University R & D Session

Two Phase Modeling in sCO_2 Power Cycles

2017. 3. 29

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Issues Studied in KAIST

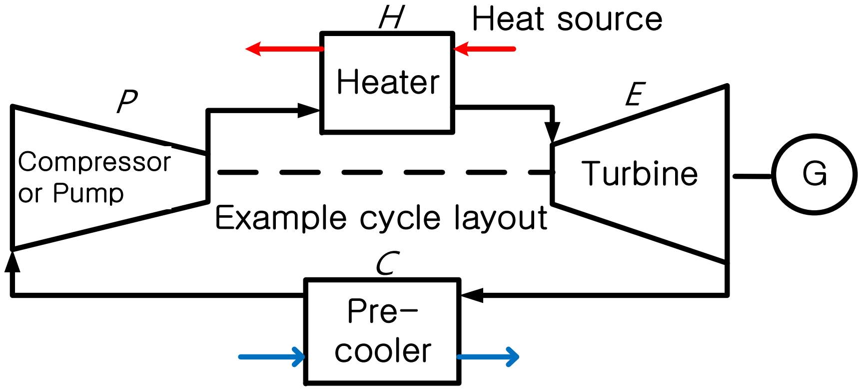
- Nuclear propulsion for maritime transport and waste heat recovery systems need to minimize human operators' involvement during operation if sCO_2 power cycle technologies are used.

- This leads to the motivation of developing more intelligent power system control technology.

- However, both systems (potentially or partially) operate in the two phase region.

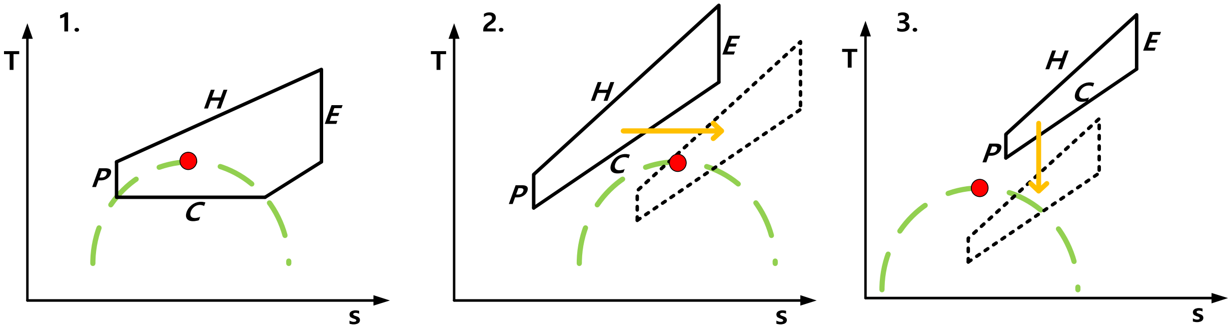
- Physical modeling of a CO_2 two phase system is necessary for the development of more intelligent control system
  → Big data generation for training

CO_2 Two Phase System



H: Heating
E: Expansion
C: Cooling
P: Pressurizing

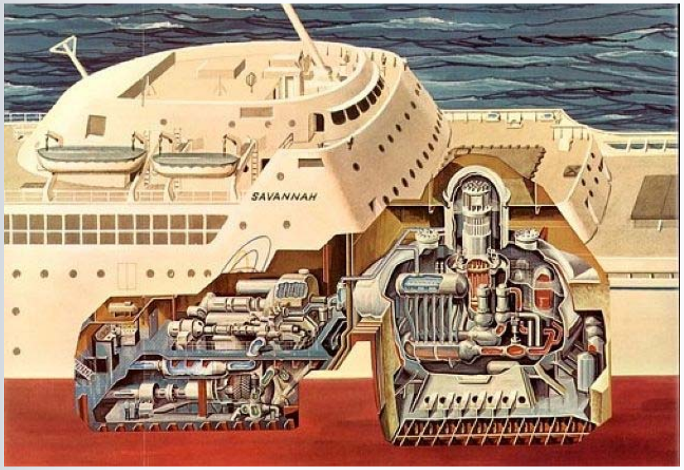
1. Trans-critical Rankine cycle
   (designed with CO_2 2-phase)
2. Trans-critical cycle
   (designed without CO_2 2-phase)
3. Brayton cycle
   (designed to pressurize CO_2 near the critical point)



— — : Saturation curve of CO_2
● : Critical point of CO_2
—— : On-design operation of cycles
-------- : Off-design operation of cycles
→ : Variation of cycle design conditions

