3rd European supercritical CO_2 Conference

TRANSIENT RESPONSE OF SUPERCRITICAL CO_2 AXIAL TURBINE FOR KAIST MMR

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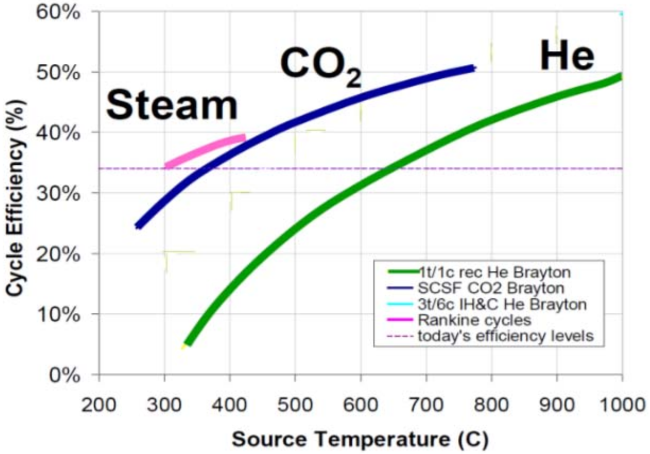
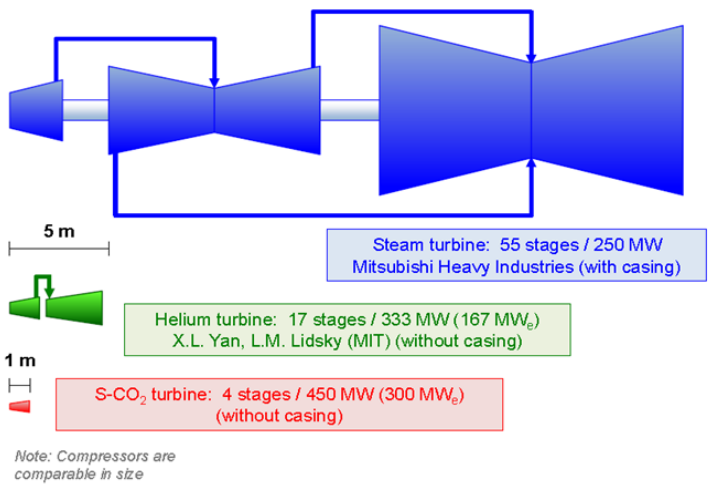
Background

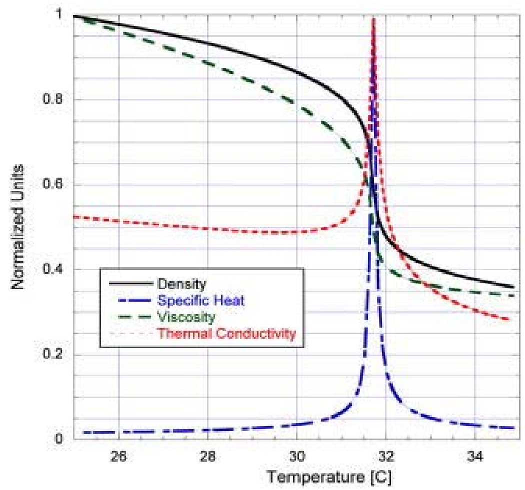


Cycle efficiency along the Source temperature



Turbomachinery size comparisons

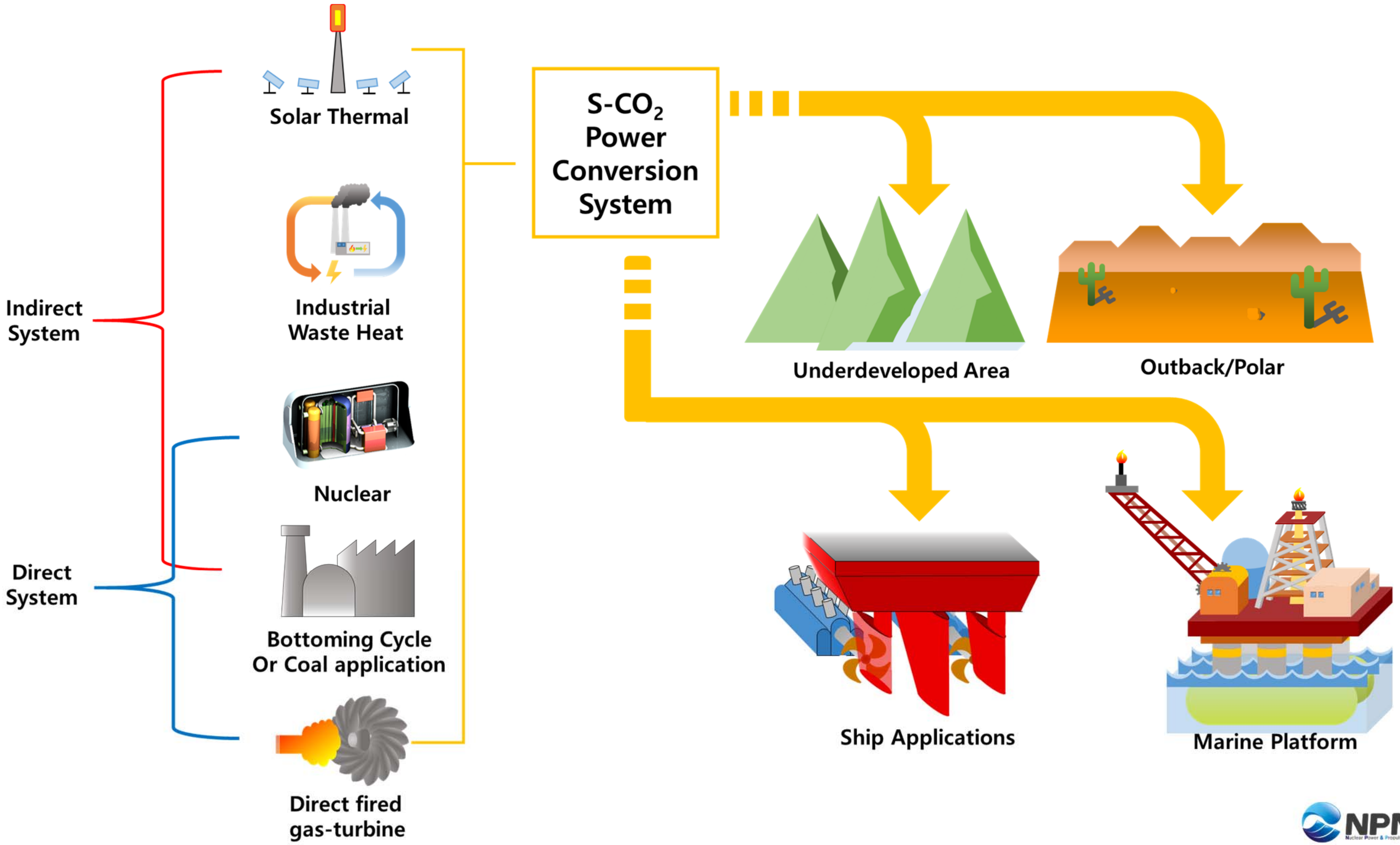
- A power generation system that utilizes the unique property changes of CO_2 occurring near the critical point (Especially compressibility)
- Component size more compact than other cycles
- Low compression work, relatively high efficiency at the low TIT



CO_2 thermodynamic properties near critical point

Background

➢ The s-CO_2 power cycle is available for all heat sources and has high application potential in various fields



