Preliminary Power Generating Operation of the Supercritical Carbon Dioxide Power Cycle Experimental Test Loop with a Turbo-generator

Tuesday, March 27, 2018

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GLOBAL KIER TECHNOLOGIES

Outline

01 Introduction of KIER's S-CO2 R&D

02 tens of kWe Test Loop & Axial Turbo-generator

03 500 °C kWe Test Loop & Radial Turbo-generator

04 Summary & Future Works

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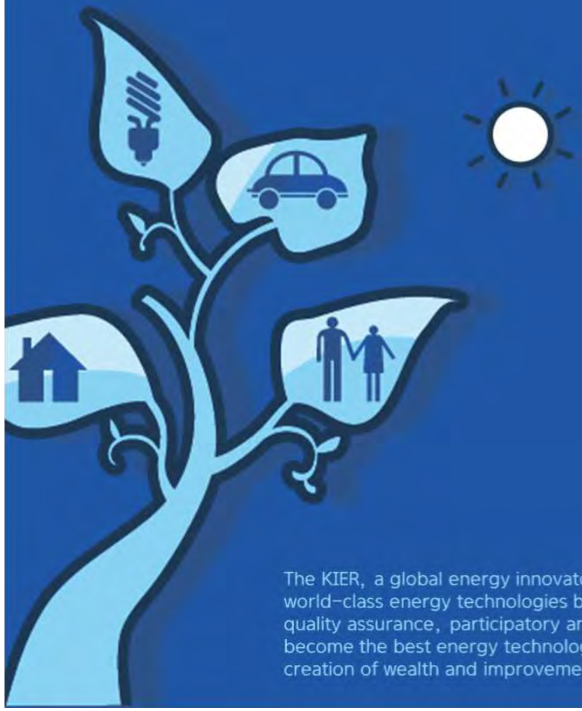
Chapter 01

Introduction of KIER's S-CO2 R&D



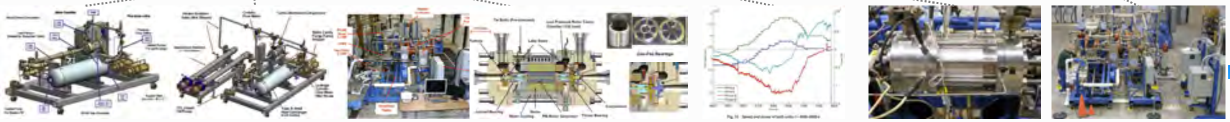
The KIER, a global energy innovator, does its best in pursuing its mission to invent world-class energy technologies based on open innovation, life-cycle research quality assurance, participatory and open communication. Therefore the KIER will become the best energy technology R&D institute in the world, contributing to the creation of wealth and improvement of quality of life for the people.

Introduction of KIER's S-CO2 R&D

S-CO_2 Power Cycle Systems in the world

2005 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019+

SNL (250kWe)
477℃/105bar/15kWe



`05 – `10 Single Comp. `10 1 TAC `11 RCBC/2 TAC/GFB `13 480℃/105bar/15kWe `14 100kWh `16 500kWh

Naval Nuclear Lab. (Bechtel) (100kWe)
282℃/141bar/40kWe

`09 – `11 1 TC, 1 TG, GFB `14 282℃/141bar/40kWe `16 226℃/136bar/40kWe

TIT (10kWe)
260℃/105bar/0.11kWe

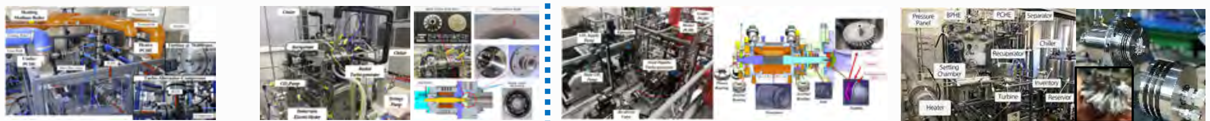
`07 – `12 1 TAC, Gas bearing, 260℃/105bar/0.11kWe

*RCBC : Recompression Closed Brayton Cycle
*TAC : Turbine-Alternator-Compressor
*TC : Turbo-Compressor
*TG : Turbo-Generator

*GFB : Gas Foil Bearing
*ACB : Angular Contact Ball Bearing
*TPB : Tilting-Pad Bearing
*DGS : Dry Gas Seal

TODAY

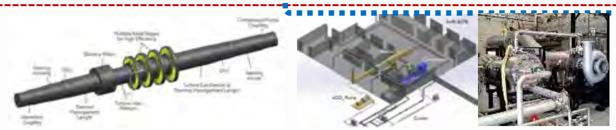
KIER (~ hundreds of kWe)
@sub-kWe, 170℃/101bar/0.67kWe (turbine)
@tens of kWe, 205℃/100bar/11kWe (turbine)
@kWe, 401℃/100bar/287We (turbine)



`13 – `14 10kWe, TAC, GFB, 83℃/85bar/30,000rpm
`14 – `16 1kWe TG (Radial), ACB, 170℃/101bar/670We (turbine)
`15–`17 60kWe TG (Axial), TPB, 205℃/100bar/11kWe (turbine)
`16 – `17 5kWe TG (Radial), ACB, 401℃/100bar/287We (turbine)

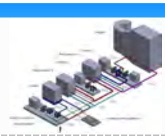
Hundreds of kWe /500℃/130bar
2 turbine
1 compressor

SwRI/GE (1MWe)
715℃/250bar/under commissioning



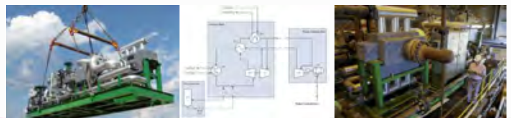
`12 ~ `17 1 Turbo-expander, DGS, TPB, 1 Compressor, 700℃/250bar/under commissioning

U.S. 10MWe Pilot Plant Project Leading Group



1-2 phase: 500℃
3 phase: 700℃

Echogen (8MWe)
275℃/ ? bar/2.35MWe



`14 1 Turbo-pump (hermetic), 1 Power Turbine (DGS, TPB), TIT design 485℃/ Test 275℃/2.35MWe

KIER S-CO2 Project Overview

- 2013-2014 : 10 kWe test loop, 200℃ (Preliminary Operation)
- 2014-2016 : sub-kWe test loop, 200℃ (Power Generation)

- 2015-2019 : 5 years project
- Vision (long-term) : Substitution of the steam Rankine cycle system (particularly in fossil fuel application)
- Mid-term goal : WHR market
- Budget : $2M/yr
- Project Leader : Young-Jin Baik, Ph.D.
  Chief of Thermal Energy Systems Laboratory at KIER
- 2015-2017 : tens of kWe test loop, 200℃ (Power Generation) **Today Presentation**
- 2016-2017 : kWe test loop, 500℃ (Power Generation) **Today Presentation**
- 2016-2019 : hundreds of kWe test loop, 500℃ (under construction)

Introduction of KIER's S-CO2 R&D

KIER S-CO2 Test loops

UPGRADE

UPGRADE

TODAY

	10 kWe-class (2013-2014)	Sub-kWe-class (2014-2016)	Tens of kWe-class (2015-2017)	kWe-class (2016-2017)	Hundreds of kWe-class (2015-2019)
Purpose	Feasibility 200°C/130bar	Power generation 200°C/130bar	Robust Turbo-generator 200°C/130bar	500°C operation 500°C/130bar	500°C Full-cycle operation for WHR application 500°C/130bar
Status	Tested @ 30,000RPM Modified to the tens of kWe test loop	670 We power generation Modified to the kWe test loop	11 kWe power generation	287 We power generation	In progress
Cycle type	Simple Un-Recuperated Closed Brayton	Un-recuperated Transcritical	Un-recuperated Transcritical	Recuperated Transcrtical	Dual Brayton
Turbomachinery	1 Turbo-Alternator-Compressor	1 Turbo-generator	1 Turbo-generator	1 Turbo-generator	2 Turbine 1 Compressor
Compressor type	Centrifugal, Shrouded	Positive displacement Pump	Positive displacement Pump	Positive displacement Pump	Centrifugal
Turbine type	Radial, Shrouded	Radial w/ Partial admission nozzle	Axial impulse w/ Partial admission nozzle	Radial w/ Partial admission nozzle	TBD
Bearing	Gas foil journal/thrust	Angular contact ball (Oil lubrication)	Tilting-pad (Oil lubrication)	Angular contact ball (Oil lubrication)	TBD
Seal	Labyrinth	Labyrinth	Carbon Ring type Mechanical Seal	Labyrinth	DGS
Rotational speed (RPM)	70,000	200,000	45,000	120,000	TBD
Heater	LNG fired Thermal Oil Boiler	Immersion electric heater	LNG fired Thermal Oil Boiler	Immersion electric heater	LNG fired flue-gas Heater
Recuperator	none	none	none	PCHE	2 PCHE

GLOBAL KIER TECHNOLOGIES

Chapter
01

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Chapter 02

Tens of kWe Test Loop & Axial Turbo-generator

The KIER, a global energy innovator, does its best in pursuing its mission to invent world-class energy technologies based on open innovation, life-cycle research quality assurance, participatory and open communication. Therefore the KIER will become the best energy technology R&D institute in the world, contributing to the creation of wealth and improvement of quality of life for the people.

Chapter
03

Chapter
04

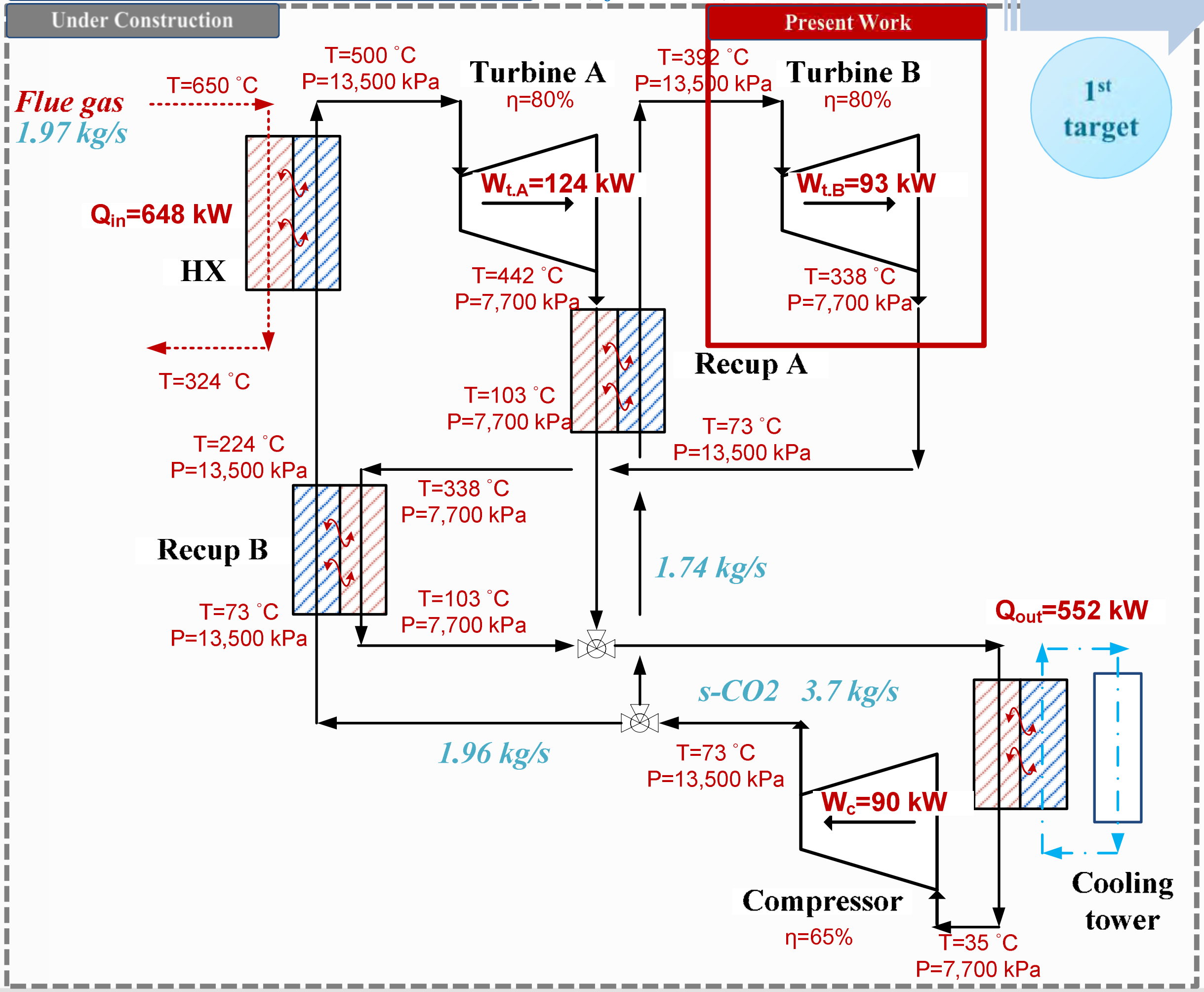
Tens of kWe Test Loop & Axial Turbo-generator

