The 6th International Supercritical CO_2 Power Cycles Symposium
March 27 - 29, 2018, Pittsburgh, Pennsylvania

Preliminary Power Generating Operation of the Supercritical Carbon Dioxide Power Cycle Experimental Test Loop with a Turbo-generator

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ABSTRACT

Korea Institute of Energy Research Institute (KIER) operates two supercritical carbon dioxide power cycle (S-CO2) experimental test loop with two different type of turbo-generator in 2017. First, a tens of kWe-class axial impulse-type turbo-generator with a conventional carbon mechanical seal and oil-lubricated tilting-bearings was developed. The objective of this turbo-generator was to develop an S-CO2 power generation system with an axial-type turbine resolving bearing failure problems reported by other research groups by applying turbomachinery technology applicable to a commercial plant. A simple transcritical cycle using a liquid CO2 pump was constructed to drive the turbo-generator. The target turbine inlet temperature and pressure were 200°C and 130 bar, respectively. Preliminary power generating operation was successful, a 11 kW of electric power was obtained under 205°C and 100 bar turbine inlet conditions, and the continuous operating time was 45 min. Second, a kWe-class small scale test loop with a radial-type turbo-generator was developed to operate a simple recuperated transcritical cycle under 500°C and 130 bar turbine inlet conditions. A 287 We of electric power and maximum of 401°C and 112 bar turbine inlet conditions were obtained.

INTRODUCTION

Researchers have studied the supercritical CO2 (S-CO2) cycle as a technology that may potentially replace the conventional power cycle. As the leading country in terms of such technology, the USA has begun to develop S-CO2 power generation cycles. The Sandia National Laboratory has implemented a 250 kWe re-compression closed Brayton cycle using two turbine-alternator-compressor (TAC) units [1-4]. Furthermore, Bechtel Marine Propulsion Co. has developed a 100 kWe S-CO2 power generation cycle test loop using one turbo-generator and one turbo-compressor [5-7]. The Tokyo Institute of Technology (TIT) developed a 10 kWe test loop for a S-CO2 power generation system consisting of one TAC unit [8]. The Southwest Research Institute and GE Global Research have been designing a 10 MWe S-CO2 axial-type turbo-expander with a dry gas seal (DGS), and are constructing a 1 MWe testing facility capable of miniaturizing and testing the device [9]. Echogen has also developed an 8 MWe S-CO2 power generation system for waste heat recovery and 2.4 MWe of power was generated [10]. Newpower is constructing 50MWth demo-plant of a direct-fired S-CO2 cycle (Allam cycle) [11].

KIER'S S-CO2 TEST LOOPS

The Korea Institute of Energy Research (KIER) has been developing a total of five experimental test

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

	10 kWe-class (2013-2014)	Sub-kWe-class (2014-2016)	Tens of kWe-class (2015-2017)	kWe-class (2016-2017)	Hundreds of kWe-class (2015-2019)
Purpose	Feasibility	Power generation	Robust Turbo-generator	500°C operation	500°C Full-cycle operation for WHR application
Status	Tested @ 30,000RPM Modified to the tens of kWe test loop	670 We power generation Modified to the kWe test loop	11 kWe power generation	287 We power generation	In progress
Cycle type	Simple Un-Recuperated Closed Brayton	Un-recuperated Transcritical	Un-recuperated Transcritical	Recuperated Transcrtical	Dual Brayton
Turbomachinery	1 Turbo-Alternator-Compressor	1 Turbo-generator	1 Turbo-generator	1 Turbo-generator	2 Turbine 1 Compressor
Compressor type	Centrifugal, Shrouded	Positive displacement Pump	Positive displacement Pump	Positive displacement Pump	Centrifugal
Turbine type	Radial, Shrouded	Radial w/ Partial admission nozzle	Axial impulse w/ Partial admission nozzle	Radial w/ Partial admission nozzle	TBD
Bearing	Gas foil journal/thrust	Angular contact ball (Oil lubrication)	Tilting-pad (Oil lubrication)	Angular contact ball (Oil lubrication)	TBD
Seal	Labyrinth	Labyrinth	Carbon Ring type Mechanical Seal	Labyrinth	DGS
Rotational speed (RPM)	70,000	200,000	45,000	120,000	TBD
Heater	LNG fired Thermal Oil Boiler	Immersion electric heater	LNG fired Thermal Oil Boiler	Immersion electric heater	LNG fired flue-gas Heater
Recuperator	none	none	none	PCHE	2 PCHE

loops and turbo-generators as step by step for distributed power source applications since 2013 as shown in Table 1. In 2014, the first 10 kWe-class loop was operated to test the feasibility of S-CO2 systems. A hermetic turbine-alternator-compressor (TAC) was successfully operated at 30,000 RPM, where all cycle states existed in the supercritical region [12].

In 2016, 670 W of electric power was produced in the second sub-kWe-class test loop with a small radial-type turbo-generator consisting of a partial admission nozzle, labyrinth seal, and oil-lubricated angular contact ball bearing. The design temperature of turbine inlet was 200°C [13].

Since 2015, based on this development experience, KIER has been manufacturing the final hundred kWe-class dual Brayton test loop with a maximum temperature of 500°C for waste heat recovery application, as illustrated on the left of Fig. 1. This cycle consists of two turbines, one compressor, two recuperators, and a flue-gas heater.

