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Verification of Heat Exchanger Design Code KAIST_HXD by Experiment

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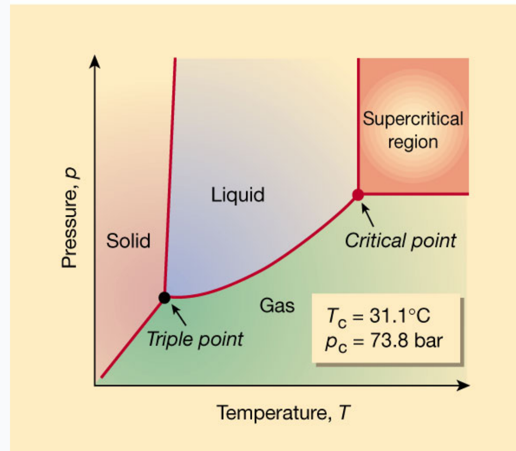
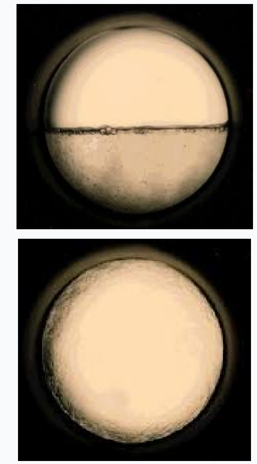
1. Introduction

(1) What is Supercritical CO_2 & Why CO_2 ?

Substance[3][4]	Critical temperature	Critical pressure
Helium	−267.96 °C (5.19 K)	2.24 atm (227 kPa)
Hydrogen	−239.95 °C (33.20 K)	12.8 atm (1,300 kPa)
Neon	−228.75 °C (44.40 K)	27.2 atm (2,760 kPa)
CH_4	−82.3 °C (190.8 K)	45.79 atm (4,640 kPa)
Nitrogen	−146.9 °C (126.2 K)	33.5 atm (3,390 kPa)
Fluorine	−128.85 °C (144.30 K)	51.5 atm (5,220 kPa)
Argon	−122.4 °C (150.7 K)	48.1 atm (4,870 kPa)
Oxygen	−118.6 °C (154.5 K)	49.8 atm (5,050 kPa)
Krypton	−63.8 °C (209.3 K)	54.3 atm (5,500 kPa)
Xenon	16.6 °C (289.8 K)	57.6 atm (5,840 kPa)
CO_2	31.04 °C (304.19 K)	72.8 atm (7,380 kPa)
N_2O	36.4 °C (309.5 K)	71.5 atm (7,240 kPa)
Ammonia[5]	132.4 °C (405.5 K)	111.3 atm (11,280 kPa)
Chlorine	143.8 °C (417.0 K)	76.0 atm (7,700 kPa)
Bromine	310.8 °C (584.0 K)	102 atm (10,300 kPa)
Water[6][7]	373.946 °C (647.096 K)	217.7 atm (22,060 kPa)
H_2SO_4	654 °C (927 K)	45.4 atm (4,600 kPa)
Sulfur	1,040.85 °C (1,314.00 K)	207 atm (21,000 kPa)
Mercury	1,476.9 °C (1,750.1 K)	1,720 atm (174,000 kPa)
Caesium	1,664.85 °C (1,938.00 K)	94 atm (9,500 kPa)
Ethanol	241 °C	62.18 atm (63 bar, 6,300 kPa)
Lithium	2,950 °C (3,220 K)	652 atm (66,100 kPa)





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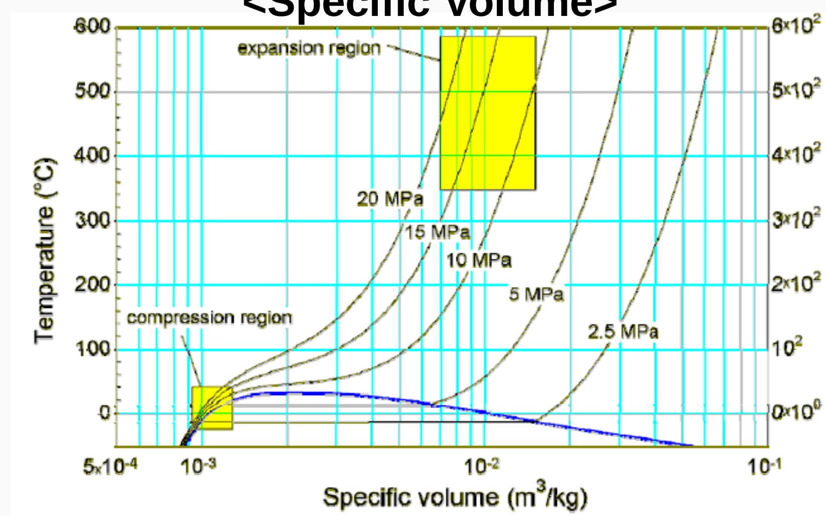


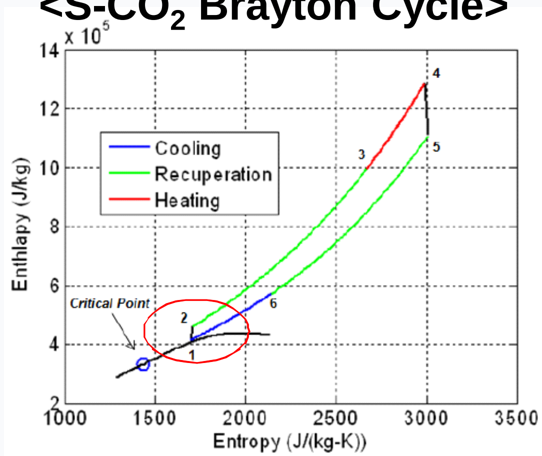
1. Introduction

(2) Supercritical CO_2 Brayton Cycle

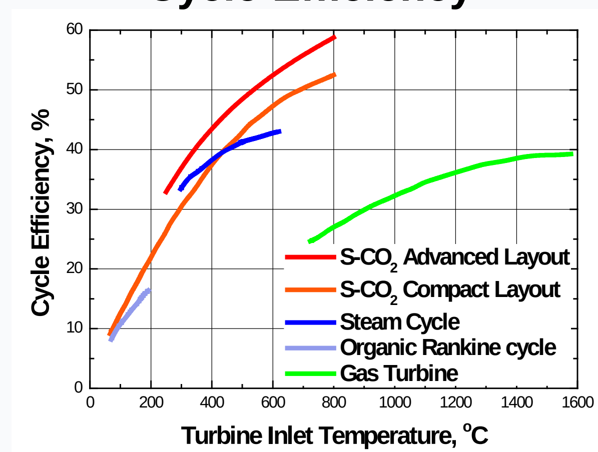
❖ Maximizing advantages from Steam Rankine and Brayton cycle
- Steam Rankine cycle → Small pumping work
- Gas Brayton cycle → High efficiency in High T.I.T

