UNCERTAINTY ON PERFORMANCE MEASUREMENT OF S-CO_2 COMPRESSOR OPERATING NEAR THE CRITICAL POINT

The 4th International Symposium - Supercritical CO_2 Power Cycles
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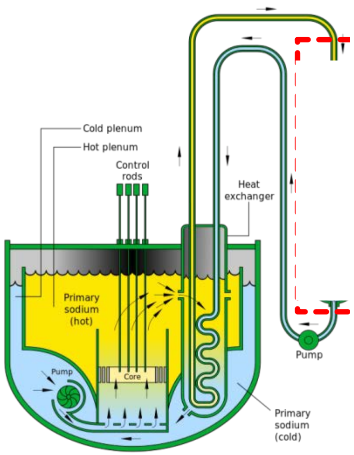
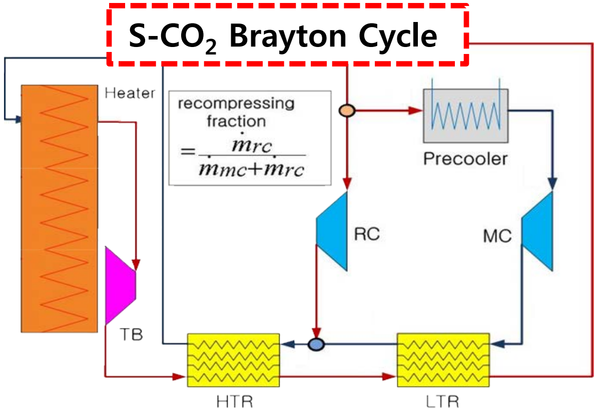
Introduction

- S-CO_2 Brayton cycle development in KAIST research team

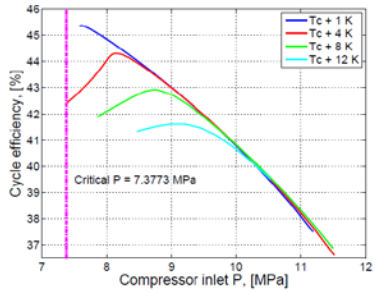


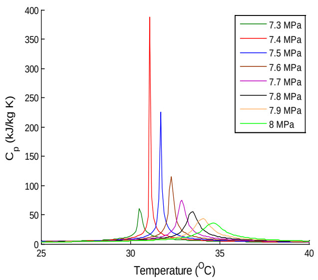


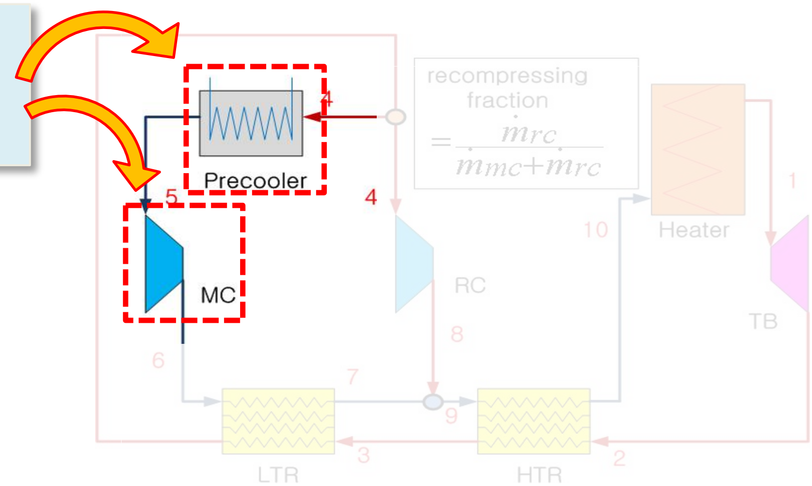
Economic benefit due to higher efficiency and compactness of power conversion system

- Difficulties on S-CO_2 Brayton cycle

Dramatic change on thermodynamic properties **near the critical point**







Introduction

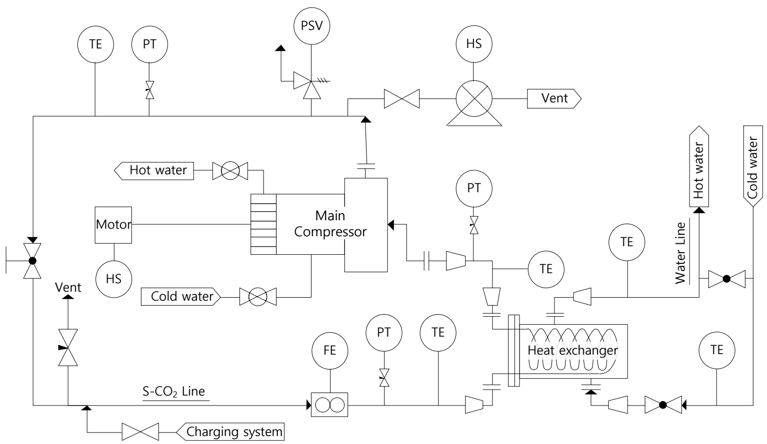
- **S-CO_2 Pressurization Experiment (SCO2PE, constructed in KAIST)**

- Components
  - 1. Overview
  - 2. Impeller
  - 3. Main compressor
  - 4. Pre-cooler
  - 5. Booster pump
  - 6. Vacuum pump
- Sensors
  - PT100 Ohm RTDs
    - Static temperature
  - Rosemount 3051S Pressure Transmitter
    - Static pressure
  - Rheonik RHM20 mass flow meter
- Accuracy

