Evaluation of S-CO_2 Compressor Inlet Temperature Controllers

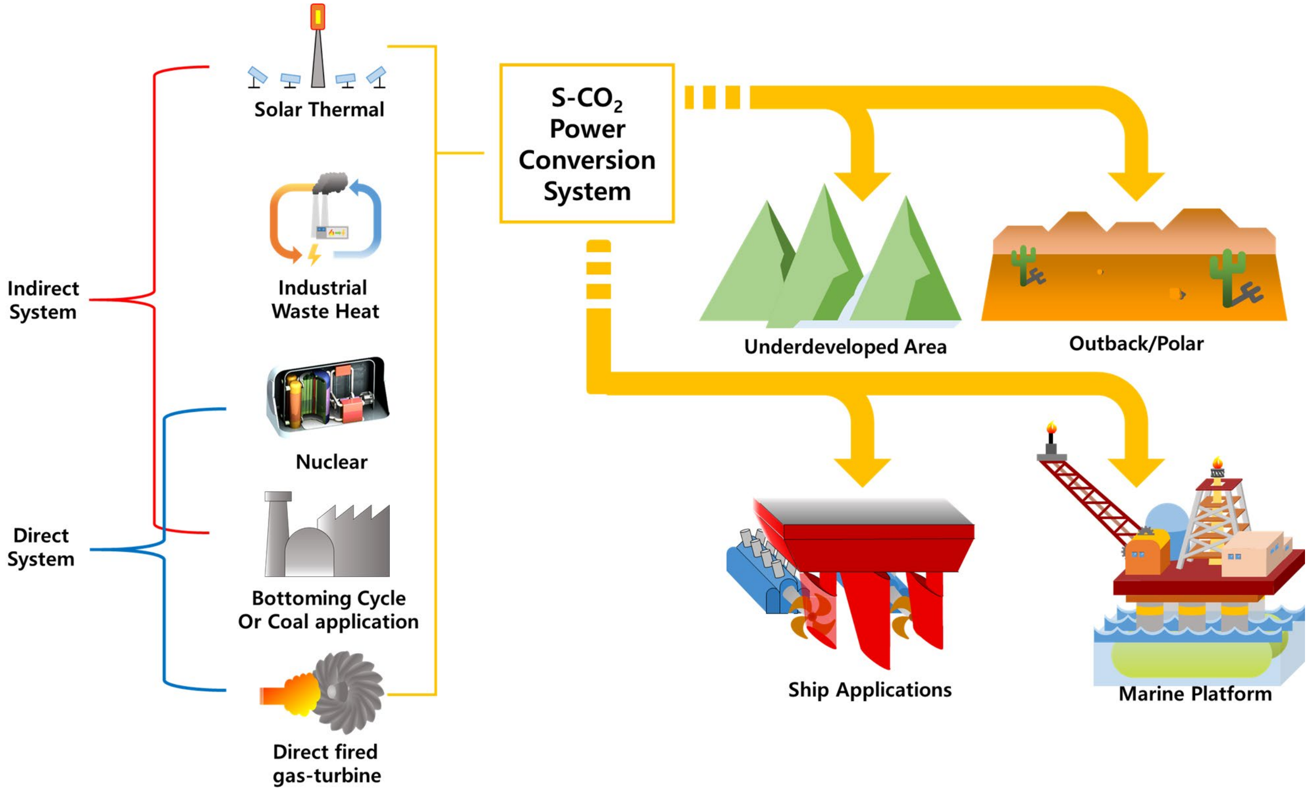
Gihyeon Kim (KAIST), Seungkyu Lee (KAIST),
In Woo Son (KAIST), Jeong Ik Lee (KAIST),

contact email : orca2005@kaist.ac.kr

Introduction

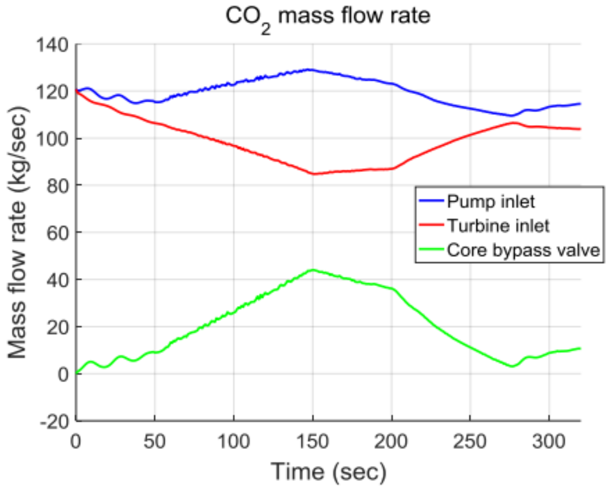
- S-CO_2 power conversion system are adaptable to a variety of heat sources with a variety of applications.
  - Waste heat recovery
  - Marine propulsion
  - Distributed generation

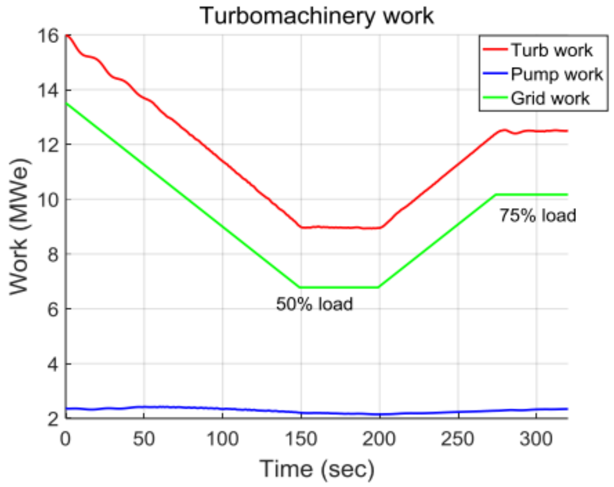
- The output of the S-CO_2 power conversion system should be changing by applications need and sources input.

