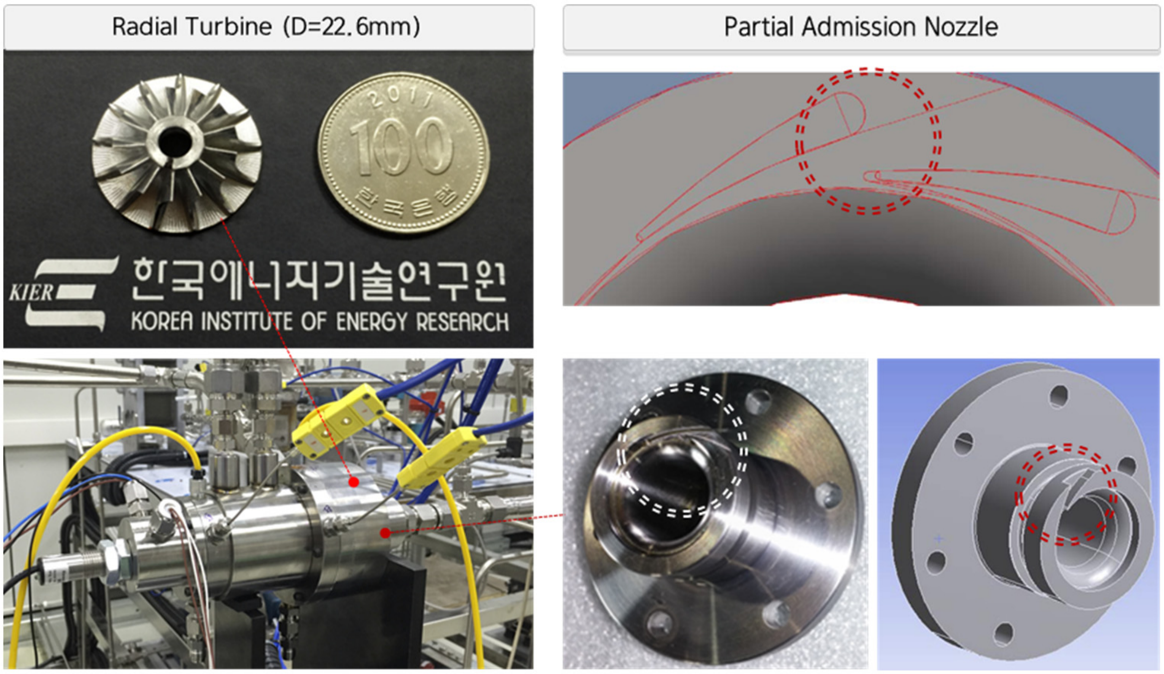

Figure 7. A high-speed turbo-generator using a radial turbine and a partial admission nozzle (dashed circle)

Specifically, a commercial angular contact ball bearing (SKF) is used to overcome technical problems of the gas foil journal and thrust bearings shown in the results from advanced research groups, such as Sandia National lab. Due to thrust balancing and high temperature operation, a gas foil bearing has operation limits. Therefore, in this study, the bearing chamber is separated from a turbine chamber using several labyrinth seals to achieve atmospheric pressure when operating the oil-lubricated ball bearing. In this design, inevitable leakage loss through the labyrinth seal occurs, so a compensation loop of the carbon dioxide from an additional CO_2 tank is also designed in the test loop.

After assembling each component, as a first step, a turbo-generator balancing process was conducted. In wide-open atmospheric condition, which is referred to as a cold-run, the turbo-generator was driven by external electric power source. The vibration level of the rotor and the temperatures of the bearings were monitored. A 140,000 rpm rotation test was successful, but some bearing operational problems were observed. After a detailed adjustment of the rotating parts, power-generating operation will be conducted.

80 kWe-CLASS TEST LOOP

In 2015, KIER designed a new 80 kWe-class test loop to develop a practical supercritical CO_2 power

