sCO2 europe

3rd European Conference on Supercritical CO_2 Power Systems in Paris

GLOBAL KIER
TECHNOLOGIES

2019. 9. 19.

DEVELOPMENT OF A PARTIAL-ADMISSION AXIAL TURBINE FOR A TENS-KWE UNDER SUPERCRITICAL CO_2 CONDITION

[Government Funded Institute]
Korea Institute of Energy Research [KIeR]

Jongjae Cho · Hyungki Shin · Junhyun Cho · Bongsu Choi ·
Beomjoon Lee · Chulwoo Roh · Ho-Sang Ra · Young-Jin Baik†

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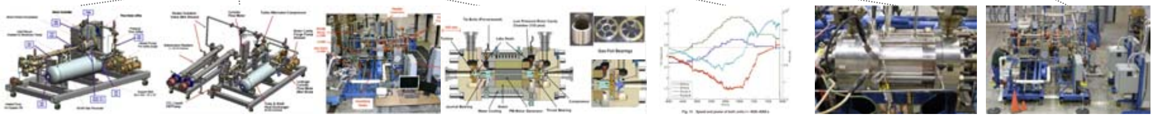
Supercritical CO_2 Power Generation Cycle

Research & Development Status of sCO_2 Power Generation Cycle

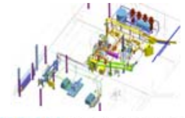
2005 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019+

SNL (250kWe)
477°C/105bar/15kWe



`05-`10 Single Comp. `10 1 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/136bar/40kWe

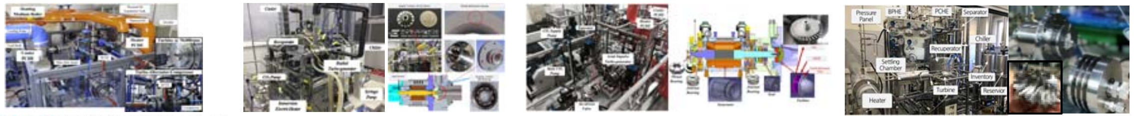
TIT (10kWe)
260°C/105bar/0.11kWe

`07-`12 1 TAC, Gas bearing, 260°C/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

KIER (~ hundreds of kWe)
@sub-kWe,170°C/101bar/0.67kWe(turbine)
@tens of kWe,216°C/123bar/12.6kWe(turbine)
@kWe, 401°C/100bar/287We(turbine)



`13-`14 10kWe, TAC, GFB, 83°C/85bar/30,000rpm

`14-`16 1kWe TG(Radial), ACB, 170°C/101bar/670We(turbine)

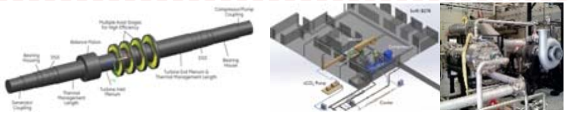
`15-`17 60kWe TG(Axial), TPB 205°C/100bar/11kWe(turbine)

`16-`17 5kWe TG(Radial), ACB, 401°C/100bar/287We(turbine)

Hundreds of kWe /500°C/130bar

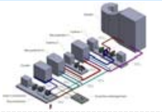
2 turbine
1 compressor

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



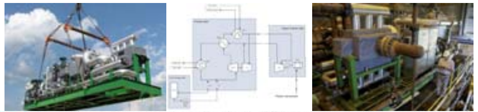
`12~`17 1 Turbo-expander, DGS, TPB,
1 Compressor, 700°C/250bar/under commissioning

U.S. 10MWe Pilot Plant Project Leading Group



1-2 phase: 500°C
3 phase: 700°C

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

Supercritical CO_2 Power Generation Cycle

KIER's sCO_2 Research Project Overview

- Budget : $2M / yr
- Research Period : 2015 ~ 2019 (5 years project)
- KIER's sCO_2 Power Generation Cycle Test Loops
  - 2013 ~ 2014 : 10 kWe test loop, 200 ℃

    Radial type turbine + Alternator + Centrifugal Compressor **(T-A-C)**
  - 2014 ~ 2016 : Sub-kWe test loop, **200** ℃ ➔ Power generation (Max. 670 We)

    Radial type turbine + Generator **(T-G)**
  - **"2015 ~ 2018 : Tens of kWe test loop, 200 ℃ ➔ Power generation"**

    Axial type turbine (Impulse) + Generator **(T-G)**
  - 2016 ~ 2018 : kWe test loop, **500** ℃ ➔ Power generation

    Radial type turbine + Generator **(T-G)**
  - **2016 ~ 2019 : Hundred of kWe test loop, 500 ℃ ➔ Under construction**

4hrs. 12 mins.
Max. 12.6 kWe

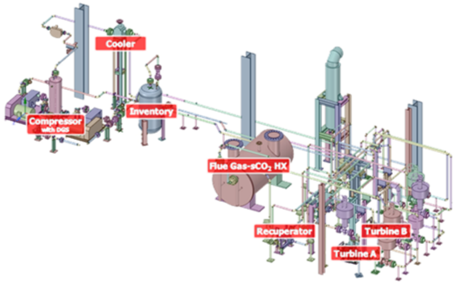
Large Scale

- Long Time Operation
- Robustness
- Reliability
- Control System

Small Scale

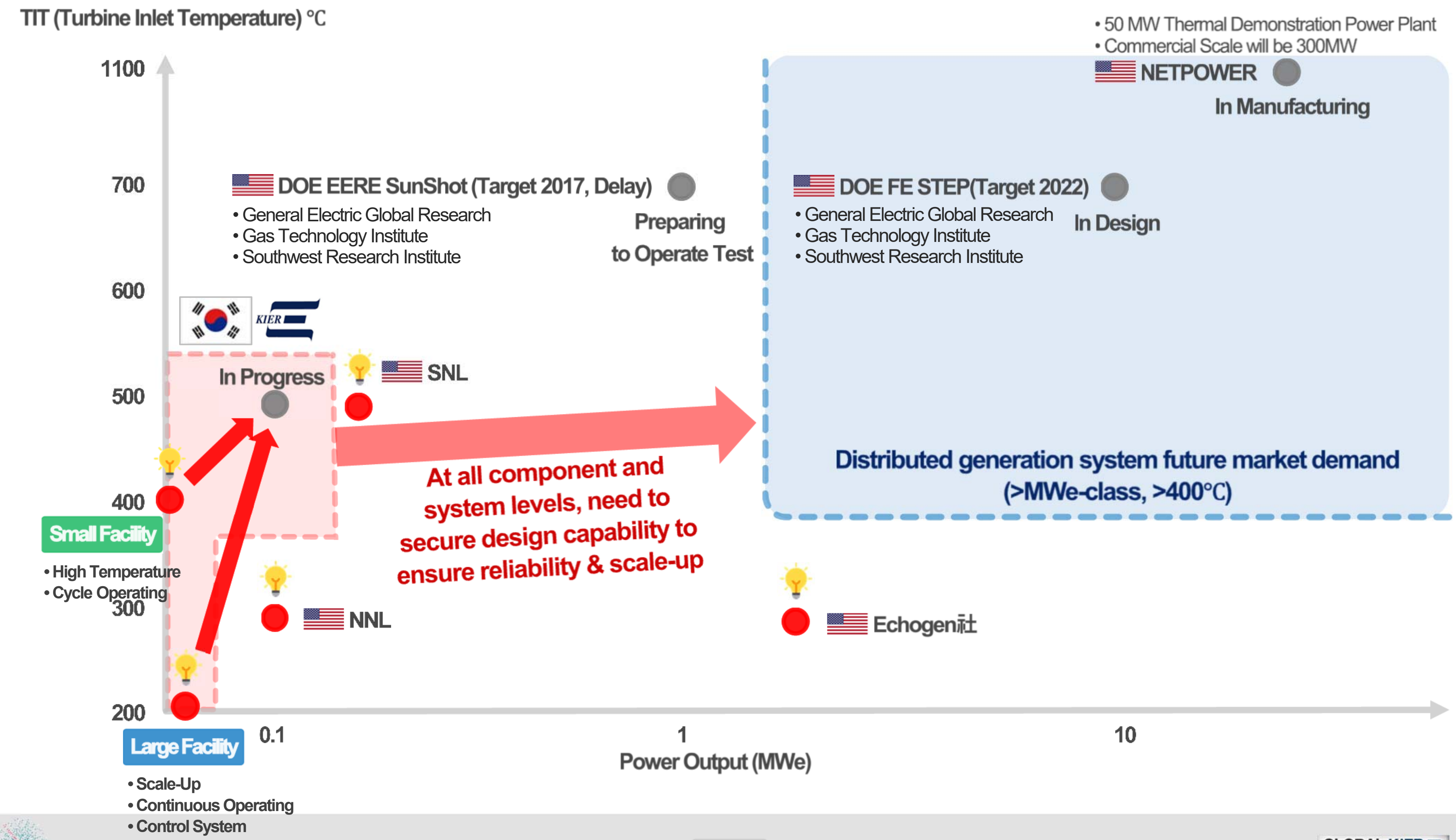
Cycle Operating Know-How

Presentation Today



Supercritical CO_2 Power Generation Cycle

Research & Development Status of sCO_2 Power Generation Cycle



- 50 MW Thermal Demonstration Power Plant
- Commercial Scale will be 300MW

NETPOWER

In Manufacturing

DOE EERE SunShot (Target 2017, Delay)

- General Electric Global Research
- Gas Technology Institute
- Southwest Research Institute

Preparing to Operate Test

DOE FE STEP(Target 2022)

- General Electric Global Research
- Gas Technology Institute
- Southwest Research Institute

In Design

At all component and system levels, need to secure design capability to ensure reliability & scale-up

Distributed generation system future market demand (>MWe-class, >400℃)

Small Facility

- High Temperature
- Cycle Operating

Large Facility

- Scale-Up
- Continuous Operating
- Control System

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Chapter 02

Design and Numerical Simulation of sCO_2 Turbine

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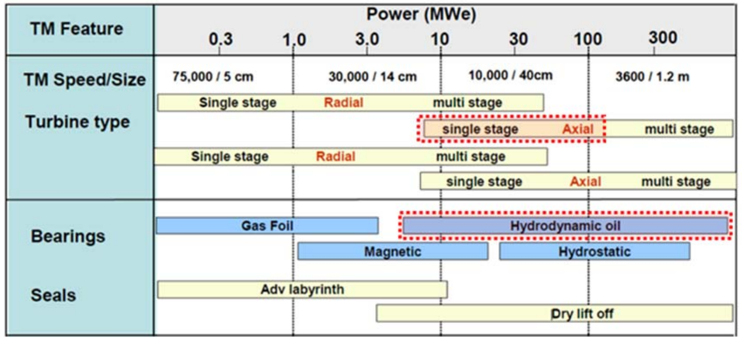
Design & Numerical Simulation of sCO_2 Turbine

Design Conditions and Results of sCO_2 Turbine

- Turbine Type : Single Stage Axial Turbine + Impulse Type
- Rotor Wheel Mean Diameter : 73 mm
- Rotor Blade Height : 8.36 mm
- Efficiency (η_{TT}) on the design point (U/C_{0S} : 0.54)

➔ **Almost meets the target efficiency**

Scaling considerations for sCO_2 cycle 1)

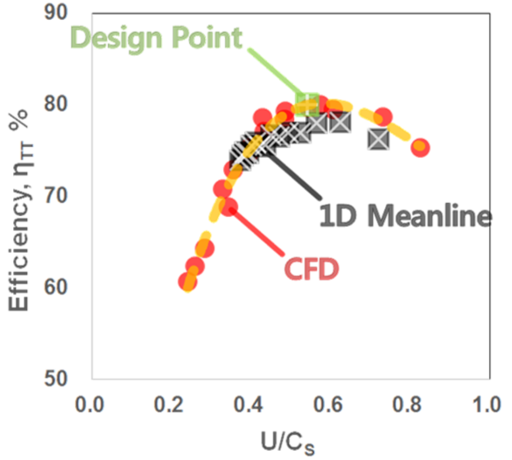


Design Conditions

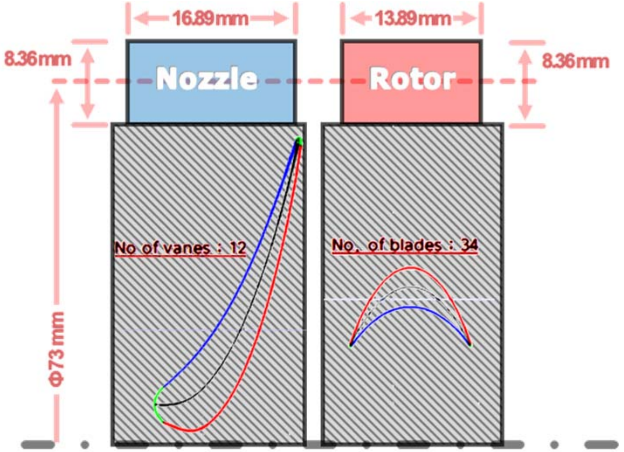
• Inlet Total Pressure [bar]	135
• Inlet Total Temperature [℃]	392
• Pressure Ratio	1.75
• Rotating Speed [rpm]	45000

※ Max. Rotational Speed of TPB

U/C_{0S} vs Efficiency



Turbine Shape



1) Fleming, D., Conboy, T., Pash, J., Rochau, G., Fuller, R., Holschuh, T., Wright, S., 2013, "Scaling considerations for a multi-megawatt class supercritical CO2 Brayton cycle and commercialization," Sandia National Laboratories, Albuquerque, NM.

