$S\text{-}CO_2$ cycle design and control strategy for the SFR application

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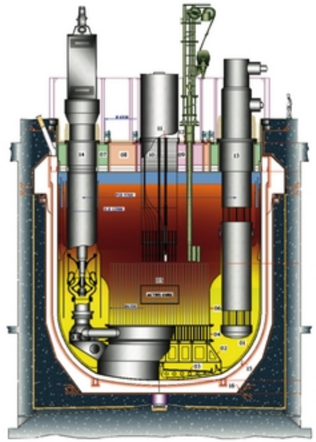
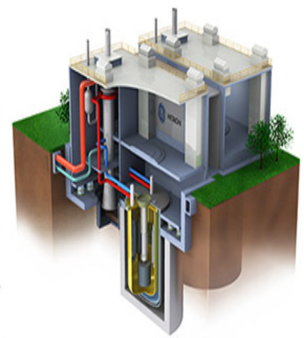
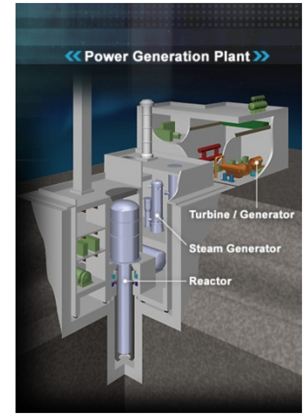
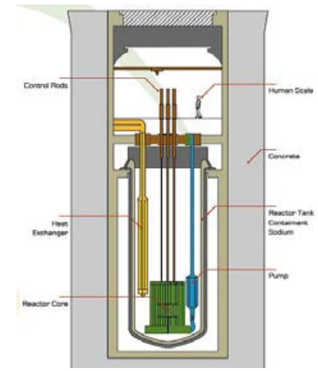
$S\text{-}CO_2$ Power Cycle Development

Small Modular sized SFR design







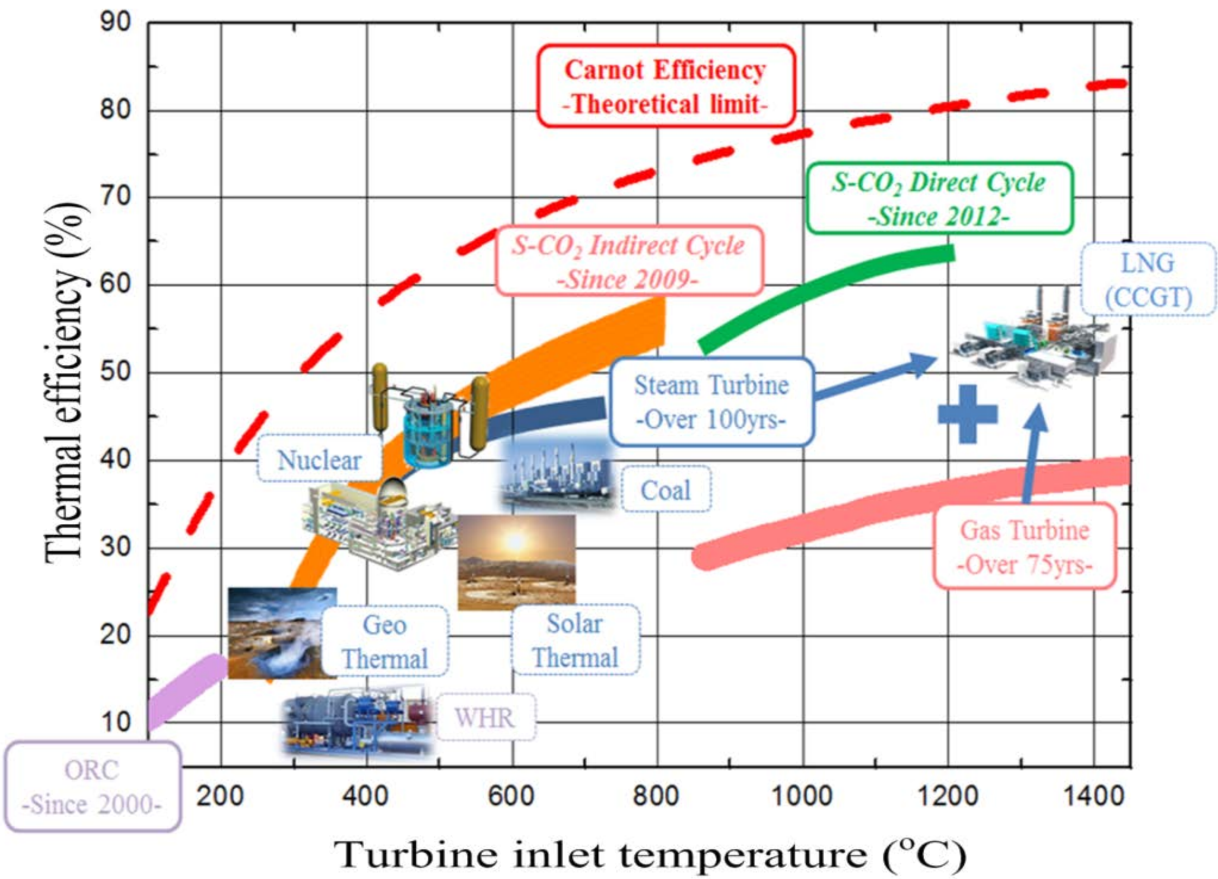


Name	CEFR	PFBR-500	PRISM	4S	ARC-100
Thermal power class	Small	Medium	Medium	Small	Small
Efficiency, %	30	40	37	37	38
Core outlet temperature ,ºC	530	547	510	510	510
Developer	CIAE	IGCAR	GE-Hitachi	Toshiba	Advanced Reactor Concepts
Country	China	India	U.S.A	Japan	U.S.A
Power conversion system	Steam Rankine				$S\text{-}CO_2$ Brayton

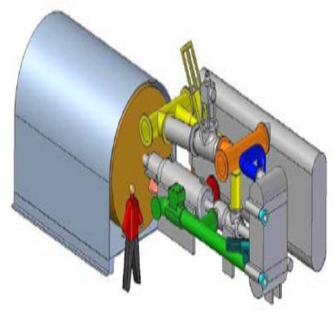
S-CO_2 Power Cycle Development

S-CO_2 cycle for the SFR application

- The benefits of the S-CO_2 cycle:
  - relatively high efficiency under the mild turbine inlet temperature condition
  - simple layout and compact size
  - Potentially enhanced the safety of the SFR system

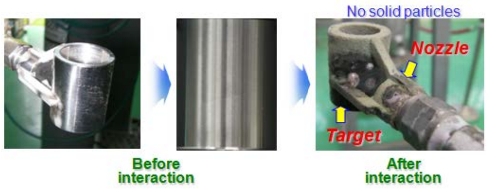


➢Thermal efficiencies of power conversion systems and applications

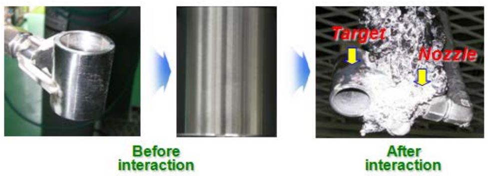


➢20MWe Recompression SCO_2 PCS Layout [P. Hejzlar et al, MIT-2007]

❑ Sodium-Water Reaction (SWR)