Full Cycle for Waste Heat Recovery

Hundreds of kWe Full Test Loop (500 °C, 2015~2019)

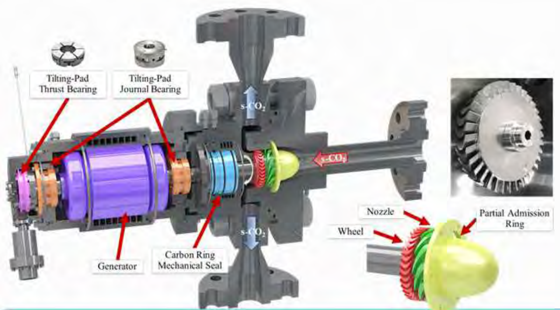
Under Construction

W_{net}=120 kW
($\eta_{generator}$=95%)



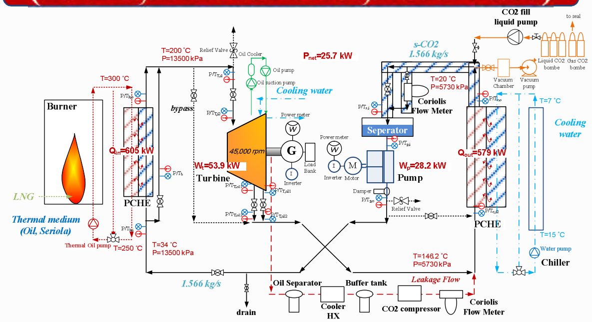
1st target

Turbine B (2015~2017)



Axial-type Turbo-generator

Tens of kWe Test Loop (200°C, Transcritical, 2015-2017)



200 °C off-design operation

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Tens of kWe Test Loop & Axial Turbo-generator

Technical Issues in S-CO_2 Turbomachinery

1. Small Size : 20 cm diameter @ 10 MWe class
2. High Speed : 30,000 RPM @ 10 MWe class

lab-scale (under MWe)

Windage Loss

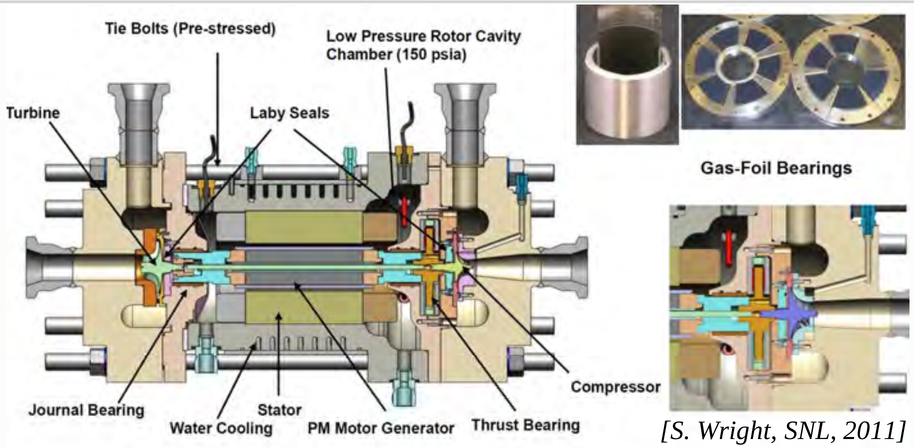
01 Fluid Friction Loss

- High pressure, High density fluid
  Windage loss at shaft & bearing
  [SNL reports]
- Limitation of 1 casing TAC Structure

Gas Foil Bearing Failure [High Thrust]

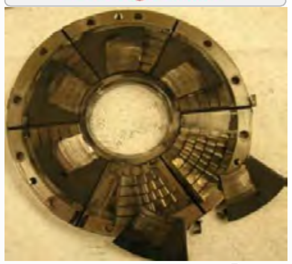
02 Bearing Failure @ High T/P

- Gas-foil bearing failure @ high temp.
  [SNL reports, NASA report]
- High thrust occurs, but very weak



[S. Wright, SNL, 2011]

Trust Gas Foil Bearing Failure



ARL-MR-0749

[NASA] Limitation of Gas Foil Bearing @ high Temp.

A Novel Thermal Management Approach for Radial Foil Air Bearings

Kevin Radil
NASA Glenn Research Center
Cleveland, OH

[K. Radil et al., ARL-MR-0749, NASA, 2010]
[T. Conboy et al., Journal of Engineering for Gas Turbines and Power, Vol. 134, 2012]

KIER Strategy

Scale-up is OK!

Non-hermetic
Mechanical Seal
or Labyrinth seal in lab-scale

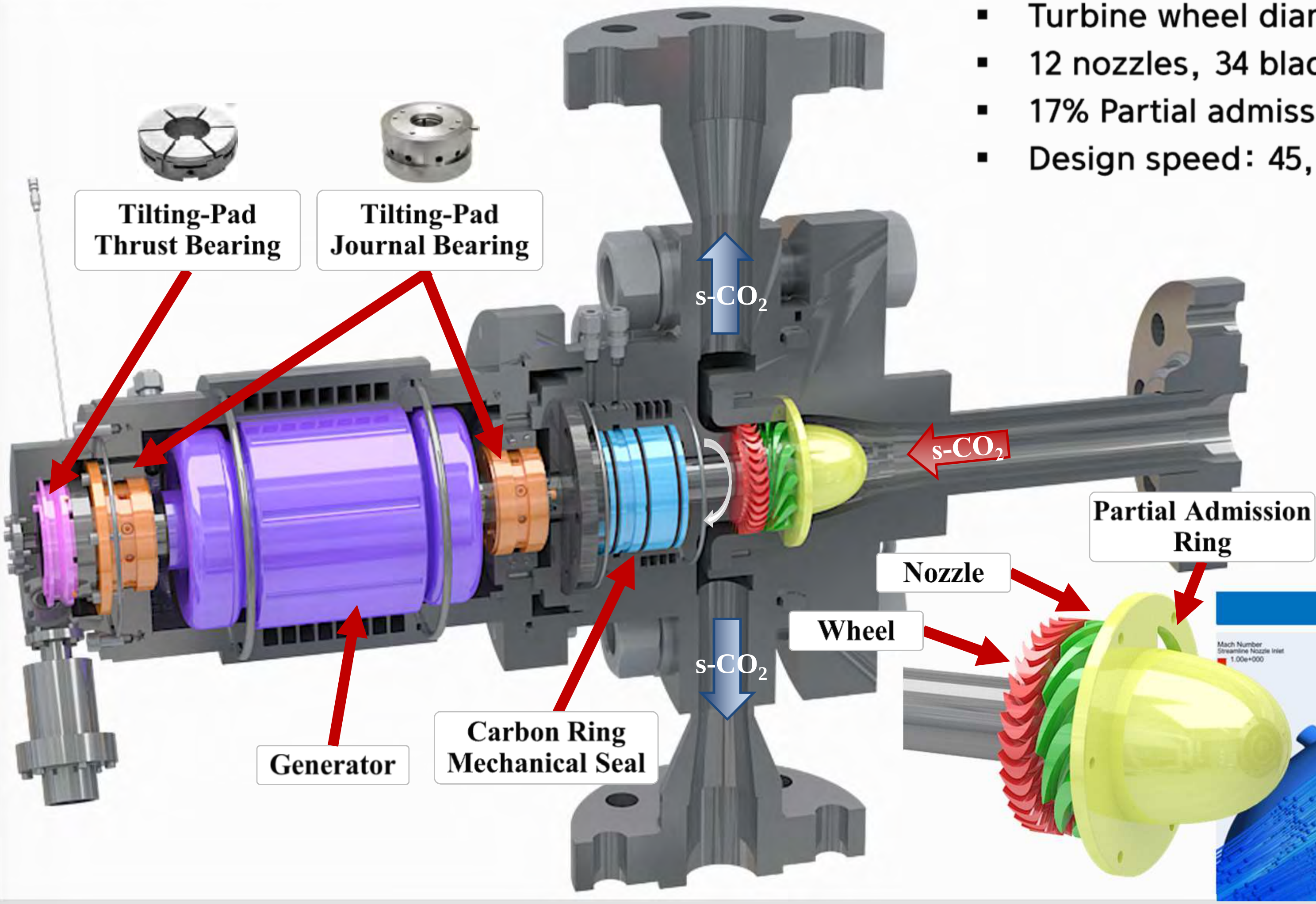
+

Oil-lubricated Bearing
Mature/Robust Commercial Bearing
High thrust force capacity

Reduce Rotational Speed !
Partial Admission Nozzle
KEY Design Strategy

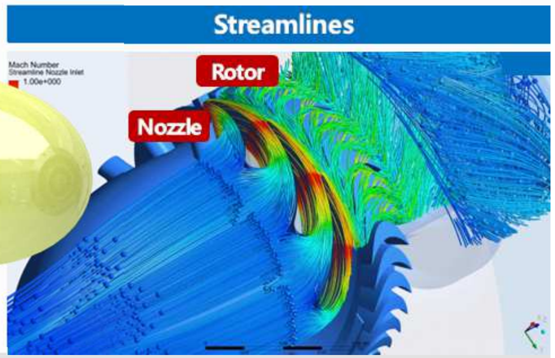
KIER S-CO_2 Axial Impulse Turbo-Generator

S-CO_2 Axial Impulse Turbo-Generator



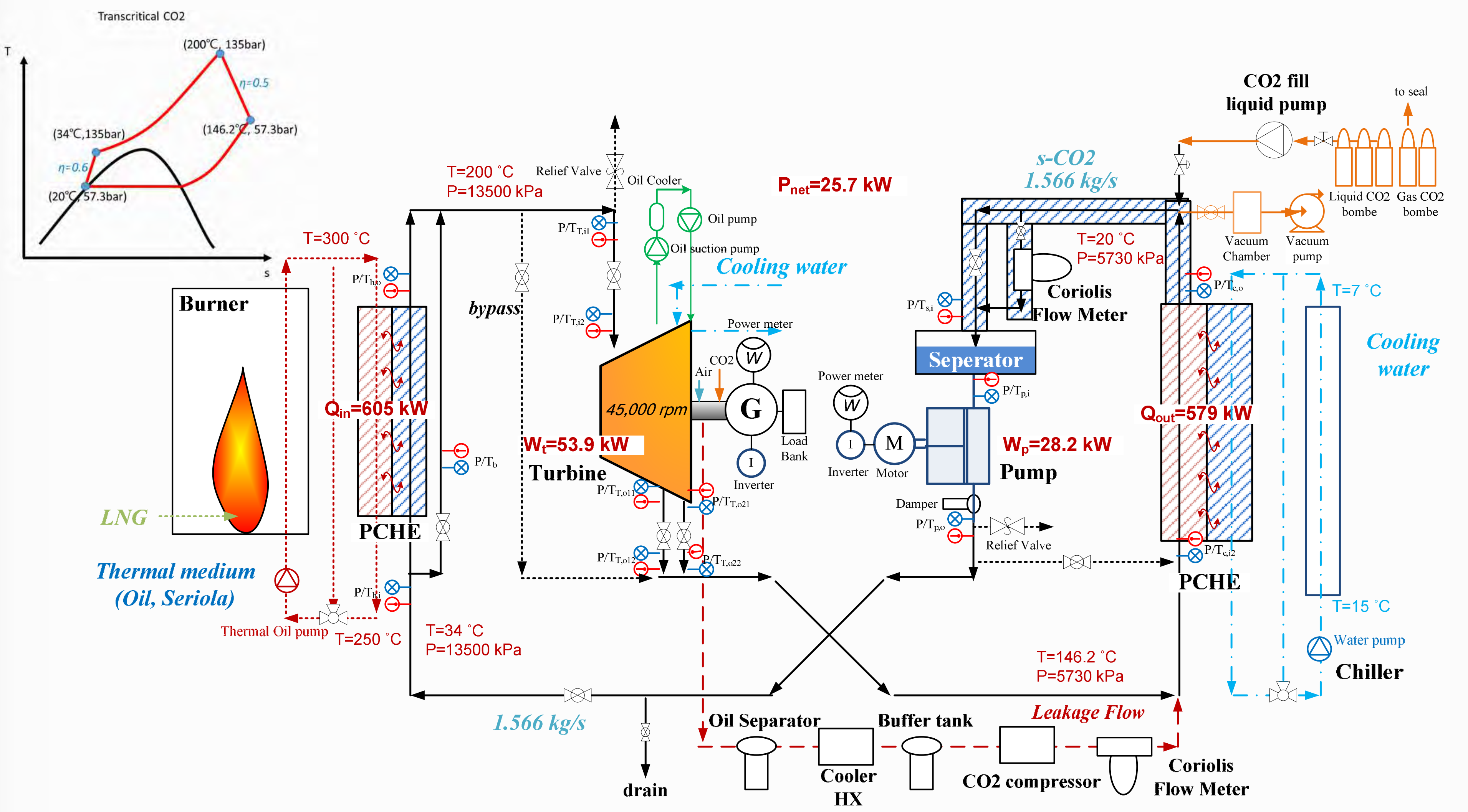
Details are shown in 'GT2017-64349'

