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DEVELOPMENT AND POWER GENERATING OPERATION OF THE SUPERCRITICAL CARBON DIOXIDE POWER CYCLE EXPERIMENTAL TEST LOOP IN KIER

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ABSTRACT

Korea Institute of Energy Research Institute (KIER) develops three supercritical carbon dioxide power cycle (S-CO2) experimental test loops: kWe, tens of kWe and hundreds of kWe class. First, a 4.5 kWe single radial-type turbo-generator with a labyrinth seal and an angular contact ball bearing was developed to operate a simple recuperated transcritical cycle. A 86 We of electric power was obtained during 30 minutes under a 320°C of turbine inlet condition. Second, a 60 kWe single stage axial impulse-type turbo-generator with a conventional carbon floating ring seal and oil-lubricated tilting-bearings was developed. A 10 kW of electric power was obtained during 4.2 hours by operating on the simple transcritical cycle using a liquid CO2 pump. A 212°C of temperature and 123 bar of pressure were maintained at the turbine inlet. A continuous closed loop was successfully operated by adding a leakage make-up loop. Third, a 120 kWe dual Brayton test loop for a 500°C and a 130 bar of turbine inlet conditions is now being developed. A flue-gas heater, a centrifugal compressor with a dry gas seal and two recuperators were developed, now, these components are being commissioned respectively.

INTRODUCTION

Researchers have studied the supercritical CO_2 (S-CO_2) cycle as a promising power cycle technology that has benefits of improved thermal efficiency, reduction in size, LCOE (Levelized cost of electricity), water use, quick response time, and various conventional and renewable heat sources applications. USA is now constructing a 10 MWe indirect S-CO_2 pilot plant operated by GTI, Southwest Research Institute (SwRI) and GE Global Research with support from U.S. Department of Energy/National Energy Technology Laboratory (U.S. DOE/NETL) [1]. The Southwest Research Institute and GE Global Research have been designing a 10 MWe S-CO_2 turbo-expander as a Sunshot program which 700°C turbine inlet temperature and are commissioning it at a 1 MWe testing facility [2]. Naval Nuclear Laboratory previously Bechtel Marine Propulson Co. has developed a 100 kWe test loop for marine application and is testing a dynamic performance of the component and the cycle [3]. Peregrine Turbine Technologies has developed a 1 MWe S-CO2 turbopump and is testing the device on the test loop facility of the Sandia National Laboratory [4]. Echogen has developed and tested an 8 MW S-CO_2 system and now is developing a 1.3 MWe leak-free S-CO_2 system [5].

A direct-fired S-CO_2 cycle as known as Allam cycle, NetPower collaborated with Toshiba is now commissioning a 50 MWth demo plant [6]. KEPCO (Korea Electric Power Corporation) with Hanhwa Power system have started project to develop 10 MWe-class direct-fired S-CO_2 system [7].

The Korea Institute of Energy Research (KIER) is operating two lab-scale S-CO_2 experimental test loops which are 500°C-kWe-class and 200°C-tens of kWe-class and is now constructing the final 500°C-hundreds of kWe-class test loop consists of two axial-type turbines for distributed power source applications. In 2017, preliminary electricity generation tests of both test loops were successful. A 287 We electricity was obtained from kWe-class radial type turbo-generator under 400°C/112bar turbine inlet conditions. A 10 kWe electricity

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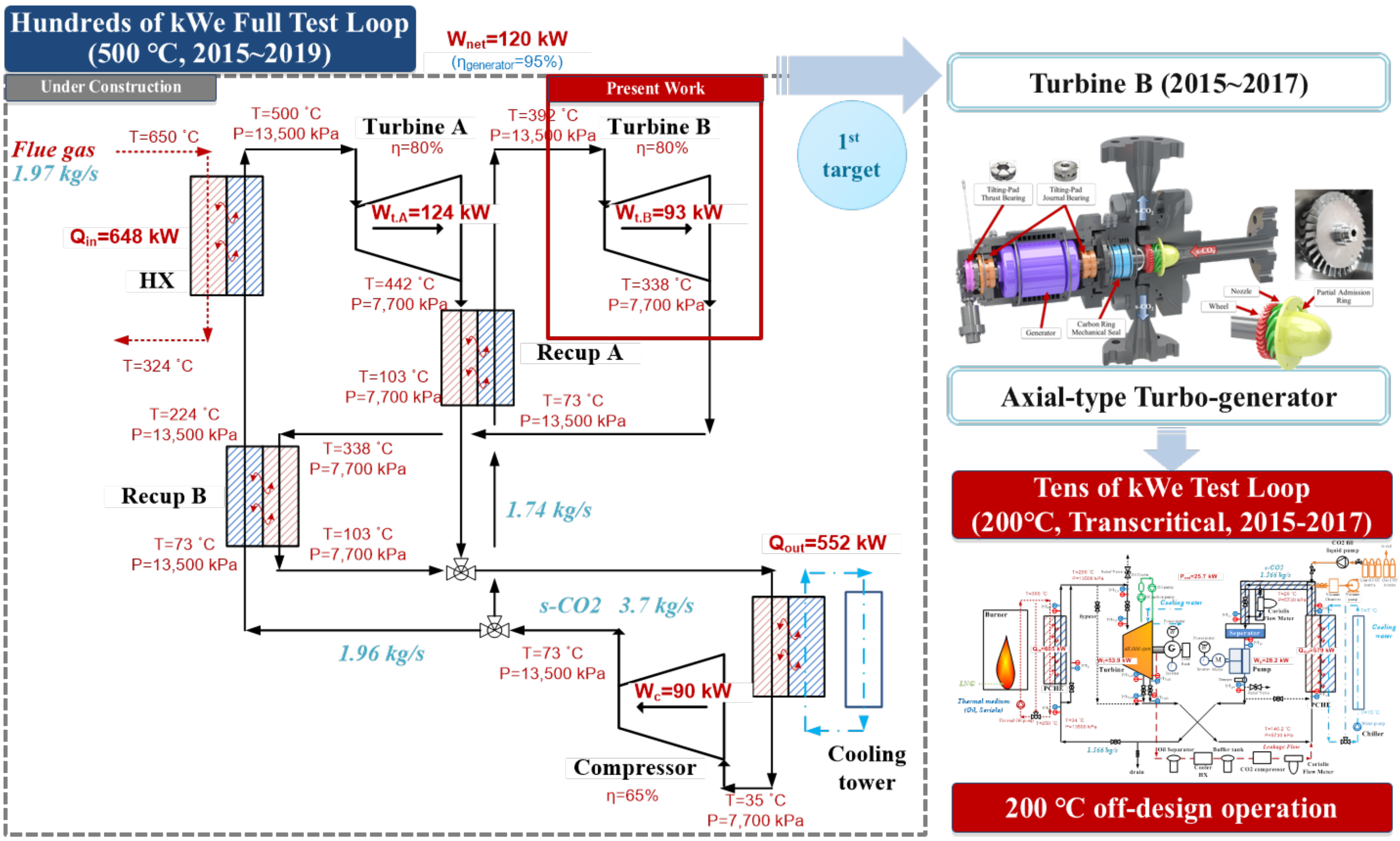