❖ Simple layout is sufficient to achieve high efficiency

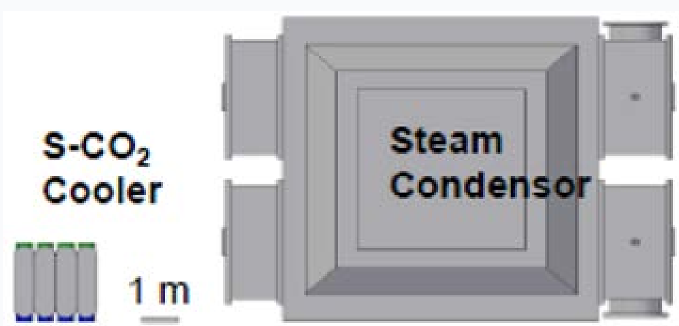
<S-CO_2 Brayton Cycle>

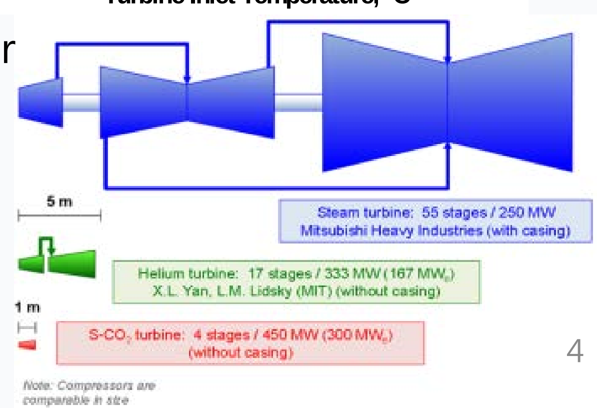


<Cycle Efficiency>



❖ Compact Turbomachinery & Heat exchanger





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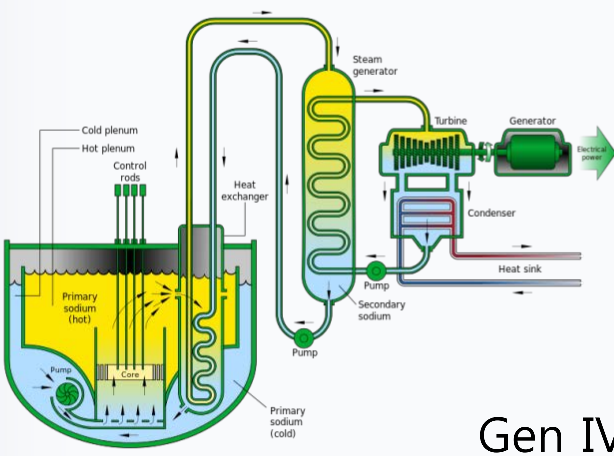
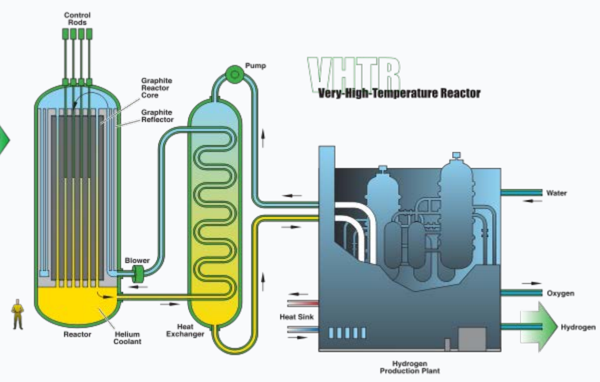
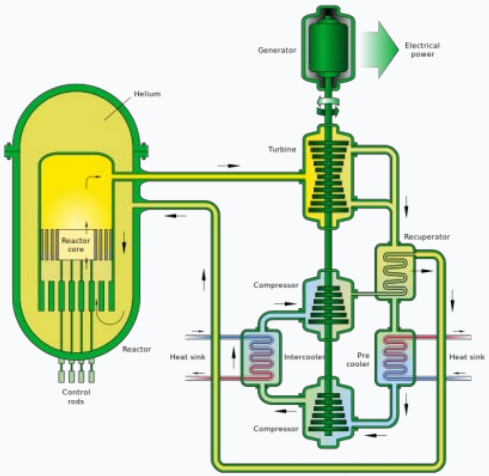
1. Introduction

(3) Supercritical CO_2 Brayton cycle application area

- ❖ Generation IV reactor
  - Sodium cooled fast reactor
  - Very high temperature reactor
  - Gas cooled fast reactor