- Turbine wheel diameter : 80 mm
- 12 nozzles, 34 blades
- 17% Partial admission
- Design speed: 45,000 RPM



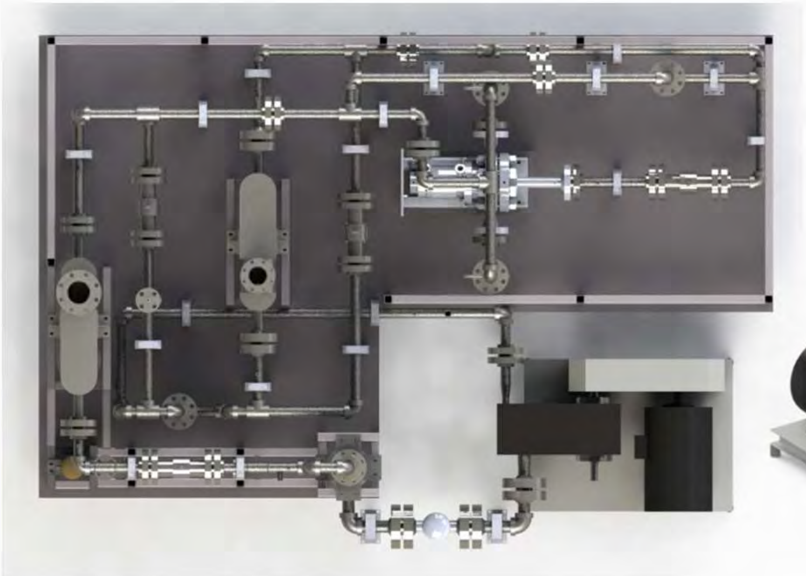
Tens of kWe Test Loop & Axial Turbo-generator

Test loop (200℃ off-design, Transcritical)



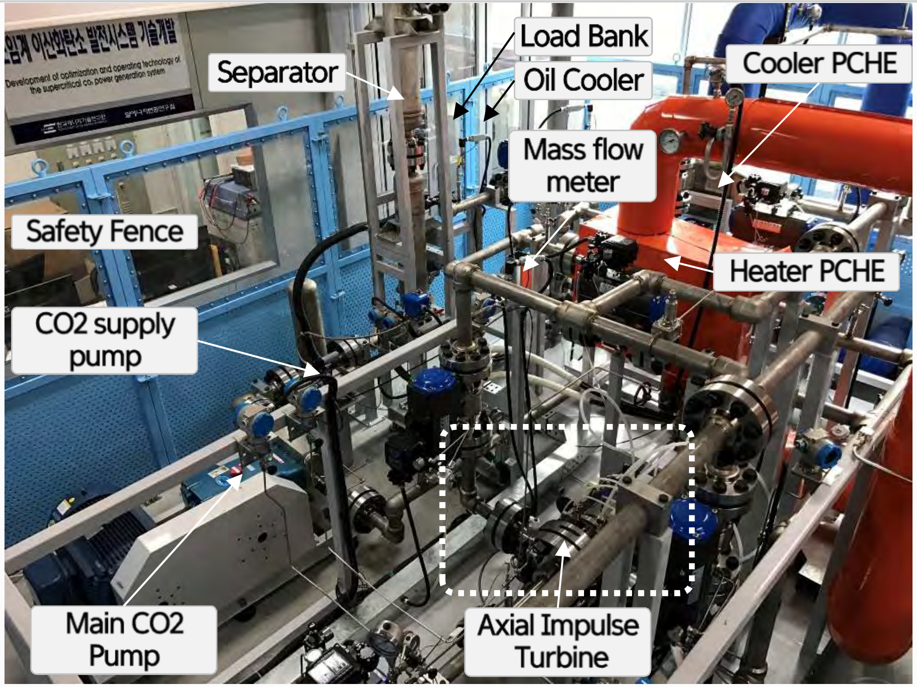
Test loop (200℃ off-design, Transcritical)

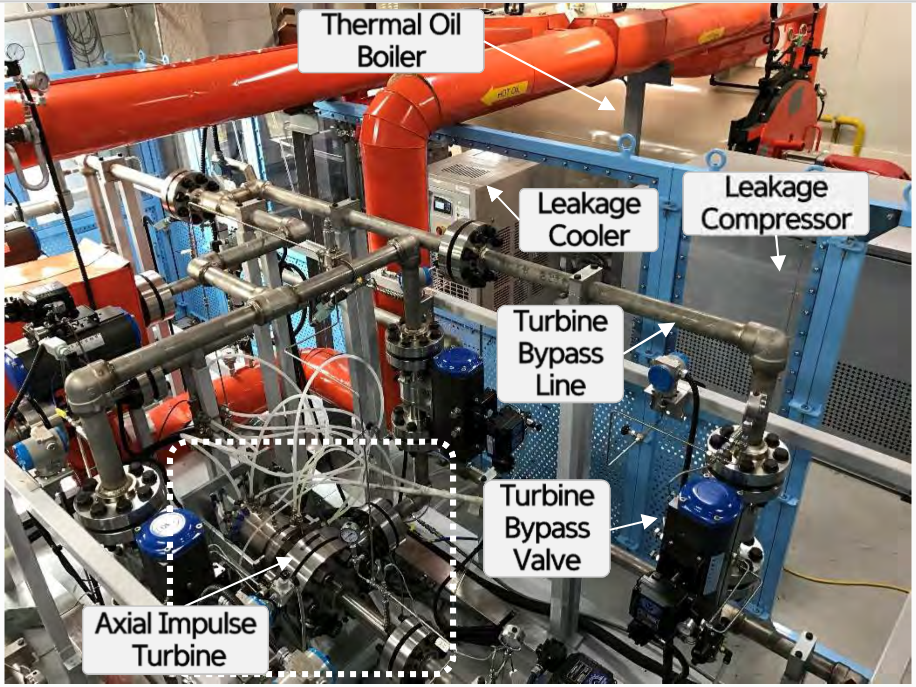
- Pressure Vessel & Piping as ASME code guideline
  - 2” SUS304, ANSI Flanges 1500, 2500 CLS
  - Metal Gaskets for CO_2
  - Air-driven Control Valves
  - Cryogenic Valves & Regulators

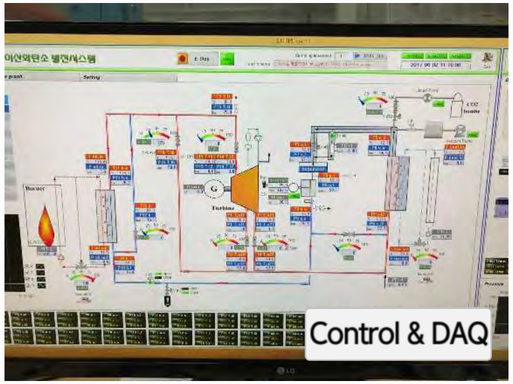


Tens of kWe Test Loop & Axial Turbo-generator

Test loop (200℃ off-design, Transcritical)

