Study of sCO_2 System Compressor Inlet Temperature Control Strategy for Marine Propulsion

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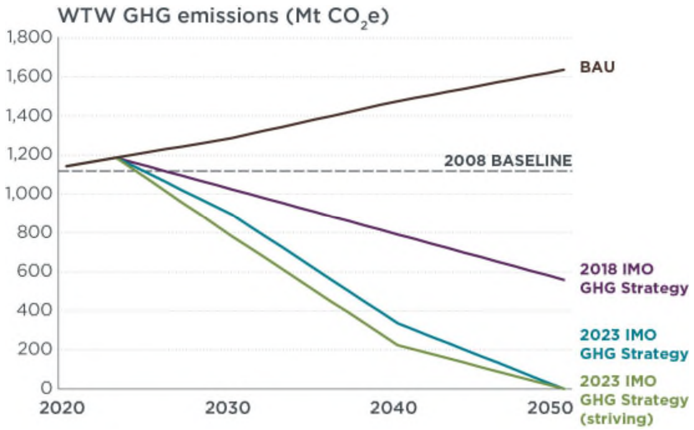
INTRODUCTION

Marine Propulsion

- Maritime transportation heavily depends on fossil fuels.
- The IMO has set a target to **phase out greenhouse gas emissions** as soon as possible.
- **Nuclear powered propulsion** is reemerging as a new maritime propulsion method.

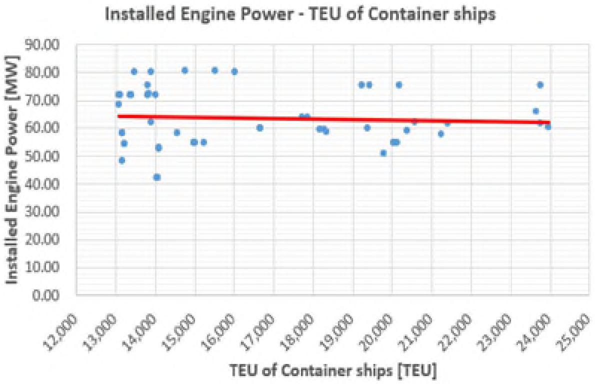


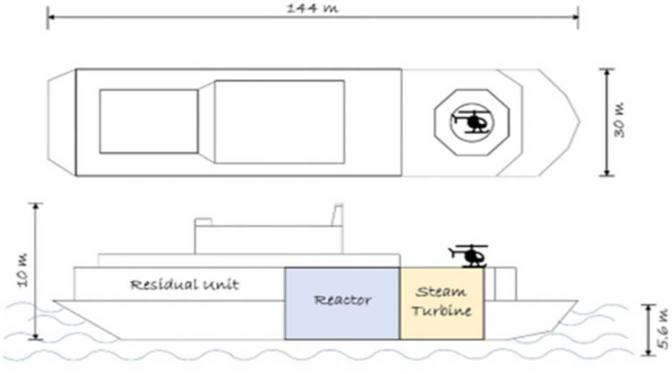
IMO GHG Strategy

Maritime SMR

- In the ship power generation range, the design should be based on a **Small Modular Reactor (SMR)** for nuclear propulsion.
- The KLT-40s, as an example, has a **power conversion system** that is **similar in size to the reactor**.
- Since reducing the size of the reactor is limited, the **power conversion system should be minimized**.

→ sCO_2 power system is promising option!



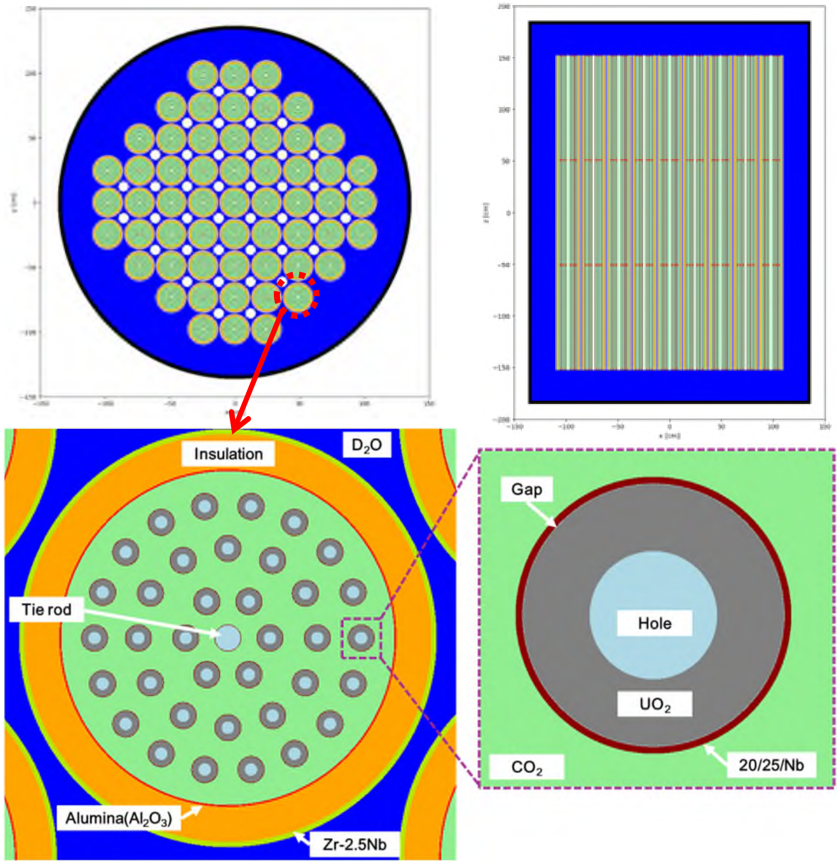


LAYOUT AND SIZE OF "AKADEMIK LOMONOSOV" FLOATING NPP

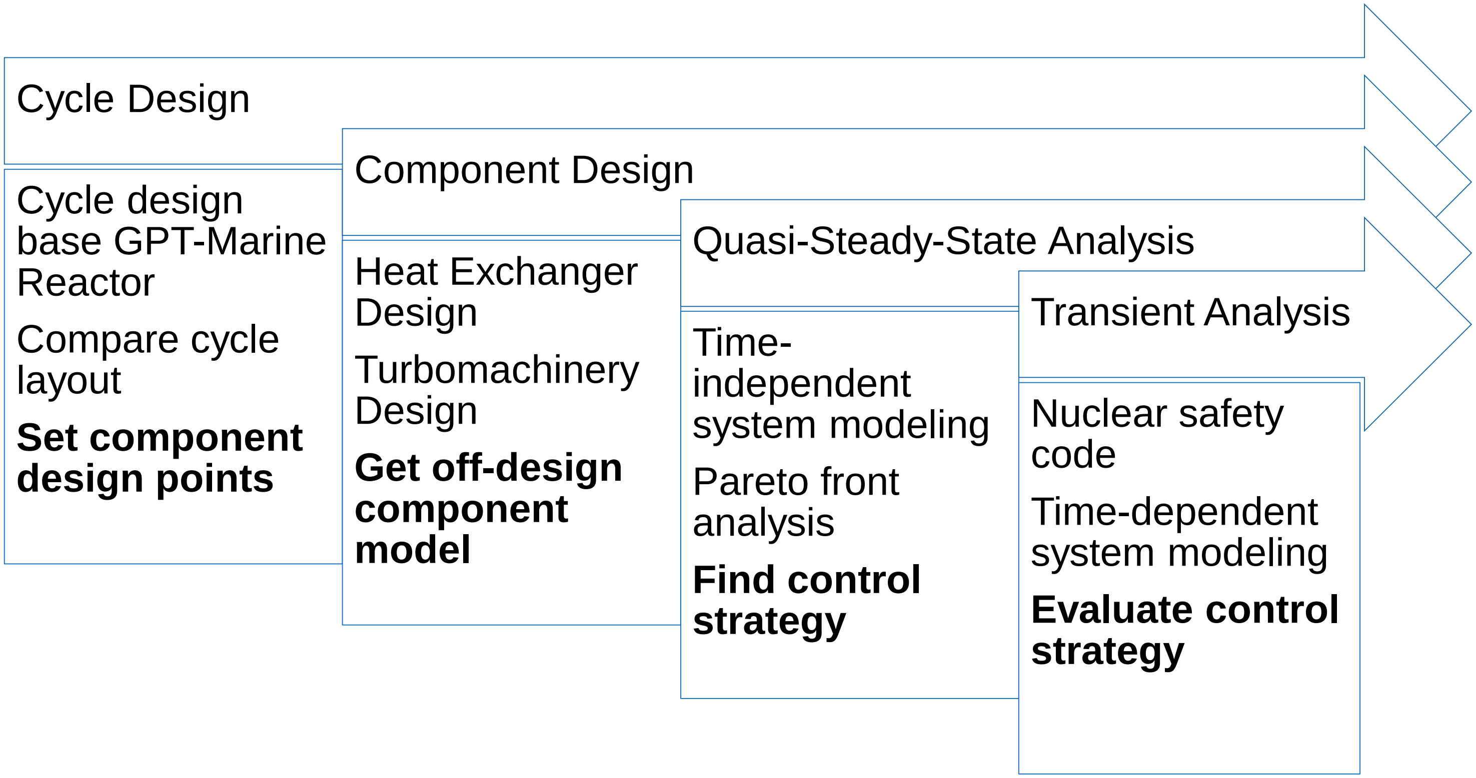
Size of Floating SMR (KLT-40S)

GPT-Marine reactor

- KAIST research team designed the Gas-cooled Pressure Tube reactor for Marine Propulsion (**GPT-Marine**).
- **Applying existing technologies** from AGR and CANDU.
- Developed specifically with the use of an sCO_2 power system in mind.
- 100MWth with reactor dimension 3.0 m(W) × 3.7 m(H)



Overall Methodology



Cycle Design

- Cycle design base GPT-Marine Reactor
- Compare cycle layout
- **Set component design points**

Component Design

- Heat Exchanger Design
- Turbomachinery Design
- **Get off-design component model**

