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

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01 Introduction of KIER’s S-CO2 R&D
02 tens of kWe Test Loop & Axial Turbo-generator
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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-CO₂ Power Cycle Systems in the world


**SNL (250kWe)**
477°C/105bar/15kWe
*05 ~ 10 Single Comp.*
*10 TAC*
*11 RCBC/2 TAC/GFB*
*13 480°C/105bar/15kWe*
*14 100kWh*
*16 500kWh*

**Naval Nuclear Lab. (Bechtel) (100kWe)**
282°C/141bar/40kWe
*09 ~ 11 1 TC, 1 TG, GFB*
*14 282°C/141bar/40kWe*
*16 226°C/139bar/40kWe*

**TIT (10kWe)**
260°C/105bar/0.11kWe
*07 ~ 12 1 TAC, Gas bearing, 260°C/105bar/0.11kWe*

**KIER (~ hundreds of kWe)**
@sub-kWe, 170°C/101bar/0.67kWe (turbine)
@tens of kW, 205°C/100bar/11kWe (turbine)
@kWe, 401°C/100bar/287We (turbine)
*13 ~ 14 10kWe, TAC, GFB, 85°C/85bar/30,000rpm*
*14 ~ 16 1kWe TG(Radial), ACB, 170°C/101bar/67kWe (turbine)*
*15 ~ 17 60kWe TG(Axial), TPB, 225°C/100bar/11kWe (turbine)*
*16 ~ 17 8kWe TG(Radial), ACB, 401°C/100bar/267We (turbine)*

**SwRI/GE (1MWe)**
715°C/250bar/under commissioning
*12 ~ 17 1 Turbo-expander, DGS, TPB, 1 Compressor, 700°C/250bar/under commissioning*

**Echogen (8MWe)**
275°C/? bar/2, 35MWe
*14 1 turbo-pump (hermetic), 1 Power Turbine (DGS, TPB)*
*TIT design 485°C / Test 275°C/2, 35MWe*

*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*

U.S., 10MWe Pilot Plant Project Leading Group

1~2 phase: 500°C
3 phase: 700°C
KIER S-CO2 Project Overview

- 2013-2014: 10 kWe test loop, 200°C (Preliminary Operation)
- 2014-2016: sub-kWe test loop, 200°C (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°C (Power Generation)
- 2016-2017: kWe test loop, 500°C (Power Generation)
- 2016-2019: hundreds of kWe test loop, 500°C (under construction)
### Introduction of KIER's S-CO2 R&D

#### KIER S-CO2 Test loops

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

**Under Construction**

**Flue gas**

1.97 kg/s

Q_{in}=648 kW

**Overlap**

1.96 kg/s

**HX**

T=650 °C
P=13,500 kPa

T=324 °C

T=224 °C
P=13,500 kPa

T=103 °C
P=7,700 kPa

T=73 °C
P=13,500 kPa

**Recup B**

**Turbine A**

W_{A}=124 kW

n=80%

T=500 °C
P=13,500 kPa

T=442 °C
P=7,700 kPa

T=103 °C
P=7,700 kPa

T=73 °C
P=13,500 kPa

**Recup A**

**Turbine B**

W_{B}=93 kW

n=80%

T=382 °C
P=13,500 kPa

T=338 °C
P=7,700 kPa

T=73 °C
P=13,500 kPa

**Present Work**

**1st target**


**Axial-type Turbo-generator**

**200 °C off-design operation**

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

**Compressor**

W_{c}=90 kW

n=65%

T=35 °C
P=7,700 kPa

**Cooling tower**

Q_{out}=552 kW

s-CO2 3.7 kg/s
**Technical Issues in S-CO₂ Turbomachinery**

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

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

**Gas Foil Bearing Failure**
- Gas-foil bearing failure @ high temp.
  - SNL reports, NASA report
- High thrust occurs, but very weak

**KIER Strategy**

**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**

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[S. Wright, SNL, 2011]


[K. Radil et al., ARL-MR-0749, NASA, 2010]

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

[K. Radil et al., ARL-MR-0749, NASA, 2010]
KIER S-CO₂ 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
Pressure Vessel & Piping as ASME code guideline
- 2” SUS304, ANSI Flanges 1500, 2500 CLS
- Metal Gaskets for CO₂
- Air-driven Control Valves
- Cryogenic Valves & Regulators
Tens of kWe Test Loop & Axial Turbo-generator

Test loop (200°C off-design, Transcritical)
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
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
  \(\rightarrow\) Inverter driving was necessary at the start
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.

July, 2017
Tens of kWe Test Loop & Axial Turbo-generator

Preliminary Power Generation

**TEST RESULTS @ TENS OF KWE TEST LOOP**

*July, 2017*

- P.cycle.max (bar)
- T.cycle.max (C)
- P.turb.in (bar)
- T.turb.in (C)
- Electric Power (x100W)

**Graph Annotations:***
- **Turbine Inlet (°C)** max 205 °C
- **Turbine Inlet (bar)** max 100 bar
- **Electric Power (x100W)** max 11 kWe
- **Cycle Operation by Bypass valve**
- **Pump speed control**
- **Turbine valves open**
- **Load control**

**Text on Graph:**
- Electric Power Generation: 45 min
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
Chapter 03

500°C kWe Test Loop & Radial Turbo-generator

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- 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
Settling Chamber at the turbine inlet
- Uniform Flow
- Better instrumentation
500°C kWe Test Loop & Radial Turbo-generator

Test loop (500°C, Transcritical)