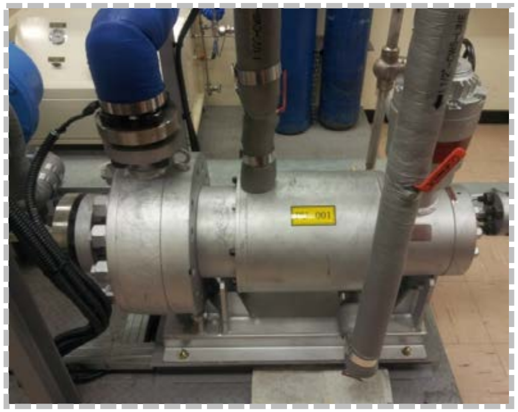
Sensor type	Accuracy
RTD	±0.2°C
Pressure transmitter	±0.09%
Mass flow meter	±0.16%
RPM	±0.1%
Power	±0.5kW

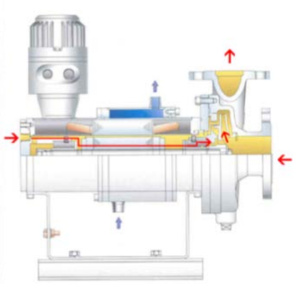
Introduction

Main compressor description



- Canned motor pump
  - ✓ 26kW motor driver
  - ✓ Sleeve journal bearing with working fluid lubrication
  - ✓ Closed(shrouded) type impeller
  - ✓ Recirculation flow exists
  - ✓ Water jacket is equipped to maintain integrity of sleeve bearing
  - ✓ Available RPM: 4620(77Hz)



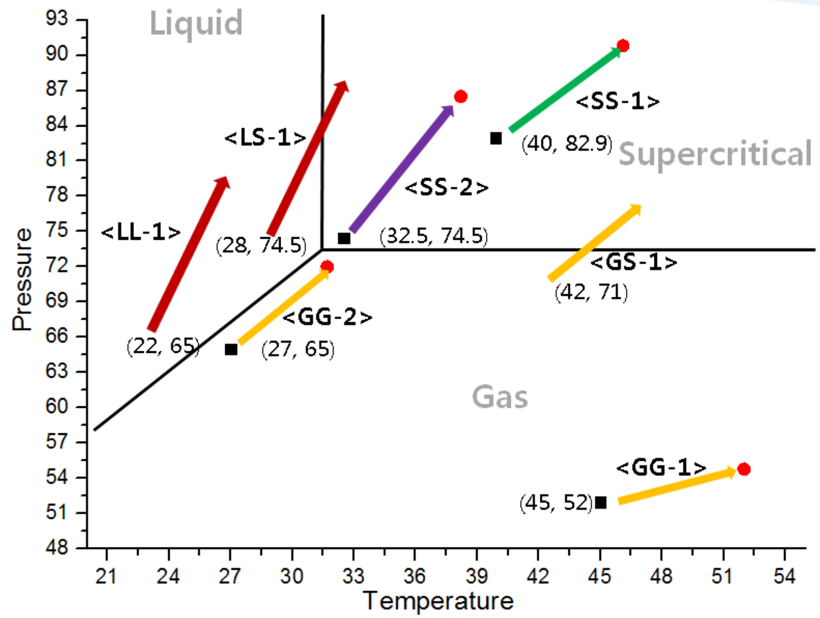


Main compressor design conditions	
Inlet pressure, MPa	7.9993
Outlet pressure, MPa	9.4692
Pressure ratio	1.18
RPM	4428
Mass flow rate, kg/s	4.49

Dimensions of mechanical parts	
Impeller type	Closed
Impeller diameter, mm	234
Journal bearing type	Sleeve
Thrust bearing type	Plain
Material	SUS316

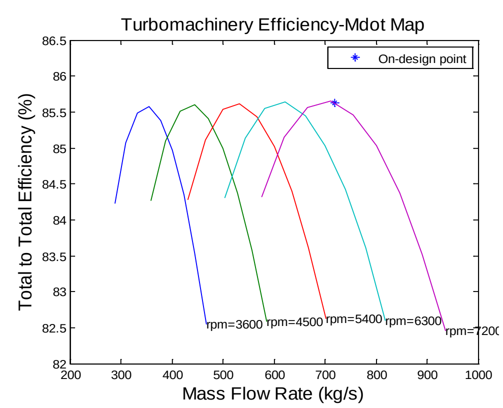
Introduction

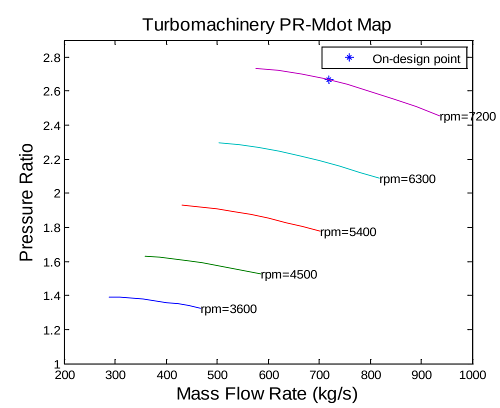
- **SCO2PE operation purpose. 1**
  - Experience to CO_2 pressurization with various fluid conditions



- **SCO2PE operation purpose. 2**
  - V&V of KAIST_TMD
    - ✓ Turbomachinery in-house code

- **SCO2PE operation purpose. 3**
  - V&V of KAIST_HXD
    - ✓ Heat exchanger in-house code