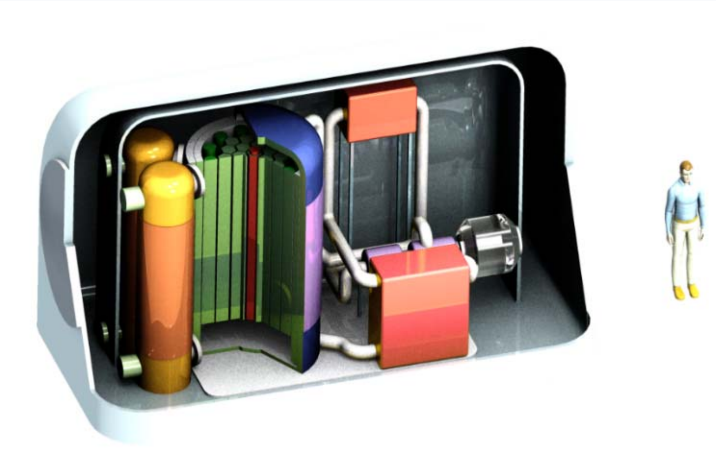
<Nuclear marine application>

<SAVANNAH (1959-1972), 15MW>

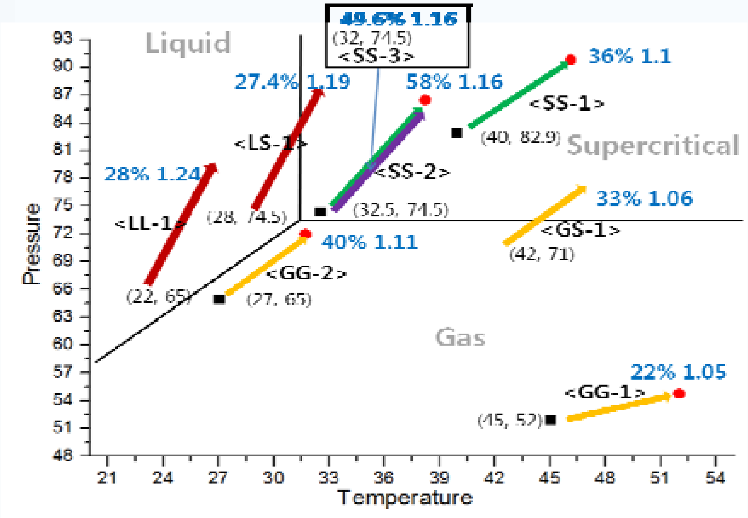


<HYUNDAI, HiMSEN engine, 10MW>

<KAIST, KAIST-MMR, 12MW>

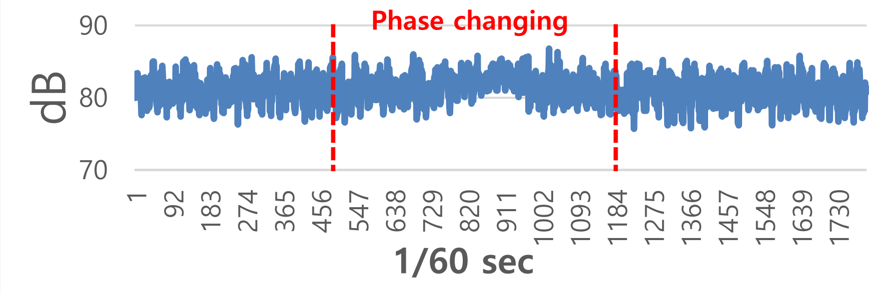


Compressing Near the Critical Point

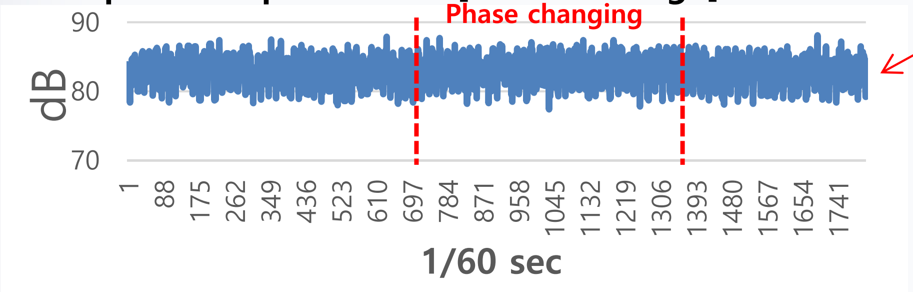


Operating results with various compressor inlet conditions.