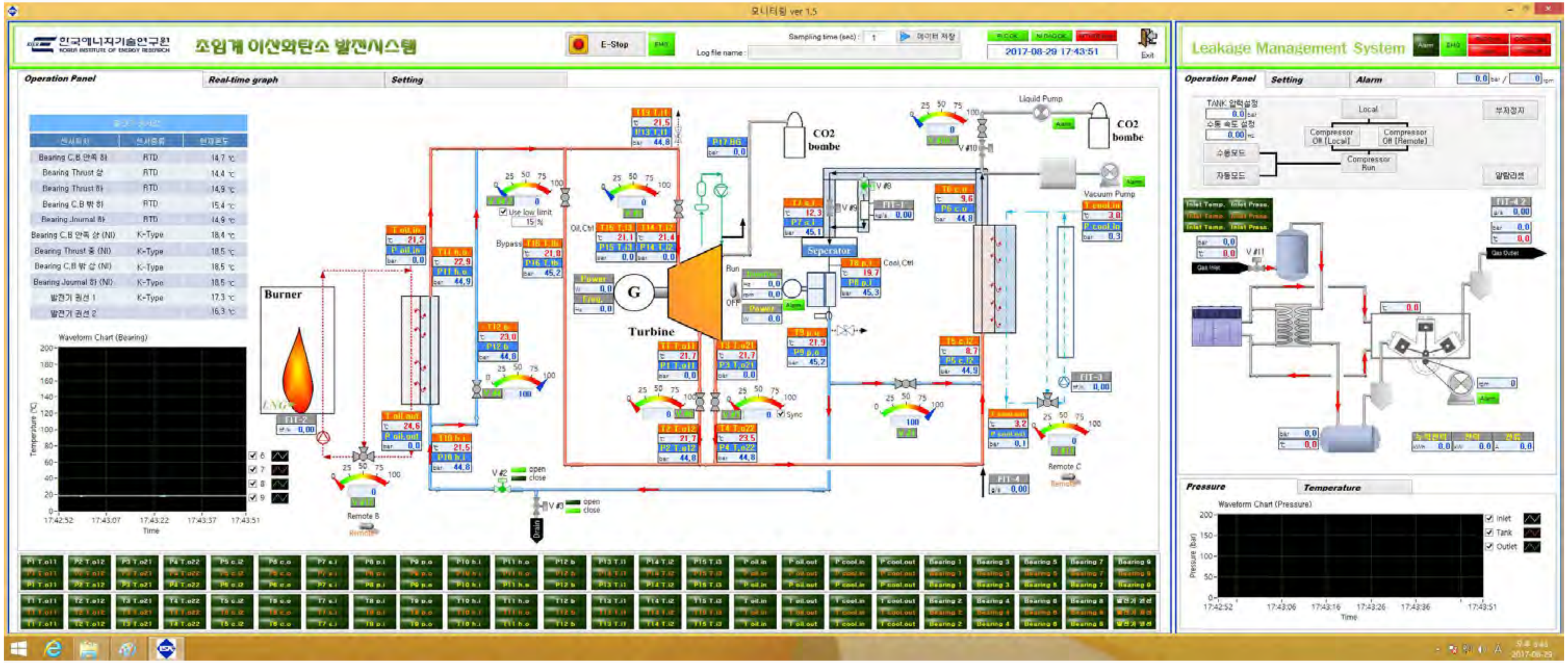






Tens of kWe Test Loop & Axial Turbo-generator

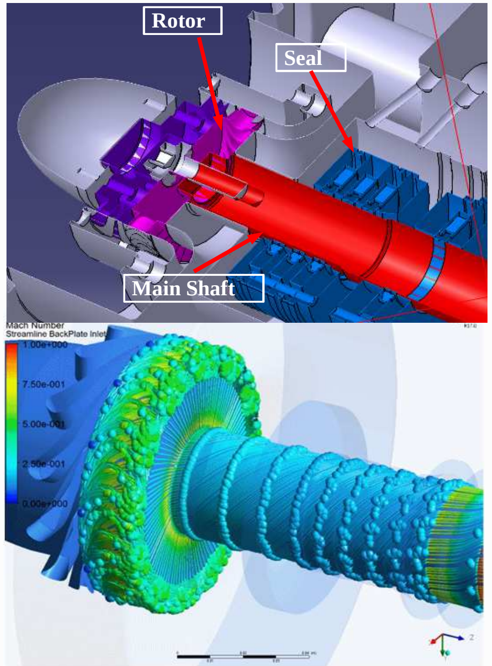
DAS & Control



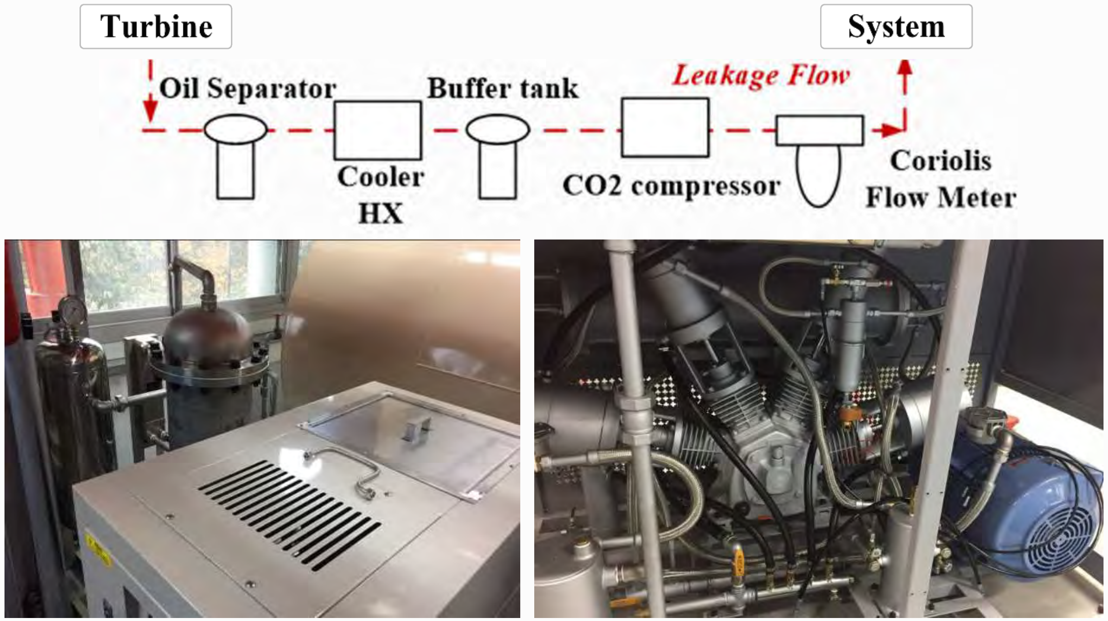
Bearing Temp. Monitoring	Main CO2 Loop Monitoring	CO2 Leakage Monitoring

Leakage Management

- Leakage Make-up System by using a 3-stages piston type compressor
    - Leakage : 2-3%(37g/s) of mass flow rate (1.57kg/s) through a floating carbon ring type mechanical seal
    - 3-stages compressor : 0.5 bar.g -> 57~80 bar.g
    - Oil-separator, Cooler HX, Buffer tank, Chiller



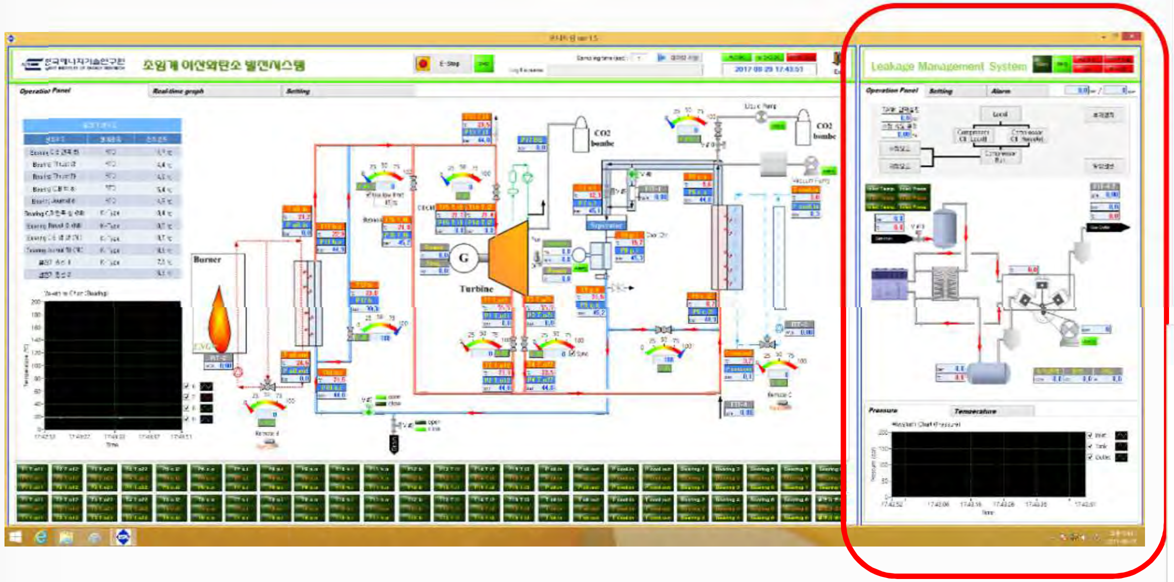
CFD analysis of leakage flow



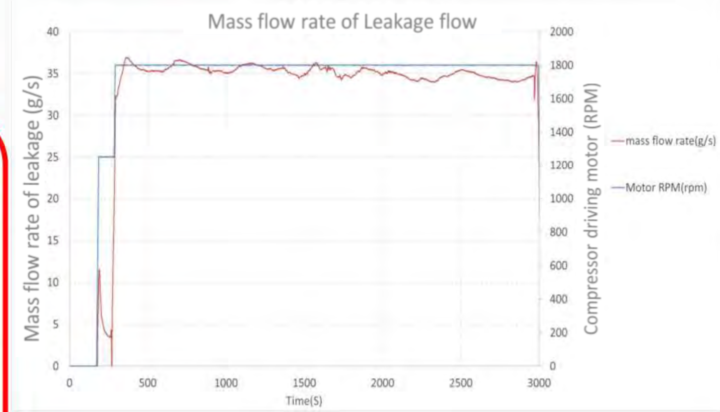
Leakage Make-up System

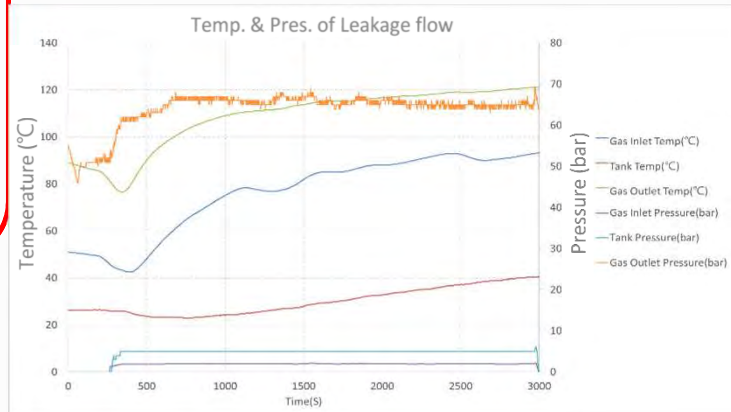
Leakage Management

- Leakage Make-up System by using a 3-stages piston type compressor
  - Continuous operation was successful



Leakage Make-up Controller



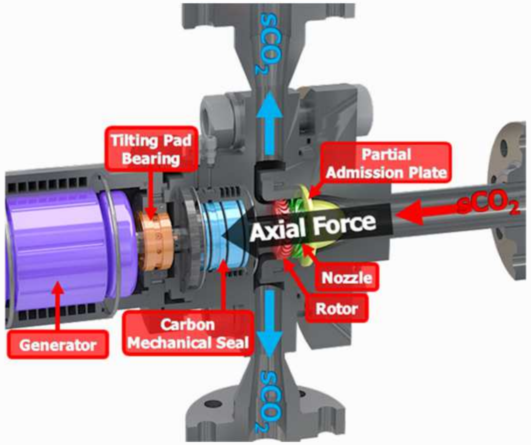


Operation Result

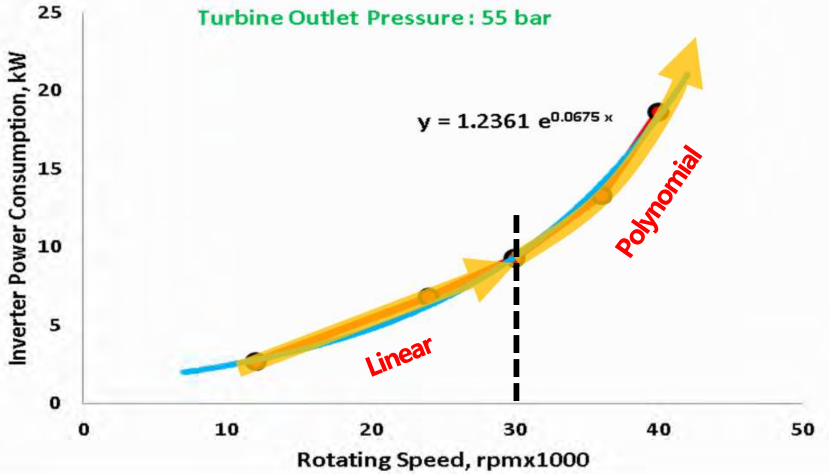
Tens of kWe Test Loop & Axial Turbo-generator

Preliminary test

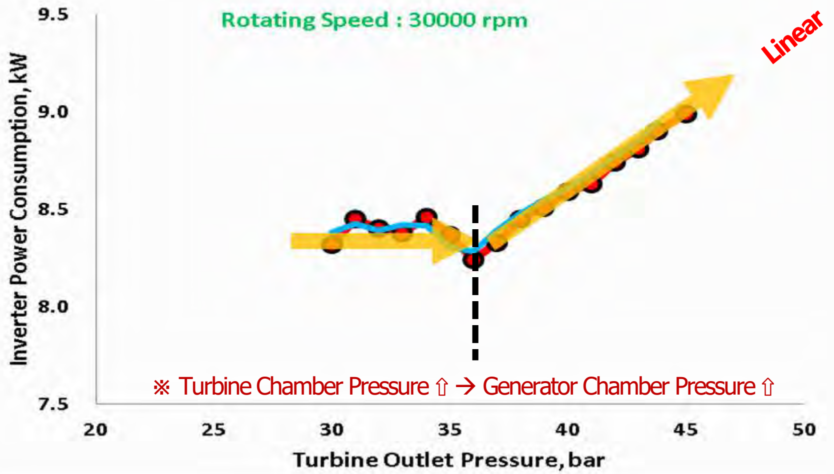
- Preliminary mechanical loss test as a RPM, Axial force
  - Turbo-generator was driven by an external electric inverter
  - Power consumption data was obtained
  - Mechanical loss of a tilting-pad bearing was estimated
  - High axial force was imposed on the bearing at the start
    -> Inverter driving was necessary at the start



"Rotating Speed" vs Power Consumption



"Turbine Chamber Pressure" vs Power Consumption



Tens of kWe Test Loop & Axial Turbo-generator

Preliminary Power Generation

- Electric Power generation with an Axial-type SCO2 Turbine

  The objective of this project was not to demonstrate the efficiency benefits of SCO2 power cycles.