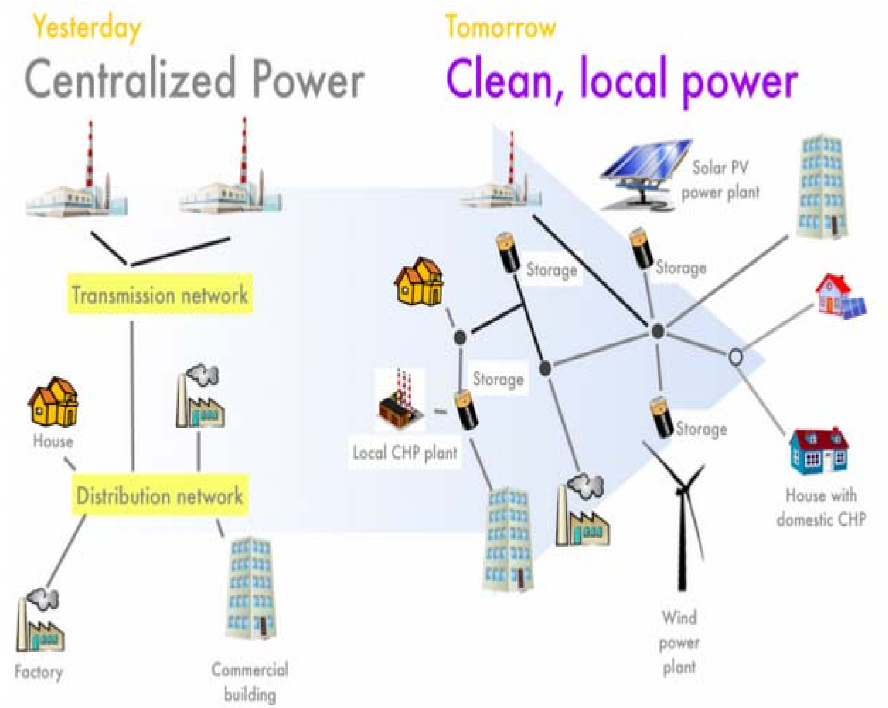
Background

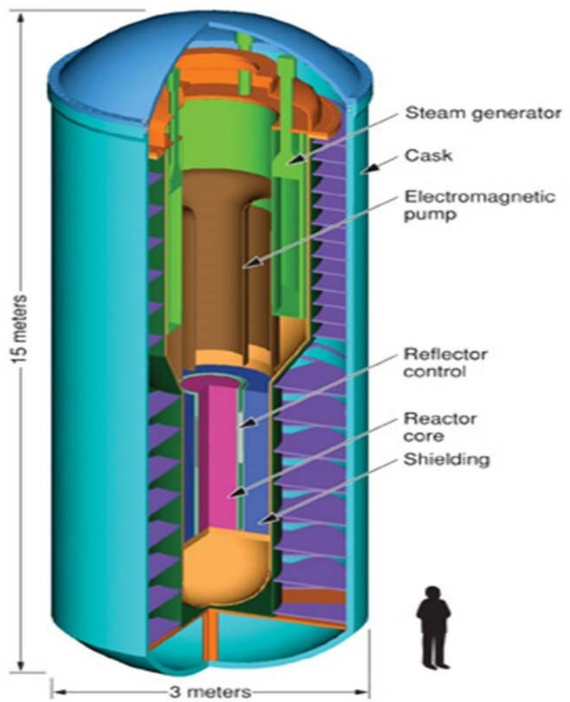
- ➢ Distributed grid

- Transmission cost reduction
- Consisted of mix of renewable energy sources and base energy source
- Favored for eco- friendly development

- ➢ Small Modular Reactor(SMR)

- Renewable energy sources not sustainable enough to support the base load
- Flexible, reliable, cost-effective and consistent electric power source





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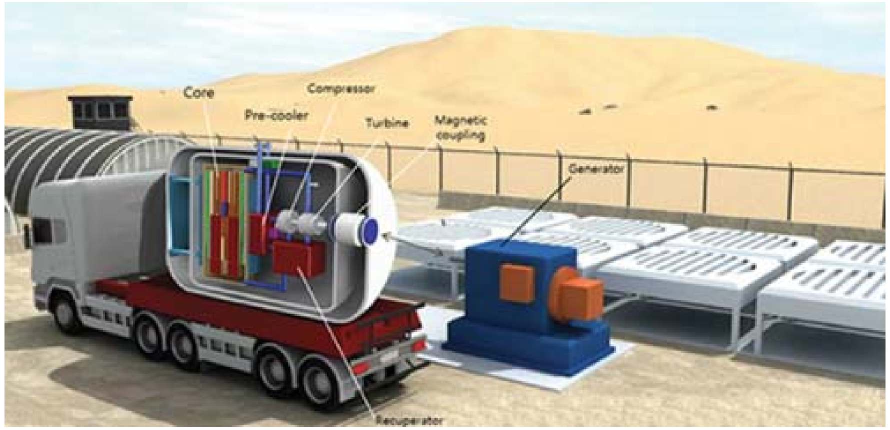
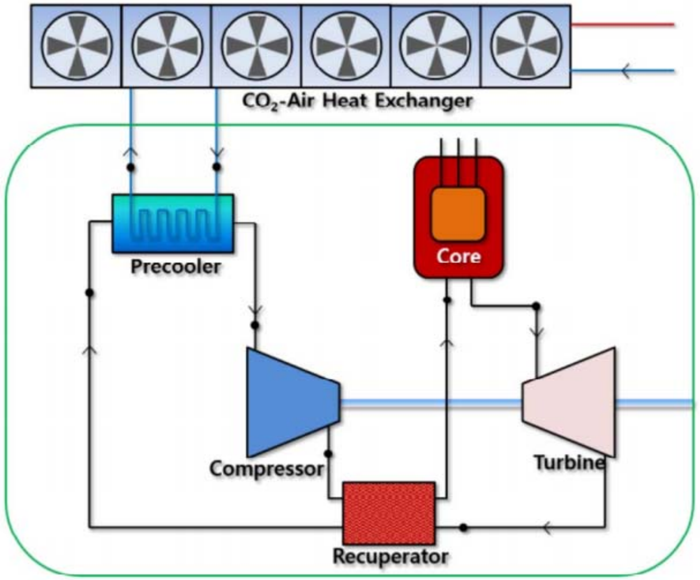
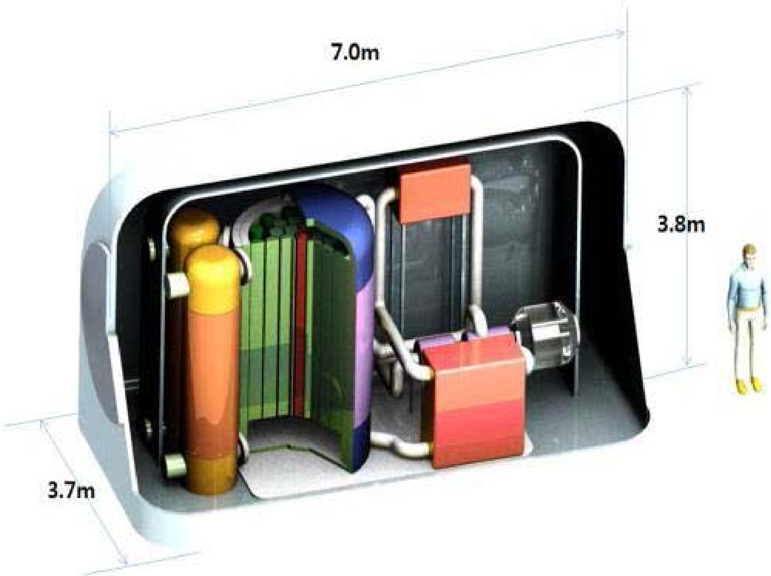




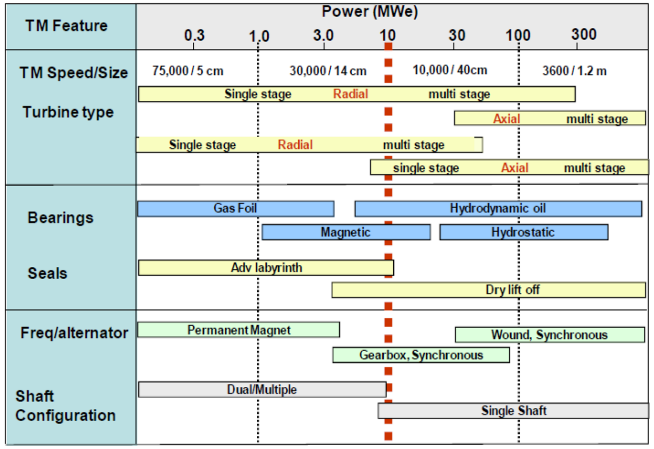


- The KAIST research team developed a micro modular reactor (MMR) by combining two technologies: SMR and gas turbine technologies.
- MMR is sized such that it can be transported via truck and the layout of MMR is shown in left figure.

Motivation

- Summary of design results of MMR

Thermal power	36.2MWth	Net electric power	12MWe
Thermal efficiency	34.09%	Mechanical efficiency	98%
Mass flow rate	180.0kg/s	Total-to-total Pressure ratio	2.49
Turbine total-to-total efficiency	92%	Compressor total to total efficiency	85%
Generator efficiency	98%	Rotating speed	19,300rpm
Recuperator effectiveness	95%	Compressor inlet pressure	8.0MPa
Design point of recuperator	Hot side inlet : 440.7°C, 8.2MPa Cold side inlet : 142.1°C, 20.0MPa Temperature difference : 22-58°C		



➢ 12MWe power system can utilized both radial turbine and axial turbine

➢ The existing MMR radial turbine was designed at the boundary between the radial turbine and the axial turbine as shown in left figure.

