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Operation Test of the Supercritical CO_2 Compressor Supported with Active Magnetic Bearing

Jae Eun Cha[a*], Seong Kuk Cho[b], Jeong IK Lee[b]
[a] *Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, Republic of Korea*
[b] *Dept. of Nuclear & Quantum Engineering, KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[*] *Corresponding author: jecha@kaeri.re.kr*

1. Introduction

The Supercritical CO_2 Brayton cycle power generation system has the potential as one of the future power conversion systems. The principal advantages of the sCO_2 Cycle are high efficiency at moderate temperature range, compact components size, simple cycle configuration, and compatibility with various heat sources[1]. The Supercritical CO_2 Brayton Cycle Integral Experiment Loop (SCIEL) has been installed in Korea Atomic Energy Research Institute (KAERI) to develop the element technologies for the sCO_2 cycle power generation system. The operation of the SCIEL has mainly focused on sCO_2 compressor development and establishing sCO_2 system control logic.

The installation of the SCIEL low compression loop was finished in December 2014 and research team succeeded in generating electric power on the supercritical state of the CO_2 in May 2015. In the SCIEL Loop, there are one sCO_2 compressor and one sCO_2 turbine supported with gas foil bearings. KAERI has also developed the sCO_2 Compressor supported with Active Magnetic Bearing to enhance the rotor rotation force since July 2015[3]. In this paper, the operation test status of the SCIEL sCO_2 AMB Compressor is briefly described.

2. SCIEL and AMB sCO_2 Compressor

2.1 sCO_2 Brayton Cycle

The Gen-IV reactor system can achieve higher cycle efficiency than the Pressurized Water Reactor since the core outlet temperature is higher than that of the steam Rankine cycle. The development of sCO_2 Brayton cycle technology was started to combine experiences and advantages from the gas turbine technology and steam Rankine cycle technology to fully utilize Gen-IV reactor potential. The principal advantages of the sCO_2 cycle are high efficiency at moderate temperature in the range of 450~700°C, compact component size, and simple cycle configuration.

Despite of these advantages, sCO_2 Brayton cycle has technical challenges on handling dramatic change in thermodynamic properties near the critical point, operation experience, system control logic development, and material data base. If its technologies mature enough for stable operation, high economic advantages can be expected from applying the sCO_2 Brayton cycle to the Gen-IV reactor[1].

KAERI has designed and constructed an integral test loop named as Supercritical CO_2 Brayton Cycle Integral Experiment Loop (SCIEL).

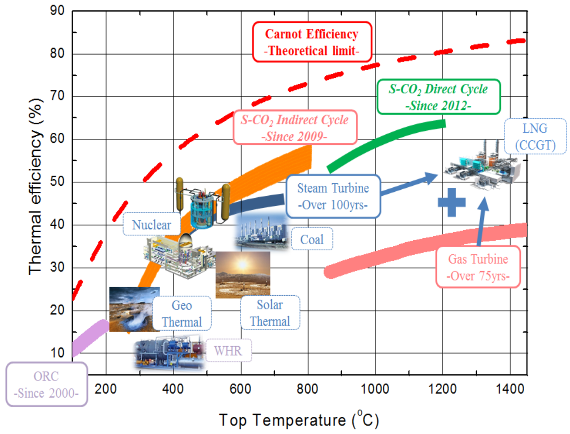

Fig. 1. Efficiency of Various Power Cycles

2.2 SCIEL Facility

To provide the fundamental data and develop key technologies about system operation for the plant grade sCO_2 Brayton cycle demonstration, KAERI developed 300kWe sCO_2 Test Loop SCIEL with KAIST and POSTECH. The main design parameters and layout are summarized in Table 1 and Fig. 2, respectively.