Because a great deal of cost and time is required to construct a full cycle test loop, as a phased approach, a relatively low-temperature turbine with an inlet temperature of 392°C, described as turbine B in the schematic, was designed and manufactured as an axial impulse-type turbo-generator, as illustrated on the right of Fig. 1. In order to drive this turbine, our previous 10 kWe-class test loop, constructed in 2013, was modified to be the tens of kWe-class transcritical test loop. This is the third tens of kWe test loop. The conventional CO2 pump was used to make the cycle as a transcritical. Because our heat source temperature is limited to 300°C, the turbine would be tested at an inlet temperature of 200°C, which is the

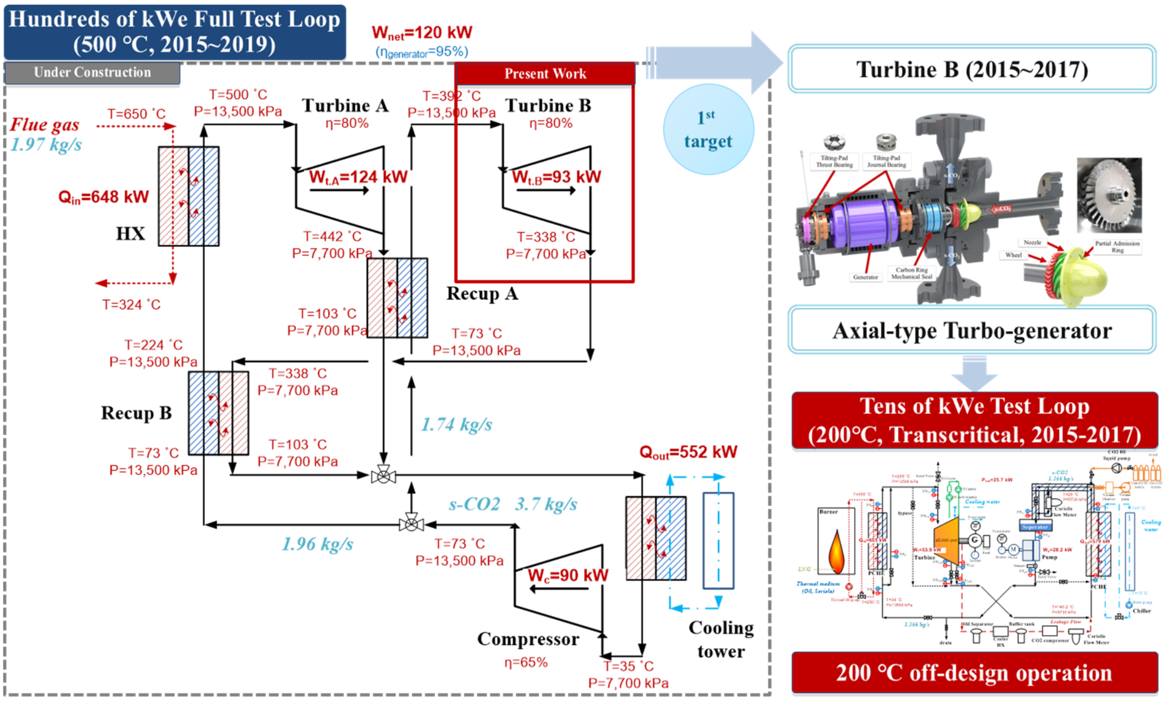


Figure 1. KIER hundreds kWe-class S-CO_2 dual Brayton cycle test loop (`19) and construction strategy

off-design condition. Preliminary electric power generating operation was successful in the summer of 2017.

Simultaneously, the second sub-kWe-class test loop was upgraded to the fourth kWe-class simple recuperated transcritical cycle test loop to test high temperature S-CO2 cycle. A new radial-type turbo-generator was designed and manufactured that operates under 500°C and 130 bar inlet condition. In addition, a printed circuit heat exchanger (PCHE) was fabricated to use as a recuperator in the cycle. Preliminary electric power generating operation was also successful in the winter of 2017.

Now, KIER operates two transcritical S-CO2 test loops with two different type of the turbo-generator. In this paper, preliminary operation results of the third tens of kWe-class test loop (200°C) with an axial-type turbo-generator and the fourth kWe-class test loop (500°C) with a radial-type turbo-generator are shown.

AXIAL-TYPE TURBO-GENERATOR FOR TENS OF KWE-CLASS TEST LOOP

In the case of a hundred kW lab-scale S-CO2 turbo-generator, the turbomachinery rotational speed is extremely high, because the mass flow rate is low and the density of the working fluid is high due to high pressure condition. Therefore, Sandia and Bechtel used gas foil bearings that are suitable for high rotational speeds and the high-pressure conditions of S-CO2. The gas foil bearings could be installed inside a hermetic turbo-generator casing; therefore, additional seal and lubrication systems were not required. However, the gas foil bearings were weak for high axial forces and windage loss conditions.

Furthermore, in the case of turbomachinery of several tens to several hundreds of MW, suitable for the actual capacities of conventional power plants, additional research is required for scaling up because axial-type turbines, oil lubricated bearings, and mechanical seal technologies other than the radial type should be applied