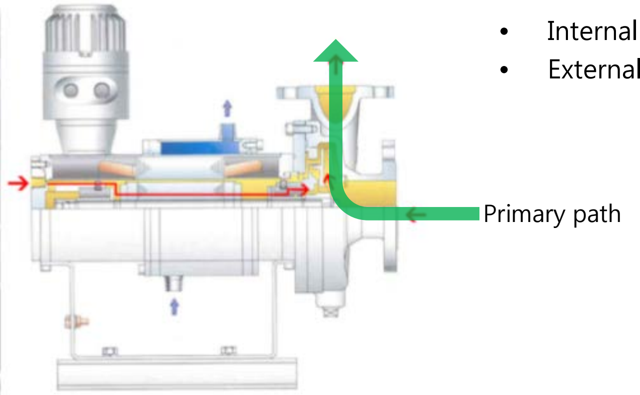
Uncertainty Analysis

Nomenclature

- PR : pressure ratio
- η : efficiency
- h : enthalpy
- $\dot{m}$: mass flow rate
- $\dot{W}$: input power
- U : impeller tip speed
- in : compressor inlet
- out : compressor outlet
- $isen$: isentropic process
- o : stagnation
- th : theoretical (Euler equation)
- $loss$: loss in compressor
- int : internal loss
- ext : external loss

Compressor performance variable

- Pressure ratio
  - ✓ $PR = \frac{P_{out}}{P_{in}}$
- Isentropic efficiency
  - ✓ 1: $\eta = \frac{h_{out,ideal} - h_{in}}{h_{out} - h_{in}}$
  - ✓ 2: $\eta = \left(h_{o,out,isen} - h_{o,in}\right)\frac{\dot{m}}{\dot{W}}$
  - ✓ 3: $\eta = \frac{\Delta h_{th} - \Delta h_{loss,int}}{\Delta h_{th} + \Delta h_{loss,ext}} \approx \frac{\Delta h_{th}}{\Delta h_{th} + \Delta h_{loss,ext}} = \frac{U_2{}^2 \dot{m}}{\dot{W}}$,(where, $\Delta h_{loss,ext} >> \Delta_{loss,int}$)



- Internal losses : Losses occurred through primary paths of working fluid in a machinery
- External losses : Losses generated from the exterior of primary paths

Uncertainty Analysis

Nomenclature

h : enthalpy
$\dot{m}$: mass flow rate
$\dot{W}$: input power
U_2 : impeller tip speed
in : compressor inlet
out : compressor outlet
$isen$: isentropic process
o : stagnation
ω : uncertainty

Uncertainty analysis

- Relative(fractional) uncertainty [2]
  - $$\frac{\omega_f}{f} = \left\{ \sum \left[\left(\frac{1}{f} \frac{\partial f}{\partial x_i} \varpi_{x_i} \right)^2 \right] \right\}^{1/2}$$
- Pressure ratio
  - $$\frac{\omega_{PR_o}}{PR_o} = \left[\left(\frac{\omega_{P_{o,out}}}{P_{o,out}} \right)^2 + \left(\frac{\omega_{P_{o,in}}}{P_{o,in}} \right)^2 \right]^{1/2}$$
- Isentropic efficiency
  - 1: $$\frac{\omega_\eta}{\eta} = \left[\left(\frac{1}{h_{o,out,isen} - h_{o,in}} \omega_{h_{o,isen}} \right)^2 + 2\left(\frac{h_{o,out,isen} - h_{o,out}}{\left(h_{o,out} - h_{o,in}\right)\left(h_{o,out,isen} - h_{o,in}\right)} \omega_{h_{o,in}} \right)^2 + \left(\frac{(-1)}{h_{o,out} - h_{o,in}} \omega_{h_{o,out}} \right)^2 \right]^{1/2}$$
  - 2: $$\frac{\omega_\eta}{\eta} = \left[\left(\frac{1}{h_{o,out,isen} - h_{o,in}} \omega_{h_{o,out,isen}} \right)^2 + \left(\frac{-1}{h_{o,out,isen} - h_{o,in}} \omega_{h_{o,in}} \right)^2 + \left(\frac{1}{\dot{m}} \omega_{\dot{m}} \right)^2 + \left(\frac{-1}{\dot{W}} \omega_{\dot{W}} \right)^2 \right]^{1/2}$$
  - 3: $$\frac{\omega_\eta}{\eta} = \left[\left(\frac{2}{U_2} \omega_{U_2} \right)^2 + \left(\frac{1}{\dot{m}} \omega_{\dot{m}} \right)^2 + \left(\frac{-1}{\dot{W}} \omega_{\dot{W}} \right)^2 \right]^{1/2}$$

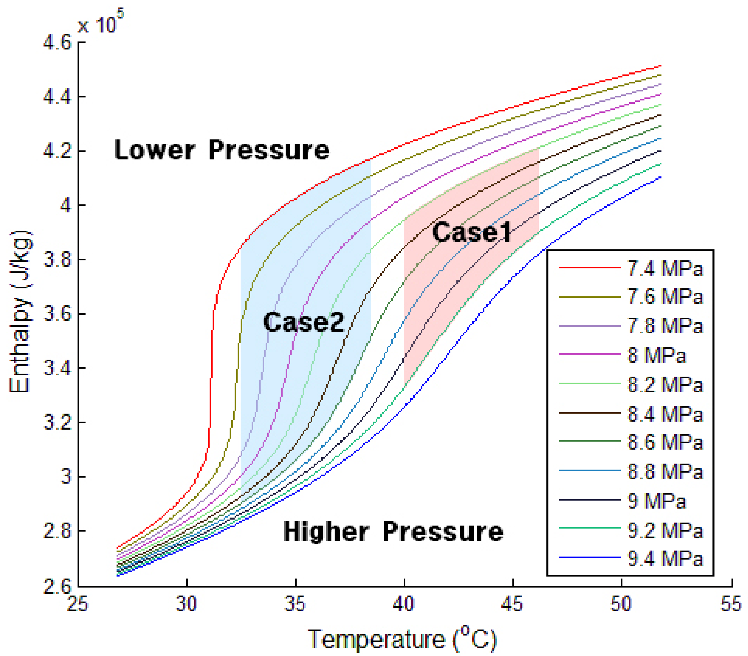
[2] Holman, J. P., 2001, Experimental Methods for Engineers, McGraw-Hill, New York, NY, USA