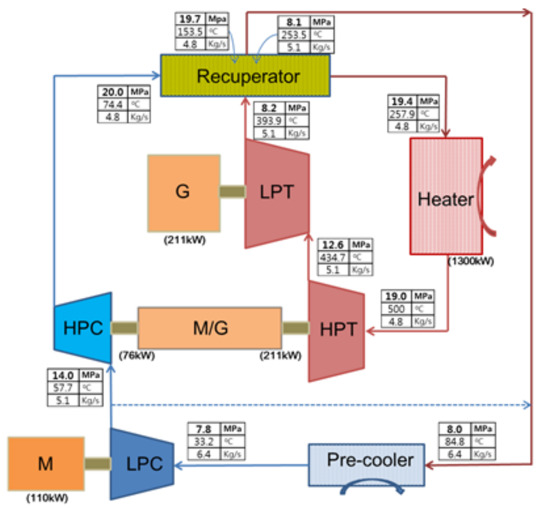

Fig. 2. Cycle layout of the SCIEL Loop

Table 1. The main design parameters of SCIEL

TIT	500℃	Cycle layout	Recuperated
COP	20MPa	Target CIT	33.2℃
CIP	7.78MPa	Recuperator effectiveness	85%
Turbine efficiency	85%	Heater / Pre-cooler ΔP	400kPa /200kPa
Compressor efficiency	65%	Recuperator HS / CS ΔP	300kPa /100kPa

As the design pressure ratio is set higher than the existing S-CO_2 integral system loops, such as Sandia National Lab (SNL), Bettis Atomic Power Lab (BAPL), the two-stage of compression and expansion process is considered to reduce the design rotation rate of the turbomachineries. By utilizing the low pressure compressor (LPC) and the low pressure turbine (LPT), the loop test of simple Brayton cycle could be performed. For the high pressure ratio operation, the high pressure compressor (HPC) and the high pressure turbine (HPT) should be added to simple Brayton cycle as Turbo-Alternator-Compressor (TAC) type. Thus, integral experiment loop adopts the stepwise upgrade plan in order to develop element technologies and conduct various experiments. As the compressor and turbine are not mechanically connected on the one shaft, they can operate separately at different rotating speed.

Twin and shrouded impeller concept was innovatively introduced to control an axial thrust load in the compressor which is the key technology for stable operation of sCO_2 compressor. The concept of shrouded impeller can fundamentally resolve the axial thrust balancing issue by canceling out the pressure difference of the front and back surface of the compressor wheel. Also, the shrouded impeller has a benefit to reduce the clearance loss of impeller[2].

The electricity generation test of sCO_2 closed Brayton cycle was also conducted at compressor inlet condition at around 7.5MPa and 32℃, which is considered as a supercritical state of the CO_2, and compressor shaft speed 24,500RPM. The power generation was performed in the low turbine inlet temperature region since the compressor supporting force should be enhanced. Research team succeeded in generating electric power around 1.2kW on the supercritical state in May 2015.

2.3 Active Magnetic Bearing

The original sCO_2 compressor of the SCIEL has gas foil bearings to support a rotor which drives twin impellers at both sides. In case of gas foil bearing, there is some instability at the clearance between rotor and bearing due to high Reynolds turbulent flow of the sCO_2 inherent high density property. Instead of gas foil bearing, Active Magnetic Bearing technology is adopted to control the supporting force of rotor. AMB controls rotor position with the electromagnetic force and gap sensor signal. The advantage of AMB is non-contact lubrication free, and low vibration. Thus, we are expecting to operate at higher rotation rate.

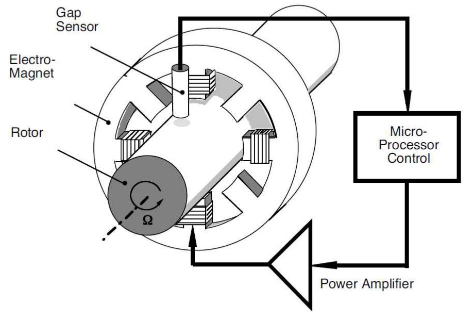

Fig. 3. Schematics of AMB rotor control

Table 2. Design Value of AMB sCO_2 Compressor

Rotation rate [RPM]	70,000	
Rotor mass [kg]	11	
Radial	Static load [N]	108
	Unbalance mass [g-mm]	3.75
	Omega square [(rad/s)^2]	53,734,512
	Dynamic load [N]	201.51
	Bearing load [N]	309.5

