Research Activities @ KAIST 2024-2026

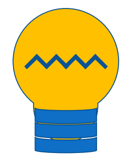
Prof. Jeong Ik Lee
KAIST

Overview of KAIST NPNP lab

Traditional TH Nuclear Safety+ ML

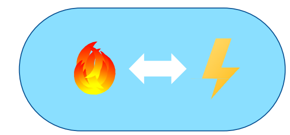
- ✓ Light Water Reactor Safety
- ✓ Big Data generation for Machine Learning
- ✓ Connecting Nuclear Safety with Machine Learning

Next Generation Power Conversion

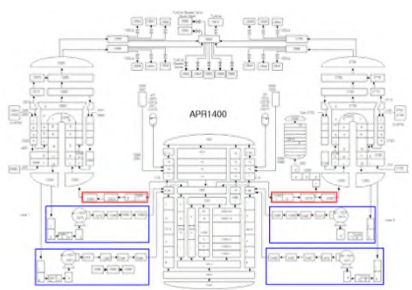


- ✓ Supercritical CO_2 Power
- ✓ Gas turbine for Nuclear Battery
- ✓ Ocean Nuclear
- ✓ Small and Micro Modular Reactor Systems

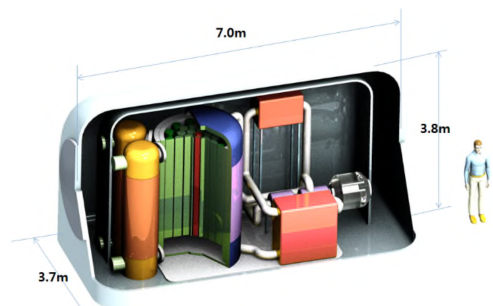
Energy Storage



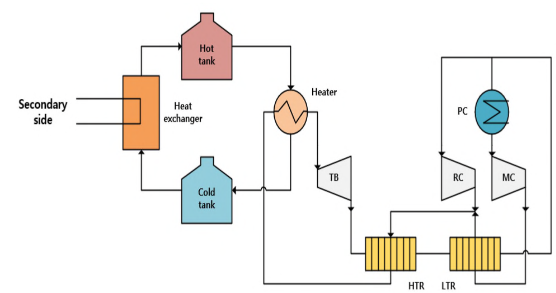
- ✓ Renewable-Nuclear Hybrid
- ✓ Load following with ESS
- ✓ ESS Optimization
- ✓ Grid Simulation



