TRANSIENT ANALYSIS OF THE SUPER-CRITICAL CARBON DIOXIDE CYCLE COUPLED TO PRESSURIZED WATER REACTOR FOR NUCLEAR POWERED SHIPS

The 4th European sCO_2 Conference for Energy Systems

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Contents

Introduction

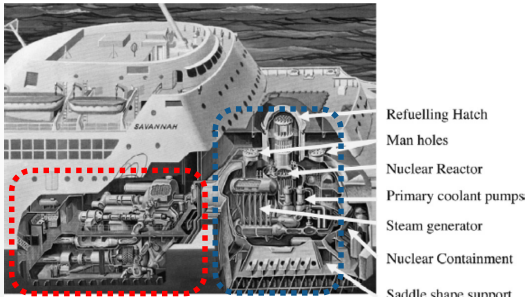
Background

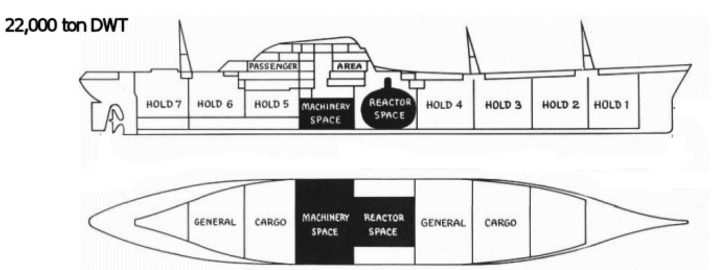
Growing attention on the nuclear merchant ships

- Nowadays, worldwide trade has been growing tremendously due to economic globalization and it is estimated shipping is responsible by 95% of global commerce.
- Due to the trend of rapid and **large-scale ships** and **international regulations on greenhouse gas emissions**, nuclear-powered merchant ships have attracted growing attention in many countries.
- Many studies suggest that nuclear propulsion systems need to be **economically enhanced** to be applied to merchant ships. (Capital cost and manning cost)

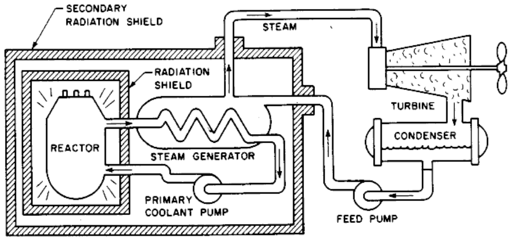
Conventional nuclear propulsion system

- Most nuclear-powered ships have employed Pressurized Water Reactor (**PWR**) and **steam Rankine cycle**.
- Among various types of reactor core, the PWR has been found to be most suitable to nuclear-powered ships in terms of safety and performance.
- However, there are still some **economic drawbacks** in using the steam Rankine cycle as the power conversion system for **nuclear merchant ships**.
  - Large volume and weight of components (steam turbine, condenser) -> reduce cargo carrying capacity
  - Complex system layout due to many auxiliary systems (e.g., steam quality control, water chemistry control, large pure water inventory tank)
  - High operation cost due to the large number of crews
- More **compact** and **simple** power conversion system is required for nuclear ships to be economically competitive.





< NS Savannah >



< PWR based propulsion system >

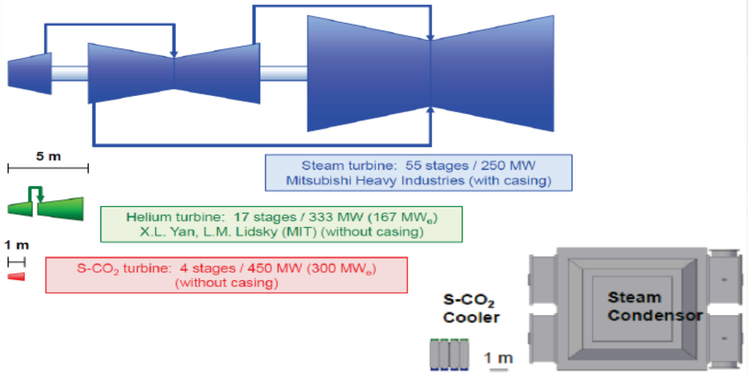
Introduction

Motivation

Super-critical carbon dioxide cycle

- The most promising power conversion system as an alternative to conventional Rankine cycle
- Simple system configuration
- High density fluid -> compact turbomachinery
- Potential for significant operational and capital cost benefits
- Single phase system -> rapid response to load change and less risk of flow instability

✓ The S-CO_2 cycle is expected to have **many advantages** when adopted as a power conversion system of **nuclear-powered ships**.



V. Dostal, et al, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, (2004)

< Comparison of component size of between Rankine cycle andS-CO_2 cycle>

Characteristics of nuclear propulsion system

- A shipboard reactor has to be capable of operating over **a wide range of power levels**, especially during the ingress and egress to ports.
- Rapid power transients can also be anticipated as the ship is transiting close to land.

✓ In order for nuclear system to be applied for marine propulsion, it should exhibit superior load following capability under **severe load changes**.

Parameter		NS Savannah	NS Otto Hahn	NS Mutsu
Displacement (tons)		21,800	25,790	25,790
Reactor thermal power		74 MW	38 MW	38 MW
Cruising speed		21 knots (39 km/h)	17 knots (31 km/h)	17 knots (31 km/h)
Cargo capacity [tons]		10,000	14,000	8,242
Crew		124	63	80
Load change requirement	Increase	**20% - 80% in 10s (6%/s)**	**10% - 100% in 90s (1%/s)**	**18% - 90% in 30s (2.4%/s)**
	Decrease	**100% - 20% in 3s (26.7%/s)**	**100% - 10% in 1s (90%/s)**	**100% - 18% in 1s (82%/s)**

< General information of nuclear merchant ships >

Research Objective

Objective & Scope

Objective: Conceptual design of S-CO_2 power conversion system under the PWR conditions for nuclear marine propulsion & Demonstrating the feasibility of proposed system to marine application by **transient analyses** under severe load changes

Conceptual Design (S-CO_2 Cycle & Main components) → Development of System analysis Code → Development of the control logic → Transient Analysis

System Design

Overview

Primary system

- Since the design of primary coolant system and reactor core is beyond the scope of this thesis, it is referred to the existing reactor system.
- Thermal characteristics are referred to **SMART** reactor, which is an integral-type PWR with the thermal power of 330 MW considering current trend of ship power.
- Reactor feedback coefficients are referred to the **ATOM** (Autonomous Transportable On-demand Reactor Module), which is a water-cooled autonomous SMR with the thermal power of 450 MW.
- Notable features that ATOM differs from the SMART is that ATOM is designed as a **soluble-boron-free** (SBF) reactor.
- This conceptual reactor is described as **ATOM-S** in this thesis.

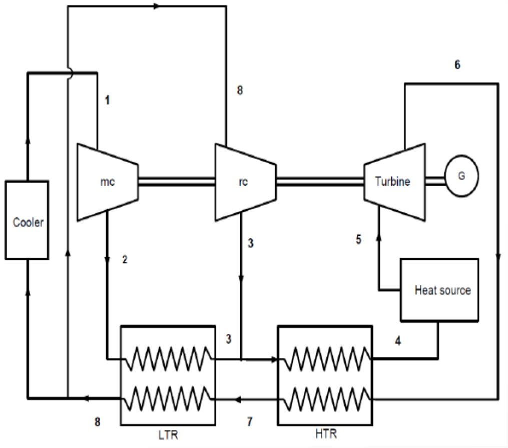
	Power
Main engine	75.57 MW
Aux. engines	7.4 MW
Aux. generator	17.9 MW
Total	100.87 MW

< Total Engine Power of MSC Gulsun >

Secondary system – Cycle layout

- Due to the relatively low turbine inlet temperature (TIT) under the PWR temperature conditions, **recompression cycle** was chosen which is generally known as the most efficient cycle among the basic cycle layouts.
- There are also potentially more efficient cycle layouts such as intercooling or reheating cycle. However, these cycle layouts are excluded in this thesis since they may result in more complex and larger system which is not suitable for ship propulsion.

✓ **The total system comprises the soluble-boron-free integral PWR type SMR and the S-CO_2 recompression Brayton cycle.**

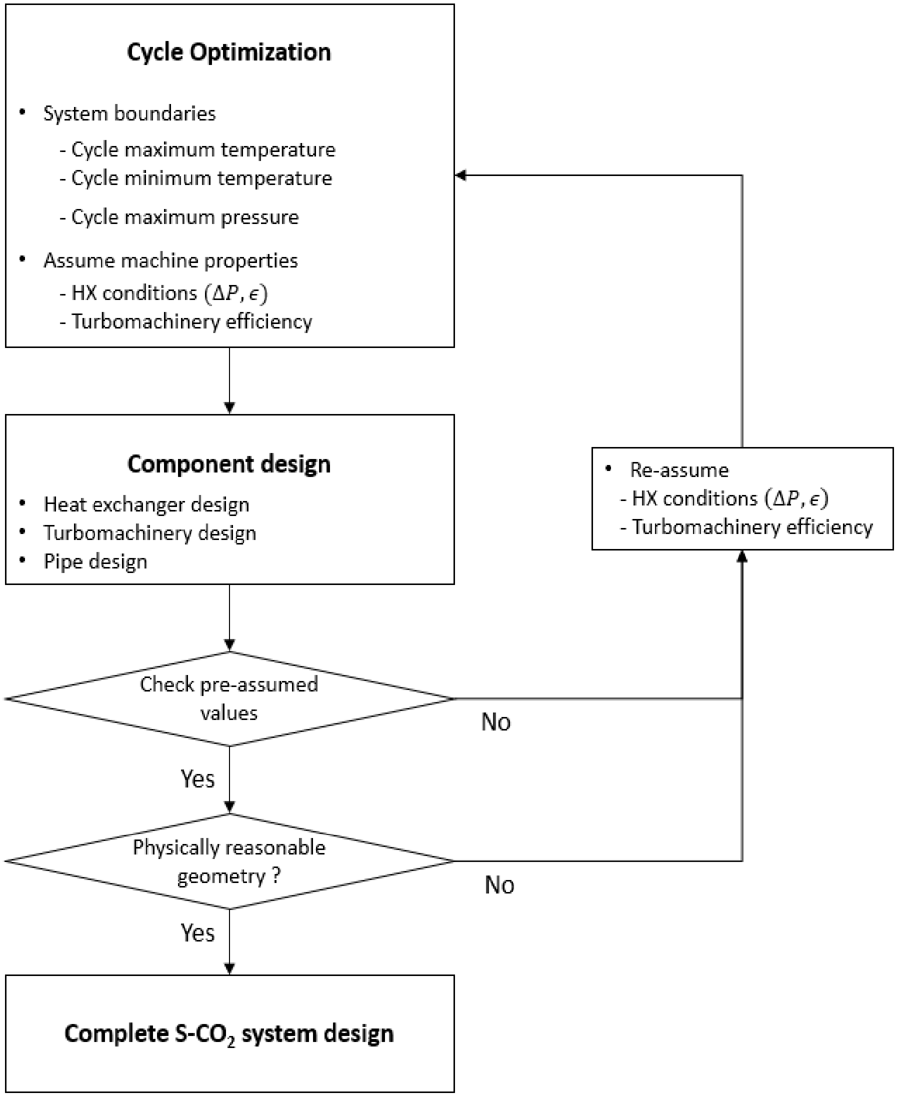


< S-CO_2 Recompression Cycle >

System Design

S-CO_2 system design

1. Cycle design
   - Optimized by KAIST-ESCA code.
   - Cycle net power is 97.6 MW with thermal efficiency of 29.6 %.
2. Turbomachinery design
   - Designed by KAIST-TMD code.
   - Axial type and single shaft configuration.
   - Geometry and off-design performance map are derived
3. Heat exchanger design
   - Conducted by KAIST-HXD code.
   - Designed as PCHE (IHX, HTR, and LTR) & Shell and tube (PC)
4. Pipe design
   - Performed by using the optimal flow velocity and ASME standards.

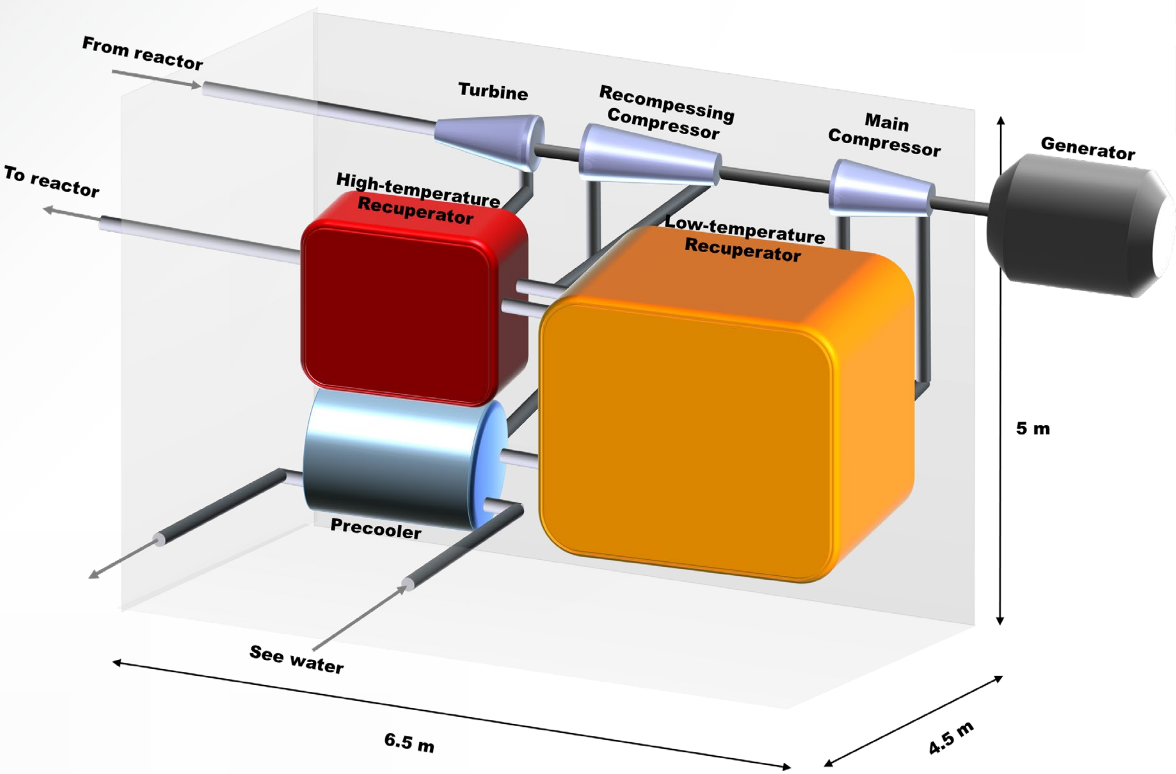


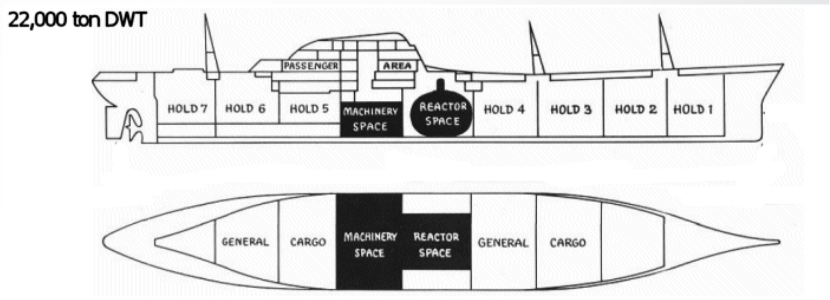
< S-CO_2 system design procedure >

System Design

$S\text{-}CO_2$ system design

Configuration of S-CO2 power conversion system





< Size comparison of machinery room>

	NS Savannah	Proposed system
Thermal power	74 MW_{th}	330 MW_{th}
PCS	Steam cycle (9-stage HPT, 7-stage LPT)	$S\text{-}CO_2$ recompression cycle
Length	**17 m**	**6.5 m**
Width	**24 m**	**4.5 m**
Height	**9.8 m**	**5 m**
Volume	**3998.4 m³**	**146.25 m³**

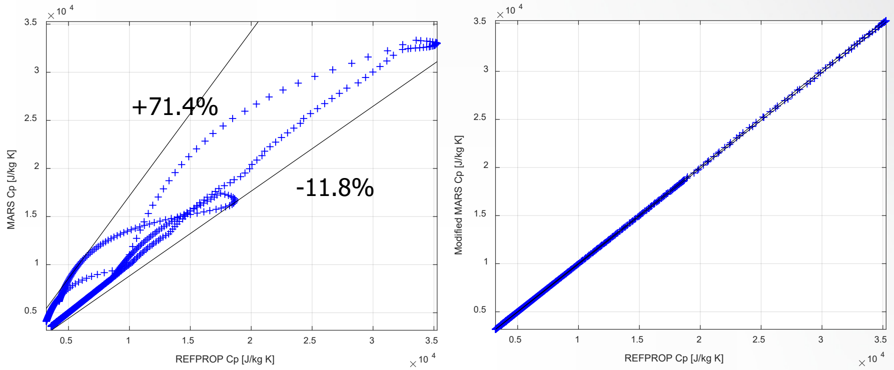
- The $S\text{-}CO_2$ power conversion system can be much smaller than the conventional shipboard steam power system.