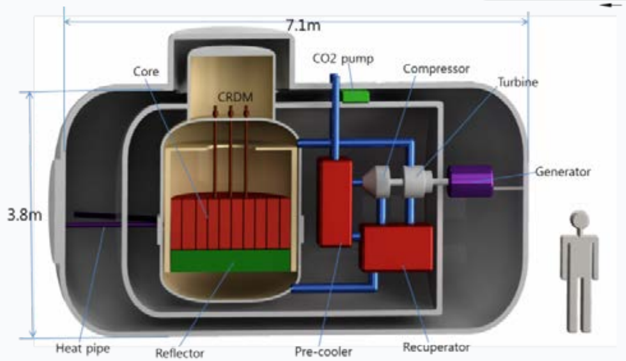




Gen IV Reactor – SFR, VHTR, GFR

Reducing initial investment cost & Modularize

- ❖ Small distributed power
- ❖ Ship propulsion



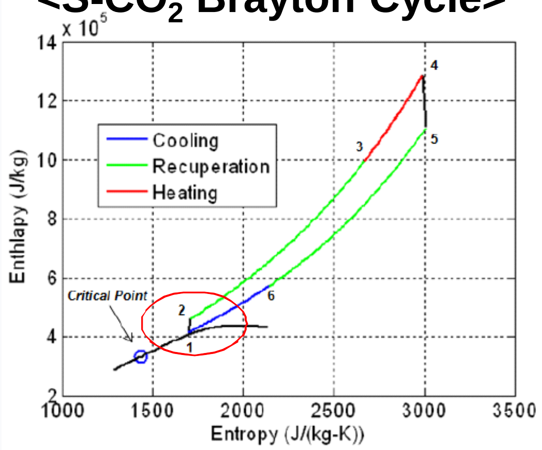
KAIST - MMR

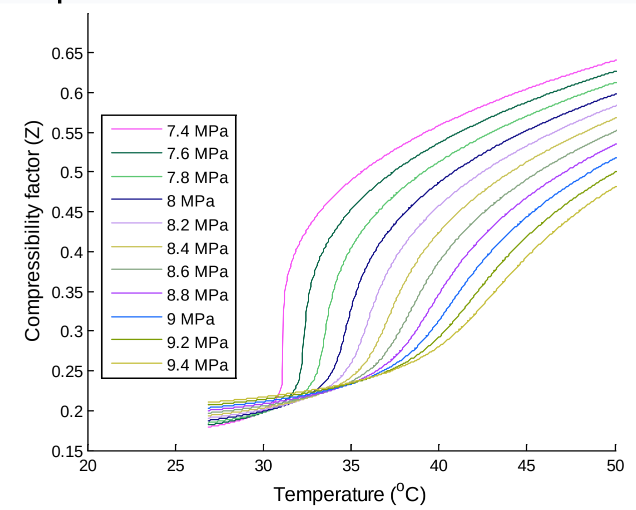
1. Introduction

(4) Supercritical CO_2 cycle characteristics

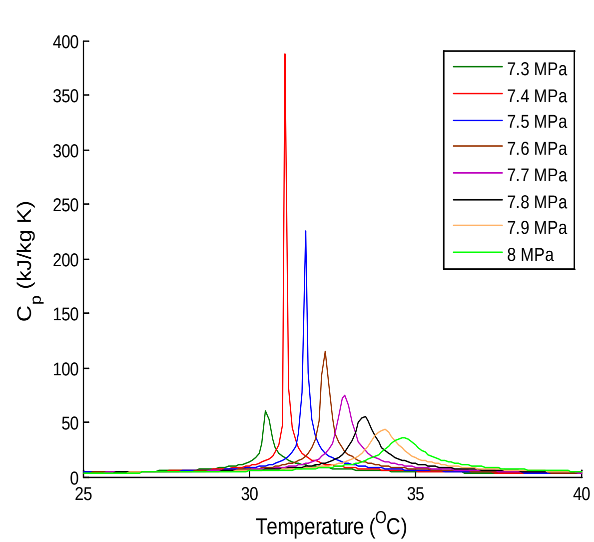
- Compressor inlet condition control is important.

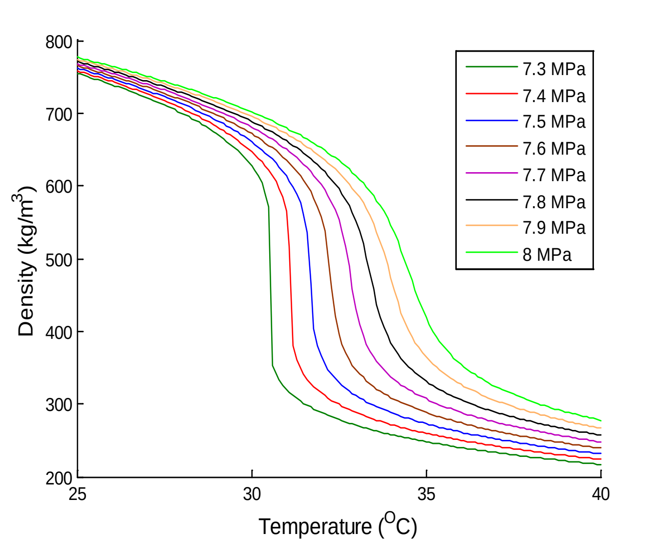
<S-CO_2 Brayton Cycle>





- Dramatic property change of S-CO_2 near the critical point (31°C, 7.4MPa)





1. Introduction

(5) Research objectives

❖ Precooler (emitting the waste heat) temperature control is important.
  - Compressor inlet condition is solely dependent on the precooler performance.

❖ Cycle minimum temperature affects more to the cycle efficiency rather than cycle operating maximum temperature.

❖ Difficulty in computational analysis or numerical design approach due to the dramatic property change of S-CO_2 near the critical point .

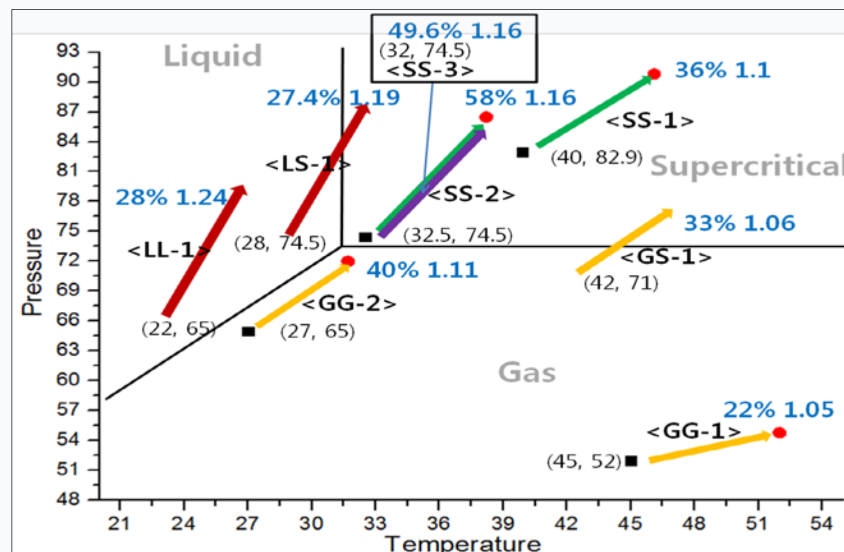
❖ Experiment and real operation experiences are necessary to support.

