Operation Results of a Closed Supercritical CO_2 Simple Brayton Cycle

JaeEun Cha*, Seong Won Bae*, Jekyoung Lee**,
Song Kuk Cho**, JeongIk Lee**, Joo Hyun Park***

* Korea Atomic Energy Research Institute
** Korea Advanced Institute of Science and Technology
*** Pohang University of Science and Technology

CONTENTS

Introduction

S-CO_2 Brayton Cycle

- Attractive features of S-CO_2 Brayton Cycle
  - ✓ Small compression work due to characteristic like liquid near critical point and high thermal efficiency at moderate temperature ranges (450~750 ℃)
  - ✓ Small specific volume throughout the whole system due to high pressure and enhanced economics due to compactness
  - ✓ Compatibility with various heat sources (Nuclear, Concentrated Solar Power, Geothermal, Fuel cell and Waste heat recovery)
- Various research organizations are involved
  - ✓ Research institutes : SNL, ANL, Bechtel/KAPL, KAERI, IAE-TIT, KIER, etc.
  - ✓ University : MIT, KAIST, Univ. of Wisconsin Madison
  - ✓ Industries : GE, Dresser-Rand, Barber-Nichols, Echogen, Toshiba, MAN, etc.

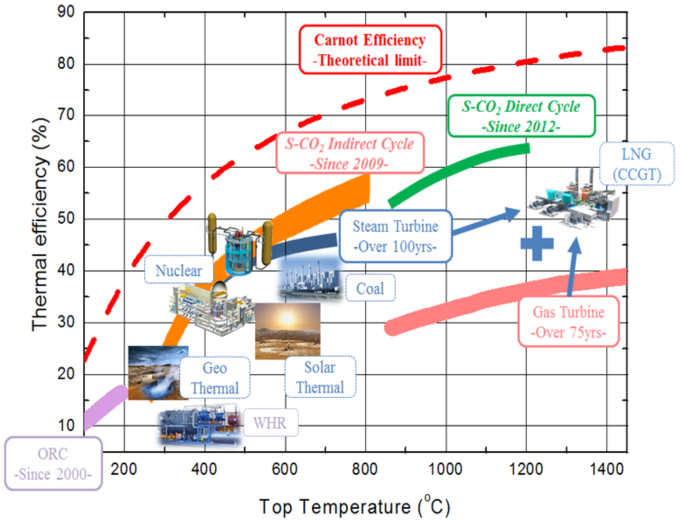


Fig. Comparison various power cycle efficiencies

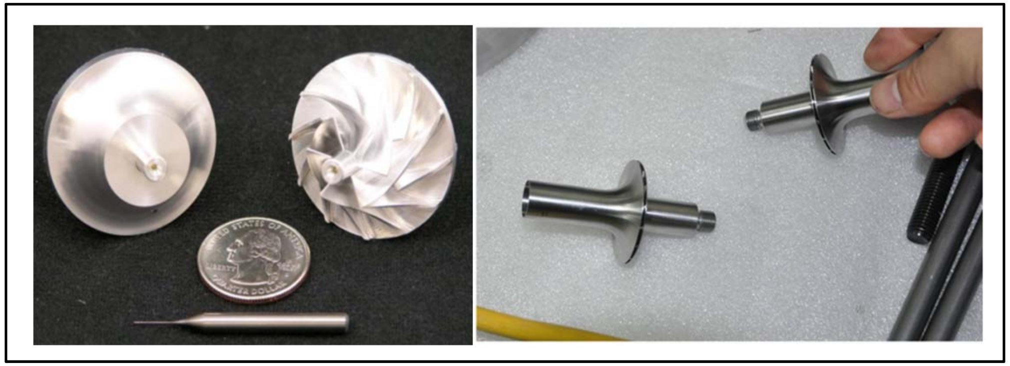


Fig. Impeller sizes for 1MWth facility SNL(left) and KAERI(right) [Wright et al, 2010]

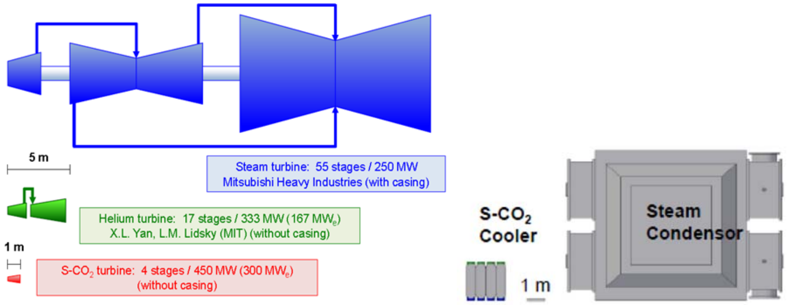


Fig. Comparing size of turbomachineries and heat exchangers [Dostal, 2004]

Introduction

Research objectives

Technological key issues on S-CO_2 Brayton Cycle

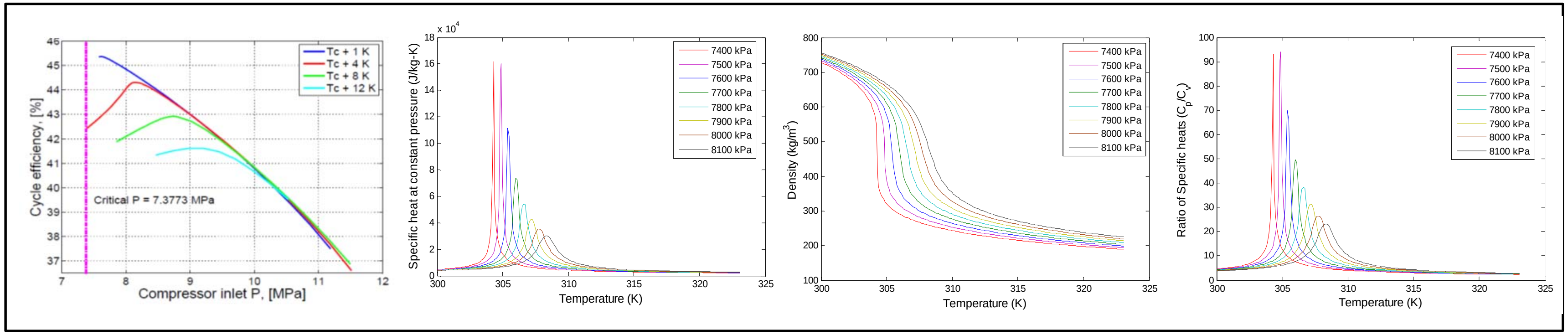


Fig. Thermal efficiency sensitivity analysis on CIT and properties variation of S-CO_2