Figure 1: KIER hundreds kWe-class S-CO_2 dual Brayton cycle test loop and construction strategy [8]

was obtained from tens of kWe-class axial type turbo-generator under 205°C/100bar [8].

In this paper, first, the target final 500°C-hundreds of kWe-class test loop cycle configuration and development strategy are presented. After that, continuous power generating operation results of tens of kWe-class transcritical cycle with an axial-type turbo-generator for 200°C turbine inlet temperature is described. Then, continuous power generating operation results of a kWe-class transcritical cycle with a radial-type turbo-generator for 500°C turbine inlet temperature are presented. Finally, back to the first, development of key components for the final test loop are described.

HUNDREDS OF KWE-CLASS TEST LOOP (FULL CYCLE)

KIER designed a hundreds kWe-class test loop with a turbine inlet temperature of 500°C, as described on the left of Fig. 1. This cycle consists of two turbines, one compressor, two recuperators, and a flue-gas heater.

In case of fuel-fired heat source such as a biomass, waste heat recovery and a bottoming cycle which the heat of the wide temperature range of the heat source has to be utilized, higher power of the cycle is preferred rather than the cycle efficiency. In this study, as shown in Fig.1, the cascade-type Brayton cycle is designed with two turbines described as a turbine A and B. To design and manufacture realistic components under limited budget, mass flow rate of the cycle which determines capacity of each component is determined as a 3.7 kg/s for the sake of manufacturable compressor impeller blade height and operable rotating speed limited by a bearing and a seal.

The maximum cycle pressure/temperature was determined as 135 bar/500°C, which is a similar level to the world's optimal operating conditions, as reported by the Sandia National Laboratory. The efficiency of the compressor and two turbines are determined to 65% and 80% respectively which are realistic values from previous researches. Detailed descriptions of the cycle are presented in our reference [11]

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, a tens of kWe-class transcritical test loop was developed using existing 300°C-class heat source and pumping facilities. Because our heat source temperature is limited to 300°C, the turbine was tested at an inlet temperature of 200°C, which is the off-design condition. During construction of the entire test

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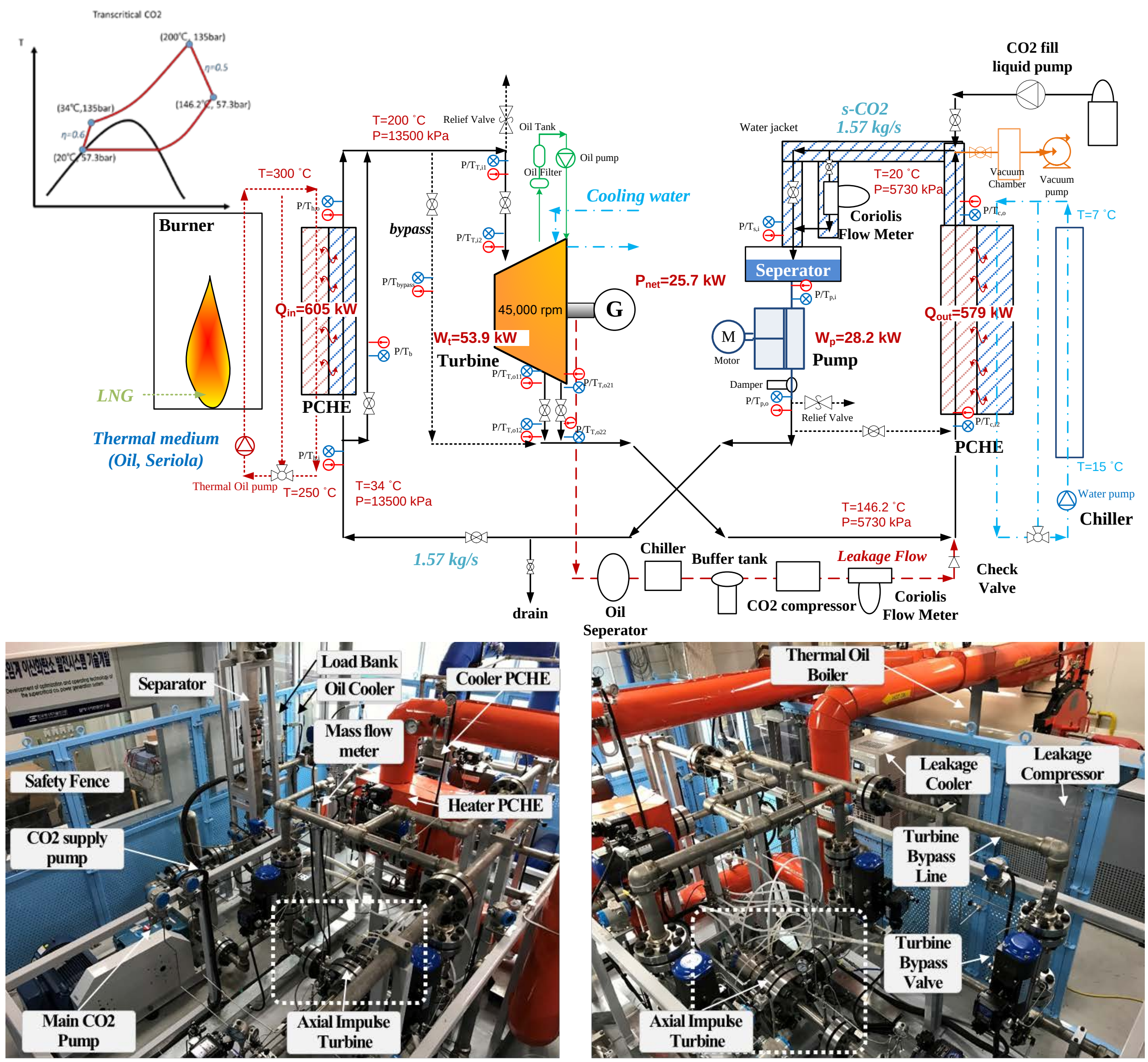