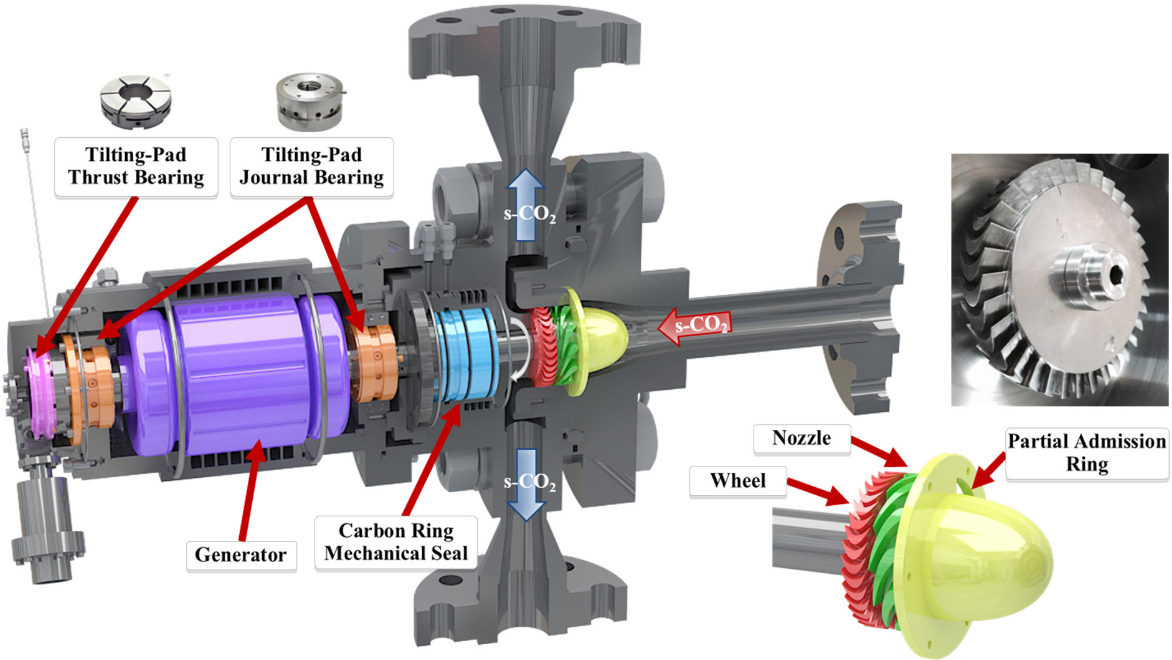


Figure 2. Axial turbo-generator

Therefore, the objectives of this project are to develop a S-CO2 power generation system with an axial type turbo-generator, resolving the bearing failure problems reported by prior research groups, by applying turbomachinery technology that is applicable to commercial plants. The design and operation results of the test loop are described.

In order to overcome reported failure problems of the radial-type turbine induced by high rotational speed and axial force, an axial-type impulse turbine and partial admission nozzle was designed and manufactured to reduce the rotational speed by up to 45,000 RPM, as well as the axial force. Thereafter, the turbine wheel part was separated by carbon ring-type mechanical seals to use the commercial oil-lubricated tilting-pad bearings, as illustrated in Fig. 2. As these bearings place a limitation on the rotational speed, it was important to reduce the shaft rotational speed. The rotor mean diameter was 73 mm and the blade height was 8.36 mm. A 60 kWe permanent magnet (PM) generator type was also designed. Using an axial-type turbine with a mechanical seal similar to the dry-gas-seal and oil-lubricated bearings, the design is meaningful as it can be applied to further MW-scale turbo-generator designs. Details were described in our other presentation [14-15].

TRANSCRITICAL TEST LOOP FOR DRIVING AXIAL-TYPE TURBO-GENERATOR

In order to develop a step-by-step, systematic technology, a transcritical S-CO2 power cycle was constructed at the turbine inlet at 200°C in one step, and the turbine was operated to obtain data under relatively stable temperature conditions through power production operation. For this purpose, the turbo-generator designed and manufactured under the target condition of 392℃ is operated for off-design operation at 200°C. A transcritical cycle test loop was designed and fabricated, as illustrated in Fig. 3. The turbine inlet pressure and temperature were determined in order to design the test loop conditions. The maximum cycle pressure was determined as 135 bar, which is a similar level to the world's optimal operating conditions, as reported by the Sandia National Laboratory. The maximum temperature was 200°C as the first step target, which is a relatively mild condition for the piping, valves, and pressure vessels of the system. The pump inlet conditions were determined considering the chiller ability and effectiveness of the heat exchangers. The coolant temperature by the chiller was 7°C; therefore,