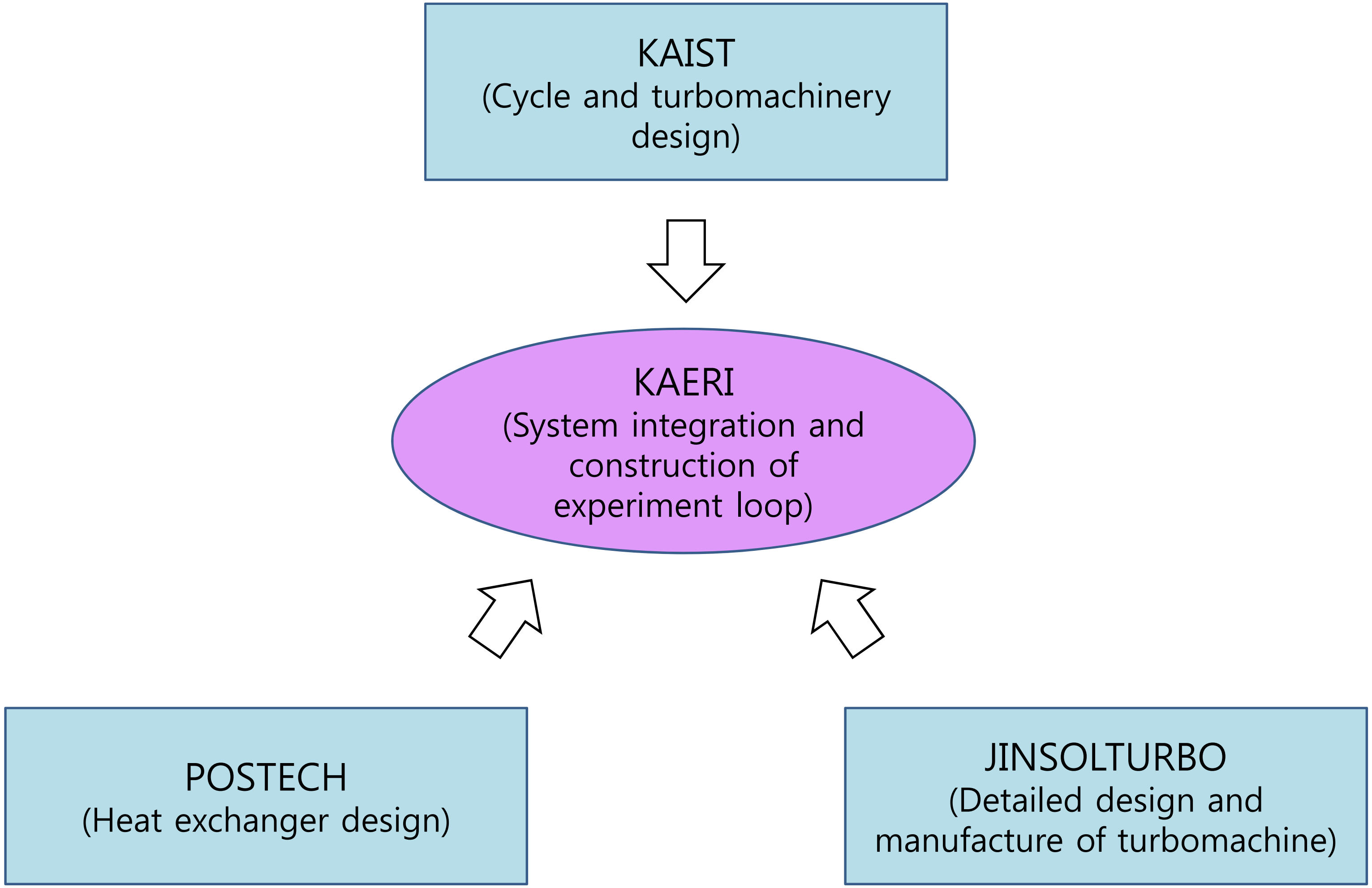
- ✓ Operation in the vicinity of critical point for high thermal efficiency
- ✓ The reliable design difficulty of S-CO_2 compressor owing to its dramatic change of thermodynamic properties near critical point (304.13K, 7377kPa)
- ✓ Manufacture and operating experience of main components (turbomachineries, heat exchangers)
- ✓ Control logics development for Reactor and Power Conversion Unit (PCU)

Goals of S-CO_2 Brayton Cycle Integral Experiment Loop (SCIEL)

- ✓ 300 kW of power generation
- ✓ Verification and accumulation of S-CO_2 turbomachine technology
- ✓ Verification of domestic PCHE technology
- ✓ Development of cycle control logics

Overview of SCIEL

- Research Organization for SCIEL Construction
  - SCIEL : Supercritical CO_2 Integral Experiment Loop



KAIST
(Cycle and turbomachinery design)

KAERI
(System integration and construction of experiment loop)

POSTECH
(Heat exchanger design)

JINSOLTURBO
(Detailed design and manufacture of turbomachine)

Overview of SCIEL

- **Research Organization for SCIEL Construction**
  - **SCIEL : Supercritical CO_2 Integral Experiment Loop**

KAIST
(Cycle and turbomachinery design)

KAERI
(System integration and construction of experiment loop)

POSTECH
(Heat exchanger design)

JINSOLTURBO
(Detailed design and manufacture of turbomachine)

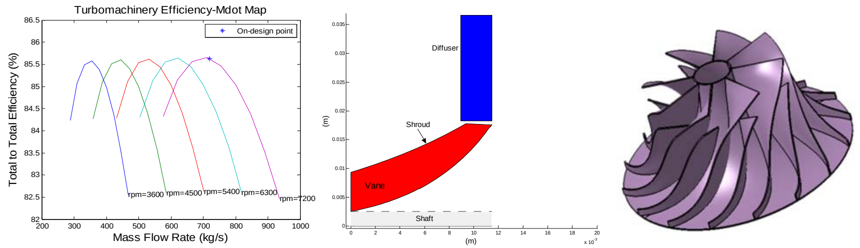
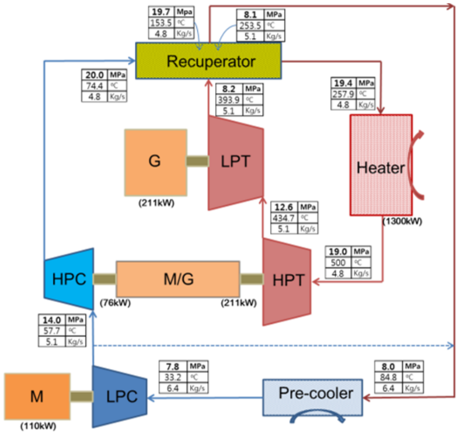
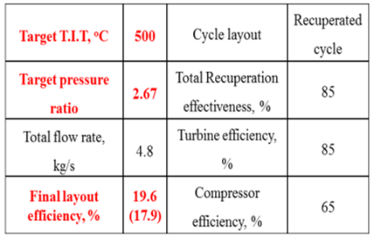