➢ Since the MMR turbine is already designed as a radia turbine, it will be newly designed and evaluated for the axial turbine.

Purpose

1. Design an axial turbine suitable for MMR

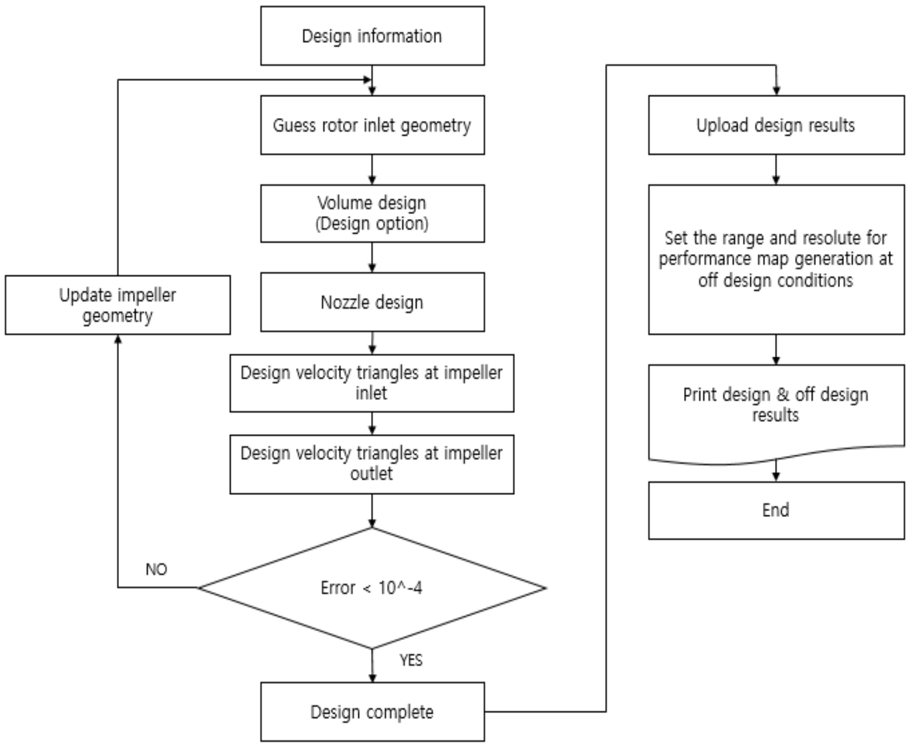
2. Evaluate the potential for using an axial turbine for MMR by comparing off design performance with originally designed single stage radial turbine.

3. The newly designed MMR was evaluated with GAMMA + code and compared to the radial turbine based on MMR.

KAIST-TMD code

- The KAIST TurboMachinery Design (TMD) code is developed by the KAIST research team written in MATLAB environment.

- It can estimate the performance and geometry of turbines at the design point and the performance at various off-design points.



Axial turbine	
Profile loss	Balje-Binsley
Secondary loss	Kacker-Okaapu
Tip clearance loss	Dunham-Came
Radial compressor	
Incidence loss	Boyce
Blade loading loss	Coppage et al.
Skin friction loss	Jansen
Clearance loss	Jansen
Disk friction loss	Daily and Nece
Mixing loss	Johnston and Dean
Recirculation loss	Oh et al.
Leakage loss	Aungier
Radial turbine	
Incidence loss	Balje
Rotor passage loss	Balje
Clearance loss	Jansen
Disk friction loss	Daily and Nece

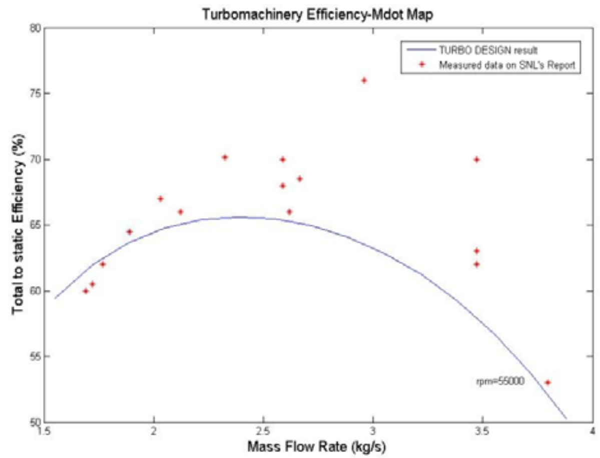
Summary of the loss model of each turbomachineries for KAIST-TMD

KAIST-TMD Validation

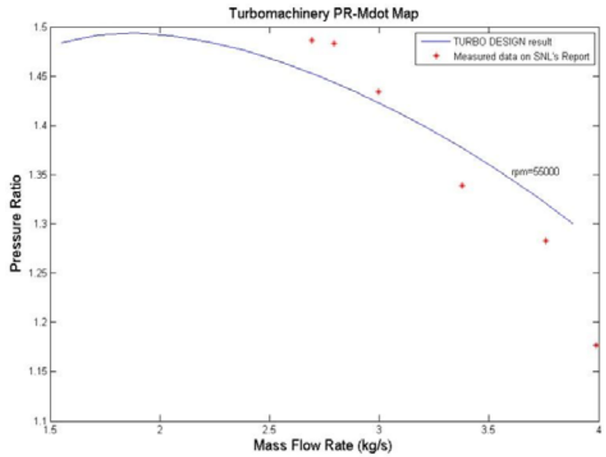
- The KAIST-TMD code for the radial compressor was validated with SNL's experiment data

Compressor Design dimensions and operating conditions in SNL's experimental data

Compressor Design Dimensions	
r_1, m	0.009372
r_3, m	0.01868
Blade height, m	0.001712
Number of blades	12
Impeller eye root radius, m	0.002537
Back swept angle, deg	-50
β_1 at tip, deg	50
Tip clearance, m	0.0002540
Compressor Operating Conditions	
Shaft speed, rpm	75000
Inlet Temperature, K	305.30
Mass flow rate, kg/s	3.53
Inlet pressure, kPa	7687



Performance of efficiency comparison



Performance of pressure ratio comparison

KAIST-TMD Validation

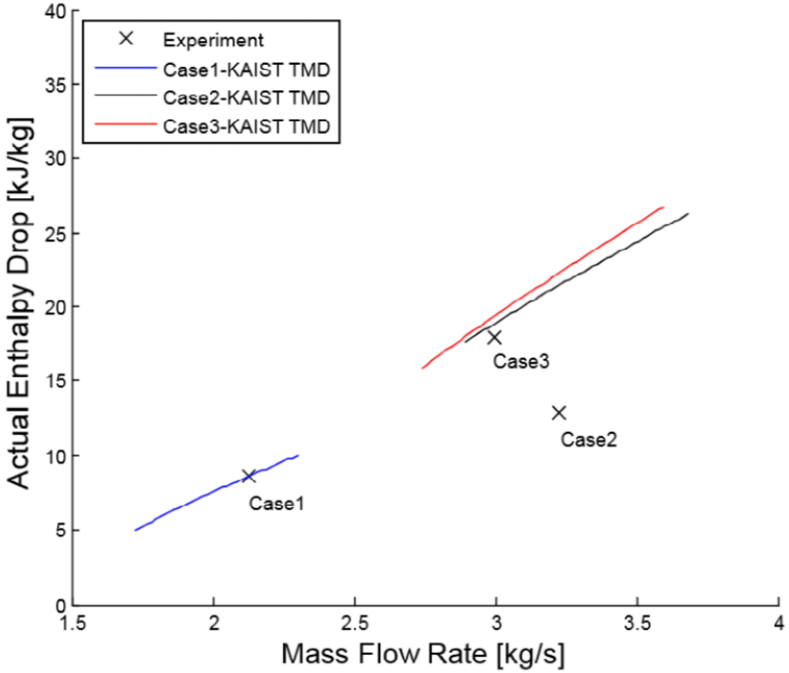
- For the same turbomachinery, equivalent conditions can provide a basis for comparing different working fluids. Furthermore, sCO_2 turbine operates where the properties are behaving similar to an ideal gas.

