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Status on the Electric-thermal Energy Storage Technology and Application of a Supercritical Carbon Dioxide Power Cycle

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Abstract

A large-scale energy storage system becomes more essential as a proportion of the renewables increases in the future electricity supply mix. Intermittent electricity supply characteristics by renewables causes instability of a grid, therefore electricity time shift technologies are needed. Batteries are representative electricity energy storage system, however, it is hard to expand for large-scale system, because of high cost, short discharge duration characteristics. The electric-thermal energy storage technology, recently called as a Carnot Battery, has been focused as a solution for the large-scale grid level energy storage applications, because it uses conventional robust heat engine technologies suitable for large-scale system. It is composed of electricity-to-heat, heat storage and heat-to-electricity system. In case of heat-to-electricity, a supercritical carbon dioxide power cycle (sCO2) is attractive option because of its potentials of wide operation range, dry-cooling, high efficiency and small foot print. Korea Institute of Energy Research (KIER) has been developed a sCO2 power cycle test loop with the turbomachinery. In this paper, concept of the electric-thermal energy storage and the technical development highlights of the sCO2 power cycle in KIER are presented.

Keywords: Carnot Battery, Electric-Thermal Energy Storage, ESS, Supercritical Carbon Dioxide Power Cycle

1. Introduction

The interest in renewable energy sources (RES) such as solar and wind has been growing due to its climate change mitigation and economic benefits. Based on REN21's 2018 report, RES accounted for approximately 18.2% of global energy consumption and the ratio have been rising gradually. In addition, in 2017, South Korea's Ministry of Trade, Industry and Energy announced the "Renewable Energy 3020" implementation plan which aims to increase a share of renewable energy from 7% to 20% of the total energy mix by 2030. Therefore, Korea will need additional 63.8 GW capacity of renewable power sources which is similar to present Korea power plant capacity (~100 GW) in 2030.

Energy storage systems (ESS) are essential because of the intermittent power generation features of renewable generation sources that can generate electricity only when the sun is there and when it is windy. The battery-based small-capacity energy storage system is applied to the small-scale new renewable power generation source, and serves as voltage correction and frequency adjustment. However, if large-scale renewable of GW class are introduced in the future, a commercially appropriate large-capacity energy storage system is required. Obviously, this will be limited by existing high-cost battery-based storage devices.

Therefore, in order to continuously use these large-capacity renewable energy sources with reliability and stability of the electric grid, low-cost, long-term energy storage devices are required. In this way, it is necessary to develop a large-capacity energy storage device that can make a time-shift of intermittent power generation at the grid level to enable renewables as a base power source uses.

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Electrochemical energy storage technologies such as a battery, a super-capacitor and a flow battery have characteristics of high efficiency, high energy density, no geographic limitation and relatively simple configuration. However, the system capacity is several kW-MW, the capacity is limited to cope with the grid and the discharge time is under several hours so that it is limited to use for a long-term storage purpose. Therefore, these are suitable for voltage correction/frequency adjustment with short discharge time. The efficiency is high, but the cost corresponding to LCOE (Levelized Cost of Electricity) is about 10 times of the pumped storage hydropower (PSH) [1].

Recently, a Carnot Battery concept is proposed for a large-capacity energy storage system. The Carnot cycle is a reversible heat engine thermodynamic cycle, the Carnot Battery uses thermodynamic cycles for the purpose of electricity storage. To use a power cycle when the ESS system generates electricity, the electricity has to be stored as a thermal type which is enough to drive a turbine. Therefore, an electric heater or a heat pump have to be used to convert the electricity to the heat. The heat pump is well known thermodynamic system for efficient heat conversion. The electric heater is simple and cheap conventional technology.

Currently, 70% of the electricity used in Korea is obtained by the steam turbine power generation cycle method that generates electricity by using steam from coal and nuclear fuel to drive turbines, and 22% is gas turbine power generation cycle is used in which the turbine is driven by high temperature air obtained from the heat of combustion of natural gas [2]. In other words, 92% of electricity is obtained through thermal-power conversion heat engine technology: power cycle, which is suitable for a large capacity plant of hundreds of MW.

In this point of view, energy storage systems that can cope with future GW-class distributed power supply systems should use technically and commercially proven power cycle technology, and have a minimum unit of several MW to several hundred MW system. Therefore, when the surplus electricity generated from the renewable is stored in the form of a large amount of thermal energy in the conditions that can generate electricity by driving a turbine, which means the Carnot Battery, it is possible to implement an energy storage system capable of low-cost/long-term power generation.