Fig. Turbomachine preliminary design





Target T.I.T, ℃	500	Cycle layout	Recuperated cycle
Target pressure ratio	2.67	Total Recuperation effectiveness, %	85
Total flow rate, kg/s	4.8	Turbine efficiency, %	85
Final layout efficiency, %	19.6 (17.9)	Compressor efficiency, %	65

Fig. S-CO_2 Brayton Cycle design

Overview of SCIEL

- **Research Organization for SCIEL Construction**
  - **SCIEL : Supercritical CO_2 Integral Experiment Loop**

KAIST
(Cycle and turbomachinery design)

KAERI
(System integration and construction of experiment loop)

POSTECH
(Heat exchanger design)

JINSOLTURBO
(Detailed design and manufacture of turbomachine)

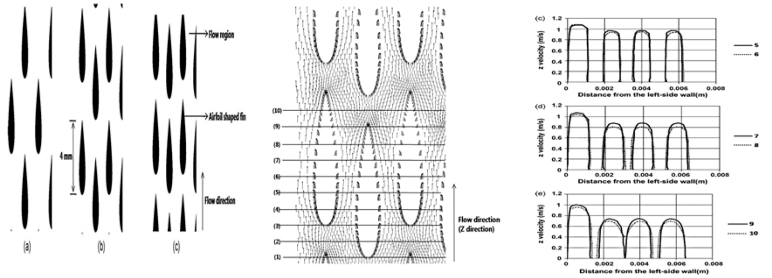


Fig. CFD simulation of airfoil fin PCHE

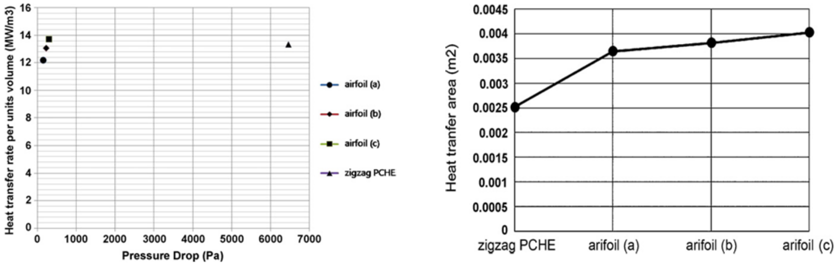


Fig. PCHE performance comparison with airfoil fin PCHE and zigzag channel PCHE

Overview of SCIEL

- **Research Organization for SCIEL Construction**
  - **SCIEL : Supercritical CO_2 Integral Experiment Loop**

KAIST
(Cycle and turbomachinery design)

KAERI
(System integration and construction of experiment loop)

POSTECH
(Heat exchanger design)

JINSOLTURBO
(Detailed design and manufacture of turbomachine)

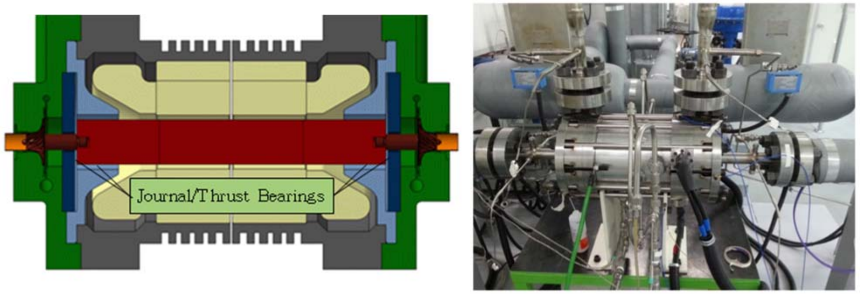


Fig. Double-sided suction S-CO_2 compressor

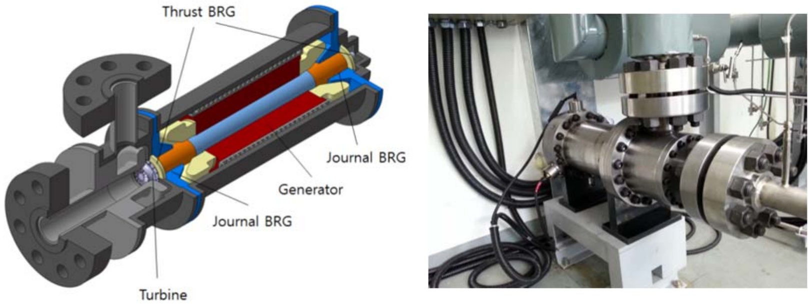
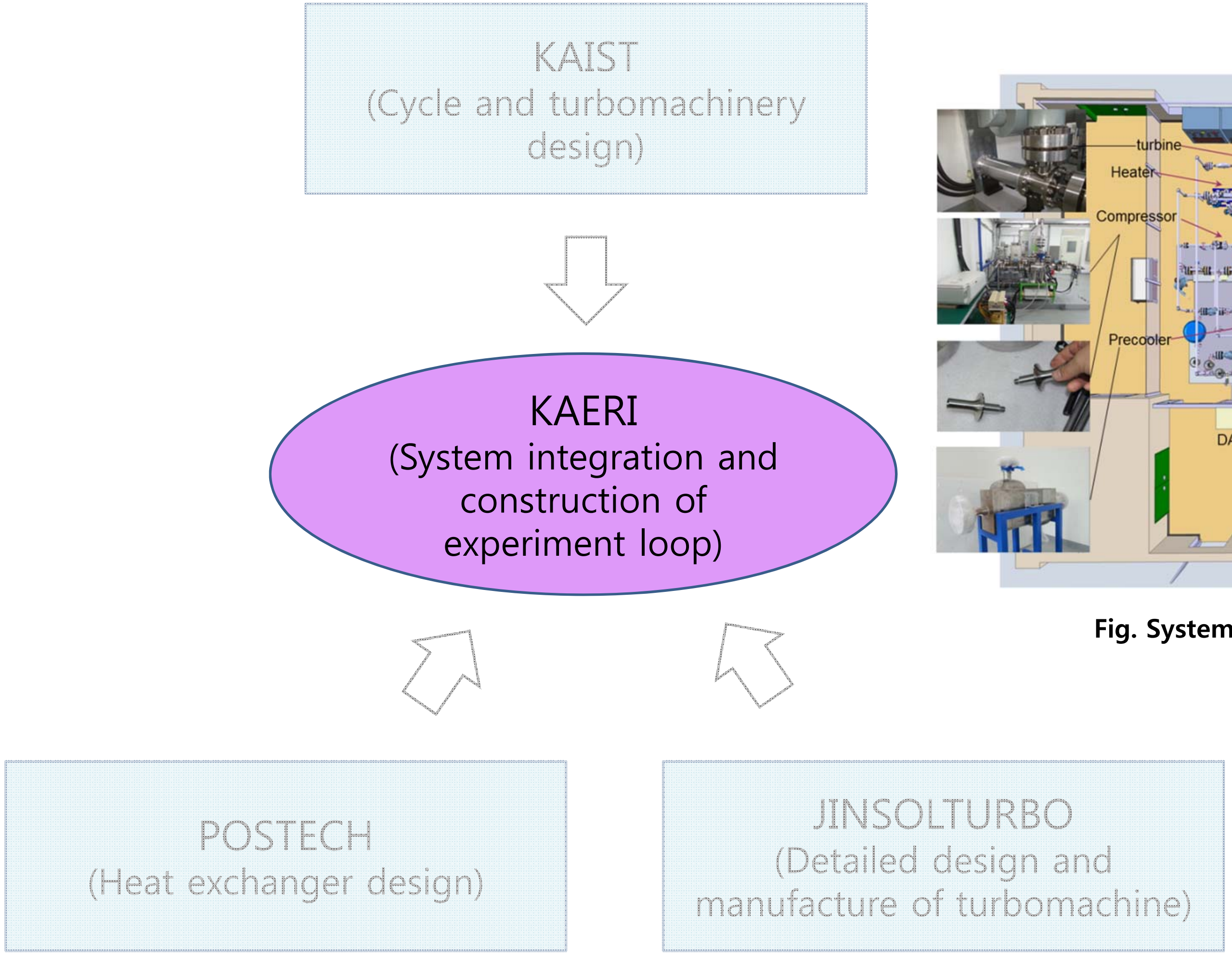