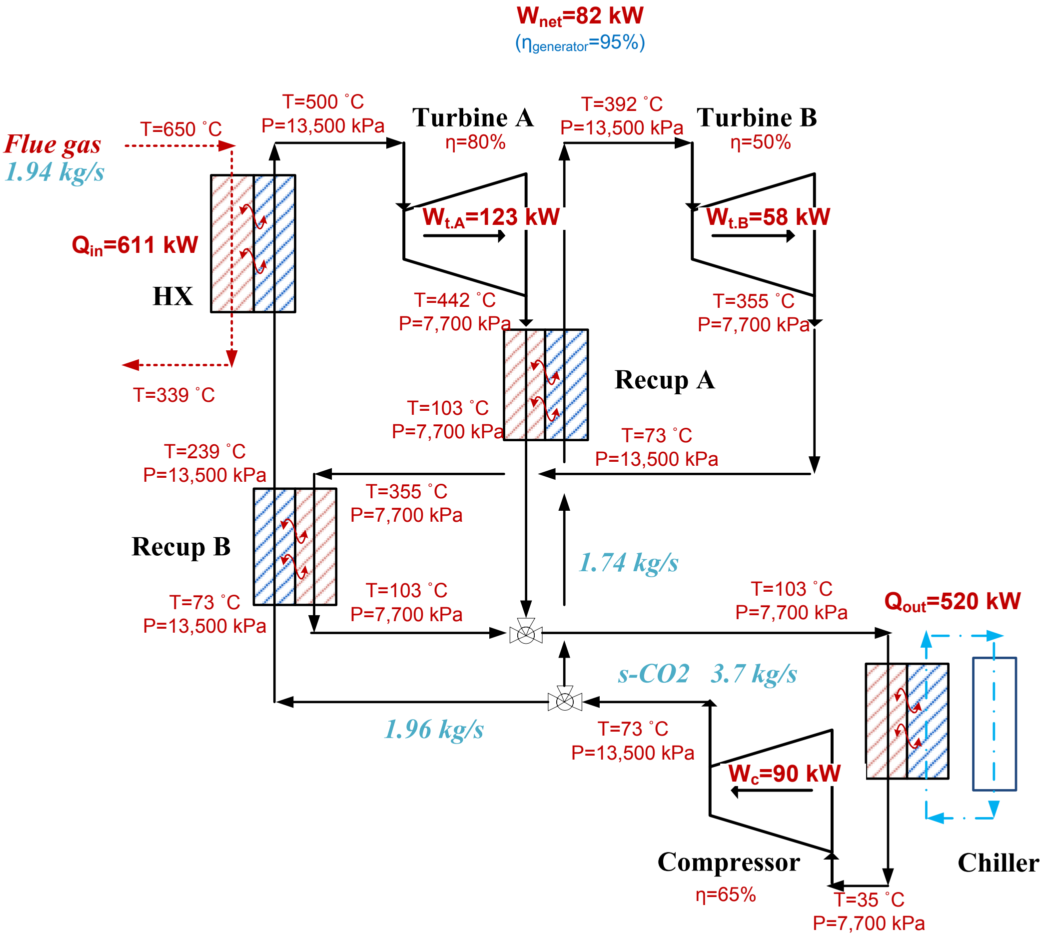

Figure 8. KIER 80 kWe-class supercritical CO2 power cycle test loop

cycle that operates as a recuperated Brayton cycle at a temperature of 500°C and at a pressure of 13,500 kPa as shown in Fig. 8

This test loop consists of two turbines, one compressor, two recuperators and one flue-gas heater. After investigating diverse layout configurations, one TAC and one turbo-generator were designed. As a first step, the turbo-generator, which is described as a turbine B (58 kW) in Fig. 8, was manufactured. An axial-type turbine and a partial admission nozzle were designed and manufactured to have merits for the scale-up. The turbine chamber was separated by a carbon ring-type mechanical