Quasi-Steady-State Analysis

- Time-independent system modeling
- Pareto front analysis
- **Find control strategy**

Transient Analysis

- Nuclear safety code
- Time-dependent system modeling
- **Evaluate control strategy**

SYSTEM AND COMPONENTS

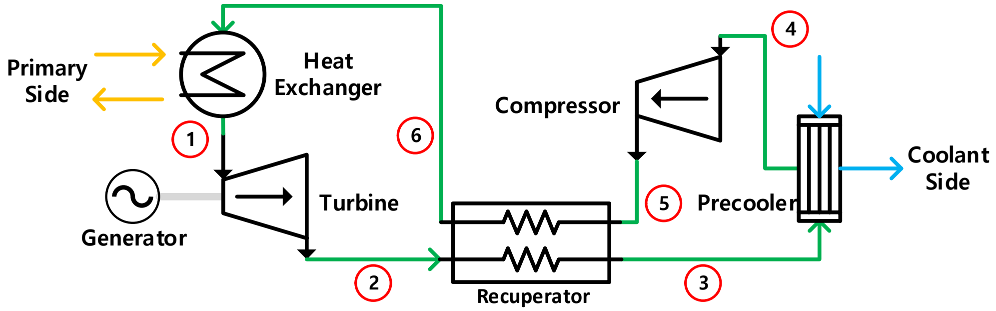
Cycle Design Conditions

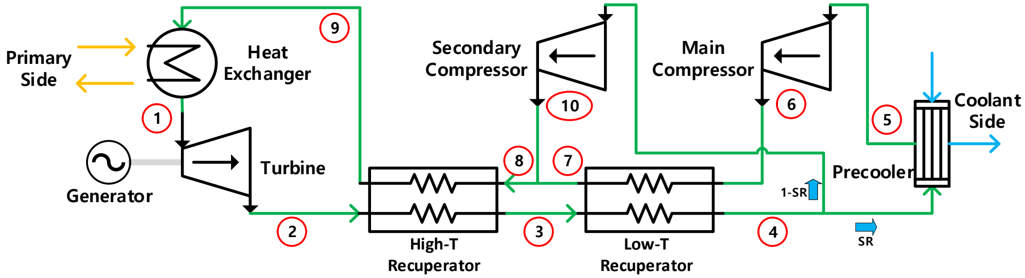
- The sCO_2 cycle design condition was selected based on the GPT-marine reactor.
  - Maximum T & P : Reactor core condition
  - Efficiency and Pressure loss : Refer to existing design cases

Condition	Value
Reactor Thermal Output	100MWth
Maximum Temperature	630°C (1166°F)
Minimum Temperature	35°C (95°F)
Compressor Efficiency	80%
Turbine Efficiency	90%
Heat Exchanger Effectiveness	95%
Heater/Pre-cooler Pressure Drop	150kPa (21.75psi)
Internal Heat Exchanger Pressure Drop	150kPa (21.75psi)
Heat Exchanger Pinch Temperature	5°C (9°F)

Cycle Design Conditions

- Cycles layout selected considering **system size**
  - Simple recuperated
  - Recompression
- **Maximize efficiency**
- Using in-house code KAIST-CCD





Cycle Design Results

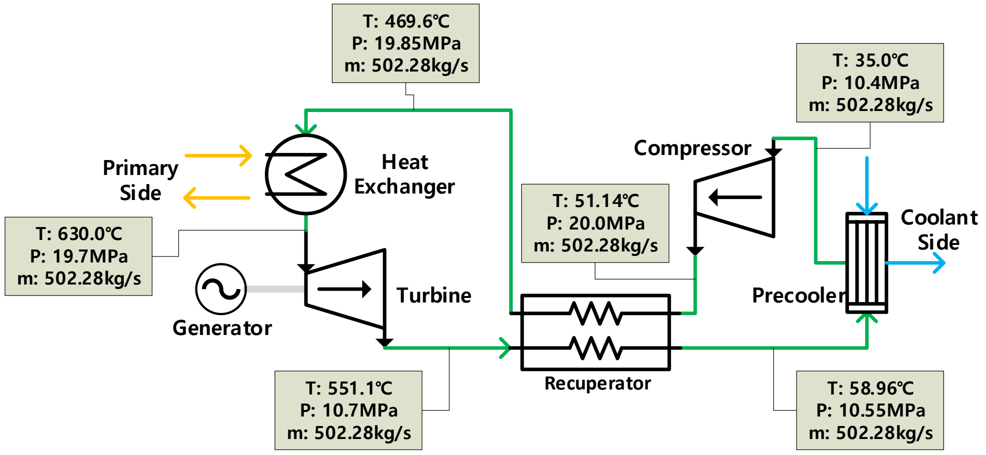
- Efficiency difference between two cycles : 7%p
- Recuperated cycle
  - Small mass flow rate
  - Small pressure ratio
  - High minimum pressure
- Recompression cycle
  - High efficiency
  - Large pressure ratio
  - Large turbine work

Design parameter	Recuperated cycle	Recompression cycle
Cycle thermal efficiency (%)	38.0	45.1
Cycle thermal input (MWth)	100	100
CO2 mass flow rate (kg/s)	502.28	536.44
Minimum pressure (MPa)	10.4	8.30
Main compressor pressure ratio	1.923	2.41
Secondary compressor pressure ratio	-	2.35
Main compressor work (MW)	7.948	7.892
Secondary compressor work (MW)	-	10.42
Turbine work (MW)	45.94	63.40
Turbine bypass ratio	-	0.65

→ sCO_2 recuperated cycle selected for future works

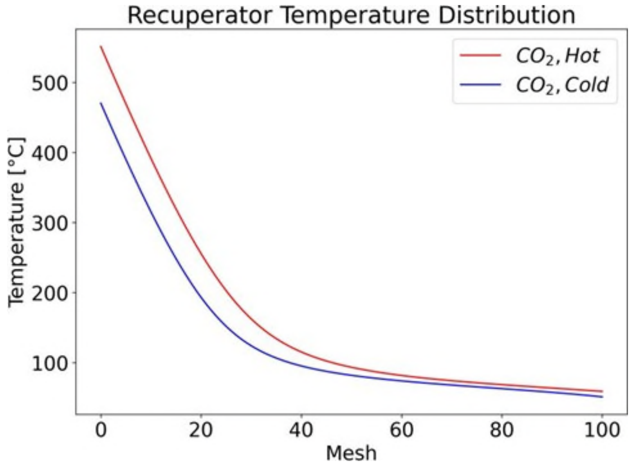
Components Conceptual Design

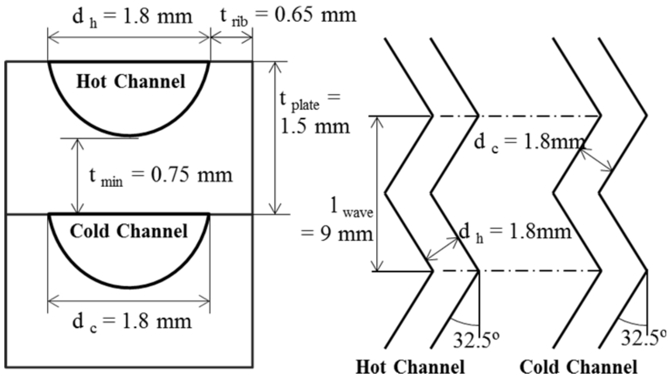
- Components design based on cycle design condition utilizing in-house code
- **Heat exchanger**
  - Recuperator & Precooler
  - Printed Circuit heat exchanger
  - 1D FDM
  - KAIST-HXD (Heat eXchanger Design)
- **Turbomachinery**
  - Compressor & Turbine
  - Radial turbomachinery
  - Speed based on Balje's n_s-d_s diagram
  - KAIST-TMD (TurboMachine Design)



Recuperator Design Results

- Zig-zag channel
- Heat transfer correlation based on experimental data
- **Only the core pressure drop** was calculated, resulting in a value **smaller** than cycle design assumption

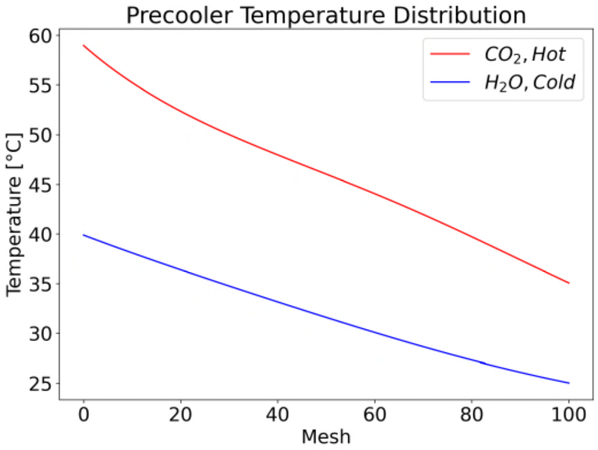




Design parameter	Design results
Heat duty (MW)	318.38
Hot side temperature difference (K)	492.1
Cold side temperature difference (K)	419.1
Hot side pressure drops (kPa)	118.5
Cold side pressure drops (kPa)	53.18
Channel numbers	960,000
Channel length (m)	1.8

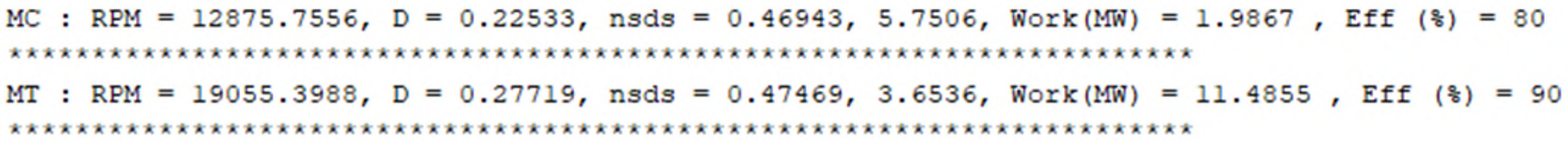
Precooler Design Results

- Zig-zag channel
- Cooling water inlet condition
  - Temperature: 25°C (75°F)
  - Pressure: 10bar (145psi)
- Designed to maintain the coolant water outlet temperature below 40°C (104°F).
  - Water mass flow rate: 1,000kg/sec