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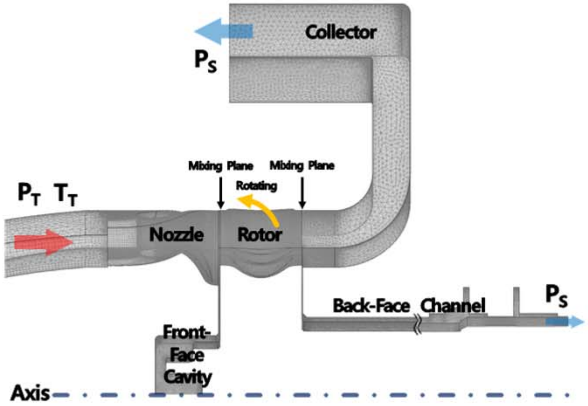
Design & Numerical Simulation of sCO_2 Turbine

Rotor Wheel Axial Force Characteristics

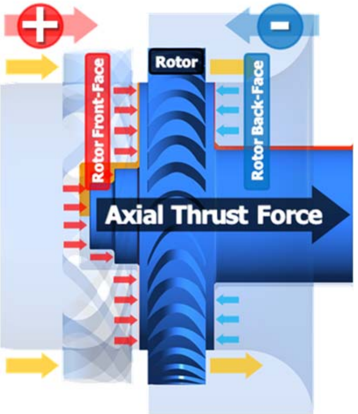
- Axial force acts from rotor front-face to its back-face
  - Area of Rotor Back-Face < Rotor Front-Face
- In despite of Impulse type turbine design, high pressure acts on tie-shaft of rotor front-face
- Adjust rotor wheel front & back face axial gaps

➔ **Axial Force on Rotor Wheel : 3.28 → 1.87 kN**

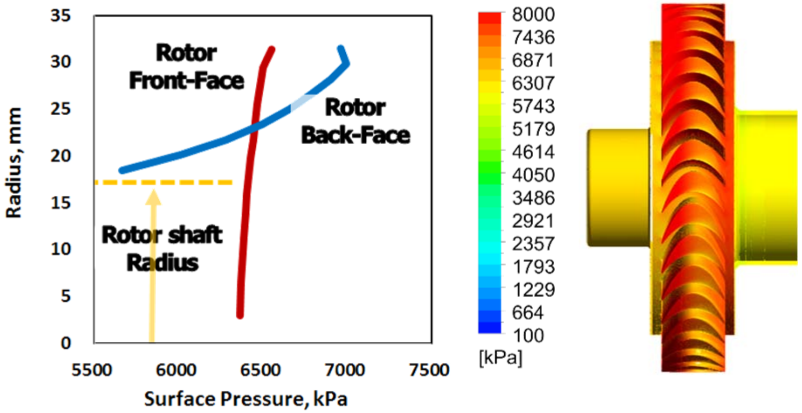
Numerical Domain



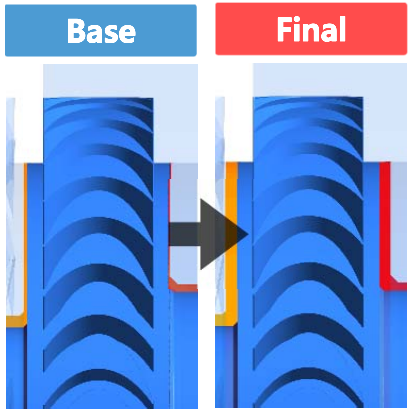
Axial Force Loading

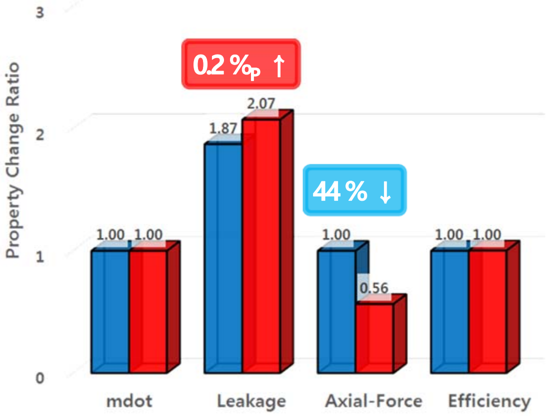


Surface Pressure @ Design Point



Comparison Cases





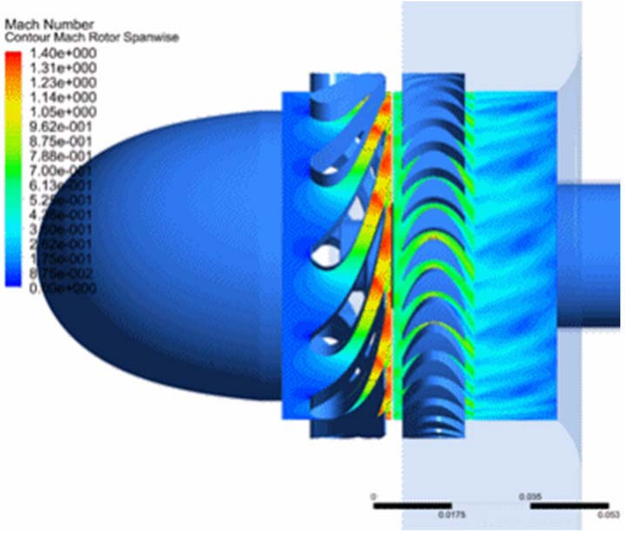
Design & Numerical Simulation of sCO_2 Turbine

Performance Characteristics according to Partial Admission Ratio

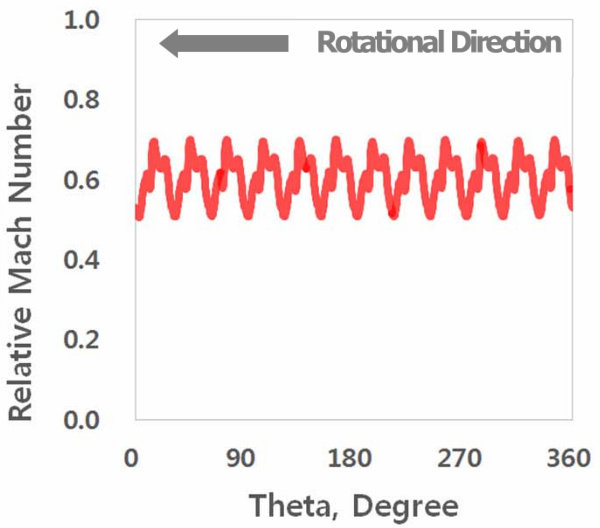
※ The turbine tests on “Partial Admission & Off-Design Condition”, because of limited capacity for performance test facility

- At partial admission conditions, Scavenge + Eddy + Diffusion + Pumping Losses are generated
- At small partial admission ratio
  - The change of filling and emptying area is almost same ➔ The change in “Scavenge & Eddy Loss & Diffusion ” value is small
  - Partial admission ratio ↓ ➔ Pumping loss ↑
- At full admission condition, Scavenge / Eddy / Diffusion / Pumping losses are not generated

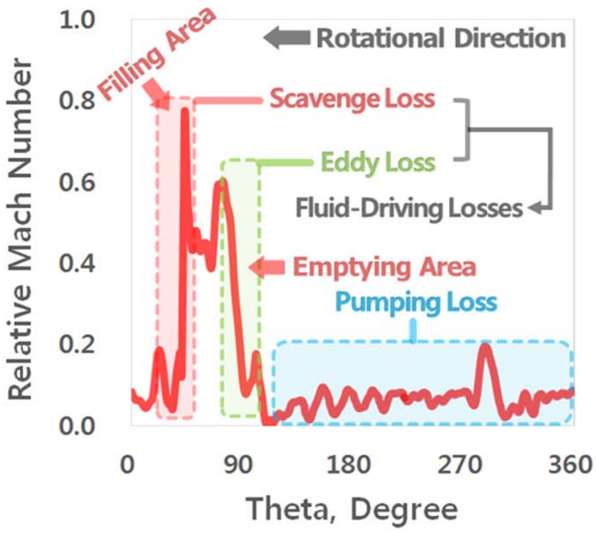
Mach Number Contour @ 50% Span



Circumferential Relative Mach Number @ Rotor Inlet



Partial Admission Losses



Design & Numerical Simulation of sCO_2 Turbine

Performance Characteristics according to Partial Admission Ratio

- Partial Admission Ratio ↓
  - By the partial admission losses, turbine efficiency ↓
  - Seal leakage flow ratio ≒ F. A. Condition
  - Axial Thrust Force ≒ F. A. Condition
- Change in efficiency according to partial admission ratio
  - CFD Results / Partial Admission Loss Equation [2] are well agree with Experimental Results [1]

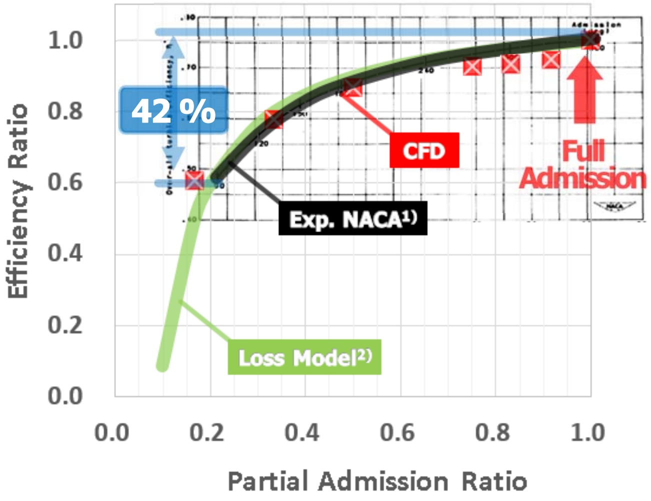
※ NACA Technical Report 1807

[P.A. Ratio 1.0 → 0.17]

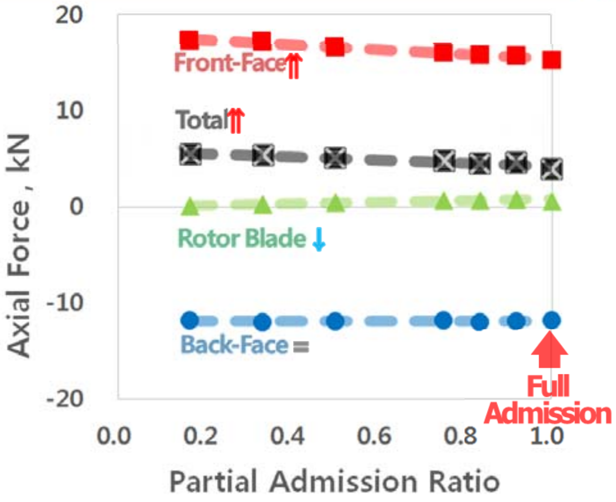
- Efficiency : 42% ↓
- Leakage Flow ≒ F. A.
- Axial Thrust Force ≒ F. A.