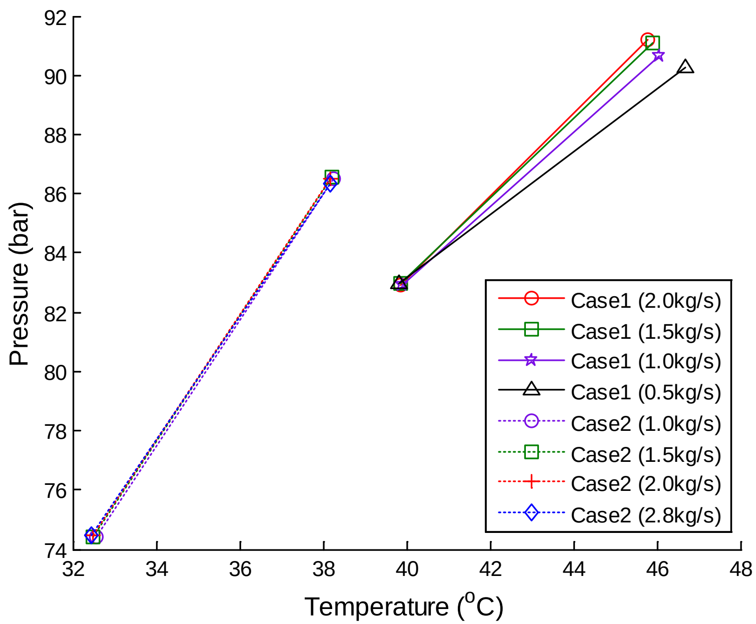
Uncertainty Analysis

- **Data cases**

Case 1, 83 bar, 40°C, above the critical operation	Mass flow rate (kg/s)	Inlet P (kPa)	Outlet P (kPa)	Inlet T (°C)	Outlet T (°C)	RPM
Measured data	2.001	8294.7	9119.3	39.869	45.775	4620
	1.519	8295.1	9111.1	39.876	45.906	4620
	0.955	8291.4	9064.6	39.894	46.070	4620
	0.502	8296.8	9025.0	39.835	46.689	4620

Case 2, 74.4 bar, 32.5°C, near the critical operation	Mass flow rate (kg/s)	Inlet P (kPa)	Outlet P (kPa)	Inlet T (°C)	Outlet T (°C)	RPM
Measured data	2.863	7443.5	8649.5	32.550	38.251	4620
	1.986	7440.0	8658.0	32.502	38.232	4620
	1.545	7444.9	8650.3	32.504	38.196	4620
	0.998	7447.9	8633.6	32.446	38.161	4620





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Uncertainty Analysis

➤ **Uncertainty calculation results**

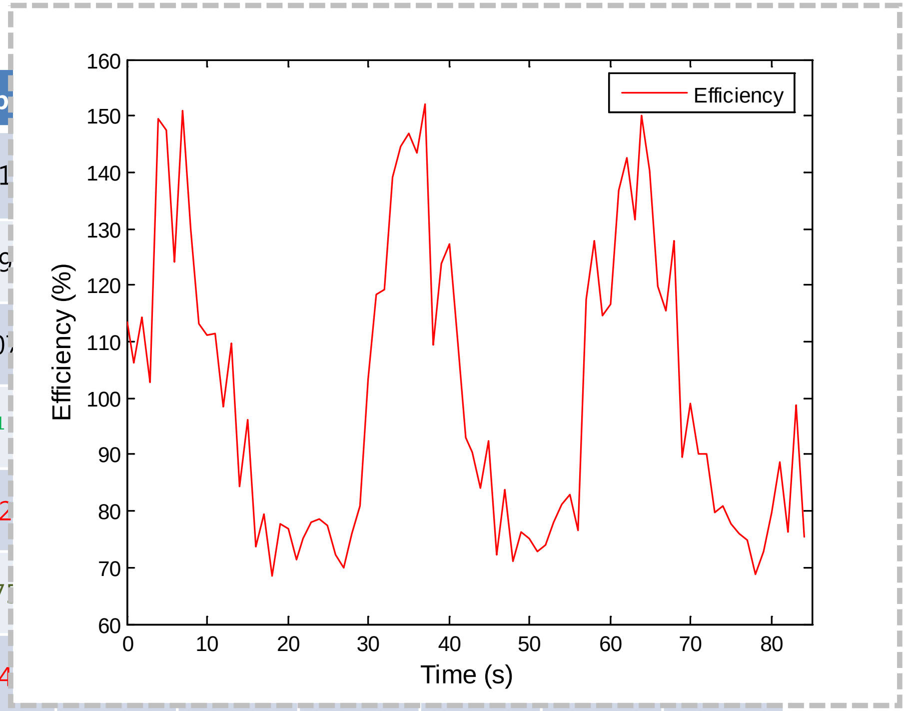
$$PR = \frac{P_{out}}{P_{in}}$$

$$\eta = \frac{h_{out,ideal} - h_{in}}{h_{out} - h_{in}}$$

$$\eta = \left(h_{o,out,isen} - h_{o,in}\right)\frac{\dot{m}}{\dot{W}}$$

$$\eta = \frac{U_2^{\,2}\dot{m}}{\dot{W}}$$

	Case 1, Sup							
Mass flow rate kg/s	2.002	1.51						
PR	1.099	1.09						
$\frac{\omega_{PR}}{PR}$	0.0073	0.007						
η , (%)	_1	_1						
ω_η / η	0.688	0.52						
η , (%)	36.071	28.7						
ω_η / η	0.541	0.54						
η , (%)	46.102	37.116	25.688	14.742	50.631	39.241	32.322	22.184
ω_η / η	0.00615	0.00628	0.00652	0.00677	0.00570	0.00586	0.00596	0.00607