❖ **Proper Precooler design!!**
  - Heat exchanger design code, validation, Performance test

2. Experimental Facility

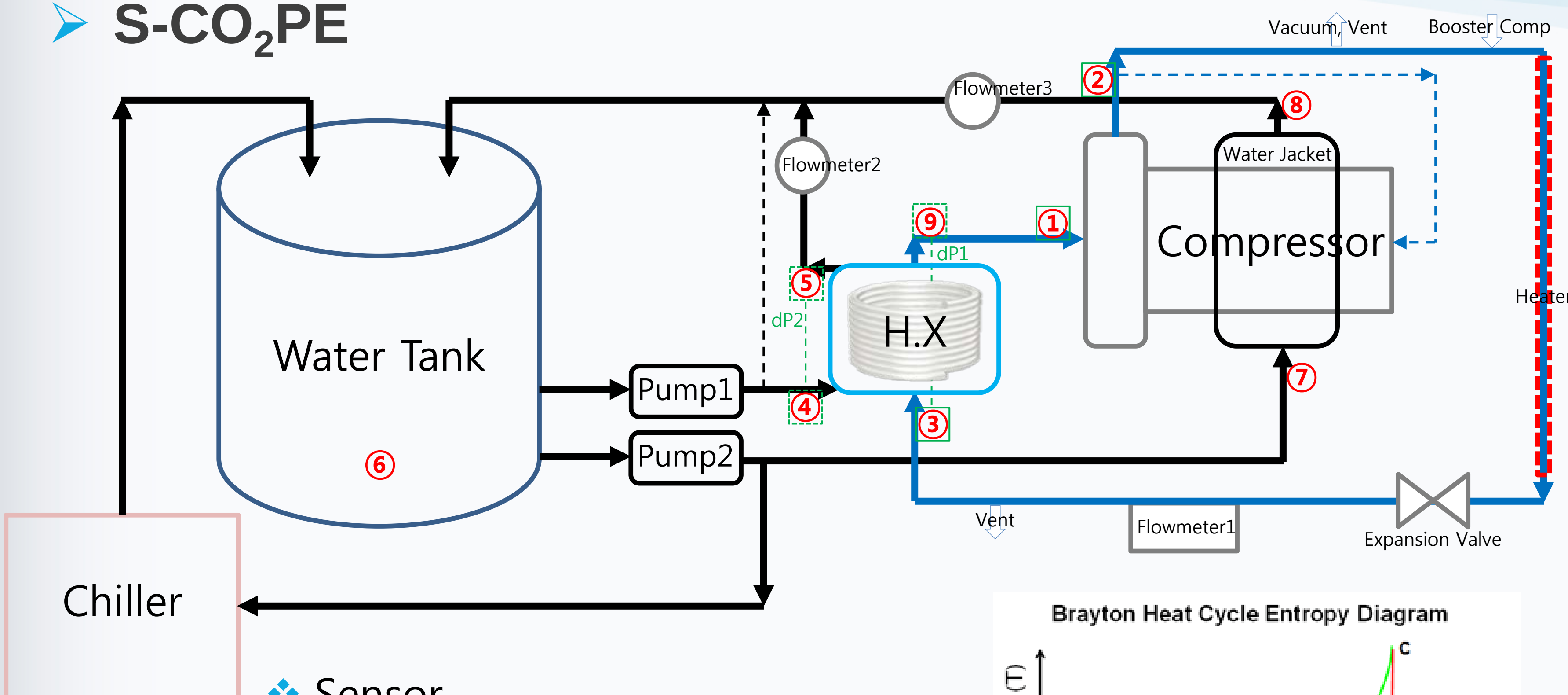
S-CO_2PE [Supercritical CO_2 Pressurizing Experiment]

Compressor type		Seal-free canned motor pump
Compressor power [kW]		26
Mass flow [kg/s]		2.78
Compressor pressure ratio		1.2
Maximum RPM		4620
Inlet Condition	Pressure	7.56 (MPa)
	Temperature	32 (^{o}C)
Electrical heater [kW]		0.5
Precooler type		Spiral tube heat exchanger



2. Experimental Facility

➢ S-CO_2PE



❖ Sensor

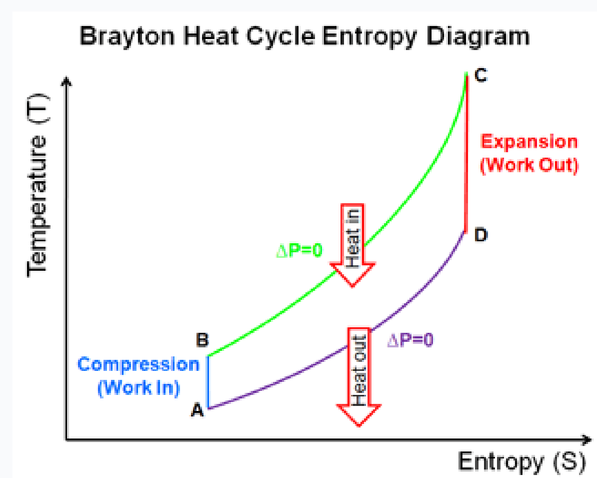
RTD sensor : 9

Pressure transmitter : 3

Differential pressure gauge : 2

Mass flowmeter(CO_2) : 1

Flowmeter(water) : 2



2. Experimental Facility

Sensor Accuracy

Sensor type	Range	Accuracy
RTD	0 ~ 100 °C	± 0.2°C
Pressure transmitter	0 ~ 120 bar	± 0.05%
Differential pressure gauge (CO_2)	0 ~ 250 kPa	± 0.065%
Differential pressure gauge (water)	0.5 ~ 100 kPa	± 0.04%
Mass flow meter (CO_2)	0 ~ 5 kg/s	± 0.16%
Flow meter (water)	0 ~ 3.33 kg/s	± 0.5%

- To decrease the measurement error
  - The RTD sensors were immersed in thermostat for calibration.
  - The pressure gauges and differential gauges were tested with calibrator.