→ Correlation Derivation

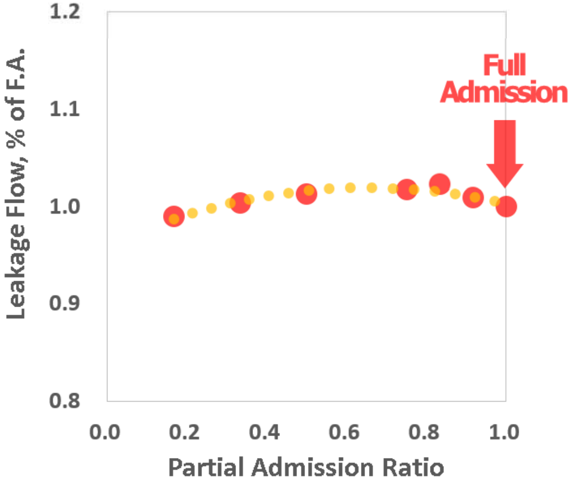
Efficiency Change according to P.A. Ratio



Axial Thrust Force @ Each Face



Leakage Flow Change according to P.A. Ratio



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[1] Kohl, R., Herzig, H., Whitney, W., 1949, "Effects of Partial Admission on Performance of a Gas Turbine," NACA Technical Report Note 1807. U/C_{0S} 0.483 0.555

[2] Technical Report, KeRC, Moscow

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Chapter 03

Supercritical CO_2 Power Generation Cycle Test Facility & Test Results

Chapter
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sCO_2 P/G Cycle Test Facility & Test Results

Tens of kWe Test Loop Facility (Turbine System)

- Turbine Type : Single Stage Axial Turbine + Impulse Type + Partial Admission[0.17]
- Seal : Carbon Mechanical Seals
- Bearing : Oil Lubricated Tilting Pad Journal & Thrust Bearing

※ Max. Rotational Speed : 45000 rpm

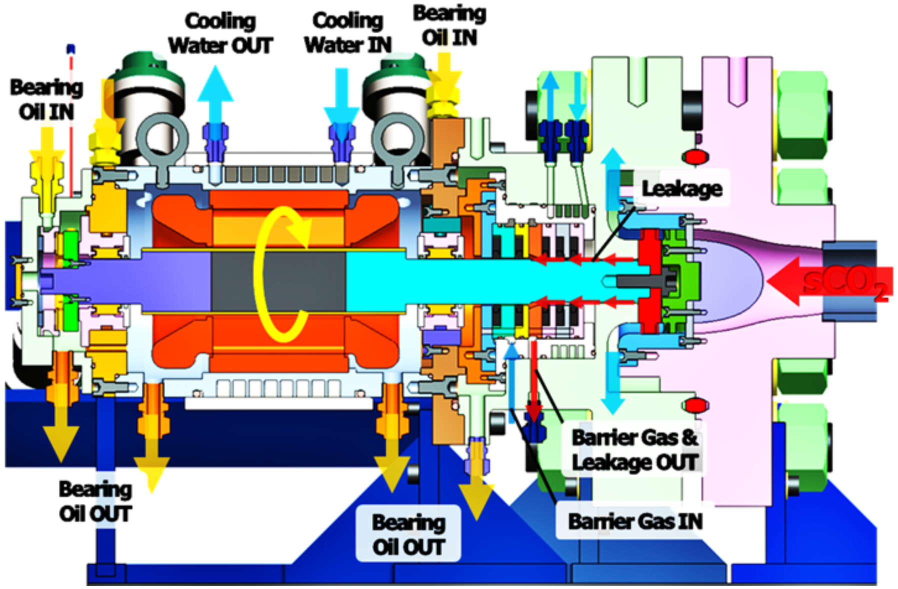
Limitation of Test Loop Capacity

Scale-up

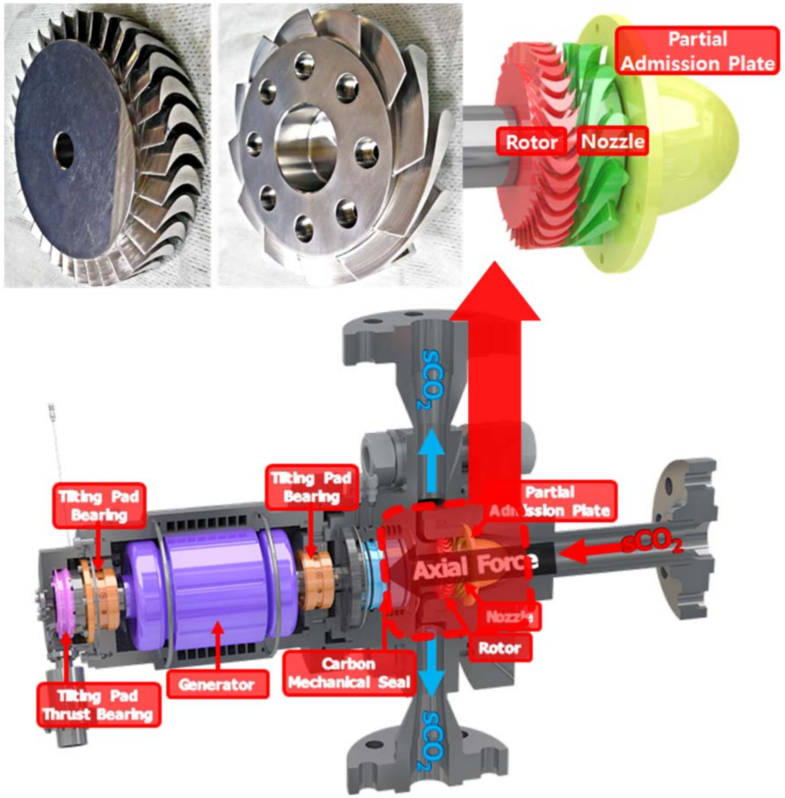
Minimize Axial Thrust Force

Reliability & Scale-up

Flow Diagram of the sCO_2 Turbine System



Layout of Turbo Generator



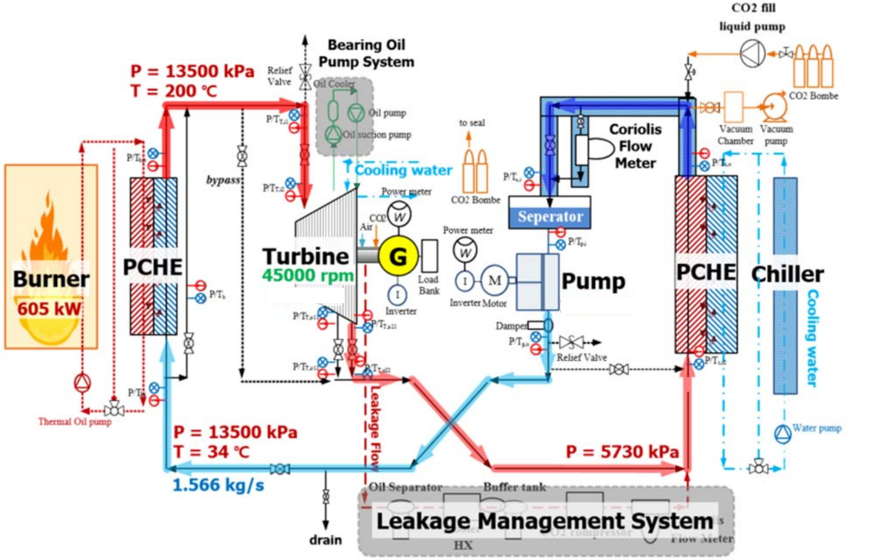
1) Fleming, D., Conboy, T., Pash, J., Rochau, G., Fuller, R., Holschuh, T., Wright, S., 2013, “Scaling considerations for a multi-megawatt class supercritical CO2 Brayton cycle and commercialization,” Sandia National Laboratories, Albuquerque, NM.

sCO_2 P/G Cycle Test Facility & Test Results

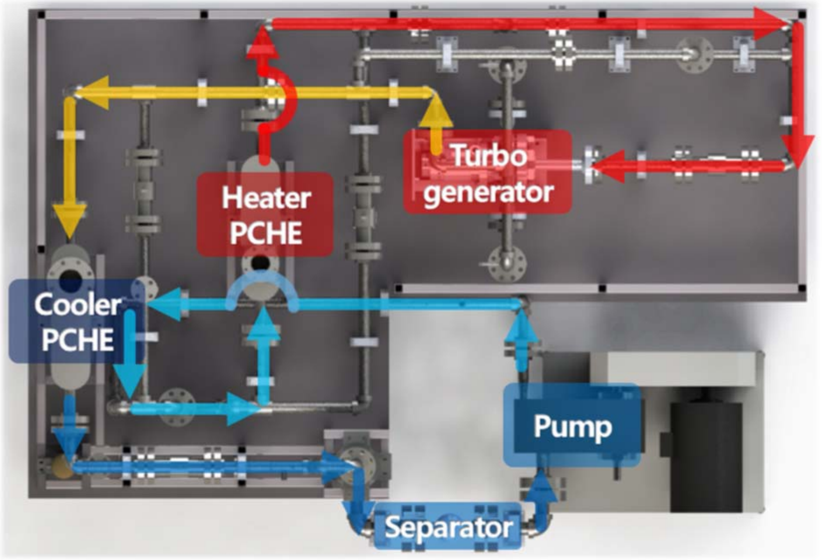
Tens of kWe Test Loop Facility (Transcritical cycle)

- Configuration
  - Burner (LNG-fired thermal oil boiler), PCHE(Cooler, Heater), Turbine, Generator, Pump, Chiller, Leakage Management System
- DAQ & Control System : NI Labview^{TM} + PLC
- Test Conditions
  - Working Fluid : CO_2 / Turbine Inlet Pressure : 135 bar (PR_{TS} 2.36) / Turbine Inlet Temperature : 200 ℃ / Mass Flow Rate : 1.57 kg/sec

Tens of kWe Test Loop for Turbine "B"



Tens of kWe Test Loop Facility

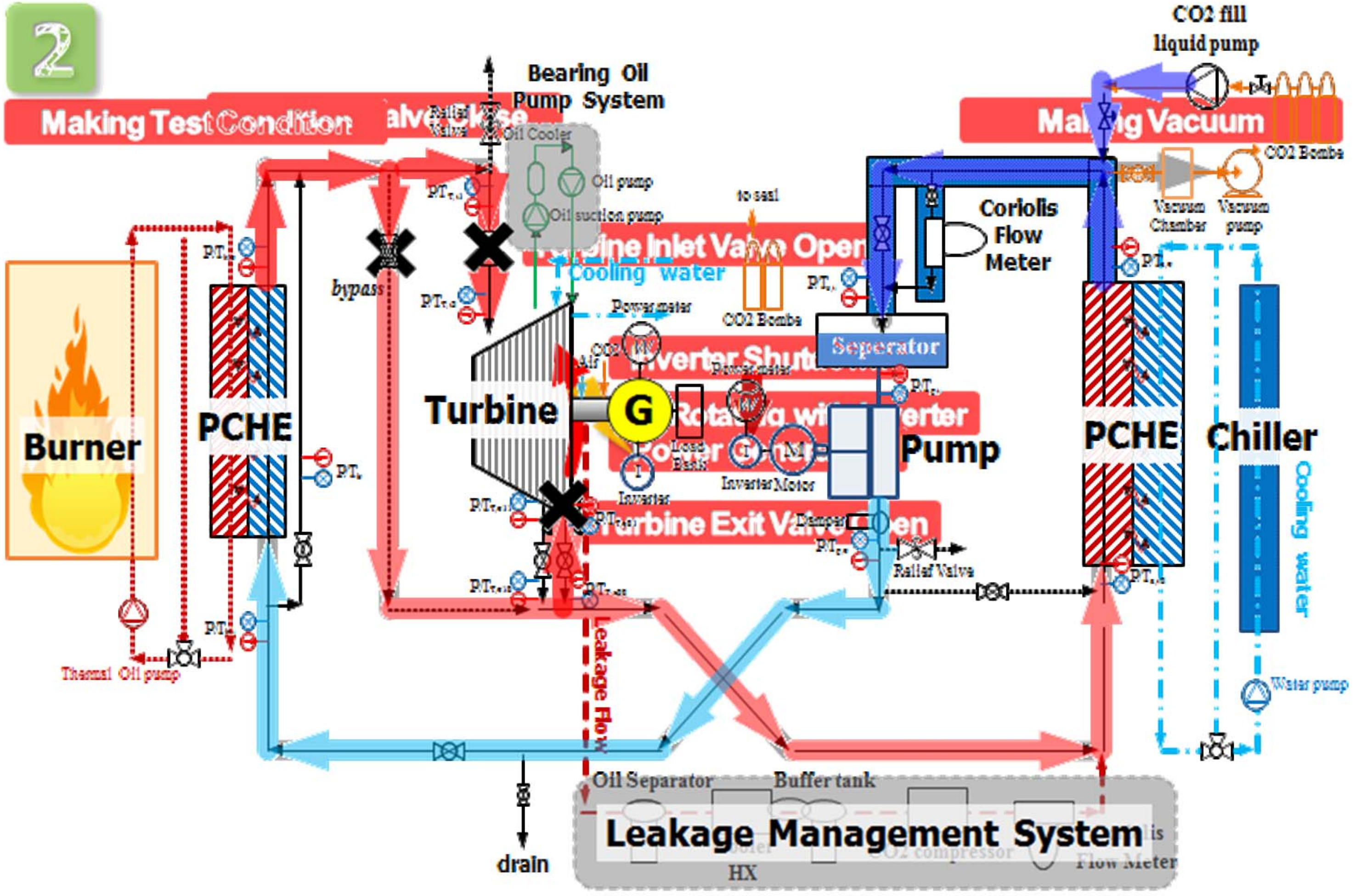


sCO_2 P/G Cycle Test Facility & Test Results

Tens of kWe Test Loop Facility (Movie Clip)

sCO$_2$ P/G Cycle Test Facility & Test Results

Tens of kWe Test Loop (Operating Procedure)