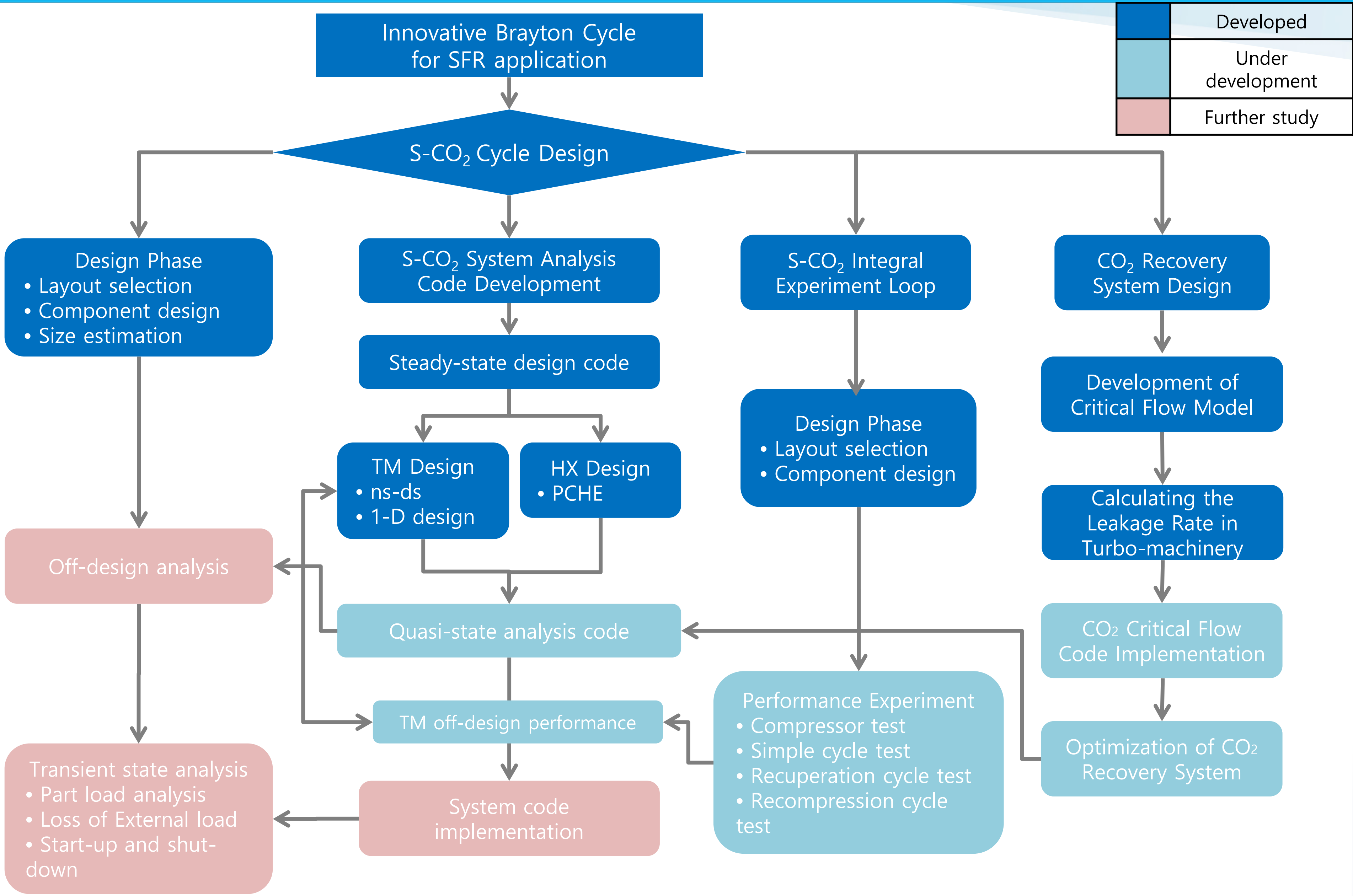
❑ Sodium-CO_2 interaction



➢Comparison of sodium reaction with water and CO_2 in a pipe [J. Eoh (2010)]

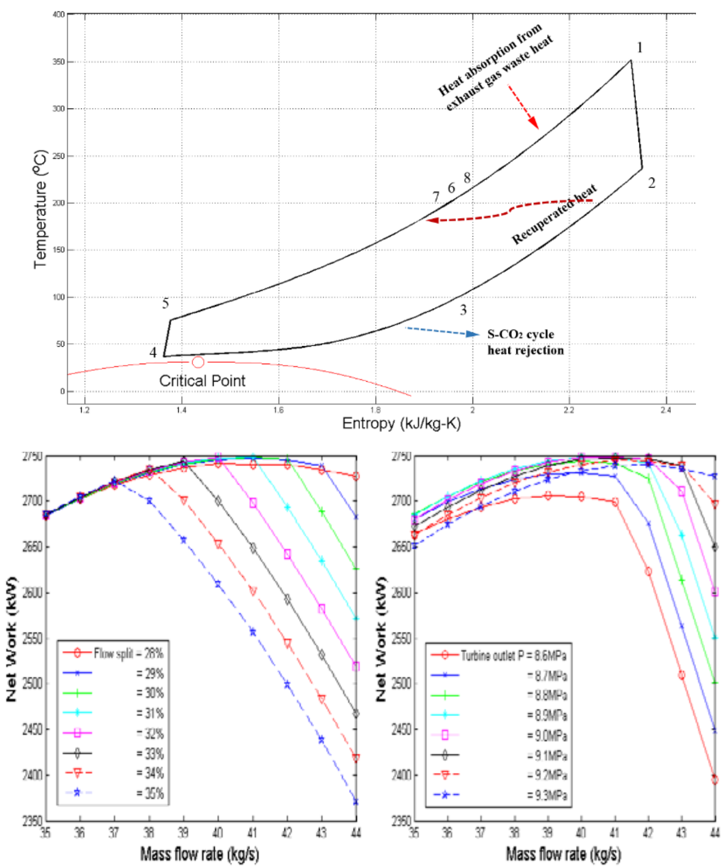
S-CO_2 Power Cycle Development

S-CO_2 cycle design flow chart

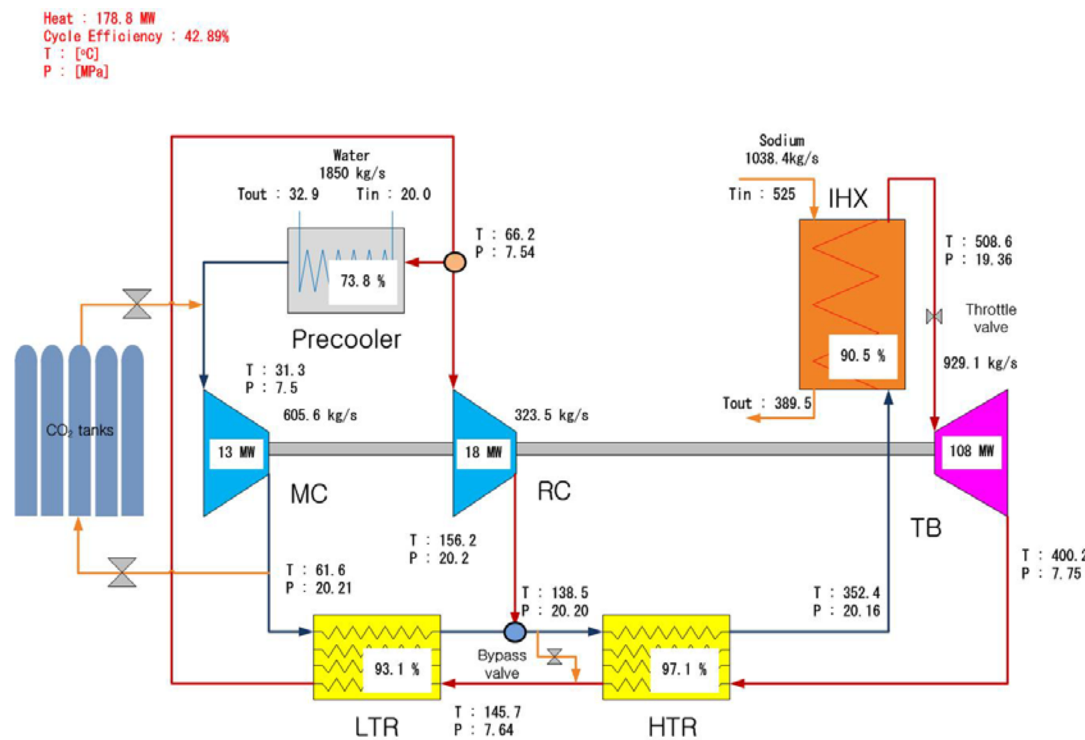


S-CO_2 cycle design

- The KAIST-Closed Cycle Design (KAIST_CCD) code, an in-house code developed by KAIST research team is based on the MATLAB.
- Enthalpy and other fluid properties information for the code calculation is provided directly by the NIST reference fluid thermodynamic and transport properties database (REFPROP).