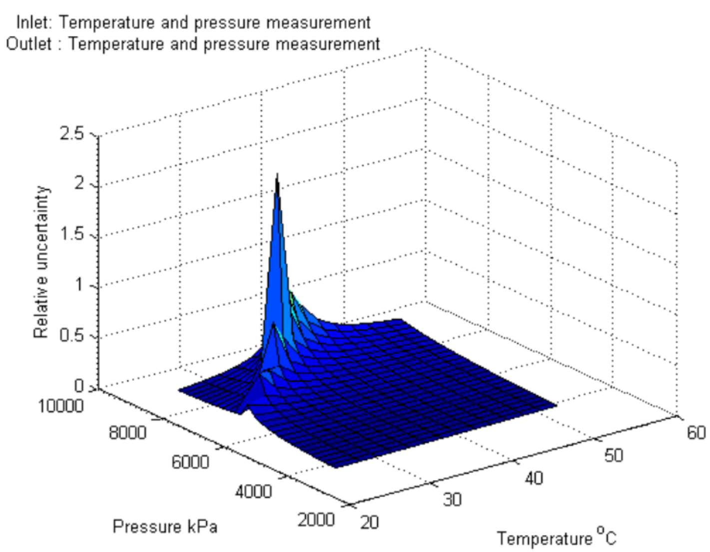


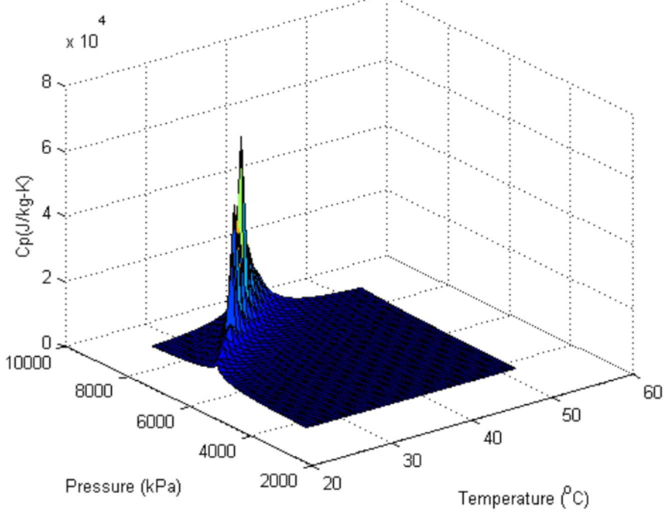
$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{1}{h_{o,out,isen} - h_{o,in}}\omega_{h_{o,out,isen}}\right)^2 + \left(\frac{-1}{h_{o,out,isen} - h_{o,in}}\omega_{h_{o,in}}\right)^2 + \left(\frac{1}{\dot{m}}\omega_{\dot{m}}\right)^2 + \left(\frac{-1}{\dot{W}}\omega_{\dot{W}}\right)^2\right]^{1/2}$$

*1 : Even near the steady state, a large fluctuation (50%-150% Range) of efficiency was observed due to very small background noise in temperature and pressure measurement. Thus it is not possible to report efficiency based on equation (3).

Uncertainty Analysis

- **Issue 1**
  - Peak region on property variation of S-CO_2 near the critical point causes high uncertainty on efficiency measurement
    - ✓ Inherent characteristic of S-CO_2 near the critical point
    - ✓ Strong correlation with specific heat and measurement uncertainties



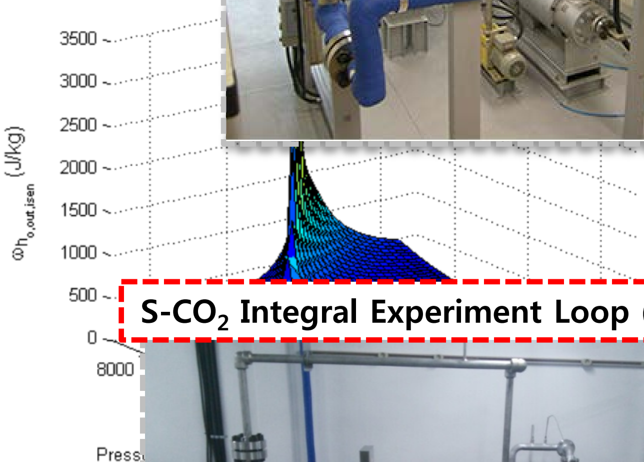


$$\frac{\omega_\eta}{\eta}=\left[\left(\frac{1}{h_{o,out,isen}-h_{o,in}}\omega_{h_{o,out,isen}}\right)^2+\left(\frac{-1}{h_{o,out,isen}-h_{o,in}}\omega_{h_{o,in}}\right)^2+\left(\frac{1}{\dot{m}}\omega_{\dot{m}}\right)^2+\left(\frac{-1}{\dot{W}}\omega_{\dot{W}}\right)^2\right]^{1/2}$$