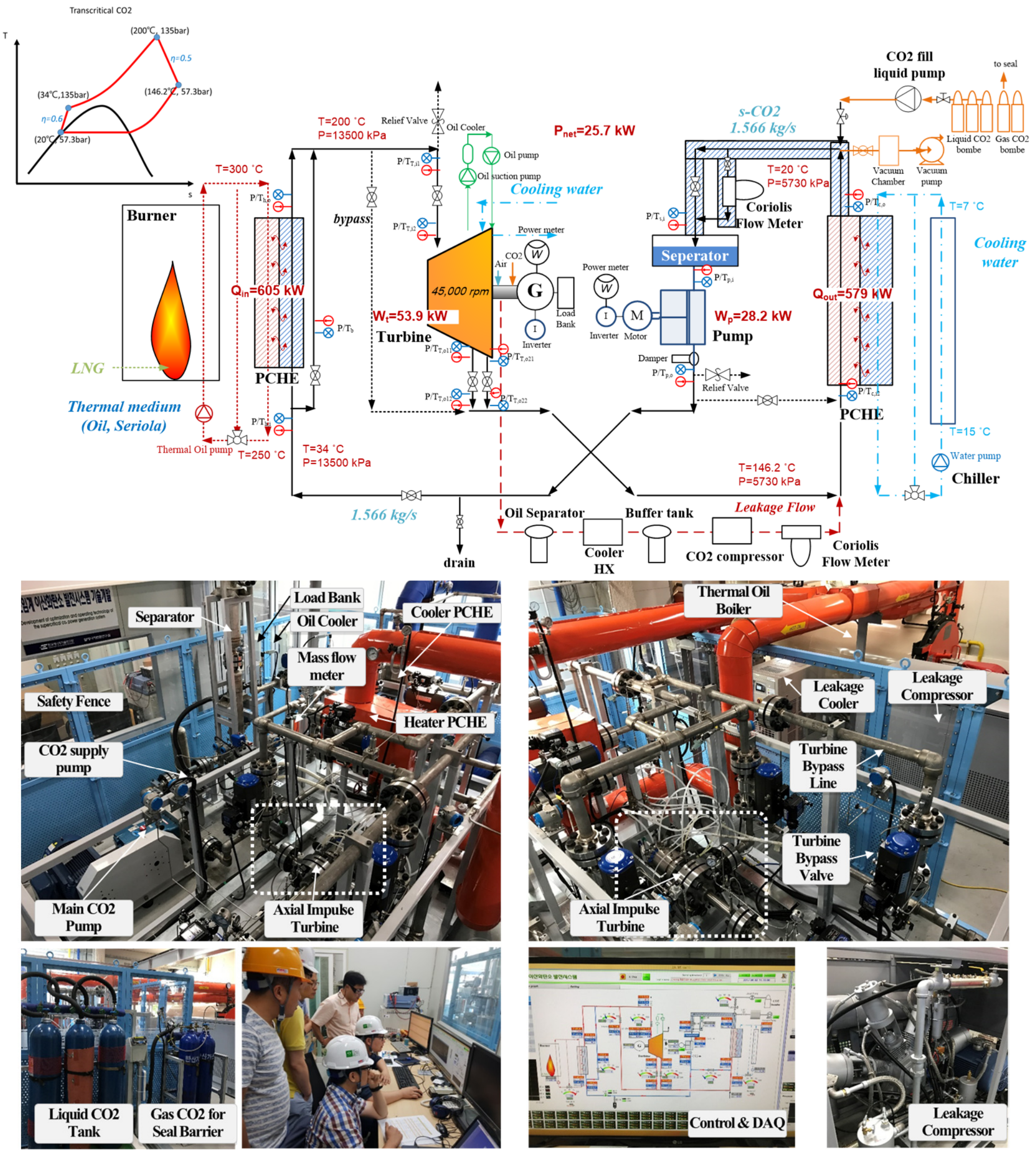


Figure 3. A tens of kWe-class transcritical supercritical CO_2 power cycle test loop

considering the mild approach temperature value, a 20°C pump inlet temperature and saturation pressure of 57 bar were determined.

Liquid CO2 at 20°C, 57 bar, and 1.566 kg/s was pressurized into a supercritical state at 135 bar using a plunger-type reciprocating liquid CO2 pump (Catpumps, USA) with an inverter-controlled electric motor in order to test the various flow conditions. An LNG-fired thermal oil boiler heated the CO2 to 200°C through a printed circuit heat exchanger (PCHE), and after driving the turbine the CO2 was cooled through the PCHE.

As the first step to developing an S-CO2 power cycle, the main objective of this test loop is to operate the cycle and drive the axial-type turbo-generator, producing electricity using S-CO2. Therefore, an un-recuperated simple transcritical cycle configuration was determined as the first step, neglecting the cycle efficiency. Furthermore, the turbine and pump efficiencies were assumed as 0.5 and 0.6, respectively. These were extremely conservative values because of the losses that are difficult to calculate. The cycle flow rate was 1.566 kg/s, the required pump power was 28.2 kW, the heat source capacity was 605 kW, and the turbine power was estimated to be 53.9 kW.

In order to use a technically stable oil-lubricated bearing, a mechanical seal was installed in the turbo-generator, which inevitably leads to turbine leakage flow. Therefore, by-pass piping was constructed using a control valve that replicates the turbine to match the cycle and turbine inlet conditions by means of a bypass operation, until turbine operation. In the current turbo-generator design, a 2 to 3% leakage flow was estimated; therefore, the leakage management system was constructed to re-inject CO2 into the system. An oil separator, cooler, and buffer tank were constructed for cooling the hot leakage flow and removing incoming bearing oil. A three-stage reciprocating oil-free-type CO2 compressor was constructed for pressurizing up to 80 bar in order to recharge the atmospheric leakage flow into the main loop. The leakage flow amount was measured with a Coriolis mass flow meter.

POWER GENERATING OPERATION RESULTS OF TENS OF KWE-CLASS TEST LOOP

For the operation of the cycle and turbo-generator, the test loop was assembled, and the leakage and hydraulic pressure test were carried out using nitrogen. A vacuum pump was used to remove all air in the test loop. Following this, CO2 was filled into the system. The amount of working fluid in the closed cycle was an important factor in the system operation. The CO2 filling mass in the system was determined while monitoring the temperature and pressure through the preliminary operation.

After operating the system through the turbine bypass valve and confirming the S-CO2 cycle configuration, the turbine inlet and outlet valves were opened and the bypass valve was closed, allowing S-CO2 to drive the turbine. The operation procedure and strategy for bearing oil lubrication, the mechanical seal barrier gas supply, turbine leakage re-injection system, and inverter driving start were developed and operated. As a result of the high operating pressure of above 57 bar, a high axial force occurred at the thrust bearing. In order to overcome the maximum static friction force of the bearing at the start, before the turbine valves opened, the turbo-generator was driven by the inverter at 30,000 RPM.