Development of System Analysis Code

Improvements of MARS code

1. Physical properties of fluids

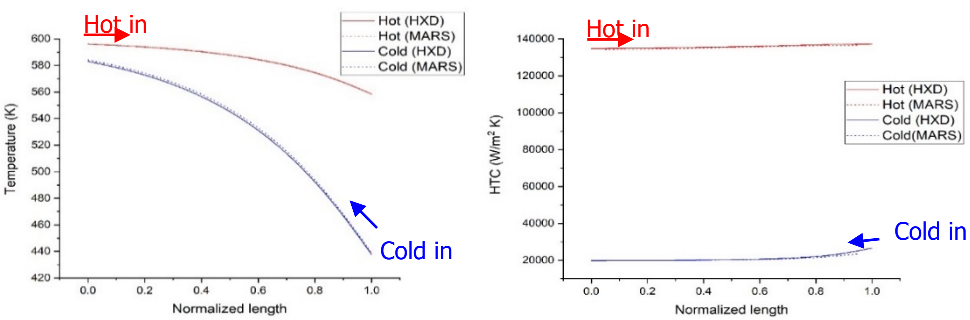
- The new property calculation option is added which directly import **NIST data** into MARS at every time step.
- It is possible to more accurately calculate the properties of CO_2 that exhibit **nonlinear** behavior near the critical point.



< Comparison of specific heat >

2. PCHE heat structure

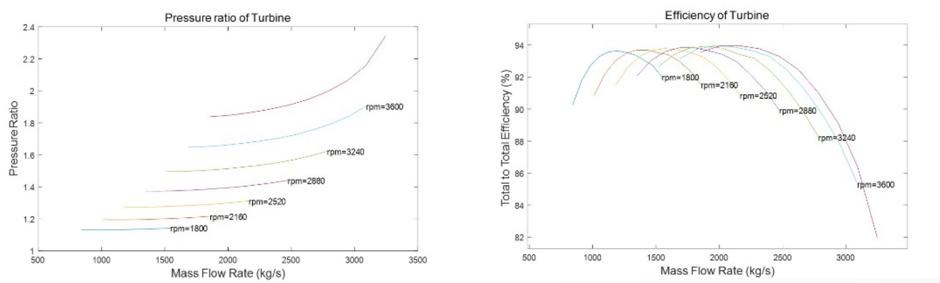
- There are several PCHE heat exchangers in the S-CO_2 system.
- For realistic transient behavior of heat exchangers, PCHE heat transfer correlation is added to heat structure sets in MARS code.



< Comparison of temperature & HTC profile >

3. Turbomachinery model

- The new turbomachinery models are added to accurately simulate S-CO_2 turbomachinery.
- CEA similitude model is implemented for dimension reduction in finding off-design pressure ratio and isentropic efficiency.



< Turbomachinery off-design performance map>

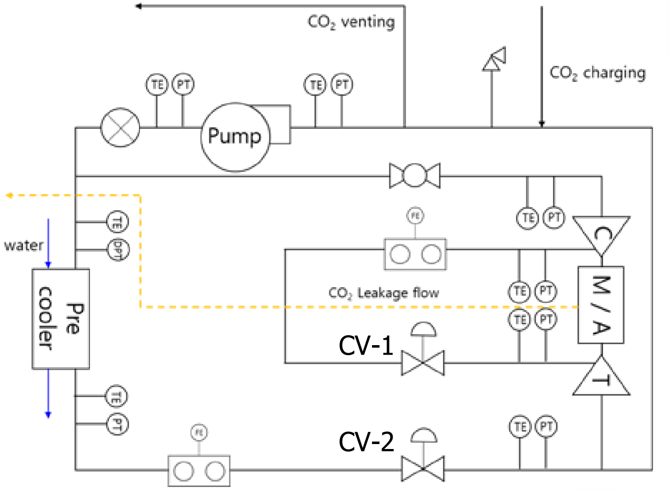
Development of System Analysis Code

Code validation with experimental data

Compressor test facility in KAIST

- To demonstrate the reliability of the newly developed code, code validation has been performed with experimental data.
- The selected experimental loop is the S-CO_2 compressor test facility installed in KAIST.
- *Experimental data generated during **compressor performance test** is used for code validation.
- Although equipped with TAC, the compressor performance test was performed without the turbine.

< S-CO_2 compressor test loop in KAIST >



< Schematic diagram of the facility >

Design conditions of KAIST compressor

Pressure ratio	1.3
Inlet total temperature	31.36 ℃
Inlet total pressure	7599 kPa
Efficiency	56 %
Rotating speed	40,000 rpm

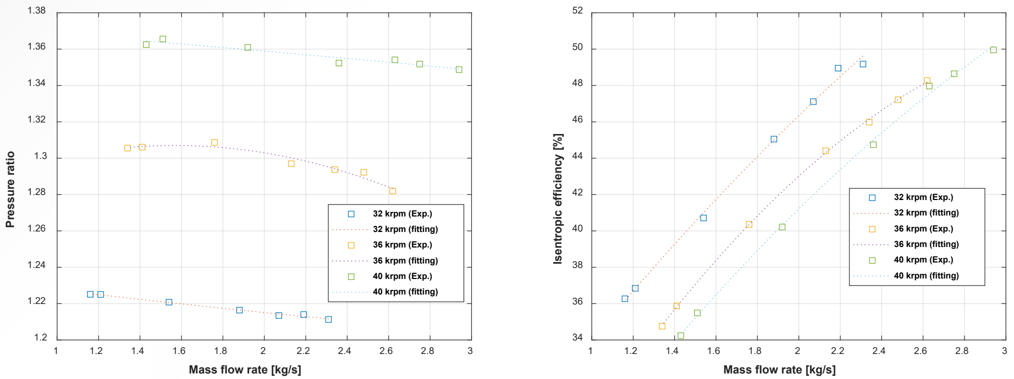
*Cho et al., "Optimum loss models for performance prediction of supercritical CO_2 centrifugal compressor (2020)

Development of System Analysis Code

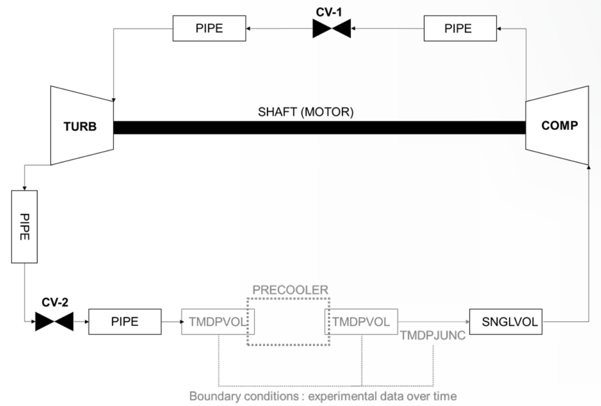
Code validation with experimental data

Modeling of experiment loop

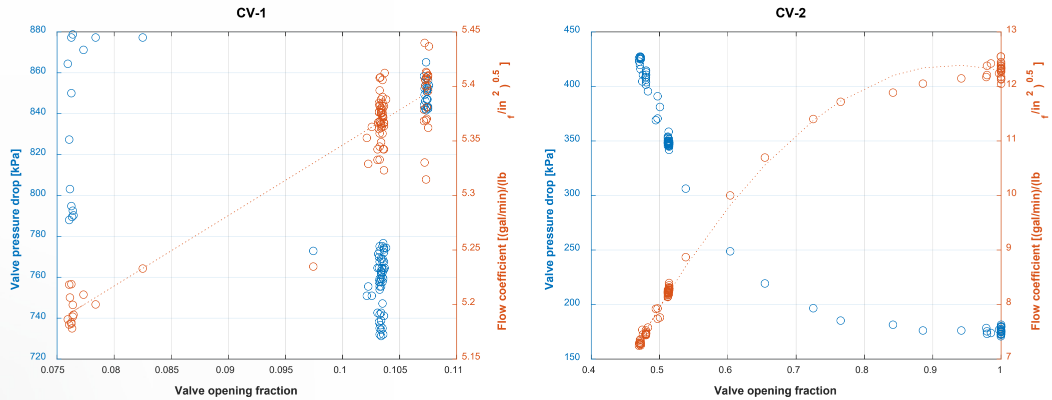
- The cooling part was treated as boundary conditions and only the S-CO_2 flow part was modeled.
- The compressor is modeled with the off-design performance map derived from the performance test results.
- Two control valves were modeled as a servo valve, and the flow coefficient for the normalized valve area of each valve was calculated from the measured pressure loss.



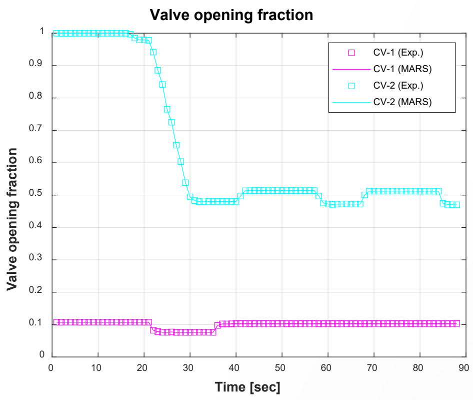
< Off-design performance map derived from compressor tests >



< Nodalization of SCIEL MARS model >



< Pressure drop and flow coefficient for normalized area of each control valve >



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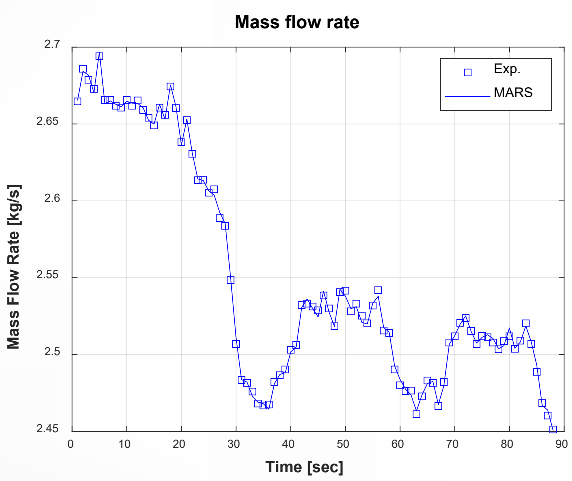
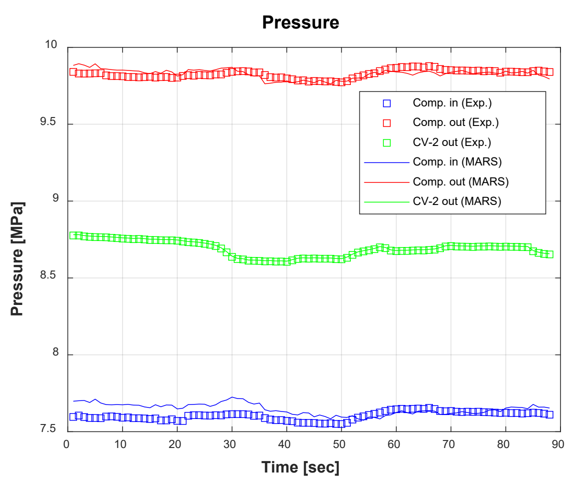
Development of System Analysis Code

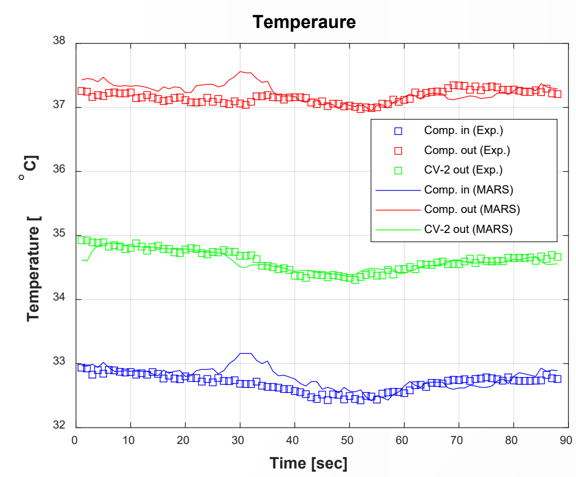
Code validation with experimental data

Results

- Total compressor mass flow rate, P&T of compressor inlet, compressor outlet, CV-2 outlet are compared to experimental data.
- In some areas, there is a slight difference in temperature and pressure values at the inlet and the outlet of the compressor.
- This seems to be caused by the uncertainty propagation of temperature and pressure to enthalpy since the experiment was performed in a region very close to the critical point.
- This is expected to be confirmed again by simulating the experimental results in the region relatively far from the critical point.
- The simulated mass flow rate, pressure, and temperature show **generally good agreement** with the experimental results.







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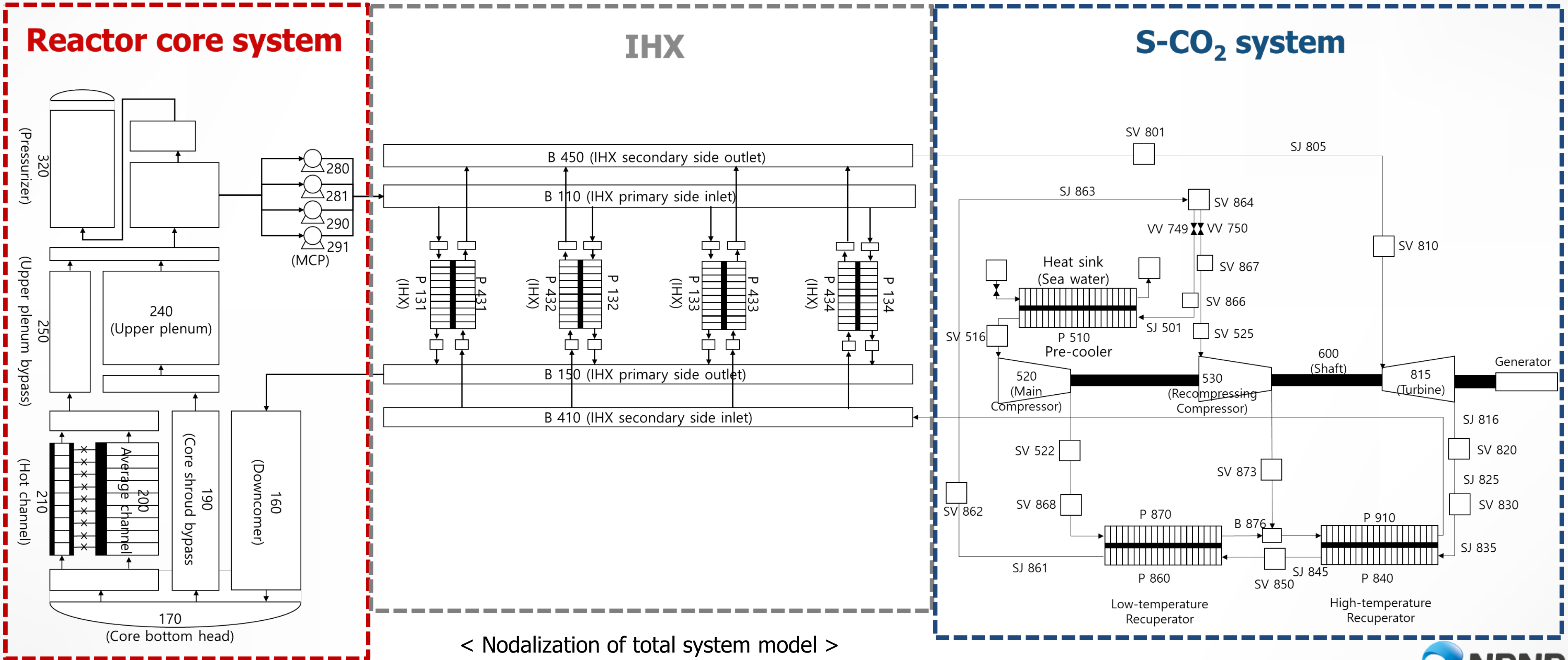
Development of System Analysis Code

Steady analysis

Steady state modeling with the developed code

- The primary side is modeled similar to the modeling of a conventional integral PWR. (4 MCPs, 1 PZR, 2 Core channels)
- IHXs are modeled in four trains to reduce the complexity of input deck. (1 train indicates 3 IHXs)
- S-CO_2 system is modeled with design values of each component including heat exchangers, turbomachinery, and pipe.
- Turbine, main compressor, recompressing compressor, and a generator are connected to single shaft.
- Each system is modeled as **fully closed loop** except heat sink side.



