Operation Results of a Closed Supercritical CO_2 Simple Brayton Cycle

Jae Eun Cha
Senior Researcher
Korea Atomic Energy Research Institute
Daejeon, Korea
jecha@kaeri.re.kr

Seong Won Bae
Senior Researcher
Korea Atomic Energy Research Institute
Daejeon, Korea
bswon@kaeri.re.kr

Jekyoung Lee
PhD Student
Korea Advanced Institute of Science and Technology
Daejeon, Korea
leejaeky85@kaist.ac.kr

Seong Kuk Cho
Master Student
Korea Advanced Institute of Science and Technology
Daejeon, Korea
skcho89@kaist.ac.kr

Jeong Ik Lee
Associate Professor
Korea Advanced Institute of Science and Technology
Daejeon, Korea
jeongiklee@kaist.ac.kr

Joo Hyun Park
Master Student
Pohang University of Science and Technology
Pohang, Korea
jhpark0425@postech.ac.kr

Dr. Jae Eun Cha is a Senior Researcher in Thermal Hydraulics Division at Korea Atomic Energy Research Institute. He received his PhD degree with the Liquid metal two-phase flow measurement under magnetic field from the Pohang University of Science and Technology. Dr. Cha's research interests include liquid metal flow measurement, thermal hydraulic experiment, reactor thermal flow similarity experiment. Currently, he has led the research on the development of S-CO_2 power generation system.

ABSTRACT

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

The installation of the 2nd phase of SCIEL loop was finished and research team succeeded in generating electric power on the state of the S-CO_2 in last year. Research on control logics of the S-CO_2 power turbine has been carried out from the operation of the 2nd phase of SCIEL facility. This paper

provides the introduction of SCIEL facility, key test results, and the progress of the transient analysis with MARS code.

Introduction

Nuclear power system has been operated using the steam Rankine cycle as the power conversion system for over half a century. It has proven a good thermal efficiency and system reliability. Nevertheless, the necessity of the next generation reactors has been constantly brought up due to these issues, such as global warming, recycling the spent fuel, and enhancing the safety level. Among various suggested candidates, S-CO_2 Brayton cycle is considered as one of a promising future power technology because it has the advantages of competitive thermal efficiency, simple cycle layout, and compact components size [1].

Despite these benefits, some technical issues (e.g. compressor operation near the critical point, high windage loss in rotor cavity, bearing stability, and seal technology) have been reported by published literatures [2]. To demonstrate and accomplish the theoretical S-CO_2 Brayton cycle performance, the integral test loops of S-CO_2 Brayton cycle are absolutely necessary. To develop the element technologies and establish the control logics of S-CO_2 Brayton cycle for the power conversion unit application of the next generation reactors, the S-CO_2 Brayton cycle Integral Experiment Loop (SCIEL) was designed by the joint research team of Korea Atomic Energy Research Institute (KEARI), Korea Advanced Institute of Science and Technology (KAIST), and Pohang University of Science and Technology (POSTECH). The installation of low compression ratio electricity generation loop (SCIEL 2nd phase) was finished and research team succeeded in generating electric power on the state of the S-CO_2 in last year. This paper provides the introduction of SCIEL facility, key test results, and the progress of the transient analysis with MARS code in order to compare the results between the transient system code and the loop test results.

Description of Supercritical CO_2 Integral Experiment Loop (SCIEL)

To provide the fundamental data and develop key technologies about system operation for the Korea national project of 10MWe S-CO_2 Brayton cycle demonstration, KAERI designed 300kWe S-CO_2 Integral Experiment Loop (SCIEL) with KAIST and POSTECH. The main design parameters and layout are summarized in Table 1 and Figure 1, respectively. 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), and Institute of Applied Energy (IAE), the 2-stage of compression and expansion process is considered. By utilizing the low pressure compressor (LPC) and the low pressure turbine (LPT), the loop test of simple Brayton cycle can be carried out. For the high pressure ratio operation, the high pressure compressor (HPC) and the high pressure turbine (HPT) will 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, two turbomachineries operate at different rotating speed.