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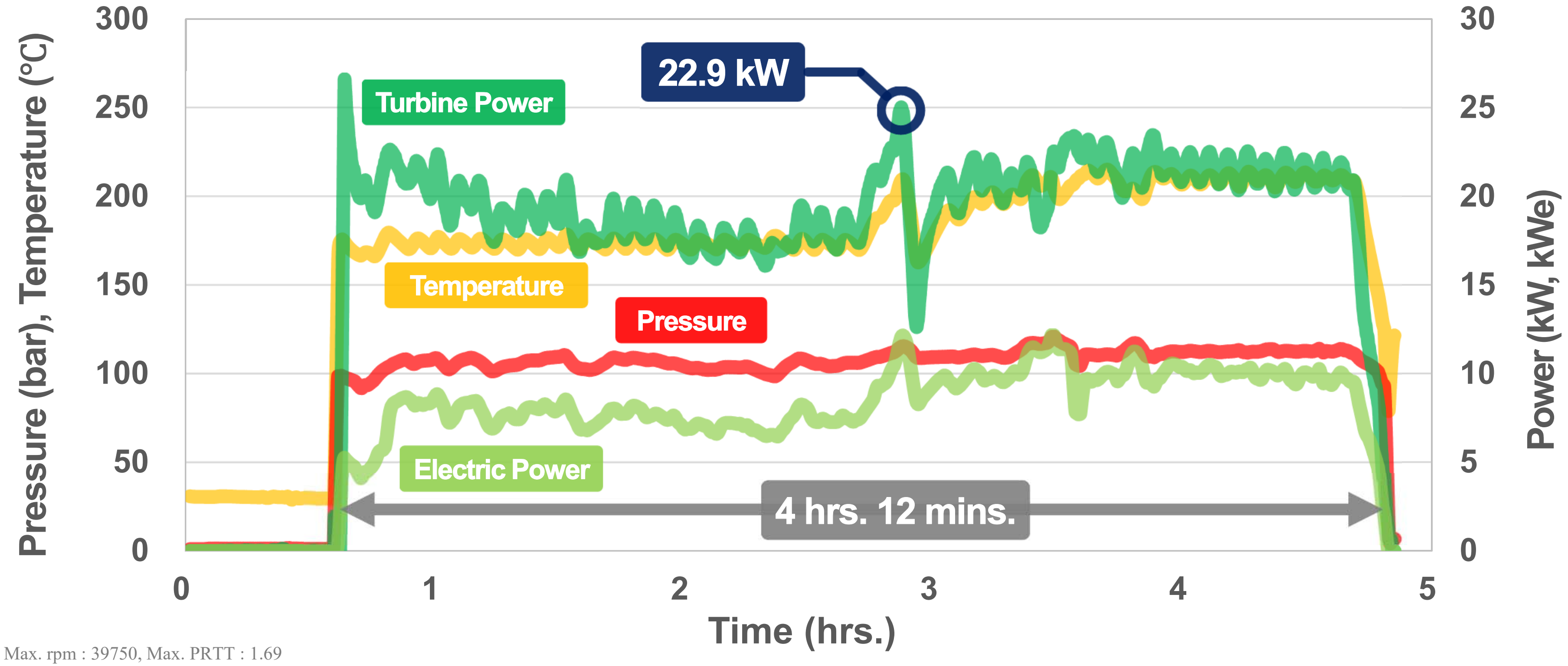
sCO_2 P/G Cycle Test Facility & Test Results

Tens of kWe Test Loop (Performance Test Results)

- Max. Turbine Inlet Pressure 123 bar / Max. Turbine Inlet Temperature 216 ℃
- Max. Turbine Power "22.9 kW" / Max. Electric Power "12.6 kWe"
- Continuous Power Generation Time : "4 hrs. 12 mins."



Max. rpm : 39750, Max. PRTT : 1.69

sCO$_2$ P/G Cycle Test Facility & Test Results

Comparisons Test and Numerical Results

- **CFD results are well agree with test results**

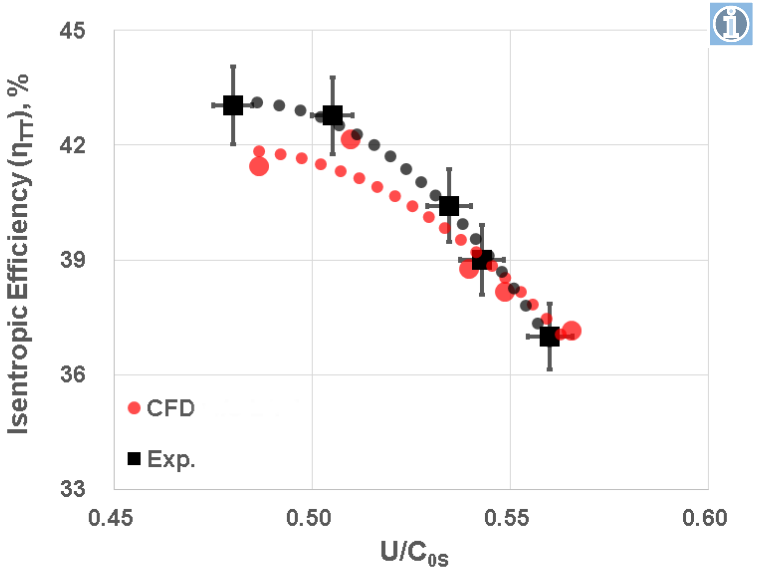
  ※ Max. efficiency difference within the comparison cases is 1.5%$_P$

  Uncertainty[1] : Jet Velocity Ratio → ±1.02%, Efficiency → ±2.34%, Turbine Power(Aerodynamic) → ±2.61%

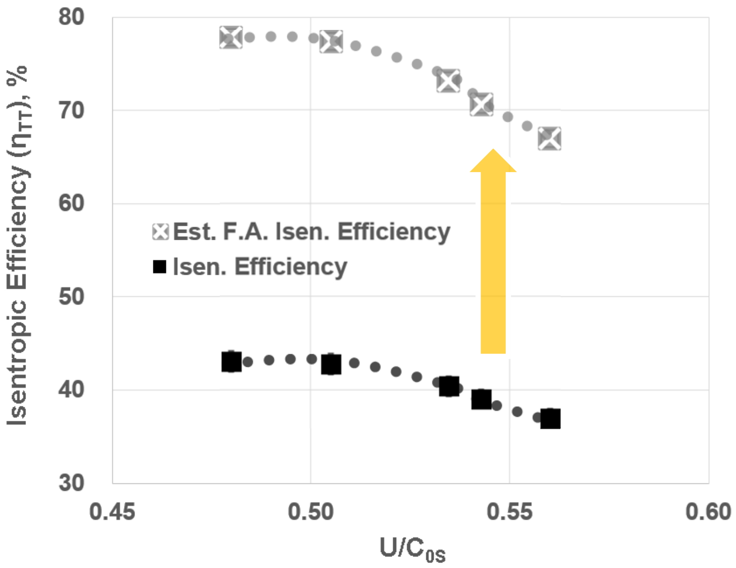
  Sensor Uncertainty : Pressure : ±0.075%, Temperature(RTD) : ±0.55℃, Flow Rate(Coriolis) : ±0.1% (※ASME PTC-22)

- **Max. predicted F. A. efficiency in the test cases → 77.9%**

Efficiency with Jet Velocity Ratio



Predicted F. A. Efficiency



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[1] Coleman, H.W., and Steele, W.G. (1999). Experimentation and uncertainty analysis for engineers, 2nd Ed., John Wiley & Sons, New York

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Chapter 04

Summarise & Future Works

Summarise

- **Tens of kWe test loop & Turbine working with sCO_2 is designed**
  - Single stage axial type turbine (Impulse) + Tilting Pad Bearing ➔ Obtain design know-how for over 10 MWe Class
  - Rotor mean diameter : 73 mm / Rotor blade height : 8.36 mm
- **sCO_2 Turbine is tested in the tens of kWe test loop**
  - Turbine TIT : 200 ℃, Turbine Inlet Pressure : 135 bar, Rotational Speed : 45000 rpm, Partial Admission Ratio : 0.17
- **Max. Turbine Inlet Pressure 123 bar / Max. Turbine Inlet Temperature 216 ℃**
- **Max. Turbine Power "22.9 kW" / Max. Electric Power "12.6 kWe"**
- **Continuous Power Generation Time : "4 hrs. 12 minutes"**
- **CFD results are well agree with test results**
  - Max. difference within the comparison cases is 1.5%$_P$

Future Works

TIT 500 ℃ sCO_2 Turbine

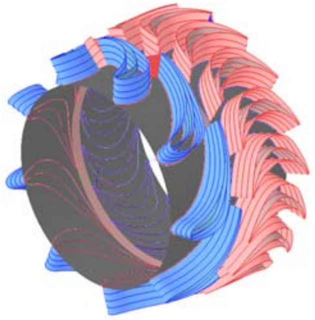
Design Conditions

• Inlet Total Pressure [bar]	135
• Inlet Total Temperature [℃]	500
• Pressure Ratio	1.75
• Rotating Speed [rpm]	70000

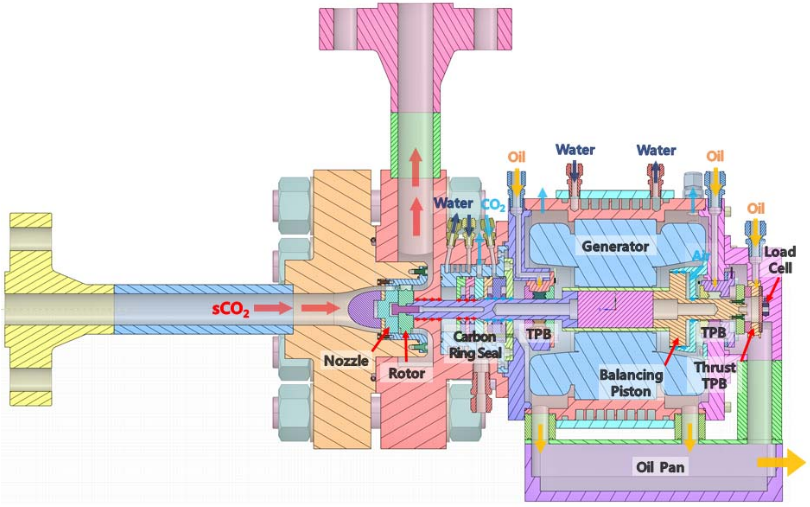
Designed Geometry

	Nozzle	**Rotor**
• Number [ea]	9	17
• Height [mm]	6.01	7.01
• Mean Diameter [mm]	51.68	52.68