It is early stage of research, so in this paper as an introductive purpose, the concept of the Carnot Battery, technical issues and its status of global research trends are described. There are several configuration of the Carnot Battery corresponding to the heat storage temperatures, various types of heat pumps and power cycles can be used. A supercritical carbon dioxide power cycle (sCO2) which is recently studied for a promising power cycle, is attractive option for the Carnot Battery due to its high efficiency, small footprints, fast response, dry cooling and wide heat source temperature range. A turbine, a compressor, a heat exchanger and thermodynamic devices for the supercritical carbon dioxide could be also used for the supercritical carbon dioxide heat pump for the Carnot Battery. Korea Institute of Energy Research (KIER) have developed core technologies of the sCO2 from 2013. And KIER try to apply sCO2 to the Carnot Battery. Brief research history and accomplishments of sCO2 in KIER are described.

2. Carnot Battery

The Carnot Battery as shown in Fig. 1 is composed of three parts: electricity-to-heat, heat storage and heat-to-electricity sub-systems. The methods of heat-to-power are (1) electric heater and (2) heat pump technology. The electric heater is a relatively simple method of converting electricity into heat to drive a heat engine. In this case, efficiency of the conventional resistive electric heater is 95-98%, then, the thermodynamic charge-discharge round-trip efficiency (RTE) is dominantly affected by efficiency of the heat-to-electricity unit which is a power cycle. In case of power cycle, ideal thermodynamic efficiency is expressed as a Carnot efficiency according to the heat source and sink temperature, in this case, the storage temperature. If a practical maximum efficiency of the power cycle is near 70% of the Carnot efficiency as temperature, at least 800℃ heat storage is required to actually implement a 50% of RTE system. The heat engine that can be used above 800℃ is a combined gas turbine power cycle. When the electric heater is used as the charging technology for simple configuration, a layout in which ultra-high heat storage and gas turbine power cycle can be used.

On the other hand, if power cycle (discharge) using a high temperature heat storage and convert to a low temperature storage, then a low temperature heat can be pumped back to a high temperature heat by using a heat pump (charging), as shown in Fig. 1. Assuming an ideal reversible process without loss (Carnot cycle), a closed charging-discharging cycle without energy loss can be configured, so called as a Carnot Battery. However, due to the presence of irreversible losses (heat losses, mechanical losses, etc.) in the actual energy utilization process, the actual round-trip efficiency of the charging and discharging process decreases.

When the layout using a heat pump is actually implemented, proper high and low temperature storage configuration is an important technical issue because trade-off of heat pump performance expressed by a

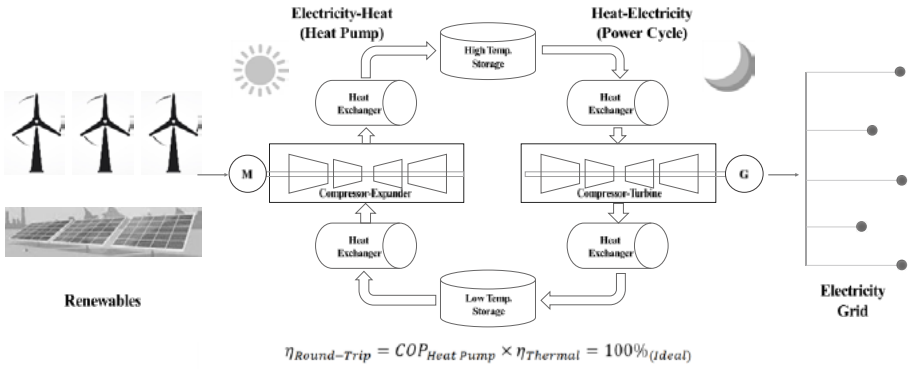


Fig. 1. Concept of the Electric-thermal energy storage system [3]

coefficient of performance (COP) and power cycle efficiency occurs. For example, if the high temperature heat storage temperature is increased to increase the efficiency of the power cycle unit, the COP of the heat pump will be reduced. This layout can be configured using by conventional steam power generation system of turbine inlet temperature 500-600℃, but there is a new technical issue of the development of ultra-high temperature heat pump. The current maximum production temperature of conventional heat pump is about 180℃ based on compressor discharge temperature by using a refrigerant.