Fig. S-CO_2 turbine and generator

Overview of SCIEL

- **Research Organization for SCIEL Construction**
  - **SCIEL : Supercritical CO_2 Integral Experiment Loop**



KAIST
(Cycle and turbomachinery design)

KAERI
(System integration and construction of experiment loop)

POSTECH
(Heat exchanger design)

JINSOLTURBO
(Detailed design and manufacture of turbomachine)

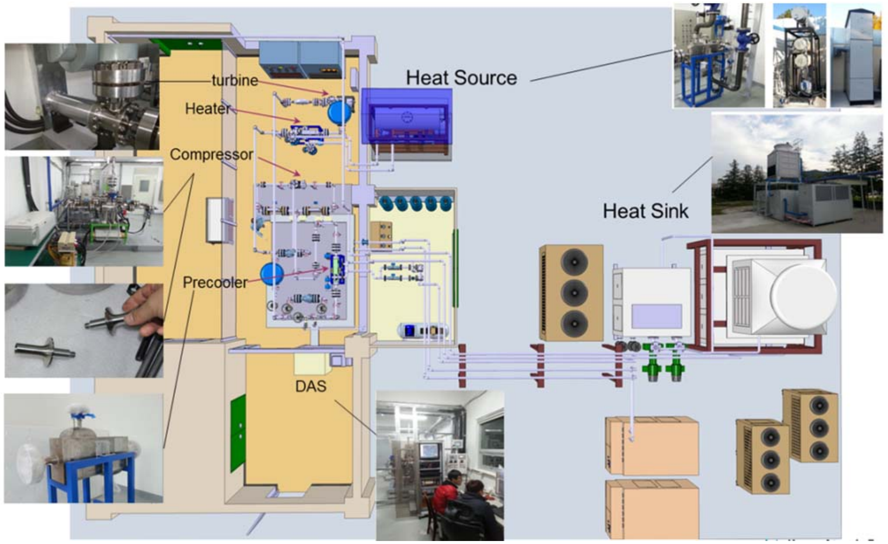


Fig. System integration and SCIEL layout

Overview of SCIEL

- **Phase development strategy**

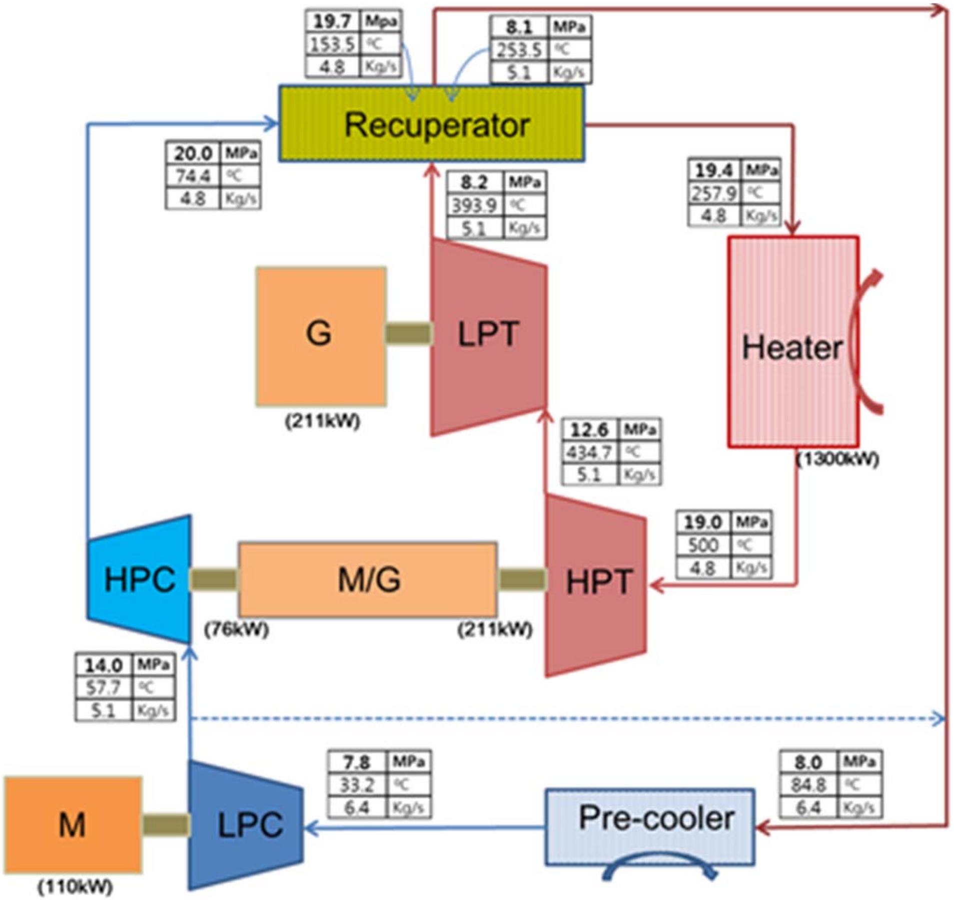


Fig. SCIEL final layout

Phase I :
Compressor Performance Test Loop

↓

Phase II :
Low Compression Ratio Power Generation Loop

↓

Phase III :
Simple Recuperation Cycle Loop

🟦	Completion of Installation
🟥	Further works

Overview of SCIEL

➢ **Accepted concepts**

Item	Concepts
Cycle concept	• Double compression double expansion simple recuperated S-CO$_2$ Brayton cycle • Cycle pressure ratio : 2.6 • Top temperature : 500^{o}C