Figure 4 displays the preliminary experimental results of the electric power production operation. The

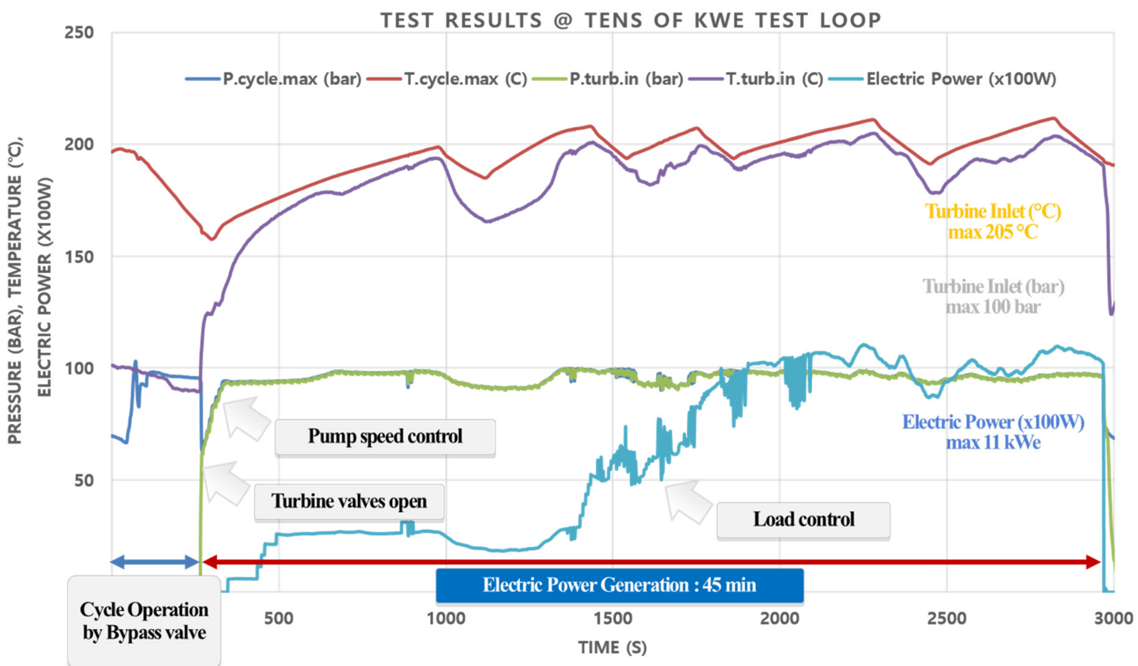


Figure 4. Power generating operation result of the tens of kWe-class test loop

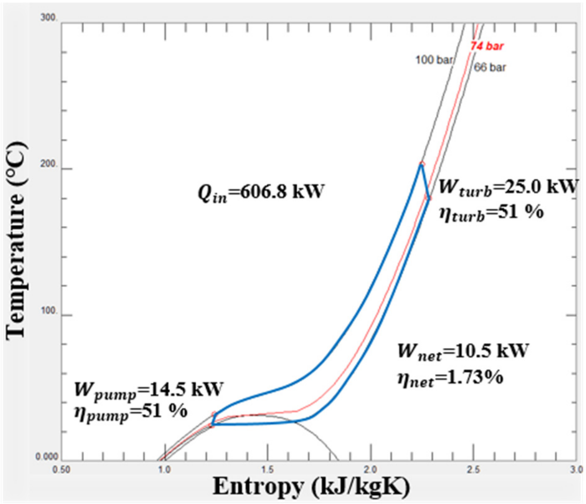


Figure 5. T-s diagram at maximum turbine power operating conditions

turbine output was adjusted by controlling the main CO2 pump speed, boiler heating temperature, and load of the load bank. A total of 11 kWe of electric power, measured by the power meter, was obtained at a maximum turbine inlet temperature of 205°C and pressure of 100 bar, and the continuous operation time of the turbine power production was 45 min.

Figure 5 and Table 2 display representative experimental results under the maximum turbine power operating conditions. The inlet/outlet states of the turbine and pump are described by the T-s chart. The heat balances are calculated by the enthalpy difference, using REFPROP v.9.0. At the pump, 14.5 kW of power is consumed in order to pressurize the CO2 from 65.9 to 99.1 bar. The isentropic efficiency of the pump is 51%. A 1 bar pressure drop occurs from the pump outlet to the turbine inlet, and the main pressure

Table 2 Experimental results of cycle at the maximum turbine power operating conditions

Parameter	***Value***
Turbine inlet temperature (°C)	203.4
Turbine inlet pressure (bar)	98.1
Turbine outlet temperature (°C)	180.1
Turbine outlet pressure (bar)	67.7
Pump inlet temperature (°C)	24.3
Pump inlet pressure (bar)	65.9
Pump outlet temperature (°C)	31.7
Pump outlet pressure (bar)	99.1
Mass flow rate (kg/s)	1.69
Leakage mass flow rate (g/s)	34.46
Expansion ratio	1.45
Turbine power (kW)*	25.0
Turbine efficiency (%)	51
Pump power (kW)*	14.5
Pump efficiency (%)	51
Net power (kW)*	10.5
Heat in (kW)*	606.8
Net efficiency (%)	1.73

*Power was calculated by enthalpy difference drop occurs at the PCHE. At the turbine, the S-CO2 expands from 98.1 to 67.7 bar. The expansion ratio across the turbine is 1.45. A total of 25.0 kW of turbine power is calculated by the enthalpy balance, and the isentropic efficiency of the turbine is 51 %. At this point, the electric power measured by the power meter is 11.0 kW, which means that a 14.0 kW power loss occurs. This is because of two main reasons. Firstly, the generator efficiency is lower at the lower rotational speed than the design speed. The number of revolutions at the operating point was one third of the design RPM. Secondly, the friction loss occurs at the tilting-pad bearings, particularly the thrust bearing. The design rotational speed is still high to use a tilting-pad bearing because of the small working fluid mass flow rate. However, in the case of a large commercial turbine, the bearing loss to turbine output ratio becomes small. Conclusively, the net power is 10.5 kW, the heat input is 606.8 kW, and the net efficiency of the cycle is 1.73%. The extremely low value is because of the cycle configuration being very simple and the pump and turbine efficiency being low at the operating point. This turbo-generator was originally designed at a 392°C turbine inlet condition in the full cycle configuration, and in this case, was operated under off-design conditions.