Nuclear Safety Analysis



KAIST Micro Modular Reactor



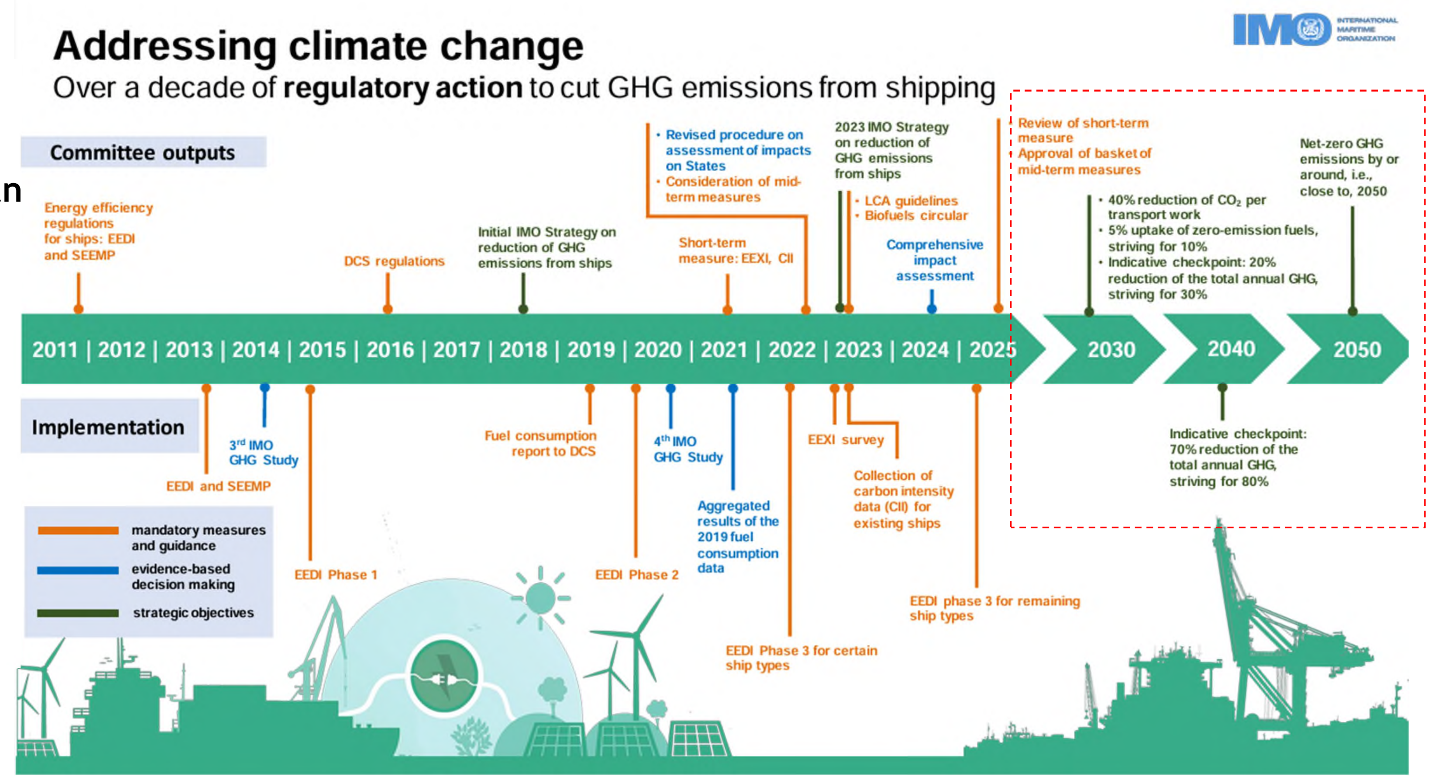
Thermal Energy Storage

Energy Transition in Maritime Transport

sCO_2 Power cycle benefits: Compact, High Efficiency, Simple

Top 10 Shipbuilding Companies

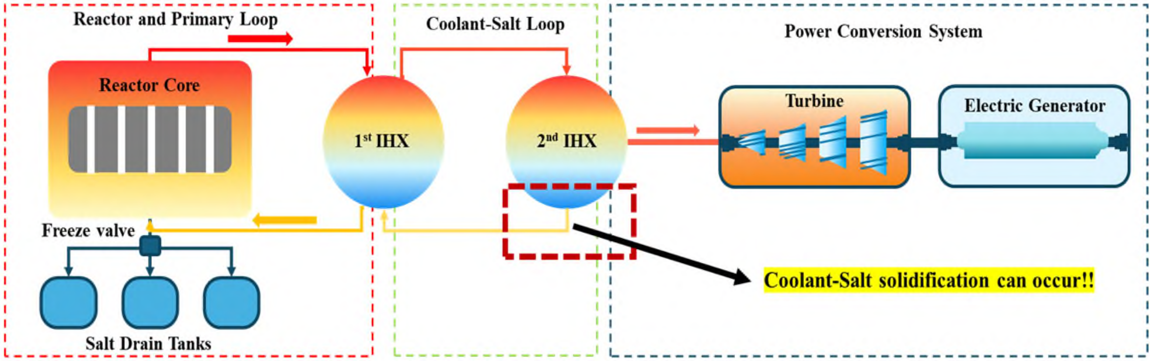
- Hyundai Heavy Industries Group
- Daewoo Shipbuilding & Marine Engineering (DSME) → Hanwha Ocean
- China State Shipbuilding Corporation (CSSC)
- Samsung Heavy Industries
- Mitsubishi Heavy Industries (MHI)
- China Shipbuilding Industry Corporation (CSIC)
- Fincantieri
- Japan Marine United Corporation (JMU)
- Aker Solutions
- Navantia



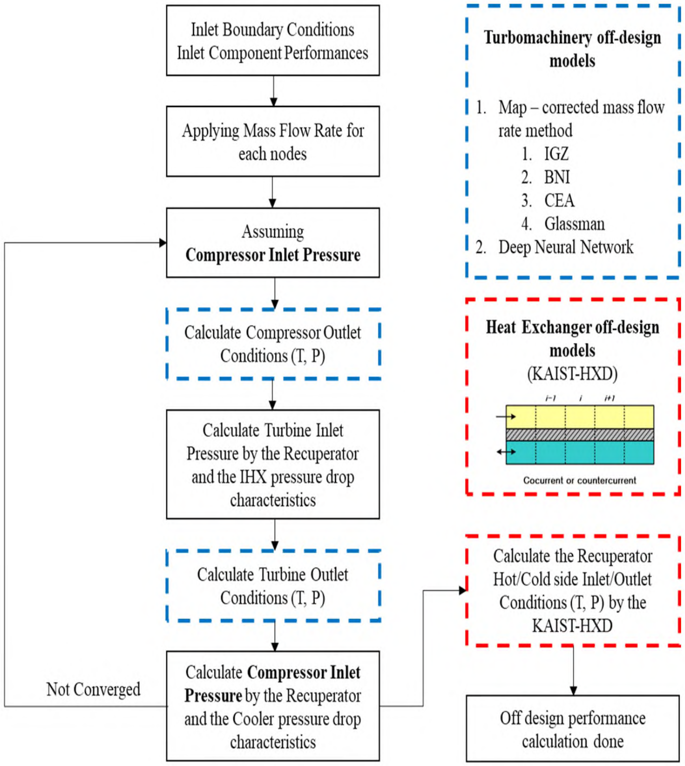
Major Research Questions:
Autonomous ?, Load Following ?, Nuclear ?

Molten Salt Reactor (MSSR) for Marine Propulsion

- Transients in MSR-sCO_2 marine propulsion system during part-load operation is studied
- By using KAIST-QCD, quasi-steady-state analysis code, control target and goal were set.
- The minimum load achievable without issues is explored with transient simulation.



Configuration of MSR-sCO_2

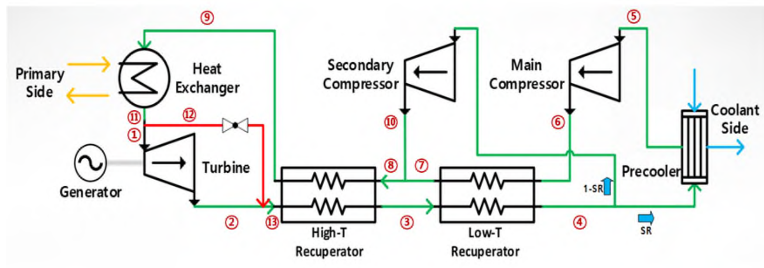


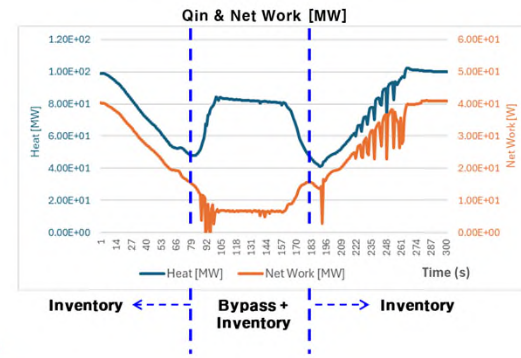
Main Algorithm of KAIST-QCD

sCO_2 Power Cycle Transient Analysis

◆ Control parameters and strategies

1. Split ratio = 0.7
2. CIT control by coolant water $\dot{m}$
3. Inventory control with pressure tanks
4. Turbine bypass control
5. Molten salt $\dot{m}$ following demanded power





◆ Limitations and Lessons learned

1. Limitation of PID control

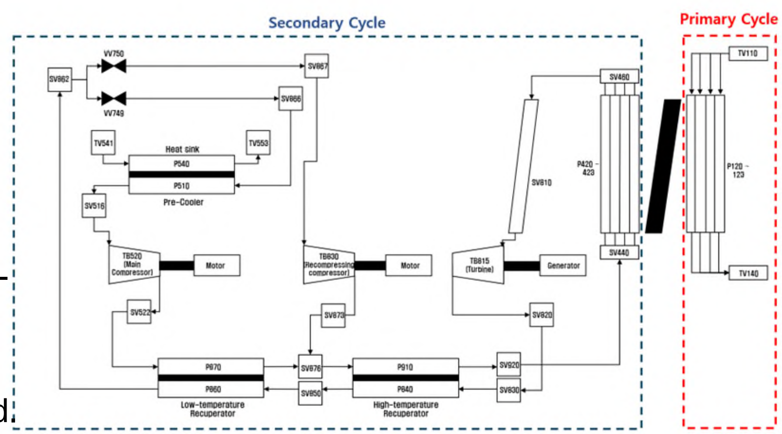
➢ Need advanced or ML control methodology.