1. Supercritical to Liquid case [Sound change]



2. Liquid to 2-phase case [Sound change]



- Phase changing experiment

1. Supercritical to Liquid case

2. Liquid to 2-phase case

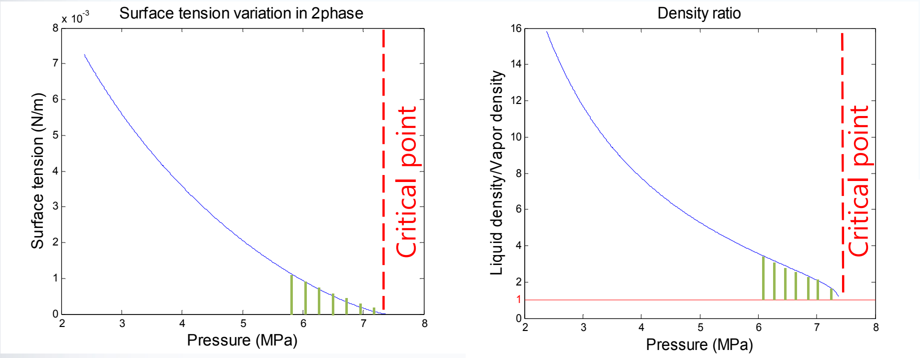
CO_2 Two Phase Flow Modeling

- The flow chart of KAIST-STA (System Transient Analysis) code

- **Homogeneous Equilibrium Model (HEM)**

$$\textit{Mechanical equilibrium} \qquad \bar{u}_g = \bar{u}_f = \bar{u}_h$$

$$\textit{Thermal equilibrium} \qquad \bar{T}_g = \bar{T}_f = \bar{T}_h$$



-Continuity equation

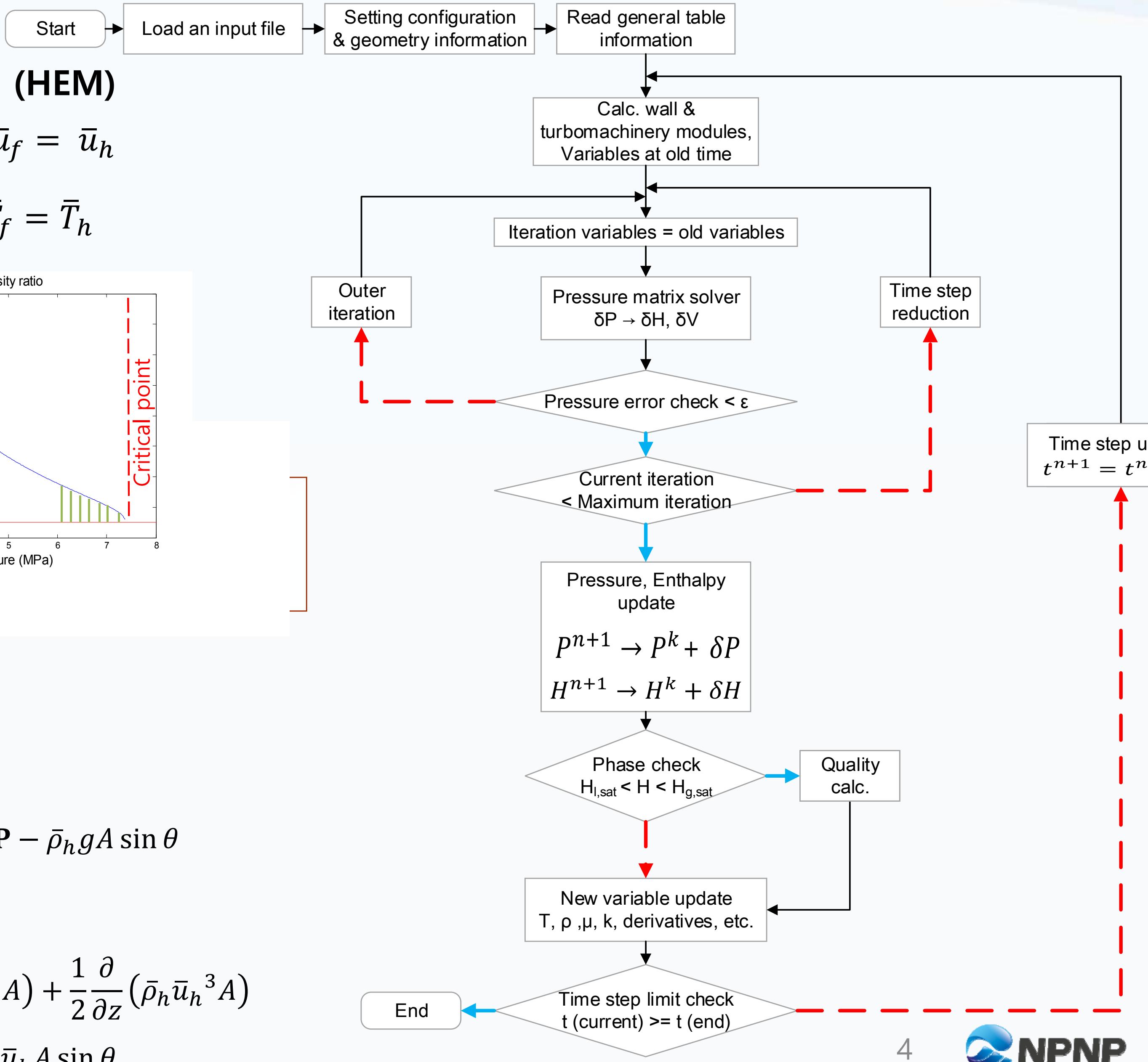
$$\frac{\partial}{\partial t}(\bar{\rho}_h A) + \frac{\partial}{\partial z}(\bar{\rho}_h \bar{u}_h A) = 0$$

-Momentum equation

$$\frac{\partial}{\partial t}(\bar{\rho}_h \bar{u}_h A) + \frac{\partial}{\partial z}\left(\bar{\rho}_h \bar{u}_h{}^2 A\right) = -A\frac{\partial P}{\partial z} - \bar{\tau}_w \mathbf{P} - \bar{\rho}_h g A \sin\theta$$

-Energy equation

$$\frac{\partial}{\partial t}(\bar{\rho}_h \bar{H}_h A) + \frac{\partial}{\partial z}(\bar{\rho}_h \bar{u}_h \bar{H}_h A) + \frac{1}{2}\frac{\partial}{\partial t}\left(\bar{\rho}_h \bar{u}_h{}^2 A\right) + \frac{1}{2}\frac{\partial}{\partial z}\left(\bar{\rho}_h \bar{u}_h{}^3 A\right)$$
$$= \mathbf{P_h} q'' + A\overline{q'''} + \frac{\partial}{\partial t}(pA) - g\bar{\rho}_h \bar{u}_h A \sin\theta$$



Start

Load an input file

Setting configuration & geometry information

Read general table information

Calc. wall & turbomachinery modules, Variables at old time

Iteration variables = old variables

Outer iteration

Pressure matrix solver δP → δH, δV

Time step reduction

Pressure error check < ε

Current iteration < Maximum iteration

Time step u

$t^{n+1} = t^n$

Pressure, Enthalpy update

$$P^{n+1} \to P^k + \delta P$$
$$H^{n+1} \to H^k + \delta H$$

Phase check $H_{l,sat} < H < H_{g,sat}$

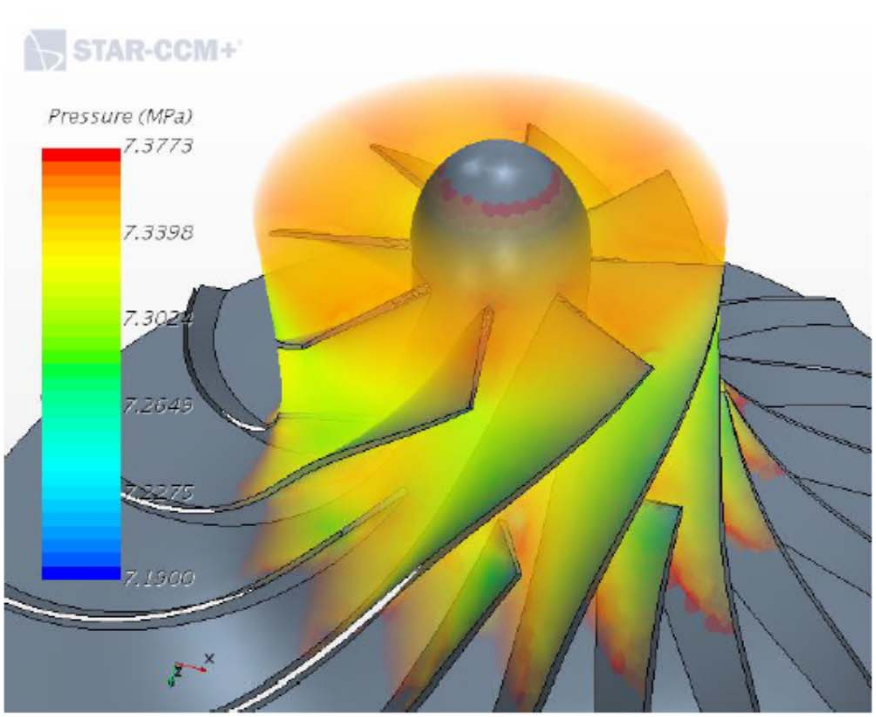
Quality calc.

New variable update T, ρ ,μ, k, derivatives, etc.