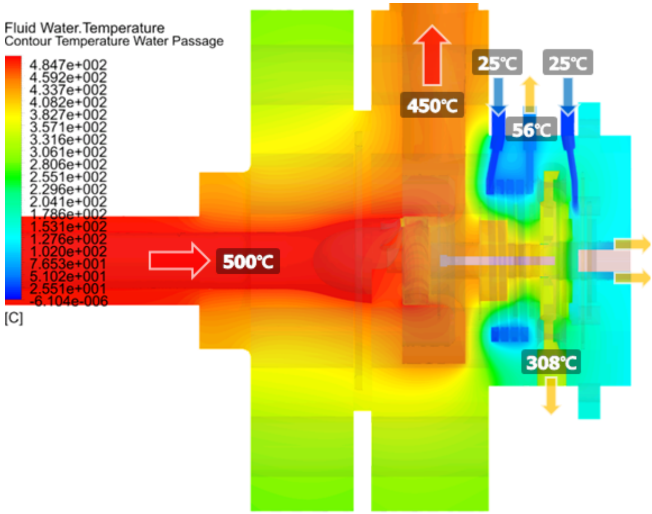
Designed Shape



Cross-Sectional View



Conjugated Heat Transfer Analysis Results



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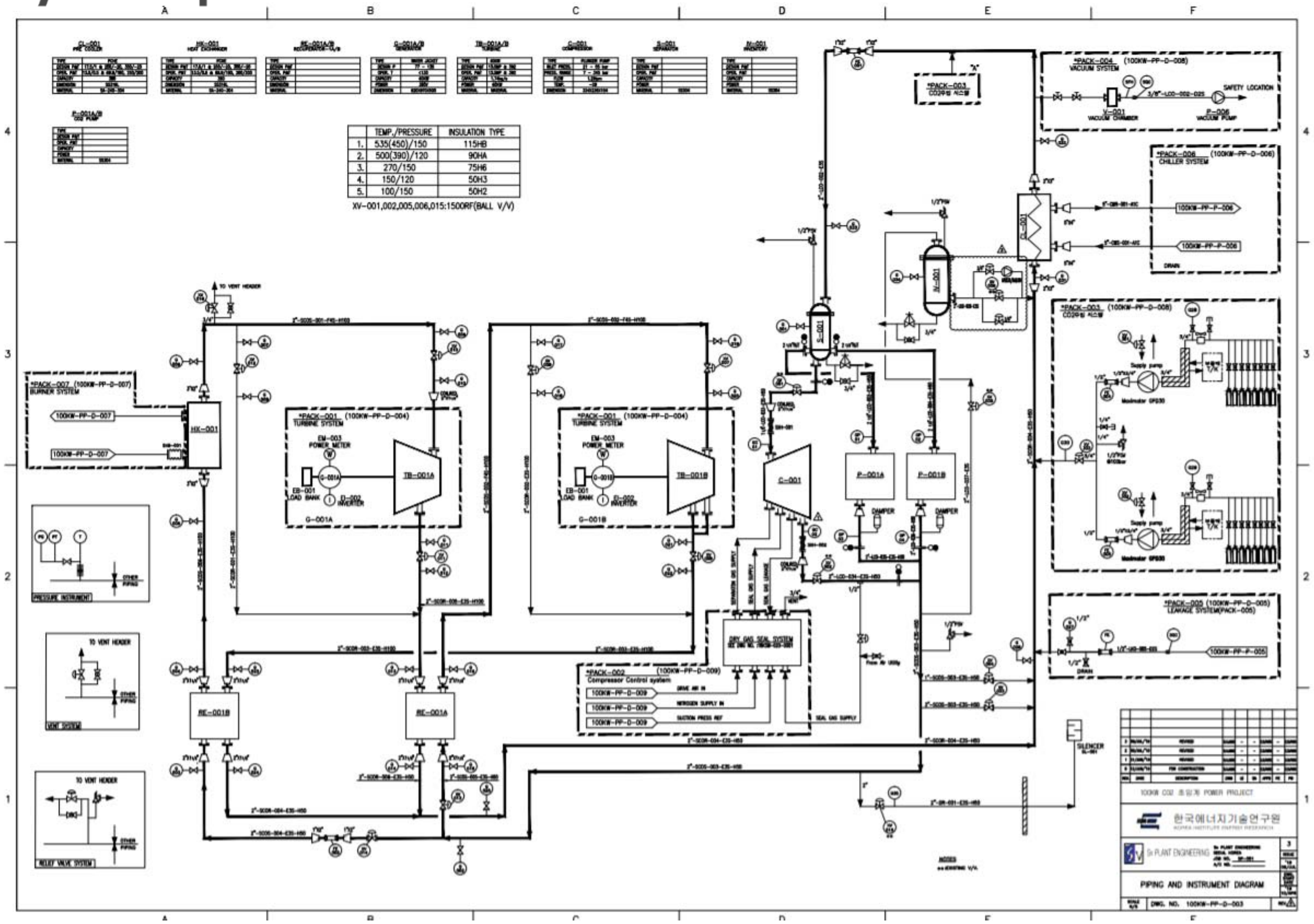
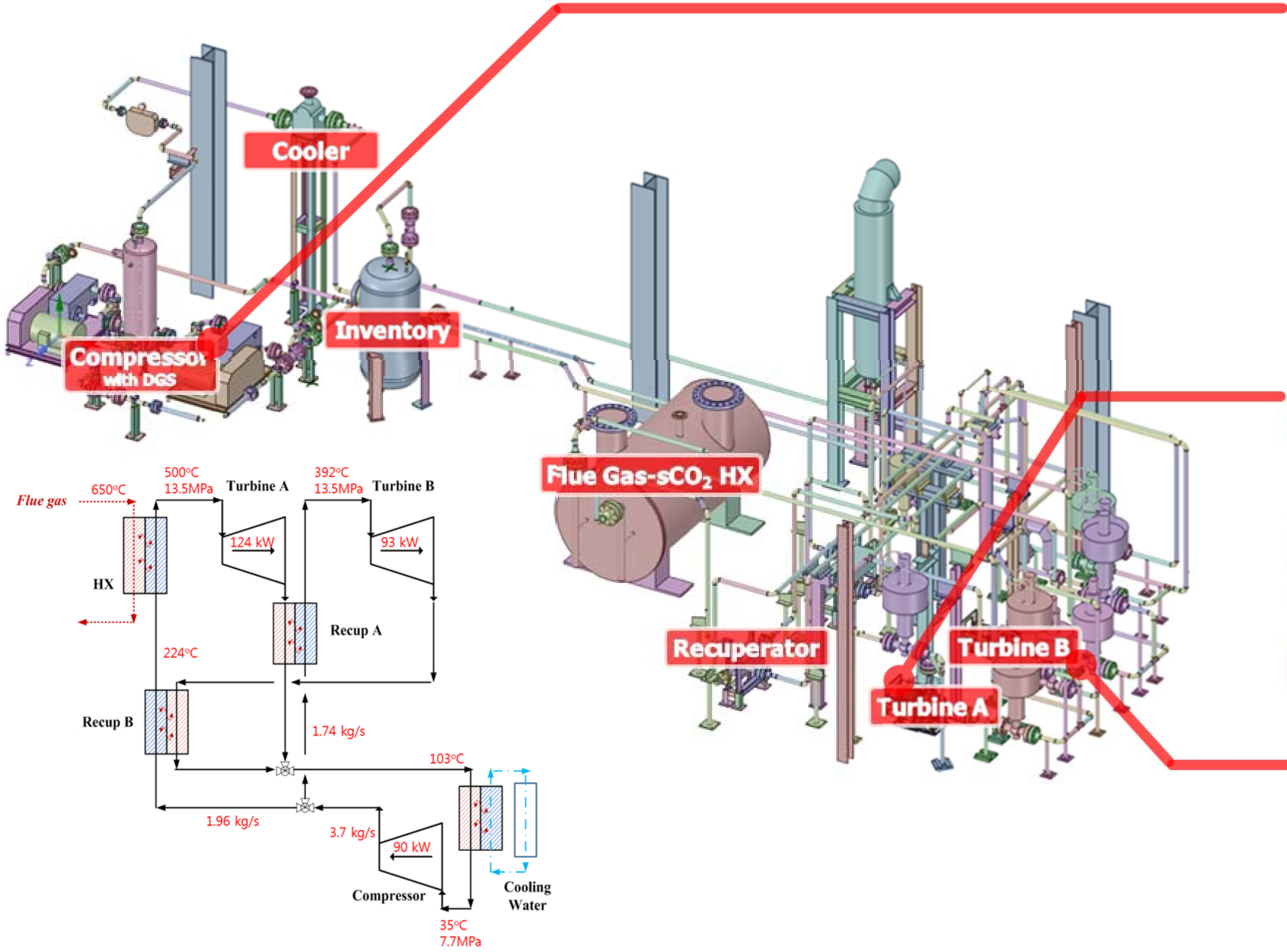
Future Works

Dual Cycle Loop

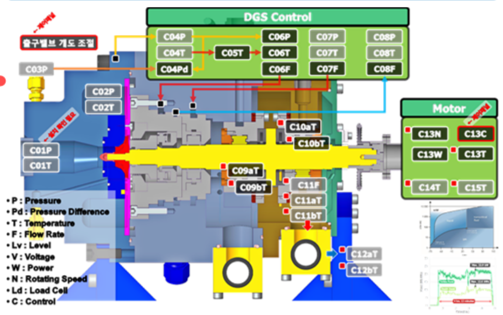


Future Works

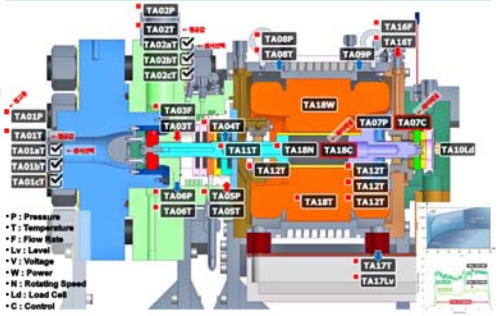
Dual Cycle Loop



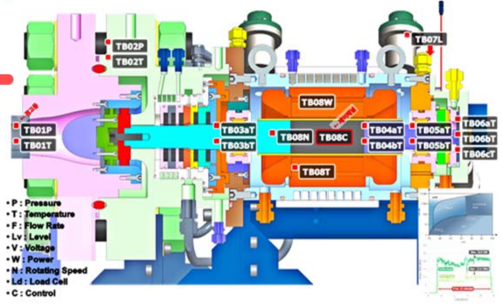
Compressor



Turbine "A"



Turbine "B"



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Thank you for your attention !

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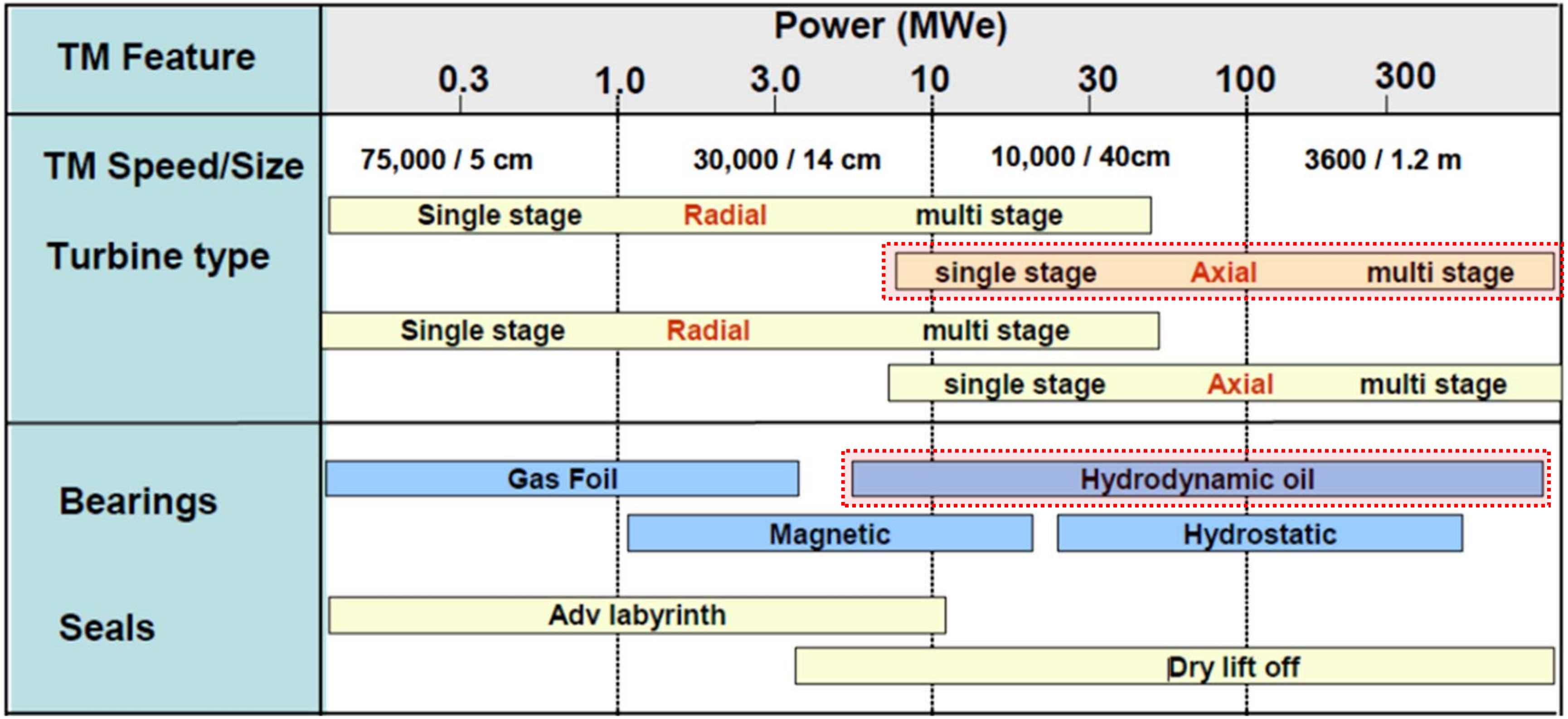
Korea Institute of Energy Research [KIeR]