Heat storage medium is also a technical issue. In case of high temperature heat storage, it is important to select a heat storage material according to the heat storage temperature. In case of molten salt, which is currently being used in Concentrating Solar Power (CSP) application, the operating temperature is about 280-550℃. Therefore, the molten salt is used in combination of a steam power cycle using the sensible heat of molten salt. Sand or rock may be used to store the high temperature of 800℃ or higher, which has the advantage of being inexpensive but has a disadvantage of poor heat exchange performance. In addition, the power cycle (discharge) system, the heat pump (charging) system, the low temperature heat storage material, the heat exchanger types are changed according to the temperature of the low temperature storage device, and thus, various system layouts can be configured according to the configuration and operating conditions of the entire cycle. [3]

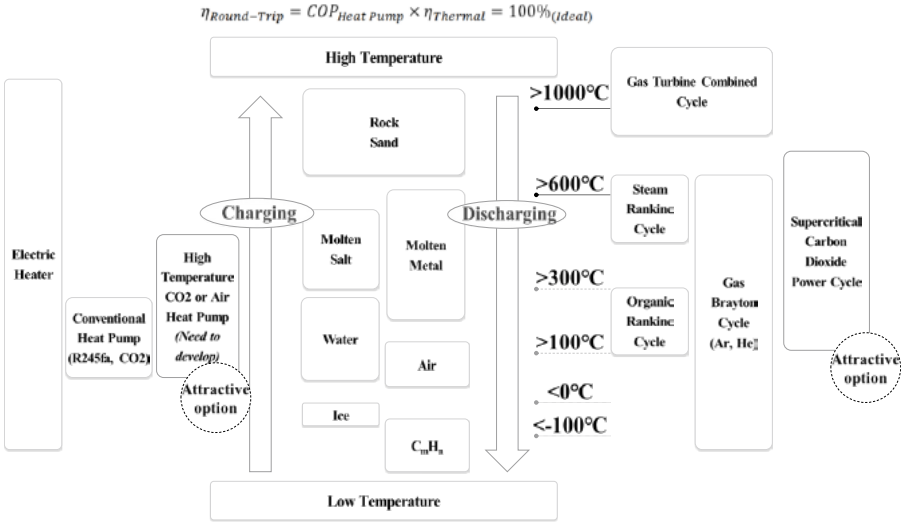


Fig. 2. Technical candidates for an electric-thermal energy storage system according to temperature [3]

Figure 2 shows technical candidates for the Carnot Battery system according to temperature. In case of thermal storage medium, a molten metal such as Tin, Sodium can be used for relatively wide operation range of the power cycle. Water is the attractive thermal storage medium due to its advantages of low cost, stability,

reliability and safety for relatively low temperature range for high temperature storage. In that case, an organic Rankine cycle (ORC) and a supercritical carbon dioxide power cycle (sCO2) can be used. Although efficiency of the power cycle is low due to low heat source temperature, the COP of the heat pump is high, therefore, RTE can be achieved by using a conventional heat pump devices.

Gas Brayton cycle using an Ar or Ne or He is possible power cycle which can make wide temperature differences between hot side and cold side of heat storage. In particular, this layout can utilizing cryogenic heat sink, so temperature difference between high and low temperature of the power cycle could be increased which means it can get a better power cycle efficiency.

Recently, a supercritical carbon dioxide power cycle has been focused on a promising power cycle technology due to its advantage of high efficiency, reduced size, small foot-print, fast response, low cost, dry-cooling, and wide operation range suitable to various heat sources. In addition, core components of the sCO2 power cycle such as a turbine, a compressor, a heat exchanger, a valve, a pipe and so on could be applied in the high temperature supercritical carbon dioxide heat pump. Therefore, a sCO2 heat pump-sCO2 power cycle Carnot Battery layout is possible.

An important consideration in this Carnot Battery concept is the cost issue. It is important to evaluate the leveled cost of storage (LCOS) value considering the costs of charging and discharging stages as well as heat storage. Economic Carnot Battery will survive in the future large-scale capacity ESS market because it will utilize surplus or cheap electricity in the off-peak time and then generate electricity in the peak time. Therefore, LCOS of Carnot Battery is a key factor for electricity time shift in the electricity grid. Since this value is determined by the hot/cold operating temperature of the cycle, the cycle working fluid, the heat storage system and the cycle layout, the optimal cycle design to minimize the LCOS value is a major technical issue. [3]

3. Research Trends

The Carnot Battery which utilize the heat pump and the heat engine for large-capacity ESS have been studied recently, and now preliminary feasibility studies were started by governments and global power system companies.