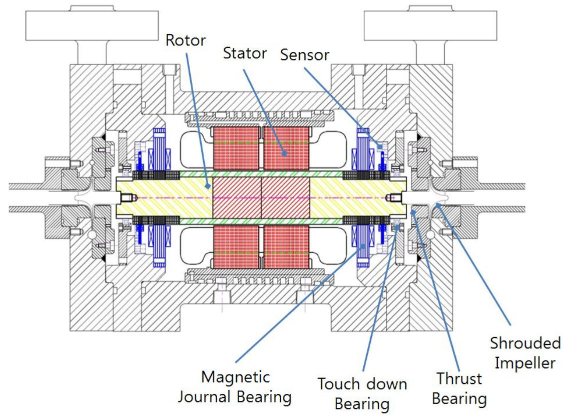

Fig. 4. Schematics of SCIEL sCO_2 AMB-Compressor

2.4 AMB sCO_2 Compressor

The objective of sCO_2 AMB turbomachinery development is to obtain the high rotation bearing technology in the supercritical fluid for the high temperature environment at around 300^{o}C. Fig. 4 shows sCO_2 AMB compressor assembly, which includes gas foil trust bearing, AMB journal bearing, sensor, and touch down bearing. In case of thrust bearing, its performance was already confirmed from the previous operation test of the SCIEL compressor. Thus, we only focused on the AMB journal bearing design by the modification of the previous sCO_2 compressor supported with gas foil bearings. Fig.5 shows major components of the AMB sCO_2 compressor. Touch down bearing is inserted to protect the rotor assembly and AMB journal bearings at sudden loss of the AMB supporting force.

Fig. 5 shows the rotor assembly, position detecting sensor, and AMB magnet assembly for the sCO_2 AMB compressor. Rotor is composed of the permanent magnet SmCo and lamination of Silicon coated plates, and outer shell Inconel pipe to protect inside magnet. At both sides of the rotor, there are smaller diameter sites to install the touch down bearing. AMB AC magnet has a total of eight poles. The critical speed of the rotor is designed at around 107,000rpm, and normal operation is permitted lower than 70,000rpm.

Fig.6 shows the AMB control system which consists of DC power supply, signal amplifier, and AMB controller.

Fig. 7 shows the SCIEL loop installation of the sCO_2 AMB compressor. Water cooling line is connected to remove the compressor stator heat and sCO_2 bypass line is connected to emit the windage heat dissipation between rotor and stator or between rotor and bearing.