Currently, S-CO_2 compressor performance test loop (1st phase) and low compression ratio electricity generation loop (2nd phase) facilities was constructed. Figures 2 and 3 depict schematic diagram of low pressure ratio electricity generation loop and the physical configuration of the test loop, respectively. Thermal oil circulation system for heating, an Intermediate Heat Exchanger (IHX), a Low Pressure Turbine (LPT), and a control valve were added to the compressor performance test loop for low compression ratio electricity generation loop. Thus, this loop can conduct compressor performance test as well as integral loop test by adjusting control valve. Whereas the existing S-CO_2 turbomachieries were designed as TAC (Turbo-Alternator-Compressor) configuration, the SCIEL adopts the configuration separated a compressor and a turbine. Specially, twin impeller and shrouded impeller concepts were newly introduced to control an axial thrust load in the compressor which is the key technology for stable operation of S-CO_2 compressor operation. 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. The leakage flow in rotor cavity is merged before passing the pre-cooler.

Table 1. The main design parameters of SCIEL

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

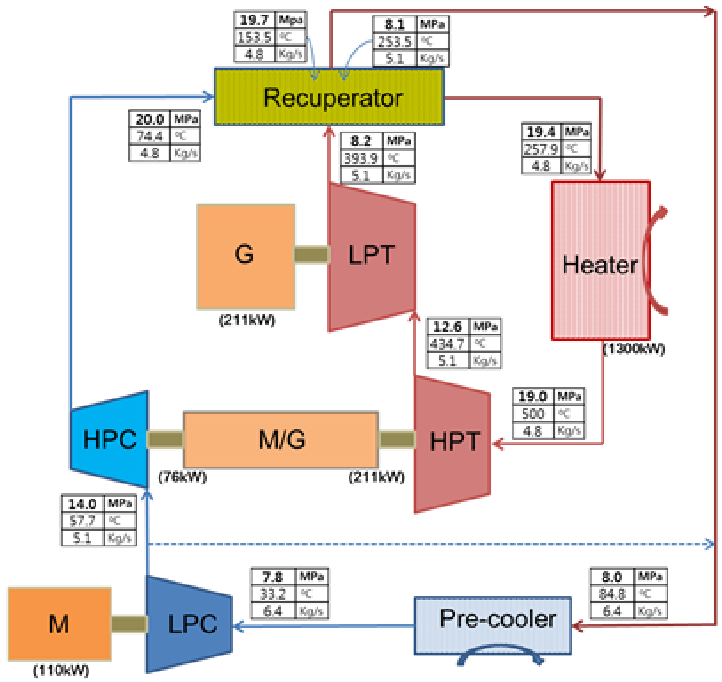

Figure 1. The final cycle layout of SCIEL

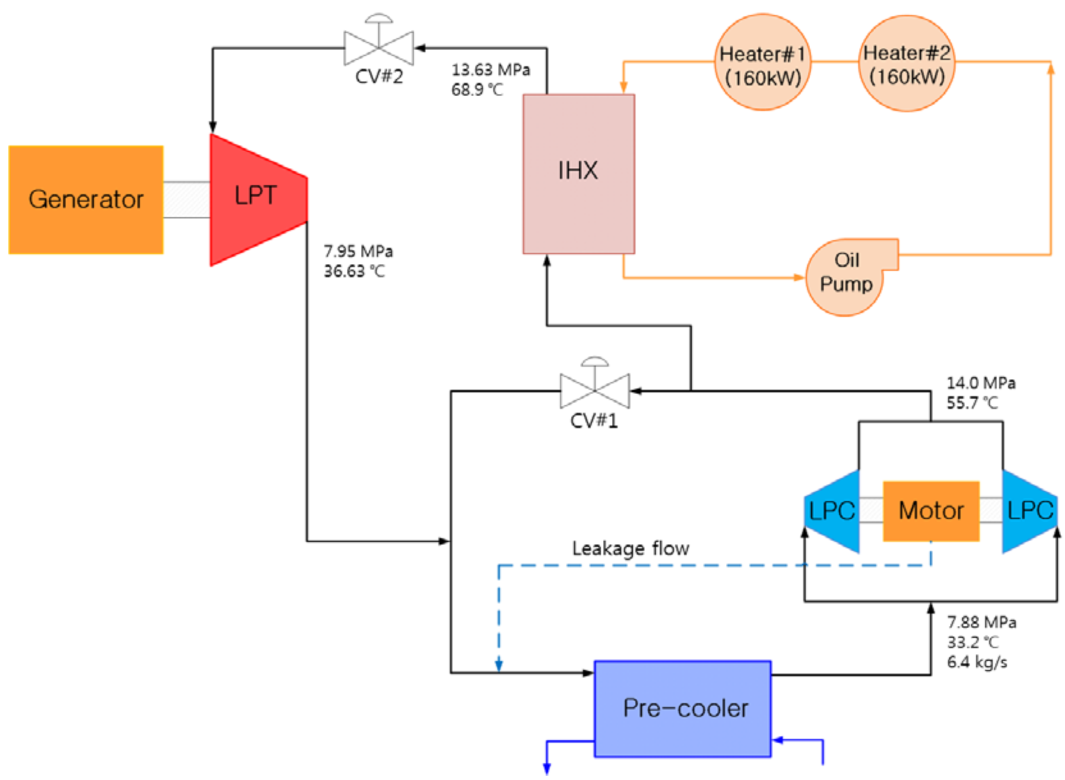

Figure 2. Schematics of low compression ratio electricity generation loop (SCIEL 2nd phase)

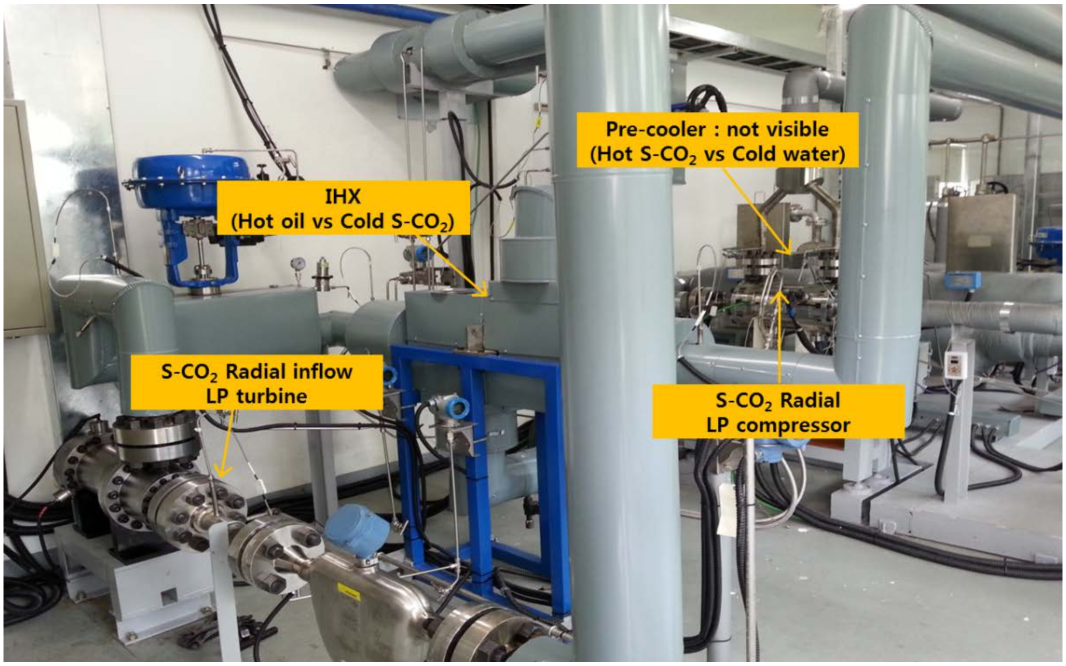

Figure 3. SCIEL components configuration

Compressor and turbine

The LPC in the SCIEL facility accepts the twin shrouded impeller concept which is one of the advanced approach to handle high pressure thrust load. Main design conditions are summarized in Table 2. According to design results with 65% of assumed compressor efficiency, each impeller consumes 50kW at full capacity operation. Shrouded impellers and a compressor assembly are shown in Figure 4.

The LPT, in common with LPC, adopts the shrouded concept. To prevent from turbine overspeed, the generator of turbine is connected with 400kW load bank system whic*h* has several resistors. Due to low pressure ratio, turbine was designed with single stage and subsonic regime. Considering turbine design efficiency and generator conversion efficiency, the maximum power of turbine is 200kW.