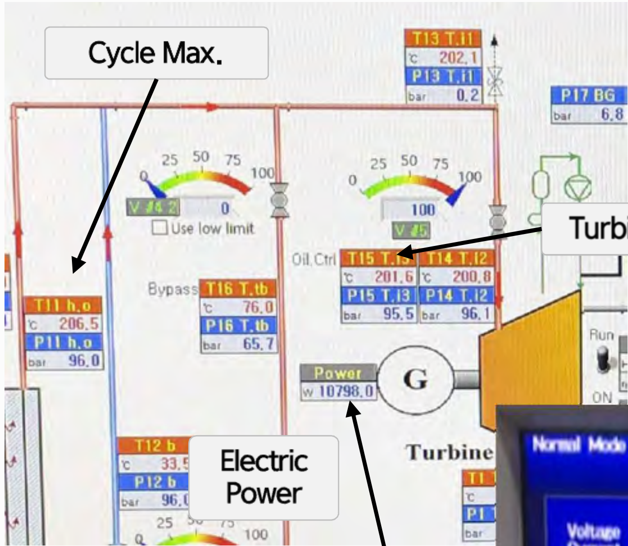
  Rather, the objective of the project was to develop an SCO2 power generation system with an axial-type turbine resolving bearing failure problems reported by other research groups by applying turbomachinery technology applicable to a commercial plant.

Cycle 103 bar & 212 ℃

Turbine Inlet 100 bar & 205 ℃

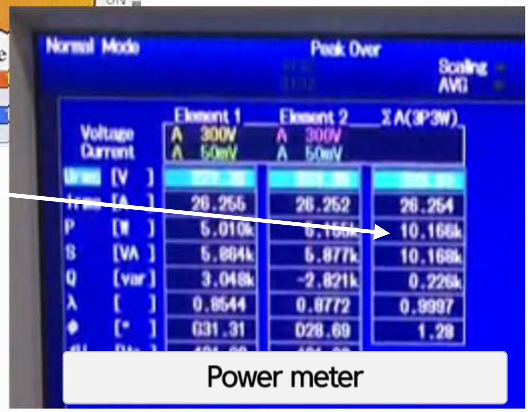
Continuous Power Gen. 45 min

Avg. Turbine Power 10 kWe

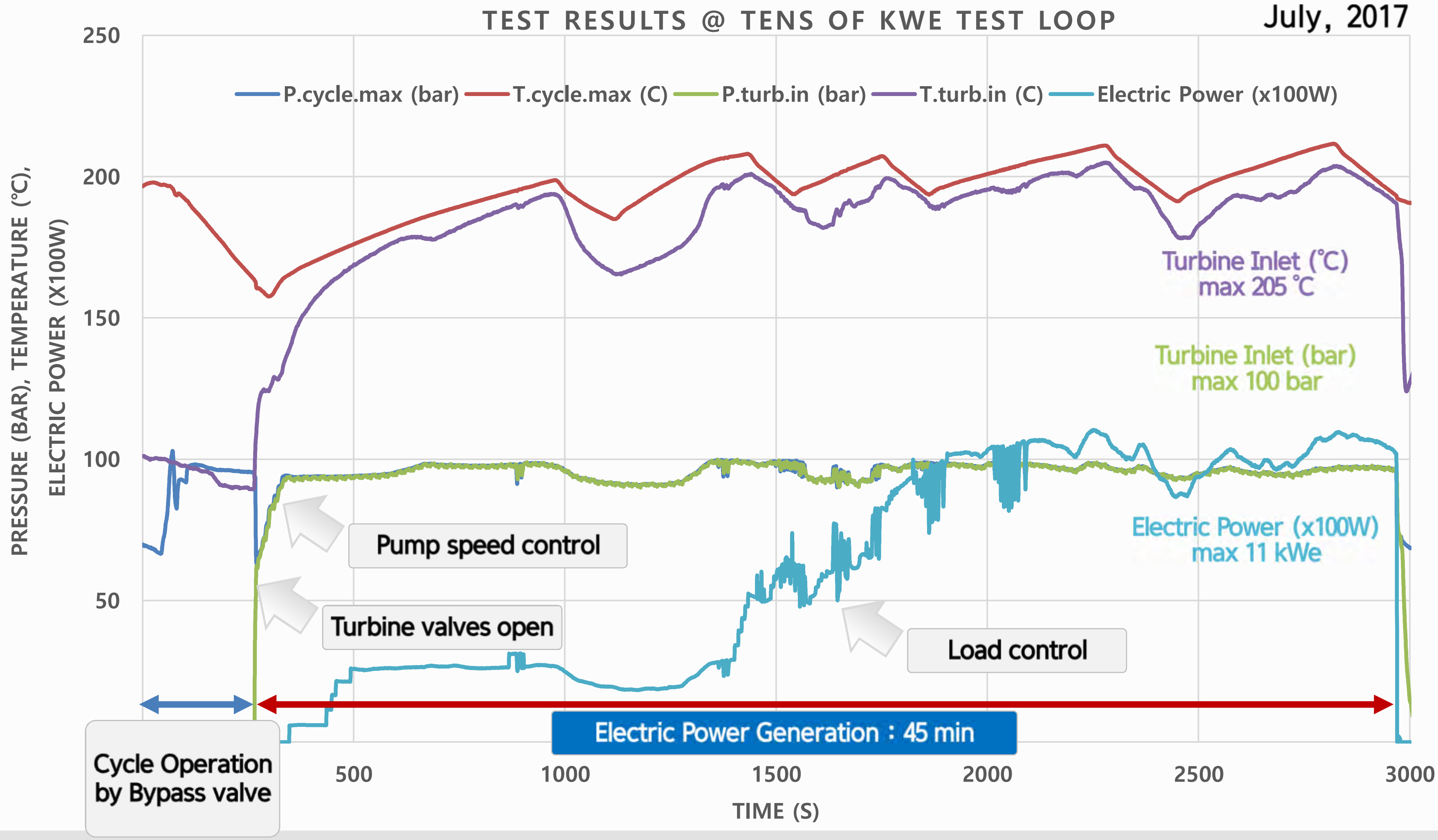


July, 2017

10 kWe

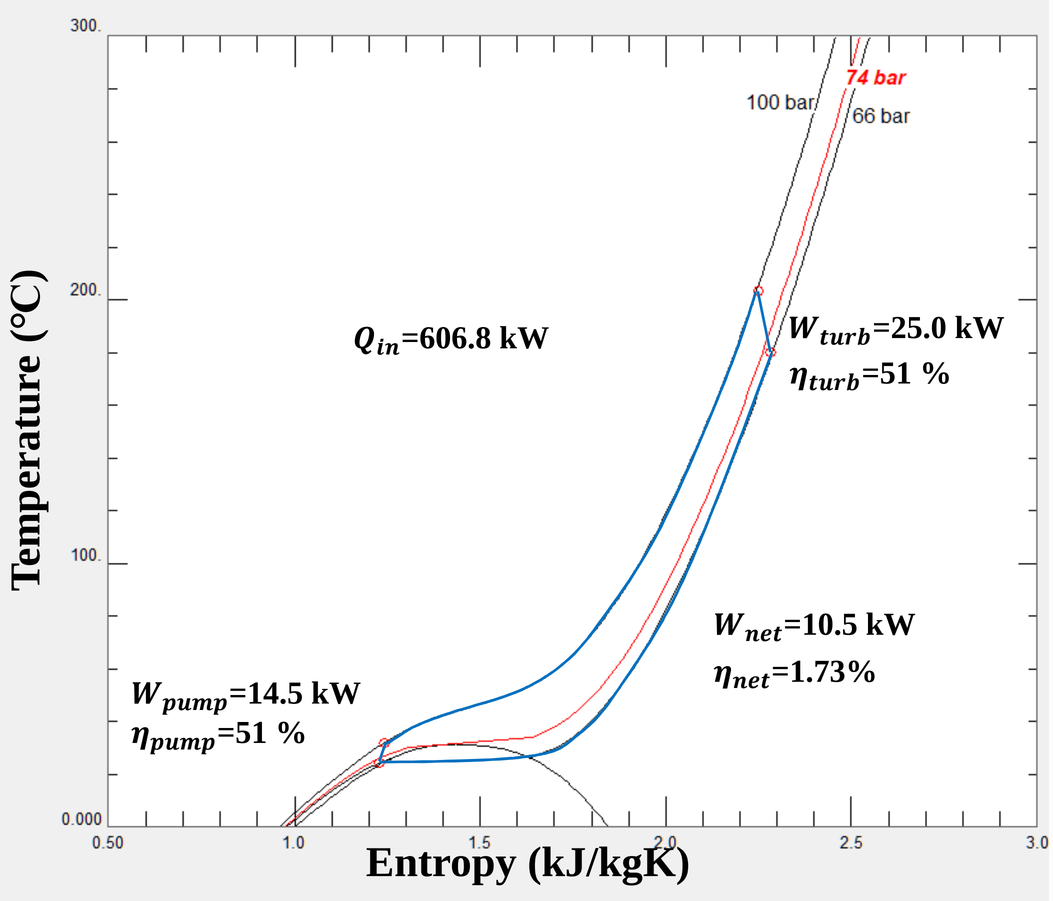


Preliminary Power Generation



Preliminary Power Generation

July, 2017



Parameter	Value
Turbine Inlet Temperature (°C)	203.4
Turbine Inlet Pressure (bar)	98.1
Turbine Outlet Temperature (°C)	180.1
Turbine Outlet Pressure (bar)	67.7
Pump Inlet Temperature (°C)	24.3
Pump Inlet Pressure (bar)	65.9
Pump Outlet Temperature (°C)	31.7
Pump Outlet Pressure (bar)	99.1
Mass flow rate (kg/s)	1.69
Leakage mass flow rate (g/s)	34.46
Expansion ratio	1.45
Turbine Power (kW)*	25.0
Turbine efficiency (%)	51
Pump Power (kW)*	14.5
Pump efficiency (%)	51
Net Power (kW)*	10.5
Heat in (kW)*	606.8
Net efficiency (%)	1.73

*Power was calculated by enthalpy difference

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Chapter 01

Chapter 02

Chapter 03

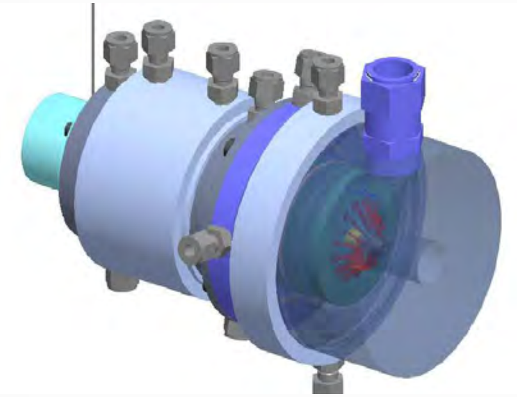
500℃ kWe Test Loop & Radial Turbo-generator

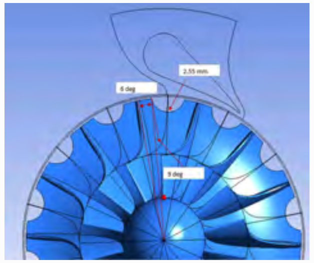
Chapter 04

The KIER, a global energy innovator, does its best in pursuing its mission to invent world-class energy technologies based on open innovation, life-cycle research quality assurance, participatory and open communication. Therefore the KIER will become the best energy technology R&D institute in the world, contributing to the creation of wealth and improvement of quality of life for the people.