Figure 2: A Transcritical supercritical CO_2 power cycle test loop [8]

loop, by operating this turbine B, we could determine the cycle characteristics and improve the design of the test loop, including the axial turbo-generator and its components such as bearings, seals, rotordynamics and leakage management. After preliminary power generating operation implemented in 2017 [8], in this study, the design of test loop and turbo-generator is reviewed and continuous operation results are presented.

AXIAL-TYPE TURBO-GENERATOR (TURBINE B)

In order to overcome reported gas-foil bearing failure problems of the radial-type turbine induced by high rotational speed and axial force [9], an axial-type impulse turbine and partial admission nozzle was designed and manufactured to reduce axial force and the rotational speed by up to 45,000 RPM. A carbon ring-type mechanical seal and conventional oil-lubricated tilting-pad journal and thrust bearings were used. A mean diameter of turbine wheel 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 reference [10].

TENS OF KWE-CLASS TRANSCRITICAL TEST LOOP FOR DRIVING AXIAL-TYPE TURBO-GENERATOR AT 200°C

As the first step to developing an S-CO_2 power cycle, a transcritical S-CO_2 power cycle was constructed at the turbine

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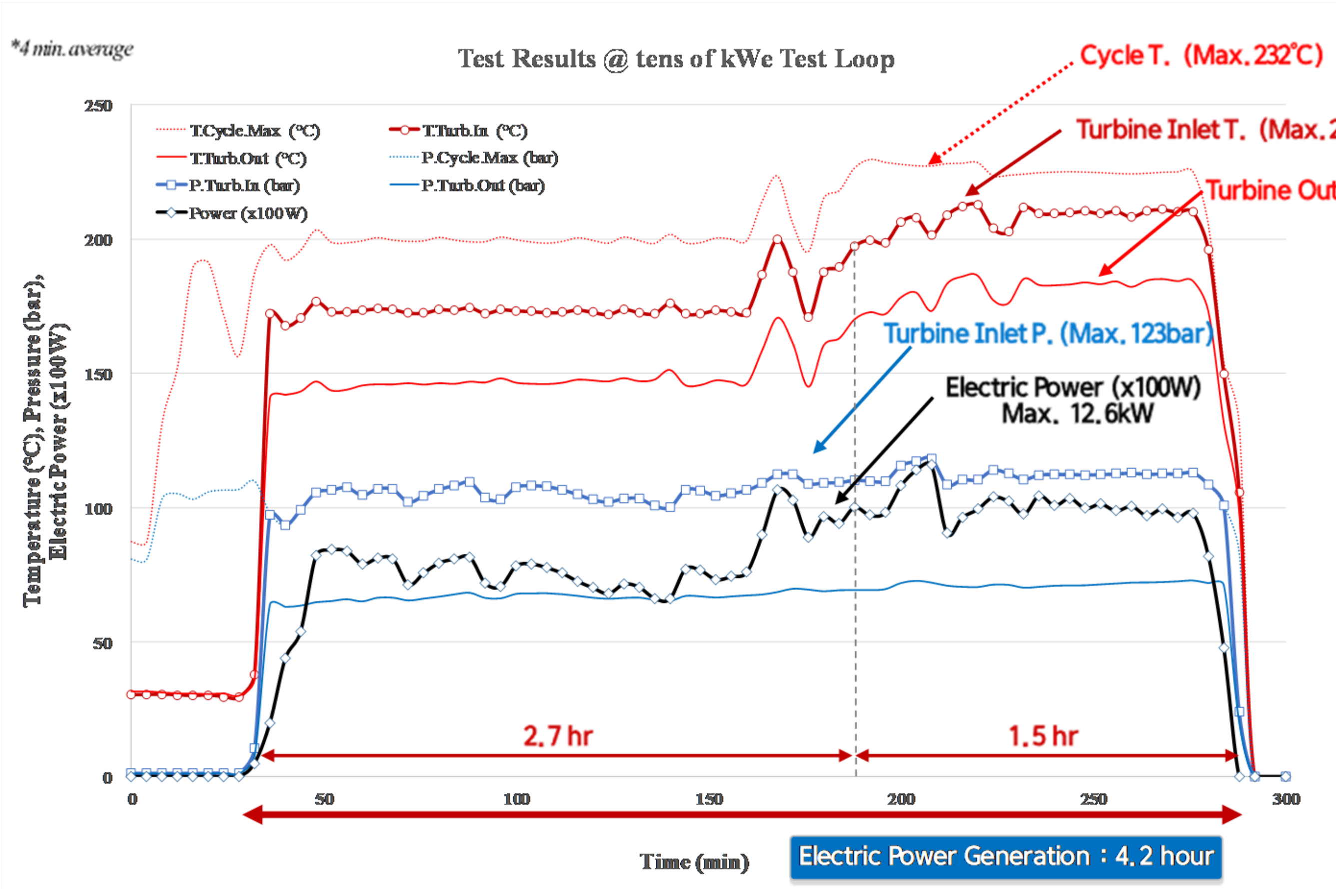