- The KAIST-TMD code was validated using NASA's air radial turbine data, which is equivalent to sCO_2 conditions for a radial turbine case

Comparison of turbine model with NASA's data

			Case1	Case2	Case3
Inlet Conditions	N (kRPM)		25.00	35.07	39.14
	$N_{correct}$ (kRPM)		33.44	46.75	49.79
	$\dot{m}$ (kg/s)		0.9734	1.631	1.630
	$\dot{m}_{correct}$ (kg/s)		2.127	3.223	2.995
	T_{ti} (℃)		148.1	147.6	203.6
	P_{ti} (MPa)		8.284	9.125	9.365
Validation Metrics	Δh_{act} (kJ/kg)	Experiment	8.6	12.91	17.98
		Model	13.51	29.00	29.24
		Error	**-4.91** (57%)	**-16.09** (125%)	**-11.26** (63%)
		Revised	8.62	21.36	19.37
		Error	**-0.02** (0.002%)	**-8.45** (65%)	**-1.39** (7.7%)

Radial turbine enthalpy drop map



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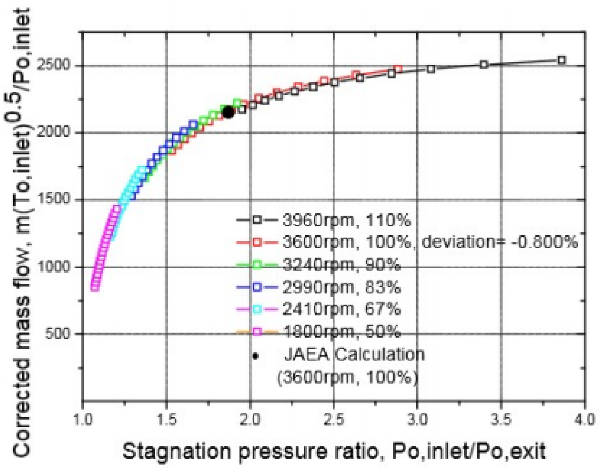
KAIST-TMD Validation

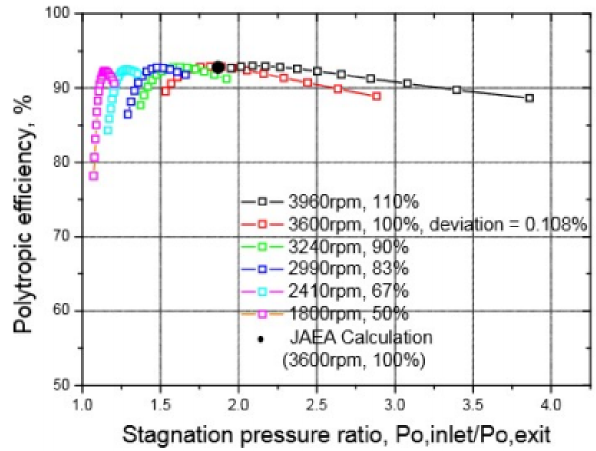
- For the axial turbine, the loss set which used in the Dr Kim Ji Hwan's doctoral thesis was used.
- The author selected the GTHTR 300 design of JAEA, a direct cycle using helium gas, as a reference model to validate the axial turbine code.

	JAEA	KAIST	Error
Pressure ratio	1.874	1.889	-0.800%
Temperature ratio	1.273	1.266	-0.550%
Polytropic efficiency (%)	92.8	92.9	0.108%
Shaft work (MW)	553.1	541.1	-2.170%

Table : Comparison of the design-point performance of the GTHTR300 turbine between JAEA and KAIST



Calculation results for pressure ratio characteristic of the GTHTR300 turbine

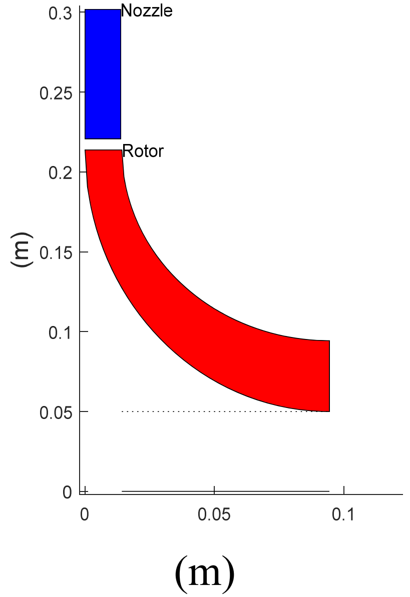


Calculation results for polytropic efficiency characteristic of the GTHTR300 turbine

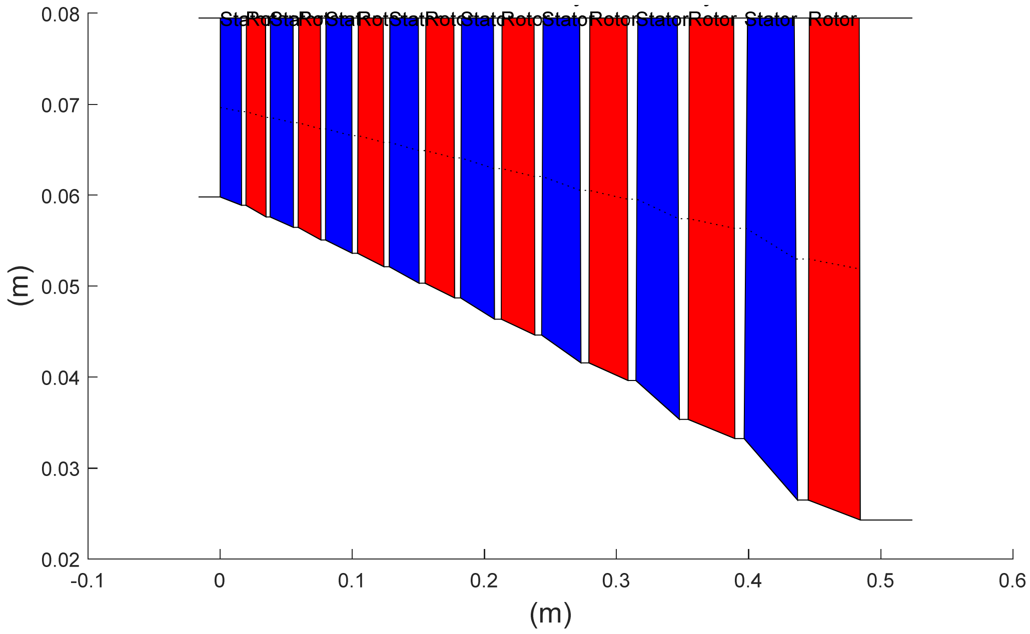
- KAIST-TMD is validated in radial compressor, radial turbine, and axial turbine with the available data.