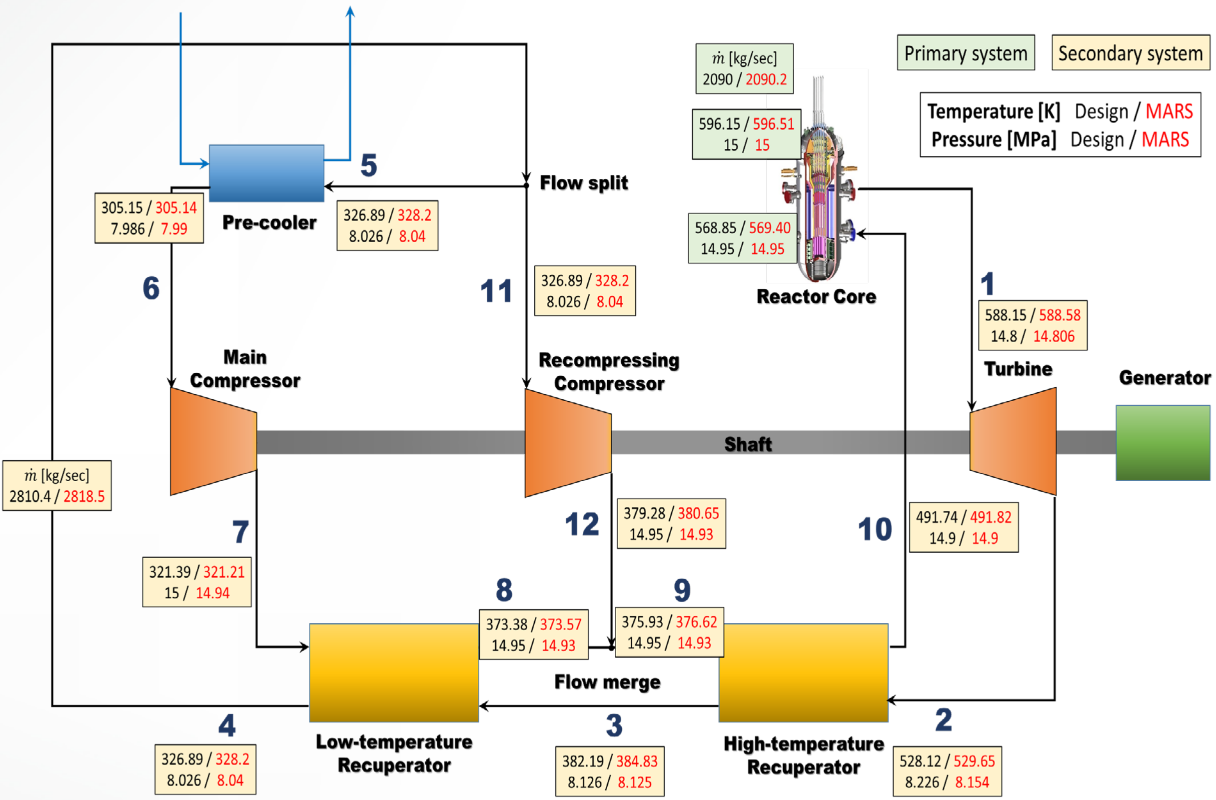
< Nodalization of total system model >

Development of System Analysis Code

Steady analysis

Steady state modeling with the developed code

- The error at each point is less than 1 %, indicating that the entire system is very accurately modeled with the developed code.



Primary System

	Property	Error (%)
Hot leg	T	0.06
	P	0.0
Cold leg	T	0.097
	P	0.0
-	$\dot{m}$	0.01

Secondary System

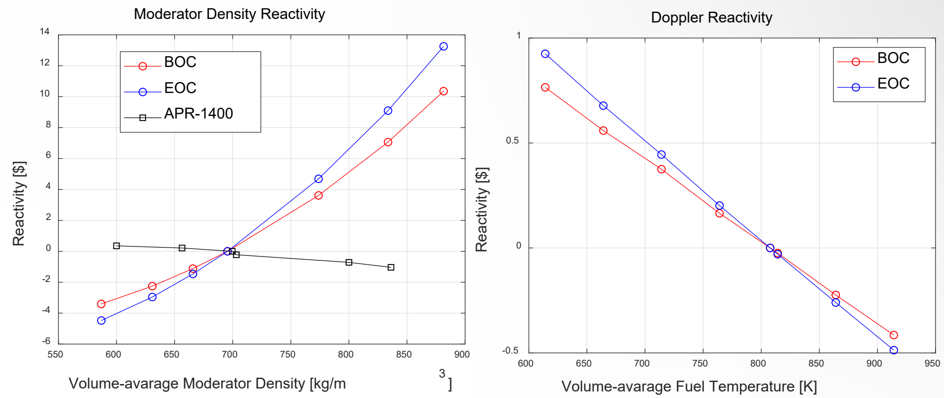
	Property	Error (%)		Property	Error (%)
1	T	0.073	7	T	0.056
	P	0.04		P	0.4
2	T	0.3	8	T	0.05
	P	0.87		P	0.13
3	T	0.69	9	T	0.18
	P	0.012		P	0.13
4	T	0.4	10	T	0.016
	P	0.17		P	0.0
5	T	0.4	11	T	0.4
	P	0.17		P	0.17
6	T	0.003	12	T	0.36
	P	0.05		P	0.13
-	$\dot{m}$	0.29	-	FSR	0.0

Transient Analysis

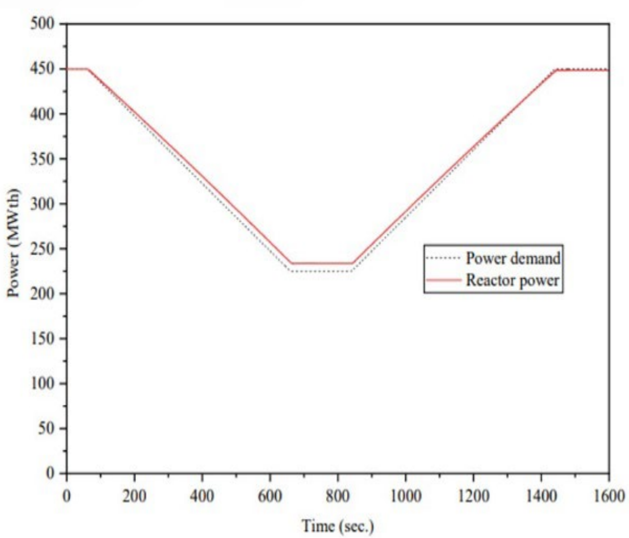
Development of control logic

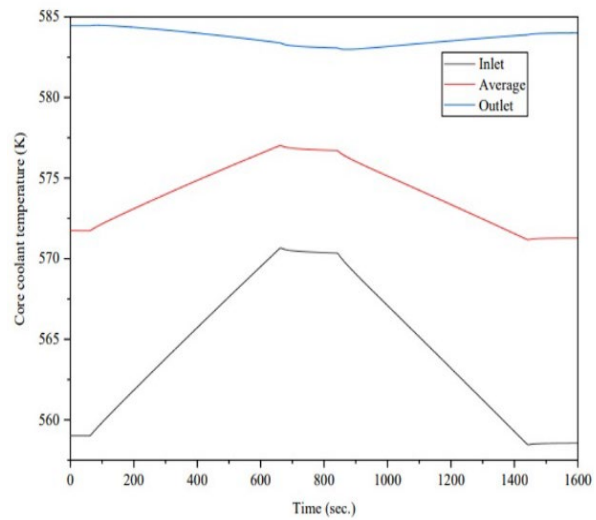
Primary system – Autonomous load following

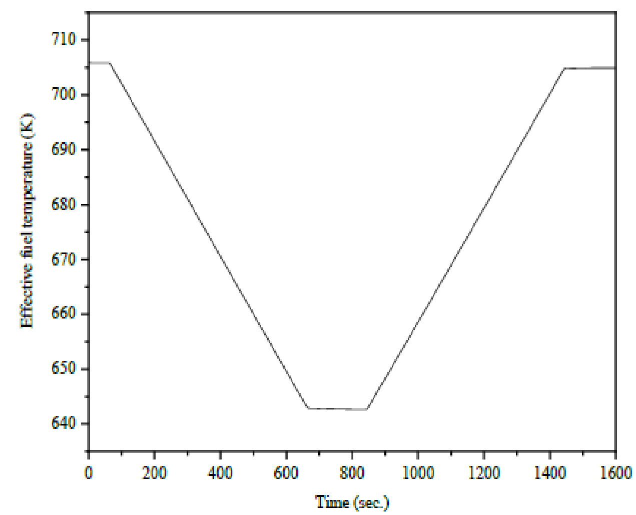
- The primary system is designed as soluble boron free reactor which has strongly negative moderator temperature coefficient.
- Previously, ATOM reactor exhibits autonomous load following by **only reactor coefficients** under the situation of 100% - 50% - 100% load change operation with 5%/min.
- Transient analyses are investigated whether the reactor power stably follows the load change **without control rods** moving even under very fast ramp rates.



< ATOM reactor feedback coefficients >







Ahmed et al., "Three-dimensional Simulations of Passively Autonomous Load-follow Operation", Transactions of the Korean Nuclear Society Autumn Meeting (2019)

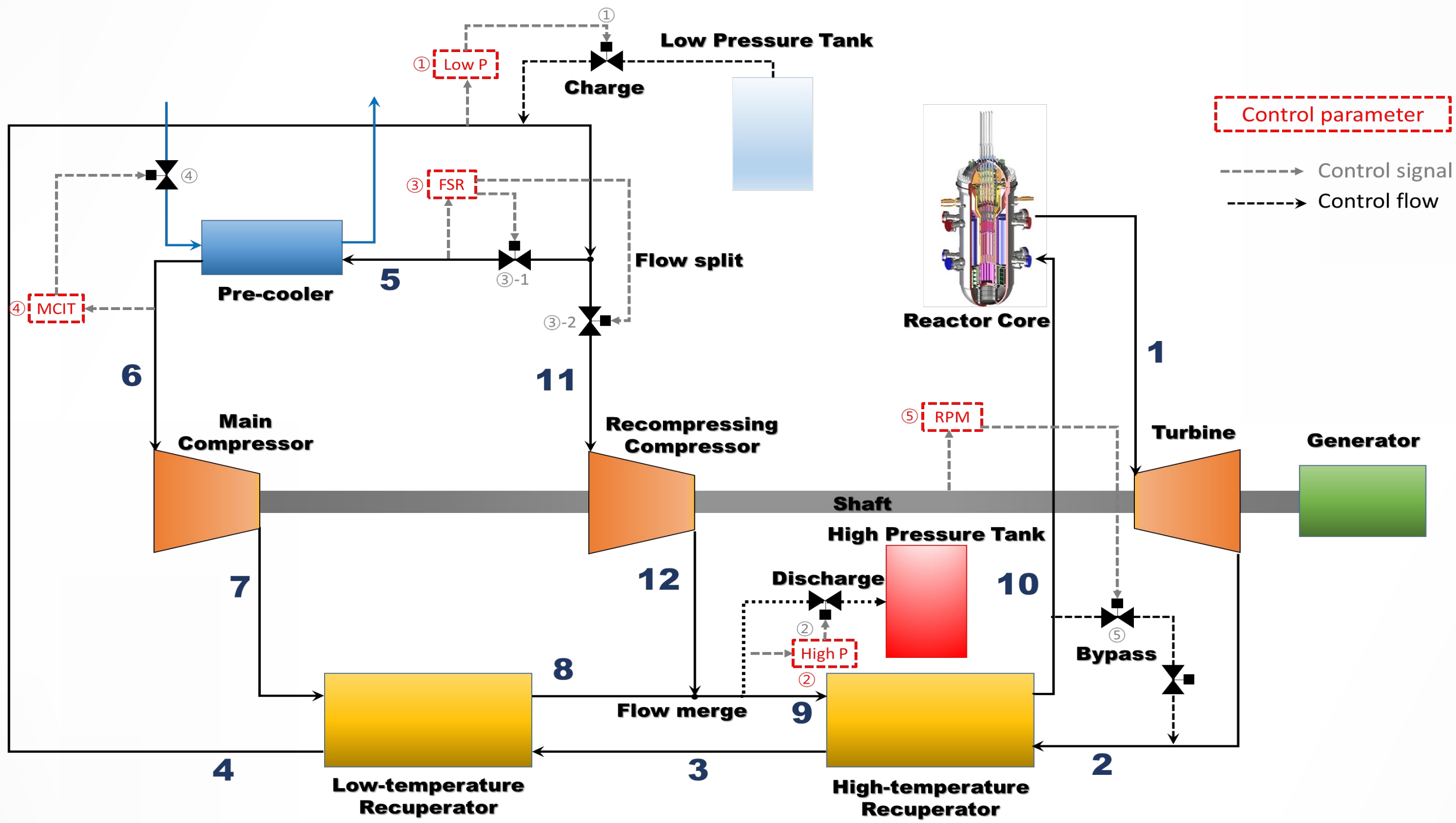
Transient Analysis

Development of control logic

Secondary system

- General S-CO_2 control strategy responding to load change : turbine bypass assisted by inventory control
- Turbine bypass : rapid response but linearly decreased efficiency
- Inventory control : slow response and requires large volume of inventory tank but compensate off design cycle efficiency

✓ Inventory control is not suitable for nuclear propulsion system -> main mechanism for the proposed system is **turbine bypass**



< Control scheme for the S-CO_2 system >

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Transient Analysis

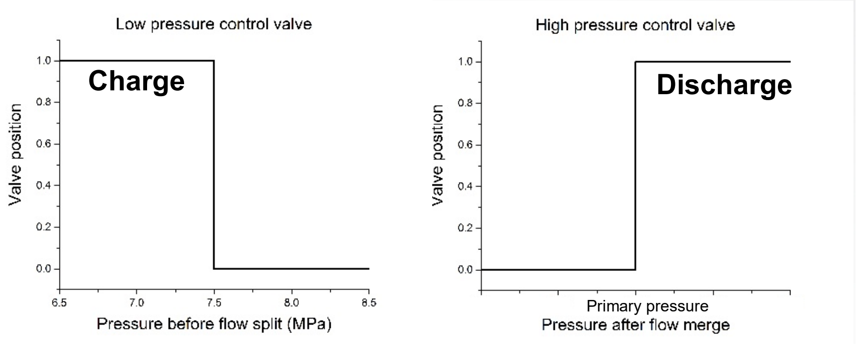
Development of control logic

Secondary system

① Low pressure control to keep the cycle minimum pressure above to **critical pressure**

② High pressure control to not exceed **the primary side pressure**

- Low pressure valve open signal : $P_{split} < 7.5\ MPa$
- High pressure valve open signal : $P_{merge} > P_{primary}$



③ Flow split ratio control to maintain the **designed value** and prevent **compressor surge**

- Flow split ratio error activates two motor valves which operate oppositely.
- Limit surge margin = 10%

$$E_{FSR} = FSR_{off} - \frac{\dot{m}_{MC}}{\dot{m}_{total}},$$

FSR : Flow split ratio, SM : Surge margin

$$FSR_{off} = FSR_{design}, \quad if\ SM_{MC}\ \&\ SM_{RC} > SM_{limit}$$

$$FSR_{off} = FSR_{Design} \times \frac{SM_{limit}}{SM_{MC}}\left(or\ \frac{SM_{RC}}{SM_{limit}}\right), \quad if\ SM_{MC}(or\ SM_{RC}) < SM_{limit}$$

④ Main compressor inlet temperature control to not deviate significantly from the **critical temperature**.

- MCIT control is conducted by regulating the **mass flow rate of heat sink** depending on the error of MCIT.

$$E_{MCIT} = \frac{MCIT(t) - MCIT_{design}}{MCIT_{design}}$$

$$\dot{m}_{sink}^{p+1} = \dot{m}_{sink}^{p} \times E_{MICT}^{P}$$

Transient Analysis

Development of control logic

Secondary system

⑤ Shaft speed control to maintain electricity **frequency** and prevent shaft **overspeed**

- **Turbine bypass valve** is designed under the 10% step reduction from 100% load.
- Ziegler-Nichols rule is applied for tuning **PID** parameters.