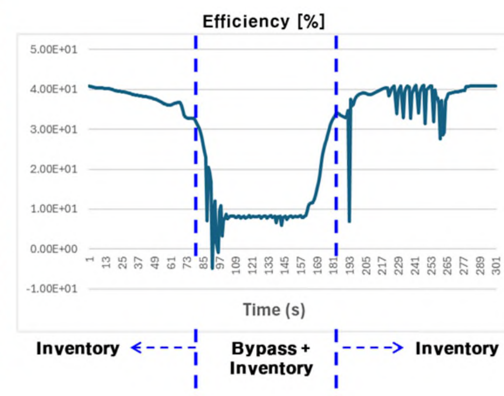
2. Model improvement necessary

➢ Method to construct accurate turbomachinery off-design map is needed.

3. Reaching 0% power without safety concern

➢ Coolant salt solidification issue should be solved.

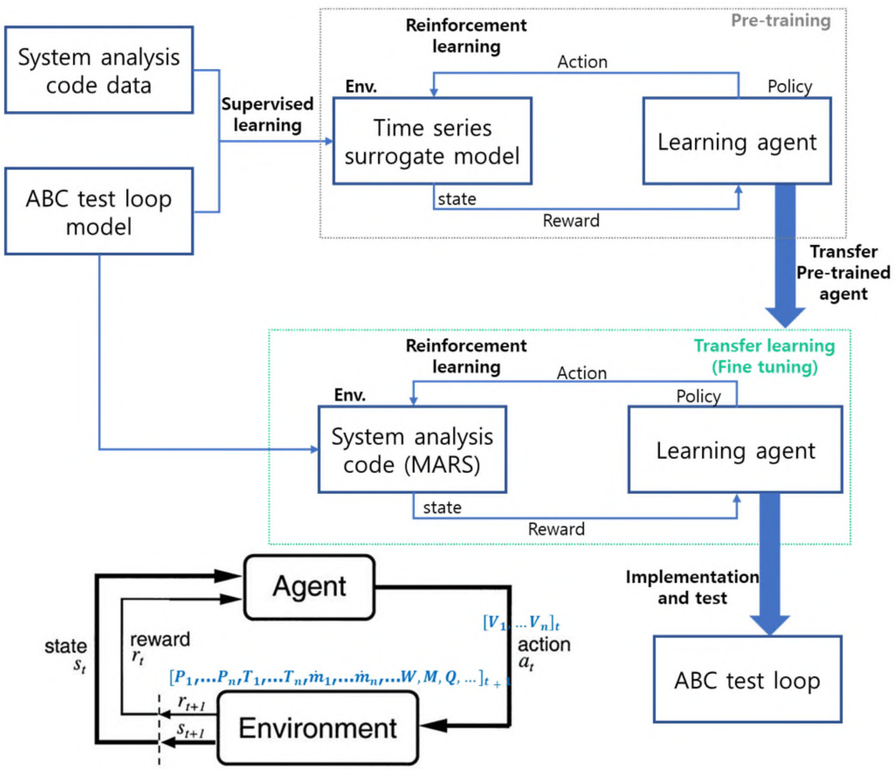




Autonomous ?

Deep Reinforcement Learning (DRL) for the Flexible Operation of S-CO_2 Power Cycle

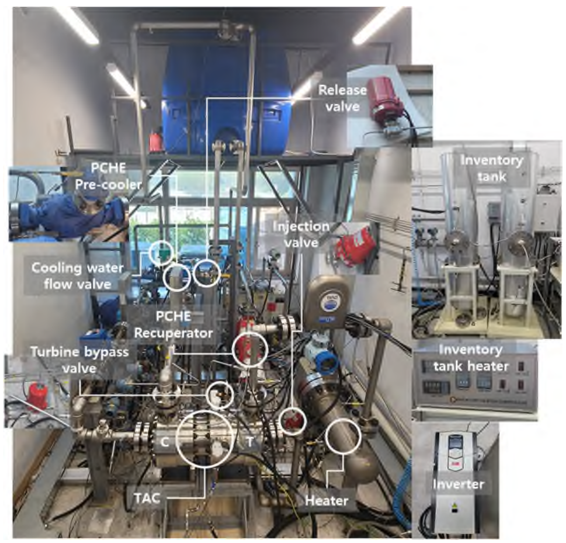
- DRL offers a way to simultaneously optimize multiple control variables and thereby achieve system-level control
- By increasing the number of independent state and control variables, DRL enables a more holistic optimization
- DRL-based Controller
  1. Trained in the KAIST ABC Test Loop
  2. Validated whether the controller trained in the simulation environment could effectively control the actual hardware facility
- Pre-training: in the time series surrogate model
- Post-training: transfer learning with the system analysis code environment



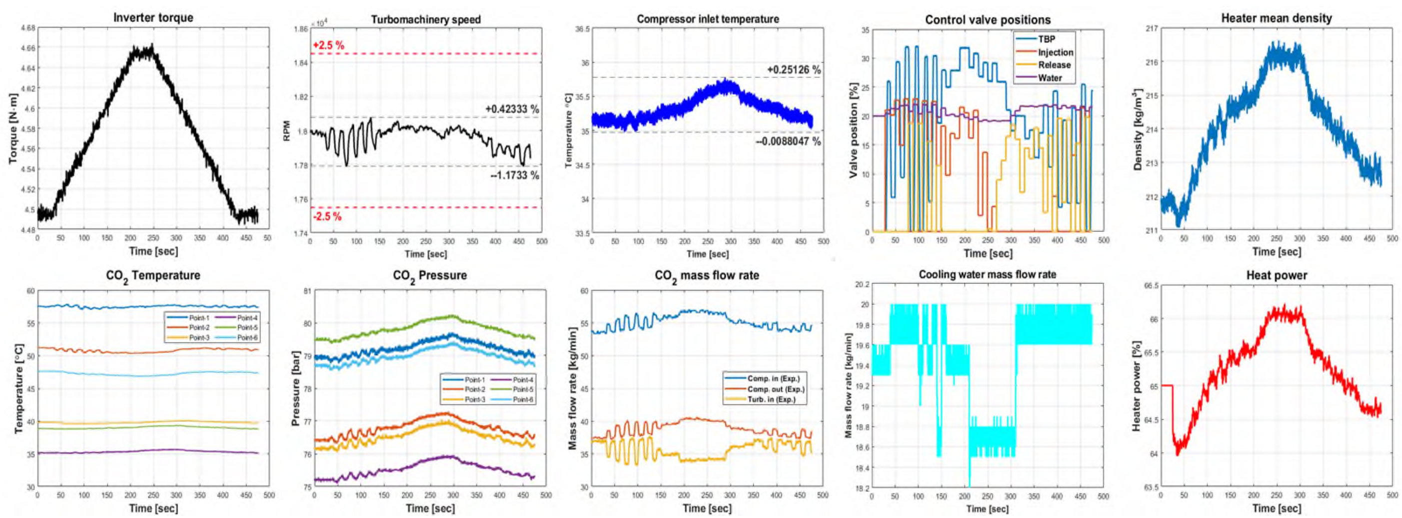
Autonomous ?