KAIST-TMD Results

Radial turbine geometry



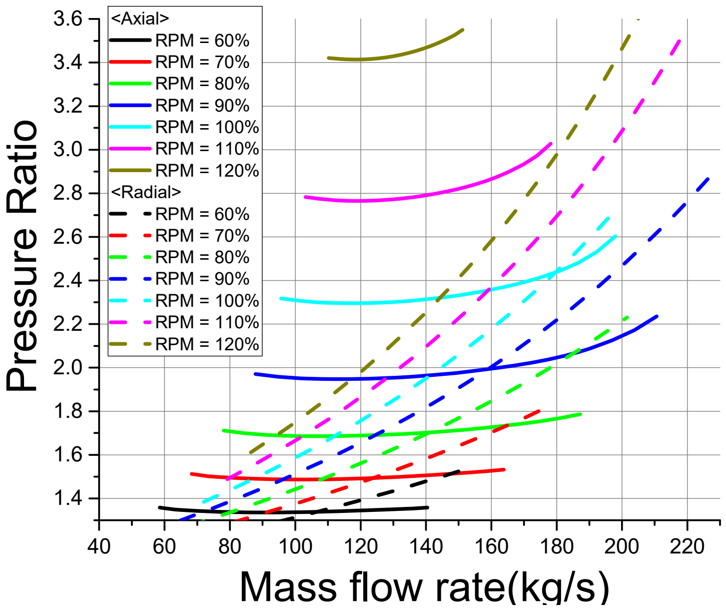
Axial turbine geometry



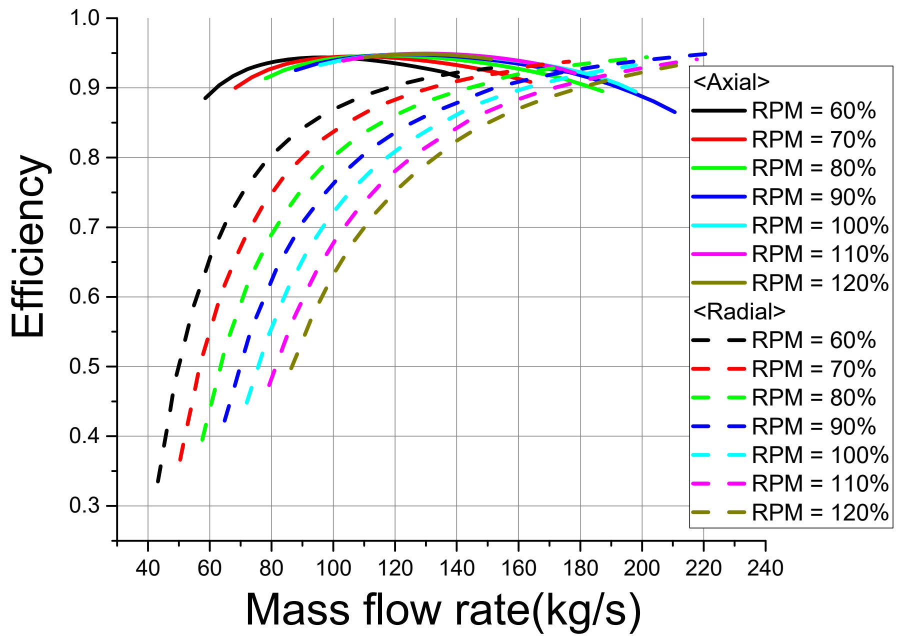
	Stage	Turbine radius	Turbine height	Total volume of turbine
Radial	1	0.302m	0.0944m	$0.0146m^3$
Axial	8	0.0795m	0.484m	$0.00962m^3$

- It is confirmed that the volume of the axial turbine is 0.66 times smaller than that of the radial turbine.
- Axial turbine : Pressure ratio = 2.44, efficiency = 91.6%

KAIST-TMD Results



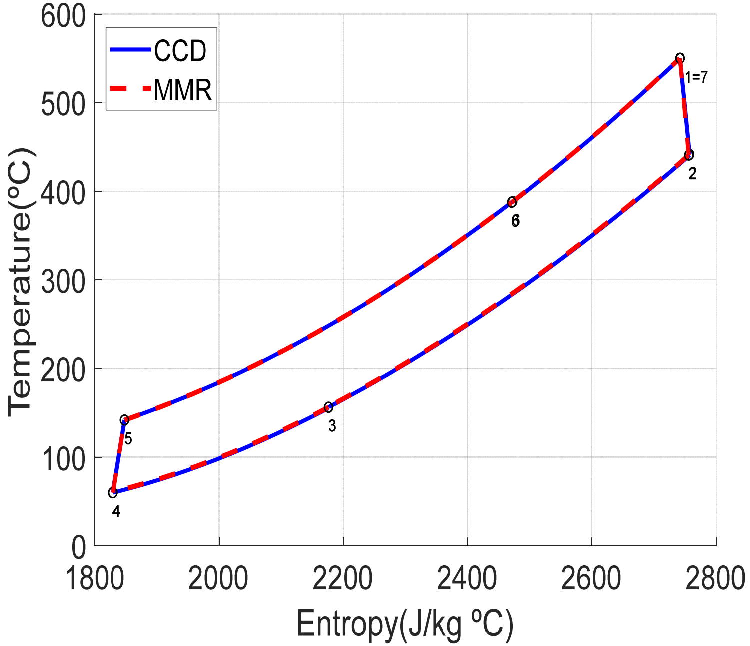
Comparison of Pressure ratio map for MMR radial and axial turbines



Comparison of efficiency map for MMR radial and axial turbines

- The slope is smooth compared to the radial turbine in both pressure ratio and efficiency for the axial turbine during off-design condition.
- It was confirmed that the axial turbine efficiency is higher than the radial turbine during the off design conditions.

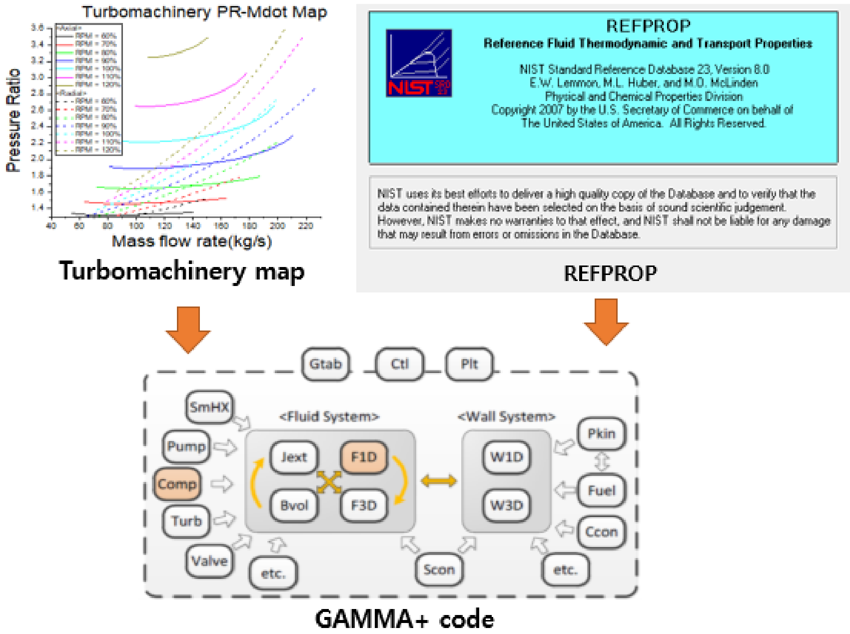
KAIST-CCD Result



Type	Radial		Axial	
Mass Flow rate (kg/s)	180		181.25	
Point	Temperature (ºC)	Pressure (Mpa)	Temperature (ºC)	Pressure (Mpa)
Turbine inlet = 1	550	19.93	550	19.93
Recuperator hot side inlet = 2	440.75	8.161	440.72	8.168
Pre-cooler inlet = 3	157.79	8.091	156.47	8.099
Compressor inlet = 4	60	8.001	60	8.009
Recuperator cold side inlet = 5	142.17	20	141.96	20
Reactor inlet = 6	386.53	19.98	388.48	19.98

- MMR using axial turbine was optimized under the original MMR condition by KAIST-CCD for selecting the highest efficiency.
- There is almost no difference in the T-s diagram between the cycle using the axial turbine with the best efficiency and that of the radial turbine.
- Since the GAMMA + code of original MMR using radial turbine is already constructed, only the turbine will be modified in the GAMMA+ transient simulation.

Modified GAMMA+ code



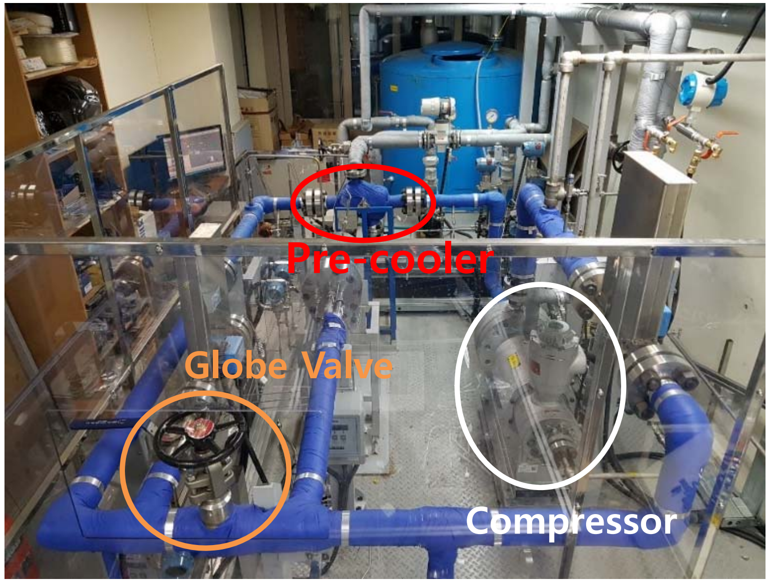
- GAMMA+ code is developed for a gas cooled reactor by KAERI.
- For MMR, it is necessary to calculate the CO_2 property values near the critical point accurately.
- The modified GAMMA + code used in the REFPROP developed by NIST which accurately calculated the thermal and transportable properties.