Shaft dynamics

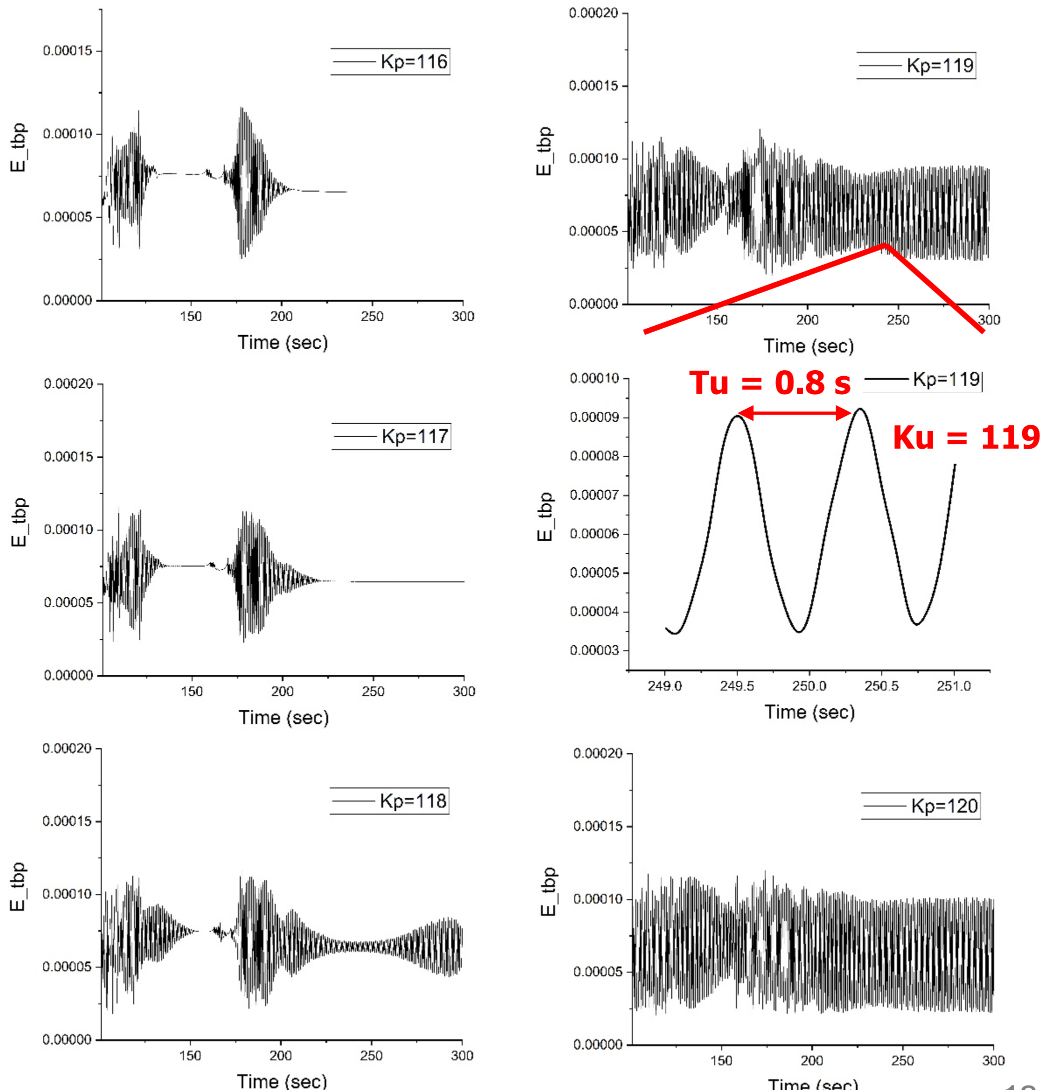
$$\frac{d\omega}{dt} = \frac{(W_{turbine} - W_{MC} - W_{RC})\varepsilon_{generator} - W_{generator}}{\sum_i I_i\,\omega}$$

$$E_{TBP} = \frac{\omega(t) - \omega_{design}}{\omega_{design}}$$

$$f_{TBP} = k_p E_{TBP} + k_i \int_0^t E_{TBP}(t)\,dt + k_d \frac{dE_{TBP}}{dt}$$

< Ziegler-Nichols method >

Control Type	K_p	K_i	K_d
P	$0.5K_u$	-	-
PI	$0.45K_u$	$0.54K_u/T_u$	-
PD	$0.8K_u$	-	$K_uT_u/10$
PID	$0.6K_u$	$1.2K_u/T_u$	$3K_uT_u/40$



Transient Analysis

Transient simulation

Transient scenarios

- Transient response is investigate under the **actual requirement** for nuclear merchant ships.
- These conditions have been determined with account taken of the maneuvering requirements normally expected of cargo ships.
- Total system should be stably operated under these fast load transients without **significant fluctuations of operational parameters**.
- Reactor safety variables and operational parameters are monitored: **FCT, PCT, MDNBR, Shaft speed, and compressor surge margins.**

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	Decrease (% steam flow)	**100% - 20% in 3s (26.7%/s)**	**100% - 10% in 1s (90%/s)**	**100% - 18% in 1s (82%/s)**

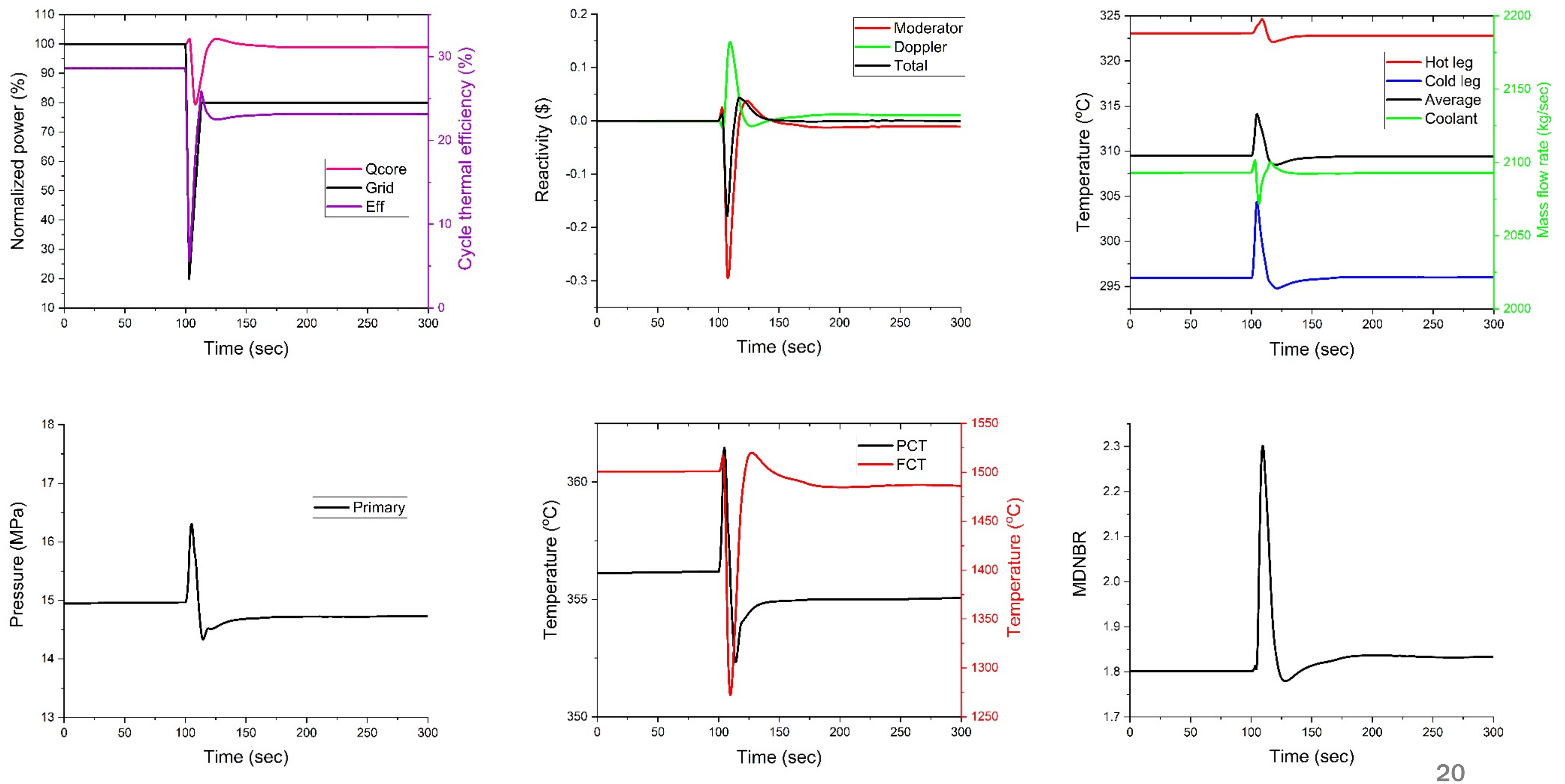
< Comparison of load change requirement for nuclear merchant ships >

Transient Analysis

NS-Savannah load change requirement

Core transient response

- Reactor system follows the load changes using only reactor coefficients.
- There are no safety related issues during load transients. (**Coolant temperature, pressure, PCT, FCT, and MDNBR**)

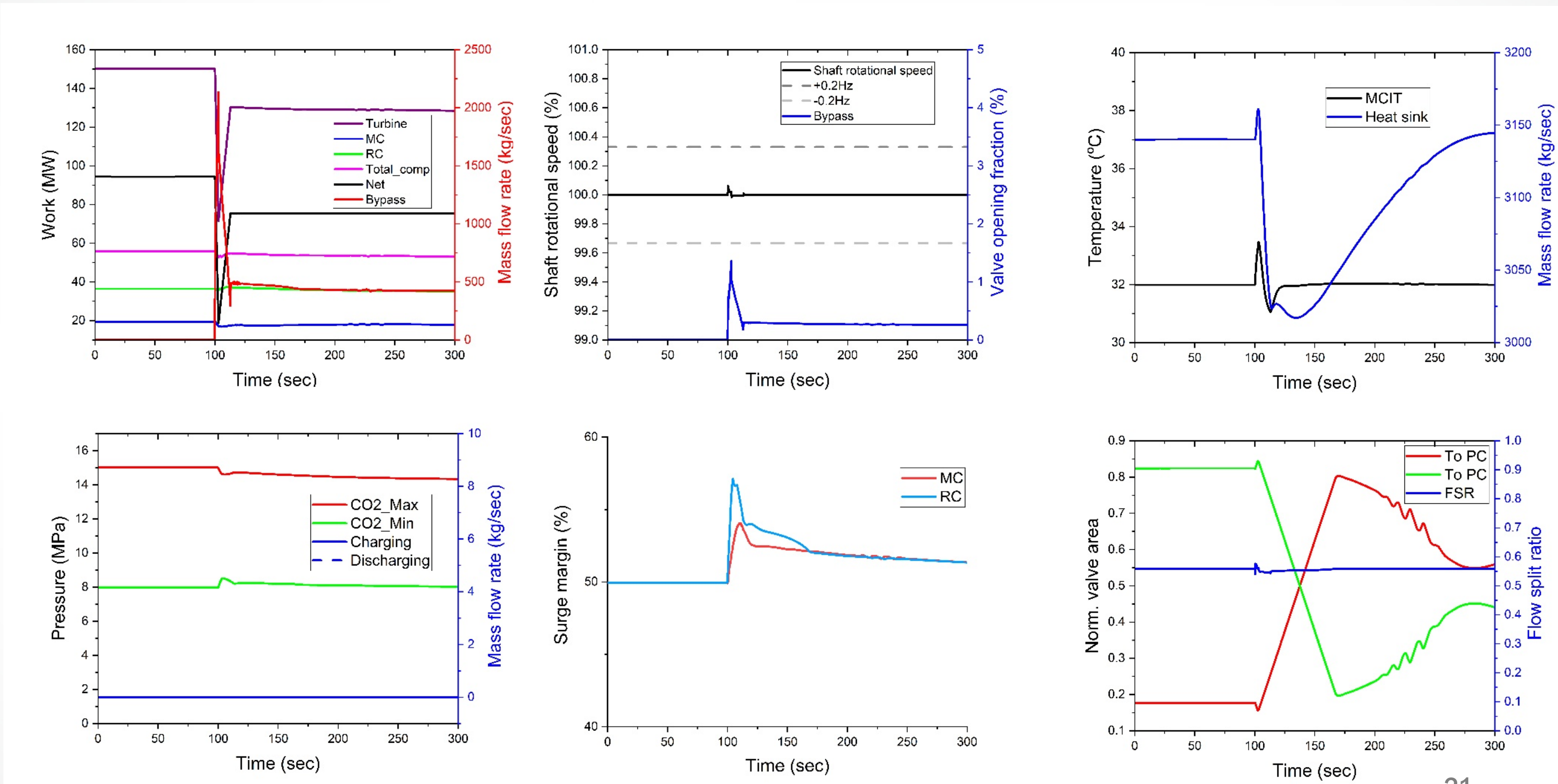


Transient Analysis

NS-Savannah load change requirement

S-CO_2 cycle transient response

- S-CO_2 power conversion system shows very fast response to load changes without severe fluctuation of control parameters.
- There are enough margins for shaft overspeed and compressor surge.



Transient Analysis

NS-Otto Hahn load change requirement

Core transient response

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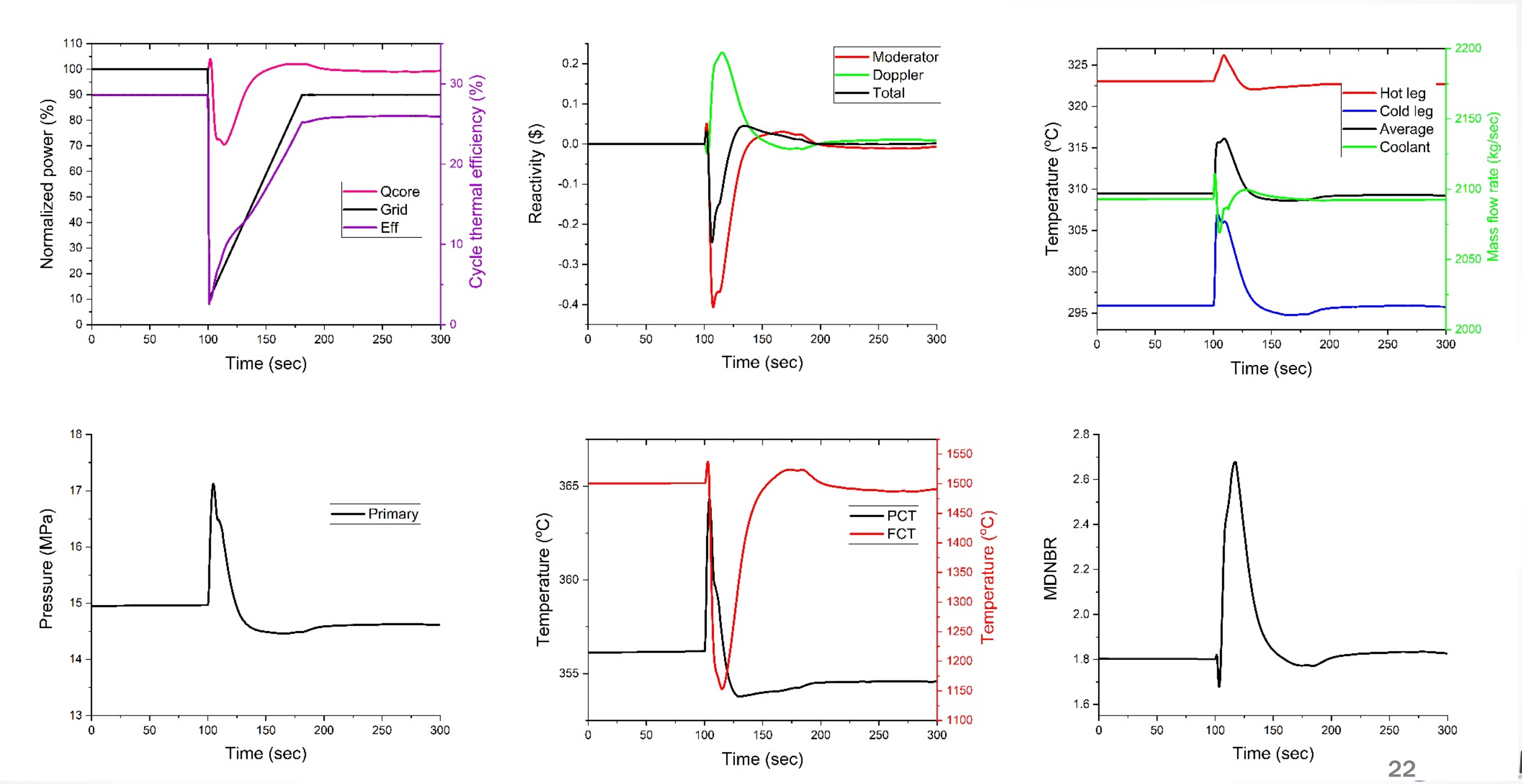