Although these experimental results are not perfect for the design conditions, they are meaningful as the results of the first attempt to operate of the axial-type turbine, which is out of the previous radial-type S-CO2 turbine results. It is important to note that the objective of this project was not to demonstrate the efficiency benefits of S-CO2 power cycles. Rather, the objective of the project was to develop an S-CO2 power generation system with an axial-type turbine resolving bearing failure problems reported by other research groups by applying turbomachinery technology applicable to a commercial plant. While it may be too early to tell if the findings from this study will benefit the long term development of the technology, the objectives/accomplishments are noteworthy.

KW-CLASS RADIAL-TYPE TURBO-GENERATOR FOR A 500°C INLET CONDITION

From this section, a kW-class experimental test loop with a radial turbo-generator for 500°C turbine inlet condition are described. Before operating the final dual Brayton cycle in 2019, it is necessary to experience

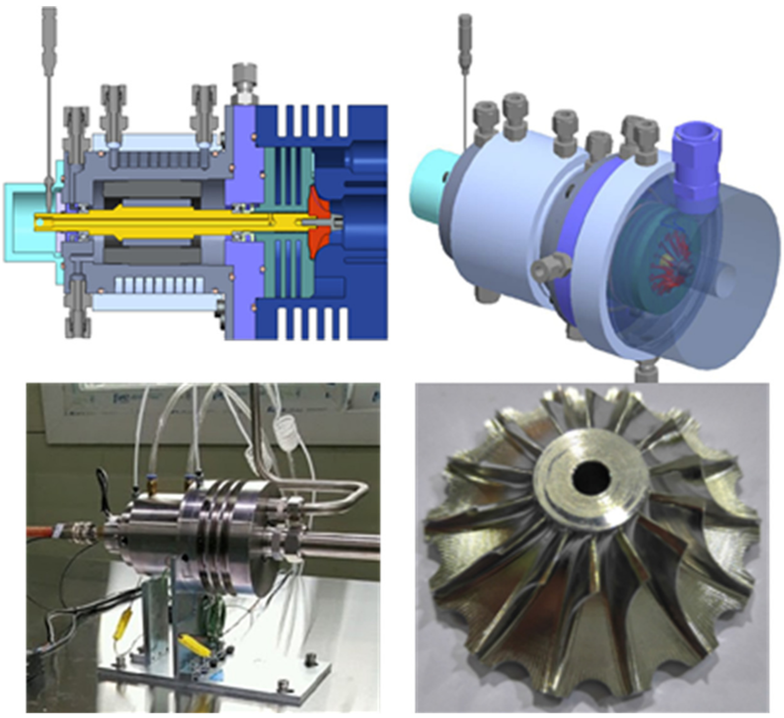


Figure 6. A kW-class radial turbo-generator for 500°C inlet condition

high temperature turbomachinery and the cycle characteristics. In order to reduce development risk, lab-scale kWe-class turbo-generator was designed and manufactured as shown in Fig.6. The design conditions of the turbine are:

Mass flow rate : 0.07kg/s

Total Inlet Temperature : 500°C

Total Inlet Pressure : 130 bar

Total Outlet pressure: 58 bar

From development experience of the small-scale radial turbo-generator during 2014-2016, the first design criteria was to reduce the rotational speed of the turbine under extremely small mass flow rate