- The GAMMA + code has been modified to use turbine and compressor performance maps because the off-design conditions of a turbomachine use a straightforward map.
- To calculate the outlet condition of turbomachineries accurately, the performance map with pressure ratio and efficiency obtained by using KAIST-TMD with GAMMA + code

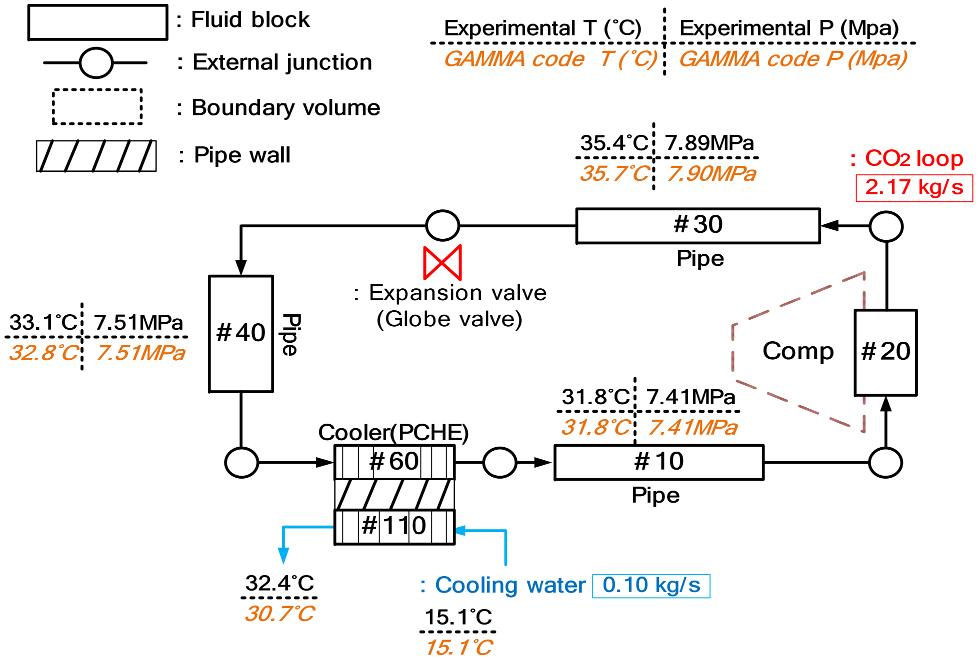
Validation of the modified GAMMA+ code

- The design conditions of SCO2PE facility

Compressor	Type		Canned motor pump
	Power		26 kW
	Pressure ratio		1.2
	Maximum RPM		4620
	Inlet condition	Pressure	7.56 MPa
		Temperature	32 ℃
Mass flow rate			2.78 kg/s
Expansion valve type			Globe valve
Pre-cooler type			PCHE



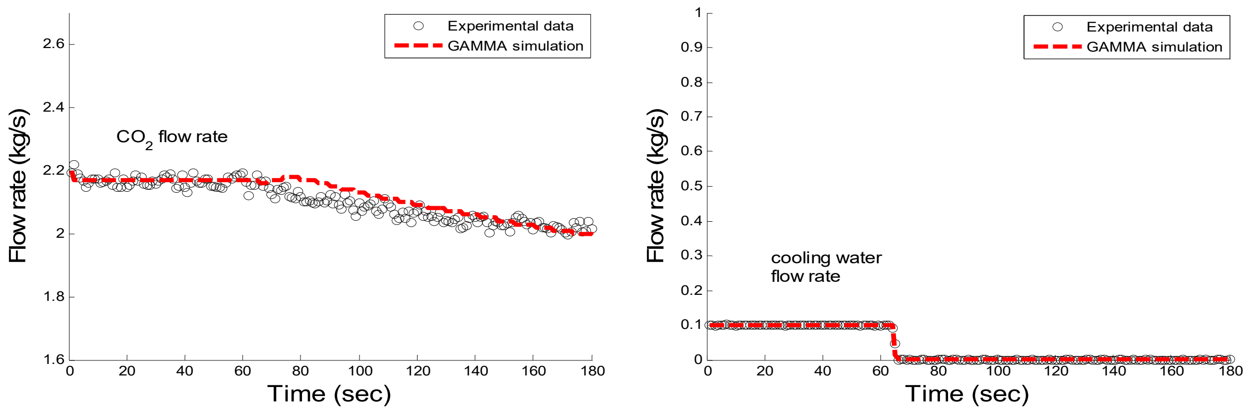
- KAIST SCO2PE facility



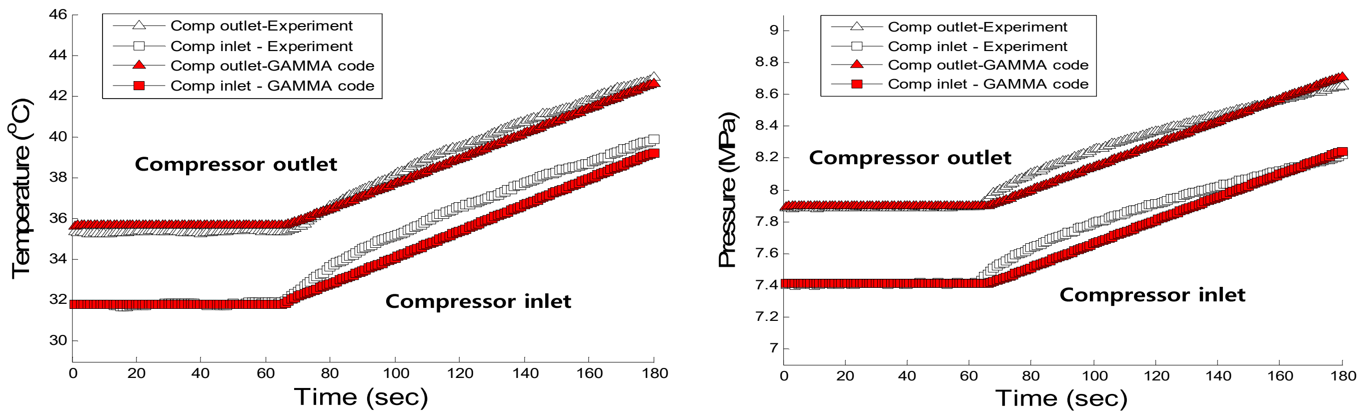
- The nodalization diagram of SCO2PE

Validation of the modified GAMMA+ code

Under cooling performance scenario(cooling water 0.1→0 kg/s)

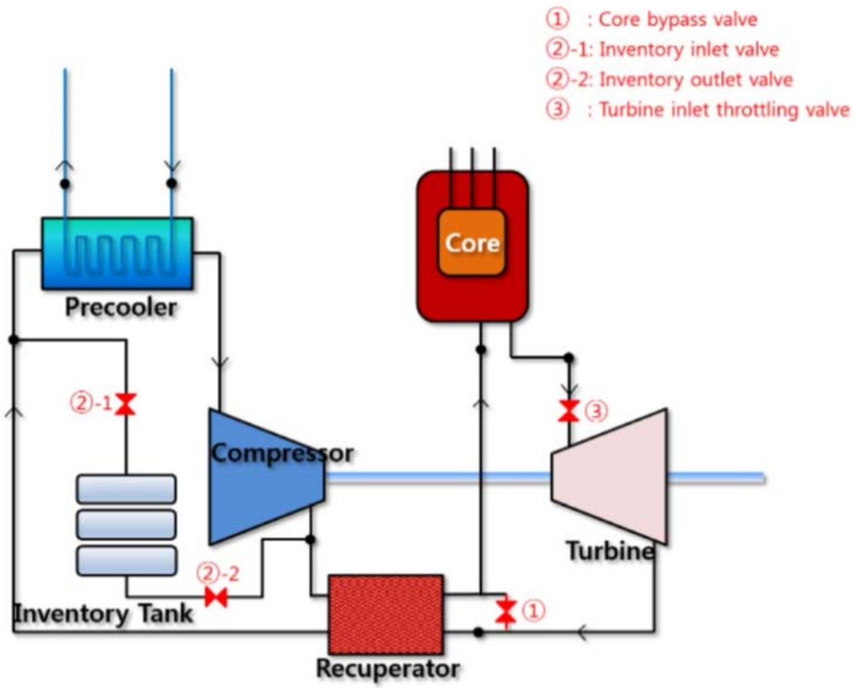


The comparison of CO_2 (left) and cooling water (right) mass flow rate variations between experiments and GAMMA code analysis (cooling water reduction scenario)



Transient temperature (left) and pressure (right) comparison between experiments and GAMMA code analysis (cooling water reduction scenario)