2. Experimental Facility

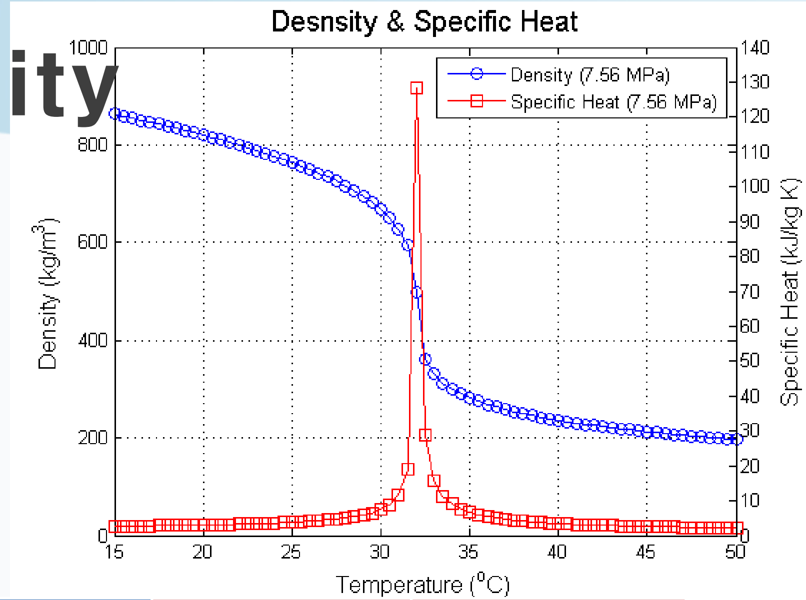
➢ STHE

- Spiral Tube Heat Exchanger
- SENTRY EQUIPMENT CORP.

- Specification data - LMTD method

	Tube side	Shell side
Fluid type	CO_2	Water
Mass flow rate [kg/s]	2.78	1.052
Inlet Temp. [°C]	**32.06**	**7**
Outlet Temp. [°C]	**32**	**12.3**
Inlet pressure [MPa]	7.56	0.45
Pressure drop [kPa]	48	13
Heat transfer area [m^2]	0.635	
Heat load [kW]	23.4	
Overall Heat transfer coefficient [W/m^2K]	1656.4	
Log mean temperature difference [°C]	**22.27**	
Volume [m^3]	0.01987	
Diameter [m]	0.324	
Length [m]	0.241	

2. Experimental Facility



➢ STHE Experiment data

➢ LMTD method : constant C_p

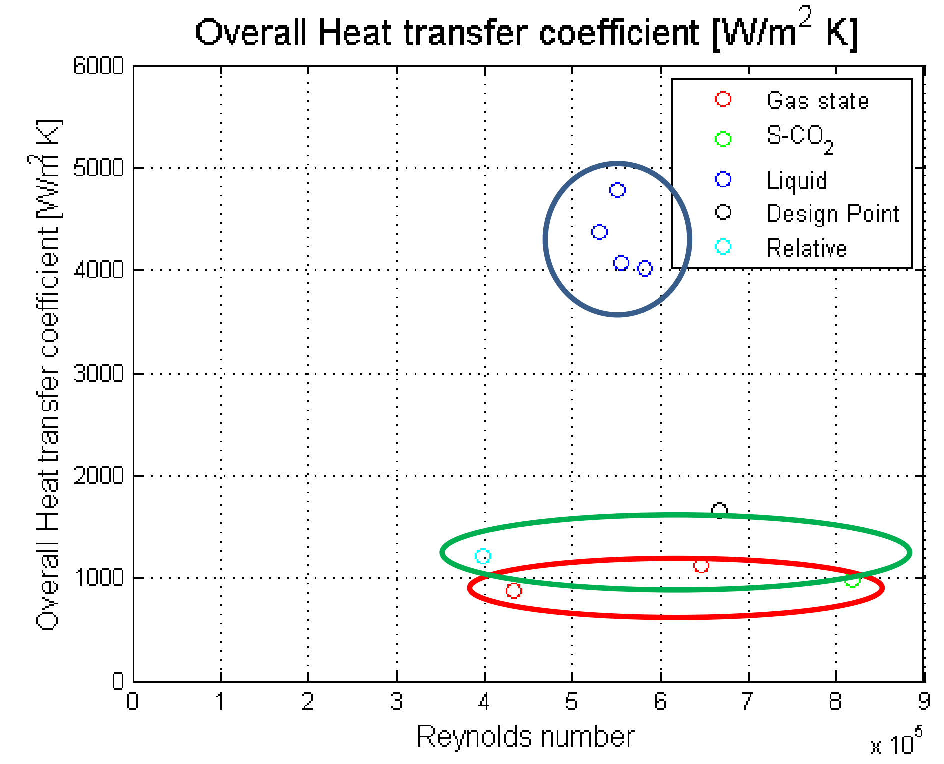
	Tube side	Shell side	Tube side	Shell side
Fluid type	CO_2	Water	CO_2	Water
Mass flow rate [kg/s]	2.78	1.052	1.016	0.078
Inlet Temp. [°C]	**32.06**	7	**36.605**	11.241
Outlet Temp. [°C]	**32**	12.3	**34.662**	33.869
Inlet pressure [MPa]	7.56	0.45	7.425	0.45
Pressure drop [kPa]	48	13	47.58	0.03
Heat transfer area [m^2]	0.635		-	
Heat load [kW]	23.4		7.4	
Overall Heat transfer coefficient [W/m^2K]	**1656.4**		**1222.7**	
Log mean temperature difference [°C]	22.27		9.6337	

2. Experimental Facility

➢ STHE Experiment data

- Overall heat transfer coefficient :
  Liquid > Supercritical state > gas state
- High Reynolds number
  - Low viscosity
  - Inner tube diameter : 8mm

Case	Mass flow rate [kg/s]	Inlet Condit' [MPa / °C]	Phase	Density [kg/m³]	Re	U [W/m²K]
1	0.93	5.42 / 50.3	Gas	116.71	434301	881.4
2	1.55	7.43 / 46.3	Gas	201.09	647222	1126.1
3	2.49	8.66 / 42.5	Supercritical	330.22	819131	985.1
4	4.28	6.95 / 23.9	Liquid	758.54	550405	4779.2
5	4.34	7.6 / 23.9	Liquid	778.99	531180	4369.9
6	4.34	7.16 / 24.3	Liquid	760.18	555834	4082.8
7	3.92	7.94 / 30.1	Liquid	695.97	582294	4026.1



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3. Heat exchanger design code KAIST_HXD