Design parameter	Design results
Heat duty (MW)	62.0
Hot side temperature difference (K)	23.96
Cold side temperature difference (K)	14.88
Hot side pressure drops (kPa)	116.3
Cold side pressure drops (kPa)	200.5
Channel numbers	150,000
Channel length (m)	0.53

Turbomachinery Design Results



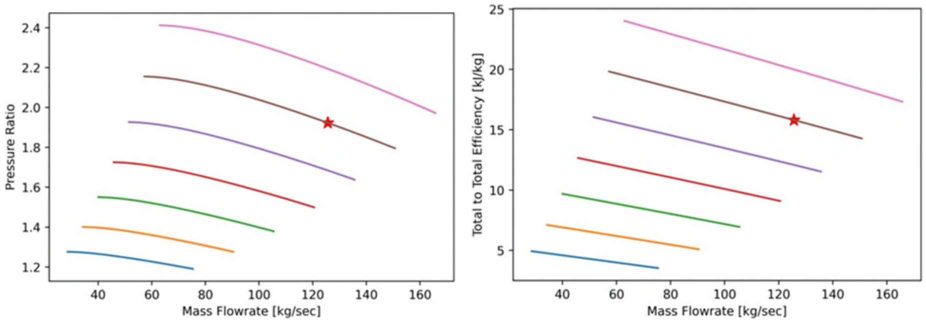
```
MC : RPM = 12875.7556, D = 0.22533, nsds = 0.46943, 5.7506, Work(MW) = 1.9867 , Eff (%) = 80
***********************************************************************
MT : RPM = 19055.3988, D = 0.27719, nsds = 0.47469, 3.6536, Work(MW) = 11.4855 , Eff (%) = 90
***********************************************************************
```

- Both compressor and turbine designed as **two sets of double-suction/discharge types**
  - Mass flow rate: 502.28 kg/sec → 125.57 kg/sec
  - Turbine work: 45.94MW → 11.49MW
  - Compressor work: 7.95MW → 1.99MW
- Assuming the compressor is motor-driven
  - Rotating speed **Turbine ≠ Compressor**
  - Compressor rotating speed: 12,000 rpm
  - Turbine rotating speed: 20,000 rpm

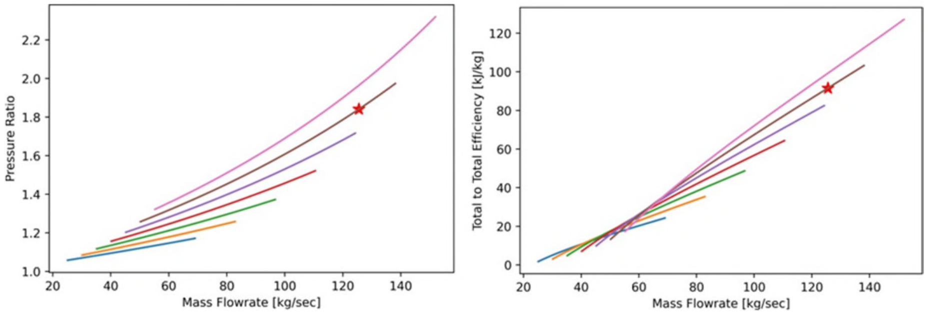
Turbomachinery Design Results

- The turbomachinery is designed within a 0.1% tolerance of the assumed values during cycle design.

Design parameter	Compressor	Turbine
Work (MW)	1.985	11.49
Pressure ratio	1.923	1.841
Efficiency (%)	80.07	90.08
Rotating speed (RPM)	12,000	20,000
Inlet axial velocity (m/sec)	32	26
Number of vanes	18	16



Compressor pressure ratio map (Left), Efficiency map (Right)

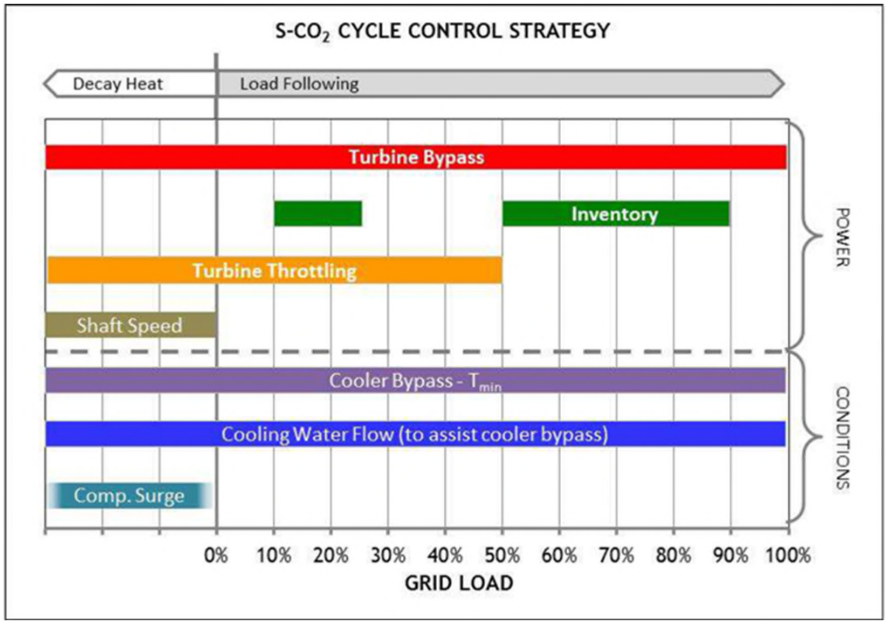


Turbine pressure ratio map (Left), Efficiency map (Right)

QUASI-STEADY-STATE ANALYSIS

Cycle Control Strategy

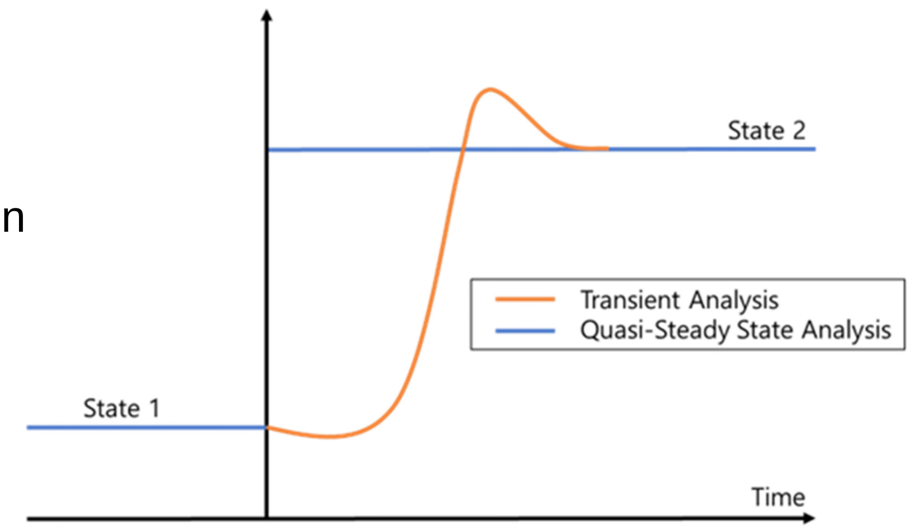
- sCO_2 cycle control strategy is well-known
  - Turbine bypass
  - Inventory
  - Min/Max Temperature…
- Need to choose favorable strategies based on off-design cycle performance analysis



J. J. Sienicki et al., Fundamentals and Applications of Supercritical Carbon Dioxide (sCO2) Based Power Cycles, 13-Nuclear power, pp. 339-391, 2017.

Off-design Analysis

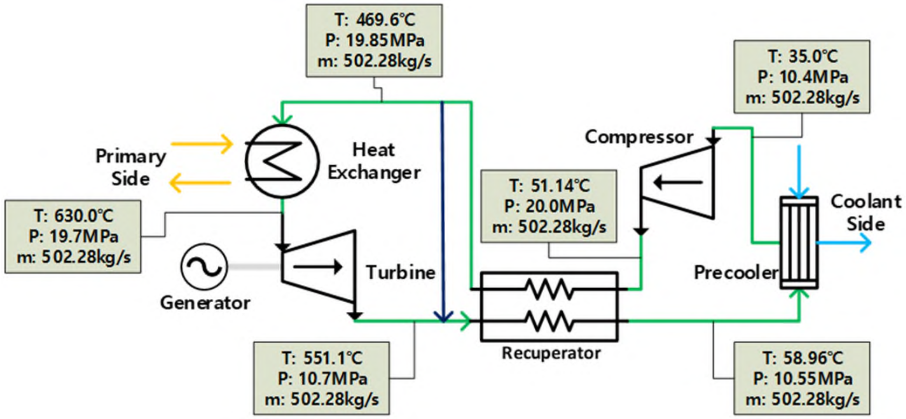
- **2 methods** for cycle off-design performance analysis
- Transient analysis
  - Performed on time domain
  - **Control performance** analysis
  - Long computation time/large computation source
- Quasi-steady-state analysis
  - Consider only new steady states that converge under given condition
  - **Control strategy** analysis
  - Short computation time/small computation source
- Performing transient analysis based on quasi-steady-state analysis



→ Quasi-steady-state analysis first

Quasi-steady-state Analysis

- Control domain
  - Inventory control
  - Turbine bypass control
  - Heat input control
  - Compressor inlet temperature (CIT) control
- Boundary condition
  - Maximum heat transfer
  - Compressor surge