In terms of the heat pump, a supercritical or transcritical carbon dioxide heat pumps were considered by GE and ABB.

GE investigated a hybrid type of Carnot Battery using the electric heater and the supercritical carbon dioxide heat pump cycle as a part of power-to-heat unit as shown in Fig.3. Since this configuration utilize the conventional steam power cycle in the heat-to-power part that turbine inlet temperature of near 500℃, the

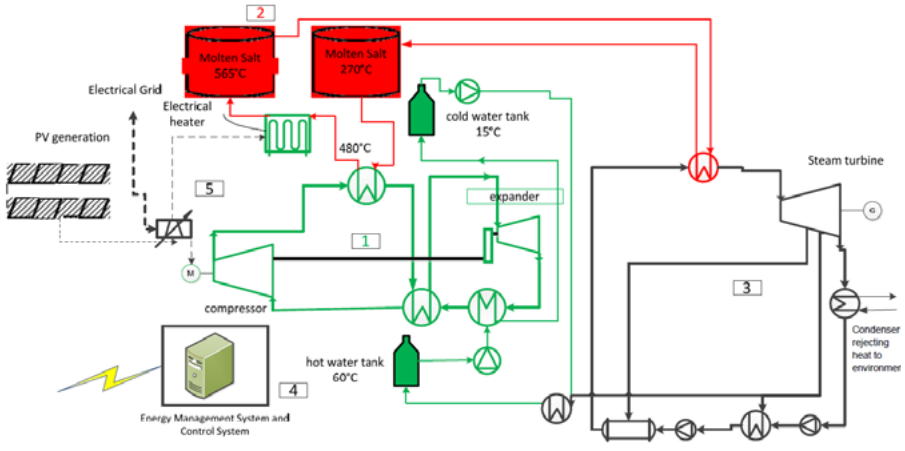


Fig. 3. GE's Carnot Battery concept using a supercritical carbon dioxide heat pump [4]

molten salt is used as a high temperature heat storage like CSP application. The molten salt storage uses

sensible heat transfer between about 250-550°C, a supercritical carbon dioxide heat pump in attractive because heat exchange profile is well matched with a sensible heat application. Also, natural refrigerants have to be used in such high temperature application of the heat pump. However, there is no high temperature supercritical carbon dioxide heat pump in these days yet, so GE suggest additional electric heater for power-to-heat purpose reducing development risk of a high temperature of supercritical carbon dioxide heat pump. [4]

ABB investigated the carbon dioxide heat pump in the Carnot Battery, however, a Transcritical carbon dioxide heat pump and a Transcritical carbon dioxide power cycle are configured as shown in Fig.4. Since, about 120°C temperature of carbon dioxide heat pump is conventional technology, all commercially available thermodynamic systems are easily configured in this Carnot Battery concept. A -2°C ice storage is used for low temperature storage. The RTE of commercial scale this Carnot Battery is evaluated up to 65% from their calculation, however, a carbon dioxide expander, a compressor and a turbine have to be developed sophisticatedly for commercialization. [5]

Recently, preliminary pilot plant scale Carnot Battery system have being constructed in Germany by Siemens. A rock is used as a high temperature heat storage, an electric heater is used for power-to-heat unit and a conventional steam power cycle is used for heat-to-power. It has lower RTE because it uses an electric heater than a heat pump, however, it is very cheap and simple so that LCOS is favourable.