Appendix

Component and Technology Options for sCO_2 Systems



Ref.) Fleming, D., Conboy, T., Pash, J., Rochau, G., Fuller, R., Holschuh, T., Wright, S., 2013, "Scaling considerations for a mulit-megawatt class supercritical CO2 Brayton cycle and commercialization," Sandia National Laboratories, Albuquerque, NM.

Appendix

Predict Performance / Axial Force / Performance Correlation

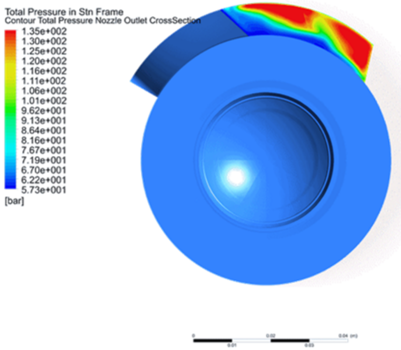
Performance Characteristics according to Partial Admission Ratio

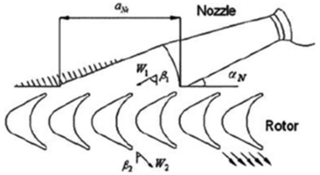
- **"Partial Admission"**
  - refers to a configuration in which the driving fluid is admitted to only a fraction of the nozzle annulus
- Losses for "Full Admission" Turbine
  - Nozzle & Rotor-Blading Aerodynamic Losses
  - Rotor-Tip Leakage Loss
  - Shaft Losses (Disk-Friction Loss + Bearing Loss)
- Losses for **"Partial Admission"** Turbine
  - Losses for Full Admission Turbine
  - **"Driving-Fluid Losses"** (Scavenge & Eddy Losses + Diffusion Loss)

    ※ Scavenge & Eddy Losses → Losses during filling and emptying of rotor blade

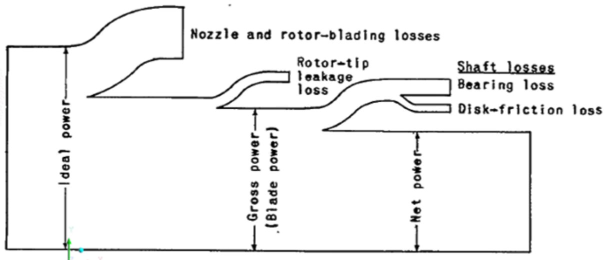
    ※ Diffusion Loss → Loss due to diffusion of gases at nozzle
  - **"Pumping Loss"** in inactive rotor blading

    ※ Pumping Loss → the induced circulation of nonworking gases in the inactive rotor passages

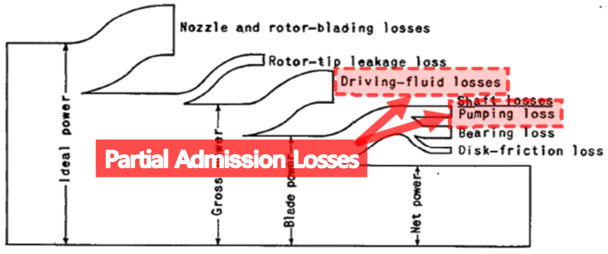




Full & Partial Admission Losses [1]



(a) Full admission (360°).



(b) Partial admission.

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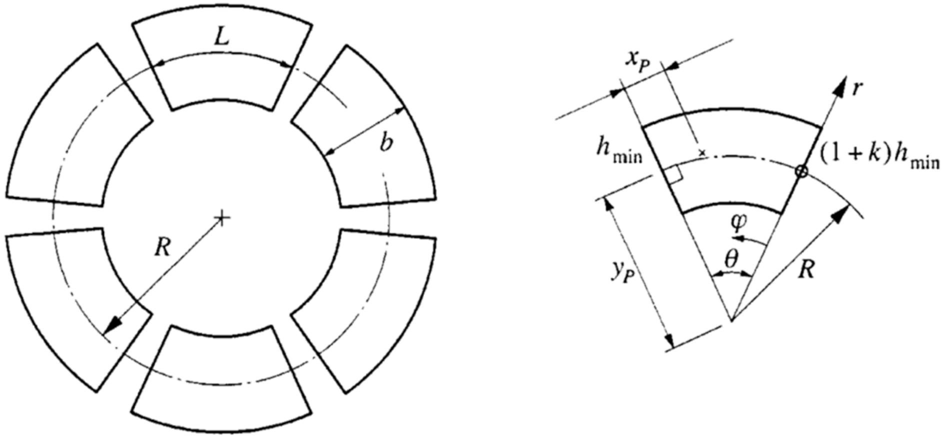
1) Kohl, R., Herzig, H., Whitney, W., 1949, "Effects of Partial Admission on Performance of a Gas Turbine," NACA Technical Report Note 1807.

Appendix

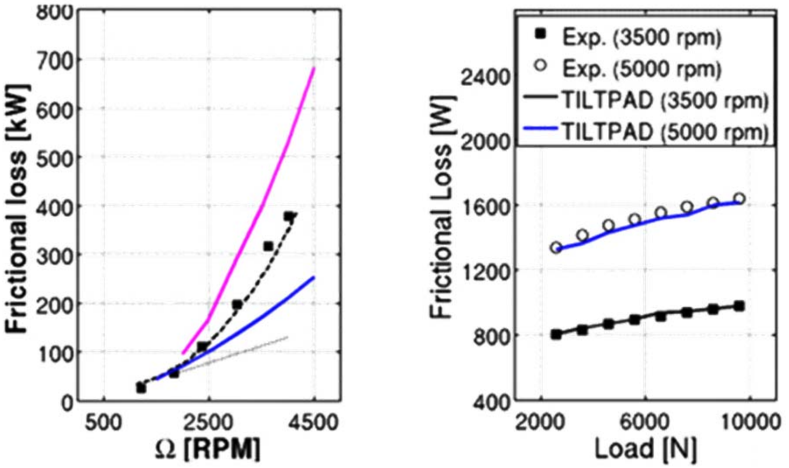
Tilting Pad Bearing Losses 1)

- **Sector-shaped Thrust Tilting Pad Bearing**
  - Power Loss : function of $(b \cdot \mu \cdot R^3 \cdot \omega^2)/h_{min}$
- **Tilting Pad Journal Bearing**
  - Power Loss : function of $(b \cdot \mu \cdot R^3 \cdot \omega^2)/\Delta r$

Sector-shaped Thrust Tilting Pad Bearing 1)

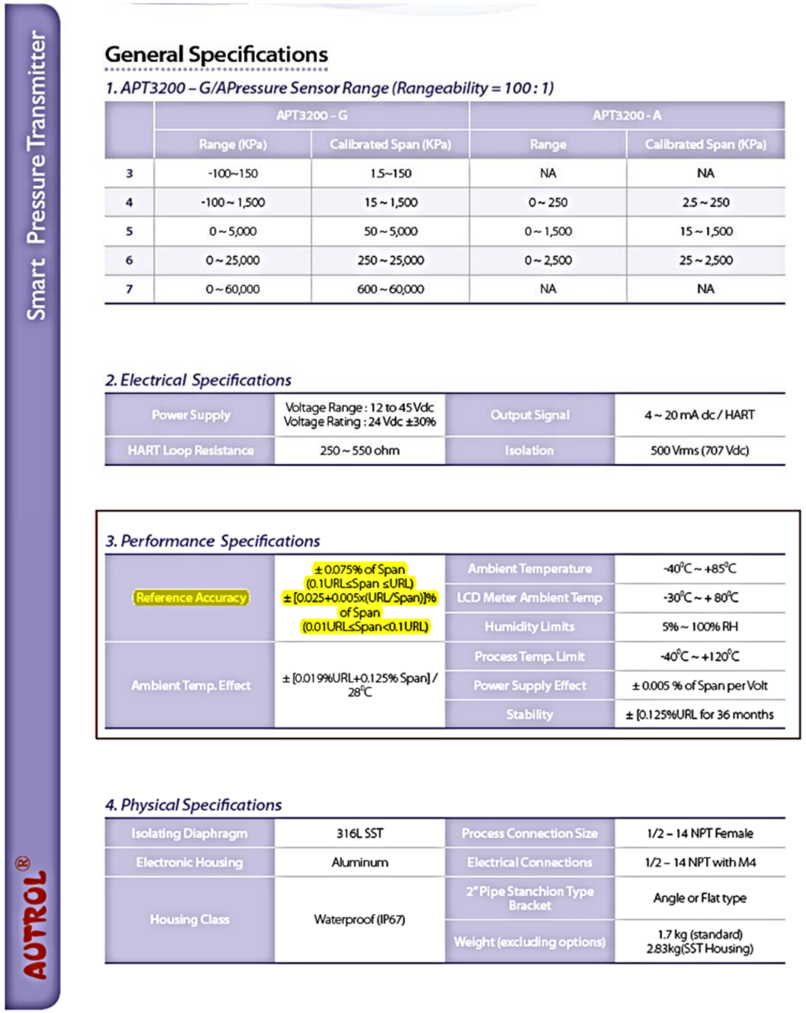


Frictional Loss with Bearing Load & rpm 2)



Ref.) ① Stahl, J., Jacobson, B. O., 2001, "Design functions for hydrodynamic bearings," Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology.
② Griffini, D., Salvadori, S., Martelli, F., 2016, "Thermo-Hydrodynamic Analysis of Plain and Tilting Pad Bearings," 71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, Turin, Italy.