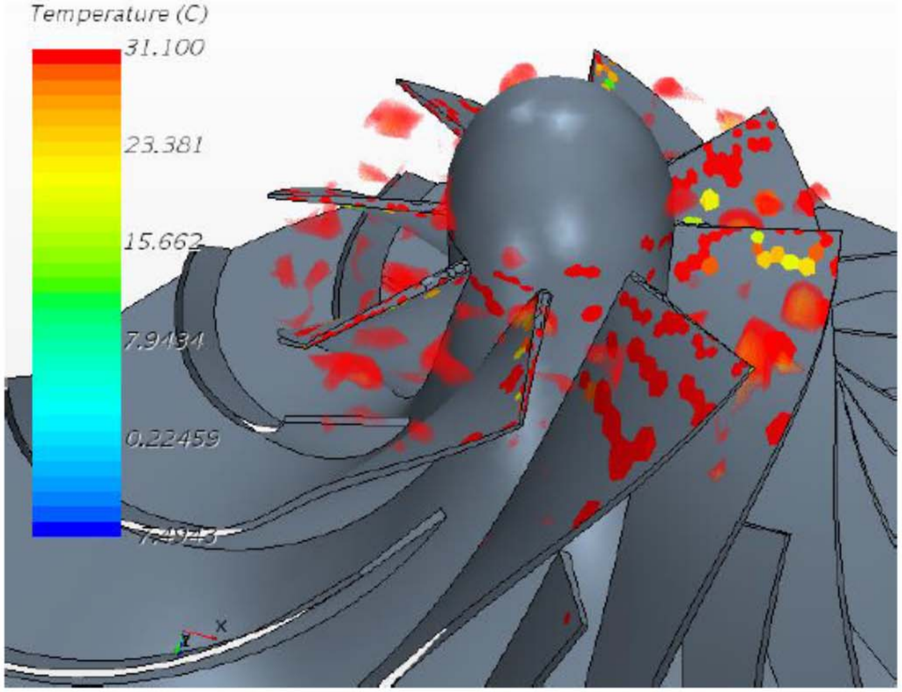
Time step limit check t (current) >= t (end)

End

CO_2 Two Phase Flow in Turbomachinery



<Static pressure, 7.47MPa 31.5℃ >

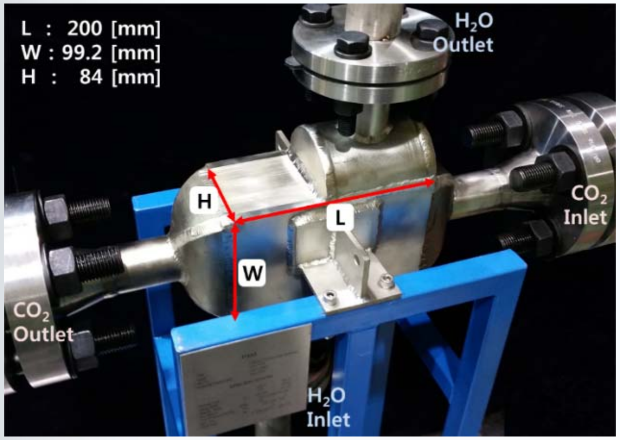


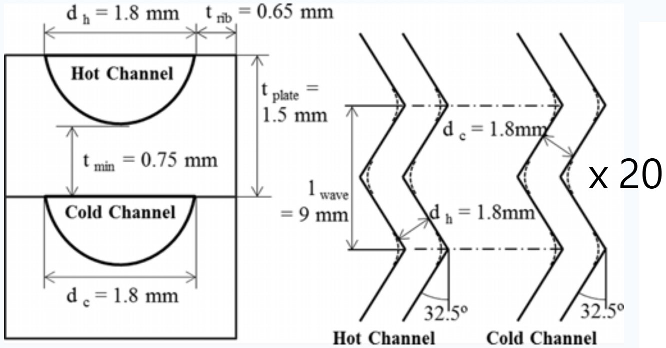
<Static temperature, 7.47MPa 31.5℃>

	Two-phase VOF	Single phase
Inlet condition	7.48MPa, 31.6℃	7.50MPa, 31.7℃
Compressor efficiency	**18.7%**	**18.1%**
Pressure ratio	**1.114**	**1.113**
Flow coefficient	0.0203	0.0206

CO_2 Two Phase Pressure Drop

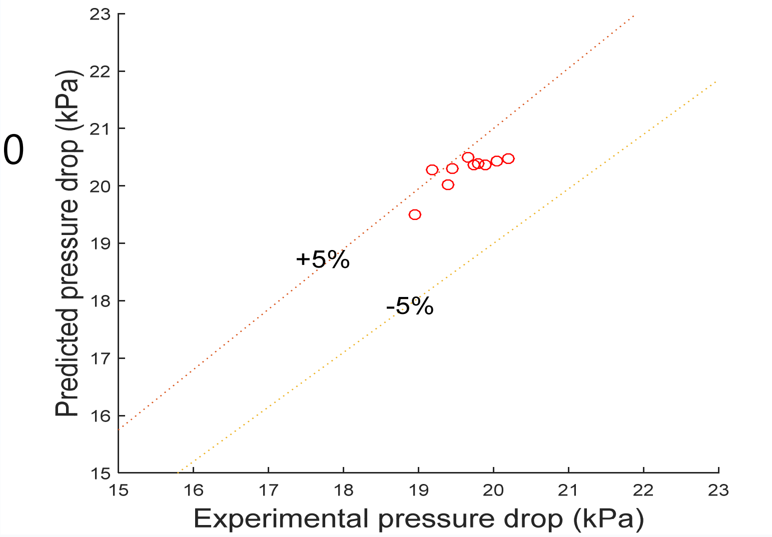
1. Single-phase cases





Operating range of the test

P = 6.99 ~ 7.45 MPa
T = 20.2 ~ 34.4 ℃
m = 0.956~ 0.995kg/s



<PCHE correlations from SCO2PE>

Reference, (Baik et al. 2017)

$$\boldsymbol{f = 0.2992Re^{-0.19}}$$

(15000<Re<85000)