US DOE have started feasibility concept studies for various Carnot Battery system layouts. NREL is investigating an electric heater – sand – gas turbine combined cycle, Brayton Energy is investigating a molten salt-gas Brayton cycle concept and Echogen is investigating concept using a supercritical carbon dioxide power cycle. [6]

DLR in Germany, has started a project for the Carnot Battery technology focusing on the power plant retrofit. Since, a coal-fired or a nuclear power plant have a steam power block so the Carnot Battery configuration would be easily constructed by substituting a boiler or a nuclear steam generator to a heat pump or an electric heater. [7]

A project called Malta, which is being promoted as a future technology by Google (Google Project X), is a Laughlin-Brayton Carnot Battery that stores electricity in the form of thermal energy in molten salt and discharges it into the power generation cycle. The company is developing the Brayton cycle and has designed the turbomachinery required for the system. [8]

4. Supercritical Carbon Dioxide Power Cycle (sCO2) in KIER

In these Carnot Battery concepts, a supercritical carbon dioxide power cycle (sCO2) is an attractive option for both medium-high and low temperature of hot storage source. In addition, small foot print of the sCO2 system due to high pressure operating condition makes Carnot Battery to be compact and modular design. Dry-cooling is also important advantage of the sCO2 because lots of PV complex would be constructed inland area.

Korea Institute of Energy Research (KIER) has developed a fundamental sCO2 test loop from 2013, now, KIER is operating a kWe-class and a tens of kWe-class sCO2 experimental test loops and is commissioning the final hundreds of kWe-class test loop. In this paper, brief descriptions of our test loops are presented.

(1) kWe-class, 500°C turbine inlet temperature (TIT), Transcritical test loop, Radial turbo-generator
(2) tens of kWe-class, 200°C turbine inlet temperature, Transcritical test loop, Axial turbo-generator
(3) hundreds of kWe-class, 500°C turbine inlet temperature, Dual Brayton test loop, 2 Axial turbo-generators, Centrifugal compressor

Figure 5 and 6 show a kWe-class for 500°C TIT(turbine inlet temperature) radial turbo-generator, a tens of kWe-class for 200°C TIT axial turbo-generator its test loops with operational results respectively.

Both test loops were developed as a transcritical cycle by using a liquid carbon dioxide pump for focusing on the developing a turbo-generator driven by a supercritical carbon dioxide, investigating cycle characteristics and developing operation and control strategy of sCO2 cycle.

In case of small kWe-class turbo-generator, a radial type of turbine was designed with a 10% of partial admission nozzle to reduce rotational speed of the rotor. Designed rotational speed was a 120,000 RPM. An angular contact ball bearing lubricated by oil mist was installed to support both radial and thrust force of the rotor due to high operating condition of the sCO2 turbomachinery. Designed capacity of the turbine was a 4.5 kW without mechanical loss.

The main components of the test loop are two pumps, a turbo-generator, two immersion type of electric heaters, a printed circuit heat exchanger (PCHE), a recuperator, a settling chamber, a chiller, and pressure vessels. The two pumps pressurized liquid CO2 into supercritical state. The supercritical CO2 flows through

the recuperator and is heated by the residual heat of turbine outlet flow. In the two electric heater, CO2 is more heated until the turbine inlet condition is reached and then, its flow characteristic becomes uniform at the settling chamber. Next, the heated sCO2 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 CO2 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 CO2 into liquid and gas because pump can pressurize the liquid CO2 only. A reservoir and an inventory are used to control the filling amount of CO2 in the test loop.

In 2017, power generating operation was successful, a 287 We of electricity was obtained at TIT of 401℃. There were rotordynamics issues induced by high axial force at high temperature and high rotating speed condition. After modification, a 30 minutes of continuous power generating results were obtained over 300℃ of TIT condition.

Through this very small sCO2 test loop, basic characteristics of closed sCO2 cycle were investigated. In particular operation strategy of sCO2 cycle was developed including inventory control to fine proper mass flow rate of working fluid. [9]