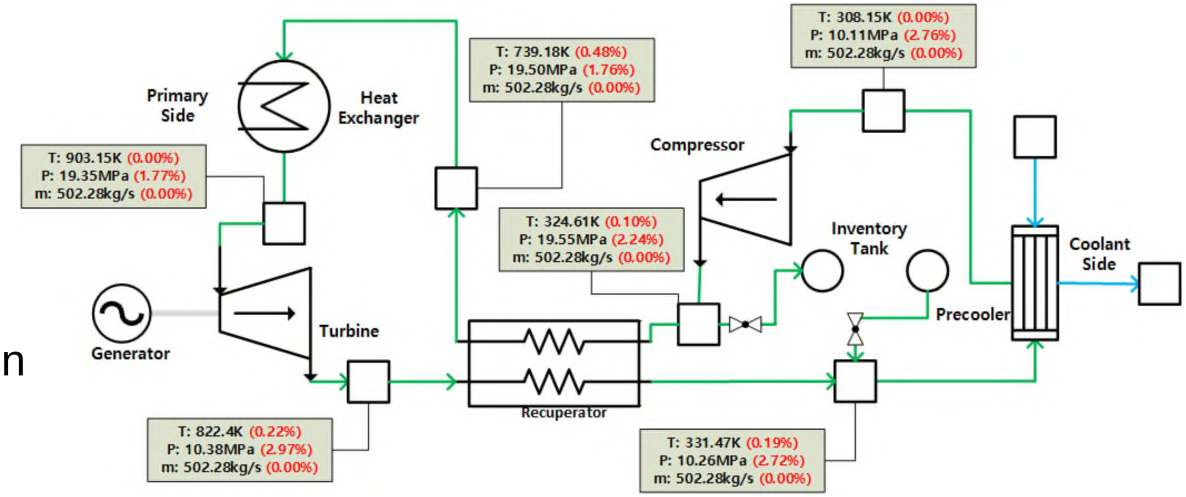


Parameter	Range
Compressor inlet temperature (°C)	35 – 55
IHX outlet temperature (°C)	550 – 630
Mass flowrate (%)	10 – 110
Turbine bypass ratio (%)	0 – 50

Code Validation

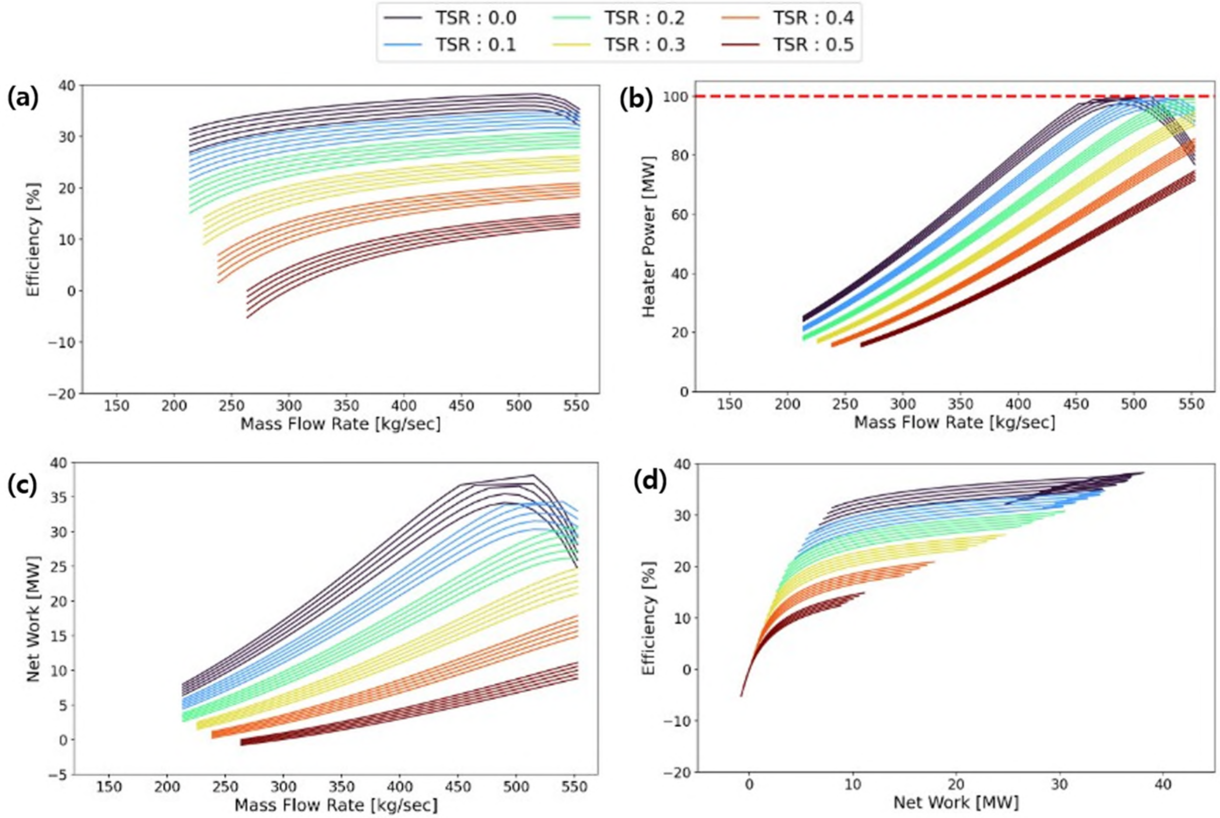
- Performed validation of the KAIST-QCD code by analyzing under on-design conditions
  - Temperature error: <0.5%
  - Pressure error: <3%

- Large pressure deviation than temperature deviation
  - Only heat exchanger core designed
  - Underestimate pressure drop in heat exchanger



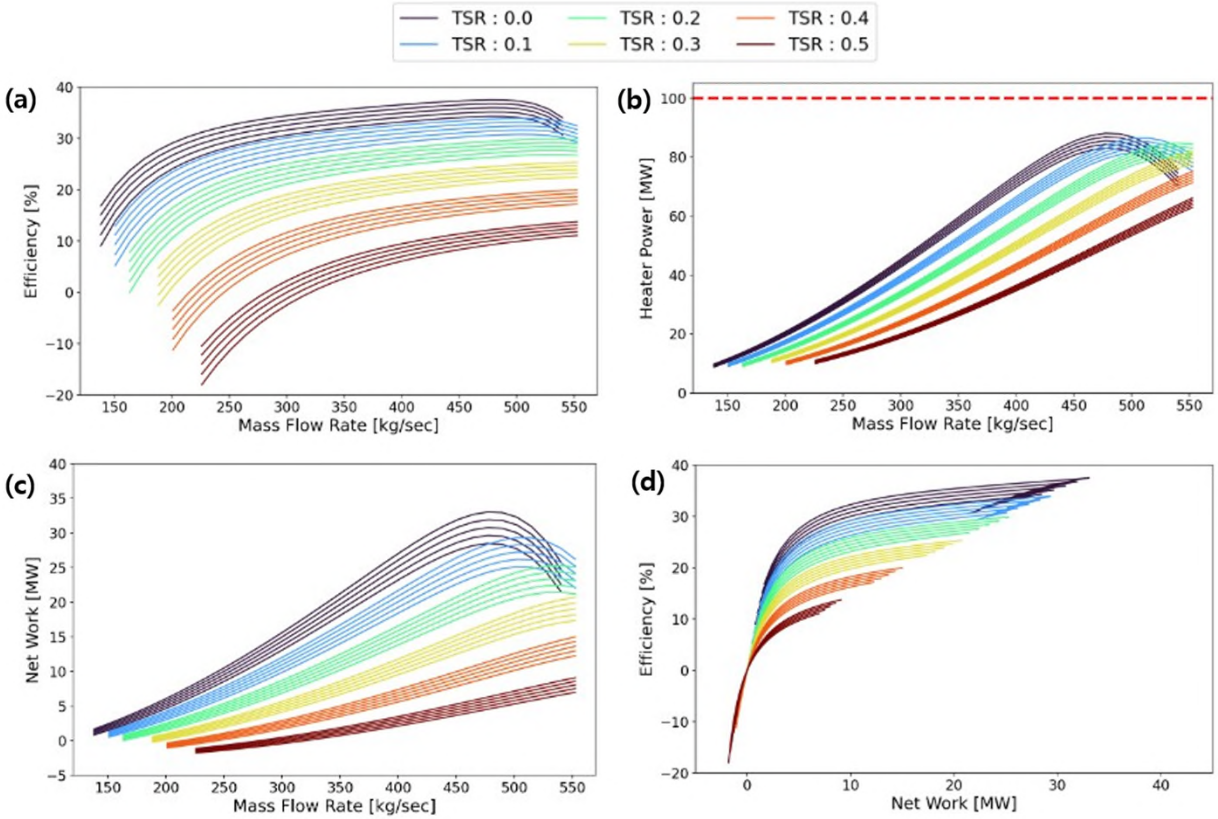
Quasi-steady-state Analysis Results

- Compressor Inlet Temperature: 35°C
  - (a) Cycle thermal efficiency
  - (b) Input thermal power
  - (c) Cycle net-work
  - (d) Cycle net-work vs cycle thermal efficiency



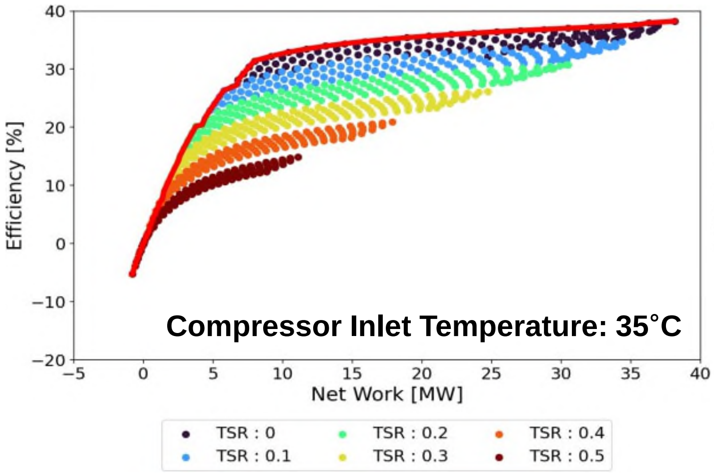
Quasi-steady-state Analysis Results

- Compressor Inlet Temperature: 40°C
  - (a) Cycle thermal efficiency
  - (b) Input thermal power
  - (c) Cycle net-work
  - (d) Cycle net-work vs cycle thermal efficiency