Uncertainty Analysis

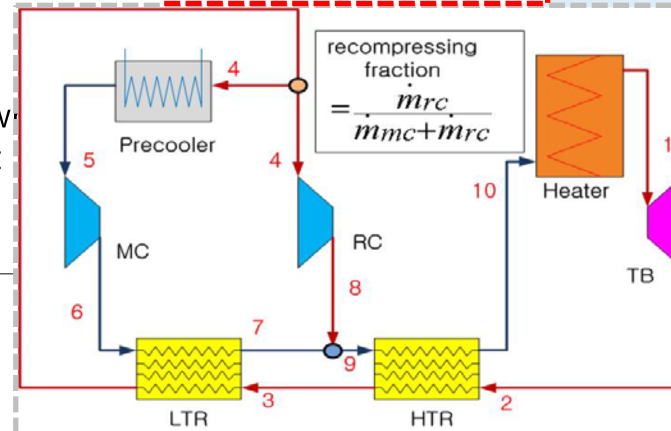
- **Issue 2**
  - Performance m… rise (w… compressor has … ement

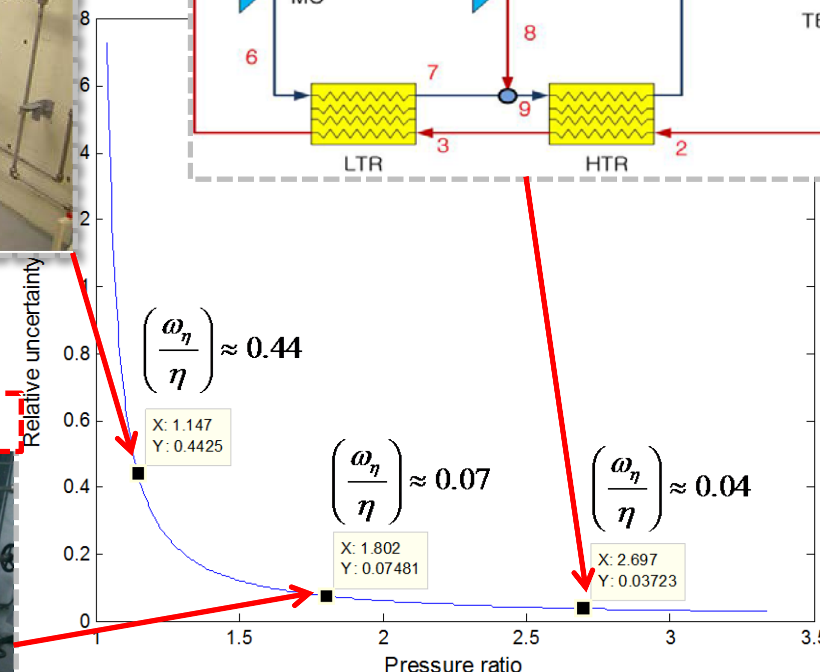
$$\omega_h \propto \left(\frac{\partial h}{\partial T}, \frac{\partial h}{\partial P}\right)$$ for …



SCO2PE

Recompression Layout





S-CO_2 Integral Experiment Loop (SCIEL)

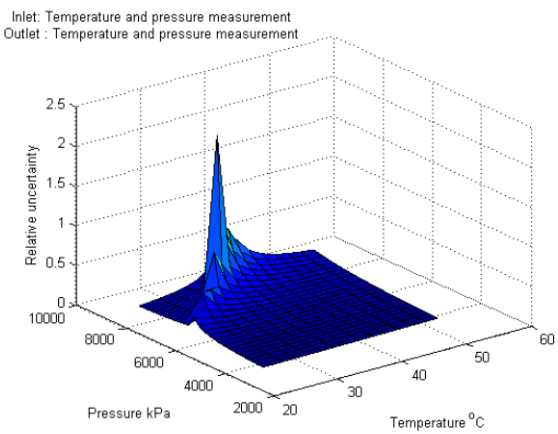
$$\frac{\omega_\eta}{\eta} = \Bigg[\Bigg(\cdots \omega_{h_{o,in}} \Bigg)^2 + \left(\frac{1}{\dot m}\omega_{\dot m}\right)^2 + \left(\frac{-1}{\dot W}\omega_{\dot W}\right)^2 \Bigg]^{1/2}$$

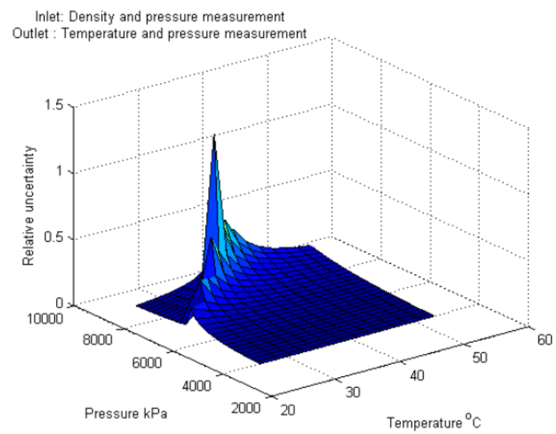
Uncertainty Analysis

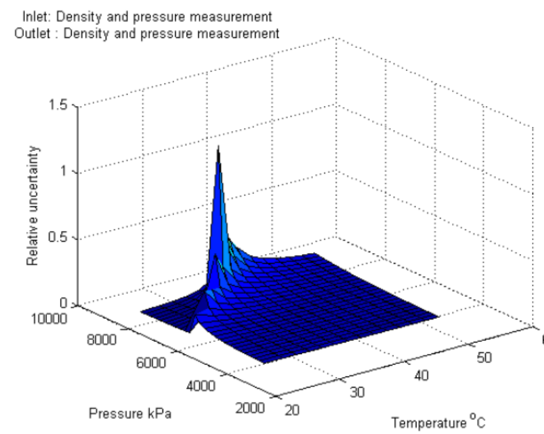
- **Issue 3**
  - Applying of density measurement at compressor inlet and outlet reduces uncertainty on efficiency measurement [1].