Transient Analysis

NS-Otto Hahn load change requirement

S-CO_2 cycle transient response

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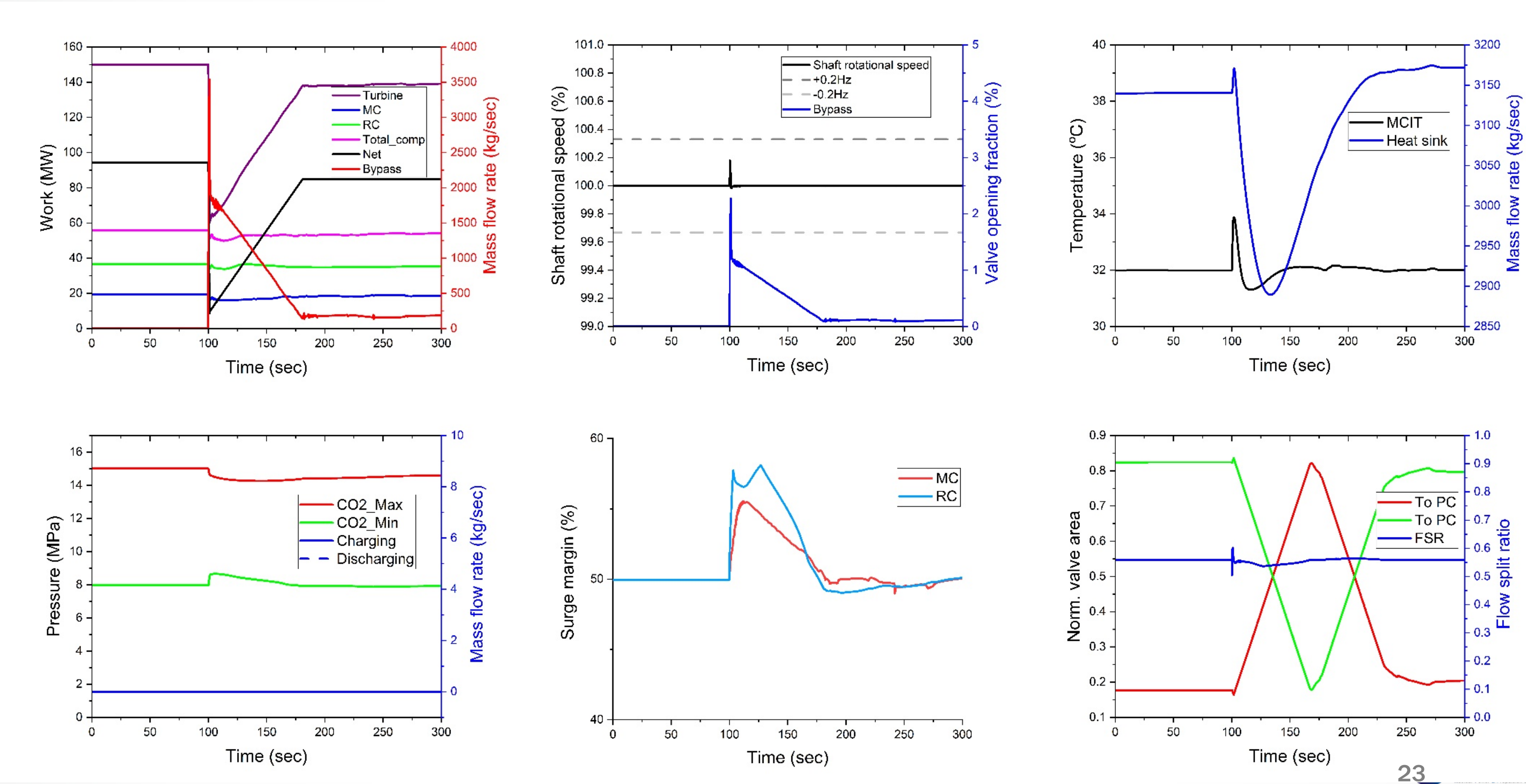
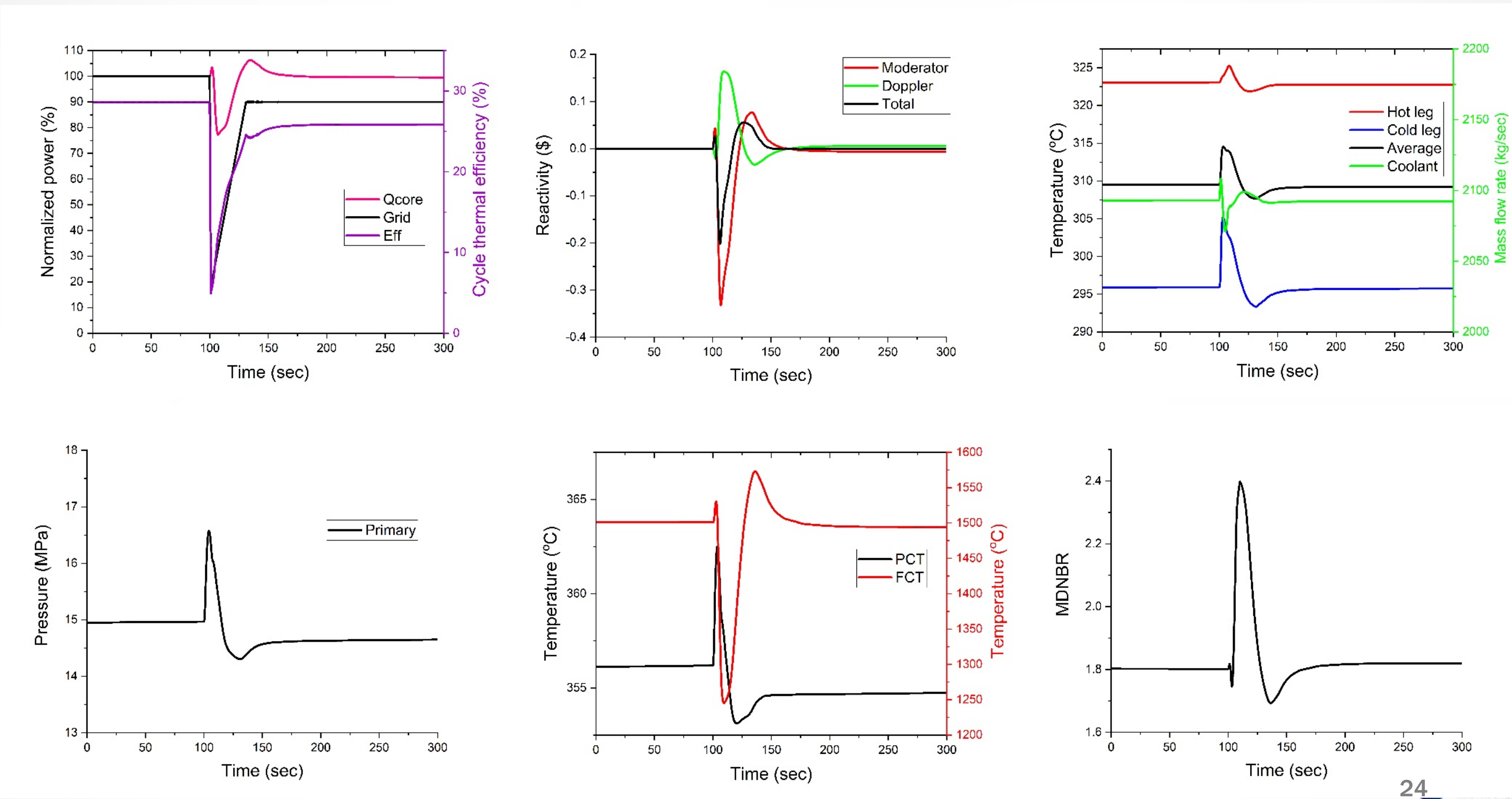


Transient Analysis

NS-Mutsu load change requirement

Core transient response

- Reactor system follows the load changes using only reactor coefficients.
- There are no safety related issues during load transients. (**Coolant temperature, pressure, PCT, FCT, and MDNBR**)

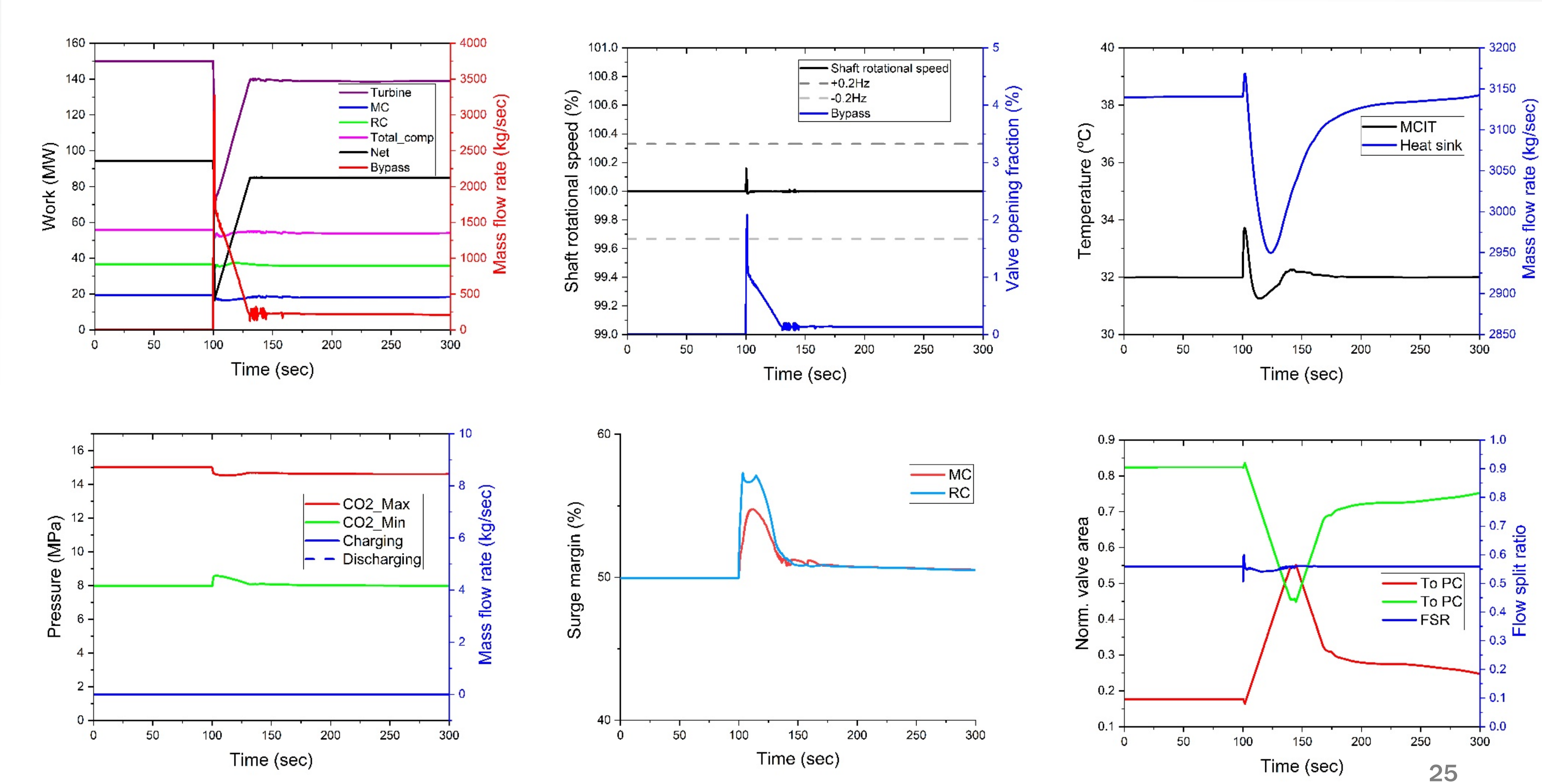


Transient Analysis

NS-Mutsu load change requirement

S-CO_2 cycle transient response

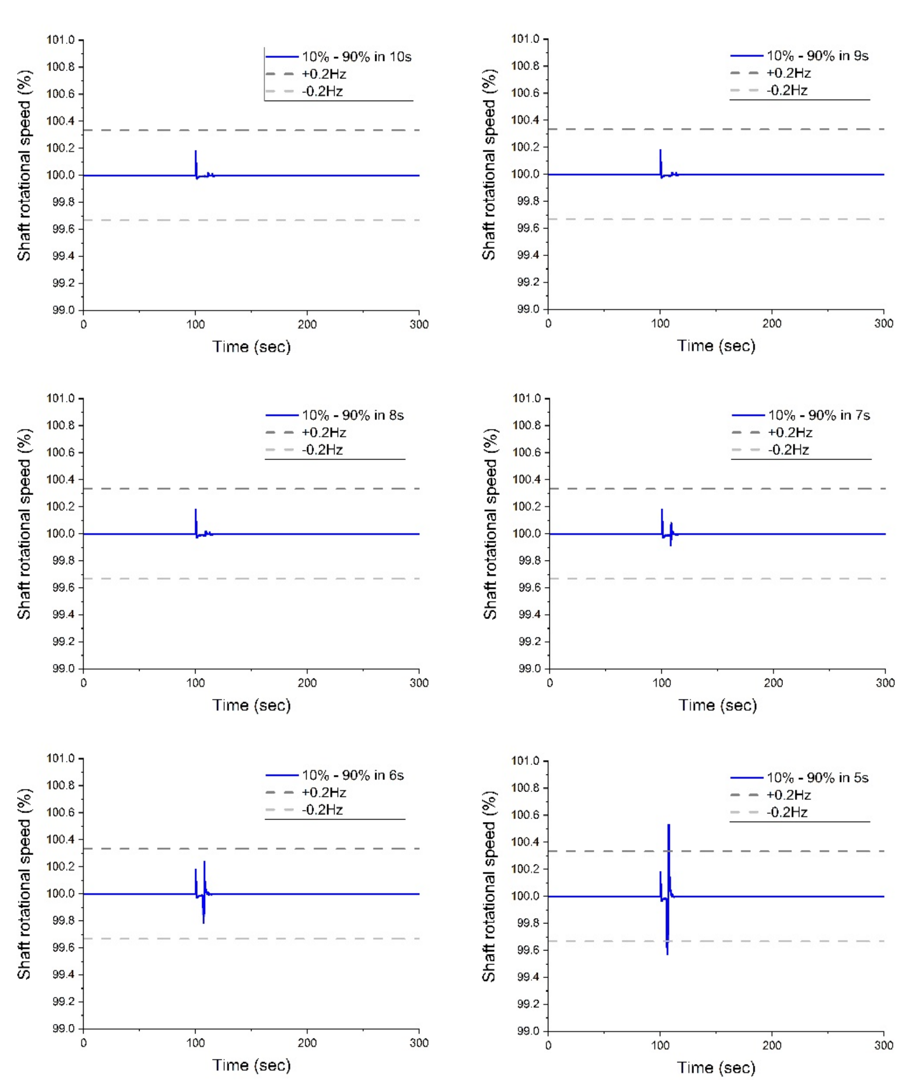
- S-CO_2 power conversion system shows very fast response to load changes without severe fluctuation of control parameters.
- There are enough margins for shaft overspeed and compressor surge.



Transient Analysis

Power maneuvering capability of the proposed system

Ramp rate test under 100% - 10% load reduction in 1sec



- Additionally, the proposed system is examined whether it can stably operate under **more severe load transients**
- Shaft speed is examined since it represents the response of S-CO_2 power conversion system
- The proposed system shows **better** power maneuvering capability than existing load change requirements.

Parameter		NS Savannah	NS Otto Hahn	NS Mutsu	Proposed system
Dead weight (tons)		9,900	14,079	14,079	228,149
Reactor thermal power [MW_{th}]		74	38	38	330
Cruising speed		21 knots (39 km/h)	17 knots (31 km/h)	17 knots (31 km/h)	18.5 knots (34.3 km/h)
Load change requirement	Increase	20%-80% in 10s (6%/s)	10%-100% in 90s (1%/s)	18%-90% in 30s (2.4%/s)	10%-90% in 8s (10%/s)
	Decrease	100%-20% in 3s (26.7%/s)	100%-10% in 1s (90%/s)	100%-18% in 1s (82%/s)	100%-10% in 1s (90%/s)

Transient Analysis

Effect of fission product poisoning

Poison reactivity feedback

- Small modular reactor is known to yield less poison reactivity feedback since its power density is generally smaller than that of large-sized pressurized water reactors.
- However, since the ship propulsion system operates under more severe load changes than land-based nuclear reactor, a preliminary analysis is conducted.
- Unfortunately, since MARS code dose not calculate the reactivity feedback from fission product poisoning, it is investigated using the simulation results from the **GAMMA+ code**.