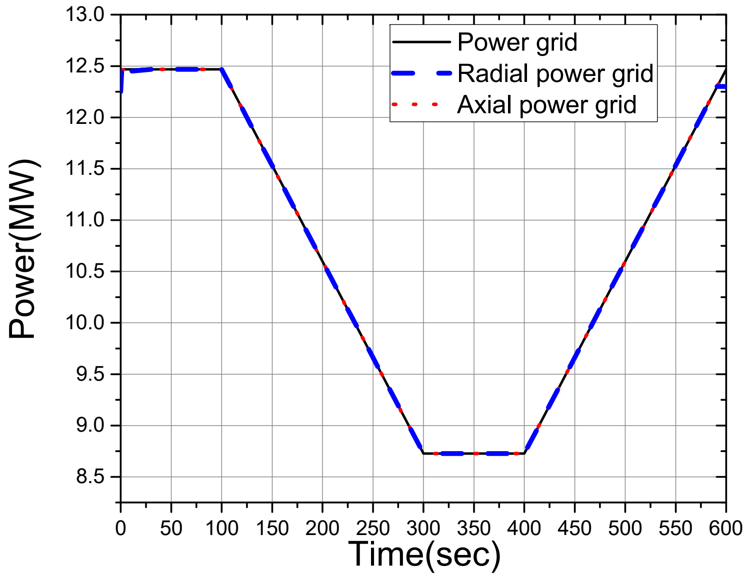
Partial loading operation for MMR



- In MMR, core by pass and inventory tank control were used in the part loading operation as follows.
- When the power grid changes, the turbine power must be changed while maintaining the rpm, so the turbine flow rate is controlled by the core by pass.
- In accordance with the pressure ratio of the turbine as described above, the part load operation is performed by controlling the mass flow rate of the compressor through the inventory control and adjusting the pressure ratio.

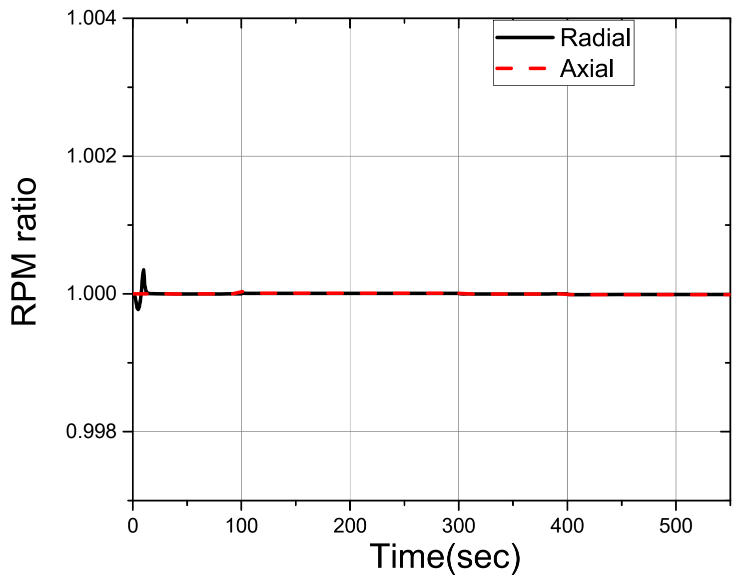
Results

- To compare the dynamic performance of the new MMR with the axial turbine and the original MMR with the radial turbine, it is assumed that a scenario simulating the load change and it is prescribed by MMR.
- This scenario starts at steady state (t = 100 s), during which the load drops from 100% to 70% (t = 100-300s) for 200 seconds and rises from 70% to 100% for another 200 seconds (t = 400-600 seconds).



Power grid of MMRs with Radial and Axial turbines

RPM ratio of MMRs with Radial and Axial turbines



Results

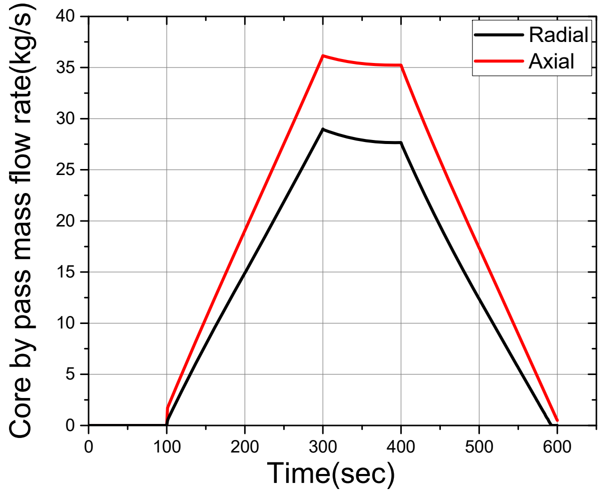


Fig1.Core by pass mass flow rate of MMRs with Radial and Axial turbines

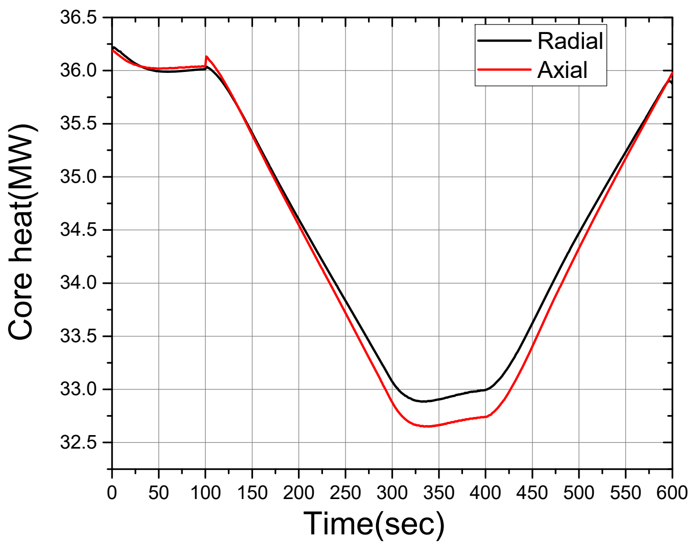


Fig3. Core heat of MMRs with Radial and Axial turbines

Fig2.Turbine mass flow rate of MMRs with Radial and Axial turbines

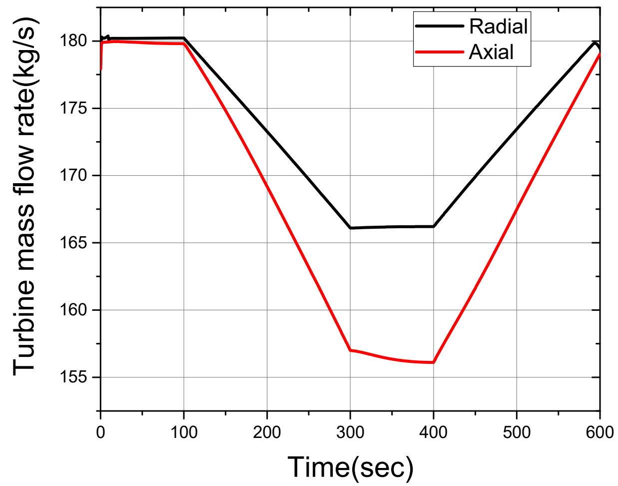
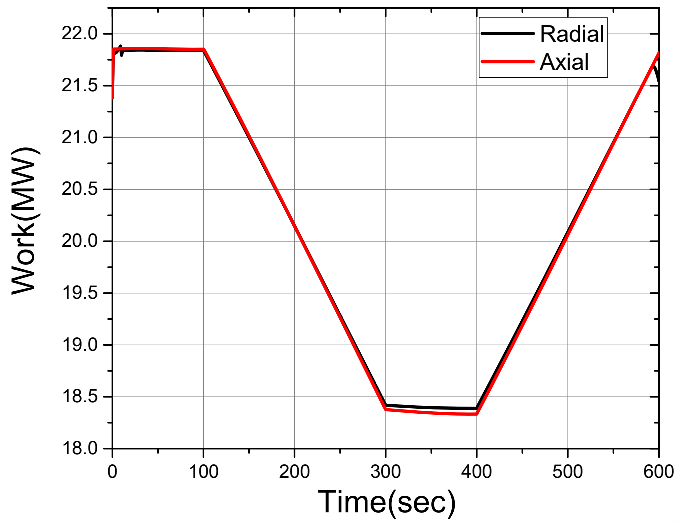