Compressor	• LPC (Manufactured by JINSOL TURBO)
	    • Shrouded Compressor
	    • Double-sided Suction
	    • No thrust collar
	    • Flow rate : 6.4 kg/s
	    • Pressure Ratio : 1.8
	    • Turbine, Compressor Separate Shaft
	    • Rotation rate : 70,000 rpm
	    • Gas foil bearing
	• HPC
	    • TBD with TAC configuration

Turbine	• LPT (Manufactured by JINSOL TURBO)
	    • Shrouded Turbine
	    • Single-sided suction
	    • Flow rate : 5.1 kg/s
	    • Rotation rate : 80,000rpm
	    • Gas foil bearing
	• HPT
	    • TBD with TAC configuration

Heat Exchanger	• PCHE (Manufactured by Cohex)
Heater	• Indirect heating by thermal oil (Manufactured by S.P. Boiler)

Phase I of SCIEL

➢ Compressor Performance Test Loop

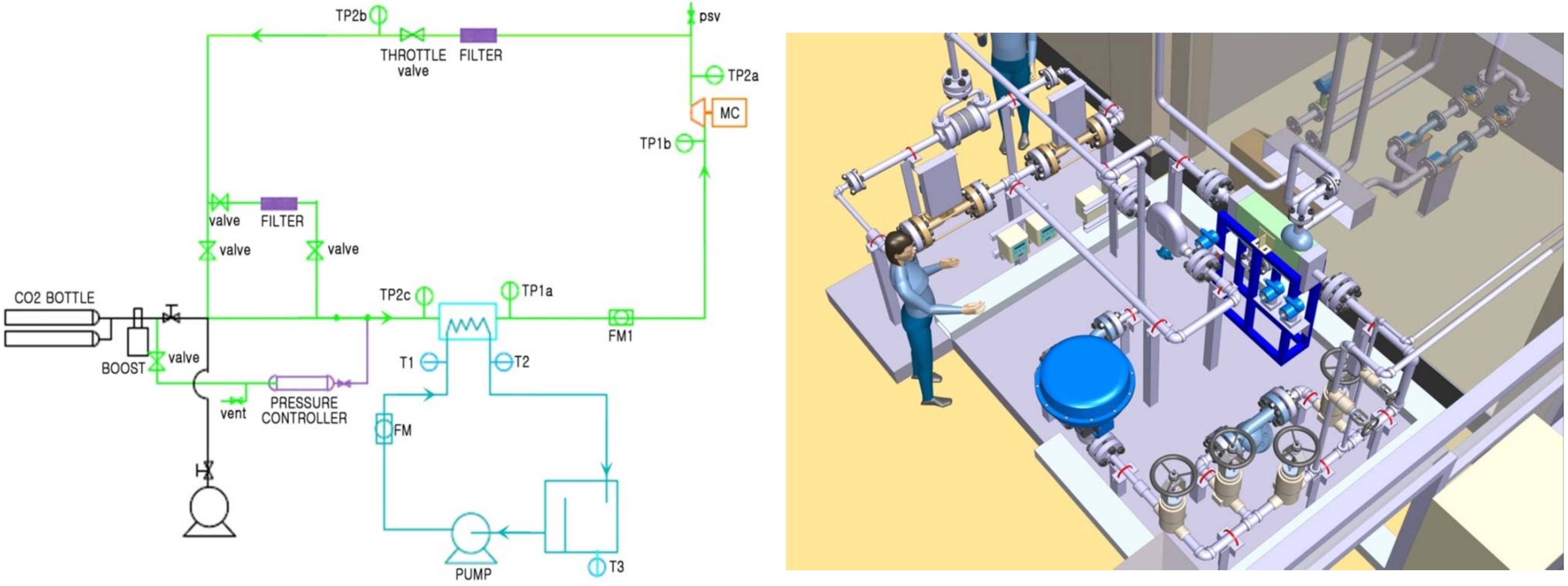


Fig. Schematic diagram of Compressor Test Loop

- ✓ The key point of S-CO_2 Brayton cycle loop experiment is performance test of compressor and pre-cooler in near critical point because they have the largest uncertainty.
- ✓ Compressor Performance Test Loop includes compressor and pre-cooler as main components to be able to verify components performance.
- ✓ It consists of pre-cooler, compressor, control valve and filters.

Phase I of SCIEL

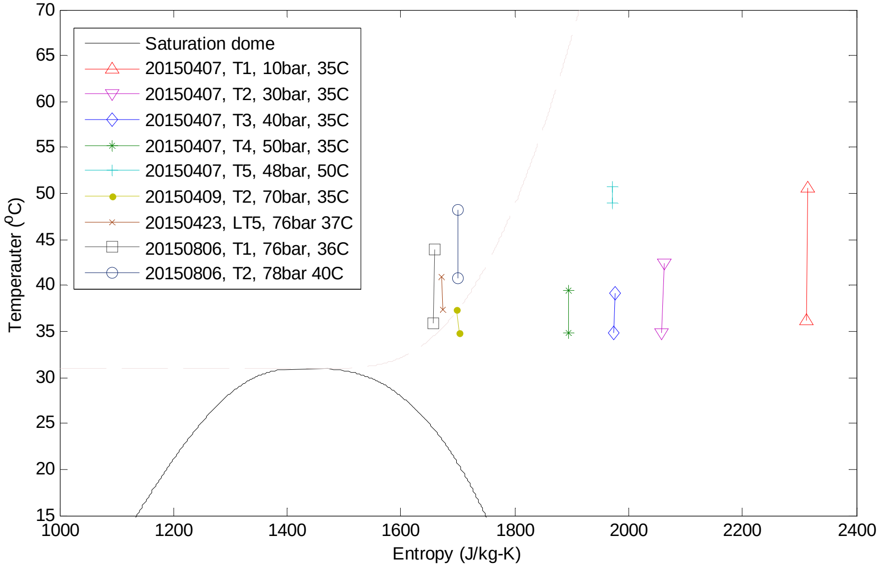
➢ Compressor Performance Test Loop

Fig. Compressor Performance Test Loop

- ✓ The key point of S-CO_2 Brayton cycle loop experiment is performance test of compressor and pre-cooler in near critical point because they have the largest uncertainty.
- ✓ Compressor Performance Test Loop includes compressor and pre-cooler as main components to be able to verify components performance.
- ✓ It consists of pre-cooler, compressor, control valve and filters.