Table 2. Main design variables of compressor and turbine

Design Variable	Compressor	Turbine
Total inlet temperature	33 ℃	435 ℃
Total inlet pressure	7,800 kPa	12,500 kPa
Pressure ratio	1.8	1.49
Mass flow rate	3.2 kg/s (each side)	5.05 kg/s
Total to total efficiency	65 %	85 %
Number of vanes	16	14
Shaft speed	70,000 RPM	80,000 RPM

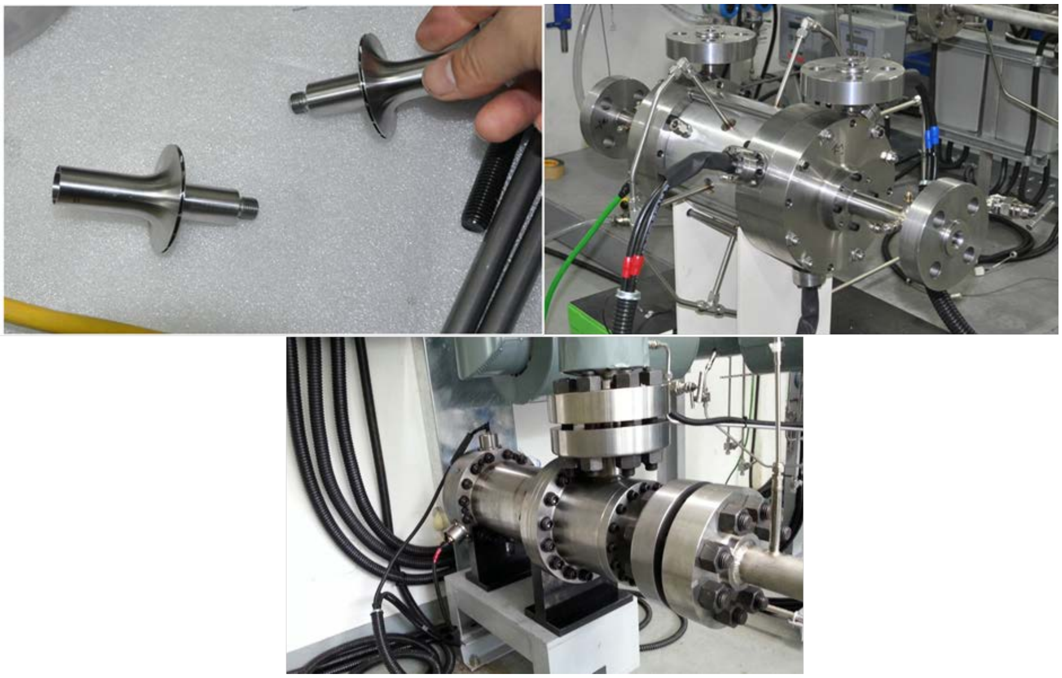

Figure 4. Shrouded impeller (upper left), compressor assembly (upper right), and turbine assembly (bottom)

Operation status

The operation of SCIEL has focused on compressor performance tests and establishing control logics for simple S-CO_2 Brayton cycle operation. By adjusting two control valves, this facility can be operated as the compressor performance test loop which consists of a low pressure compressor and a pre-cooler and the low compression ratio electricity generation loop which is composed of a low pressure compressor, an IHX, a low pressure turbine, and a pre-cooler.

First of all, the compressor performance test was carried out to obtain the compressor performance map near critical point. This was conducted by running the compressor at constant shaft speed and then gradationally closing the control valve. The shaft speed of the compressor reached up to 35,000RPM near critical point. Figure 5 is experimental data of pressure ratios and efficiencies with compressor rotational speed in the range of 25,000RPM to 35,000RPM in the supercritical conditions.

The electricity generation test of S-CO_2 closed Brayton cycle was also conducted at compressor inlet condition, 7.5MPa and 32^{o}C, and compressor shaft speed, 24,500RPM. Because the compressor shaft speed is lower than the designed shaft speed, 70,000RPM, the loop was operated with about 1.3kg/s. The generated current is dissipated in the load bank. Finally, research team succeeded in generating electric power around 1.2kW, on the state of the S-CO_2. Measured values and T-s diagram are represented in Figure 6.