2. Two-phase cases

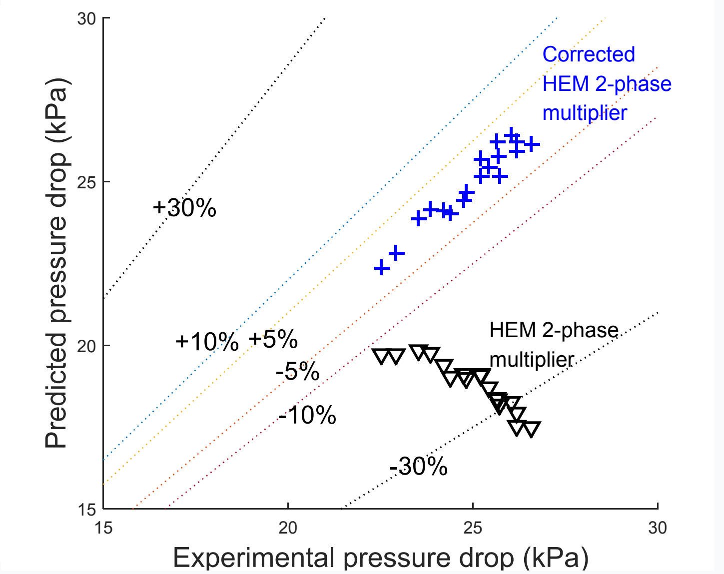
$$f_h = A \cdot Re_h^n \,, \quad \frac{1}{\mu_h} = \frac{x}{\mu_g} + \frac{1-x}{\mu_f}$$

In case of a homogeneous flow,
the 2-phase multiplier is equal to

$$corrected\ \phi_{go}^2 = max\left[1, -20.3\left(\frac{P}{P_{crit}}\right) + 19.9\right]\left[x + \frac{v_f}{v_g}(1-x)\right]\left[\frac{\mu_g}{\mu_f} + x\left(\frac{\mu_f - \mu_g}{\mu_f}\right)\right]^n$$

Operating range of the test

P = 6.62 ~ 6.82 MPa
T = 26.3 ~ 27.5 ℃
x = 0.768 ~ 0.996



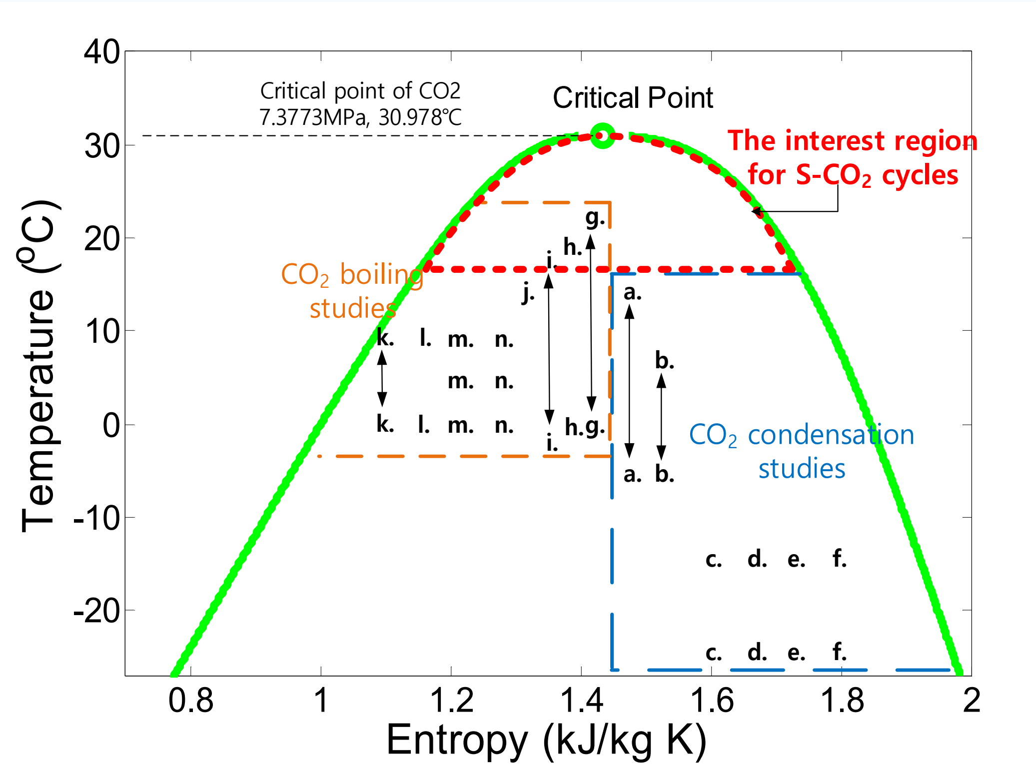
CO_2 Two Phase Heat Transfer

Table. Previous studies on CO_2 condensation heat transfer

	Reference	Channel diameter (mm)	Mass velocity (kg/m^2 s)	Condensation temperature (℃)
a.	Zhang et al.	0.9	180, 360, 540	-5 ~ 15
b.	Heo et al.	1.5, 0.78, 0.68	400 ~ 800	-5 ~ 5
c.	Kim et al.	3.51	200 ~ 800	-25 and -15
d.	Zilly et al.	6.1	171 ~ 445	-25 and -15
e.	Jang and Hrnjak	6.1	200 ~ 400	-25 and -15
f.	Park and Hrnjak	0.89	200 ~ 800	-25 and -15

Table. Previous studies on CO_2 boiling heat transfer

	Reference	Channel diameter (mm)	Mass velocity (kg/m^2 s)	Boiling temperature (℃)
g.	Pettersen	0.8	190 ~ 570	0 ~ 25
h.	Pettersen	0.98	100 ~ 580	0, 20
i.	Huai et al.	1.31	130 ~ 400	-3 ~ 17
j.	Wang et al.	0.7, 1, 2	360 ~ 1440	15
k.	Siegismund and Kauffeld	0.81	10 ~ 100	0 ~ 10
l.	Koyama et al.	1.8	100 ~ 250	0 and 10
m.	Yun and Kim	0.98, 2	500-3000	0, 5, 10
n	Yun et al.	1.08 ~ 1.54	200 ~ 400	0, 5, 10