▲ T-s diagram and sensitivity analysis through the KAIST_CCD



▲ S-CO_2 cycle condition for SFR application

*** TB : turbine, MC : main compressor, RC : recompression compressor, IHX : intermediate heat exchanger, HTR : high temperature recuperator, LTR : low temperature recuperator**

S-CO_2 Component Design

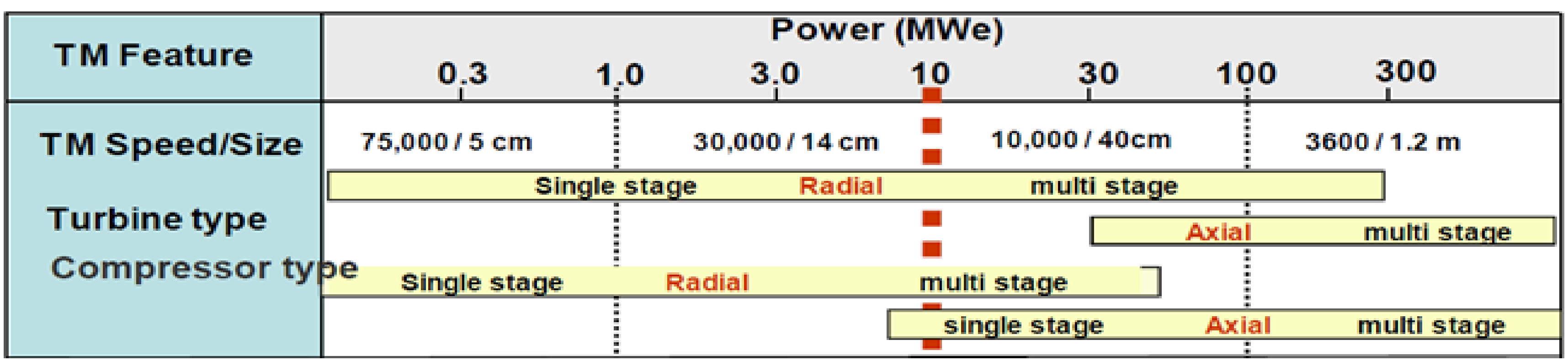
S-CO_2 cycle turbomachinery design

- Generally, in a large scale system, axial type turbomachineries are favored over other types.
- However, in the S-CO_2 cycle, radial type turbomachineries can be more appropriate even for the relatively large scale MW output system due to the high density and low pressure ratio cycle characteristics.

-Operating characteristics between axial and radial turbomachinery (Gong et al., 2006)

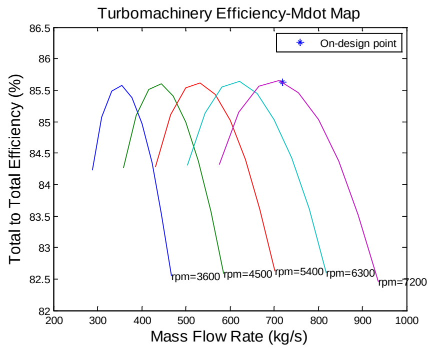
Radial	Axial
Relatively constant flow, variable head	Relatively constant head, variable flow behavior
Best suited for lower flow rate	Best suited for higher flow rate
Higher pressure ratio applications	Moderate pressure ratio applications
Fewer or single stage	Commonly used with multi stage configurations
Shorter axial length due to fewer stages	Longer axial length due to multi stages
Relatively wider operating range	Limited operating range
Lower efficiency by up to 4% in general compared to the axial machine	Higher efficiency, especially if shrouded

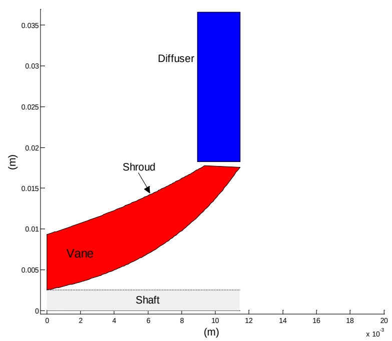
- Turbomachinery Technology options for S-CO_2 cycle [Sienicki, J., 2011]

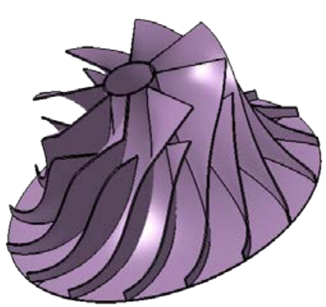


Turbomachinery design code [KAIST_TMD]

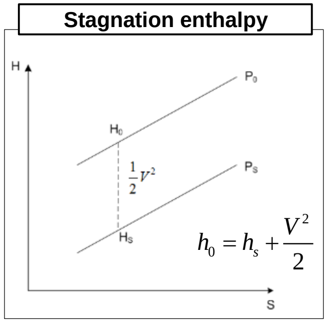
KAIST_TMD

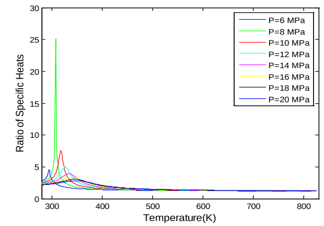


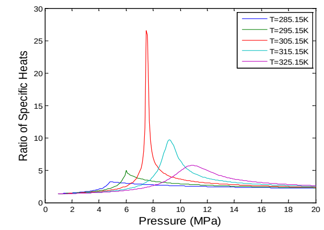




- Ideal gas based correlations cannot be used for S-CO_2







Ideal gas correlations

$$T_0 C_P = T_s C_P + \frac{V^2}{2}$$

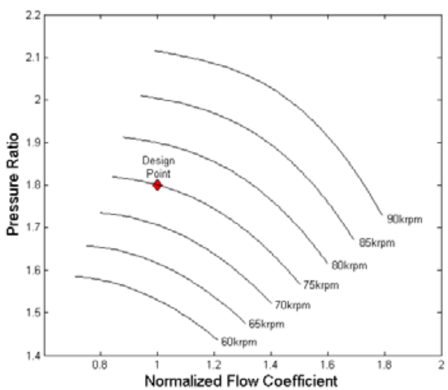
$$\frac{T_o}{T_s} = 1 + \frac{V^2}{2C_p T_s} = 1 + \frac{\gamma - 1}{2} M^2$$

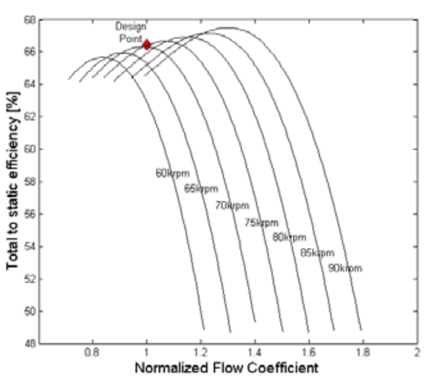
$$\frac{P_o}{P_s} = \left(\frac{T_o}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

- Governing Equation (Continuity equation + Euler equation)

$$\dot{m} = \rho(h_s, P_s)AV \qquad h_{02} - h_{01} = U_2 W_{w2} - U_1 W_{w1}$$

Call from NIST property database



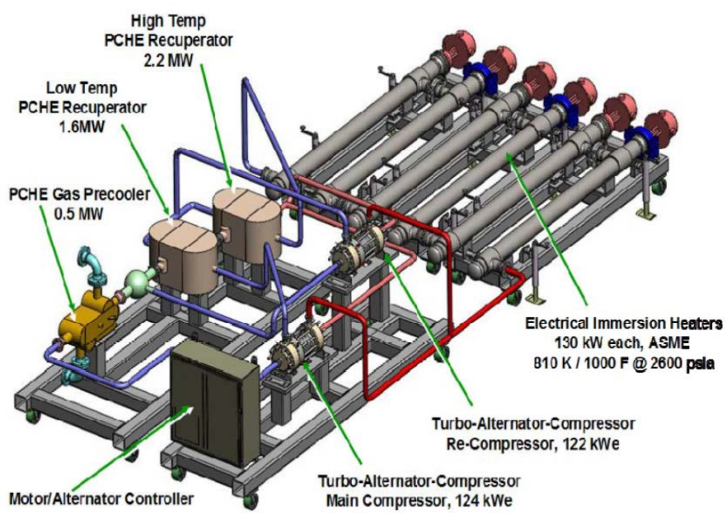


▲ **Predicted off-design performance map (Sandia National Lab.)**

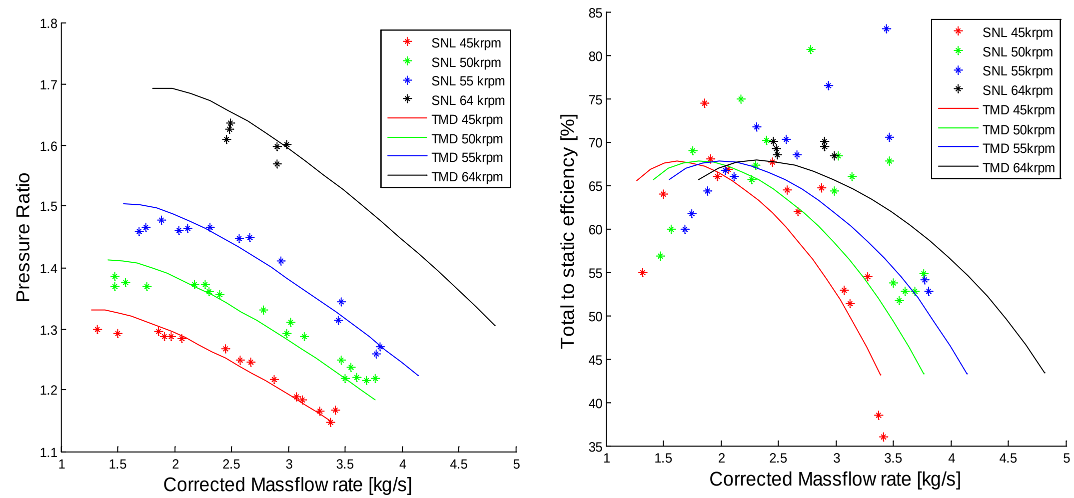
Turbomachinery design code [KAIST_TMD]