Fig4. Turbine work of MMRs with Radial and Axial turbine



Results

Fig 5. Efficiency of MMRs with Radial and Axial turbines

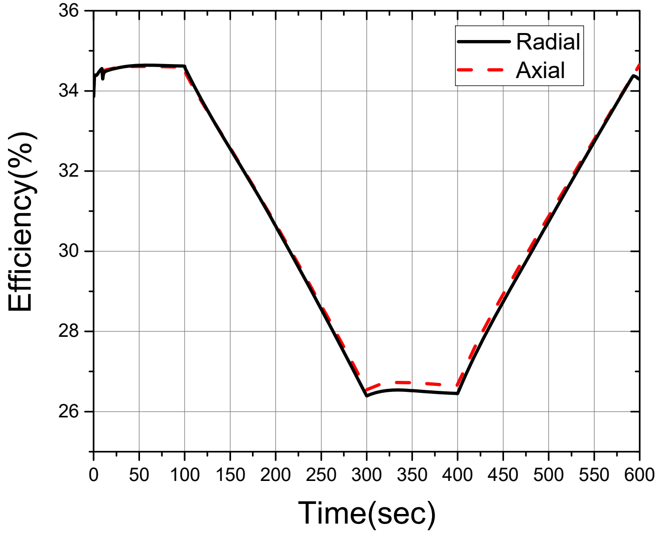
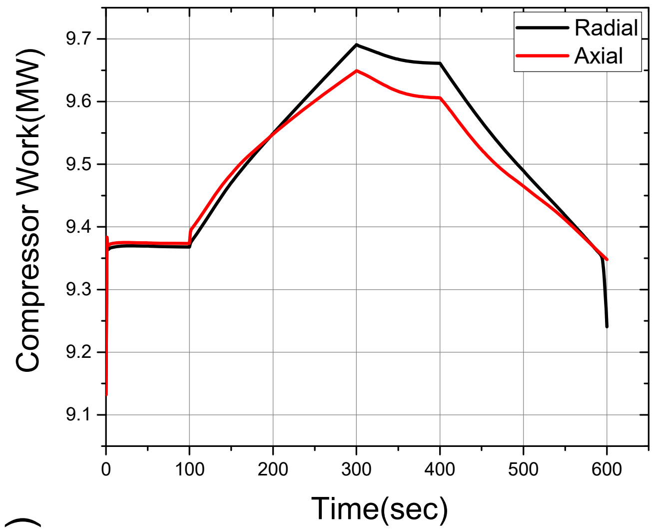


Fig 6.Compressor work of MMRs with Radial and Axial turbines



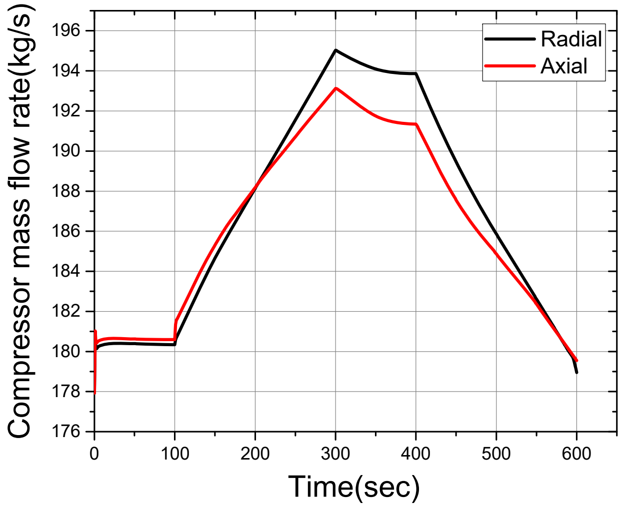


Fig 7. Compressor mass flow rate of MMRs with Radial and Axial turbines

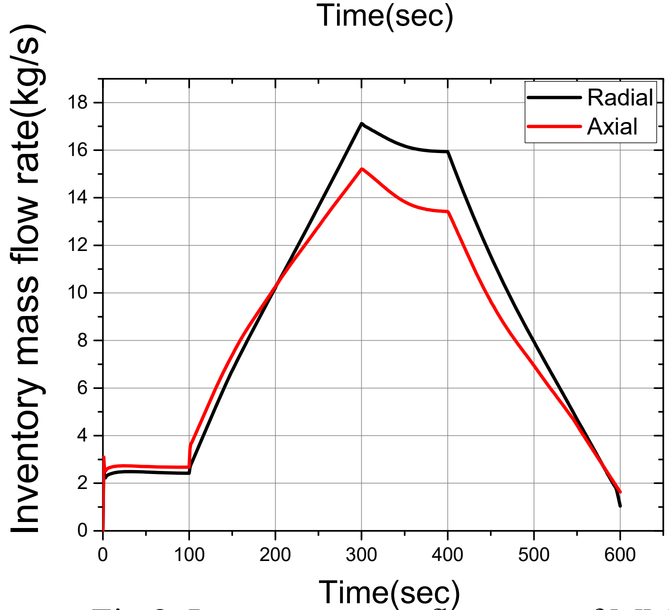


Fig 8. Inventory mass flow rate of MMRs with Radial and Axial turbines

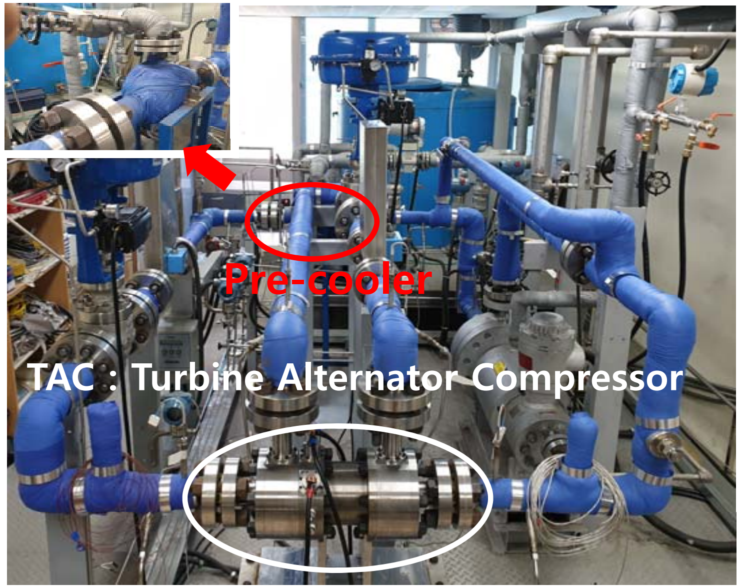
Conclusions

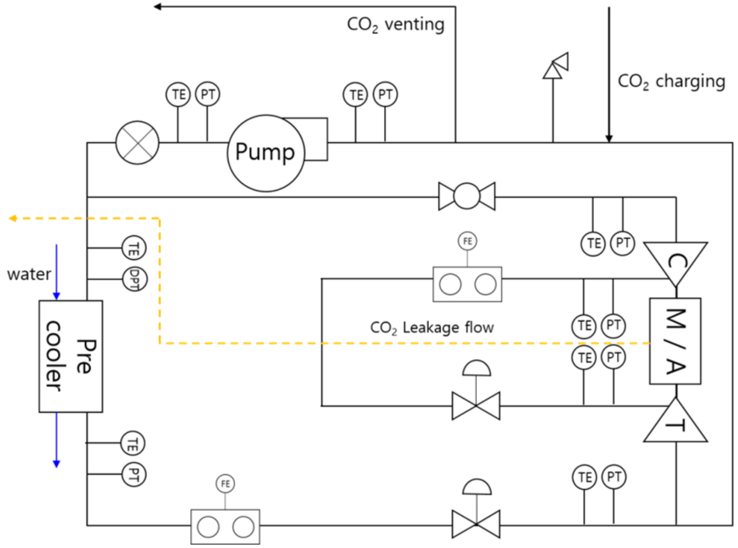
1. The potential of the axial turbine was confirmed in terms of inventory tank size under the off-design conditions when axial turbine or radial turbine is used. Also, the axial turbine volume is 0.66 times smaller than that of the radial turbine.

2. The axial turbine is more advantageous with respect to the reduction of the inventory tank compared to the radial turbine under off-design conditions and these advantages will be amplified as the system becomes large.

3. The planned future works are to analysis of transient response in partial loading operation where RPM changes

Future work





<Diagram of the S-CO_2 TAC experiment facility>

- Unlike the previous SCO2PE facility, a new TAC(Turbine alternator Compressor) component was added

- Additional TAC allow evaluation of dynamics performance of turbine and compressor for different scenario situations

Thank you

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