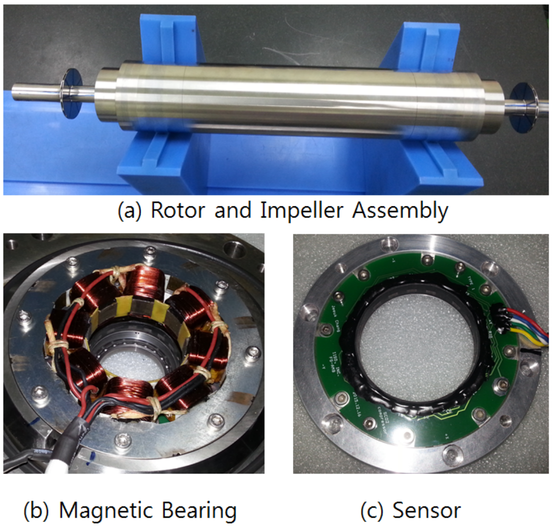

Fig. 5. Major Components of the SCIEL sCO_2 AMB-Compressor

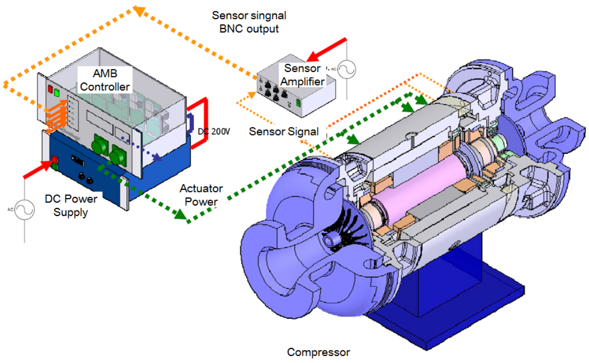

Fig. 6. AMB Control system of the SCIEL sCO_2 AMB-Compressor

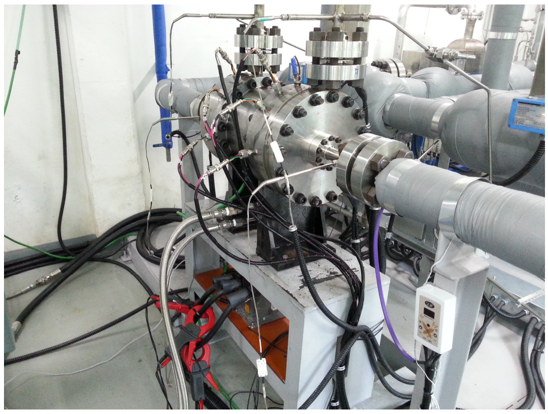

Fig. 7. Installation of SCIEL sCO_2 AMB-Compressor

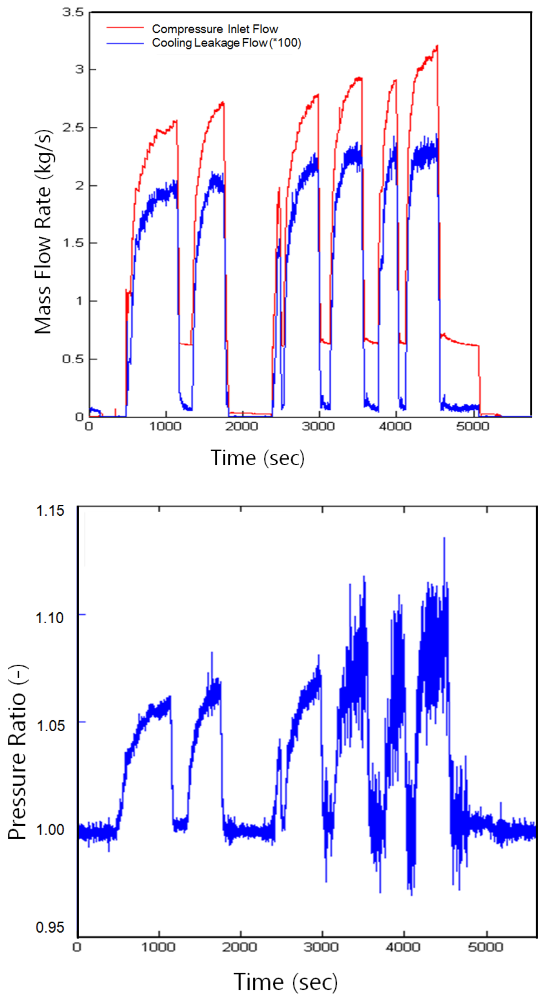

Fig. 8. Measured Mass Flow Rate and Pressure of the SCIEL sCO_2 AMB-Compressor

Fig. 8 shows the measured mass flow rate history and pressure ratio variation with changing compressor rotational speed. The blue line and the red line depict the compressor leakage flow after passing seal and the mass flow rate of compressor inlet, respectively. The leakage flow increases with the compressor mass flow rate and is about 0.8 % percent of the compressor mass flow rate in normal experimental conditions. The maximum compressor rotational speed achieved 40,000 rpm under the supercritical environment. Also, as shown in Fig. 8, the mass flow rate and the pressure ratio reached at 3.3 kg/s, and 1.12, respectively. For the full power operation, it is necessary to improve the control methodology of AMB compressor and also enhance the magnetic force.

3. Summary

The SCIEL has been built in KAERI to develop the element technologies and the system control logics for the sCO_2 cycle power conversion unit of the next generation reactor. For the stable operation of the sCO_2 compressor under high rotational speed, the AMB sCO_2 compressor was developed and achieved the maximum 40,000 rpm.

As further works, the turbomachinery performance test under off design operating conditions and power generation test with AMB compressor will be conducted within second half year of 2016 under supercritical state.

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[3] J. E. Cha, et al., “Supercritical CO_2 Compressor with Active Magnetic Bearing”, Korean Nuclear Society Spring Meeting, Jeju, Korea, May 12-13, 2016.