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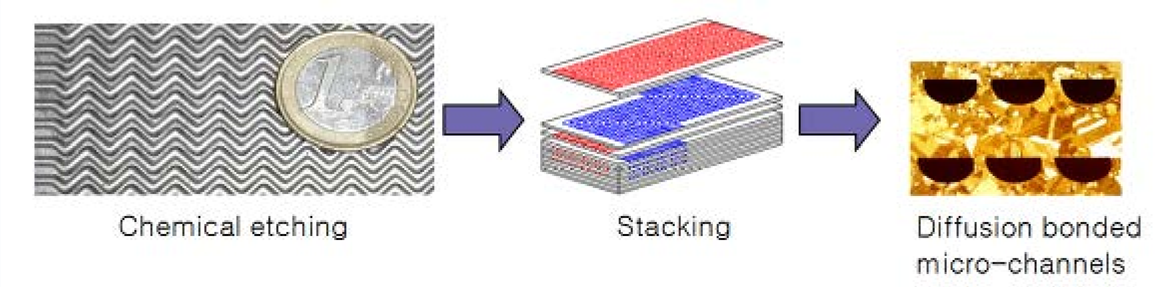
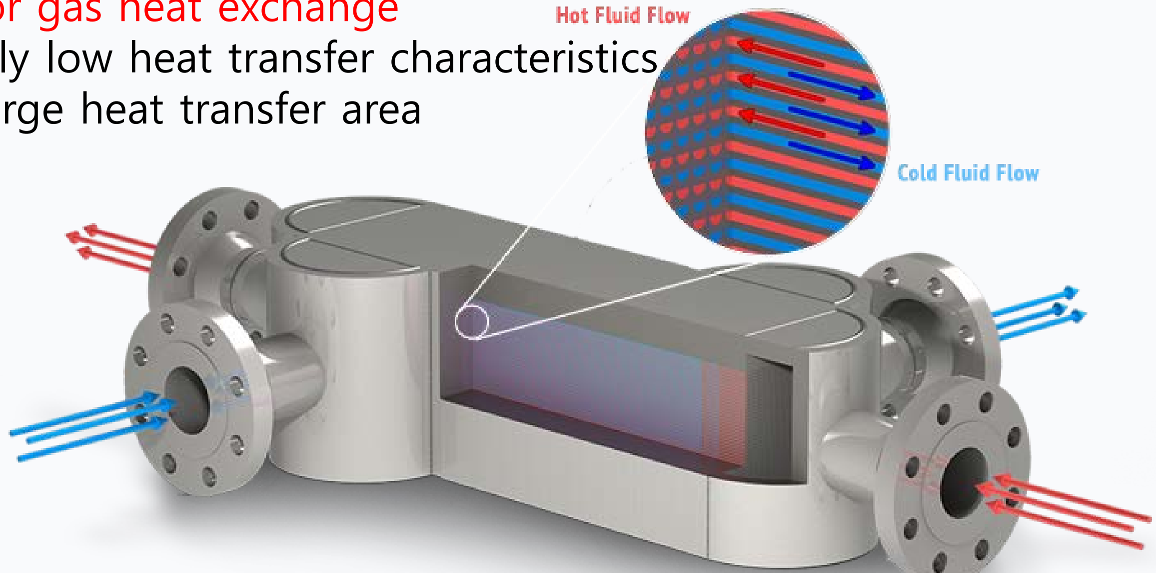
3. Heat Exchanger Design Code

➢ PCHE (Printed Circuit Heat Exchanger)



- High Temperature, High Pressure ($S\text{-}CO_2$ power cycle application)
- High Compactness[m^2/m^3] Heat exchanger
- Available for gas heat exchange
  - Relatively low heat transfer characteristics
  - Need large heat transfer area