❖ Code validation and verification (V&V)

- ✓ The Sandia National Laboratory (SNL) data are the only available compressor performance data on the S-CO_2 cycle research field so far.
- ✓ To validate KAIST_TMD, the compressor off design map from it compared with experimental data from SNL.
- ✓ KAIST_TMD has similar tendency in pressure ratio, whereas the efficiencies were predicted with some errors.
- ✓ It suggests that internal loss models based on air yield reasonable results with S-CO_2.
- ✓ Three external impeller loss models are considered such as recirculation, disk friction, and leakage.
- ✓ External losses are added only to the impeller exit stagnation enthalpy without any pressure change. It means external losses only affect efficiencies.



SolidWorks schematic of the delivered split-flow recompression loop



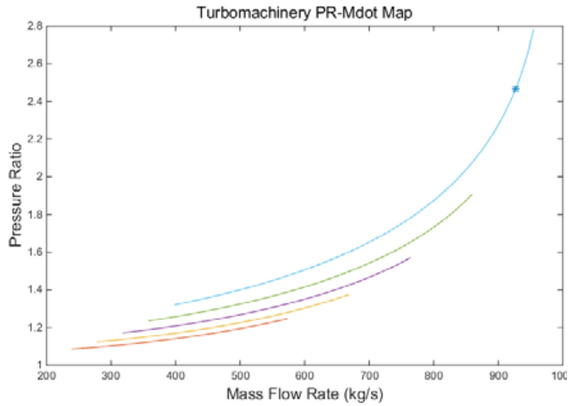
▲ KAIST_TMD code validation with SNL data

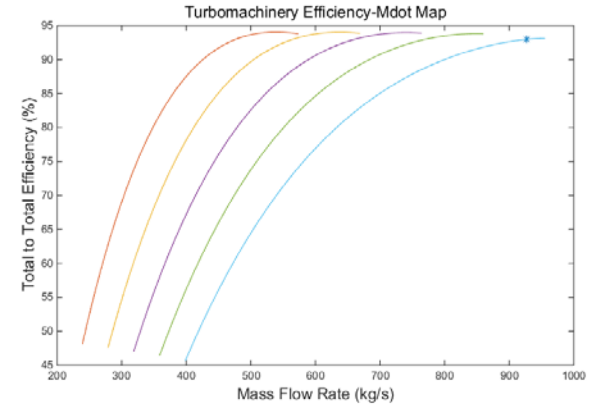
***Source: S.A. Wright. et al., Operation and Analysis of a S-CO_2 Brayton cycle, 2010**

$S\text{-}CO_2$ cycle turbomachinery design

Turbine Performance

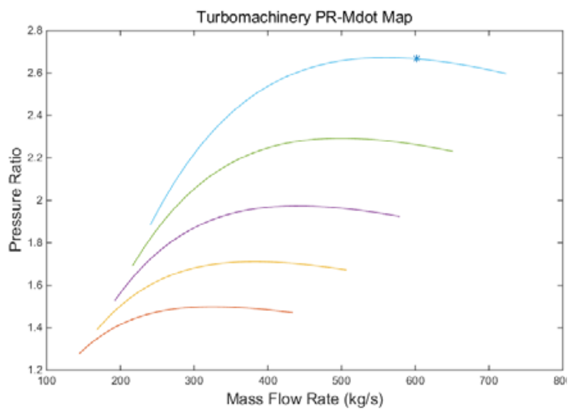
Impeller diameter: 0.95m
Rotating speed: 7200rpm->3600rpm

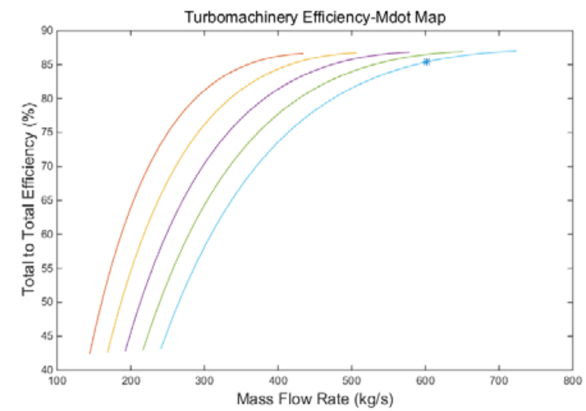




Main Compressor Performance

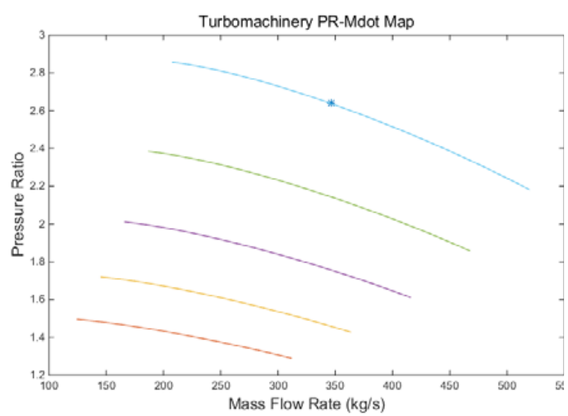
Impeller diameter: 0.55m
Rotating speed: 7200rpm->3600rpm

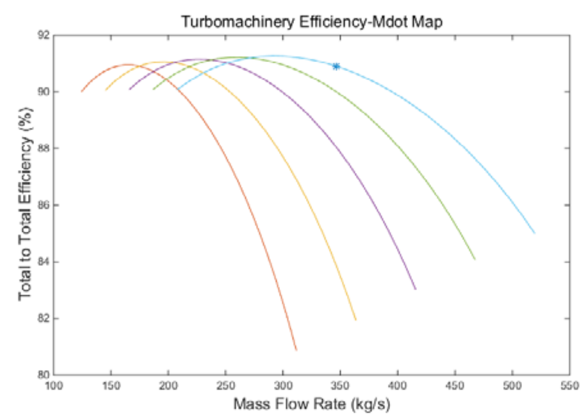




Recompression compressor Performance

Impeller diameter: 0.74m
Rotating speed: 7200rpm->3600rpm



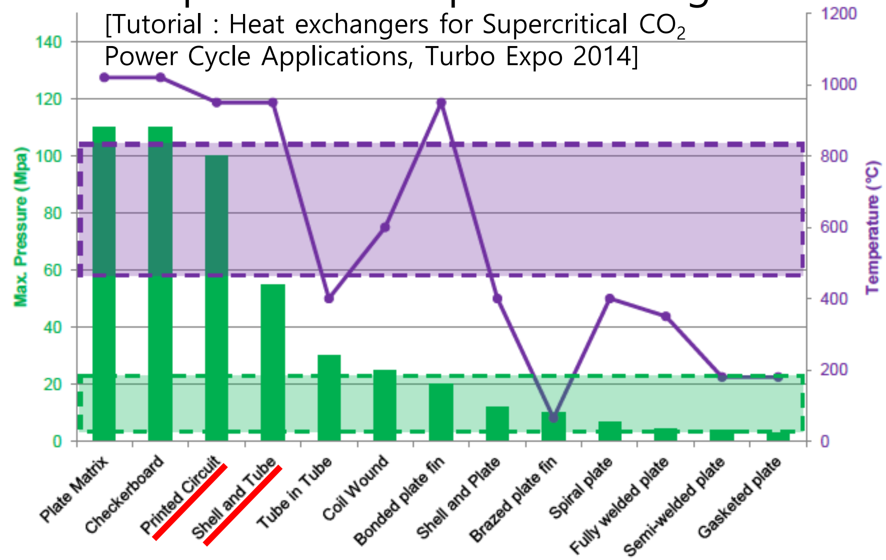


S-CO_2 cycle heat exchanger design

Operating condition

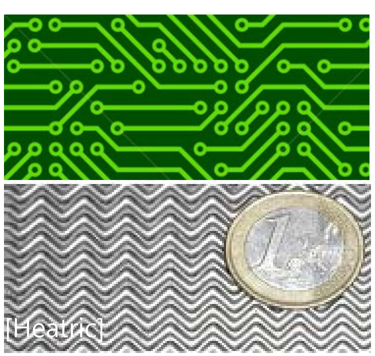
- High pressure (P_{min} > 7.4 MPa)
- High temperature