Figure 3: A 4.2 hours continuous power generating operation result [11]

inlet at 200°C in one step. For this purpose, the turbo-generator originally designed and manufactured under the target condition of 392℃ is operated for off-design operation at 200°C. An un-recuperated transcritical cycle test loop neglecting the cycle efficiency was designed and fabricated, as illustrated in Fig. 2.

The maximum temperature was 200°C as the first step target, which is a relatively mild condition for the system. Liquid CO_2 at 20°C, 57 bar, and 1.57 kg/s was pressurized into a supercritical state at 135 bar using a plunger-type reciprocating liquid CO_2 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 CO_2 to 200°C through a printed circuit heat exchanger (PCHE), and after driving the turbine the CO_2 was cooled through the PCHE.

In order to use a technically stable oil-lubricated bearing, a floating carbon ring type mechanical seal was installed in the turbo-generator, which inevitably leads to turbine leakage flow. In the current turbo-generator design, a 2 to 3% leakage flow was estimated; therefore, the leakage management system was constructed to re-inject CO_2 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 CO_2 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. Also, details of test loops are described in our reference [8, 11].

CONTINUOUS POWER GENERATING OPERATION RESULTS (AXIAL TURBO-GENERATOR, TURBINE B)

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. Thereafter, each component, such as auxiliary equipment for turbine driving, a main pump, boiler, chiller, leakage management system, CO_2 supply system, control, and measurement. A vacuum pump was used to remove all air in the test loop, and the vacuum level was approximately 1.33 Pa. Following this, CO_2 was filled into the system. The amount of working fluid in the closed cycle was an important factor in the system operation. The CO_2 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-CO_2 cycle configuration, the turbine inlet and outlet valves were opened and the bypass valve was closed, allowing S-CO_2 to drive the turbine. The

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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. [8]

Figure 3 displays the continuous experimental results of the electric power production operation. The turbine output was adjusted by controlling the main CO_2 pump speed, boiler heating temperature, re-injection/make-up amount of CO_2 and load of the load bank. An average of 10 kWe of electric power (Max. 12.6 kWe), measured by the power meter, was obtained at a maximum turbine inlet temperature of 212°C and pressure of 123 bar, and the continuous operation time of the turbine power production was 4.2 hours. Our target was 2 hours. From the start operation, the temperature of the turbine inlet is maintained below 200°C for safe continuous operation to check all parameters of the test loop. Vibration level of the rotor was stable, pressure and temperature conditions at each part of the test loop were well controlled. The temperature of the bearing was stable under 60°C.

The turbine leakage from the seal was larger than the estimation at the start before heat-up, as the turbine body was heated up leakage flow decreases. Because the turbine B was designed at the temperature of 392°C, the leakage flow passage was designed suitable for original operating conditions. So, leakage mass flow rate was inevitably larger than the design value at relatively low temperature condition in this test. Also, the mass flow rate of the leakage compressor was designed at the conditions of 392°C operation that leakage flow was estimated as a 2-3% of the main stream, so in this low temperature off-design operation, the mass flow rate exceeded over capacity of the leakage compressor. Therefore, the back pressure was increased up to 8 bar at the mechanical seal flow passage, so injection pressure of the barrier CO_2 gas from the gas tank was increased to above 9 bar. In addition, bypass line was installed between the turbine leakage outlet and the leakage compressor inlet to throw away the excess leakage flow from the seal. So, the charging mass in the test loop was slightly decreased during operation. Therefore, the CO_2 was continuously refilled using a filling liquid pump from the liquid CO_2 tank.

After 2.7 hours operation without any problems, the turbine inlet temperature was increased above 200°C which is operating goal of the Transcritical cycle test loop. After additional 1.5 hours operation, test was normally shut-downed for the next step operation.

In Fig. 3, low frequency oscillations of pressures and temperatures were because of slow response of a thermal oil boiler temperature on/off control. And oscillations of the leakage flow from the seal as a temperature change induced charging mass in the system, so pressure of the turbine inlet was oscillated. Therefore, amount of the driving air of the filling pump was continuously controlled by using a control valve opening level in order to adjust amount of the charging mass.