- Test loop components

- Test Procedure

Valve Test → Emergency test → Leak test → CO₂ Charging mass test → Pump Bypass test → Turbine Bypass test → Heating test → Turbine Driving
500°C kWe Test Loop & Radial Turbo-generator

Test loop (500°C, Transcritical)

- Final test loop with an insulation & safety fence
500°C kWe Test Loop & Radial Turbo-generator

Preliminary Power Generation

Cycle Max.
127 bar & 477 °C

Turbine Inlet
112 bar & 401 °C

Turbine Power
287 We

November, 2017
500°C kWe Test Loop & Radial Turbo–generator

Preliminary Power Generation

TEST RESULTS @ KWE TEST LOOP

November, 2017

- Cycle T. max 477 °C
- Turbine Inlet T. max 401 °C
- Cycle P. max 127 bar
- Turbine Inlet P. max 112 bar
- Turbine Power 287 Wₜ
- 101bar–56bar Expansion ratio: 1.8

- Turbine Bypass Valve close
- Turbine Inlet Valve open
- Cycle Operation by Bypass valve
- Turbine Outlet valves open

KIER

Global Kier Technologies
### 500°C kWe Test Loop & Radial Turbo-generator

#### Preliminary Power Generation

**November, 2017**

- **Heat In**: 49.12 kW
- **Heat Out**: 13.61 kW
- **Recuperator**: 38.53 kW (Hot CO2)
- **Net Power**: 4.05 kW
- **Net Efficiency**: 8.2%

<table>
<thead>
<tr>
<th></th>
<th>Temp. (℃)</th>
<th>Pressure (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pump.Inlet</td>
<td>6.2</td>
<td>64.9</td>
</tr>
<tr>
<td>2. Pump.Outlet</td>
<td>12.4</td>
<td>128.2</td>
</tr>
<tr>
<td>3. Recup.Cold.Inlet</td>
<td>12.7</td>
<td>126.9</td>
</tr>
<tr>
<td>4. Recup.Cold.Outlet</td>
<td>96.3</td>
<td>126.8</td>
</tr>
<tr>
<td>5. Heater.Inlet</td>
<td>95.8</td>
<td>124.5</td>
</tr>
<tr>
<td>7. Turbine.Inlet</td>
<td>398.75</td>
<td>110.5</td>
</tr>
<tr>
<td>8. Turbine.Outlet</td>
<td>349.9</td>
<td>67.3</td>
</tr>
<tr>
<td>11. Cooler.Inlet</td>
<td>25.4</td>
<td>65.5</td>
</tr>
<tr>
<td>12. Cooler.Outlet</td>
<td>17.1</td>
<td>65.3</td>
</tr>
</tbody>
</table>

**Mass flow rate**: 110.19 g/s

**Turbine Leakage**: 7.66 g/s (7%)  

### Parameters

- **Turbine Work**: 5.06 kW  
- **Turbine Efficiency**: 81%  
- **Expansion Ratio**: 1.64  
- **Heat In**: 49.12 kW  
- **Heat Out**: 13.61 kW  
- **Recuperator Approach Temp.**: 15 °C  
- **Recuperator CO2 pressure drop**: 0.1 bar (Cold CO2)  
- **Recuperator CO2 pressure drop**: 0.2 bar (Hot CO2)  
- **Net Power**: 4.05 kW  
- **Net Efficiency**: 8.2%
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.
KIER’s S-CO2 Power Cycle Test Loops:

- **2013-2014**: 10 kWe test loop, 200°C
- **2014-2016**: sub-kWe test loop, 200°C (Power Generation)
- **2015-2017**: tens of kWe test loop, 200°C (Power Generation)
  - Axial impulse turbo-generator
- **2016-2017**: kWe test loop, 500°C (Power Generation)
  - Radial turbo-generator
- **2016-2019**: hundred of kWe test loop, 500°C (under construction)
Future Works (In-direct)

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

Flue gas 1.97 kg/s

\( Q_{in} = 648 \text{ kW} \)

\( T = 650^\circ C \)
\( P = 13,500 \text{ kPa} \)

\( T = 500^\circ C \)
\( P = 13,500 \text{ kPa} \)

Turbine A
\( \eta = 80\% \)
\( W_A = 124 \text{ kW} \)

\( T = 442^\circ C \)
\( P = 7,700 \text{ kPa} \)

\( T = 392^\circ C \)
\( P = 13,500 \text{ kPa} \)

Turbine B
\( \eta = 80\% \)
\( W_B = 93 \text{ kW} \)

\( T = 338^\circ C \)
\( P = 7,700 \text{ kPa} \)

\( T = 338^\circ C \)
\( P = 7,700 \text{ kPa} \)

Recup A
\( 1.74 \text{ kg/s} \)

\( T = 33^\circ C \)
\( P = 13,500 \text{ kPa} \)

\( T = 73^\circ C \)
\( P = 13,500 \text{ kPa} \)

Recup B
\( 1.96 \text{ kg/s} \)

\( T = 73^\circ C \)
\( P = 13,500 \text{ kPa} \)

\( T = 224^\circ C \)
\( P = 13,500 \text{ kPa} \)

\( T = 324^\circ C \)

\( Q_{in} = 648 \text{ kW} \)

\( s\text{-CO}_2 \)
\( 3.7 \text{ kg/s} \)

\( T = 73^\circ C \)
\( P = 13,500 \text{ kPa} \)

\( T = 73^\circ C \)
\( P = 13,500 \text{ kPa} \)

Compressor
\( \eta = 65\% \)
\( W_c = 90 \text{ kW} \)

\( T = 35^\circ C \)
\( P = 7,700 \text{ kPa} \)

\( Q_{out} = 552 \text{ kW} \)
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
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.