T: Temperature, P: Pressure, D: Density

Inlet : T – P Outlet : T - P	21% Improvement →	Inlet : D – P Outlet : T - P	33% Improvement →	Inlet : D – P Outlet : D - P
$\left(\frac{\omega_\eta}{\eta}\right)_{avg} = 0.637$		$\left(\frac{\omega_\eta}{\eta}\right)_{avg} = 0.499$		$\left(\frac{\omega_\eta}{\eta}\right)_{avg} = 0.333$







$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{1}{h_{o,out,isen} - h_{o,in}}\omega_{h_{o,out,isen}}\right)^2 + \left(\frac{-1}{h_{o,out,isen} - h_{o,in}}\omega_{h_{o,in}}\right)^2 + \left(\frac{1}{\dot{m}}\omega_{\dot{m}}\right)^2 + \left(\frac{-1}{\dot{W}}\omega_{\dot{W}}\right)^2\right]^{1/2}$$

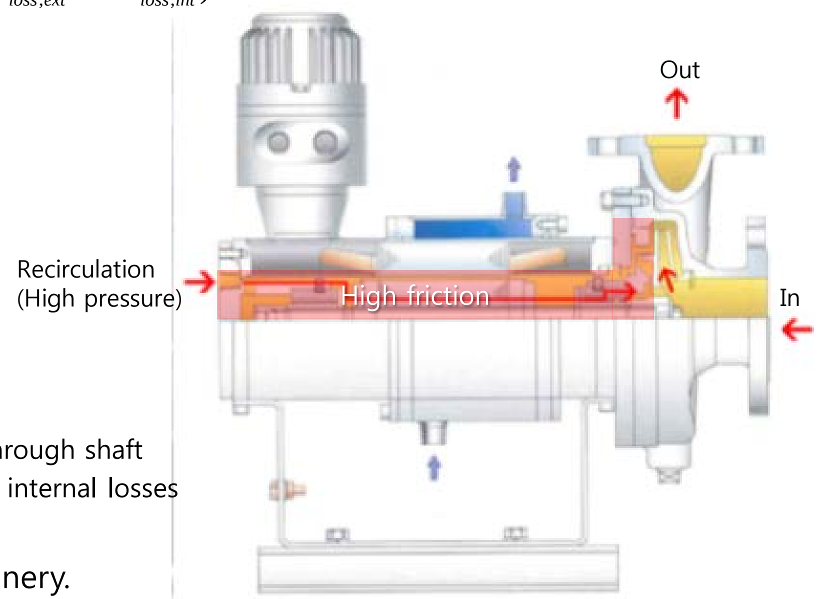
[1] Wahl, G. D., 2009, "Efficiency Uncertainty of a Turbine Driven Compressor in a Supercritical CO_2 Brayton Cycle", Proceedings of S-CO_2 Power Cycle Symposium, RPI, Troy, NY

Uncertainty Analysis

- **Issue 4**
  - Approximation on efficiency calculation is necessary for low pressure ratio S-CO_2 compressor with near the critical operation condition
    - Due to uncertainty of enthalpy terms on efficiency calculation equations, high uncertainty always involves when S-CO_2 compressor inlet condition is near the critical point
  - ✓ Approximation on efficiency calculation for main compressor of SCO2PE

$$\eta = \frac{\Delta h_{th} - \Delta h_{loss,int}}{\Delta h_{th} + \Delta h_{loss,ext}} \approx \frac{\Delta h_{th}}{\Delta h_{th} + \Delta h_{loss,ext}} = \frac{U_2{}^2 \dot{m}}{\dot{W}} \quad \text{,(where, } \Delta h_{loss,ext} >> \Delta_{loss,int}\text{)}$$

$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{2}{U_2} \omega_{U_2} \right)^2 + \left(\frac{1}{\dot{m}} \omega_{\dot{m}} \right)^2 + \left(\frac{-1}{\dot{W}} \omega_{\dot{W}} \right)^2 \right]^{1/2} \approx 0.006$$



  - ✓ Basis
    - low specific speed design
    - Some portion of high(discharge) pressure S-CO_2 recirculates through shaft
    - Thus, it is fair assumption that external losses are greater than internal losses
  - ✓ It doesn't represent actual isentropic efficiency of machinery.

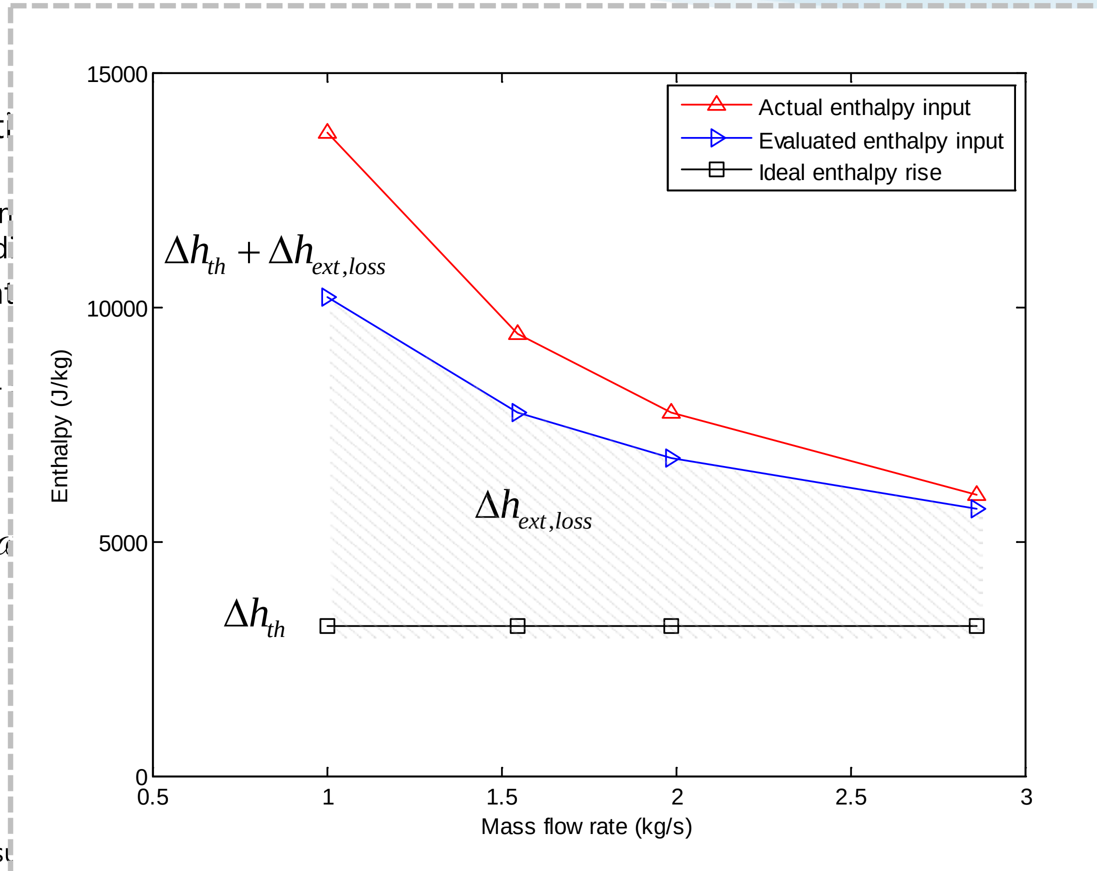
However, it can be utilized for the base data for operation with low uncertainty