Phase I of SCIEL

➢ Results of Compressor Performance Test Loop



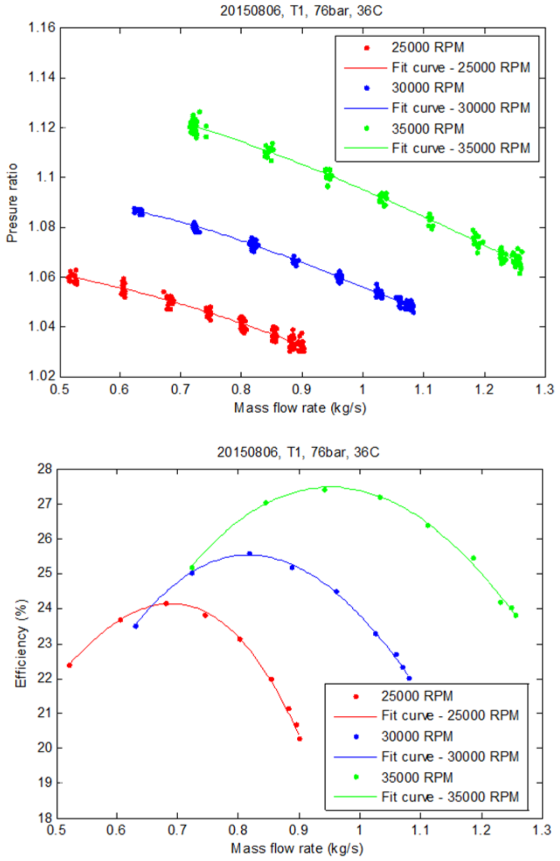
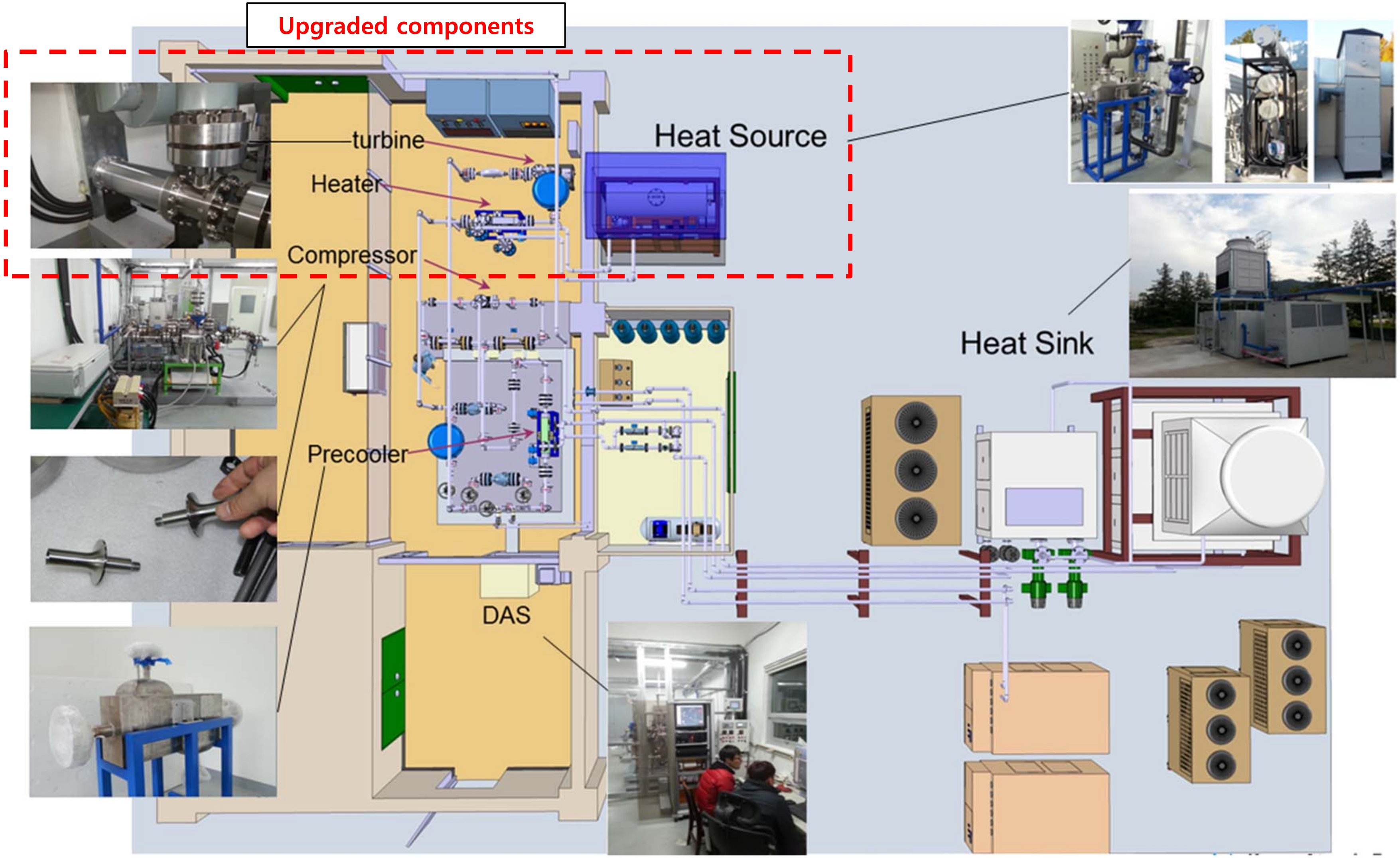


Fig. Various compressor performance test cases (left) and examples of compressor performance curve (right)

- ✓ Performance tests in various compressor inlet conditions were conducted.
- ✓ Compressor performance test was performed up to 35000rpm (74 bar, 31 ℃).
- ✓ Although the shaft speed was relatively low, the results showed tendencies like performance curves of conventional compressors.