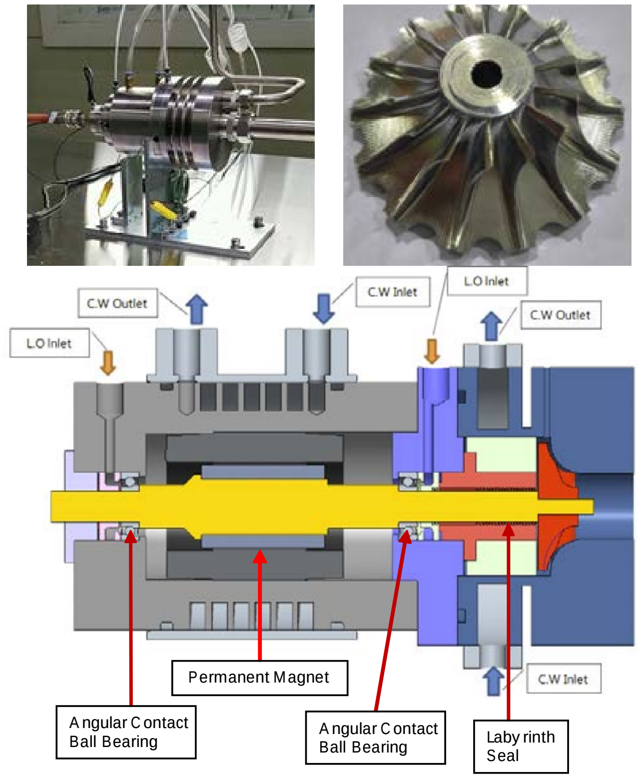

Figure 4: A kW-class radial turbo-generator for 500°C inlet condition [8]

Although these experimental results are not perfect for the design conditions, it is important to note that the objective of this project was not to demonstrate the efficiency benefits of S-CO_2 power cycles. Rather, the objective of the project was to develop an S-CO_2 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. Through continuous operating results during 4.2 hours, it was shown that robust and stable operation and control was possible [11].

In addition, it was the first operating results of S-CO_2 test loop with a re-injection system to compensate the turbine leakage from the mechanical seal. To configure make-up system, a barrier gas to the floating carbon ring seal was supplied from pure CO_2 gas tank, a 3-stage oil-free reciprocating CO_2 compressor, a reservoir, an oil separator and a cooling system were installed. In addition, operating strategy was developed according to turbine operating procedure. Theses caused additional costs and power loss which affect total plant efficiency and LCOE. It is inevitable and important technical issue in the S-CO_2 system. From these lessons learned, a novel CO_2 leakage re-injection strategy studies by using an ejector cycle and a heat pump cycle were done and presented in the our references [12, 13]

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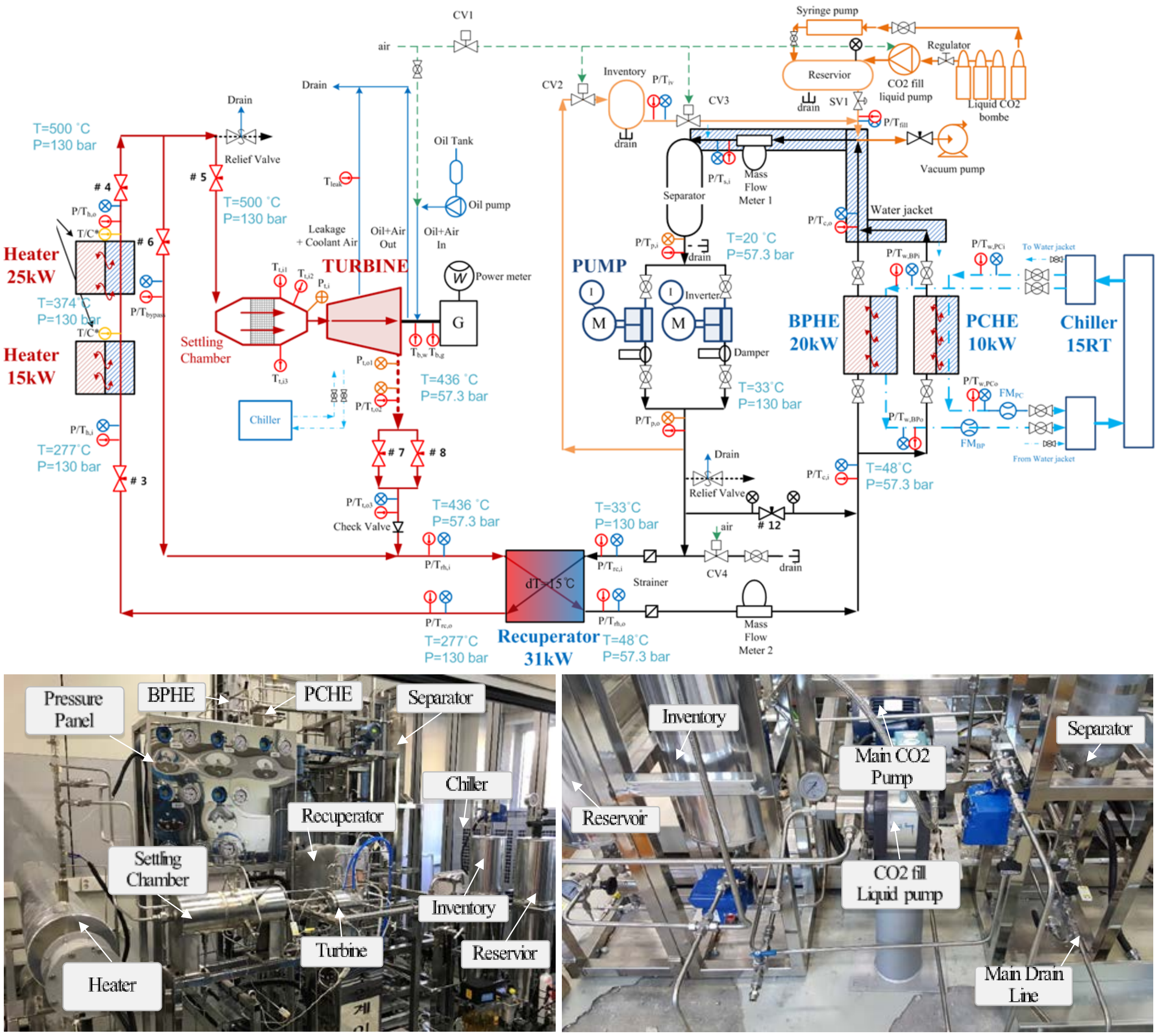