Appendix



Smart Pressure Transmitter

AUTROL®

General Specifications

1. APT3200 – G/APressure Sensor Range (Rangeability = 100 : 1)

	APT3200 - G		APT3200 - A	
	Range (KPa)	Calibrated Span (KPa)	Range	Calibrated Span (KPa)
3	-100~150	1.5~150	NA	NA
4	-100 ~ 1,500	15 ~ 1,500	0 ~ 250	2.5 ~ 250
5	0 ~ 5,000	50 ~ 5,000	0 ~ 1,500	15 ~ 1,500
6	0 ~ 25,000	250 ~ 25,000	0 ~ 2,500	25 ~ 2,500
7	0 ~ 60,000	600 ~ 60,000	NA	NA

2. Electrical Specifications

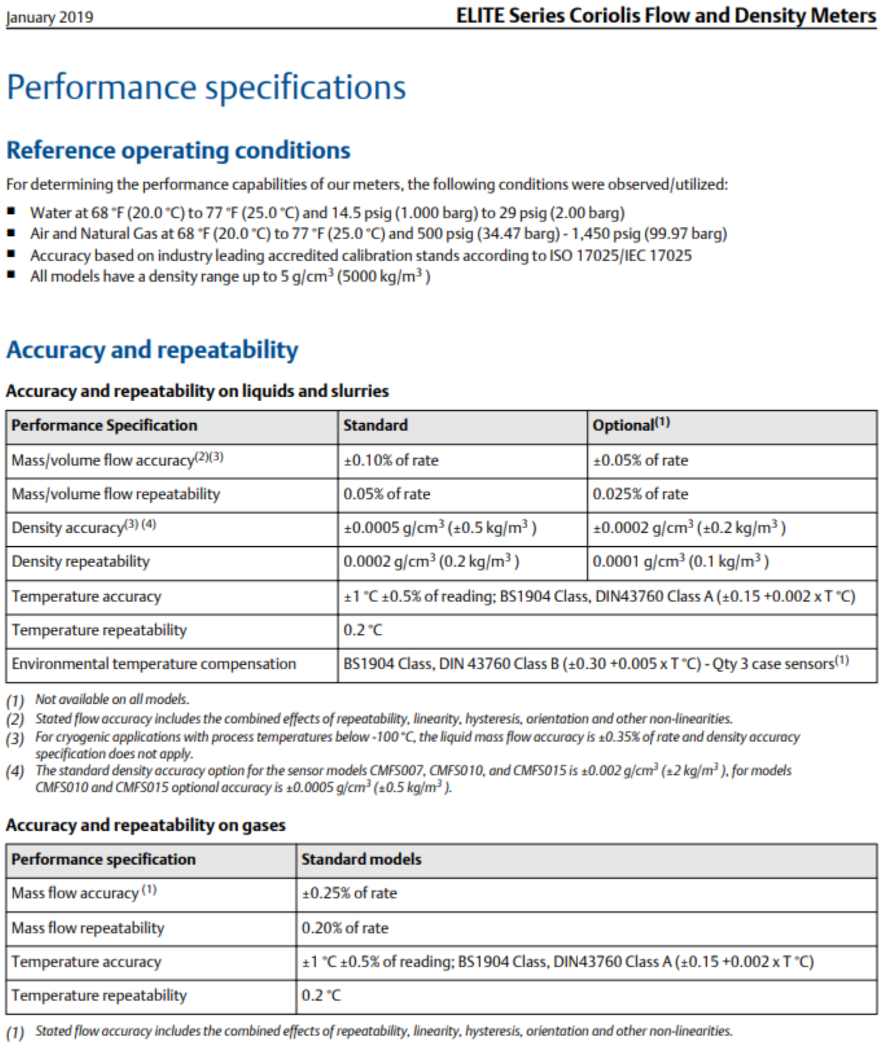
Power Supply	Voltage Range : 12 to 45 Vdc Voltage Rating : 24 Vdc ±30%	Output Signal	4 ~ 20 mA dc / HART
HART Loop Resistance	250 ~ 550 ohm	Isolation	500 Vrms (707 Vdc)

3. Performance Specifications

Reference Accuracy	± 0.075% of Span (0.1URL≤Span ≤URL) ± [0.025+0.005x(URL/Span)]% of Span (0.01URL≤Span<0.1URL)	Ambient Temperature	-40°C ~ +85°C
		LCD Meter Ambient Temp	-30°C ~ + 80°C
		Humidity Limits	5% ~ 100% RH
Ambient Temp. Effect	± [0.019%URL+0.125% Span] / 28°C	Process Temp. Limit	-40°C ~ +120°C
		Power Supply Effect	± 0.005 % of Span per Volt
		Stability	± [0.125%URL for 36 months

4. Physical Specifications

Isolating Diaphragm	316L SST	Process Connection Size	1/2 – 14 NPT Female
Electronic Housing	Aluminum	Electrical Connections	1/2 – 14 NPT with M4
Housing Class	Waterproof (IP67)	2" Pipe Stanchion Type Bracket	Angle or Flat type
		Weight (excluding options)	1.7 kg (standard) 2.83kg(SST Housing)



January 2019 **ELITE Series Coriolis Flow and Density Meters**

Performance specifications

Reference operating conditions

For determining the performance capabilities of our meters, the following conditions were observed/utilized:

- Water at 68 °F (20.0 °C) to 77 °F (25.0 °C) and 14.5 psig (1.000 barg) to 29 psig (2.00 barg)
- Air and Natural Gas at 68 °F (20.0 °C) to 77 °F (25.0 °C) and 500 psig (34.47 barg) - 1,450 psig (99.97 barg)
- Accuracy based on industry leading accredited calibration stands according to ISO 17025/IEC 17025
- All models have a density range up to 5 g/cm^3 (5000 kg/m^3)

Accuracy and repeatability

Accuracy and repeatability on liquids and slurries

Performance Specification	Standard	Optional(1)
Mass/volume flow accuracy(2)(3)	±0.10% of rate	±0.05% of rate
Mass/volume flow repeatability	0.05% of rate	0.025% of rate
Density accuracy(3) (4)	±0.0005 g/cm^3 (±0.5 kg/m^3)	±0.0002 g/cm^3 (±0.2 kg/m^3)
Density repeatability	0.0002 g/cm^3 (0.2 kg/m^3)	0.0001 g/cm^3 (0.1 kg/m^3)
Temperature accuracy	±1 °C ±0.5% of reading; BS1904 Class, DIN43760 Class A (±0.15 +0.002 x T °C)	
Temperature repeatability	0.2 °C	
Environmental temperature compensation	BS1904 Class, DIN 43760 Class B (±0.30 +0.005 x T °C) - Qty 3 case sensors(1)	

(1) *Not available on all models.*

(2) *Stated flow accuracy includes the combined effects of repeatability, linearity, hysteresis, orientation and other non-linearities.*

(3) *For cryogenic applications with process temperatures below -100 °C, the liquid mass flow accuracy is ±0.35% of rate and density accuracy specification does not apply.*

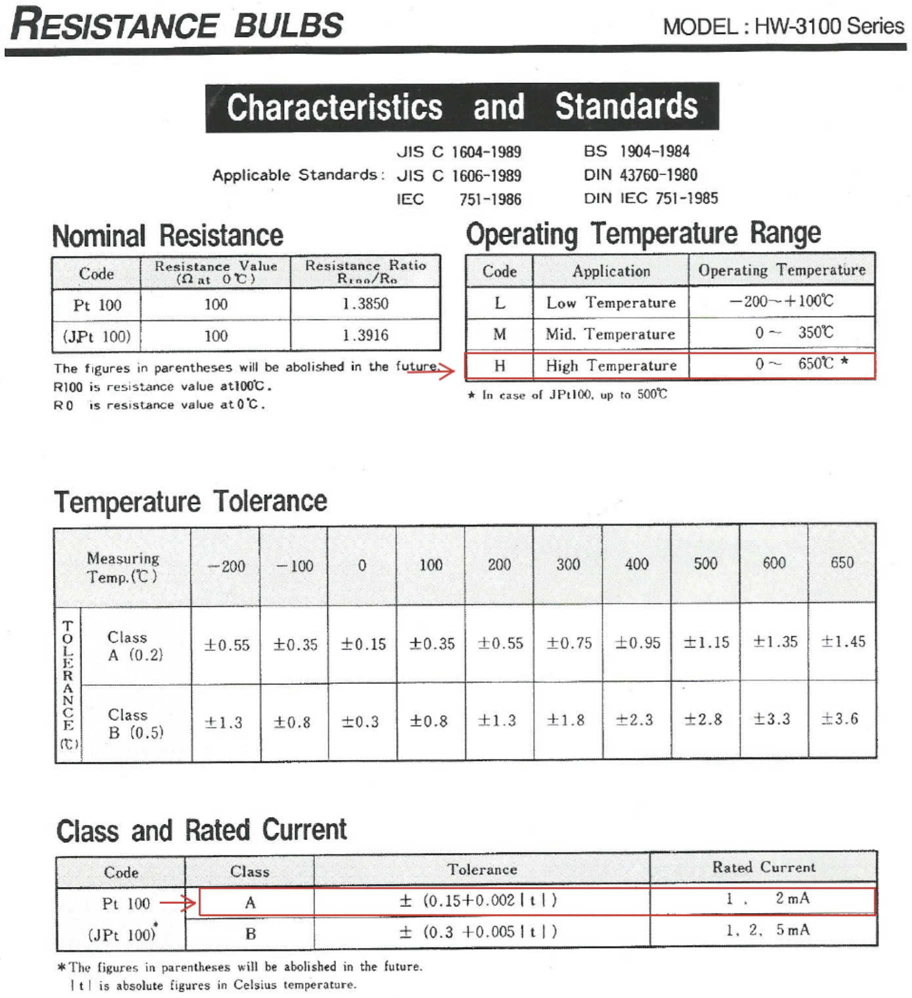
(4) *The standard density accuracy option for the sensor models CMFS007, CMFS010, and CMFS015 is ±0.002 g/cm^3 (±2 kg/m^3), for models CMFS010 and CMFS015 optional accuracy is ±0.0005 g/cm^3 (±0.5 kg/m^3).*

Accuracy and repeatability on gases

Performance specification	Standard models
Mass flow accuracy (1)	±0.25% of rate
Mass flow repeatability	0.20% of rate
Temperature accuracy	±1 °C ±0.5% of reading; BS1904 Class, DIN43760 Class A (±0.15 +0.002 x T °C)
Temperature repeatability	0.2 °C

(1) *Stated flow accuracy includes the combined effects of repeatability, linearity, hysteresis, orientation and other non-linearities.*

Appendix



RESISTANCE BULBS

MODEL : HW-3100 Series

Characteristics and Standards

Applicable Standards :		
	JIS C 1604-1989	BS 1904-1984
	JIS C 1606-1989	DIN 43760-1980
	IEC 751-1986	DIN IEC 751-1985

Nominal Resistance

Code	Resistance Value (Ω at 0℃)	Resistance Ratio R_{100}/R_0
Pt 100	100	1.3850
(JPt 100)	100	1.3916

The figures in parentheses will be abolished in the future.
R100 is resistance value at100℃.
R0 is resistance value at 0℃.

Operating Temperature Range

Code	Application	Operating Temperature
L	Low Temperature	−200∼+100℃
M	Mid. Temperature	0∼ 350℃
H	High Temperature	0∼ 650℃ *

* In case of JPt100, up to 500℃

Temperature Tolerance

	Measuring Temp.(℃)	−200	−100	0	100	200	300	400	500	600	650
TOLERANCE (℃)	Class A (0.2)	±0.55	±0.35	±0.15	±0.35	±0.55	±0.75	±0.95	±1.15	±1.35	±1.45
	Class B (0.5)	±1.3	±0.8	±0.3	±0.8	±1.3	±1.8	±2.3	±2.8	±3.3	±3.6

Class and Rated Current

Code	Class	Tolerance	Rated Current
Pt 100	A	± (0.15+0.002 | t |)	1 , 2 mA
(JPt 100)*	B	± (0.3 +0.005 | t |)	1, 2, 5 mA

*The figures in parentheses will be abolished in the future.
\| t \| is absolute figures in Celsius temperature.