Deep Reinforcement Learning (DRL) for the Flexible Operation of S-CO_2 Power Cycle

- The DRL agent, which was pre-trained in the time-series surrogate model and post-trained in the system analysis code environment, is able to effectively control the actual hardware.



KAIST ABC Test Loop

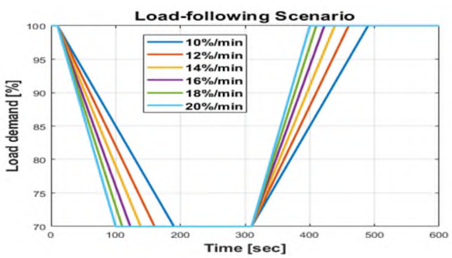


Hardware control test results with the post-TL agent

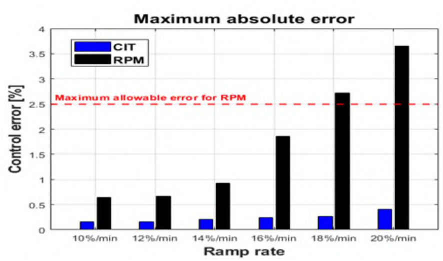
Autonomous ?

Deep Reinforcement Learning (DRL) for the Flexible Operation of S-CO_2 Power Cycle

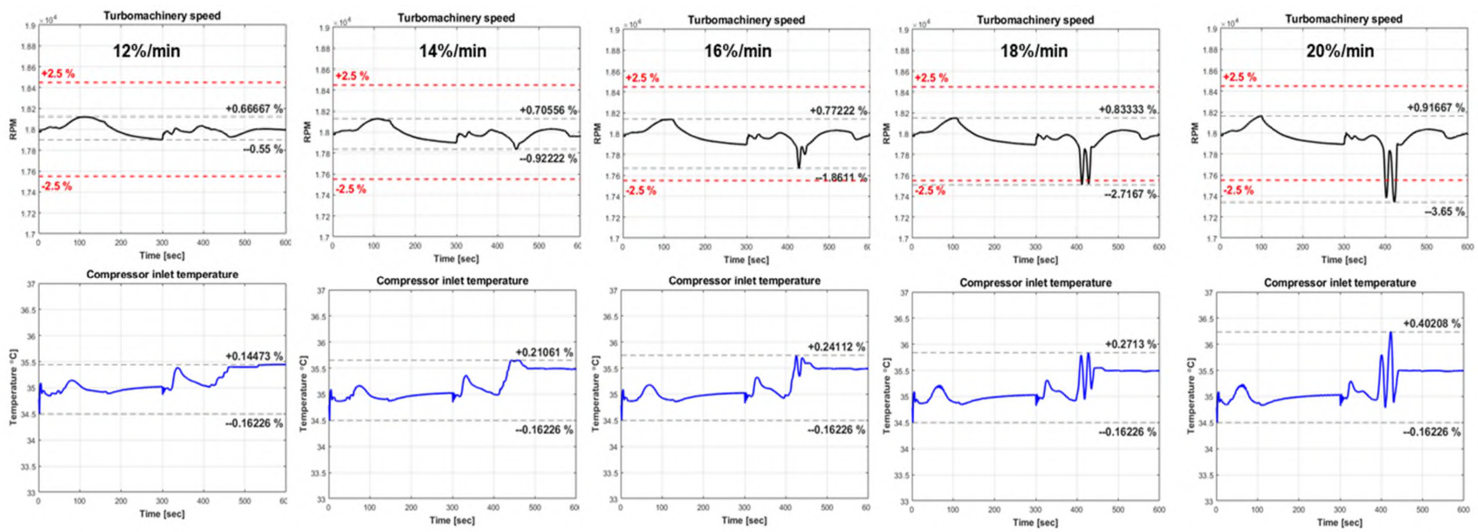
- DRL agent has demonstrated robustness in untrained scenario beyond a trained range
- It was trained for a 10%/min ramp rate
- Robustness demonstrated within allowable limits up to a 16%/min ramp rate.