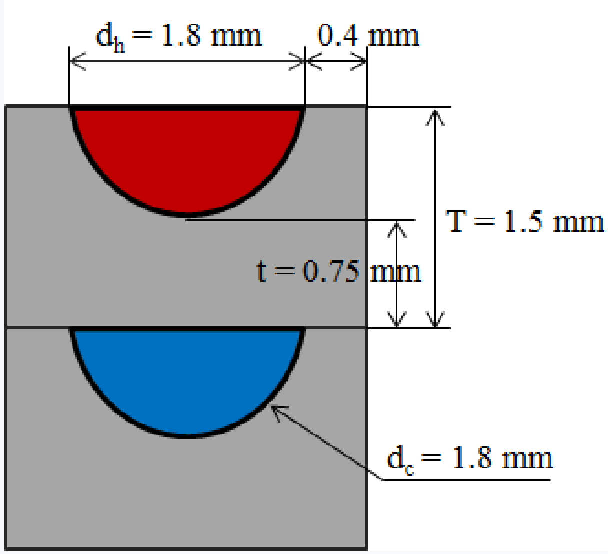
PCHE from Vacuum Process Engineering

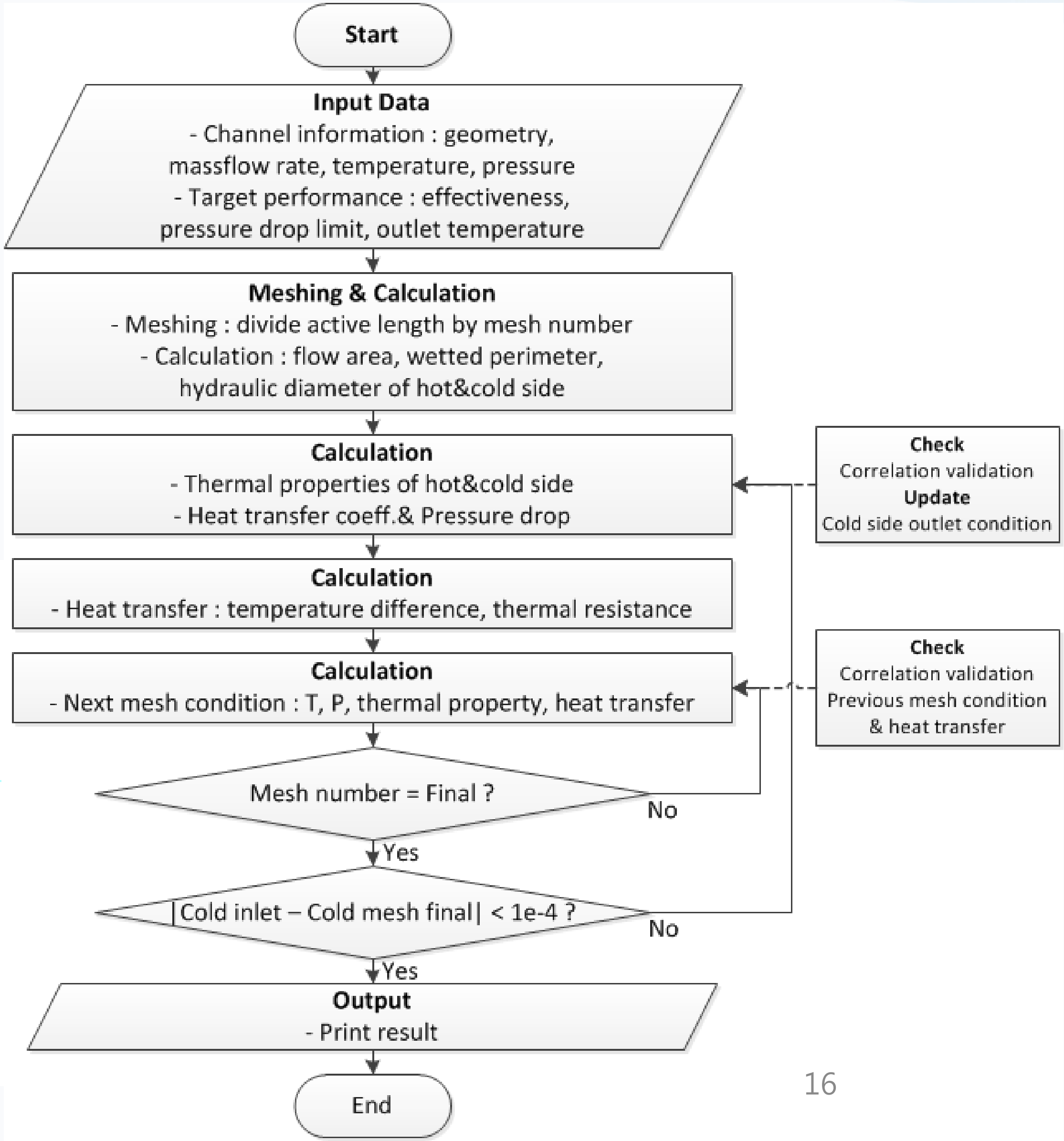
3. Heat Exchanger Design Code

➤ KAIST_HXD

- MATLAB based code
  - Performance
  - Pressure drop

- PCHE core design
  - Flow type :
    Counter-current
    Cross flow
  - Exclude header

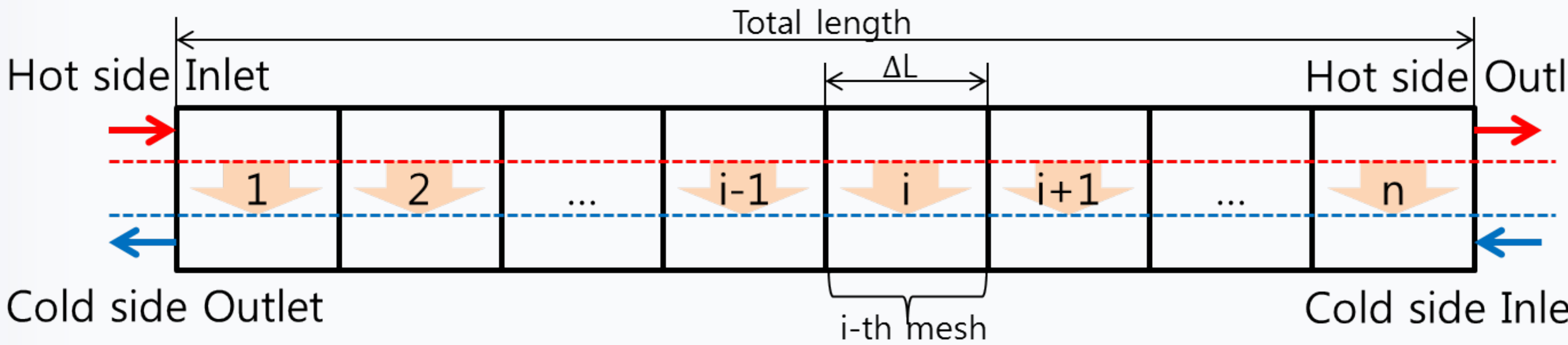




3. Heat Exchanger Design Code

➢ KAIST_HXD

- Due to the repetitive channel geometry of PCHE, the overall computation can be simply interpreted from a set of representative hot and cold unit channel



- Heat transfer

$$Q = U\,A\,\Delta T = \frac{1}{R_{conv.Hot} + R_{cond} + R_{conv.Cold}}\,A\,\Delta T = \frac{1}{\frac{1}{h_{Hot}} + \frac{t}{k_{cond}} + \frac{1}{h_{Cold}}}\,A\,\Delta T$$

- Pressure drop

$$\Delta P = 4f\,\frac{l}{D}\frac{\rho V^2}{2}$$

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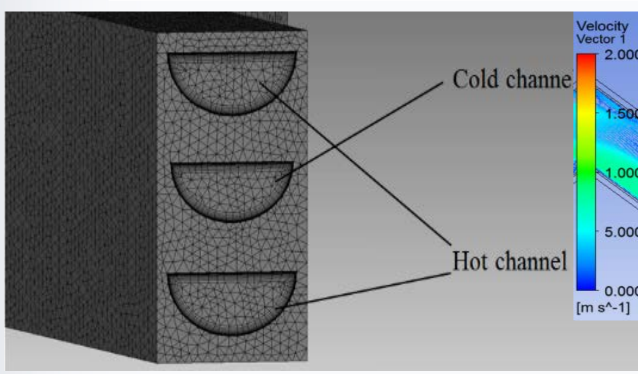
3. Heat Exchanger Design Code