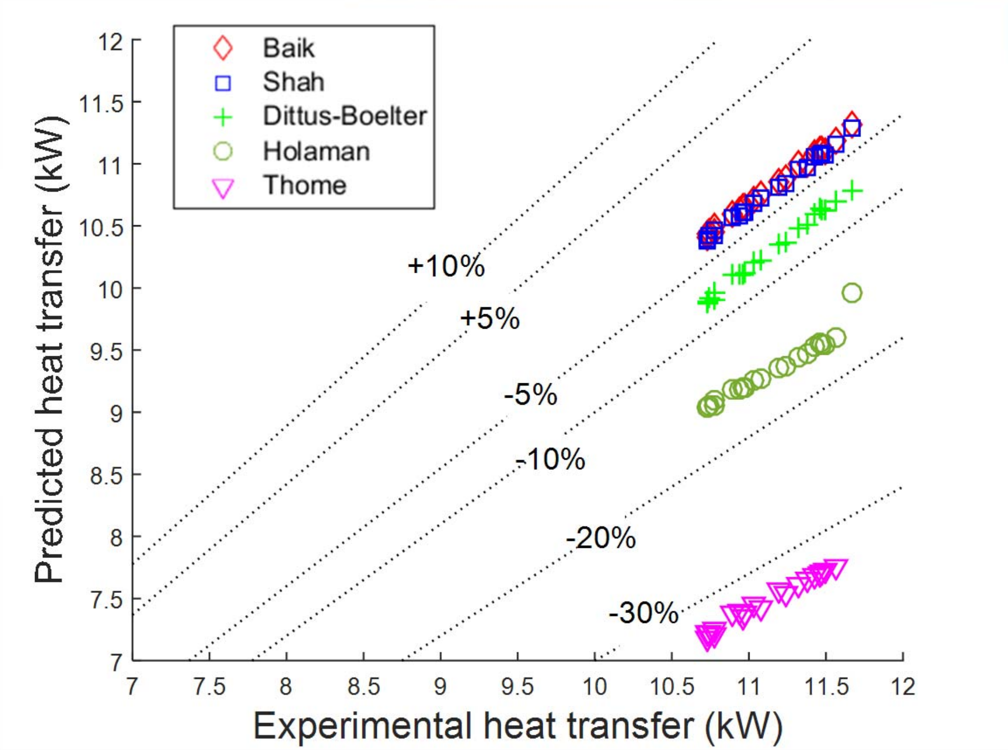
- ➢ Several researches related to the CO_2 boiling and condensation has been carried out.
- ➢ But, the studies near the critical point region are still not widely conducted yet.

CO_2 Two Phase Heat Transfer in PCHE

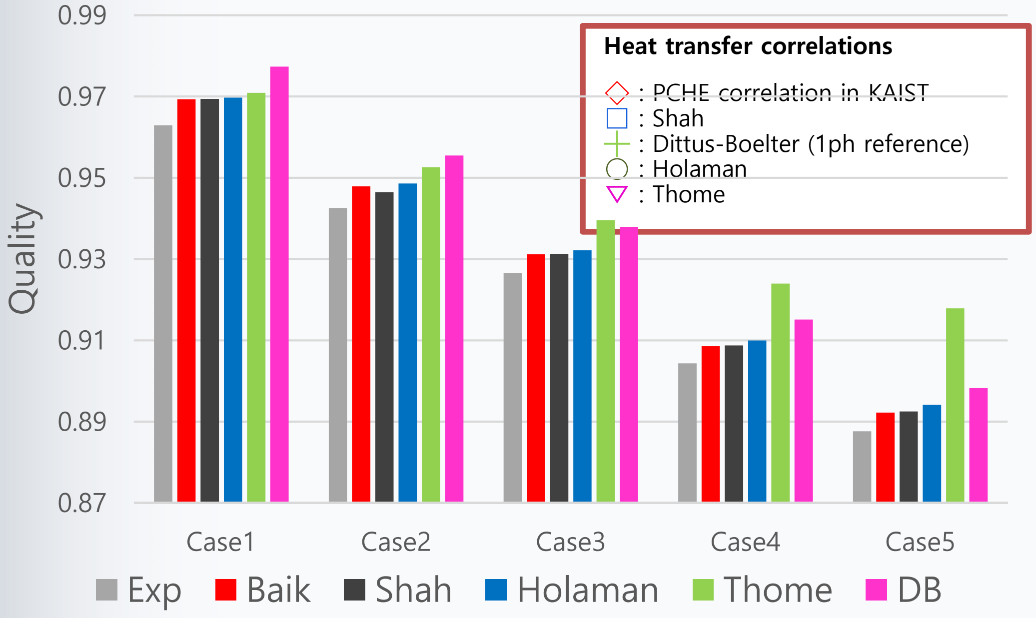
Results

	Tin ('C)	Pin(MPa)	Tout ('C)	Pout(MPa)	Xout	mass flow rate (kg/s)
Case1	27.66	6.82	27.41	6.80	0.883	1.016
Case2	27.52	6.82	27.33	6.79	0.872	1.010
…	…	…	…	…	…	…
Case20	26.48	6.66	26.29	6.63	0.771	1.009
Case21	26.43	6.65	26.24	6.62	0.768	1.010

<The test cases and experimental data>

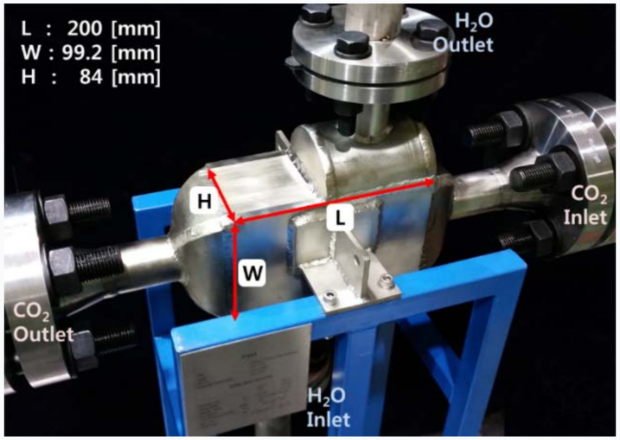


x : CO2 quality (at HX outlet)



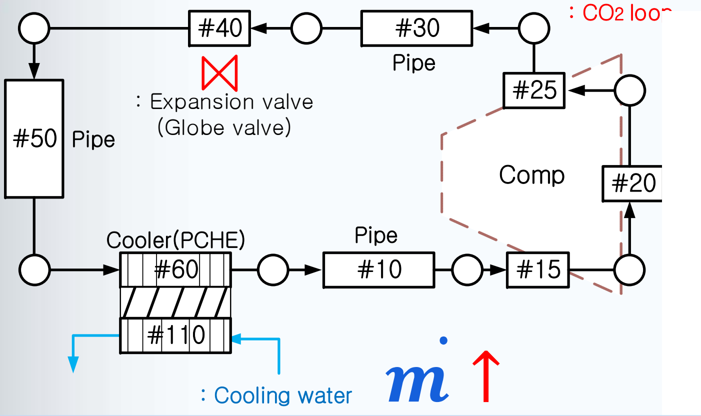
Heat transfer correlations

◇ : ~~PCHE correlation in KAIST~~
□ : Shah
+ : Dittus-Boelter (1ph reference)
○ : Holaman
▽ : Thome