Poisoning transients in GAMMA+ code

Reactivity of poison materials

$$\rho_{Xe} = -\frac{\sigma_a^{Xe} C_{Xe}/\Sigma_f}{\nu p \varepsilon}, \rho_{Sm} = -\frac{\sigma_a^{Sm} C_{Sm}/\Sigma_f}{\nu p \varepsilon}$$

σ_a : Microscopic Absorption cross section
Σ_f : Macroscopic fission cross section
ν : Neutron number per fission
p : Resonance escape probability
ε : Fast fission factor

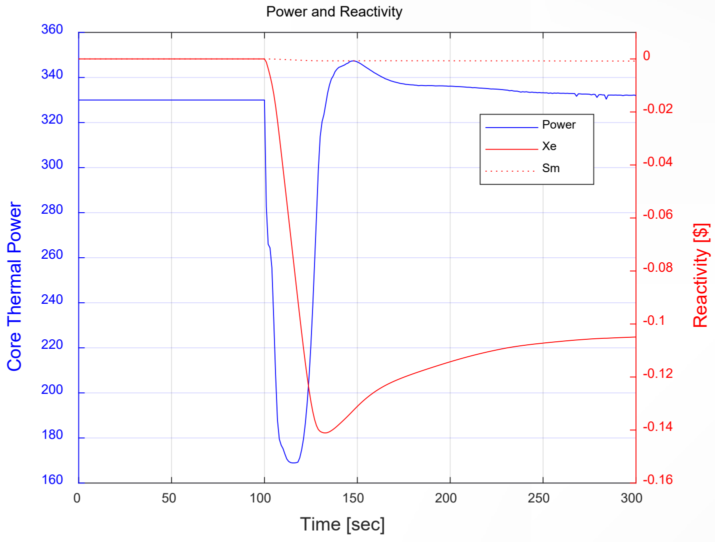
Decay chain for poison concentration dynamics

$$\frac{dC_I}{dt} = \gamma_I \Sigma_f \phi_T - \lambda_I C_I$$

$$\frac{dC_{Xe}}{dt} = \lambda_I C_I + \gamma_{Xe} \Sigma_f \phi_T - \lambda_{Xe} C_{Xe} - \sigma_a^{Xe} \phi_T C_{Xe}$$

$$\frac{dC_{Pm}}{dt} = \gamma_{Pm} \Sigma_f \phi_T - \lambda_{Pm} C_{Pm}$$

$$\frac{dC_{Sm}}{dt} = \lambda_{Pm} C_{Pm} - \sigma_a^{Sm} \phi_T C_{Sm}$$



< Core thermal power and poison reactivity simulated by GAMMA+ code >

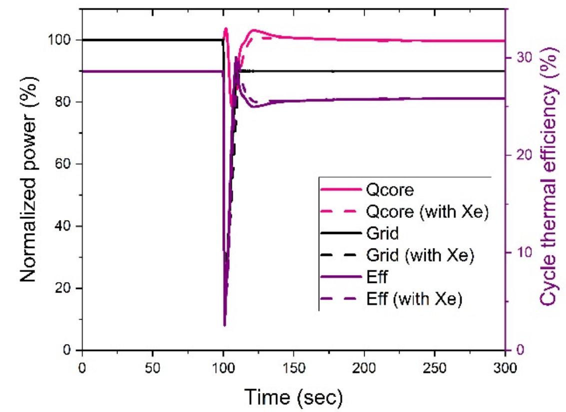
NPNP

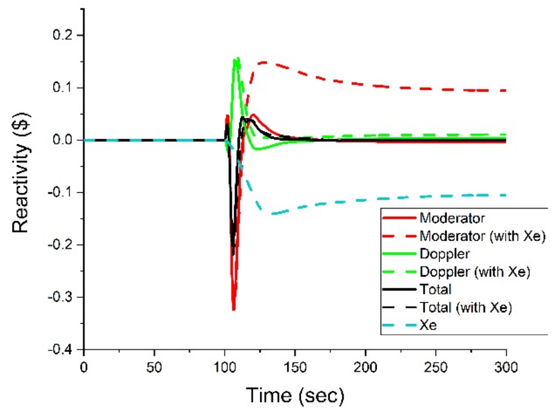
Transient Analysis

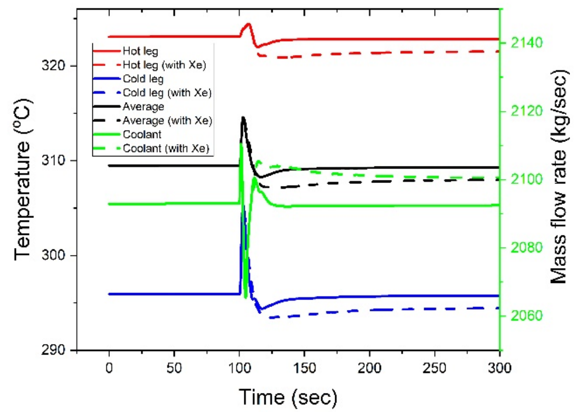
Effect of fission product poisoning

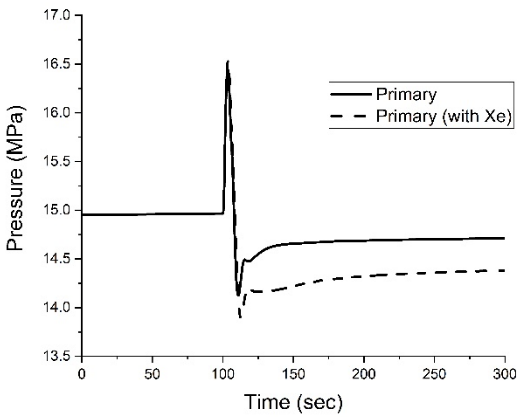
Core transient response

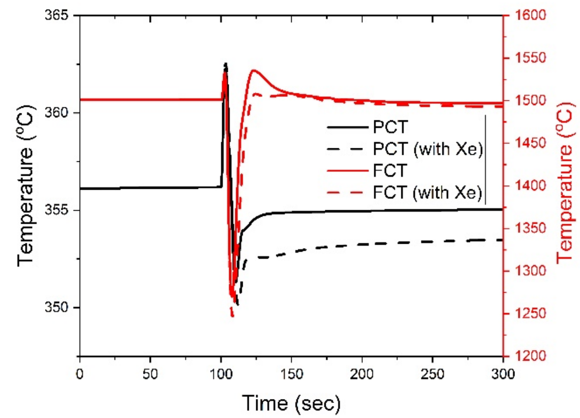
- Even if Xenon effect is considered, the proposed system shows stable response under fast load changes.
- As a result, ATOM-S + S-CO_2 system can be operated under severe load transients required for ship propulsion.

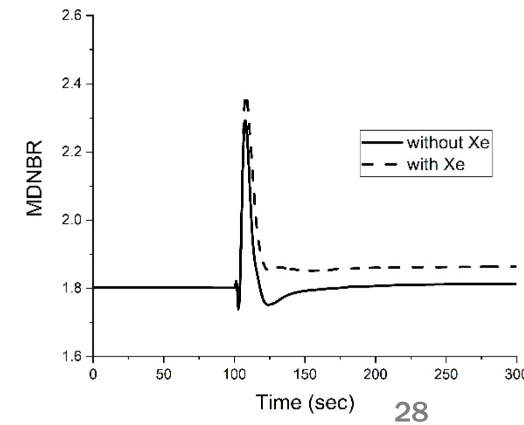












Summary and Conclusion

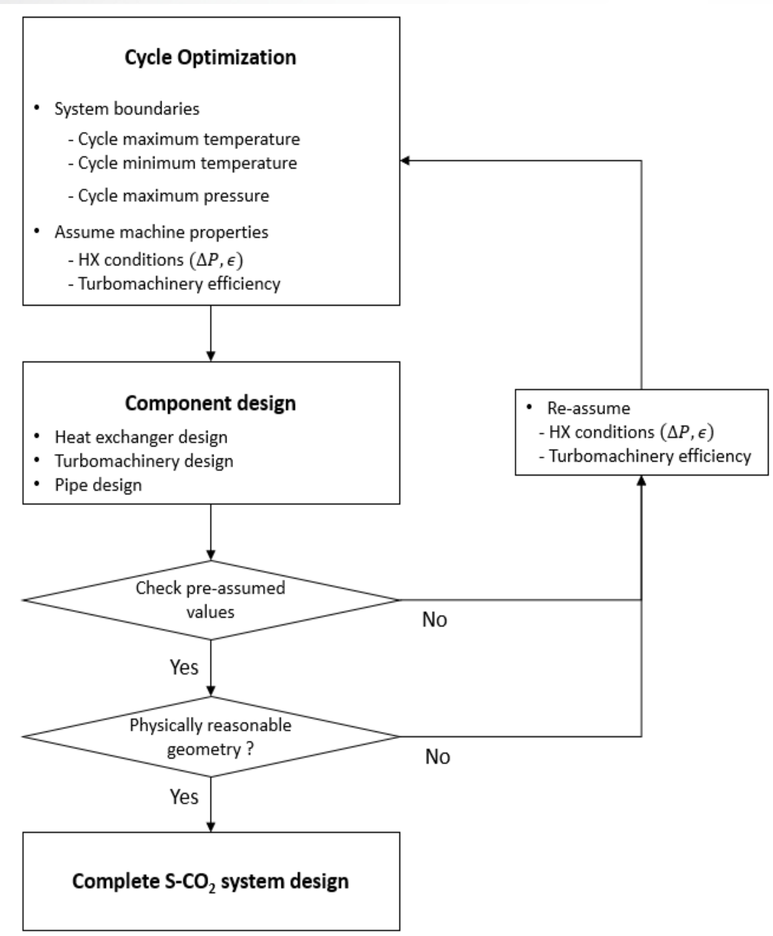
- For more economically efficient nuclear propulsion system, the S-CO_2 cycle is proposed as the power conversion system for marine pressurized water reactor.
- Reactor primary system is conceptually referred to thermal characteristics of SMART reactor and reactor kinetics of ATOM reactor. (ATOM-S)
- The S-CO_2 power conversion system is designed under ATOM-S conditions including cycle design, component design, and pipe design. The size of power conversion system is reduced compared to conventional shipboard steam power system.
- To accurately conduct transient simulations, the system analysis code is developed based on the MARS code. After code validation with experimental data of S-CO_2 compressor test loop in KAIST, steady state input deck of total system is very accurately modeled.
- Control strategy for ship propulsion system is developed and each controller is designed.
- To investigate applicability of total system to nuclear propulsion system, transient simulations has been performed under actual load change requirements of the nuclear merchant ships. As a result, it is verified that the proposed system exhibits fast and stable response under ship's load change requirements even if the effect of Xenon transients is considered.

Thank you for your attention

Q & A

System Design

Cycle design



< S-CO2 system design procedure >

Core thermal power [MW_{th}]	330	Primary system conditions
Core Coolant Flow rate [kg/sec]	2090	
Pressurizer pressure [MPa]	15	
Core inlet temperature [℃]	296	
Core outlet temperature [℃]	323	
Maximum pressure [MPa]	15	Secondary System boundaries
Maximum temperature [℃]	315	
Minimum temperature [℃]	32	
IHX pressure drop [kPa]	100	Assumed mechanical properties
High temperature recuperator hot side pressure drop [kPa]	100	
High temperature recuperator cold side pressure drop [kPa]	50	
Low temperature recuperator hot side pressure drop [kPa]	100	
Low temperature recuperator cold side pressure drop [kPa]	50	
High temperature recuperator effectiveness [%]	95	
Low temperature recuperator effectiveness [%]	90	
Turbine efficiency [%]	0.92	
Main compressor efficiency [%]	0.85	
Recompressing compressor efficiency [%]	0.88	
Turbine expansion ratio	1.799	Optimization results from KAIST-ESCA code
Flow split ratio [%]	55.857	
Turbine work [MW_e]	153.58	Cycle design results
Main compressor work [MW_e]	18.79	
Recompressing compressor work [MW_e]	37.2	
Cycle net work [MW_e]	97.6	
Cycle thermal efficiency [%]	29.58	

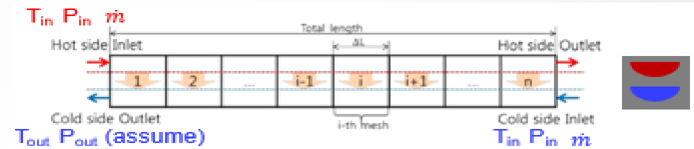
< Cycle design results >

System Design

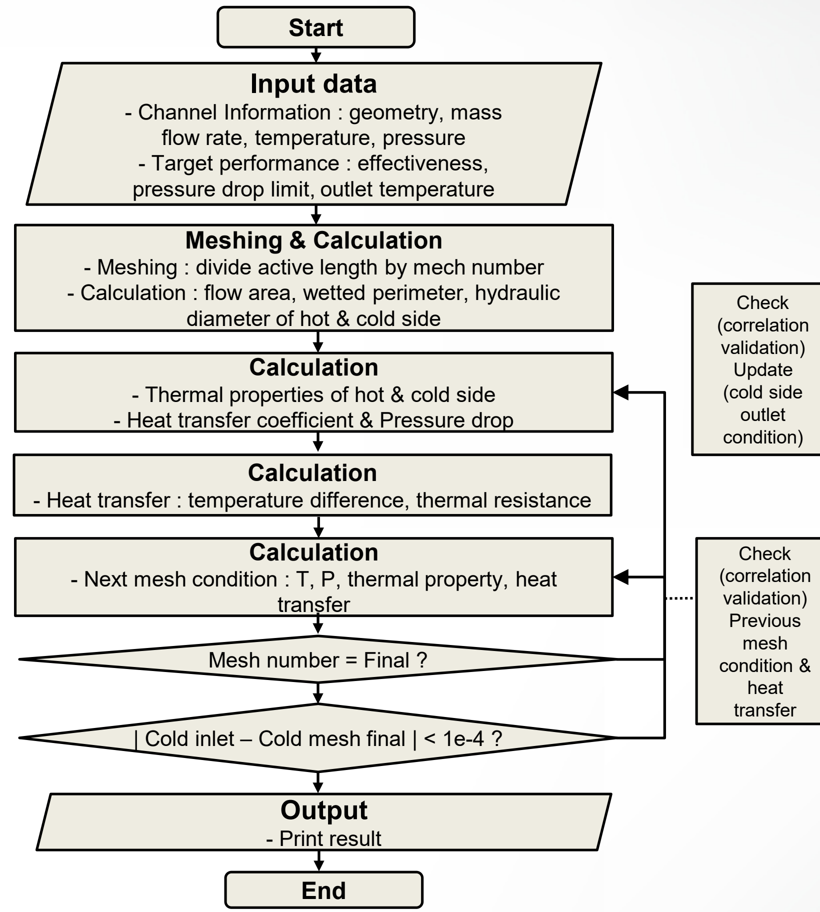
Component design

Heat exchanger

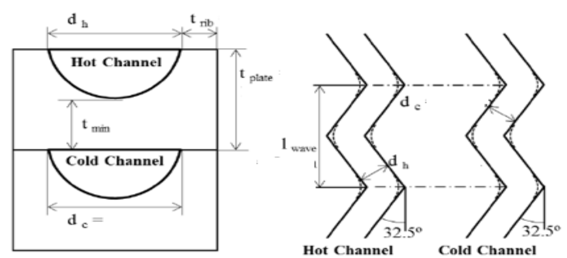
- IHX, HTR, LTR are designed to Printed Circuit Heat Exchanger (PCHE) due to its high performance and compactness.
- PC was designed as the shell and tube heat exchanger considering sea water condition
- KAIST-HXD (Heat eXchanger Design) code was used.
- PCHE Correlations
  : S. G. Kim (2,000 < Re < 58,000, 0.7 < Pr < 1.0)
  $$Nu = 0.0292Re^{0.8137}, f = 0.2515Re^{-0.2031}$$
- Shell and tube Correlations
  : Gnielinski (3,000 < Re < 5×10^6, 0.5 < Pr < 2000)
  $$Nu = \frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)^{1/2}(Pr^{2/3}-1)}, f = (0.79\,ln(Re) - 1.64)^{-2}$$



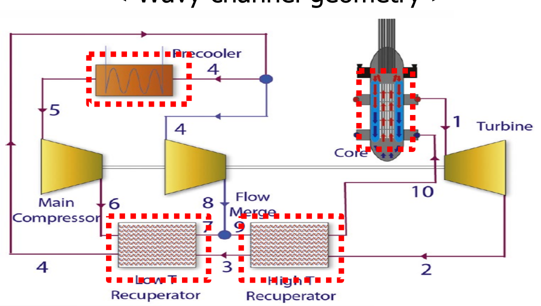
< Concept of Channel Nodalization in KAIST-HXD code >