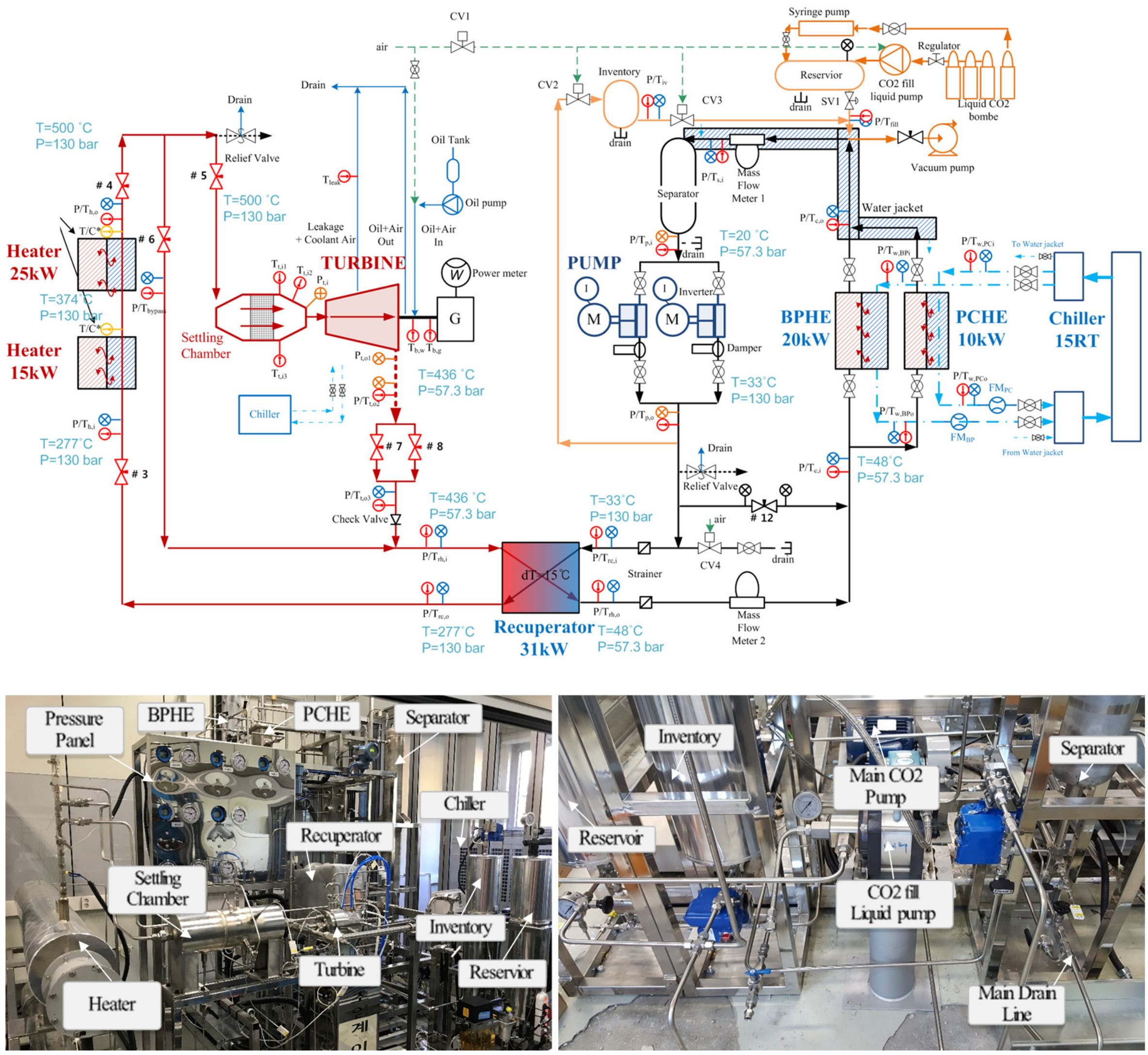


Figure 7. A tens of kWe-class transcritical supercritical CO_2 power cycle test loop

condition. Therefore, a 1/10 partial admission nozzle was designed. A target rotational speed was 120,000 RPM. In addition, in order to reduce axial force, the scalloped geometry was applied to the turbine wheel. Most challenging work was thermal design induced by high inlet temperature at high pressure. In order to cool the rotor, cooling block was installed just after the turbine wheel. As a result, the length of the rotor increased, so the rotordynamics was difficult. To overcome challenging rotor instability, bearing stiffness and damping were sophisticatedly considered. Because of small diameter and high speed of the rotor, the labyrinth seal and the conventional oil-lubricated angular contact ball bearings were used.

TRANSCRITICAL TEST LOOP FOR DRIVING RADIAL-TYPE TURBO-GENERATOR FOR 500°C INLET CONDITION

KIER's second sub-kWe-class test loop as shown in Table 1 was extended to the kW-class test loop to make 500°C and 130 bar of the supercritical carbon dioxide as shown in Fig.7. For this purpose, an additional 25 kW of immersion type electric heater was added to the test loop. In order to reduce heating capacity, a 31 kW of printed circuit heat exchanger (PCHE) was fabricated and installed as a recuperator. A 15°C of approach temperature was design criteria. For better turbine inlet flow distribution, a settling chamber was designed and fabricated. A multi-holed conical plated was welled inside of the chamber and several ports were made for better measurement of temperature and pressure. Two inverter-controlled plunger-type CO2 liquid pump were used. A separator which was installed before the CO2 pump, was modified to have higher height and bigger capacity. An inventory tank was installed between pump outlet and cooler outlet to control the charging mass of the system by controlling the motor-driven valves. Since, there was inevitable leakage flow through the labyrinth seal, a continuous CO2 supply valve train was installed. Two Coriolis mass flowmeter were installed to measure total mass flowrate and leakage mass flowrate.

POWER GENERATING OPERATION RESULTS OF TENS OF KWE-CLASS TEST LOOP

Operating procedure was similar to that of the tens of kWe-class test loop described in previous section.