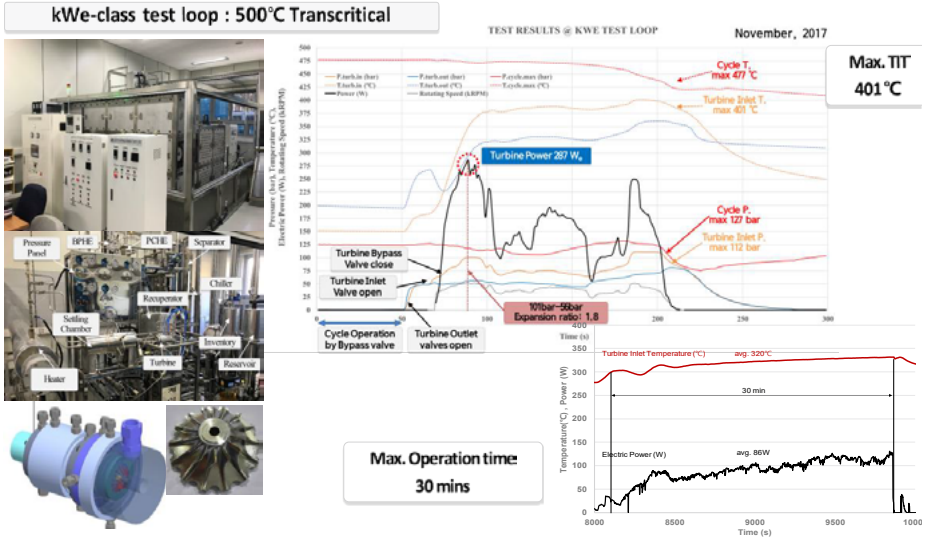


Fig. 5. 500℃ kWe-class radial turbo-generator and Transcritical test loop with operation results

Figure 6 shows a tens of kWe-class for 200℃ TIT axial turbo-generator and its test loop. The axial turbo-generator was actually designed for 392℃ TIT condition for KIER's final target test loop. Before constructing whole test loop, the low temperature turbine was firstly fabricated and was tested under off-design condition by using existing test facilities. In this approach, 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 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.

In order to develop a step-by-step, systematic technology, a transcritical 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. 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. 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

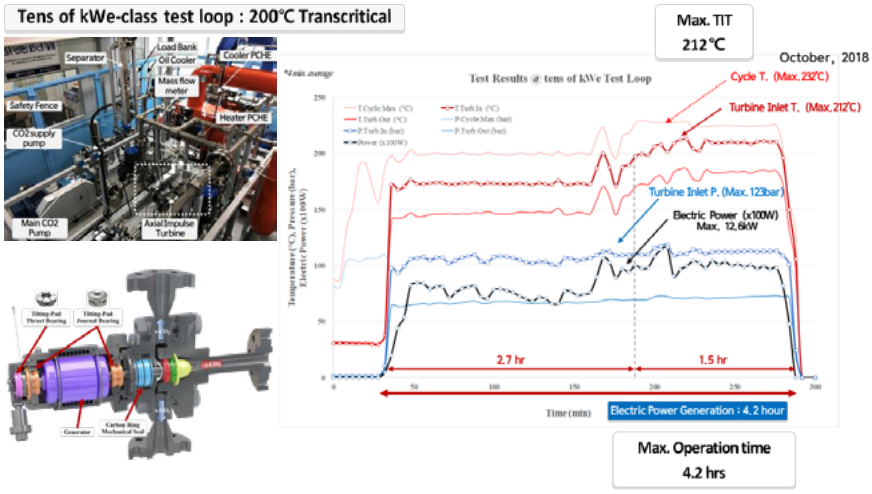


Fig. 6. 200℃ tens of kWe-class axial turbo-generator and Transcritical test loop with operation results

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.

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. 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.

In 2018, a 4.2 hours continuous electricity generating operation was successful under TIT of 212°C. A robust turbo-generator design, a leakage make-up system and operation strategy leads success of safe operation. [9]

In 2019, a 500°C hundreds of kWe-class two axial turbo-generator and Brayton test loop was commissioning. In this test loop, 650°C, 1.75 MWth burner was developed for heat source and a shell-and-finned-tube type heat exchanger was also fabricated for heating a 135 bar of supercritical carbon dioxide. In addition, for Brayton cycle, a centrifugal supercritical carbon dioxide compressor was developed and fabricated. A compressor was driven by high-speed motor connected with a coupling. A design rotating speed of the compressor was 70,000 RPM. In this compressor, in order to reduce leakage flow, a dry gas seal (DGS) was fabricated in the rotor. In addition, in order to supply dried carbon dioxide into seal face, an additional DGS supply control system consists of a booster, a heater and so on was developed.

Two axial turbo-generator for 500°C and 392°C of TIT were developed for this test loop. As described above, the second low temperature turbo-generator for 392°C already fabricated and tested in the previous tens of kWe-class transcritical test loop. In this final test loop, new 500°C of TIT axial turbo-generator was developed which is composed of an oil-lubricated tilting pad journal and thrust bearing that operates at 70,000 RPM. In this turbo-generator, a balancing piston which is driven 6 bar of compressed air was fabricated to reduce axial force on the rotor. By controlling a pressure of supply air, semi-active axial force balancing is possible.