CO_2 Two Phase System Modeling

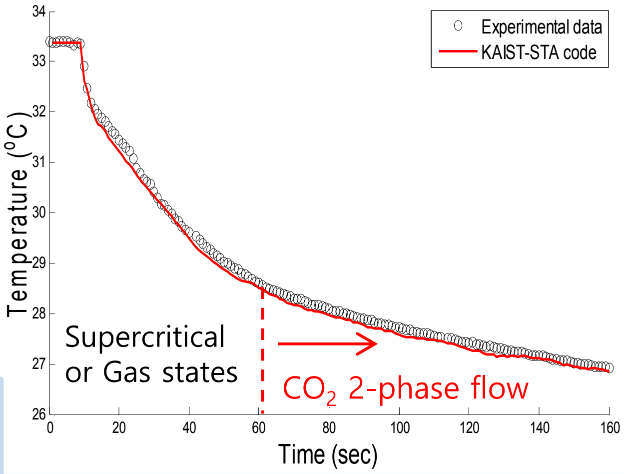
SCO_2PE loop modeling (a cooling performance increasing situation)



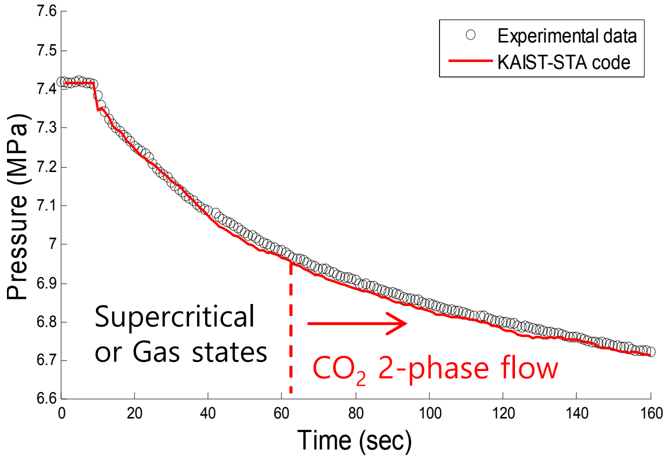
Operating range of the test

CO_2 loop	**Water loop**
P = 6.72 ~ 7.83 MPa	T = 8.3 ~ 34.2 ℃
T = 26.9 ~ 37.6 ℃	m = 0.055~0.150 kg/s
m = 0.956~1.023 kg/s	