Test scenarios



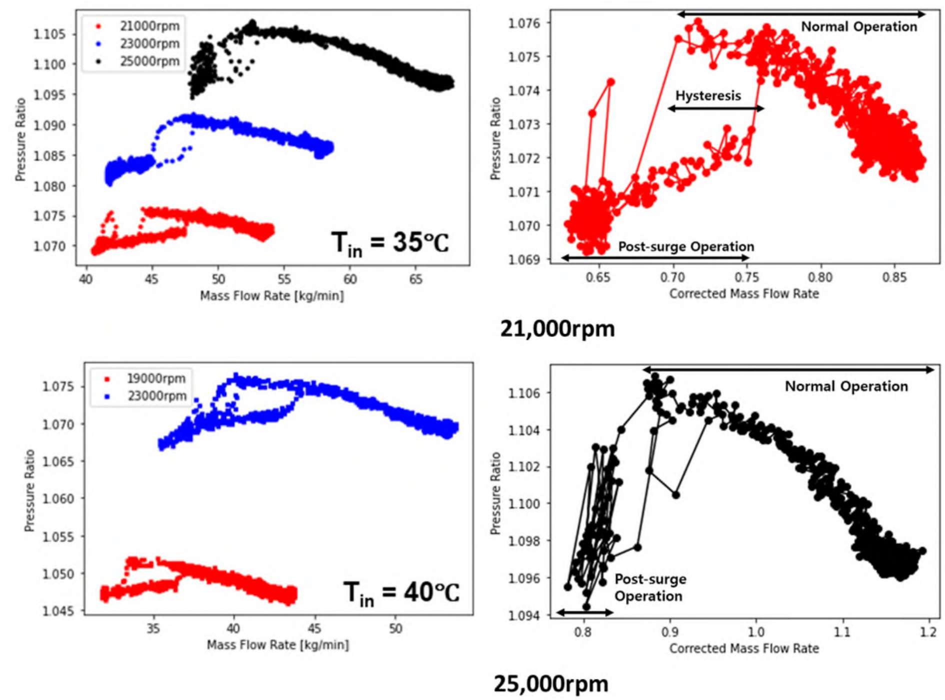
$|E\_max|$ vs ramp rate



Control performance under different ramp rate scenarios

Compressor Surge and Post-Surge Behavior

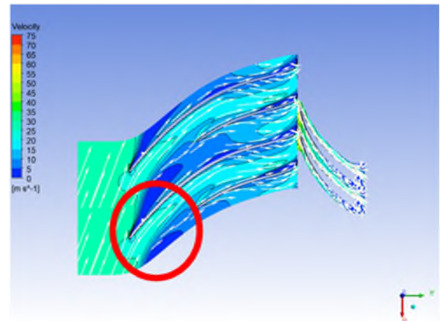
- Compressor surge and post-surge behavior is studied experimentally and analytically
- Inlet temperature and system CO_2 inventory affect surge behavior of compressor
  - The inlet temperature changes the type of instability from surge to rotating stall
- Surge and rotating stall can be distinguished by post-surge and recovery performance
- Continuously conducting experimental studies on post-surge behavior under various inlet conditions

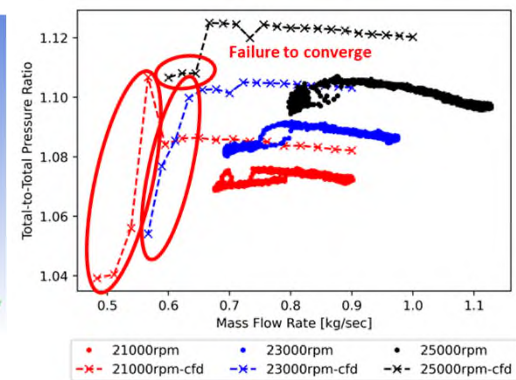


Load-Following ?

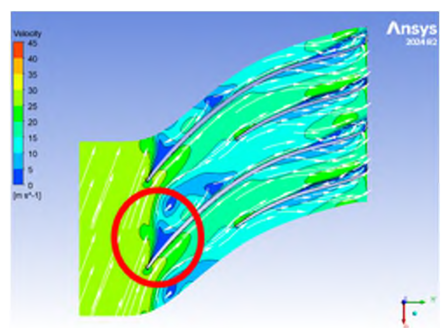
Compressor Surge and Post-Surge Behavior

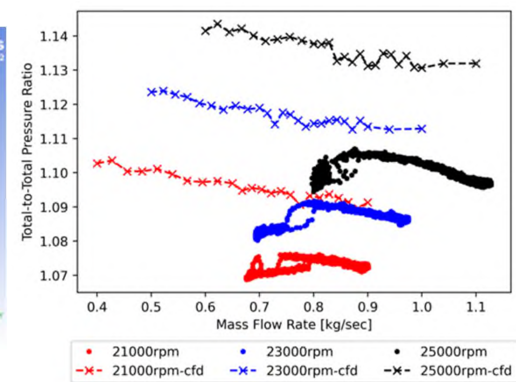
- Research is being conducted to predict flow rates at which surges occur based on CFD
- When CFD was performed on the blade alone versus including the diffuser, it showed significant differences in results within the surge region
- Research is continuously being conducted to accurately predict surges through CFD





Blade & Diffuser





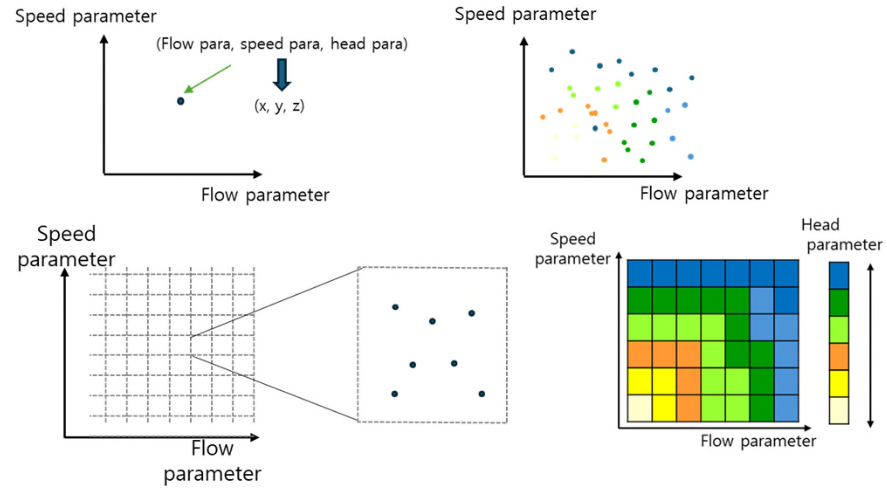
Only Blade

Load-Following ?

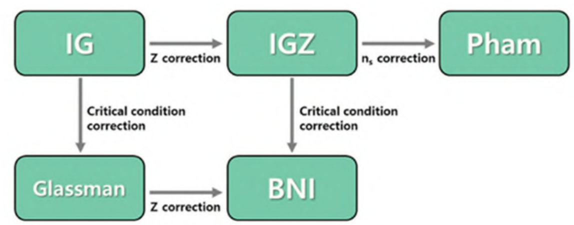
Heatmap-based turbomachinery off-design performance representation

- A method was proposed that clearly displays large amounts of experimental data and can reflect the nonlinear properties of sCO_2.

1. Using the real gas model, $\dot{m}$, RPM, Δh are converted into flow, speed, head parameters, respectively.
2. Set the flow and speed parameters as the x and y axes, respectively. Divide the data into small cells and collect data points falling within each cell.
3. Calculate the average of the head parameter for the collected data points and represent this as a heatmap.