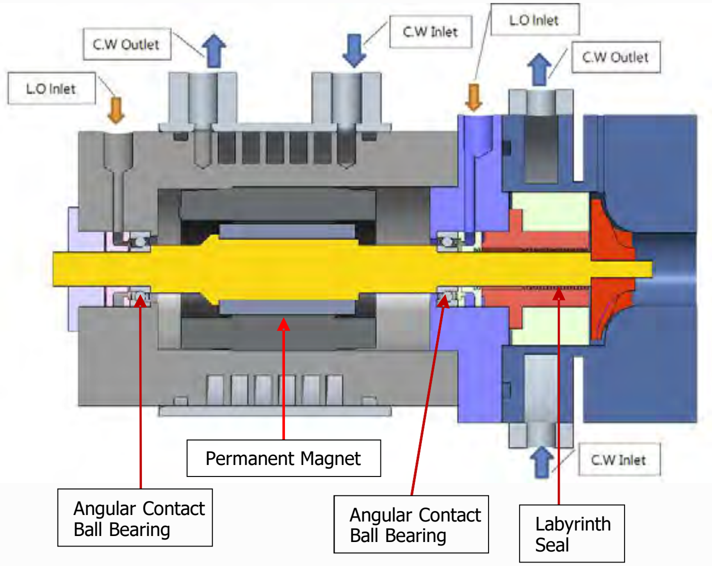
Turbo-generator for 500℃ TIT

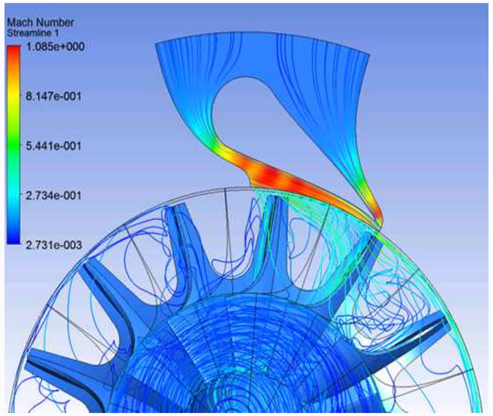
- Design power: 4.5 kW (w/o mechanical loss)
- Design rotational speed: 120,000 RPM
- Design axial force: 2 N
- 1/10 Partial admission nozzle



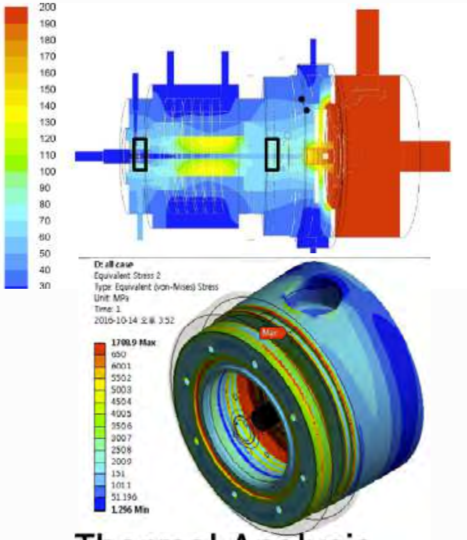


Scallop

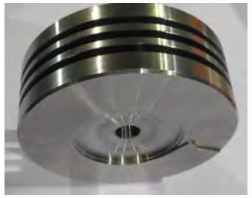




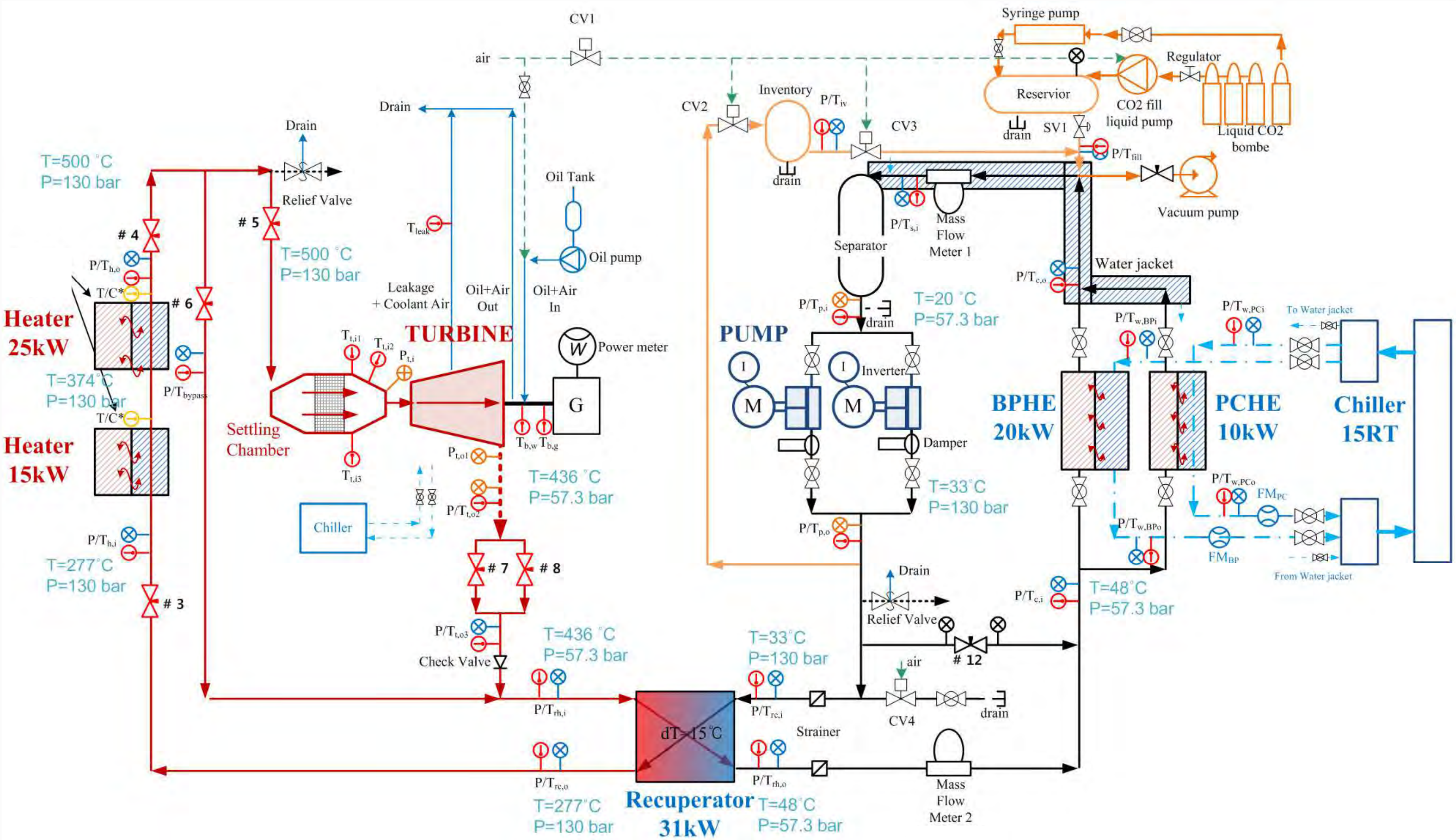
Partial admission CFD



Thermal Analysis

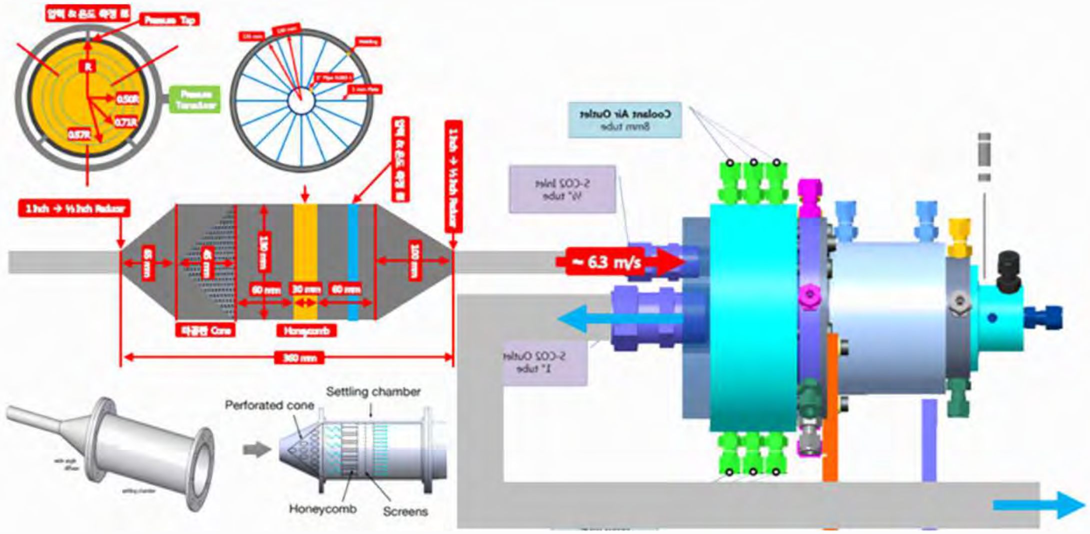


Test loop (500℃, Transcritical)

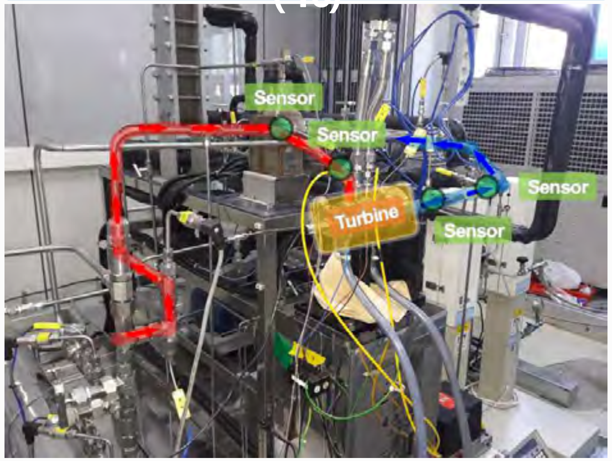


Test loop (500℃, Transcritical)

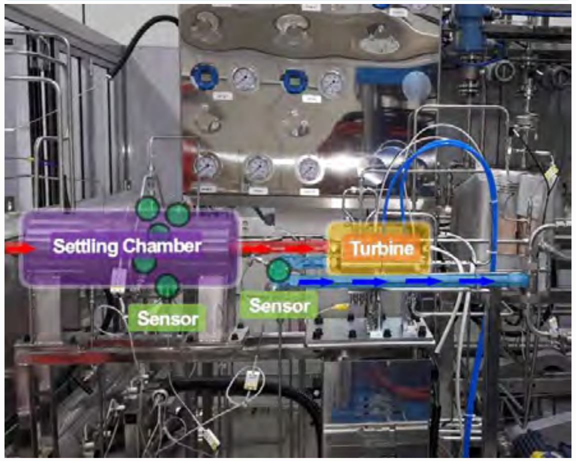
- Settling Chamber at the turbine inlet
  - Uniform Flow
  - Better instrumentation



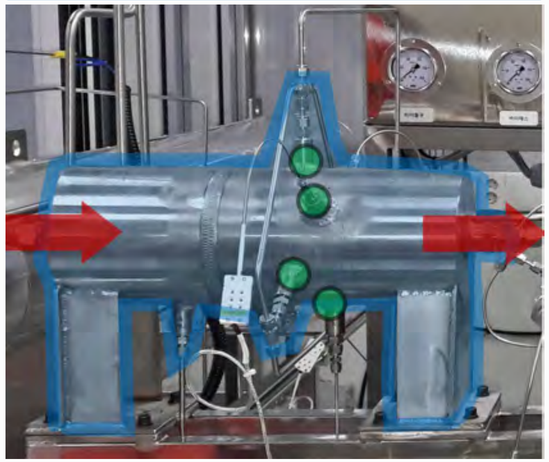
Previous Cycle Loop Test Facility ('16)



Cycle Loop Test Facility ('17)