Temperature and pressure ranges
[Tutorial : Heat exchangers for Supercritical CO_2 Power Cycle Applications, Turbo Expo 2014]

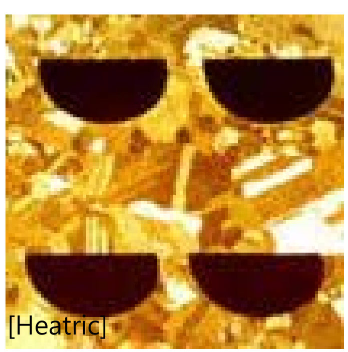


Printed Circuit Heat Exchanger

- Highly compact & effective – Excellent choice for gas heat exchanger
- Parallel core stacking - Enables to use on large systems



Chemical etching

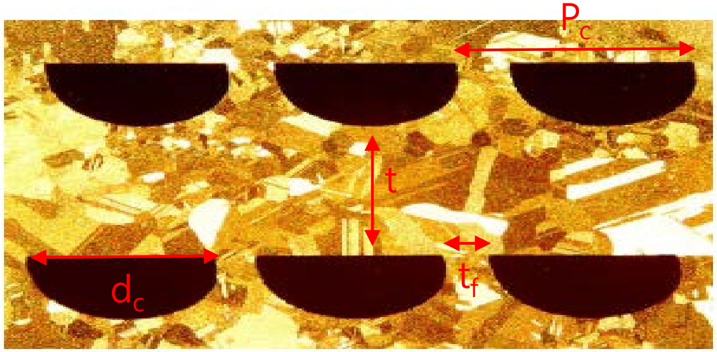


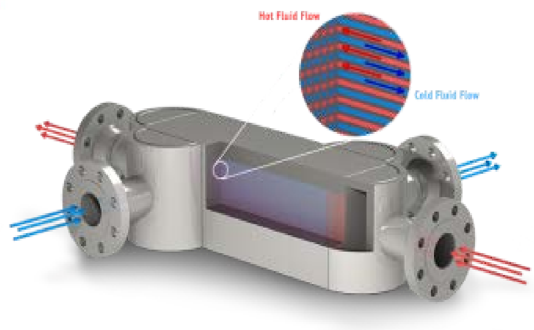
Diffusion bonding

Core stacking

Heat exchanger design code [KAIST_HXD]

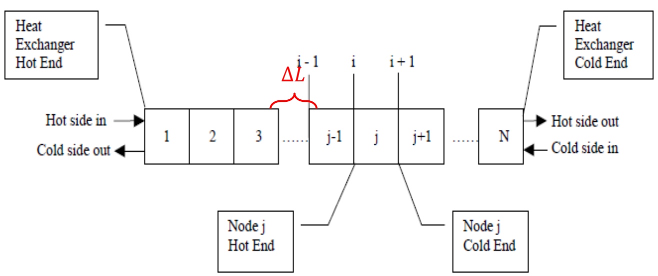
- Heat exchanger design
  - All heat exchanger is assumed to be the Printed Circuit Heat Exchanger (PCHE) type.
  - KAIST-HXD(Heat Exchanger Design) in-house code is used.





- Material : SUS 316
- Material density = 8000 kg/m3
- Material melting point = 1375~1400 'C
- Channel diameter, dc = 1.8~2.2mm
- t(Plate thickness) = 0.5 mm
- Pc(Channel pitch) = 2.2~2.6 mm,
- $P_c = d_c + t_f$ => t_f = 0.4 mm
- Recuperator Effectiveness(%) : 95

Fig. PCHE configuration



Counter current flow type PCHE
PCHE type heat exchanger scheme drawing

Fluid	sodium	helium	CO_2	N_2	water
Nu Correlation	$Nu = 7 + 0.025 \cdot Pe^{0.8}$	$Nu = 4.065 + 0.00305 \cdot Re$	$Nu = 0.1696 \cdot Re^{0.629} \cdot Pr^{0.317}$		
F correlation	$f = 4 \cdot (0.0014 + 0.125 \cdot Re^{-0.32})$	$f = \frac{16.51}{Re} + 0.1627$	$f = 01924 \cdot Re^{-0.091}$		
Applicable range, $[N_{Re}]$	Not limited	250-350	2,500-33,000		
reference	Hejzlar et al., 2007	Kim, 2009	Ngo et al., 2007		

Table. Heat exchanger design parameters of 75MWe S-CO_2 cycle

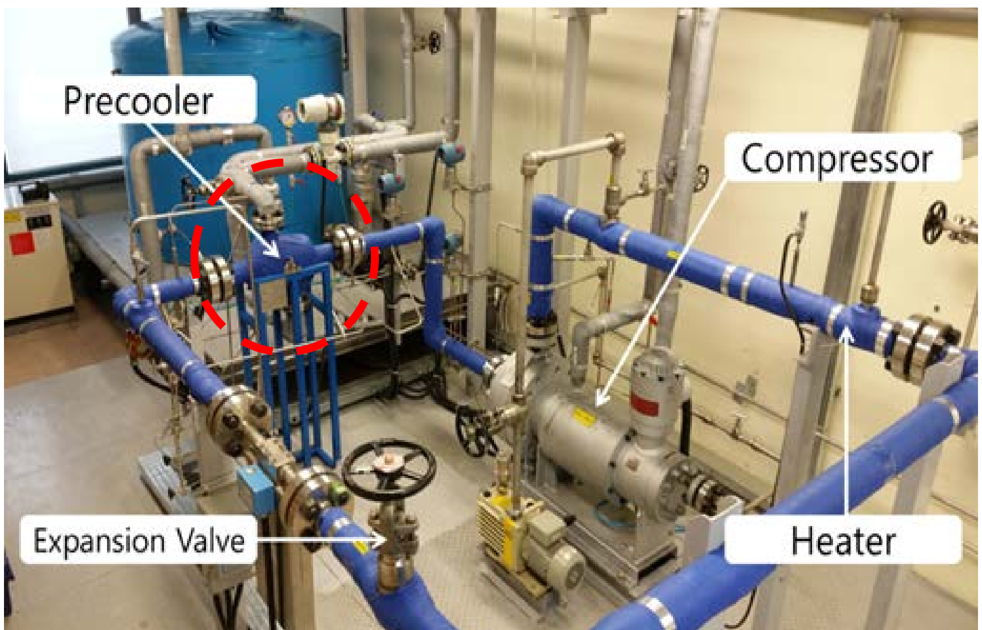
Heat exchanger	HTR	LTR	PC	IHX
Heat, MW	108.2	268.7	102.1	178.8
Effectiveness, %	97.1	93.1	73.8	90.5
Volume, m^3	6.9	8.5	3.07	2.3
Geometry, m (L x W x H)	1.1 x 2.5 x 2.5	1.4 x 2.5 x 2.5	1 x 1.75 x 1.75	0.6 x 2.1 x 2.1