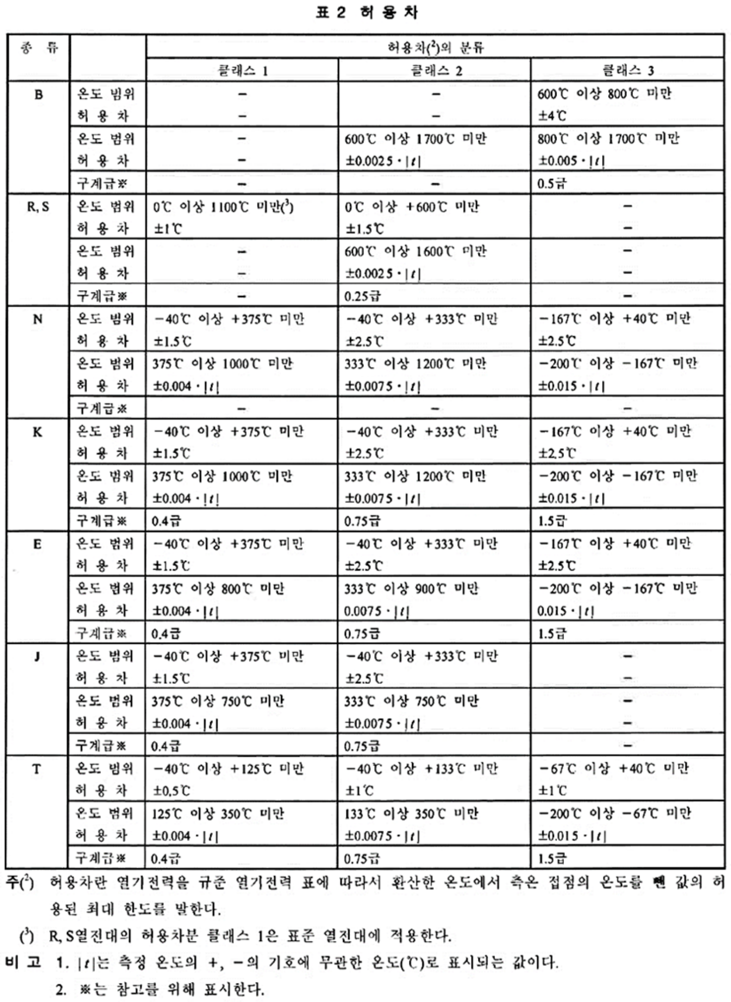


표 2 허 용 차

종 류		허용차(²)의 분류		
		클래스 1	클래스 2	클래스 3
B	온도 범위	−	−	600℃ 이상 800℃ 미만
	허 용 차	−	−	±4℃
	온도 범위	−	600℃ 이상 1700℃ 미만	800℃ 이상 1700℃ 미만
	허 용 차	−	±0.0025 · |t|	±0.005 · |t|
	구계급※	−	−	0.5급
R, S	온도 범위	0℃ 이상 1100℃ 미만(³)	0℃ 이상 +600℃ 미만	−
	허 용 차	±1℃	±1.5℃	−
	온도 범위	−	600℃ 이상 1600℃ 미만	−
	허 용 차	−	±0.0025 · |t|	−
	구계급※	−	0.25급	−
N	온도 범위	−40℃ 이상 +375℃ 미만	−40℃ 이상 +333℃ 미만	−167℃ 이상 +40℃ 미만
	허 용 차	±1.5℃	±2.5℃	±2.5℃
	온도 범위	375℃ 이상 1000℃ 미만	333℃ 이상 1200℃ 미만	−200℃ 이상 −167℃ 미만
	허 용 차	±0.004 · |t|	±0.0075 · |t|	±0.015 · |t|
	구계급※	−	−	−
K	온도 범위	−40℃ 이상 +375℃ 미만	−40℃ 이상 +333℃ 미만	−167℃ 이상 +40℃ 미만
	허 용 차	±1.5℃	±2.5℃	±2.5℃
	온도 범위	375℃ 이상 1000℃ 미만	333℃ 이상 1200℃ 미만	−200℃ 이상 −167℃ 미만
	허 용 차	±0.004 · |t|	±0.0075 · |t|	±0.015 · |t|
	구계급※	0.4급	0.75급	1.5급
E	온도 범위	−40℃ 이상 +375℃ 미만	−40℃ 이상 +333℃ 미만	−167℃ 이상 +40℃ 미만
	허 용 차	±1.5℃	±2.5℃	±2.5℃
	온도 범위	375℃ 이상 800℃ 미만	333℃ 이상 900℃ 미만	−200℃ 이상 −167℃ 미만
	허 용 차	±0.004 · |t|	0.0075 · |t|	0.015 · |t|
	구계급※	0.4급	0.75급	1.5급
J	온도 범위	−40℃ 이상 +375℃ 미만	−40℃ 이상 +333℃ 미만	−
	허 용 차	±1.5℃	±2.5℃	−
	온도 범위	375℃ 이상 750℃ 미만	333℃ 이상 750℃ 미만	−
	허 용 차	±0.004 · |t|	±0.0075 · |t|	−
	구계급※	0.4급	0.75급	−
T	온도 범위	−40℃ 이상 +125℃ 미만	−40℃ 이상 +133℃ 미만	−67℃ 이상 +40℃ 미만
	허 용 차	±0.5℃	±1℃	±1℃
	온도 범위	125℃ 이상 350℃ 미만	133℃ 이상 350℃ 미만	−200℃ 이상 −67℃ 미만
	허 용 차	±0.004 · |t|	±0.0075 · |t|	±0.015 · |t|
	구계급※	0.4급	0.75급	1.5급

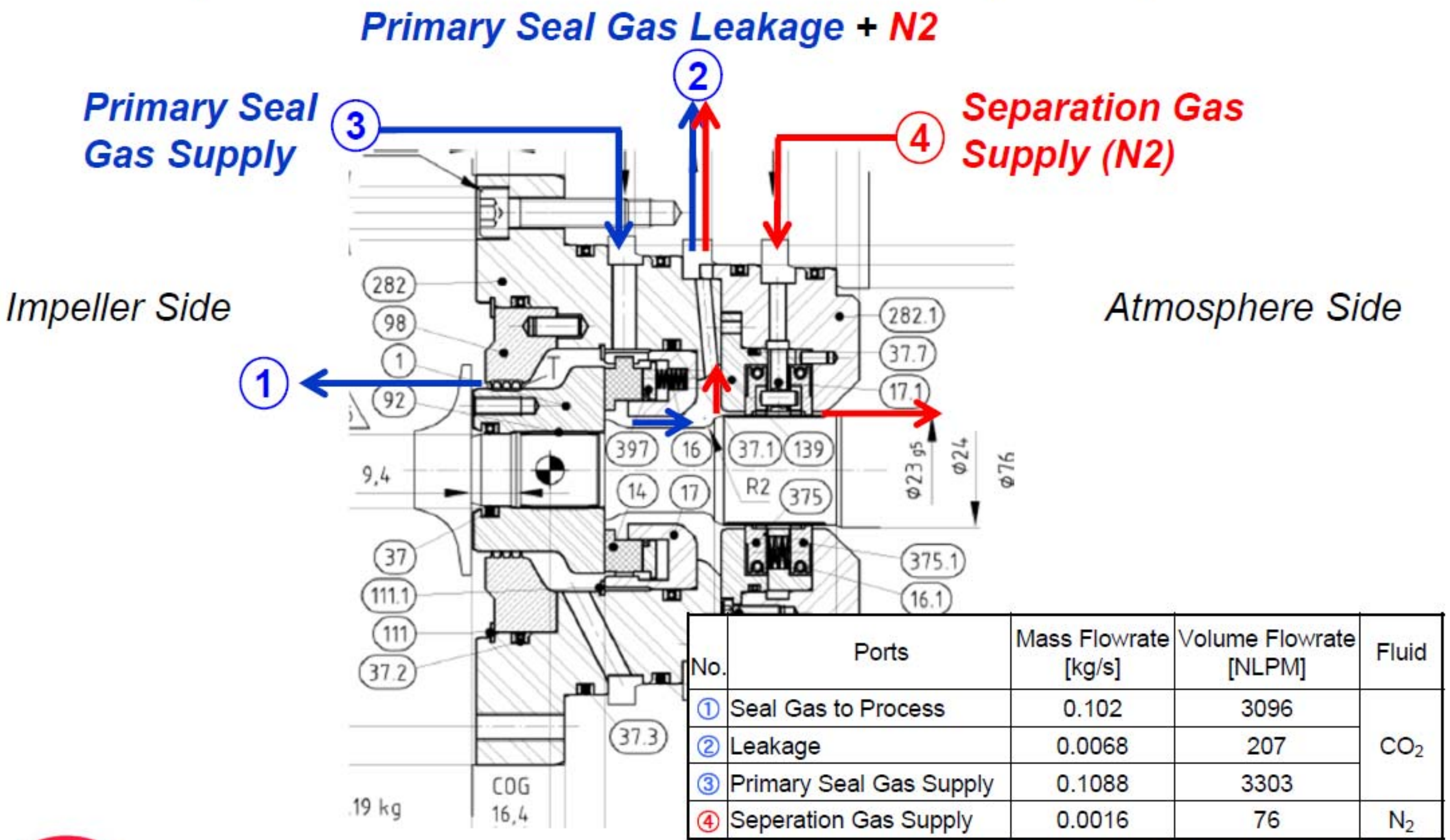
주(²) 허용차란 열기전력을 규준 열기전력 표에 따라서 환산한 온도에서 측온 접점의 온도를 뺀 값의 허용된 최대 한도를 말한다.

(³) R, S열전대의 허용차분 클래스 1은 표준 열전대에 적용한다.

비 고 1. \|t\|는 측정 온도의 +, −의 기호에 무관한 온도(℃)로 표시되는 값이다.
2. ※는 참고를 위해 표시한다.

Appendix

2. Gaspac S-IR (Seal Gas Consumption)



Primary Seal Gas Leakage + N2

②

Primary Seal Gas Supply ③

④ Separation Gas Supply (N2)

Impeller Side

Atmosphere Side

①

No.	Ports	Mass Flowrate [kg/s]	Volume Flowrate [NLPM]	Fluid
①	Seal Gas to Process	0.102	3096	CO_2
②	Leakage	0.0068	207	
③	Primary Seal Gas Supply	0.1088	3303	
④	Seperation Gas Supply	0.0016	76	N_2

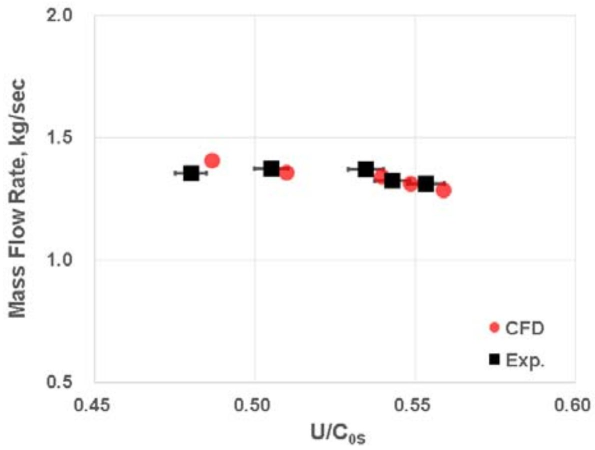
Flow Solutions Division

Appendix

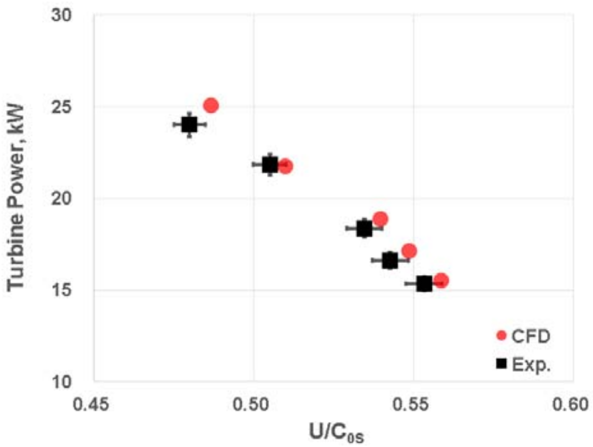
Comparisons Test and Numerical Results

- **Max. Difference between CFD and Test Results**
  - Mass Flow → 3.7%, Turbine Power → 4.5% Efficiency → 1.5%$_P$
- **Test Uncertainty**(1)
  - Jet velocity ratio → ±1.02%, Mass Flow → ±0.1%, Turbine Power → ±2.61%, Efficiency → ±2.34%

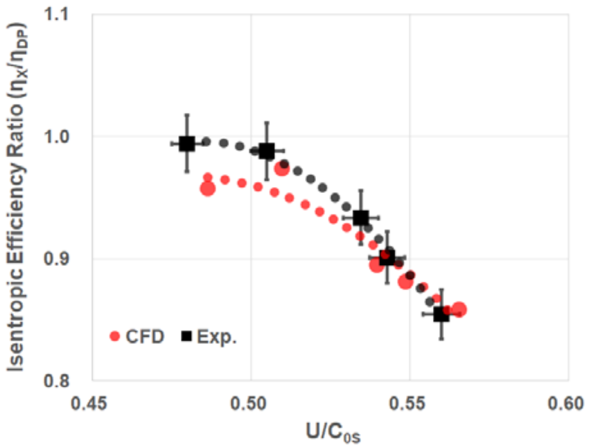
Mass Flow Rate Comparisons



Turbine Power Comparisons



Isentropic Efficiency Comparisons



1) Coleman, H.W., and Steele, W.G. (1999). Experimentation and uncertainty analysis for engineers, 2nd Ed., John Wiley & Sons, New York