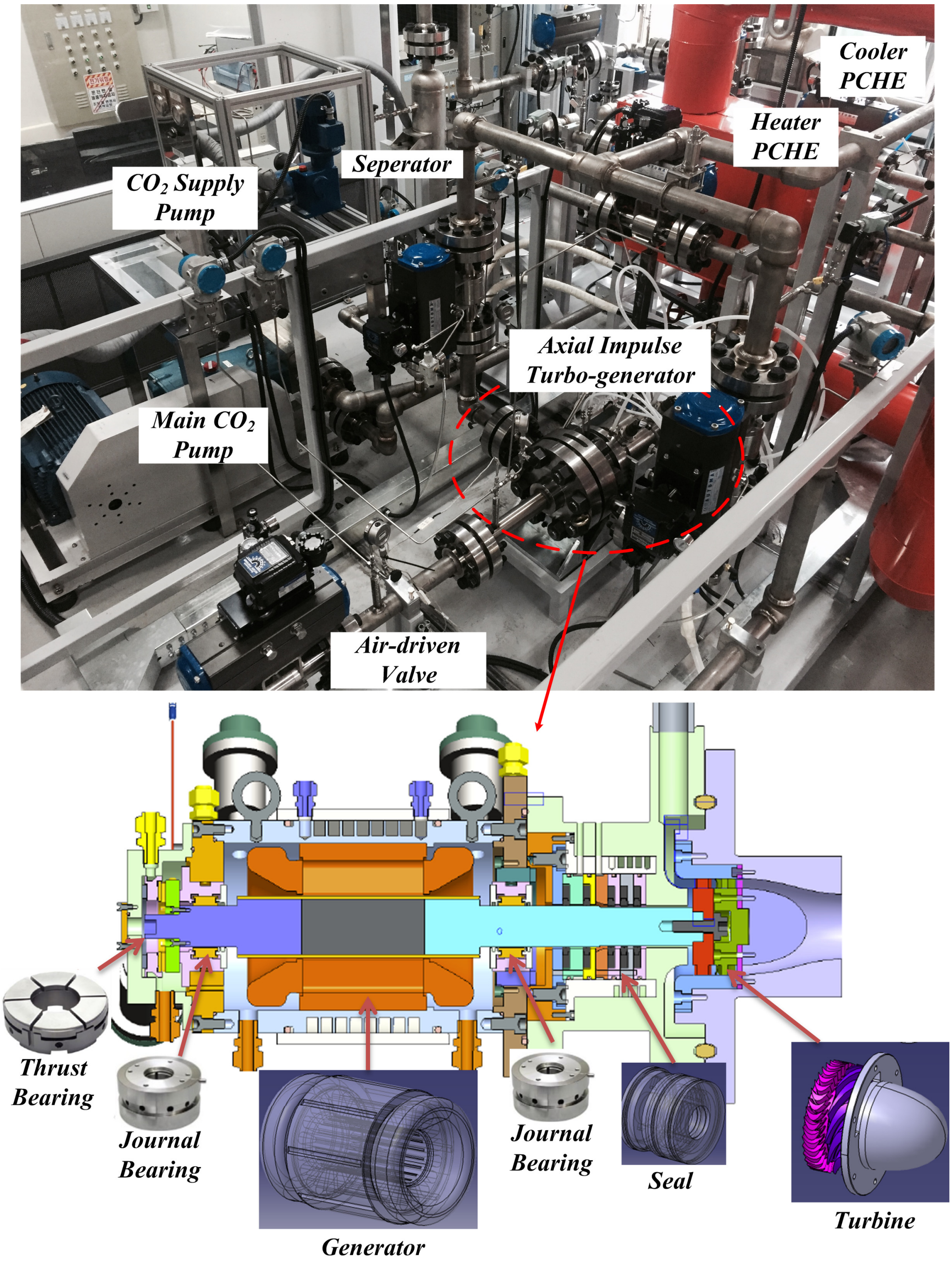

Figure 9. The axial impulse type turbo-generator and test loop

seal using the oil-lubricated tilting-pad journal and thrust bearings. To test the turbo-generator, our 10 kWe-class test loop that is described in Fig. 1 was modified to the transcritical cycle test loop using the liquid carbon dioxide pump. The PCHEs and the heat source/sink facilities were re-used as shown in Fig. 9. The cold-run test of 43,000 RPM was successful and all balance of plants were tested. After trial-and-error during initial operation, we expect power generation through the turbo-generator soon. In addition, other parts of the 80 kWe-class test loop such as TAC, recuperators, flue-gas heaters and balance of plants will be manufactured in 2016.

CONCLUSIONS

KIER constructed three supercritical carbon dioxide power cycle test loops. The first 10 kWe-class test loop was constructed as an un-recuperated simple Brayton cycle using a TAC unit that consists of a shrouded centrifugal compressor and a radial turbine to investigate the feasibility of the supercritical carbon dioxide power cycle. We found out that the gas foil bearings were not proper for this application after investigating diverse studies reported by prior research group. Therefore, we tried to use the commercial bearings to overcome bearing failure problem. And also, we want a small test loop for easy operation. In this background, the second 1 kWe-class test loop was constructed to evaluate cycle characteristics and to develop a control strategy. This test loop consists of carbon dioxide pumps, an electric heater and a high-speed turbo-generator. The design rotational speed of the turbo-generator was 200,000 RPM due to its small mass flow rate, it was very difficult condition to achieve stable operation. The third 80 kWe-class test loop was designed, and some parts were manufactured. We tried to reduce the rotational speed of the turbomachinery to use the oil-lubricated tilting pad bearings which can support the high axial force. In addition, we tried to design the axial-type turbine for scale-up study for the next step. Conclusively, a 60 kW turbo-generator using the axial impulse turbine was manufactured.

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