	Flow parameter	Speed parameter	Head parameter
IG	$\frac{\dot{m}\sqrt{\gamma RT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma RT}}$	$\frac{\Delta H}{\gamma RT}$
IGZ	$\frac{\dot{m}\sqrt{\gamma ZRT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma ZRT}}$	$\frac{\Delta H}{\gamma ZRT}$
Glassman	$\frac{\dot{m}\sqrt{\gamma RT_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma RT_{cr}}}$	$\frac{\Delta H}{\gamma RT_{cr}}$
BNI	$\frac{\dot{m}\sqrt{\gamma ZRT_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma ZRT_{cr}}}$	$\frac{\Delta H}{\gamma ZRT_{cr}}$
Pham	$\frac{\dot{m}\sqrt{n_s ZRT}}{n_s P}$	$\frac{N}{\sqrt{n_s ZRT}}$	$\frac{\Delta H}{n_s ZRT}$

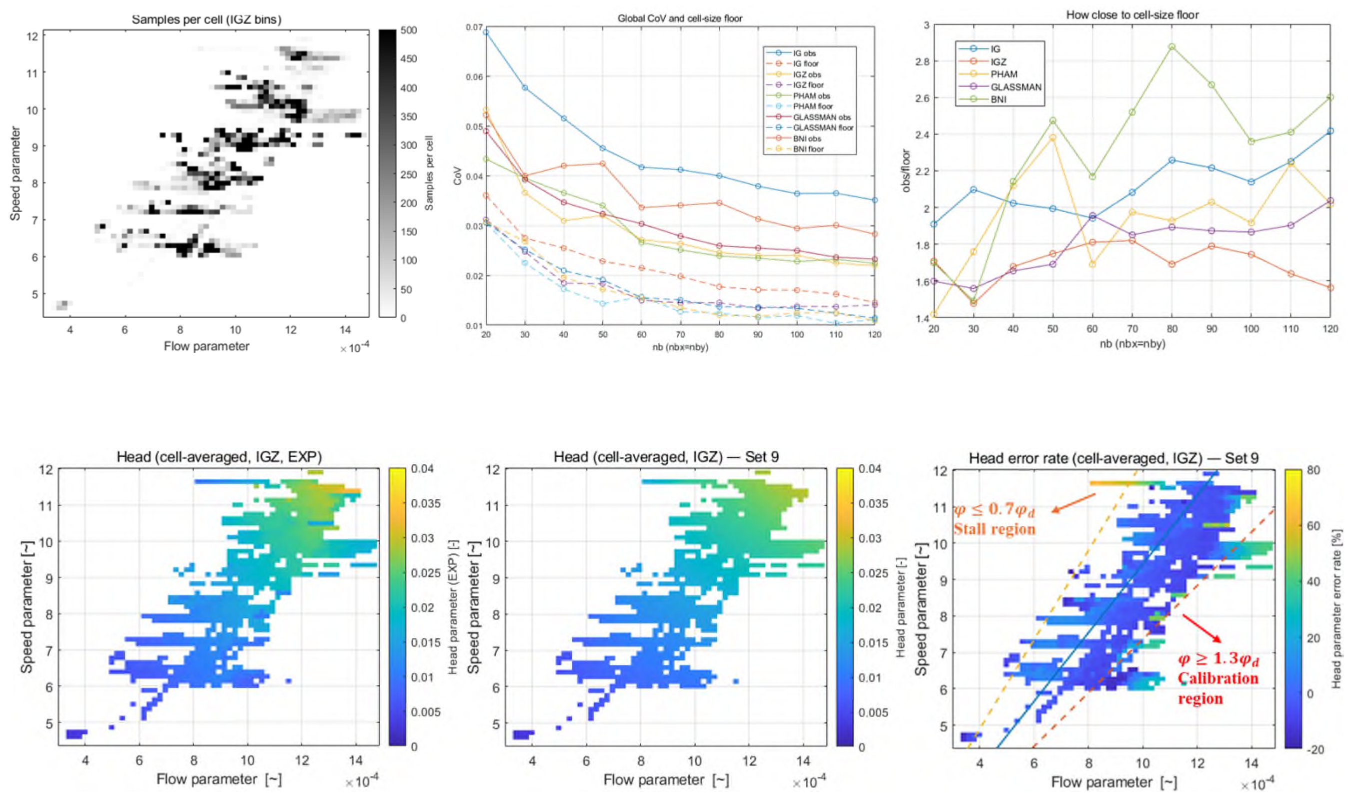


Load-Following ?

Heatmap-based turbomachinery off-design performance representation

- Using the presented method, the following tasks can be performed.

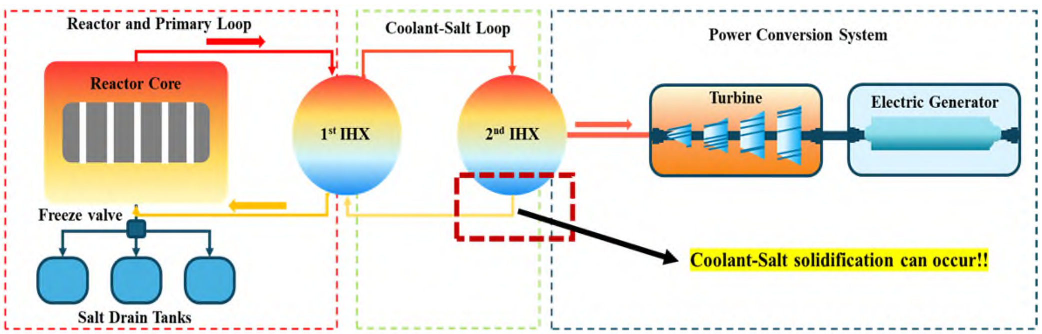
1. The number of samples in each cell can be checked for statistical meanings.
2. Standard deviation of the z-values can be used to evaluate the real gas models.
3. 1-D code verification with the experimental data. Identifying the areas where large errors occur, enabling modifying in those sections.