< KAIST-HXD Algorithm >



< Wavy channel geometry >



< HX location >

< Prandtl number profile >

HX	Location	Pr
IHX	Hot in	0.847
	Hot out	0.958
	Cold in	0.934
	Cold out	0.799
HTR	Hot in	0.78
	Hot out	0.846
	Cold in	1.147
	Cold out	0.934
LTR	Hot in	0.846
	Hot out	1.246
	Cold in	1.9
	Cold out	1.16
PC	Hot in	1.246
	Hot out	6.089
	Cold in	7.0
	Cold out	4.34

Kim et al., CFD aided approach to design printed circuit heat exchangers for supercritical CO2 Brayton cycle application (2016)
I.H. Kim, "Experimental and Numerical Investigations of Thermal-hydraulic Characteristics for the Design of a Printed Circuit Heat Exchanger (PCHE) in HTGRs," Doctoral dissertation, Korea Advanced Institute of Science and Technology (2012).
Baik et al., Verification of Heat Exchanger Design Code KAIST-HXD by Experiment (2014)

System Design

Component design

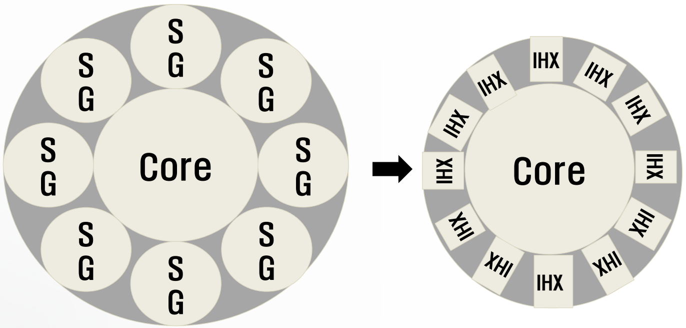
Heat exchangers

< Design conditions of SMART Helical S.G >

Parameters	Helical S.G
Mass flow rate [kg/sec]	261
Primary inlet T [°C]	323
Primary outlet T [°C]	294.5
Primary inlet P [MPa]	15
Primary pressure drop [kPa]	**55**

< Size of Helical S.G and IHX >

	Helical S.G	PCHE IHX
Total # of HX	8	12
Width [cm]	134	80.446
Length [cm]	134	77.2
Height [cm]	600	80.446
Volume [m³]	8.58	0.592



< Design Results of Heat Exchangers >

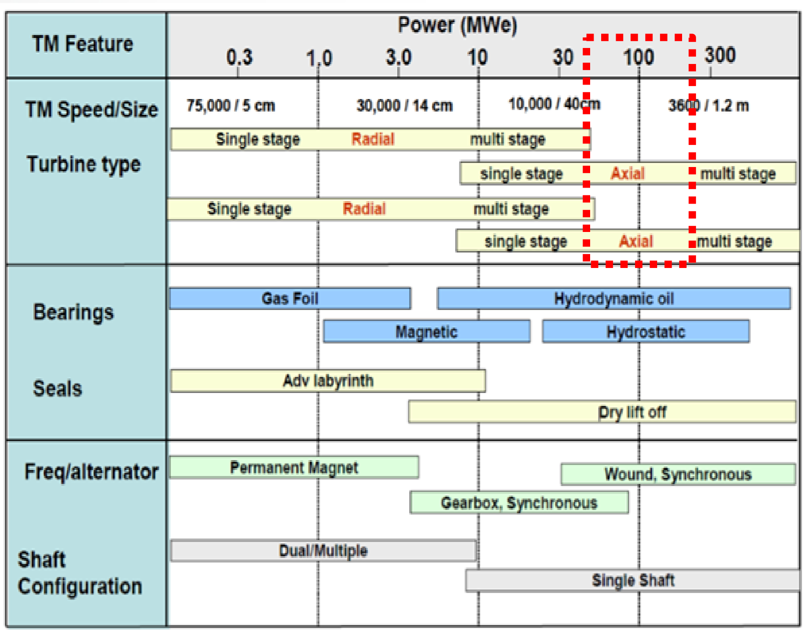
	IHX (1ea)	HTR (1ea)	LTR	PC
Type	PCHE	PCHE	PCHE	Shell and tube
No. of HX	**12**	**4**	1	1
No. of mesh	200	200	200	200
Heat load [MW]	27.5	119.67	241.99	232.4
Hot fluid	Water (coolant)	CO_2	CO_2	CO_2
Cold fluid	CO_2	CO_2	CO_2	Water (see water)
Material	SS316L	SS316L	SS316L	Inconel 625
Hot channel D [mm]	5 (semi-circular)	5 (semi-circular)	5 (semi-circular)	1 (circular tube)
Cold channel D [mm]	5 (semi-circular)	5 (semi-circular)	5 (semi-circular)	8.2 (pitch)
Hot channel No.	12000	141000	650000	185000
Cold channel No.	24000	141000	325000	185000
Hot side Avg. Re #	54780	68691	66659	137943
Cold side Avg. Re #	106698	59227	38310	2629
ΔP_{Hot} **[kPa]**	**55**	104.9	106.2	40
ΔP_{Cold} **[kPa]**	103.2	48.8	49.2	20.6
Length [m]	0.83	2.24	4.55	3.64
Width [m]	0.818	2.29	4.26	2.086 (circular)
Height [m]	0.818	2.29	4.26	2.086 (circular)
Volume [m³]	0.66	13.92	97.8	12.4

System Design

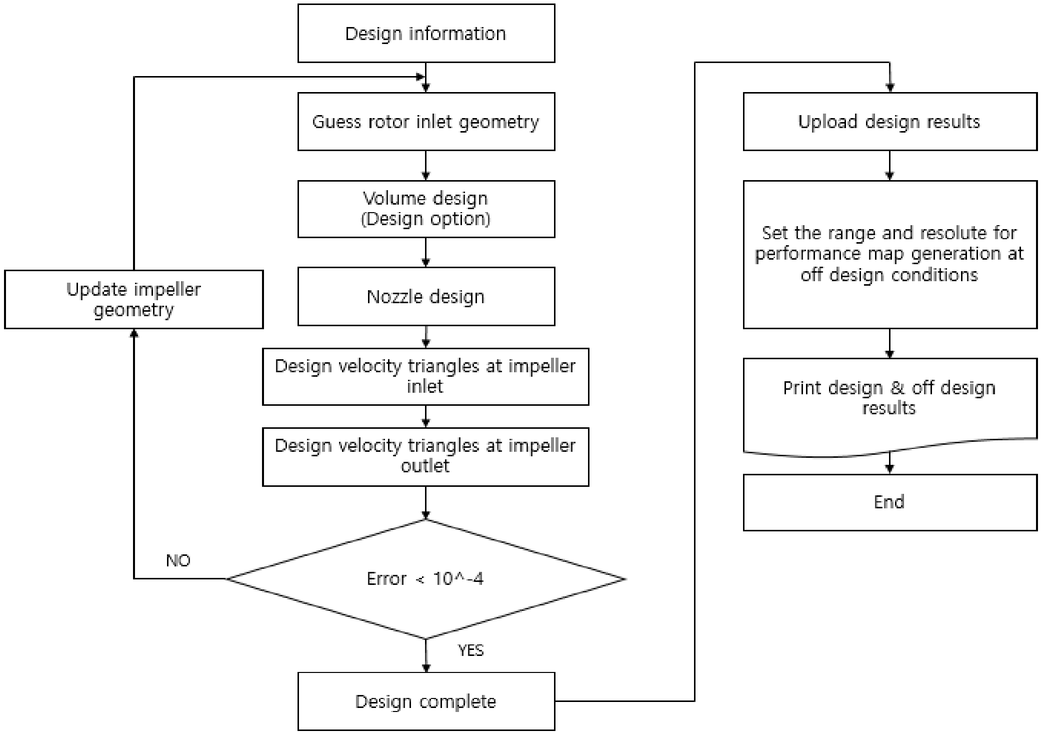
Component design

Turbomachinery

- Recompression cycle has 1 turbine and 2 compressors.
- Designed with KAIST-TMD (TurboMachinery Design) code (Axial turbomachinery)
- Design Result : Geometry & Off-design performance maps



< Scale dependence of S-CO_2 turbomachinery technology [ANL] >



< KAIST-TMD Algorithm >

I. W. Son et al., Design and Evaluation of Supercritical CO2 Axial Turbine for Micro Modular Reactor (2018)

System Design

Component design

Turbomachinery

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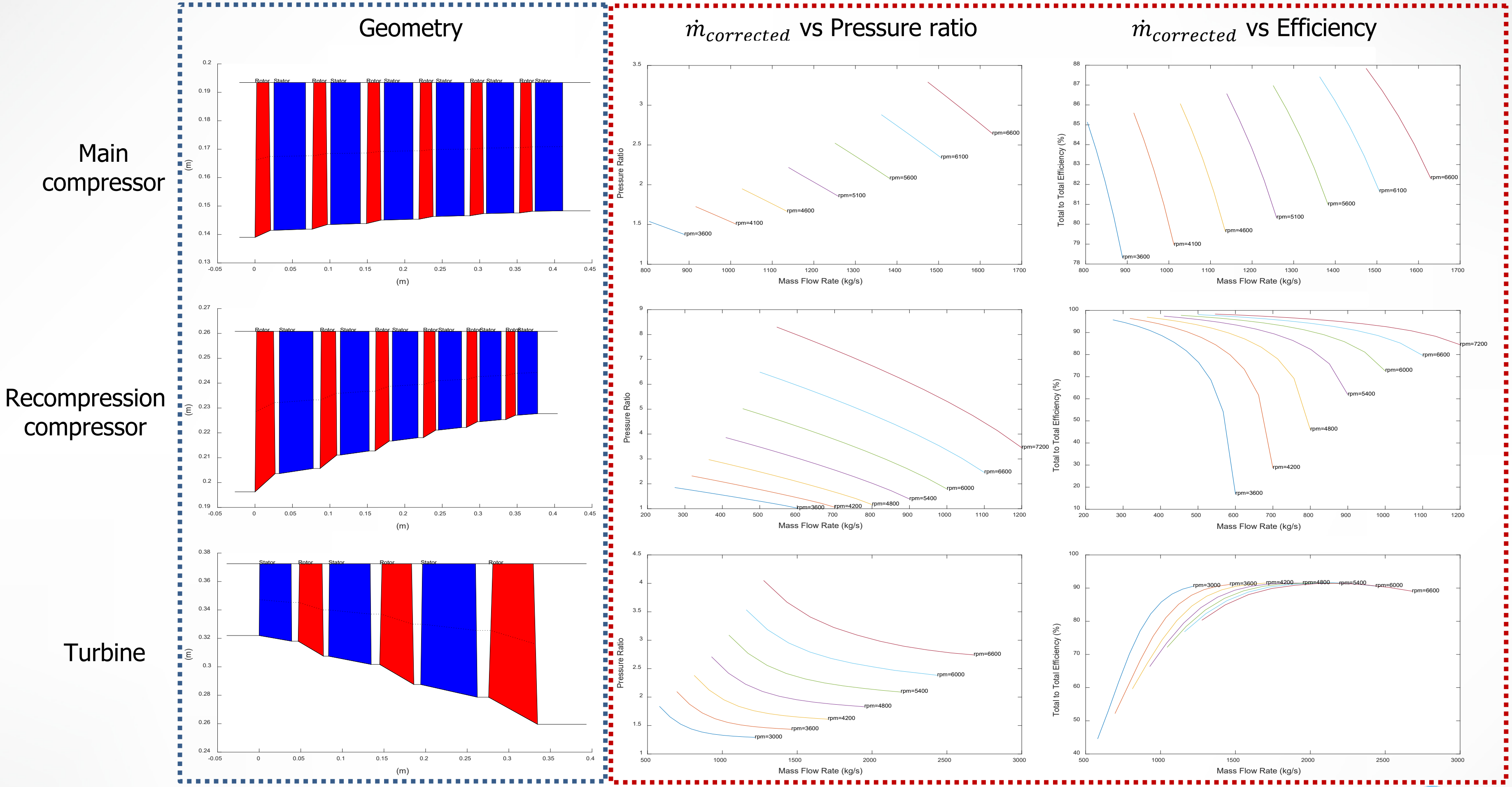
- Designed with KAIST-TMD (TurboMachinery Design) code (Axial turbomachinery)
- Design Result : Geometry & Off-design performance maps



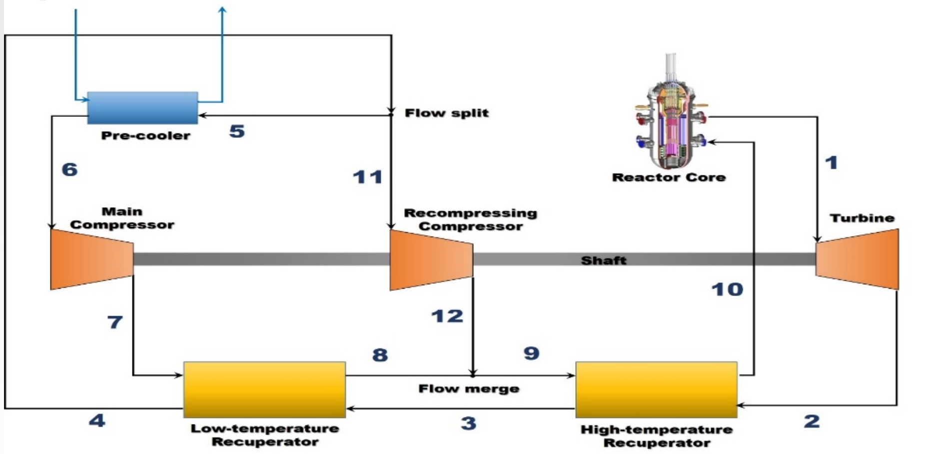
< Design results of turbomachinery >

NPNP

System Design

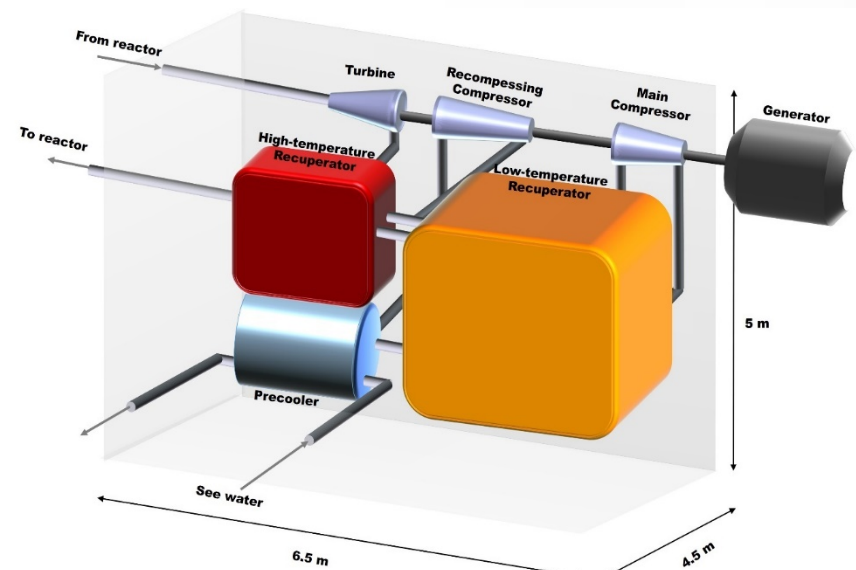
Component design

Pipe



- Pipe design is also important since it is directly related to the capital cost, the total amount of fluid mass, and the size of total system.
- However, most of procedures about pipe design are based on the water or steam system and there is very limited research on the pipe design of the S-CO_2 system.
- Pipes are preliminarily designed with the simple method using the optimal flow velocity and ASME standard.
- Optimal flow velocity -> $V = f_{pv}/\rho^{0.3}$

Location	Velocity [m/s]	D_o [m]	Thickness [m]	Length [m]
1	7.834	2.032	0.2062	3
2	11.668	2.032	0.1427	0.6
3	7.304	2.032	0.1427	0.5
4	6.039	1.829	0.1427	1.2
5	5.861	1.422	0.1427	0.6
6	4.216	0.965	0.1113	2.8
7	4.854	0.965	0.2062	1.8
8	4.873	1.321	0.2062	1.2
9	5.515	1.626	0.2062	0.6
10	6.065	2.032	0.2062	3
11	5.612	1.321	0.1588	1.6
12	5.065	1.219	0.2223	1.2



< Configuration of S-CO_2 power conversion system >

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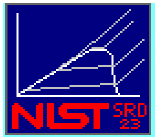
Development of System Analysis Code

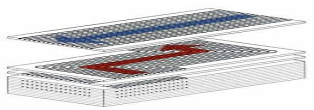
MARS Code

MARS Code

- MARS code is nuclear system analysis code being used by the Korean regulator (KINS).
- It was developed by KAERI and the backbones are the RELAP5/MOD3.2.1.2 and the COBRA-TF codes of USNRC.
- It adopts two-fluid model for flow of a two-phase steam-water mixture.
- The two-fluid equations are formulated in terms of volume and time-averaged parameters of the flow.
- However, the code has to be improved in order to **accurately simulate S-CO_2 power conversion system**.
- New modules were added to the original MARS code to conduct transient analysis of proposed system.