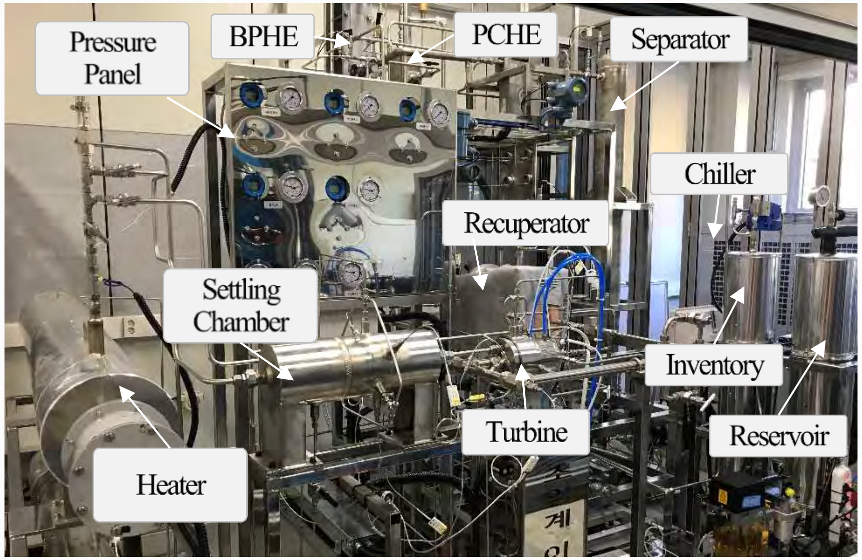


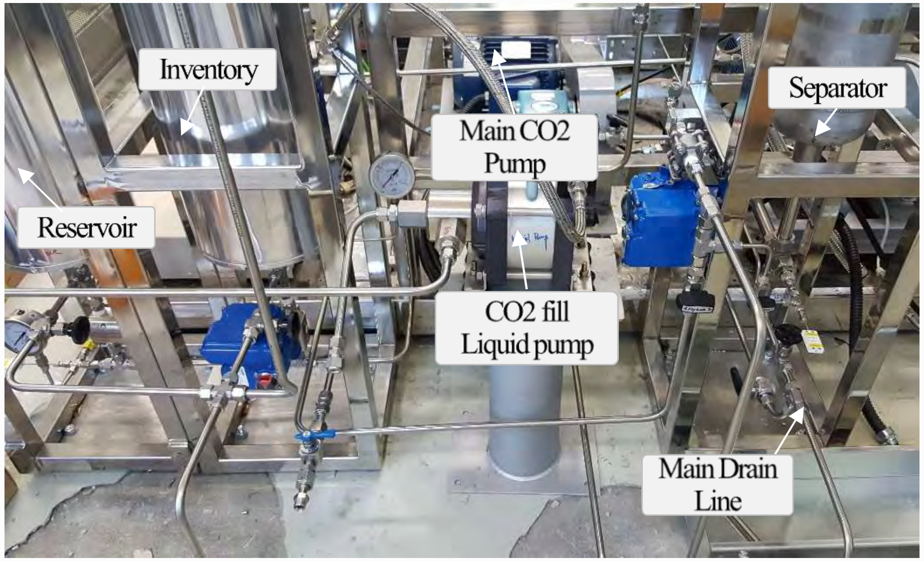
Manufactured Settling Chamber



Test loop (500℃, Transcritical)

- Test loop components



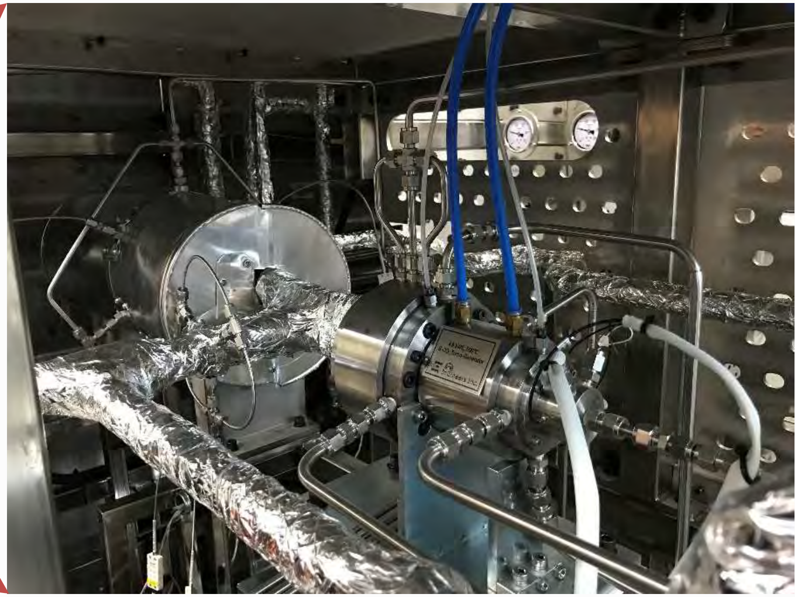


Test Procedure

Valve Test → Emergency test → Leak test → CO_2 Charging mass test → Pump Bypass test → Turbine Bypass test → Heating test → Turbine Driving

Test loop (500℃, Transcritical)