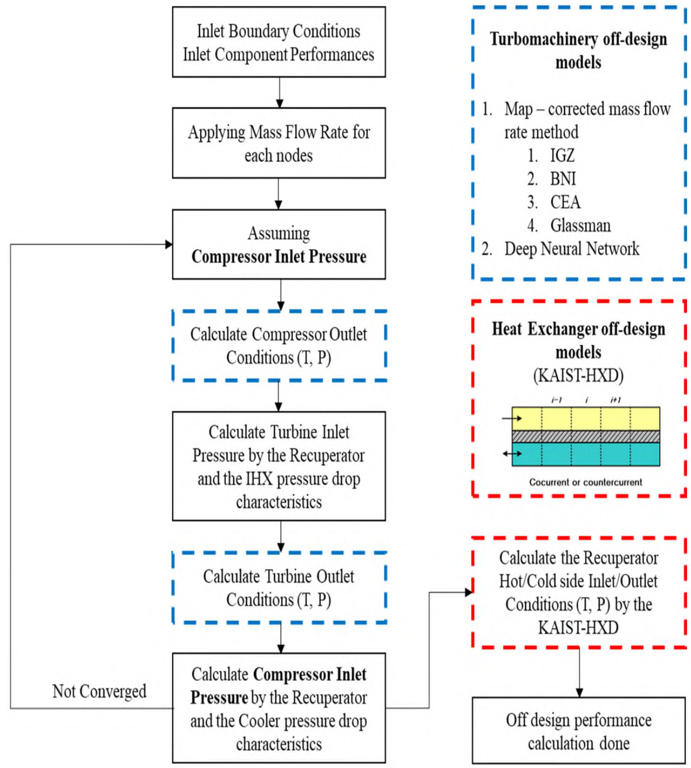
Nuclear ?

Coolant-Salt Solidification in MSR for Marine Propulsion

- Coolant-salt solidification in MSR-sCO_2 marine propulsion system during part-load operation is studied
- By using KAIST-QCD, quasi-steady-state analysis code, coolant-salt solidification is analyzed
- After identifying the minimum load achievable without solidification, a new control strategy was developed to enable operation down to 0% load



Configuration of MSR

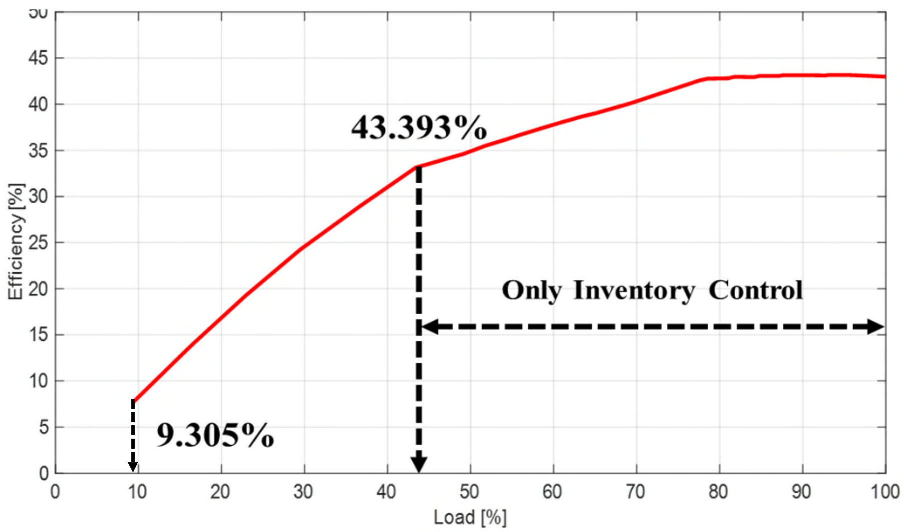


Main Algorithm of KAIST-QCD

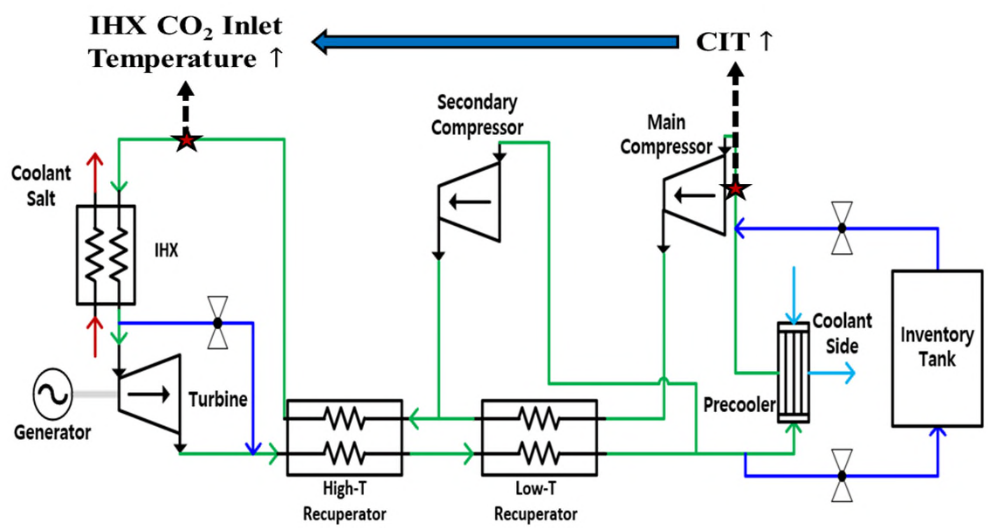
Nuclear ?

Coolant-Salt Solidification in MSR for Marine Propulsion

- With inventory control and turbine bypass control, the minimum achievable load without solidification is 9.3%
- Solidification is avoided by raising IHX inlet CO_2 temperature via higher CIT
- Higher CIT also increases compressor work by moving away from the critical point



Part-Load Operation Results

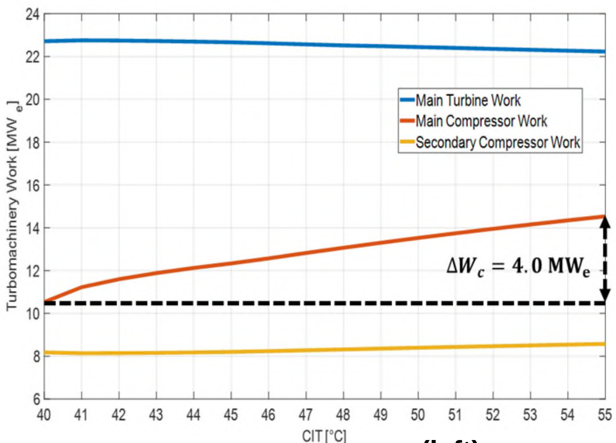


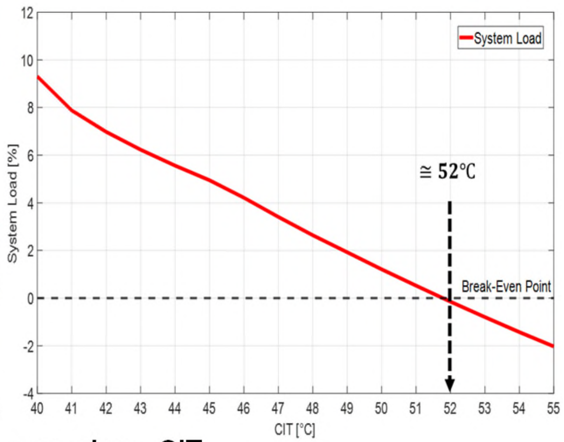
CIT control for preventing coolant-salt solidification

Nuclear ?