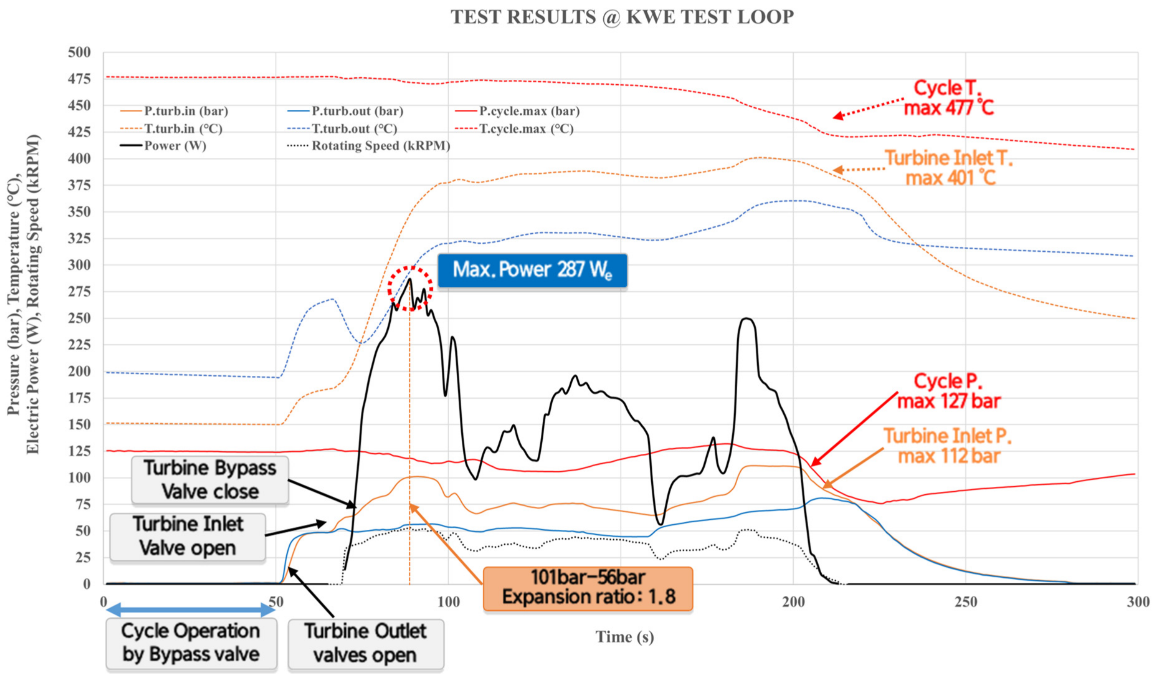
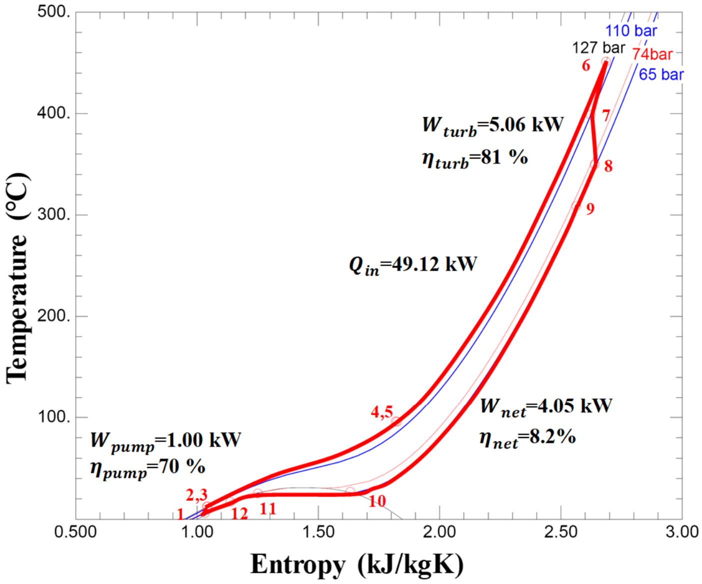


Figure 8. Power generating operation result of the kWe-class test loop



	Temp. (°C)	Pressure (bar)
1. Pump.Inlet	6.2	64.9
2. Pump.Outlet	12.4	128.2
3. Recup.Cold.Inlet	12.7	126.9
4. Recup.Cold.Outlet	96.3	126.8
5. Heater.Inlet	95.8	124.5
6. Heater.Outlet	451.2	124.5
7. Turbine.Inlet	398.75	110.5
8. Turbine.Outlet	349.9	67.3
9. Recup.Hot.In	309	67.2
10. Recup.Hot.Out	27	67
11. Cooler.Inlet	25.4	65.5
12. Cooler.Outlet	17.1	65.3
Mass flow rate	110.19 g/s	
Turbine Leakage	7.66 g/s	
Pump Work	1.00 kW	
Pump Efficiency	70 %	
Turbine Work	5.06 kW	
Turbine Efficiency	81 %	
Expansion Ratio	1.64	
Heat In	49.12 kW	
Heat Out	13.61 kW	
Recuperator	38.53 kW (Hot CO2)	
Recuperator Approach Temp.	15 °C	
Recuperator CO2 pressure drop	0.1 bar (Cold CO2) 0.2 bar (Hot CO2)	
Net Power	4.05 kW	
Net Efficiency	8.2 %	

Figure 9. T-s diagram at maximum turbine power operating conditions of the kWe-class test loop

Figure 8 and 9 show the preliminary experimental results of the electric power production operation. The turbine output was adjusted by controlling the main CO2 pump speed, electric heater heating temperature, and load of the load bank. A maximum cycle temperature of 477°C and pressure of 127bar was obtained in bypass cycle operation. A total of 287 We of electric power, measured by the power meter, was obtained. A maximum turbine inlet temperature of 401°C and pressure of 100 bar was obtained. Because this is very early stage of system operation, it is hard to maintain stable operation considering leakage/make-up balance. After several operation/control experience, steady-state power generation would be expected.

CONCLUSIONS

Two preliminary operating results of the supercritical carbon dioxide power cycle are shown. First, a tens of kWe-class un-recuperated transcritical cycle with an axial-type turbo-generator was developed and operated. The purpose of this turbo-generator was to design S-CO2 turbo-generator with conventional type of components such as an axial-type wheel, a mechanical seal and an oil-lubricated bearing for further scale-up research. An 11 kWe electric power was successfully obtained. Through this work, it was founded that leakage characteristics of the S-CO2 system was technical challenge to improve cycle operability and cycle net efficiency. In addition, a high axial force imposed in the wheel and the bearing was big issue during start-up.

Second, a kWe-class recuperated transcritical cycle for 500°C of turbine inlet condition with a radial-type turbo-generator was developed and operated. The purpose of this turbo-generator and test loop was to experience high temperature operating condition of the S-CO2 system. Due to thermal part of the rotor just after turbine wheel, a rotordynamics was technical challenge under high speed and small diameter condition of the rotor. A 287 We electric power was obtained, however, additional improvement would be necessary.

Finally, KIER has been constructing a hundreds of kWe-class dual Brayton test loop. Power generating operation of this test loop is expected in 2019.

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ACKNOWLEDGEMENTS

This work was conducted under the framework of the Research and Development Program of the Korea Institute of Energy Research (KIER) (B8-2413). Furthermore, this work was supported by the On Demand Development Program of Core Technology for Industrial Fields (10063187, Engineering Technique for Power Generation System Design using Industry Waste Heat), funded by the Ministry of Trade, industry & Energy (MI, Korea).