Figure 5: Schematic of kWe-class sCO_2 transcritical cycle test loop [8]

KWE-CLASS TRANSCRITICAL TEST LOOP FOR DRIVING RADIAL-TYPE TURBO-GENERATOR AT 500°C

As a two-track development strategy, in order to experience 500°C of supercritical carbon dioxide condition before development of the final test loop, a small kWe-class radial turbo-generator and its test loop assembled by tube fittings were developed and operated.

Figure 4 shows a 4.5 kWe-class radial type turbo-generator and Figure 5 shows its test loop for 500°C turbine inlet condition. 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 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. [8]

In Fig.5, a simple recuperated transcritical test loop configuration is described. The main components are two pumps, a turbo-generator, two immersion type of electric heaters, a printed circuit heat exchanger (PCHE) type recuperator, a settling chamber, a chiller, and pressure vessels. The two liquid pumps pressurized liquid CO_2 into supercritical state. The supercritical CO_2 flows through the recuperator and

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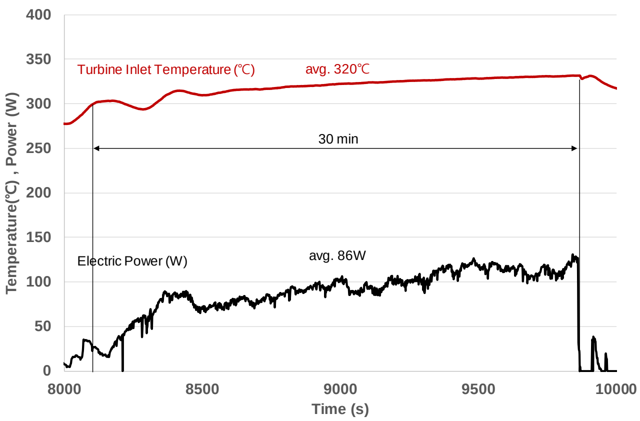

Figure 6: Power generation of the kWe-class sCO_2 test loop

is heated by the residual heat of turbine outlet flow. In the two electric heater, CO_2 is more heated until the turbine inlet condition is reached and then, its flow characteristic becomes uniform at the settling chamber. Next, the heated sCO_2 drives the turbo-generator by the expansion work and the generated power is measured with a power meter. In the turbine outlet, because the supercritical CO_2 still has a large amount of energy, it is cooled down at the recuperator. In the cooler PCHE, it is cooled to make a pump inlet condition which is equal to the minimum temperature of the cycle. A separator is used to divide two phase CO_2 into liquid and gas because pump can pressurize the liquid CO_2 only. A reservoir and an inventory are used to control the filling amount of CO_2 in the test loop. [8]

CONTINUOUS POWER GENERATING OPERATION RESULTS (RADIAL TURBO-GENERATOR)

A preliminary test at the 300℃ is first performed prior to a test at 500℃. Test results are shown in Fig. 6. An electric power is generated for 30 min and its average is measured as 86 W at an average turbine inlet temperature of 320℃. The fluctuation of the power results from the leak of the turbo-generator and variability of a heater control system. When the 10% amount (7 g/s) of main mass flow rate (70 g/s) CO_2 leaks through the turbo-generator, the filling amount of CO_2 in the system is decreased. Therefore, the filling pumps starts to operate and then, make-up CO_2 is injected into the test loop. In this process, the filling amount continue to change and the turbine inlet conditions such as pressure and temperature are changed together. In addition, slow response of the electric heater also affects to the variation. In the future work, a test will be performed at the maximum temperature of 500℃ with the kWe-class test loop. In addition, based on the experience of tens of kWe-class and a kWe-class test loops, the final test loop will be manufactured and operational in November 2019.

DEVELOPMENT OF HUNDREDS OF KWE TEST LOOP (CONSTRUCTION)

Back to our final target test loop described in Fig.1, Figure 7 shows main components of the test loop. First, a 90 kW centrifugal type compressor with a mass flow rate of 3.7 kg/s was developed by our research group collaborated with domestic research institute and domestic vendor. A 77 bar of compressor inlet pressure condition was determined for the sake of stable operation at the slightly far from the critical point of carbon dioxide. A 135 bar of compressor outlet pressure was determined to similar level of Sandia National Lab's test loop target. A compression ratio of 1.7 and a rotational speed of 70,000 RPM compressor was designed. The diameter of the compressor impeller is 43.6 mm, and the efficiency was estimated by a CFD analysis as 79.3%. Using a dry gas seal (DGS) which is well known as the best low leakage conventional seal technology and high speed oil-lubricating tilting-pad bearings compressor layout was designed and rotordynamics analysis was performed.