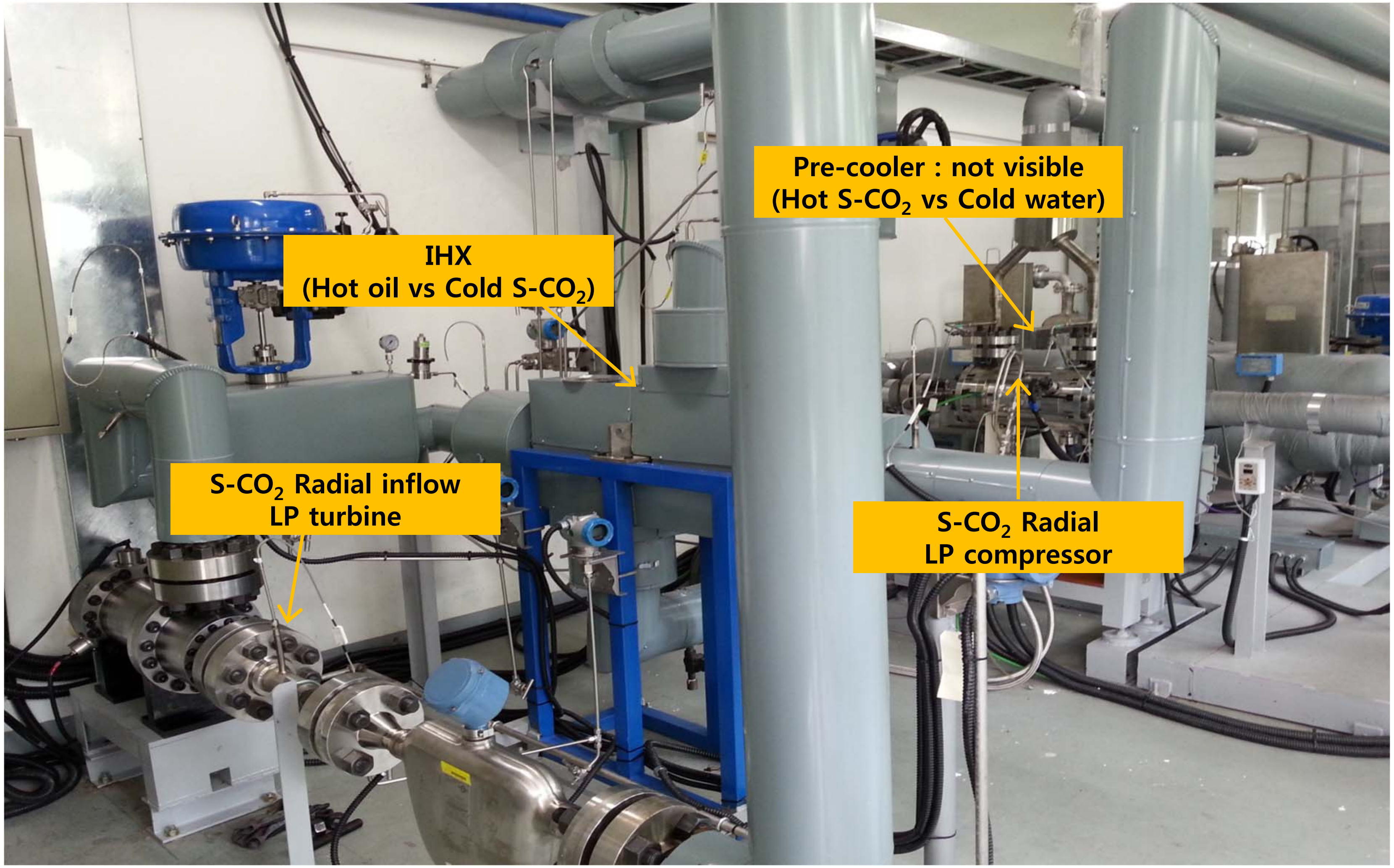
Phase II of SCIEL

- Low Compression Ratio Power Generation Loop



Phase II of SCIEL

- Low Compression Ratio Power Generation Loop



Pre-cooler : not visible (Hot S-CO_2 vs Cold water)

IHX (Hot oil vs Cold S-CO_2)

S-CO_2 Radial inflow LP turbine

S-CO_2 Radial LP compressor

Phase II of SCIEL

➢ Results of Low Compression Ratio Power Generation Loop

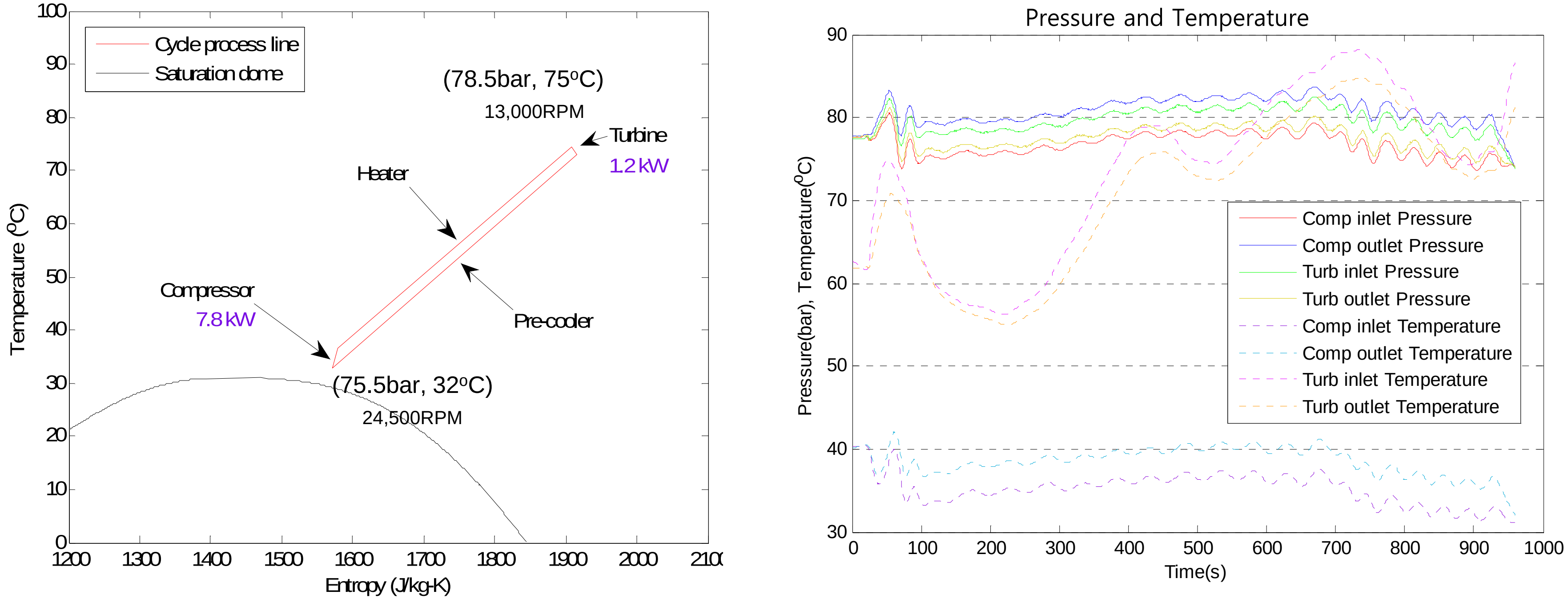


Fig. T-s cycle diagram (left) and compressor-turbine temperature and pressure at inlet and outlet (right)

- ✓ Power generation test was performed with compressor inlet condition above critical point, compressor shaft speed, 24500 rpm and mass flow rate 1.3 kg/s.
- ✓ At the beginning, turbine load of 15kW was set to prevent the turbine overspeed. The generation test proceeded with removing turbine load taps step by step.
- ✓ Consequently, the power generation, 1.2kW, was accomplished with a turbine shaft speed of 13000rpm.