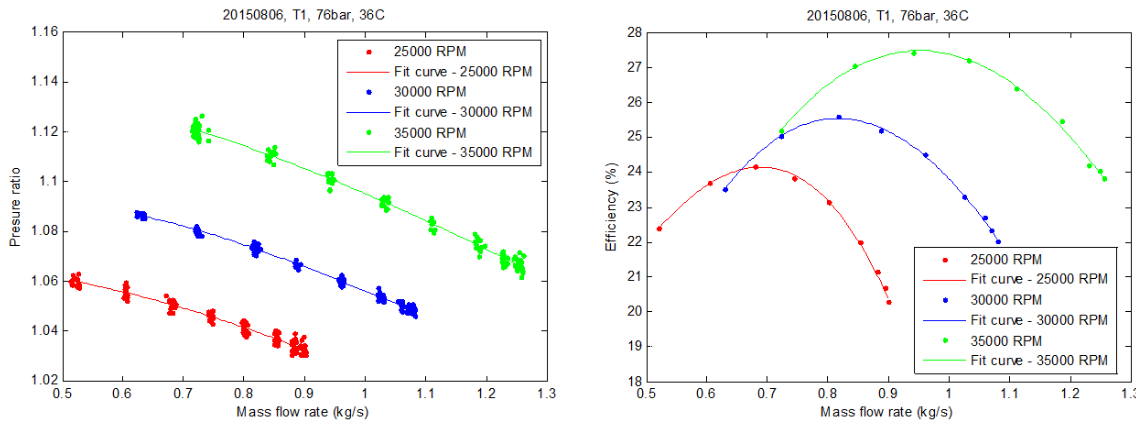

Figure 5. Compressor performance maps with different RPMs

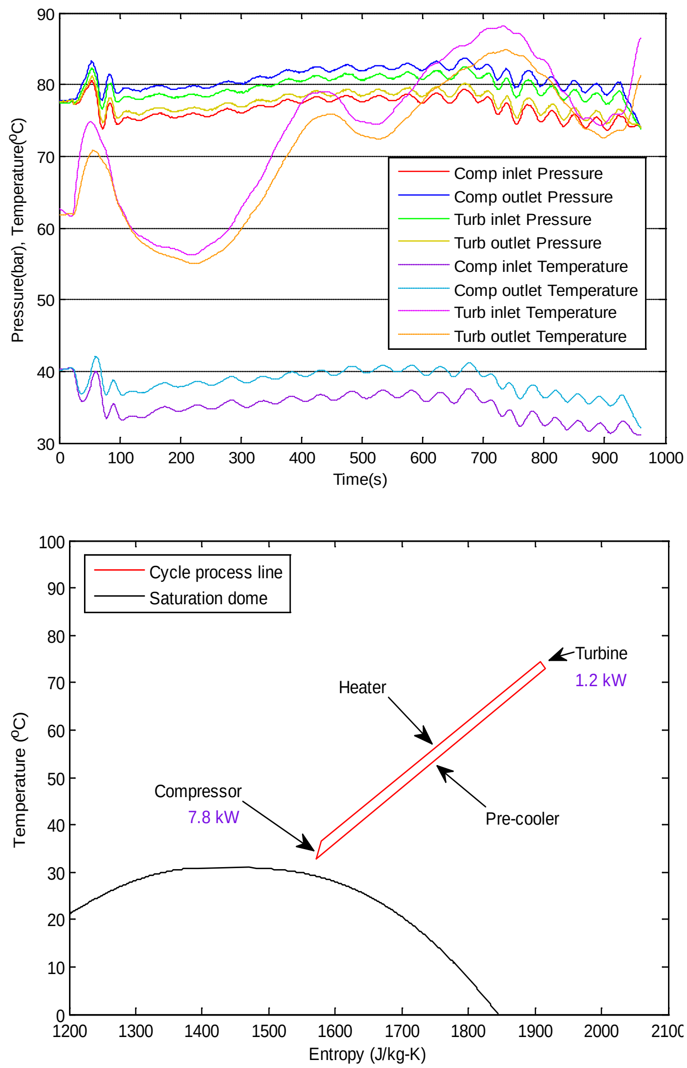

Figure 6. Measured pressure and temperature at compressor and turbine (top) and T-s diagram (bottom)

Transient analysis of SCIEL for Cycle Control Strategy

The cycle operation strategy is one of the significant issues of S-CO_2 Brayton cycle. Up to now, the experience of the operation with the S-CO_2 Brayton cycle is insufficient, so that a study on the S-CO_2 cycle operation strategy is needed to safely operate the system. Through performance of transient analysis of the S-CO_2 Brayton cycle loop, a new cycle control method and an ideal analysis platform should be developed in order to operate and control the S-CO_2 power generation system.