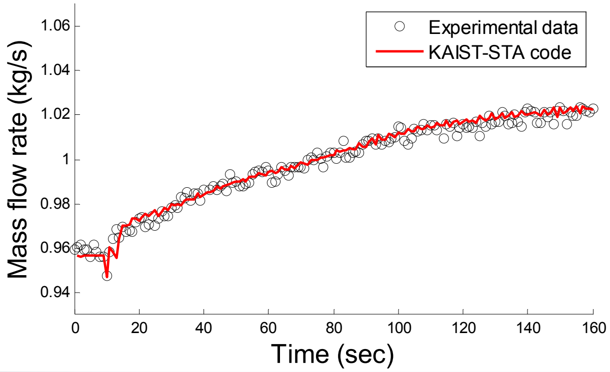
<Compressor inlet T>



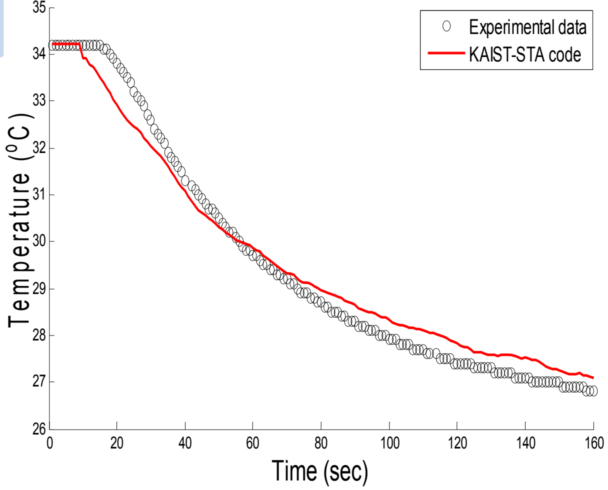
<Compressor inlet P>



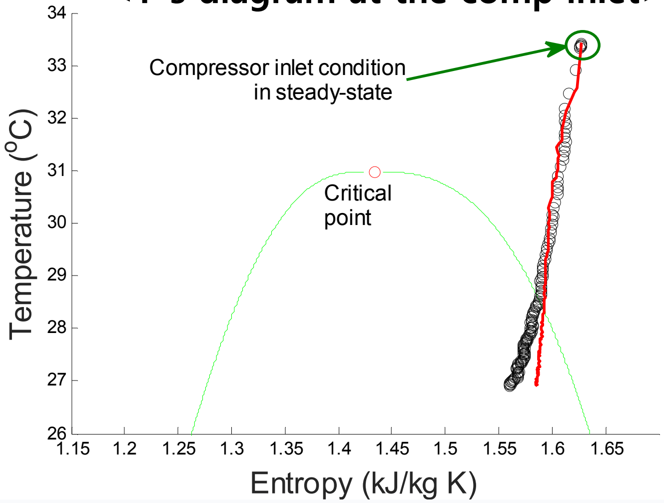
<CO_2 mass flow rate>



<Cooling water T (outlet)>



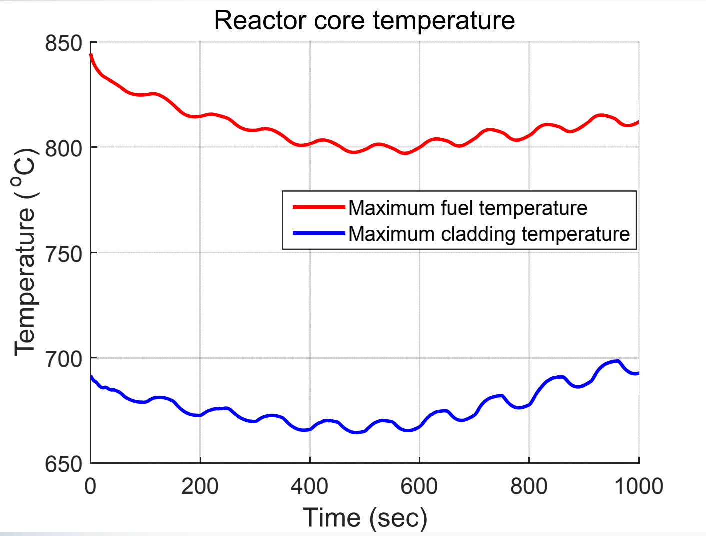
<T-s diagram at the comp inlet>

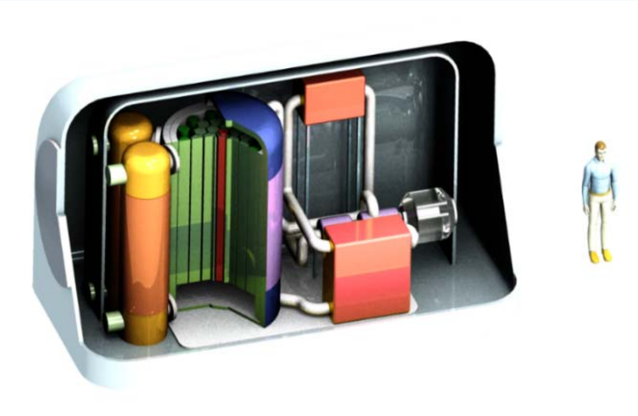


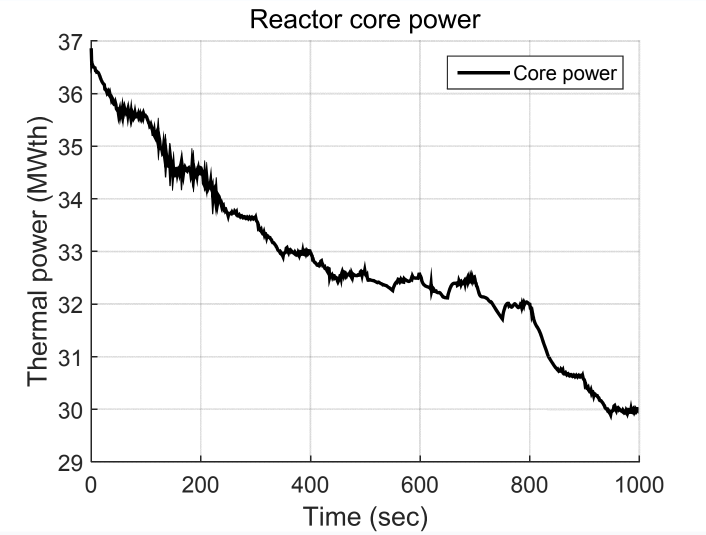
✓ Results of KAIST-STA code show that reasonably similar to the SCO_2PE experimental data under the transient condition not only in the single-phase, but also in the 2-phase condition.

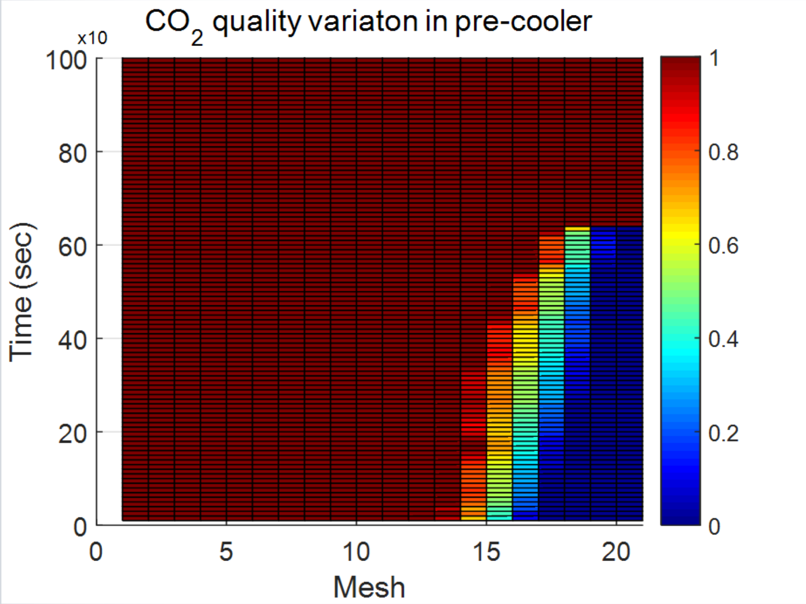
CO_2 Two Phase System Modeling

- 100~0% load reduction operation (using Core bypass control and Inventory control)









Design parameter	Safety limit	Part load operation
Fuel centerline temperature	2507 ℃	838 ℃
Peak cladding temperature (ODS)	1200 ℃	669.4 ℃
Maximum coolant temperature	676 ℃	556.0 ℃
Maximum system pressure	24 MPa	20 MPa
Turbine rotational speed	125% of nominal speed	100.4%

- Part load operation of KAIST-MMR is properly carried out with the KAIST-STA code and CO_2 two-phase correlations.

Recent R&D Activities in KAIST

- Cycle studies
  - Developing a multiphase system transient analysis code for an industrial application of sCO$_2$ power cycle.
  - In collaboration with Saudi Aramco for developing a cycle and control strategies of direct fired sCO$_2$ power cycle.
  - Created a thermodynamic framework of using an isothermal turbomachinery for an sCO$_2$ power cycle.
  - Suggested and demonstrated a new way of optimizing cycle design and control parameters that can accelerate the calculation by two orders of magnitude compared to the genetic algorithm.

Recent R&D Activities in KAIST

- Turbomachinery
  - Testing a multiphase critical flow for sCO_2 turbomachinery seal design.
  - Experimental and theoretical investigation of fluid induced instability in magnetic bearing and gas foil bearing operating in high pressure sCO_2 conditions.

- Heat Exchanger
  - Developed a new approach for an off-design modeling (including multiphase region) of PCHE in sCO_2 power cycle that can accelerate the calculation time by an order of magnitude.
  - Demonstrated that artificial neural network can be used for predicting the inner pinch during sCO_2 power cycle design with high reliability and speed.