Phase II of SCIEL

➢ Results of Low Compression Ratio Power Generation Loop

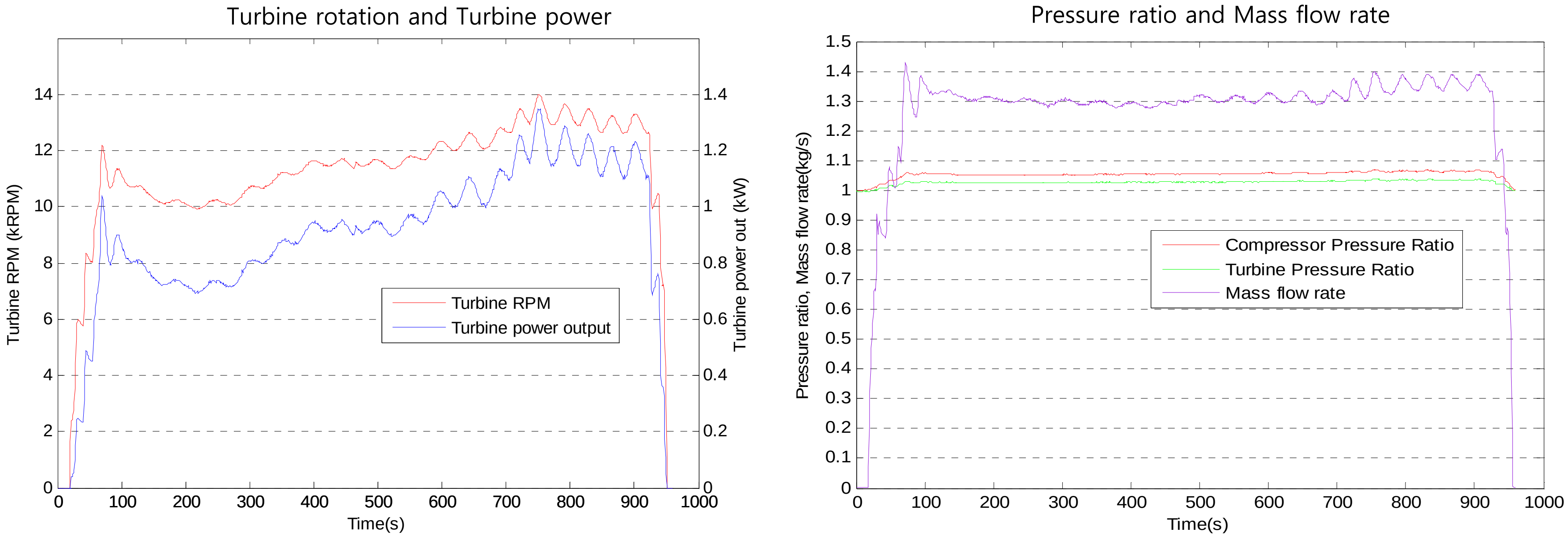


Fig. Power output and shaft speed of turbine (left) and mass flow rate of compressor-turbine (right)

- ✓ Power generation test was performed with compressor inlet condition above critical point, compressor shaft speed, 24500 rpm and mass flow rate 1.3 kg/s.
- ✓ At the beginning, turbine load of 15kW was set to prevent the turbine overspeed. The generation test proceeded with removing turbine load taps step by step.
- ✓ Consequently, the power generation, 1.2kW, was accomplished with a turbine shaft speed of 13000rpm.

Summary and further works

Main result summary

- KAERI has constructed a $S\text{-}CO_2$ Brayton Cycle Integral Experiment Loop (SCIEL) with 200-300kWe net power to develop base technologies for the $S\text{-}CO_2$ turbomachinery and compact heat ex-changer.
- Operation and control test have being conducted to develop an operation strategy in the $S\text{-}CO_2$ cycle.
- KAERI finished the installation of the 2^{nd} phase of SCIEL loop (the low compression ratio loop) succeeded in generating the electric power with supercritical CO_2.

Further works

- The control logic development will be carried out from the operation of the 2^{nd} phase of SCIEL facility.
- Additional TAC (Turbo-Alternator-Compressor) will be installed to finish the facility construction.
- The demonstration of high pressure ratio operation with high temperature heat source will be followed afterwards.

Summary and further works

SCIEL MARS Model and Transient analysis

- MARS (Multi-dimensional Analysis of Reactor Safety) code is being developed by KAERI for a multi-dimensional and multi-purpose realistic system analysis of reactor transients.
- The backbones of MARS are the RELAP5 and COBRA-TF

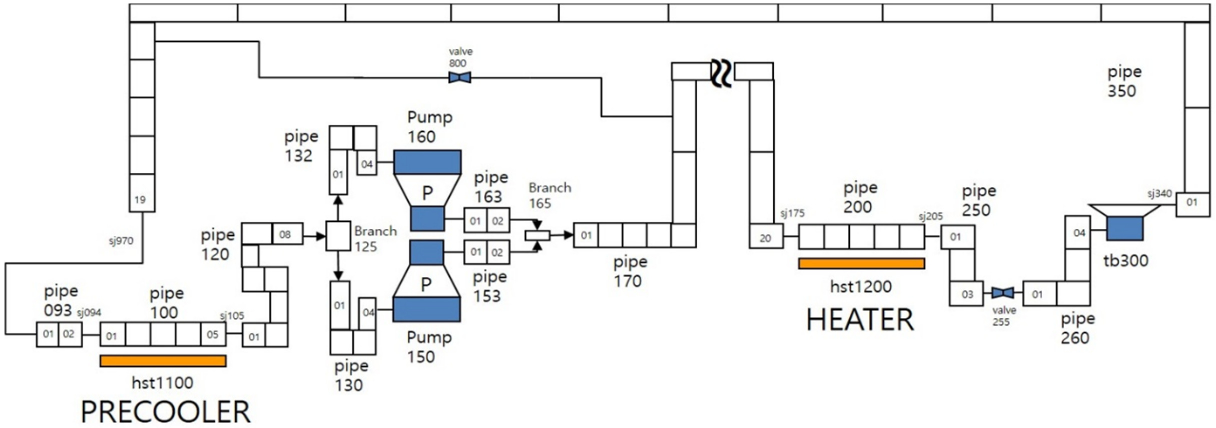


Fig. Schematic of SCIEL MARS model

- Normal transient analysis : Consecutive power control of decrease and increase state
  The cycle has to reduce power from 100% to 60%
  The cycle has to increase power from 60% to 105%
- Abnormal transient analysis : Pipe break condition, unusual operation conditions of each component

THANK YOU