S-CO_2 Component Design

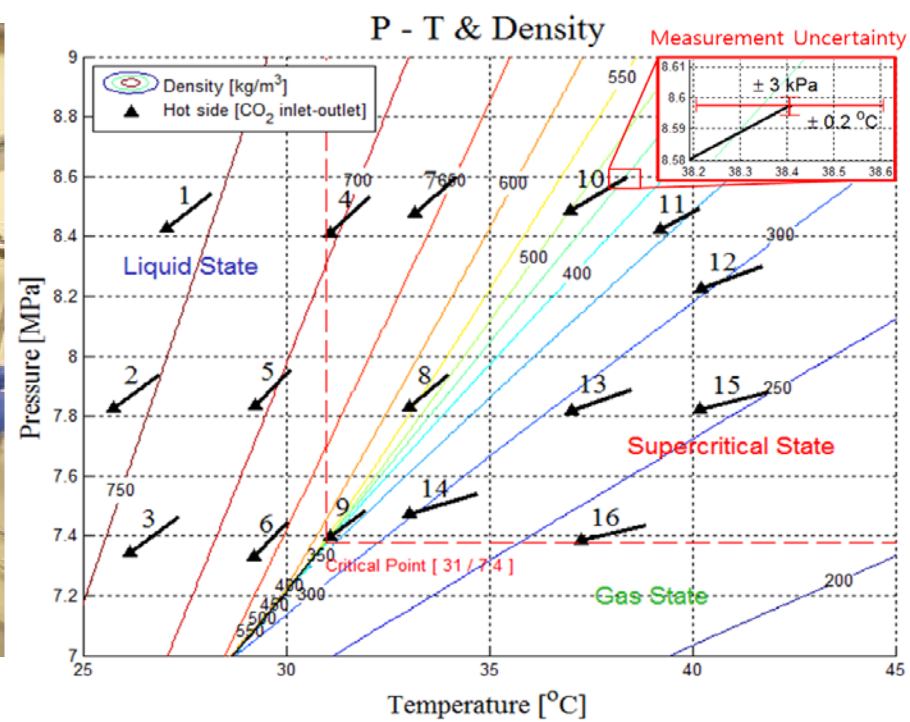
Heat exchanger design code [KAIST_HXD]

❖ Code validation and verification (V&V)

- ✓ Developed KAIST_HXD can be used for :
  1. Design optimization
  2. Steady state performance analysis
- ✓ Lab-scale PCHE was designed with the design code and manufactured by a Korean manufacturer.
- ✓ Manufactured PCHE was installed to a KAIST S-CO_2 cycle experimental facility (S-CO_2PE) and the performance test was conducted.
- ✓ Experimental data was accumulated for reliable design code validation



▲ View of the S-CO_2PE facility & designed PCHE

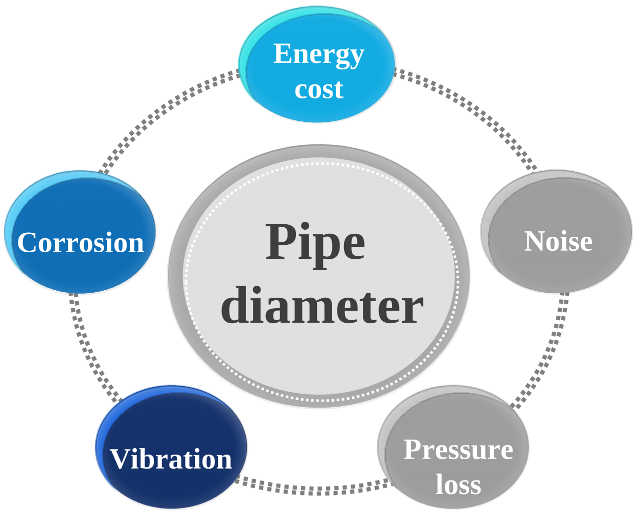


▲ Designed Printed Circuit Heat Exchanger (PCHE)

▲ Experimental data of CO_2 side

$S\text{-}CO_2$ Pipe Design

Determination of Pipe Diameter and Thickness for $S\text{-}CO_2$ Cycle



Flow Velocity

$$V = f_{pv}/\rho^{0.3}$$

by Ronald W. Capps(Chem. Eng. 1995.6)

V : optimal flow velocity $[m/s]$

f_{pv} : pipe velocity factor $[m(\frac{kg}{m^3})^{0.3}/s]$

ρ : density of flow $[\frac{kg}{m^3}]$

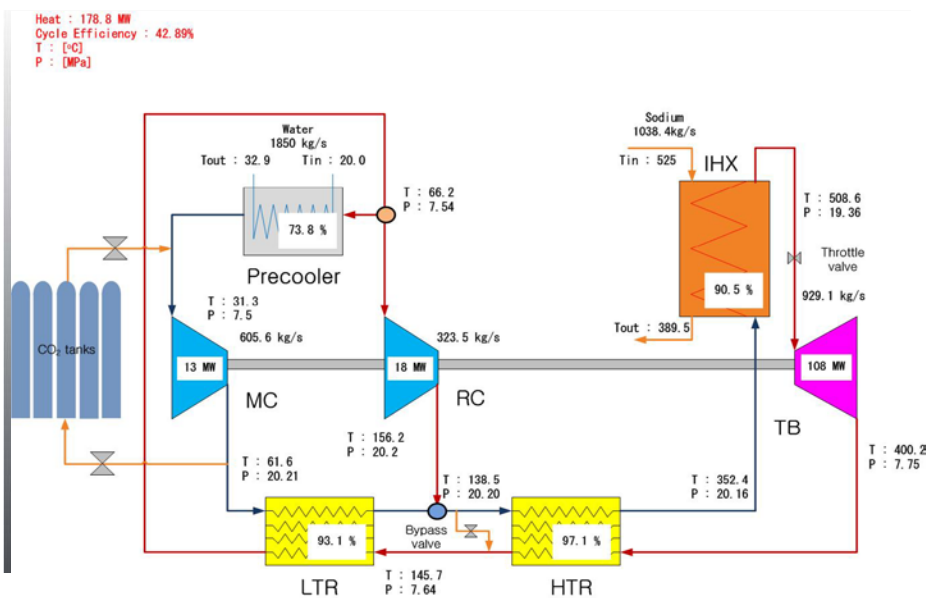
PIPE VELOCITY FACTORS	
Motive Energy Source	m $(kg/m^3)^{0.3}$ /s
Centrifugal Pump, Blower	14
Compressor Pipe dia<6in. Pipe dia>6in.	24 29
Steam Boiler	63 ~ 68

Minimum thickness

$$t_m = \frac{PD_0}{2(SE+Py)} + A$$

t_m: minimum required wall thickness [m]
P: internal design pressure [Pa]
Do: outside diameter of pipe [m]
S: maximum allowable stress [Pa]
E: weld joint efficiency
Y: coefficient
A: additional thickness [m]

- Conceptual design of $S\text{-}CO_2$ Recompression Cycle
  - 3D Schematic



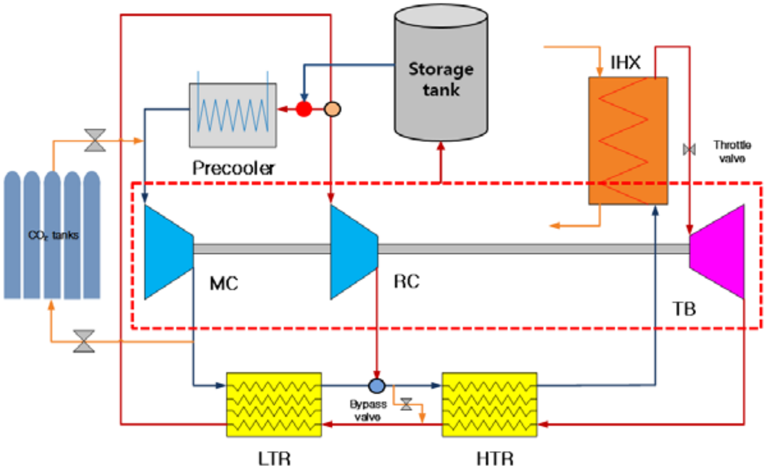
➢ Piping was selected in accordance with the ASME standard

S.C.	Nominal Pipe Size	External Diameter (m)	**Velocity (m/s)**	Thickness(m)	Material type	Pressure drop (kPa)
①	24	0.610	31.8	0.03493	Nickel and High Nickel Alloys, N06600, B 168	46.68
②	28	0.711	42.7	0.01905		28.47
③	28	0.711	25.3	0.01905		60.78
④	28	0.711	15.8	0.01748	Low and Intermediate Alloy Steel, P91 A335	8.50
⑤	28	0.711	10.3	0.01748		13.17
⑥	24	0.610	3.9	0.01588		0.91
⑦	24	0.610	3.7	0.03493	Nickel and High Nickel Alloys, N06600, B 168	2.25
⑧	24	0.610	7.7	0.03493		22.95
⑨	24	0.610	7.6	0.01588	Low and Intermediate Alloy Steel, P91 A335	4.75
⑩	24	0.610	4.4	0.03493	Nickel and High Nickel Alloys, N06600, B 168	2.81
⑪	24	0.610	12.5	0.03493		6.94
⑫	24	0.610	23.8	0.03493		89.39
Total pressure drop uncluding minor loss (kPa)						287.60