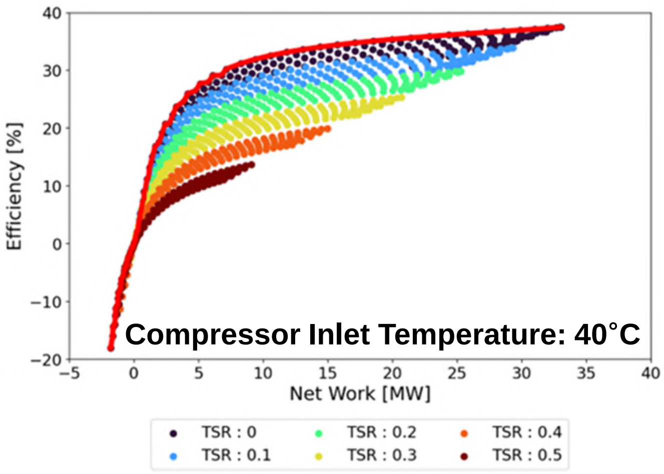


Quasi-steady-state Analysis Results

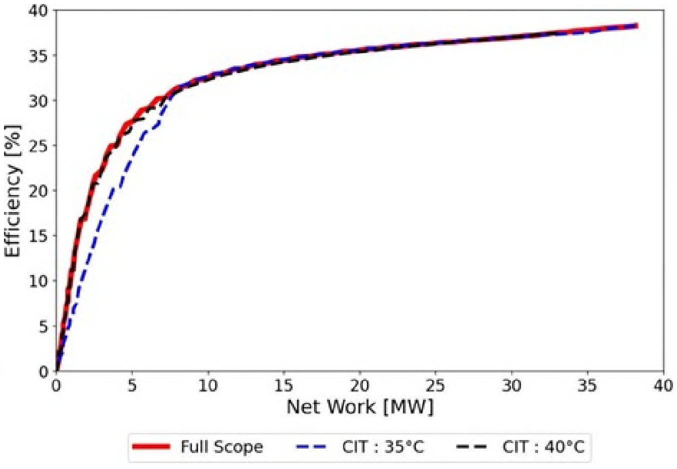
- Full scope Pareto front follows 35°C at high-power region, follows 40°C at low-power region
- **Increasing the CIT** to control the system is advantageous for improving **efficiency in the low-power domain**.



Compressor Inlet Temperature: 35°C



Compressor Inlet Temperature: 40°C



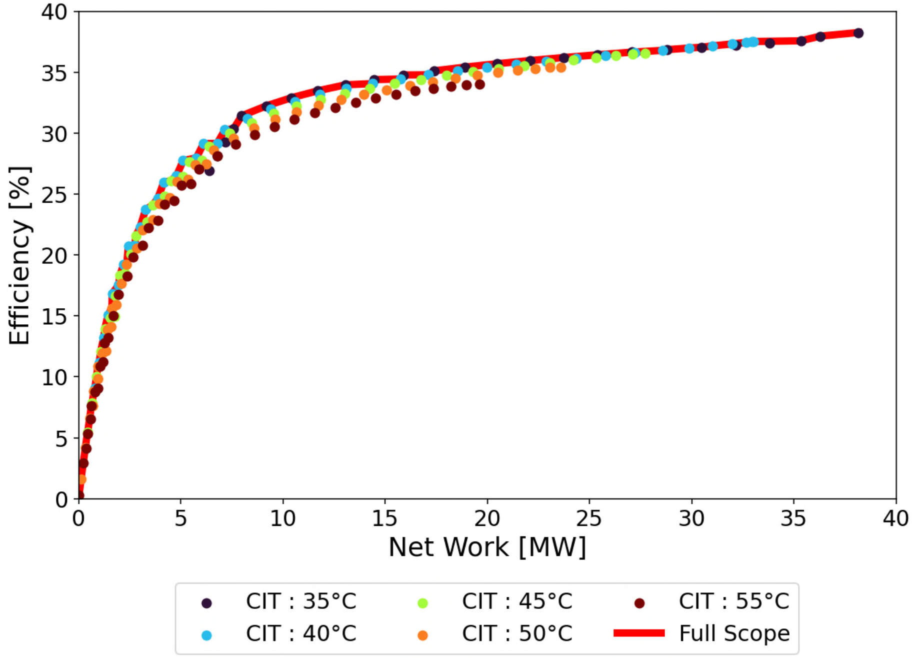
Control Without Turbine Bypass

- When **turbine bypass control** is engaged, a significant **decrease in efficiency** occurs.
- **Not using the turbine bypass is advantageous**
  - Higher Efficiency: Eff(CIT↓, Bypass O) < Eff(CIT↑, Bypass X)
  - Simple cycle layout
  - No needs for high temperature valve
  - Marine systems can incorporate water-cooled precoolers, which are advantageous for controlling CIT.

→ **Analysis of control performance using only compressor inlet control and inventory control**

Full Range Operation Without Turbine Bypass

- Zero net work: CIT 55°C
- **Full-range control achievable** through temperature control and inventory control **without turbine bypass**



→ Perform transient analysis based on QCD results.

TRANSIENT ANALYSIS

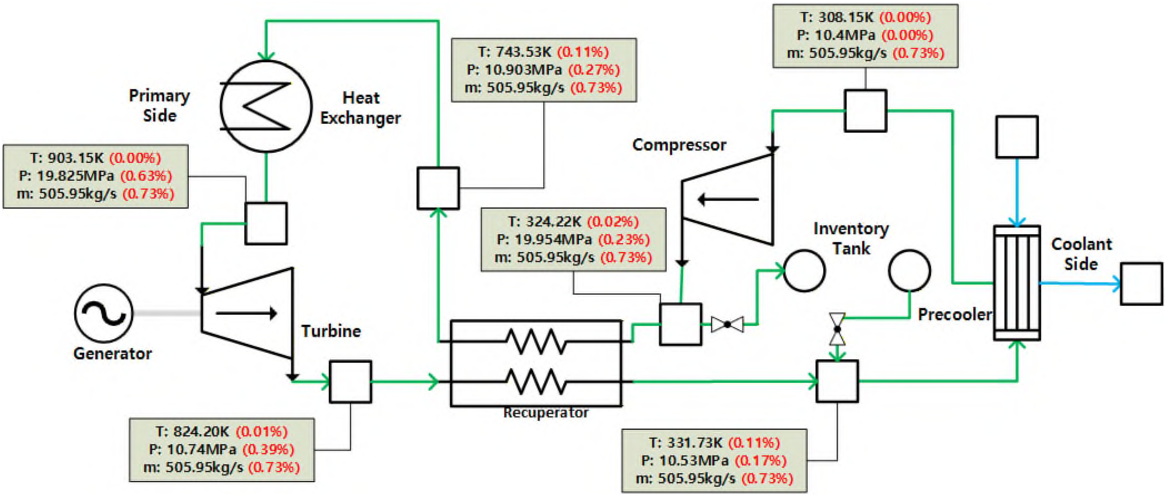
Methodology

- As nuclear power systems, **transient analysis** is performed based on **Korean regulatory codes**, **MARS**.
- The Multi-dimensional Analysis of Reactor Safety (**MARS**) code was developed to calculate the transient multi-dimensional behavior of thermal-hydraulic systems in LWR for nuclear thermal-hydraulic safety purpose
- **MARS modification for sCO_2** system analysis
  - Precise **physical properties** of CO_2 based on NIST's REFPROP
  - Heat transfer correlation of **PCHE**
  - Similitude-based **turbomachinery** model

Code Validation

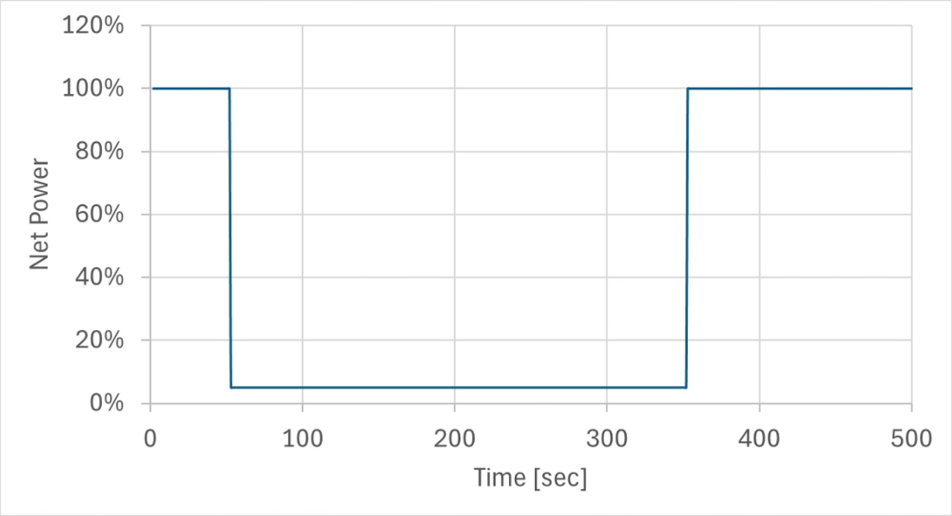
- Performed validation of the MARS code by analyzing under on-design, steady-state conditions
  - Temperature error: <0.15%
  - Pressure error: <0.7%
  - Mass flow rate error: 0.73%

- Smaller error than the results from KAIST-QCD
  - Heat exchanger header also included
  - More accurate pressure drop in heat exchanger