Uncertainty Analysis

- **Issue 4**
  - Approximation on efficiency calculati near the critical operation condition
    - Due to uncertainty of enthalpy terr when S-CO_2 compressor inlet cond
  - ✓ Approximation on efficiency calculat

$$\eta = \frac{\Delta h_{th} - \Delta h_{loss,int}}{\Delta h_{th} + \Delta h_{loss,ext}} \approx \frac{\Delta h_{th}}{\Delta h_{th} + \Delta h_{loss,ext}}$$

$$\frac{\omega_\eta}{\eta} = \left[\left(\frac{2}{U_2} \omega_{U_2} \right)^2 + \left(\frac{1}{\dot{m}} \omega_{\dot{m}} \right)^2 + \left(\frac{-1}{\dot{W}} \omega \right. \right.$$



  - ✓ Basis
    - low specific speed design
    - Some portion of high(discharge) pressu
    - Thus, it is fair assumption that external losses are greater than internal losses

  - ✓ It doesn't represent actual isentropic efficiency of machinery.

However, it can be utilized for the base data for operation with low uncertainty

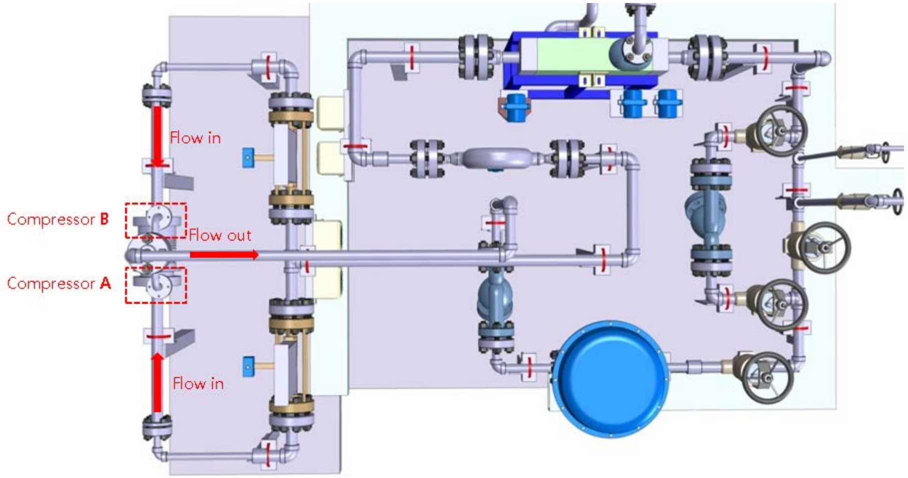
Summary and further works

- **Issues on uncertainty on efficiency measurement of near the critical operation S-CO_2 compressor**
  - 1. Peak region on property variation of S-CO_2 near the critical point causes high uncertainty on efficiency measurement
    - ✓ Inherent characteristics of S-CO_2 near the critical point
  - 2. Performance measurement on low isentropic enthalpy rise (which is related with pressure ratio) compressor has high uncertainty on efficiency measurement
    - ✓ Machine dependency
    - ✓ At 2.7 pressure ratio, this issue will be mitigated with under 0.1 of relative uncertainty.
  - 3. Applying of density measurement at compressor inlet and outlet reduces uncertainty on efficiency measurement [1].
    - ✓ It is true that it increases measurement confidence. However it doesn't provide remarkable improvement for low pressure ratio S-CO_2 compressor.
  - 4. Approximation on efficiency calculation is necessary for low pressure ratio S-CO_2 compressor with near the critical operation condition
    - ✓ Just for SCO2PE compressor which has relatively high external losses
    - ✓ It doesn't represent actual efficiency but it can be used for performance indicator for operation with low uncertainty

Summary and further works

➢ **Further works**

- Uncertainty analysis for the compressor of S-CO_2 Integral Experiment Loop (SCIEL)
  - ✓ Construction field : Korea Atomic Energy Research Institute (KAERI)
  - ✓ 2014 construction : Simple cycle demonstration



- analysis on each loss model will be carried out to make better approximation on performance measurement.

THANK YOU