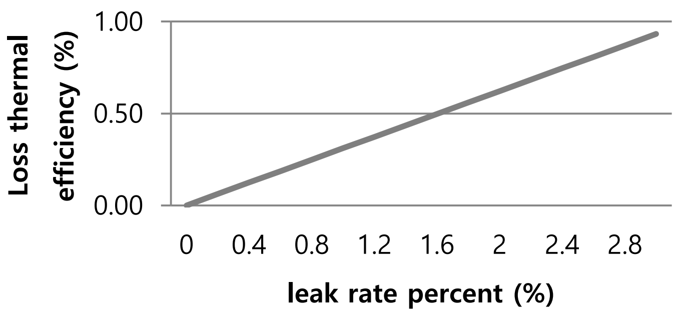
CO_2 Recovery System Design

- The suggested concept
  - Conventional leak rate is assumed, which the conventional leak rate is less than **1kg/s** per seal.
  - To reduce the thermal efficiency loss with CO_2 recovery
  - It is not only **simple** and **intuitive** but also has relatively very low additional W_{comp}.
  - It does not need **additional compressor**.
  - Calculate the $W_{net,loss}$ → **0.312 MW_e**
  - **Thermal efficiency loss** caused by CO_2 inventory recovery system is **0.17 %.**

Inventory total mass
= CO_2 in Pipe + CO_2 in HX
= (1224.2+2766.0) kg
= 3990.2 kg
(It considers the HXs and Pipes)



▲ **Preliminary design on CO_2 inventory recovery system of S-CO_2 power cycle for 75MWe SFR application**



- One loss was considered
  - $W_{net,loss}$
    - Loss due to the **$\dot{m}$ change** of turbines and compressors

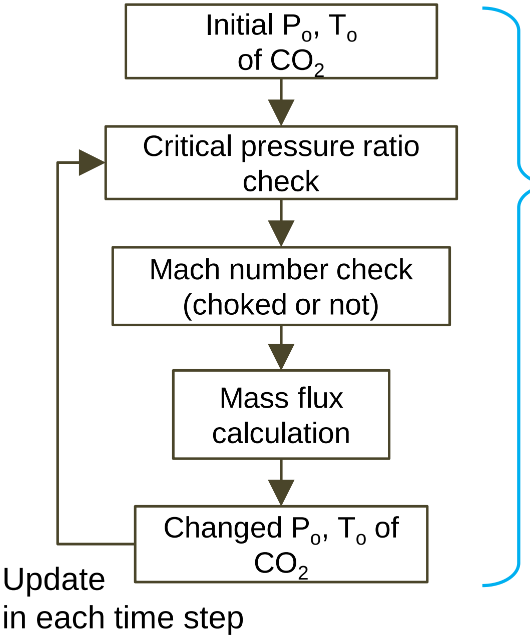
$$W_{net,loss} = W_{net,design} - W_{net,new}$$
$$= W_{net,design} - (W_{turb,new} - W_{comp,new})$$

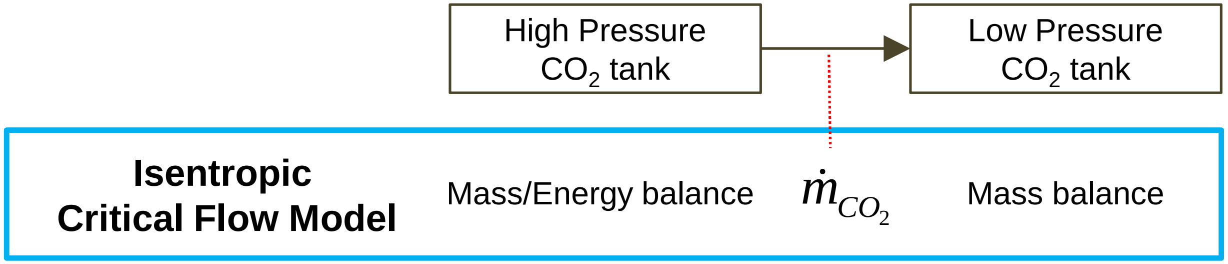
Storage tank (Low-pressure tank)	Leakage position (High-pressure tank)	T (°C)	P (MPa)	$\dot{m}$ (kg/s)
66.2 °C 7.6 MPa	1. TB inlet	508.6	19.36	1.0
	2. MC outlet	61.6	20.21	
	3. RC outlet	156.2	20.20	
Total mass flow rate				**3.0**

CO_2 Recovery System Design

CO_2 critical flow model

- **Description of CO_2 critical flow model**





Governing equations

$$G = \rho V_{elocity} = constant$$

$$\frac{P_0}{P_{critical}} = \left(1 + \frac{\gamma - 1}{2}\right)^{\gamma/(\gamma-1)}$$

$$M = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_o}{P}\right)^{(\gamma-1)/\gamma} - 1\right]}$$

$$G = \frac{P_o}{\sqrt{RT_o}}\sqrt{\gamma}M\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

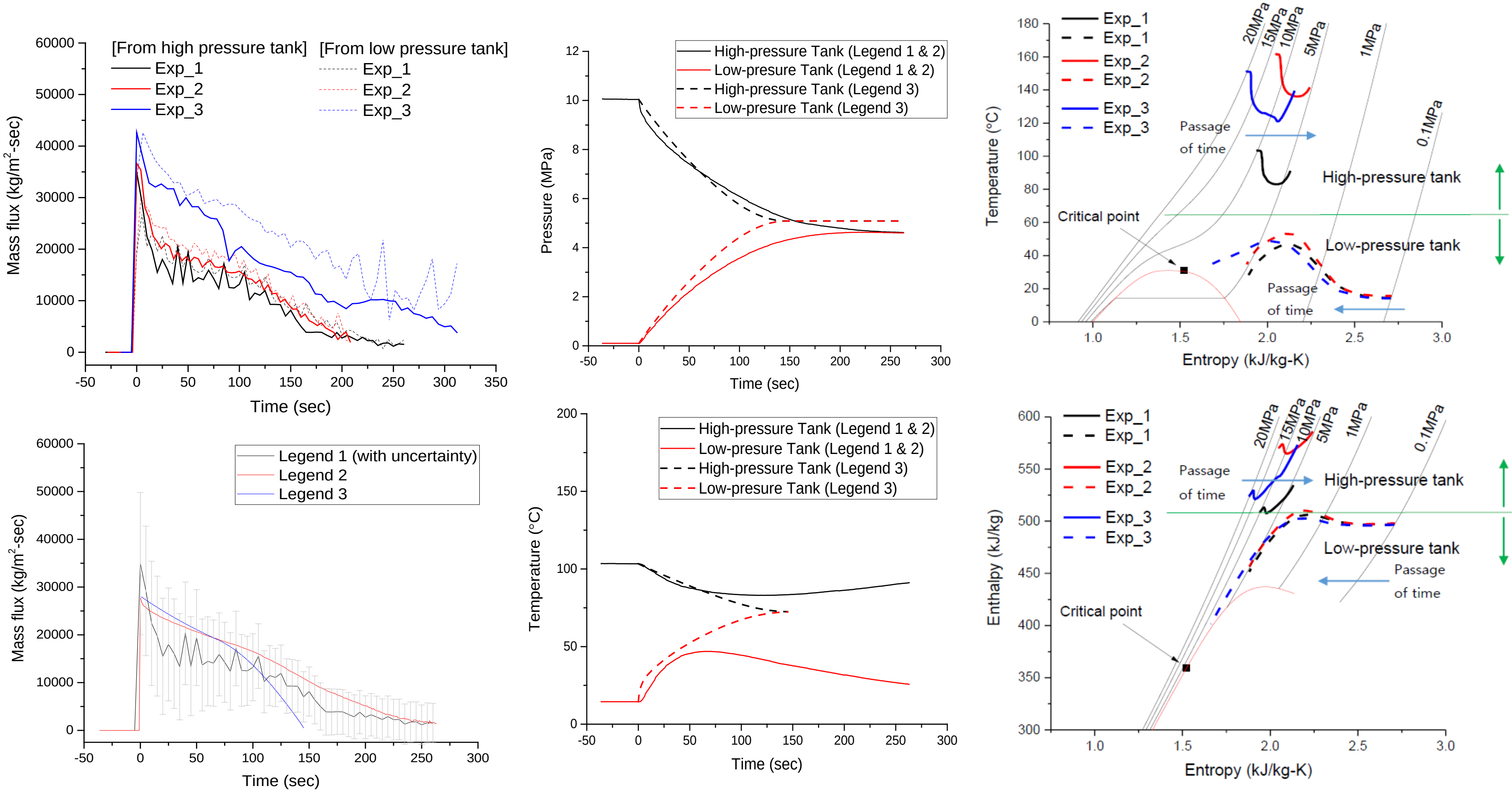
▲ **Experimental Facility for CO_2 leak simulation**