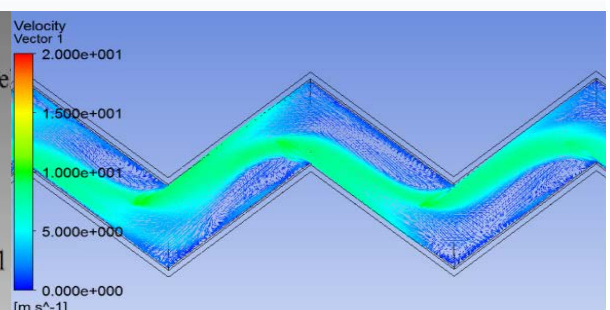
➢ KAIST_HXD

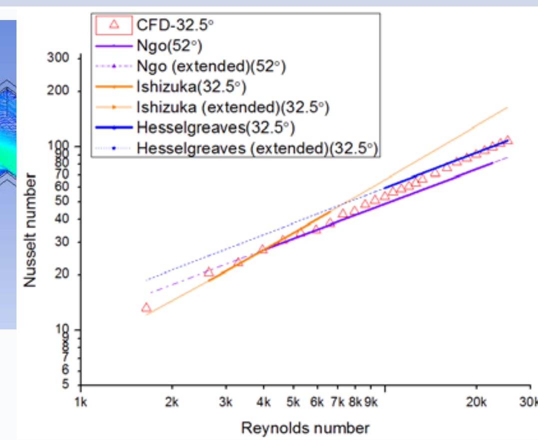
❖ Heat transfer coefficient (Nusselt number) & Friction factor

- CFD analysis (ANSYS CFX) [Seung Gu Kim et al.]
- Experimental study of Ishizuka (2400<Re<6000)

Fin angle	32.5°
Diameter	1.9 mm
Reynolds number	**2,000 < Re < 58,000**
Nusselt number	$\mathbf{Nu = (0.02925 \pm 0.00153)Re^{0.8138 \pm 0.00501}}$ $R^2 = 0.99904$
Friction factor	$\mathbf{f = (0.25150 \pm 0.00969)Re^{-0.20315 \pm 0.00414}}$ $R^2 = 0.98341$







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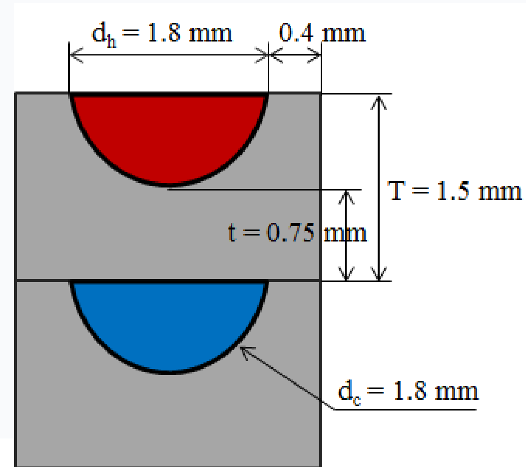
4. Summary & Further works

➤ Designed PCHE for S-CO_2PE facility

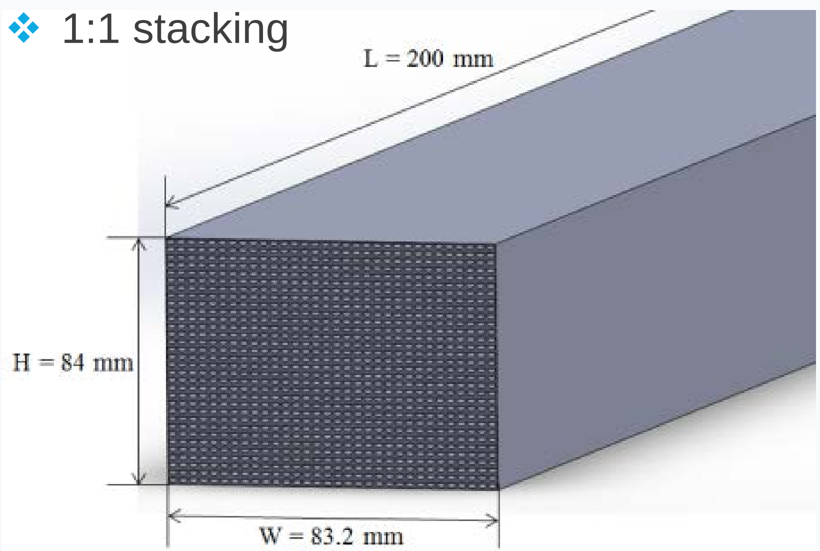
❖ Specification

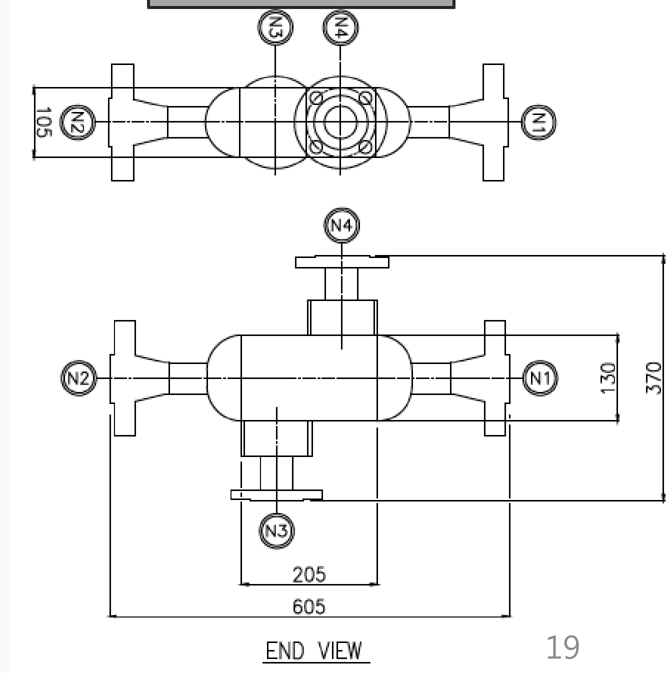
Material		SS316L
Density [g/cm³]		7.9
Thermal conductivity [W/m·K]		15.3
Hot side	Maximum Pressure [MPa]	19.5
	Maximum Temperature [°C]	150
Cold side	Maximum Pressure [MPa]	1.3
	Maximum Temperature [°C]	150



❖ 56 row x 32 channel (896channels each)

❖ 1:1 stacking





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4. Summary & Further works

Further works

- PCHE Experiment for KAIST_HXD code Validation
- CFD analysis comparing with experiment result

- Various range experiment for equilibrium-state cycle condition

- Comparing with STHE heat exchanger, PCHE availability, characteristics.

5. References

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THANK YOU

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