- Final test loop with an insulation & safety fence



KIER

500℃ kWe Test Loop & Radial Turbo-generator

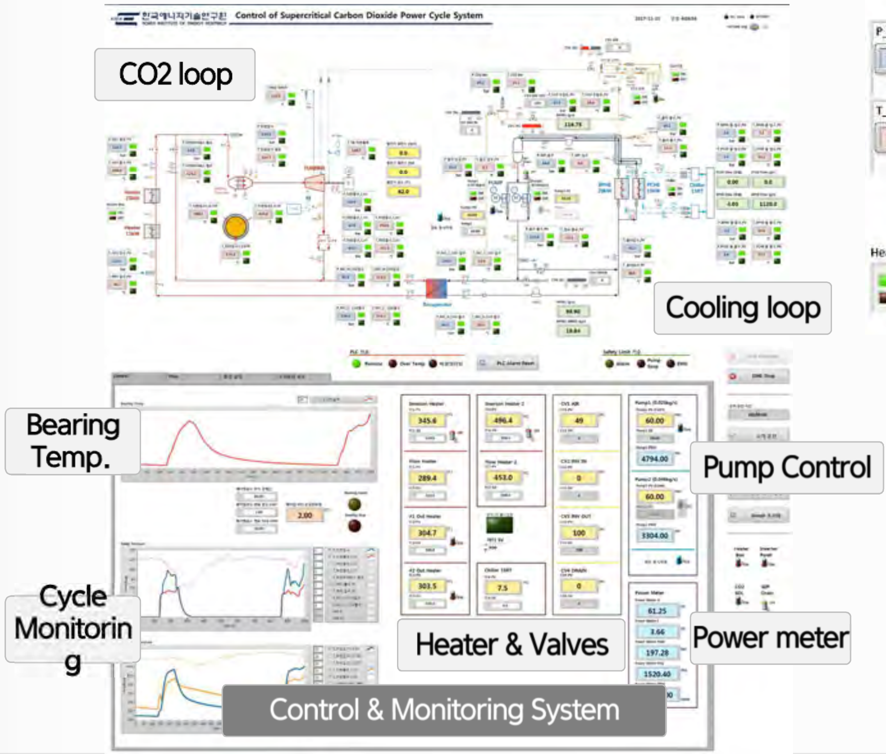
Preliminary Power Generation

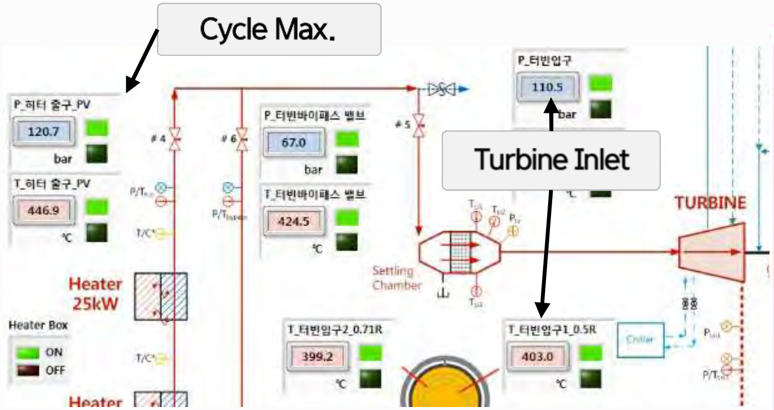
Cycle Max.
127 bar
& 477 ℃

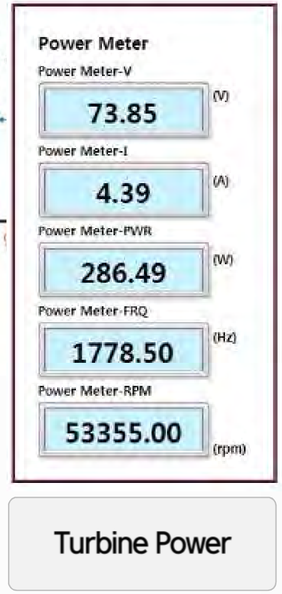
Turbine Inlet
112 bar
& 401 ℃

Turbine Power
287 We

November, 2017

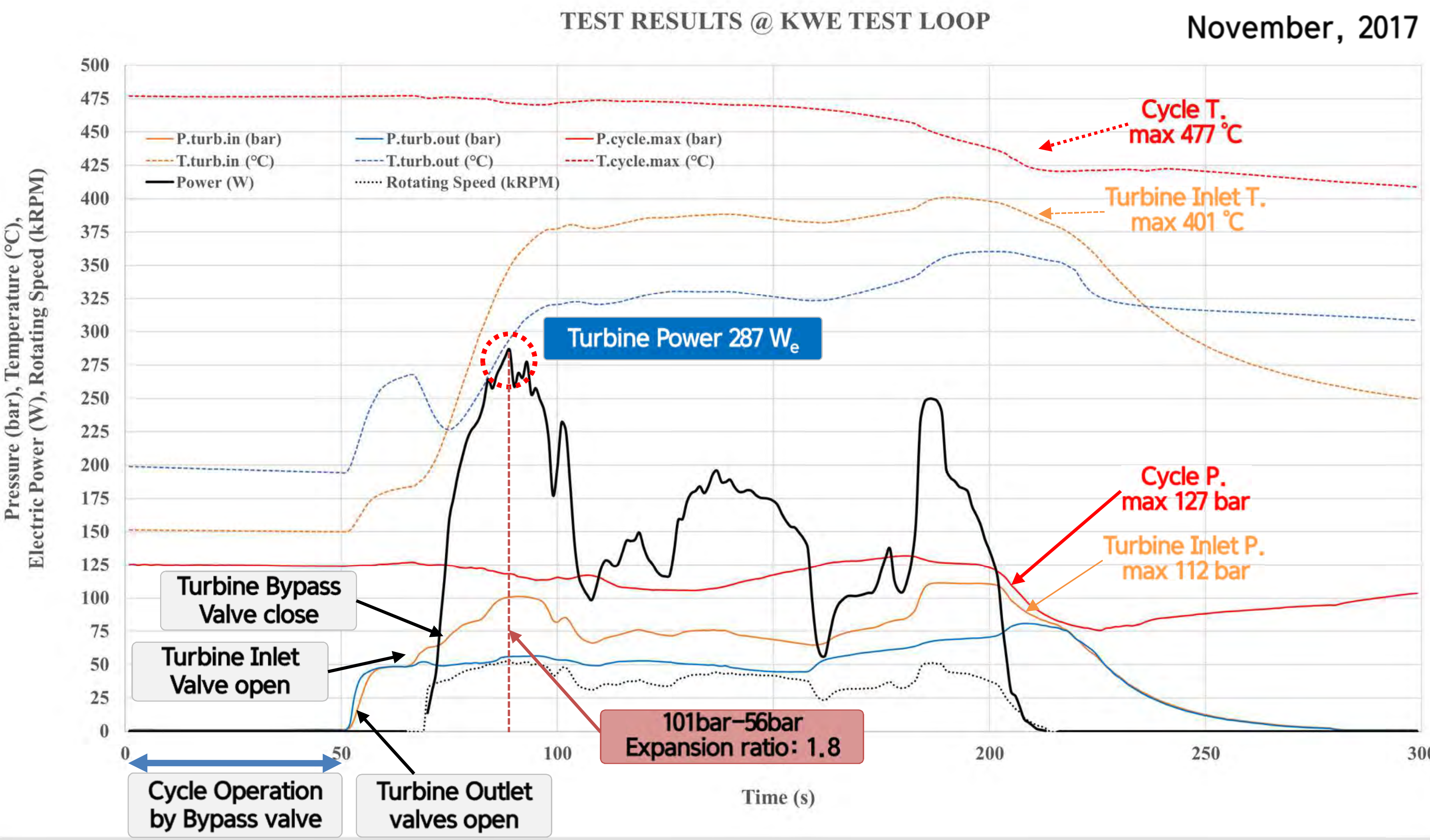






500℃ kWe Test Loop & Radial Turbo-generator

Preliminary Power Generation

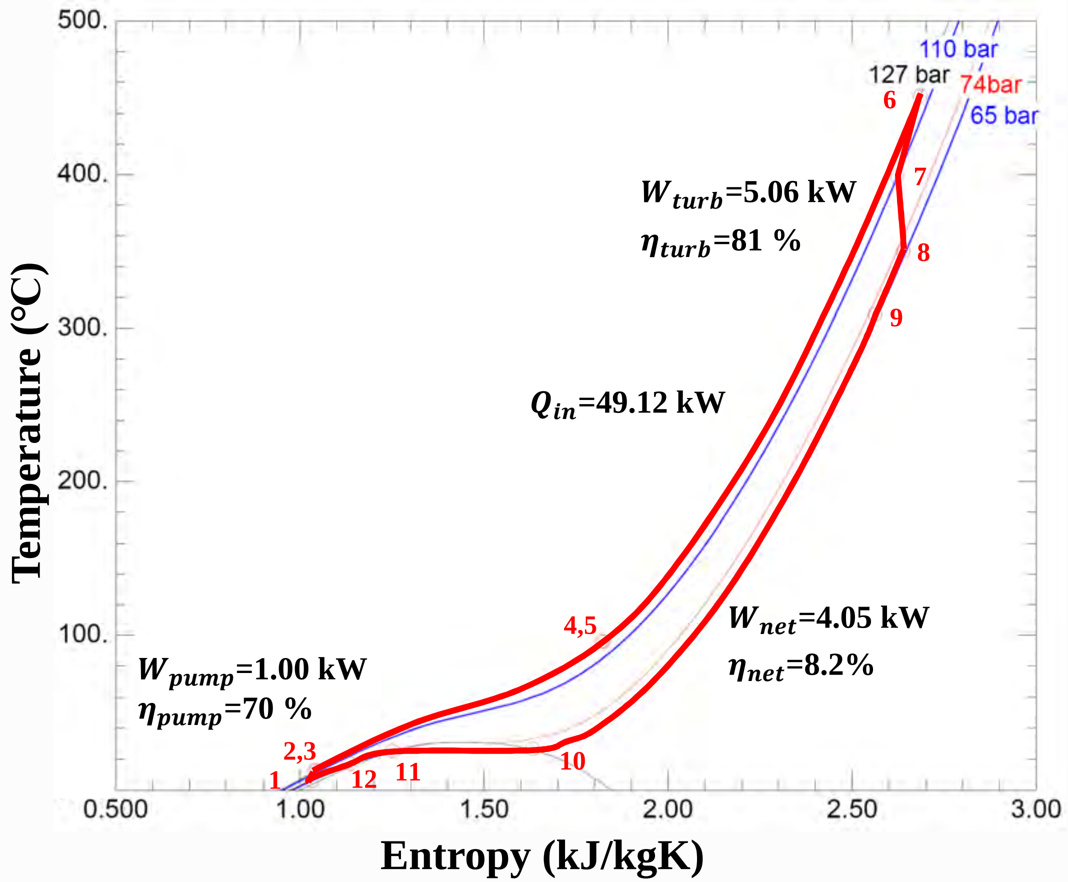


GLOBAL KIER TECHNOLOGIES

500℃ kWe Test Loop & Radial Turbo-generator

Preliminary Power Generation

November, 2017



	Temp. (°C)	Pressure (bar)
1. Pump.Inlet	6.2	64.9
2. Pump.Outlet	12.4	128.2
3. Recup.Cold.Inlet	12.7	126.9
4. Recup.Cold.Outlet	96.3	126.8
5. Heater.Inlet	95.8	124.5
6. Heater.Outlet	451.2	124.5
7. Turbine.Inlet	398.75	110.5
8. Turbine.Outlet	349.9	67.3
9. Recup.Hot.In	309	67.2
10. Recup.Hot.Out	27	67
11. Cooler.Inlet	25.4	65.5
12. Cooler.Outlet	17.1	65.3
Mass flow rate	110.19 g/s	
Turbine Leakage	7.66 g/s (7%)	
Pump Work	1.00 kW	
Pump Efficiency	70 %	
Turbine Work	5.06 kW	
Turbine Efficiency	81 %	
Expansion Ratio	1.64	
Heat In	49.12 kW	
Heat Out	13.61 kW	
Recuperator	38.53 kW (Hot CO2)	
Recuperator Approach Temp.	15 ℃	
Recuperator CO2 pressure drop	0.1 bar (Cold CO2) 0.2 bar (Hot CO2)	
Net Power	4.05 kW	
Net Efficiency	8.2 %	

Chapter 01

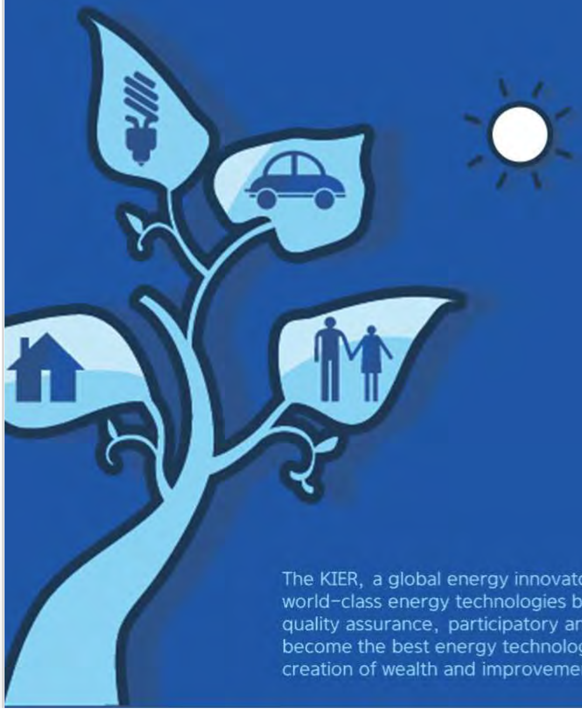
Chapter 02

Chapter 03

KIER

Chapter 04

Summary & Future Works



The KIER, a global energy innovator, does its best in pursuing its mission to invent world-class energy technologies based on open innovation, life-cycle research quality assurance, participatory and open communication. Therefore the KIER will become the best energy technology R&D institute in the world, contributing to the creation of wealth and improvement of quality of life for the people.

Summary

- **KIER's S-CO2 Power Cycle Test Loops :**
  - 2013-2014 : 10 kWe test loop, 200℃
  - 2014-2016 : sub-kWe test loop, 200℃ (Power Generation)
  - 2015-2017 : tens of kWe test loop, 200℃ (Power Generation)

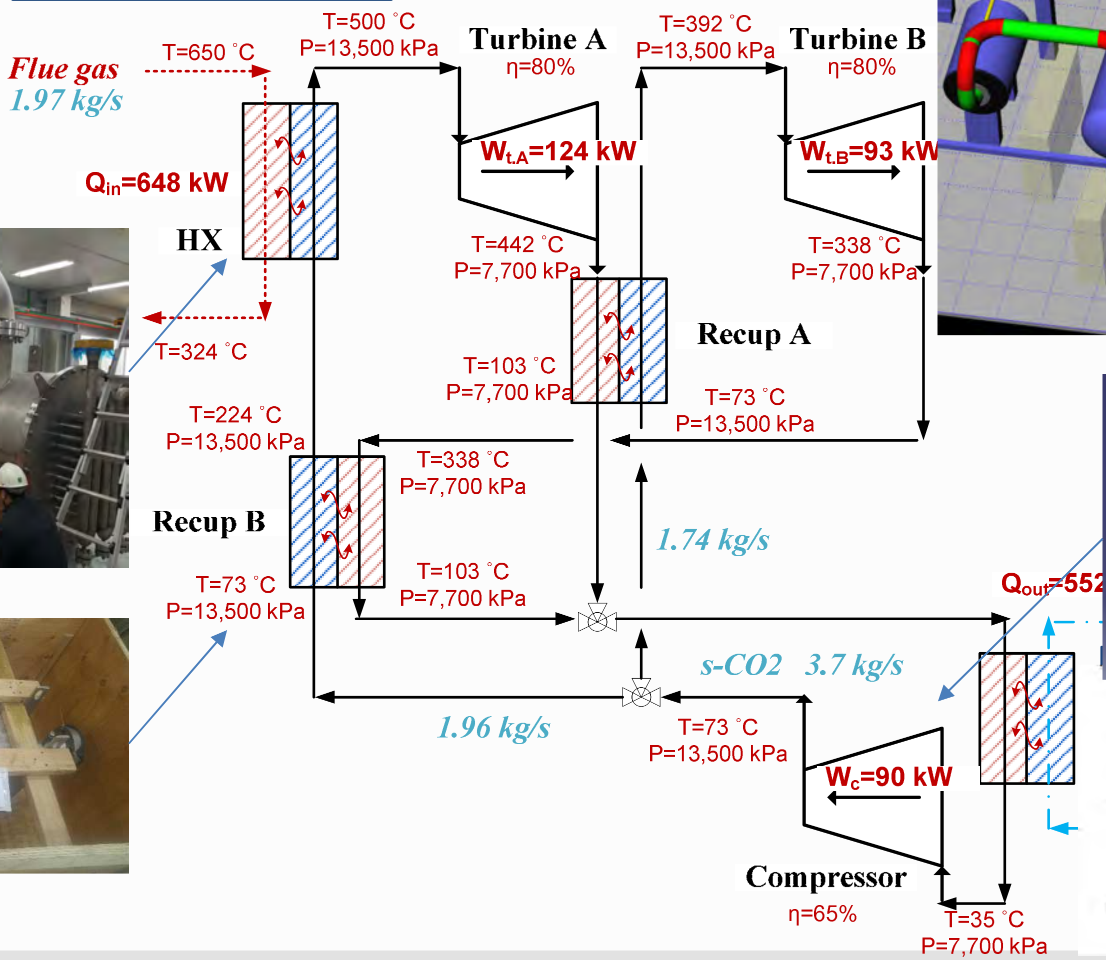
    Axial impulse turbo-generator
  - 2016-2017 : kWe test loop, 500℃ (Power Generation)

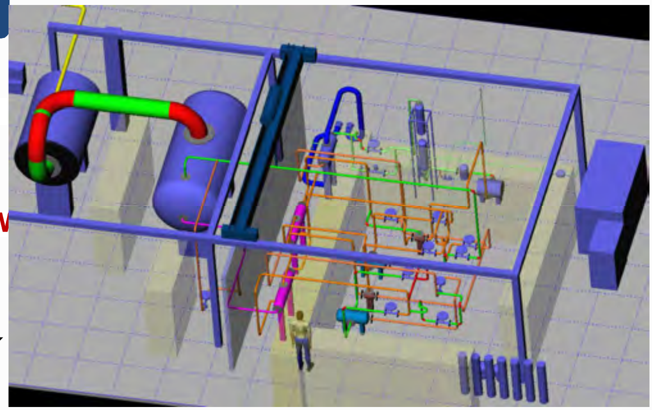
    Radial turbo-generator
  - 2016-2019 : hundred of kWe test loop, 500℃ (under construction)

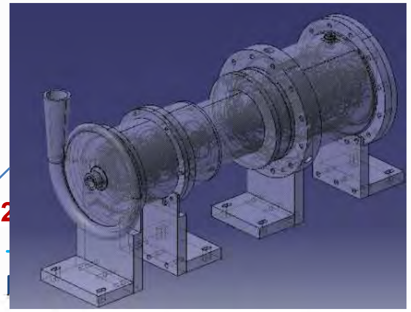
Future Works (In-direct)

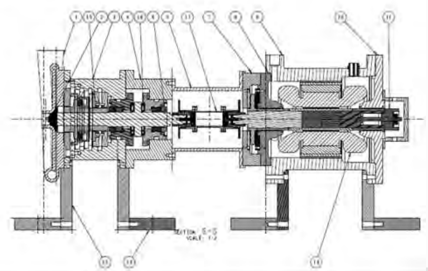
Hundreds of kWe Full Test Loop (500 °C, 2015~2019)

Under Construction









Future Works (Direct)

- **Development of a combustor for direct SCO2 (Allam cycle)**
  - KIER started small project in 2018
  - Development of a basic combustion test loop

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GLOBAL KIER
TECHNOLOGIES

Thank you for your attention

The KIER, a global energy innovator, does its best in pursuing its mission to invent world-class energy technologies based on open innovation, life-cycle research quality assurance, participatory and open communication. Therefore the KIER will become the best energy technology R&D institute in the world, contributing to the creation of wealth and improvement of quality of life for the people.