▼ **Design specifications for experimental system**

	Design Parameters	
High/Low-pressure tank	Pressure (MPa)	22
	Temperature (℃)	200
	Volume (L)	47 I.D.: 200mm H: 1,500mm
Pipe connecting two tanks	I.D. (mm)	57
	Length (mm)	1090
Heater (Jacket-type)	Electric capacity (kW)	5
Valve type	Ball valve	

CO_2 critical flow model

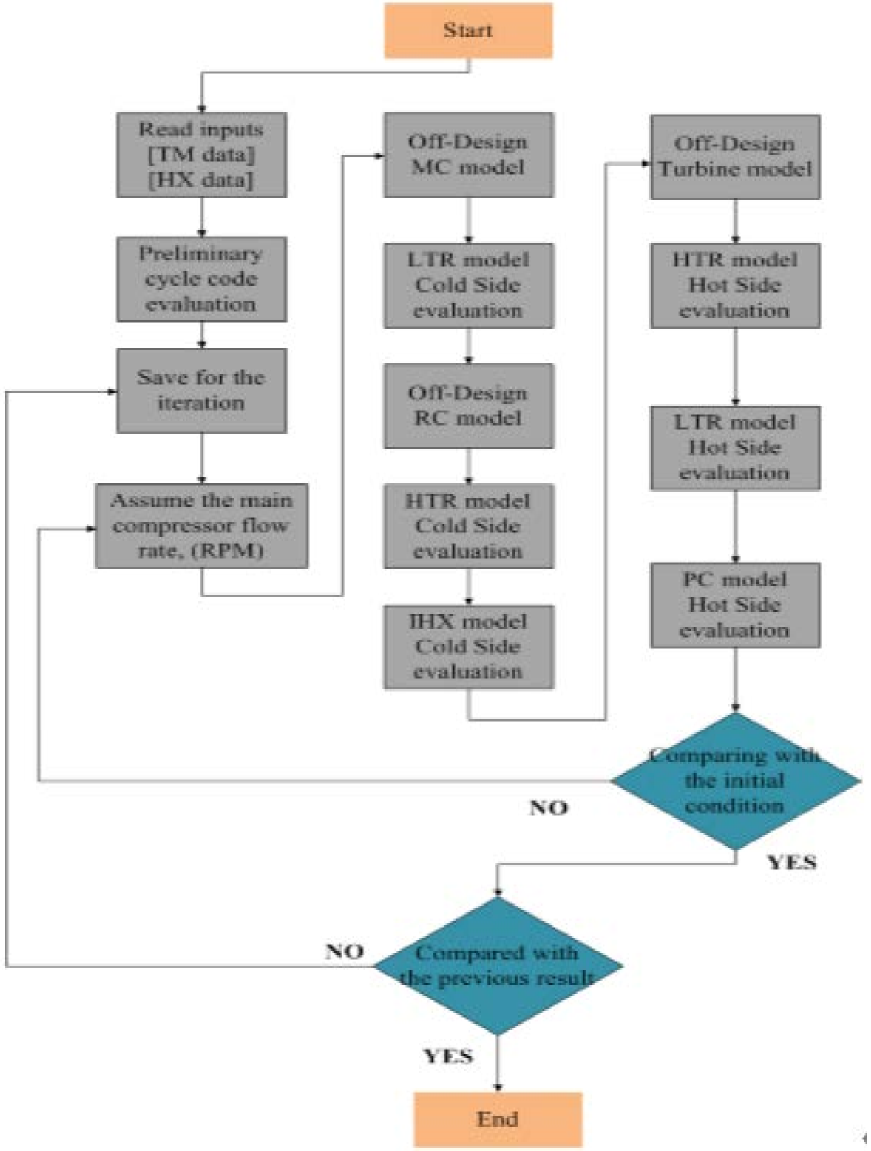
- **Code validation and verification (V&V)**
  - KAIST research team conducted experiments with CO_2 critical flow simulation facility in turbine inlet and compressor outlet conditions.
  - The mass flux calculated by using the measured values has similar trend with the result of CO_2 critical flow model in all cases.



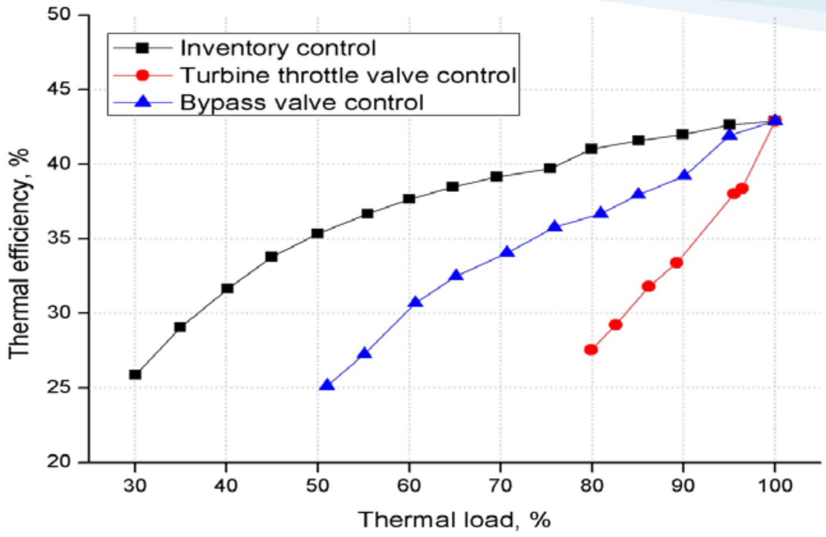
▲ **CO_2 critical flow model validation with experimental data**

S-CO_2 Cycle Control Strategy

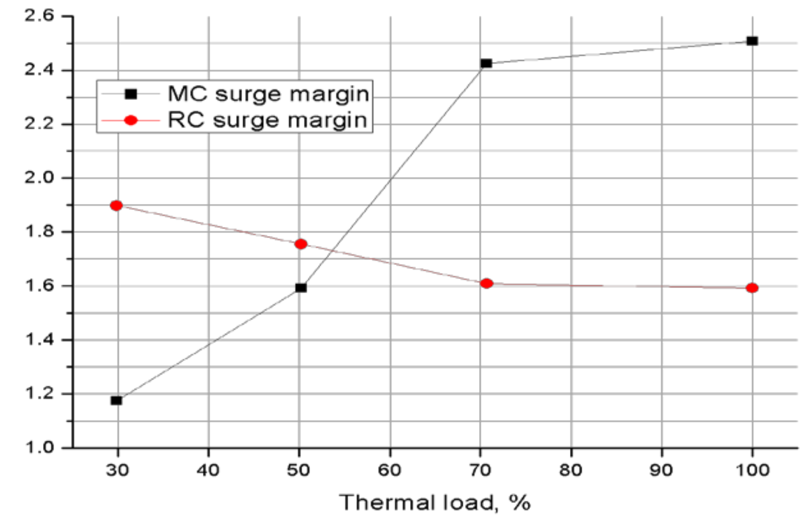
Part load operation control strategy of S-CO_2 cycle



▲ S-CO_2 cycle quasi-static analysis code algorithm



▲ Comparison of S-CO_2 cycle performance in part load conditions



▲ Comparison of compressor surge margin in part load conditions

Conclusions and Future Work

- **Conclusions**

  ✓ The S-CO_2 power conversion system is suitable for the small modular SFR application due to the safety, high efficiency, and small footprint.

  ✓ The S-CO_2 cycle design can be potentially applied with existing lab-scale experimental data.

  ✓ KAIST research team has accumulated many reliable data of main component's software and hardware for the S-CO_2 cycle design, but further code V&V should be performed for the complete power system design with control strategy.

- **Future work**

  ✓ Code V&V for turbomachinery and heat exchanger design codes will be further performed.

  ✓ The leakage flow and physical phenomena in the turbomachinery seal sections will be further studied in the future.

  ✓ To establish the most efficient strategy for the part load conditions, the potential of the valve and inventory controls will be further investigated.

  ✓ Real time simulation in various operation conditions will be conducted through the transient analysis code.

  ✓ For the safety analysis of Sodium leak scenario, study of Na-CO_2 reaction in heat exchanger will be performed.