From these requirements, previous studies were performed about transient analysis of S-CO_2 Brayton cycle [3-6]. As a representative study, transient analysis was performed by using the IST plant TRACE model [4]. The Plant Dynamics Code (PDC) has been specifically developed for the analysis of the S-CO_2 cycle and transient analysis was conducted using PDC [5]. As the preceding study, research team has developed the separate analysis model for SCIEL and other cycle loop.

MARS, multi-dimensional thermal-hydraulic system analysis code in Korea, was primarily developed for the safety analysis of light water reactors. MARS was chosen as an analytical tool to analyze the transient characteristics of the S-CO_2 Brayton cycle power generation system in the SCIEL facility. The MARS code was used to analyze the S-CO_2 Brayton Cycle Integral Experiment Loop (SCIEL). And a Visual System Analyzer (ViSA) simulator is used to control of transient analysis and calculation result interpretations [7]. As the first step of the analysis, the node modeling of the SCIEL loop with the MARS code was conducted. Nodalization was completed as shown in Fig.7 to obtain the numerical solutions using MARS. Numerical solutions were obtained from the input file with pump, turbine, pipe, and heat-structure.

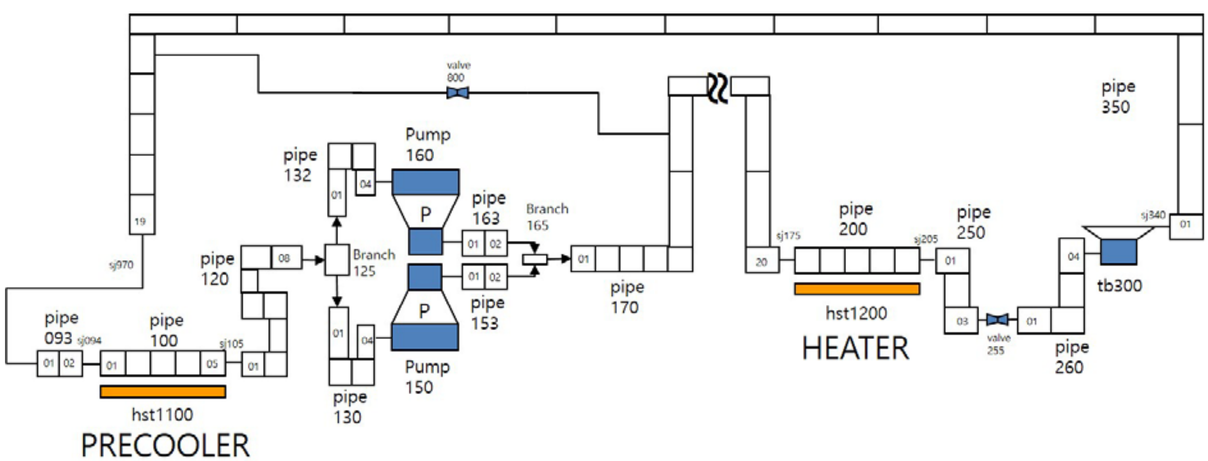

Figure 7. MARS Nodalization of SCIEL

Now, research team completed making a MARS input. System transient analysis based on the input will be performed. As in the transient analysis, there are two points that are normal transient operating conditions and abnormal transient operating conditions. The normal transient analysis is about consecutive power control of decrease and increase state. The abnormal transient analysis is about pipe break condition and unusual operation conditions of each component.

Summaries and further works

To develop the element technologies and establish the control logics of S-CO_2 Brayton cycle for the power conversion unit application of the next generation reactors, the S-CO_2 Brayton cycle Integral Experiment Loop (SCIEL) was designed by the joint research team of KEARI, KAIST, and POSTECH. Currently, the installation of low compression ratio electricity generation loop (SCIEL 2nd phase) was finished and research team succeeded in generating electric power on the state of the S-CO_2. Research on the system transient analysis with MARS has been conducted to develop proper control logics under abnormal operational conditions.

As further works, the compressor performance test in higher speed regions and various inlet conditions will be steadily performed. Also, the evaluation of CO_2 mass inventory necessity, the protection system of turbomachinery, and the location of valves for a bypass will be covered in MARS.

Acknowledgments

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