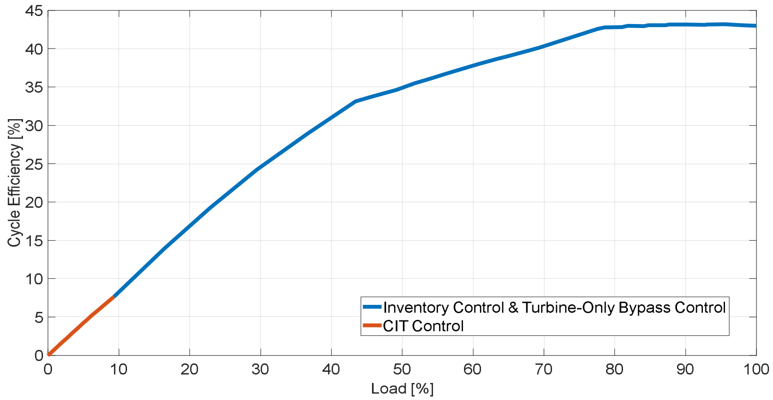
Coolant-Salt Solidification in MSR for Marine Propulsion

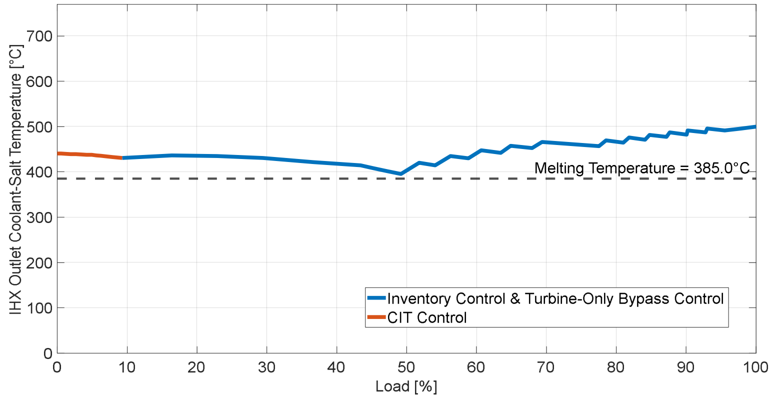
- Increasing CIT kept the IHX inlet CO_2 temperature above the melting point
- Increasing CIT increased main compressor work, enabling solidification free operation down to 0% load
- CIT control mitigated coolant-salt solidification during part load operation





(left) compressor work vs. CIT
(right) system load vs. CIT



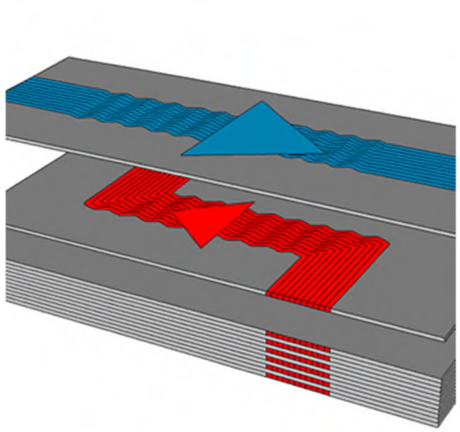


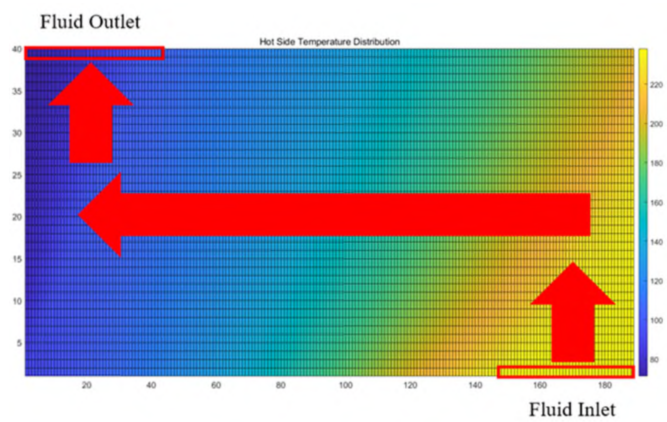
Part-Load Operation Results with CIT Control

Nuclear ?

2-D Printed Circuit Heat Exchanger Analysis

- The two-dimensional PCHE analysis code was improved and evaluated based on experimental data.
- From the perspective of both heat transfer and pressure drop, the 2D results are closer to the experimental values than the 1D results.





	Parameter	1D	2D	Experiment
Input	Hot Side Mass Flow Rate [kg/s]	1.333		
	Hot Side Inlet Temperature [℃]	57.770		
	Cold Side Mass Flow Rate [kg/s]	0.980		
	Cold Side Inlet Temperature [℃]	42.891		
Output	Hot Side Outlet Temperature [℃] (Percentage Error [%])	45.006 (1.63)	45.107 (1.41)	45.750
	Cold Side Outlet Temperature [℃] (Percentage Error [%])	55.436 (3.83)	55.790 (4.50)	53.390
	Hot Side Pressure Drop (Core) [kPa] (Percentage Error [%])	33.752 (60.71)	60.181 (29.95)	85.910
	Cold Side Pressure Drop (Core) [kPa] (Percentage Error [%])	16.317 (60.40)	29.100 (29.37)	41.200
	Heat Duty [kW] (Percentage Error [%])	38.004 (12.74)	36.872 (9.38)	33.709

Nuclear ?

2-D Printed Circuit Heat Exchanger Analysis

- In the case of comparing Coolant-Salt Solidification, analysis based on 1D FDM shows no solidification occurs, whereas analysis based on 2D FDM indicates partial solidification may occur at the outlet.
- Cross flow should be reflected when evaluating heat exchangers.