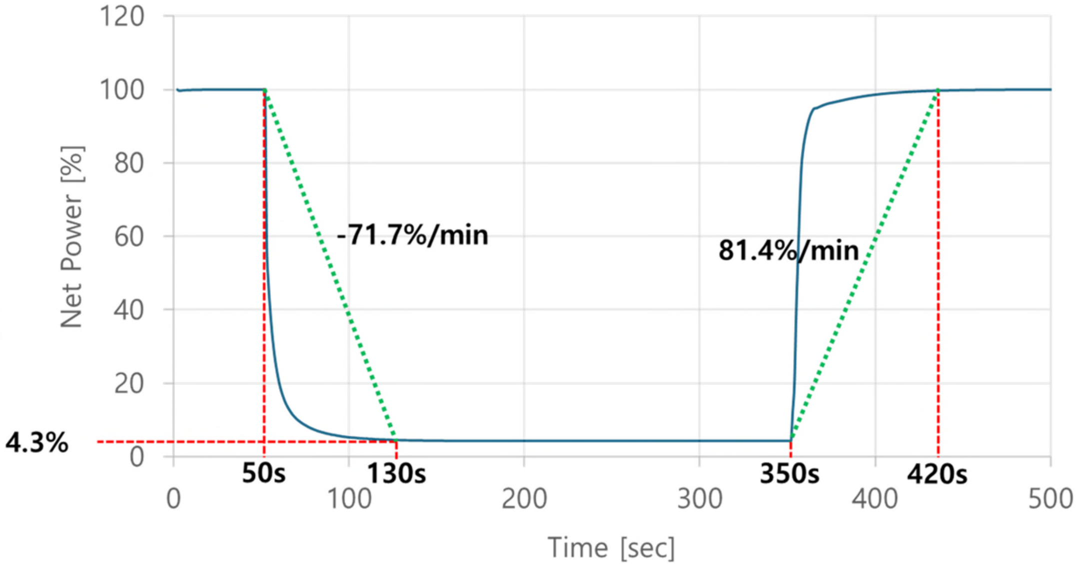
Transient Simulation

- Net power 100%-5%-100%
  - Verify load **reduction/increase change rate**
- Based on quasi-steady-state results
- Control using **PI controllers**



Simulation Results

- At output power changes 100%-5%-100%
  - Load reduction rate: **71.7%/min**
  - Load increase rate: **81.4%/min**
- Differences between MARS and KAIST-QCD results
  - Pressure drop
  - Turbomachinery off-design performance prediction methods



Summary

- Research is underway on **nuclear systems** for **civilian ship propulsion**, and the **sCO_2 cycle is optimal** as a power conversion system.
- The sCO_2 cycle is designed based on the **GPT-Marine reactor**, which was designed with the use of the sCO_2 cycle in mind.
- Based on **quasi-steady-state analysis**, using **compressor inlet temperature** control is more **advantageous** than turbine bypass control during load-following operation.
- **Zero net work can be achieved without turbine bypass control** at an inlet temperature of 55°C.
- **Control speed** is evaluated using **transient code** when employing inventory control and CIT control.
- Achieved a **load reduction rate of 71.7%/min** and a **load increase rate of 81.4%/min** in the net power **100%-5%-100% scenario**.

Conclusions & Future Works

- The output of the sCO_2 system can be controlled within a meaningful control speed through the compressor and turbine inlet temperatures, along with inventory system control.

→**Controlling the sCO_2 system without a turbine bypass is also worth considering.**

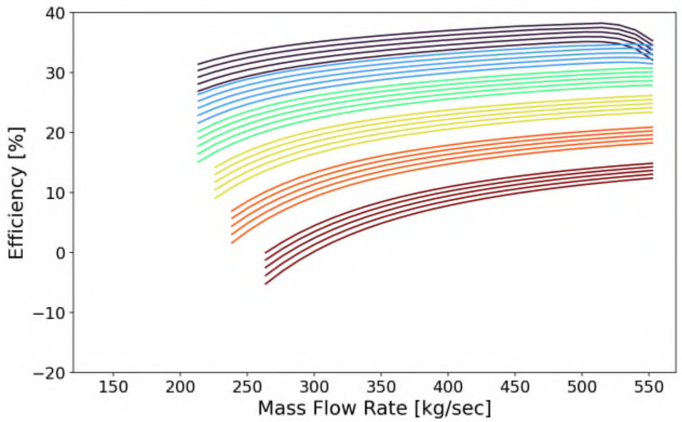
- Testing compressor inlet temperature-based control for **various cycle layouts**
- **Improving control speed and accuracy** using controllers other than PI controllers
- **Enhancing transient analysis** accuracy through transient simulation based on turbo machinery 1D mean streamline code