In particular, in order to reduce leakage though the compressor at high pressure, high axial force and high speed condition, the DGS and DGS control system that supplementary CO_2 and N_2 supply equipment were designed. A CO_2 booster and a CO_2 electric heater were added in this DGS control system to maintain dry condition of the CO_2 at the seal face. Because of Joule-Tomson effect at the seal face, CO_2 can be iced due to large pressure decrease and it could occur seal failure. Also in order to reduce axial force imposed on the compressor, the DGS part was designed and modified according to compressor layout design. Leakage was estimated to be 0.1 to 0.2% of main mass flow rate. Using a high-speed coupling and a high-speed driving motor supplied by domestic vendor, the compressor is now on the commissioning process. After component level test on the compressor test-rig, performance curves will be obtained and then the compressor will be assembled to the final test loop.

A 500°C-class turbine described as turbine A in Fig. 1 was designed as an axial-type turbo-generator as shown in Fig. 7. A capacity of turbine power was 110 kW, a wheel mean diameter was 52.7 mm and a rotational speed was 70,000 RPM. As similar to the turbine B, oil-lubricated tilting-pad journal and thrust bearings and a floating carbon ring-type mechanical seal were used. A 56% of partial admission nozzle was also designed. To reduce axial force imposed to the thrust bearings, a balancing piston was designed between two journal bearings. A compressed air of 6 bar from utility air compressor would be supplied to the back face of the balancing piston to compensate axial force. A pressure of air is controlled by sensing axial force measured by a load cell installed at the end of the shaft. To reduce length of the shaft for better rotordynamics, the balancing piston and a high speed generator stator were designed to have short length as possible.

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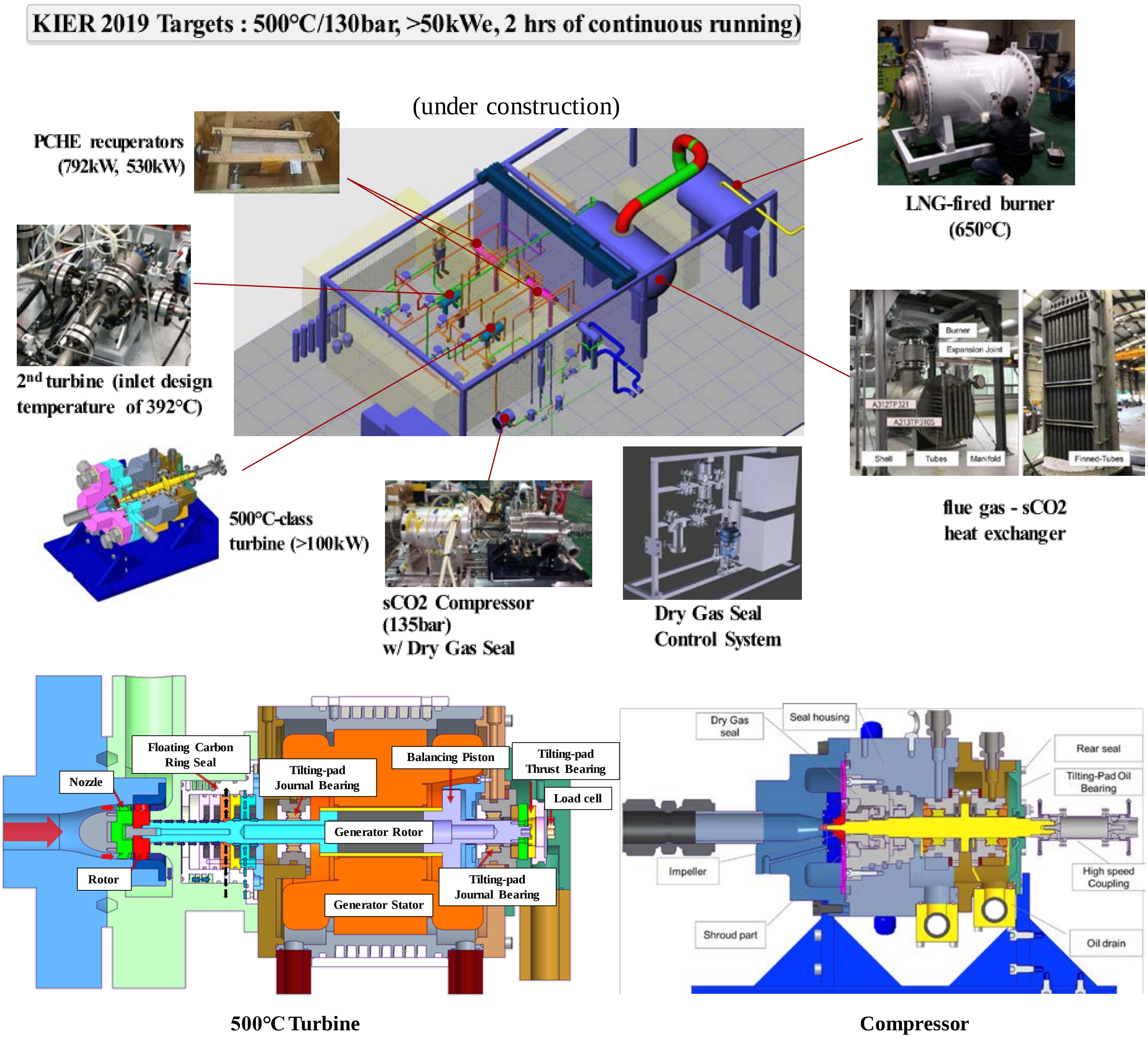

Figure 7: The final hundreds of kWe-class sCO_2 cycle test loop

To generate 500°C supercritical carbon dioxide at 135bar condition, a LNG-fired flue gas heater was designed and manufactured by domestic vendor. It consists of a burner and a shell-and-finned tube type heat exchanger. A capacity of the burner and the heat exchanger were 1,500,000 kcal/hr and 648 kW respectively. A 650°C of hot gas is generated in the burner by mixing with a cool air using a blower. A 5 kPa of supply pressure and a 6,000 Nm^3/hr flow rate conditions were satisfied. The heat exchanger was fabricated with the A312TP321 shell and A213TP310S seamless tubes. The outer diameter of the tube was 42.7 mm and the thickness was 9 mm. Finned tubes were assembled to the manifold and 2500 class of 3 inches ANSI flanges were welled. In order to mitigate thermal expansion of the burner and the heat exchanger estimated as a 15 mm, a high temperature expansion joint was fabricated with A312TP321 by domestic vendor. Now 350°C flue-gas was generated to heat S-CO2 up to 120 °C by preliminary combustion test.