Two PCHEs were fabricated for recuperators and one PCHE was fabricated for a cooler. Since there are leakages from two turbo-generator and one compressor, one leakage recompressing system was developed in the loop, and a 600 L of inventory tank was fabricated for supplying carbon dioxide corresponding to leakage. All piping were constructed as ASME standard. All test loop was assembled. Now commissioning progress is conducted. After investigating these core components of supercritical carbon dioxide power cycle, a part of preliminary Carnot Battery system would be constructed and tested in the future.

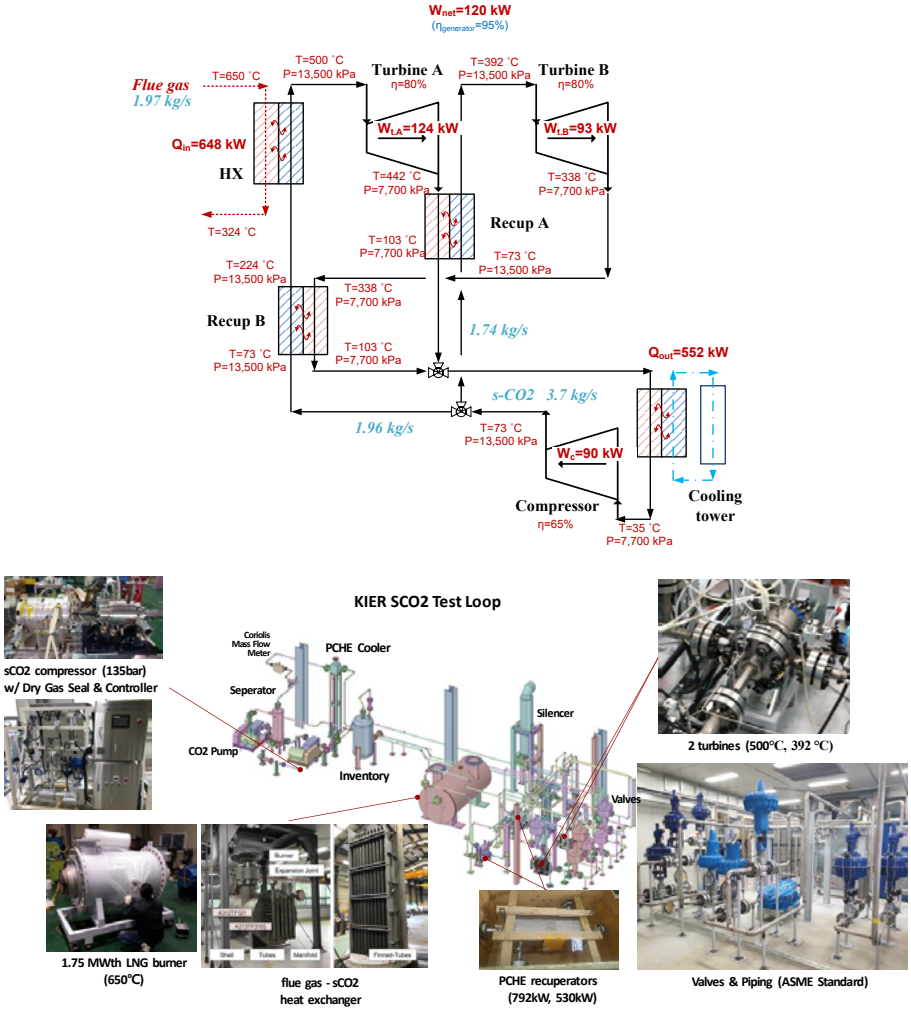


Fig.7. 500℃ hundreds of kWe-class two axial turbo-generator and Brayton test loop

5. Summary and Future Works

There are several layout options for the Carnot battery as a hot storage temperature. A conventional gas turbine combined cycle and a conventional steam turbine cycle can be utilized. In addition, a supercritical carbon dioxide power cycle is an attractive option in the Carnot battery concept due to its advantages. KIER has been developed sCO2 power cycle technology for future power generation system. Various capacities of sCO2 turbomachinery and test loops have been developed and operated as shown in this paper.

Therefore, KIER is now considering sCO2-Carnot Battery concept utilizing our sCO2 technology. Further studies on cycle layouts, economics and development of a small-scale test loop of the Carnot battery would be done as a next step.

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