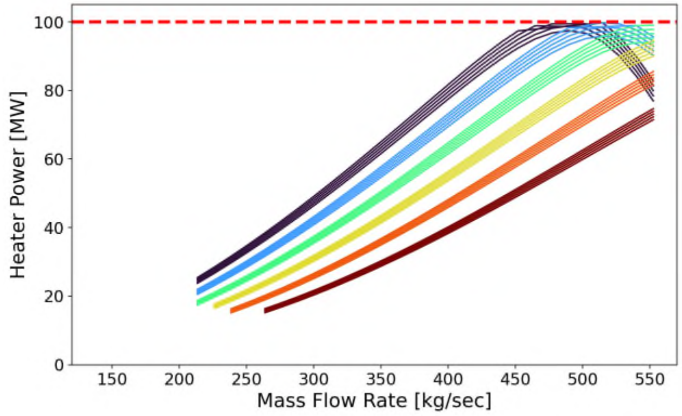
APPENDIX

Inlet Temperature – 35℃

— TSR : 0.0
— TSR : 0.1
— TSR : 0.2
— TSR : 0.3
— TSR : 0.4
— TSR : 0.5

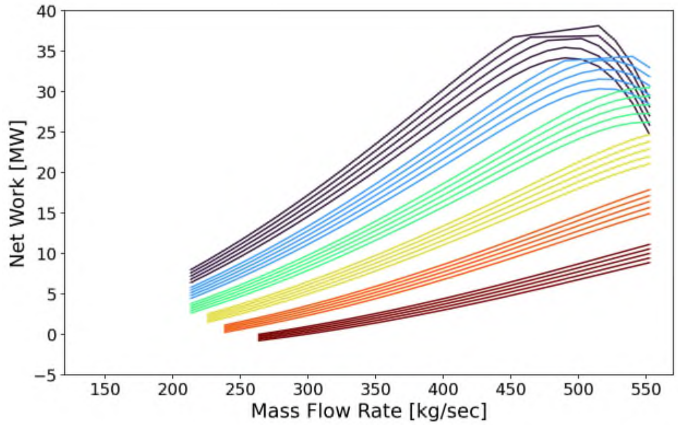
Efficiency

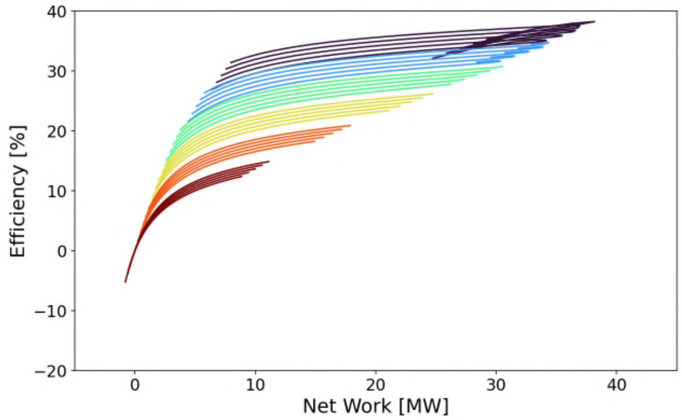




IHX Input

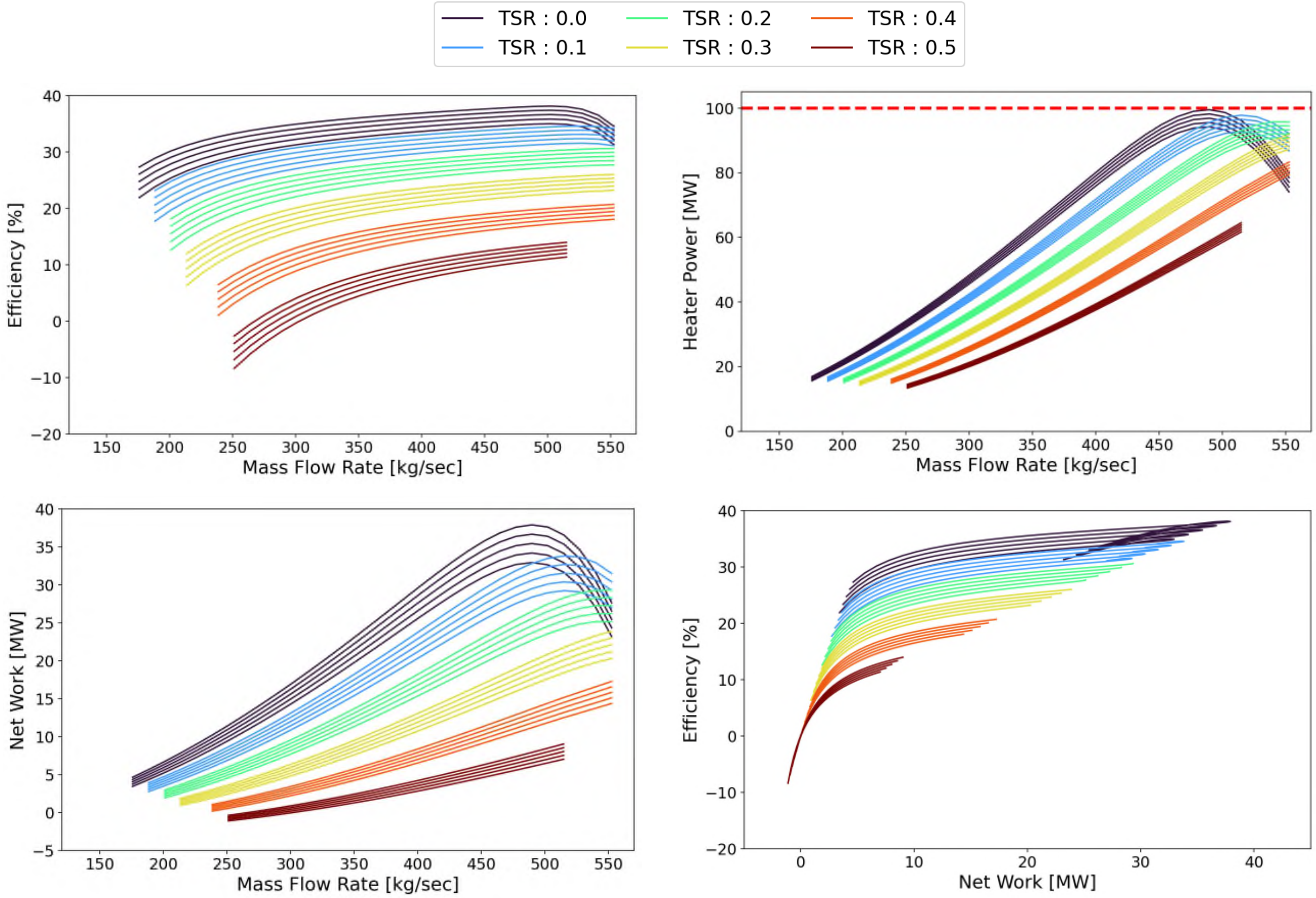
Net Work





Net Work to Efficiency

Inlet Temperature – 36℃



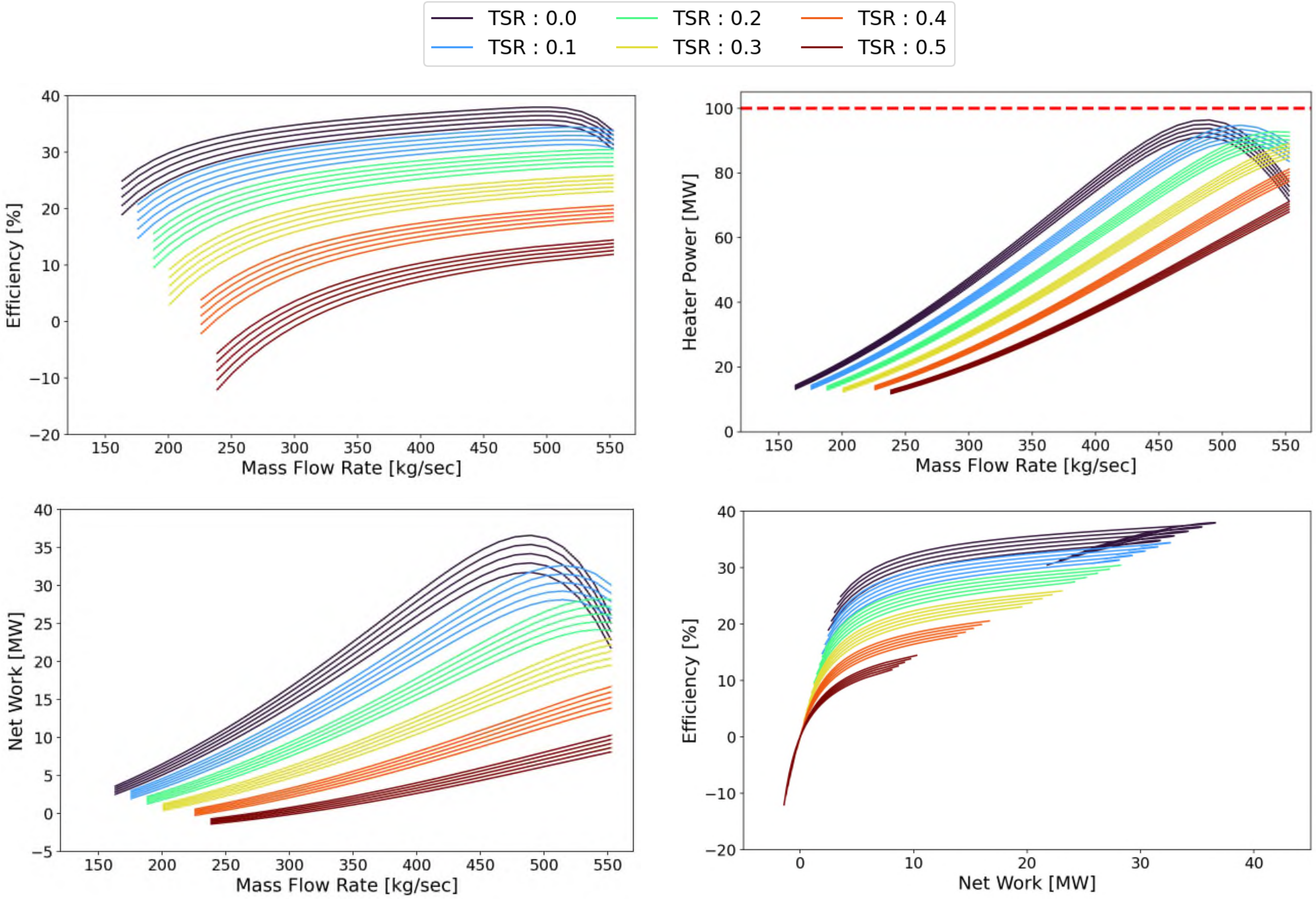
Efficiency

Heater Input

Net Work

Net Work to Efficiency

Inlet Temperature – 37℃



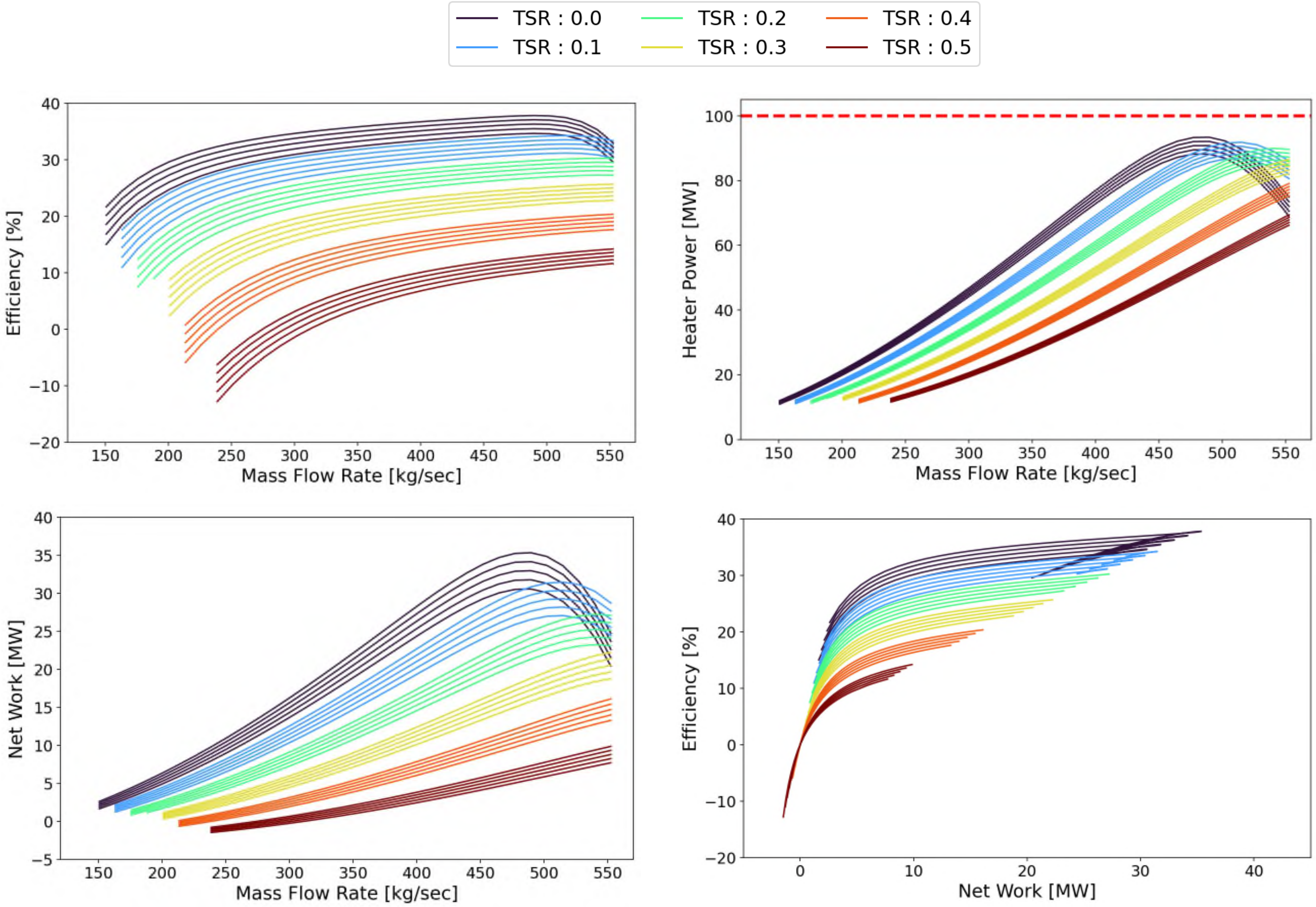
Efficiency

Heater Input

Net Work

Net Work to Efficiency

Inlet Temperature – 38℃



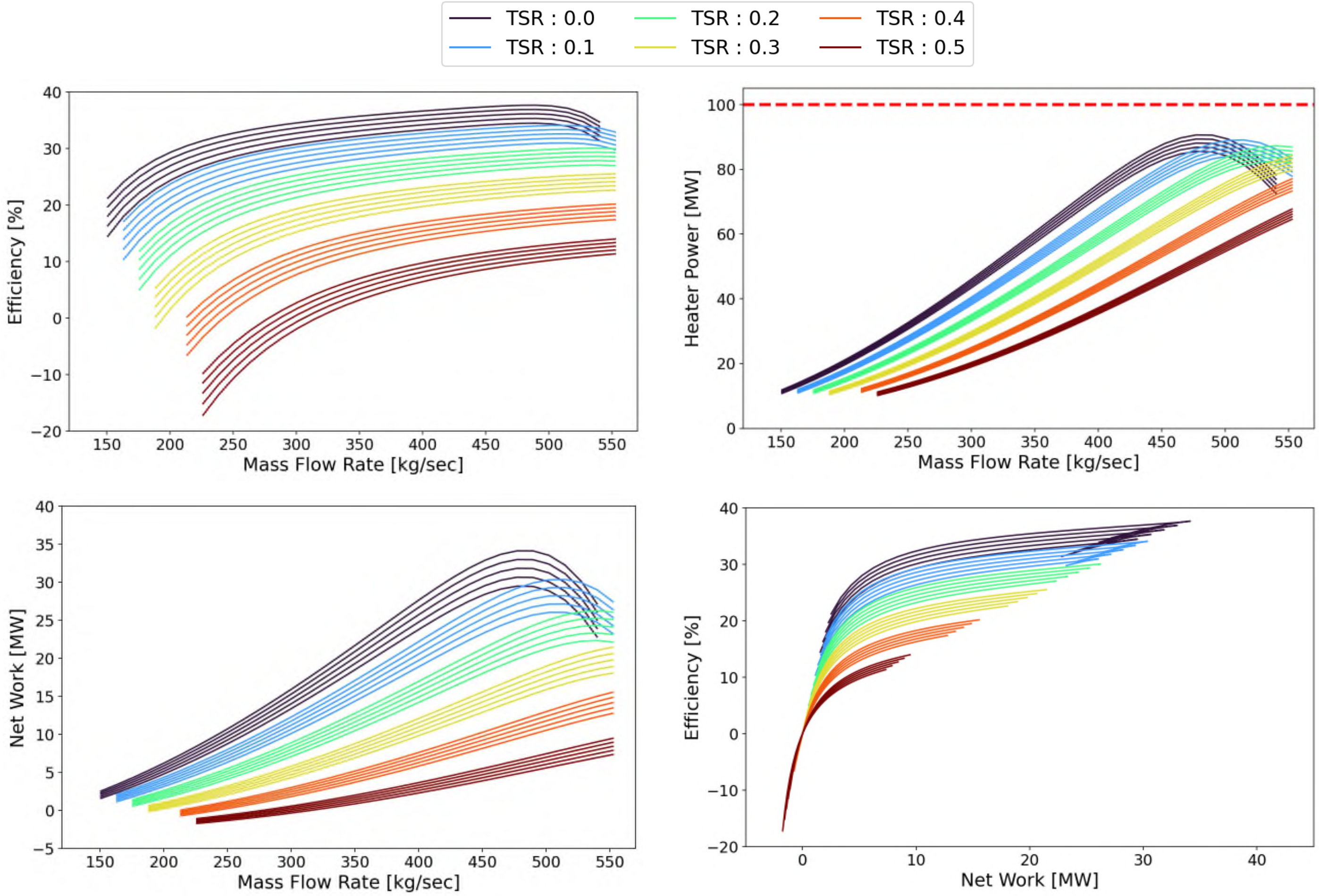
Efficiency

Heater Input

Net Work

Net Work to Efficiency

Inlet Temperature – 39℃



Efficiency

Heater Input

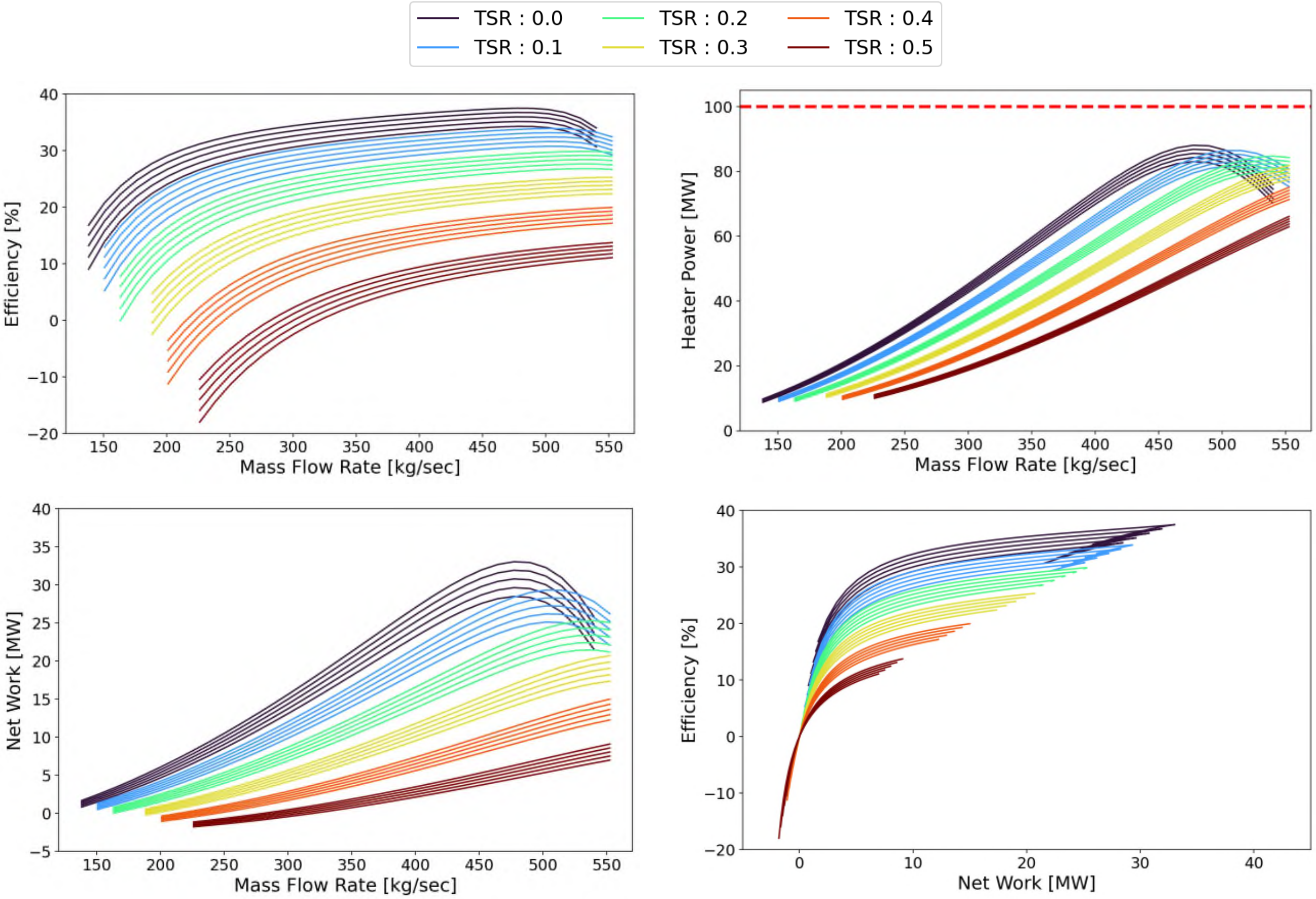
Net Work

Net Work to Efficiency

Inlet Temperature – 40℃

Efficiency

Heater Input