Two PCHE recuperators and one PCHE cooler were designed and fabricated by VPE(USA). A pressure drop conditions for all nozzles were 0.3 bar and the material was SS316L. Strainers were included at the flanges. High pressure/temperature globe type control valves were also designed and fabricated by domestic vendor to configure

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operating strategy such as bypass operation, compressor operation and turbine operations. A 2 inches ANSI 2500 class flanges were fabricated. Simultaneously, piping design and preliminary piping stress analysis were performed including all major devices, supports and control valves as following ASME B31.1 standard.

Now, we are commissioning each components, designing and fabricating other components, after that, preliminary operation results will be obtained on November, 2019. [11]

CONCLUSIONS

A hundreds of kWe-class S-CO_2 test loop with a 500°C turbine inlet temperature condition was developed and partially fabricated. Two axial-type turbo-generators, one centrifugal-type compressor, two PCHE recuperators, one flue gas heater and one PCHE cooler were designed. As a step-by-step approach, the low temperature turbine which inlet temperature of 392°C was designed and manufactured with a carbon floating mechanical seal and an oil-lubricating tilting-pad bearing which are suitable technologies for a commercial large-scale plant. To drive this turbine, existing test facilities were used. A 4.2 hrs continuous electricity generating operation test was conducted at 200°C off-design condition. Turbine leakage flow was re-injected to the system by using a leakage compressor. It shows additional technical issue of the S-CO_2 system.

In addition, a small kW-class radial turbo-generator and its transcritical test loop which operates at 500°C was developed and operated to investigate characteristic of S-CO_2 components at the high temperature condition. A 30 mins of continuous power generation was succeeded over 300°C turbine inlet temperature condition. Because of thermal design of the rotor, a shaft has to be long, it causes rotordynamics problems. It would be improved after modifying rotordyamics of the high speed turbo-generator.

Finally, a centrifugal type compressor with a dry gas seal and a tilting-pad bearings and an axial type turbo-generator with a balancing piston, floating carbon ring seal and a tilting-pad bearings were developed for the final test loop. A LNG-fired flue gas heater with a shell-and-finned tube heat exchanger that generate 500°C S-CO_2 was also designed and preliminarily tested. Other parts such as recuperator, cooler and piping systems were also designed and partially manufactured. It is expected to operate entire test loop in end of 2019.

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REFERENCES

[1] Vann Bush, Keynote-GTI STEP forward on sCO2 power, The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[2] Jeffrey Moore, Commissioning of a 1 MWe Supercritical CO2 Test Loop, The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[3] Lewis J, Clementoni EM, Cox T. Effect of Compressor Inlet Temperature on Cycle Performance for a Supercritical Carbon Dioxide Brayton Cycle. The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[4] David S. Stapp, SCO2 Turbomachinery Developments, The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[5] Jason D. Miller, Test Results of a 1.5MW High Speed Motor-Generator in a Pressurized CO2 Environment, The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[6] David Freed, A Gas Turbine-driven, Integrally Gear Compressor solution: Enabling the Carbon Capture of the sCO2 Allam Cycle Power Plant. The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[7] Jang SH, Keynote presentation, The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[8] Cho J, Shin H, Cho J, Ra H-S, Roh C, Lee B, Lee G, Choi B, Baik Y-J. Preliminary Power Generating Operation of the Supercritical Carbon Dioxide Power Cycle Experimental Test Loop with a Turbo-generator. The 6th International Supercritical CO2 Power Cycles Symposium, March 27 - 29, 2018, Pittsburgh, Pennsylvania

[9] Thomas C, Steven W, James P, Darryn F, Gary R, Robert F. Performance Characteristics of an Operating Supercritical CO2 Brayton Cycle, Journal of Engineering for Gas Turbines and Power, Vol. 134, 2012, 11703-1

[10] Cho J, Shin H, Cho J, Baik Y-J, Choi B, Roh C, Ra H-S, Kang Y, Huh J. Design, Flow simulation and performance test for partial admission axial turbine on supercritical CO2 condition. Proceedings of ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition, GT2018-76508, June 11 – 15, 2018, Oslo, Norway

[11] Choi B, Cho J, Shin H, Cho J, Roh C, Lee B, Lee G, Ra H-S, Baik Y-J. DEVELOPMENT OF A HUNDREDS OF KWE-CLASS SUPERCRITICAL CARBON DIOXIDE POWER CYCLE TEST LOOP IN KIER, Proceedings of ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition GT2019 June 17–21, 2019, Phoenix, Arizona USA

[12] Muhammad HA, Lee G, Cho J, Bhatti UH, Baik Y-J, Lee B, Design and optimization of CO2 pressurization system integrated with a supercritical CO2 power cycle for the CO2 capture and storage system, Energy Conversion and Management, 195, 2019, pp.609-619

[13] Muhammad HA, Lee B, Lee B, Cho J, Baik Y-J, Investigation of leakage reinjection system for supercritical CO2 powercycle using heat pump, Renewable Energy, 144, 2019, pp.97-106

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