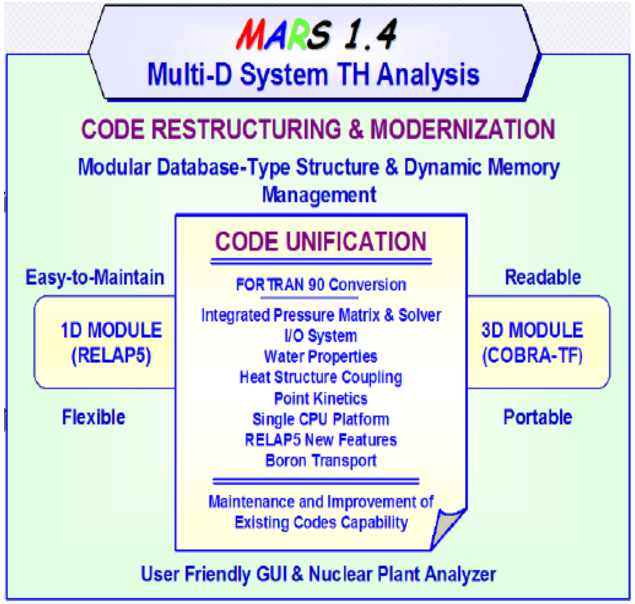
Accurate CO_2 properties





PCHE model

Turbomachinery model



< Conceptual diagram of MARS code improvements >

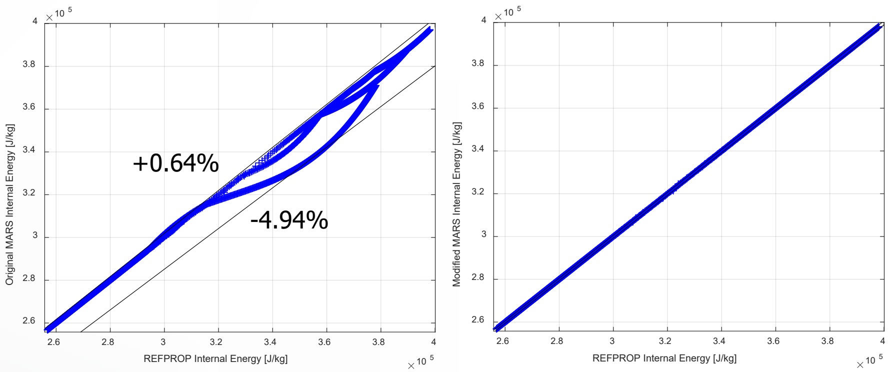
Development of System Analysis Code

Improvements of MARS code

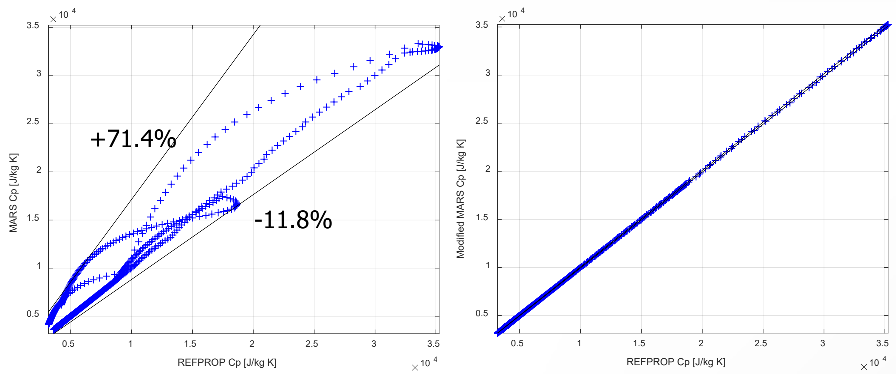
1. Physical properties of fluids

- To maximize the efficiency of the S-CO_2 cycle, compressor inlet conditions should be maintained near the critical point.
- Since physical properties of the S-CO_2 change dramatically in the vicinity of the critical point, it is very important to accurately predict its properties in order to simulate the total system.
- The original MARS code calculate properties of fluids by linearly interpolating property table generated by NIST data points.
- However, the lack of data points limits the inability to accurately calculate abrupt changes in physical properties near the critical point.
- The new property calculation option was added which directly import NIST data into MARS at every time step.
- It is possible to more accurately calculate the properties of CO_2 that exhibit nonlinear behavior near the critical point.

Test range : P ; 7.5, 8.0, 8.5 [MPa] T ; 32 - 45 [°C] (P_{cr} = 7.39MPa, T_{cr} = 31.1 °C)



< Comparison of internal energy >



< Comparison of specific heat >

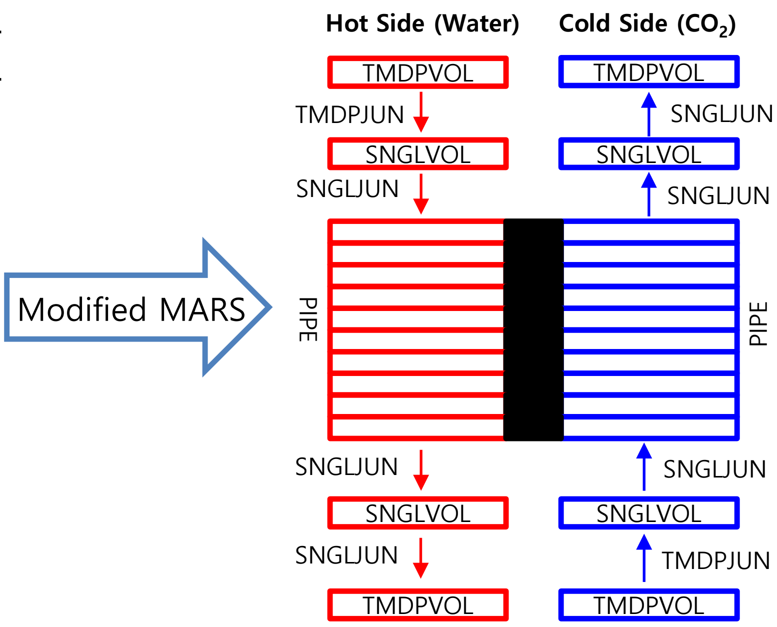
Development of System Analysis Code

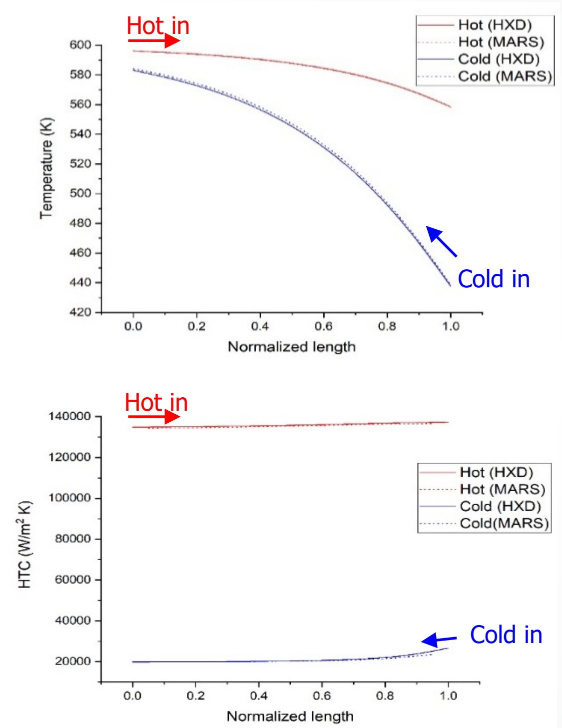
Improvements of MARS code

2. PCHE model

- Typically, heat exchangers of the S-CO_2 cycle are designed as the PCHE type due to its high performance and compactness.
- However, since there is no heat structure model of PCHE in the original MARS code, there must be a gap between the design parameters and the system code input deck.
- PCHE correlations were added to the heat structure sets of the MARS code so that design values such as heat transfer area and heat transfer length derived from the heat exchanger code (KAIST-HXD) can be applied to input deck.

HXD Parameters	IHX
Hot side $\dot{m}$ [kg/sec]	129.5
Cold side $\dot{m}$ [kg/sec]	135.44
Hot side D_e [m]	9.7762e-4
Cold side D_e [m]	9.7762e-4
Heated length [m]	0.2771
Flow area [m^2]	0.08907
Total heated area [m^2]	100.98
Mesh [#]	10





< Test of the newly added PCHE model >

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Development of System Analysis Code

Improvements of MARS code

3. Turbomachinery model

- The only equations that are modified as a result of the turbine model are the momentum equations, in which the pressure gradient terms are multiplied by the coefficient (1-η).
- The original MARS code has the gas turbine option and receive performance maps in the input deck.
- However, only a performance map for a single RPM can be entered and the pressure ratio and turbine work are not properly calculated from the performance map.

$$[\rho v A(\frac{1}{2}v^2 + h)]_1 = [\rho v A(\frac{1}{2}v^2 + h)]_2 + (\rho v A)_1 W$$

$$\frac{1}{2}v_2^2 - \frac{1}{2}v_1^2 = -(h_2 - h_1) - W$$

$$\text{Isentropic Process : } dh = \frac{1}{\rho}dP$$

$$h_2 - h_1 = \frac{1}{\rho}(P_2 - P_1)$$

$$W = -\eta \int dh = -\eta \int \frac{1}{\rho}dP$$

$$W = -\eta \frac{1}{\rho}(P_2 - P_1)$$

$$\frac{1}{2}v_2^2 - \frac{1}{2}v_1^2 = -\frac{(1-\eta)}{\rho}(P_2 - P_1)$$

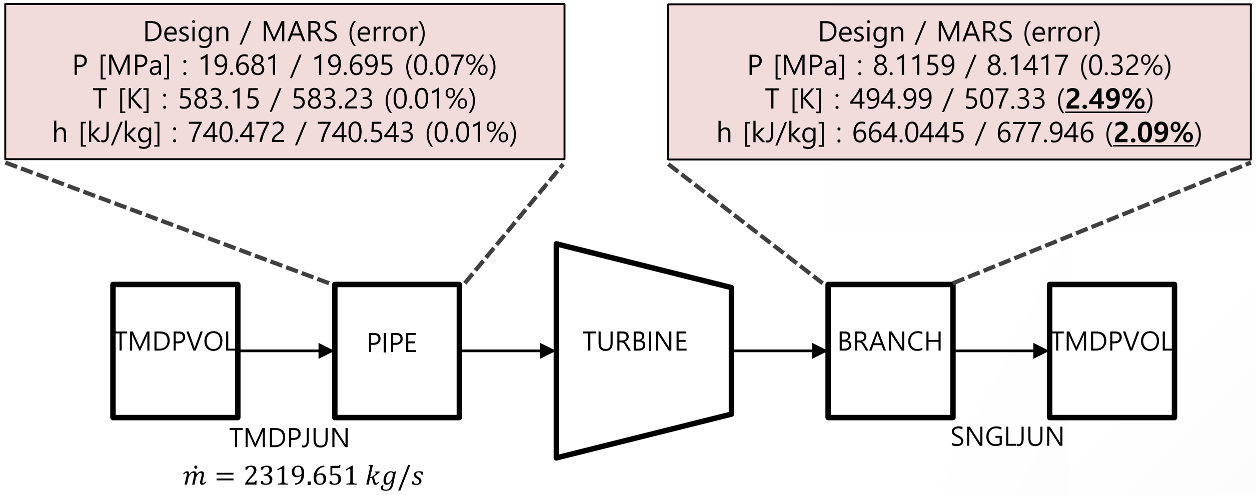
$h_2 \neq h_2$

Turbine momentum equation

$$(\alpha_g \rho_g)\left(\frac{\partial v_g}{\partial t} + v_g \frac{\partial v_g}{\partial x}\right) = -\alpha_g (1-\eta) \frac{\partial P}{\partial x} - C_g$$

$$(\alpha_f \rho_f)\left(\frac{\partial v_f}{\partial t} + v_f \frac{\partial v_f}{\partial x}\right) = -\alpha_f (1-\eta) \frac{\partial P}{\partial x} - C_f$$

MARS-KS 1.4 Theory Manual



< Test results of S-CO_2 turbine in the original MARS code >

Development of System Analysis Code

Improvements of MARS code

3. Turbomachinery model

- To accurately simulate the S-CO_2 turbomachinery, new options were added.
- With new options, code uses the modified governing equations for turbomachinery reflecting additional pressure and enthalpy difference from performance maps.
- CEA similitude model was implemented for dimension reduction in finding off-design pressure ratio and isentropic efficiency.
- Compressor model was added which does not exist in the original MARS code.
- Performance maps for various RPM can be entered.

CEA Similitude Model

Inlet Conditions: $T, P, \dot{m}, RPM$ → Performance: Pr, eff

Corrected properties

$$\dot{m}_c = \left(\frac{\dot{m}\sqrt{n_s RZT}}{n_s P}\right)\left(\frac{n_s P}{\sqrt{n_s RZT}}\right)_{Ref} \qquad \Delta H_c = \left(\frac{\Delta H}{n_s RZT}\right)(n_s RZT)_{Ref}$$

$$N_{rpm,c} = \left(\frac{N_{rpm}}{\sqrt{n_s RZT}}\right)\left(\sqrt{n_s RZT}\right)_{Ref} \qquad n_s = -\frac{v}{P}\left(\frac{\partial P}{\partial v}\right)_s$$

Original momentum conservation equation

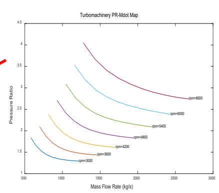
$$\alpha_g\rho_g A\frac{\partial v_g}{\partial t} + \frac{1}{2}\alpha_g\rho_g A\frac{\partial v_g^2}{\partial x} = -\alpha_g A\frac{\partial P}{\partial x} + \alpha_g\rho_g B_x A - (\alpha_g\rho_g A)FWG(v_g) + \Gamma_g A(v_{gI} - v_g) - (\alpha_g\rho_g A)FIG(v_g - v_f) - C\alpha_g\alpha_f\rho_m A\left[\frac{\partial(v_g - v_f)}{\partial t} + v_f\frac{\partial v_g}{\partial x} - v_g\frac{\partial v_f}{\partial x}\right]$$

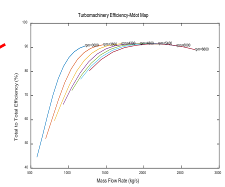
$+ \Delta P_{add}$

Original energy conservation equation

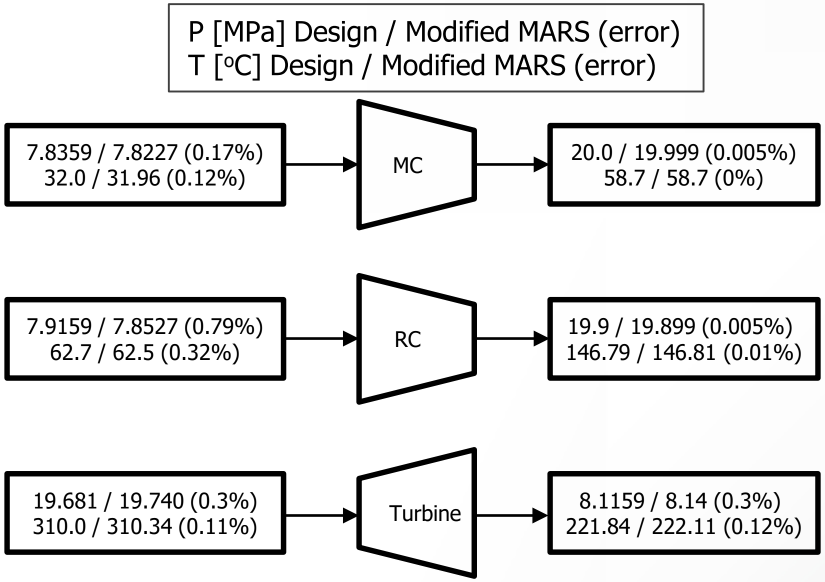
$$\frac{\partial}{\partial t}(\alpha_g\rho_g U_g) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_g\rho_g U_g v_g A) = -P\frac{\partial \alpha_g}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_g v_g A) + Q_{wg} + Q_{ig} + \Gamma_{ig}h_g^* + \Gamma_w h_g' + DISS_g$$

$+ \Delta h_{add}$





< Modified governing equations for turbomachinery>



< Test results of designed turbomachinery in the modified MARS code >