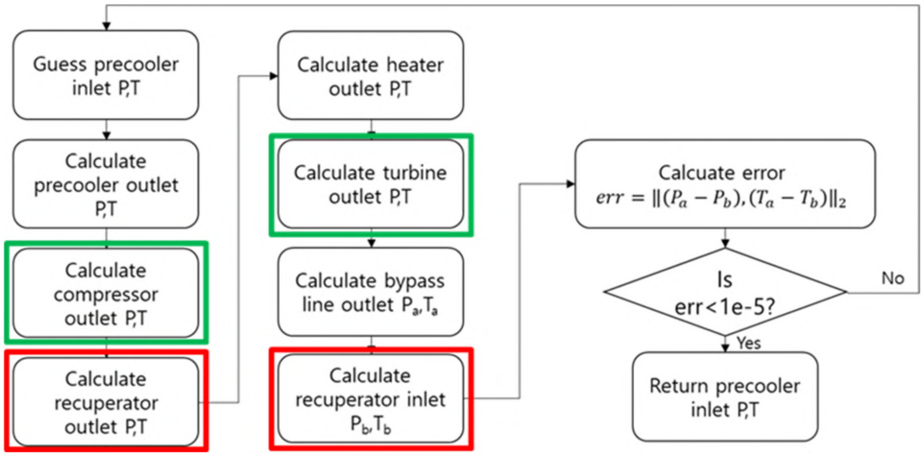


Net Work

Net Work to Efficiency

Quasi-steady-state Analysis

- Quasi-steady-state analysis conducted using the in-house code, KAIST-QCD
- Utilize components off-design performance code
  - Green: KAIST-QCD
  - Red: KAIST-HXD



Guess precooler inlet P,T

Calculate precooler outlet P,T

Calculate compressor outlet P,T

Calculate recuperator outlet P,T

Calculate heater outlet P,T

Calculate turbine outlet P,T

Calculate bypass line outlet P_a,T_a

Calculate recuperator inlet P_b,T_b

Calcuate error

$err = \|(P_a - P_b),(T_a - T_b)\|_2$

Is err<1e-5?

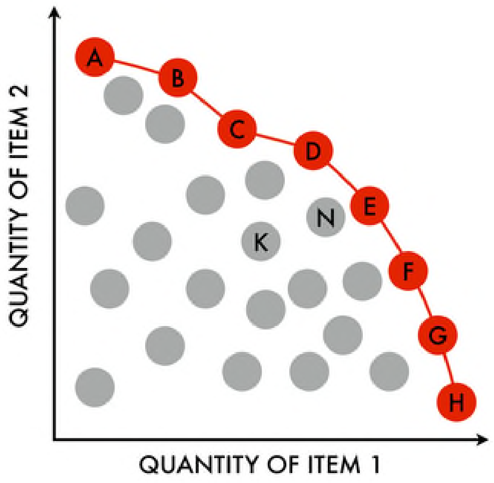
No

Yes

Return precooler inlet P,T

Quasi-steady-state Analysis Results

- Optimal operation condition: **Maximize efficiency at same power**
- Pareto front at Net work vs Efficiency Graph
- Need to compare Pareto front at each compressor inlet temperature



Simulation Results