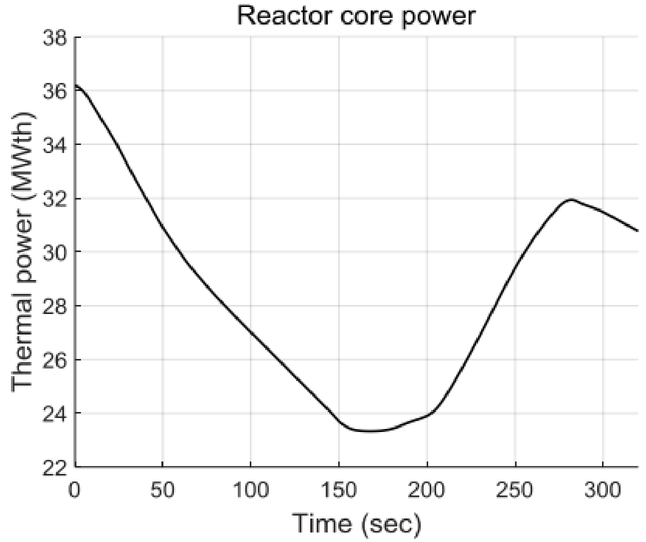


Introduction

- Load-following operation is possible using well-studied control strategies.
- Using known control strategies, system mass flow rate and the work of the turbomachinery changes.
- This changes make the inlet properties of the compressor changes, which is the closest to the critical point.

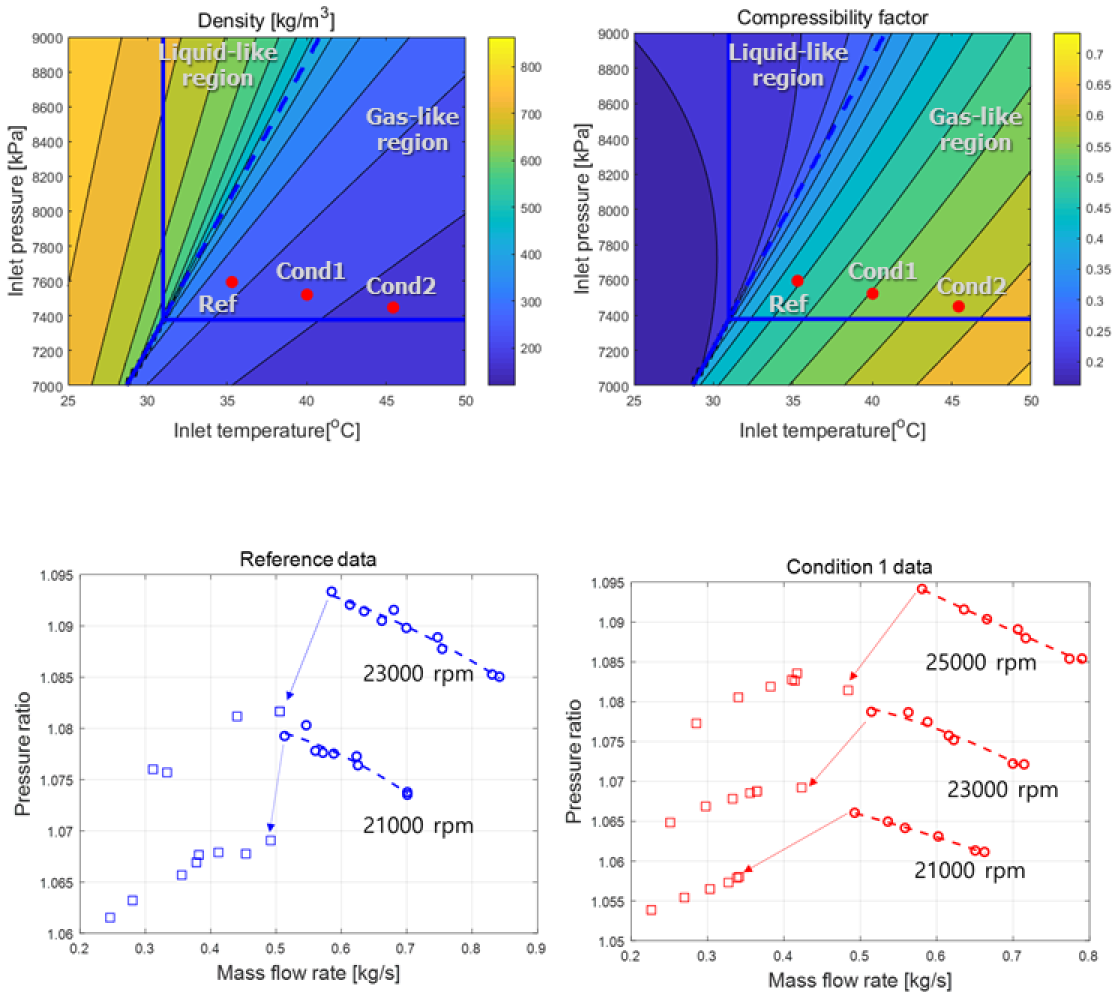






Introduction

- The changes in compressor inlet temperature and pressure affect:
  - Compressor related thermodynamic properties
  - Compressor surge line
  - Compressor efficiency
  - Compressor safety margin
- For safe and efficient compressor operation during the load following, compressor inlet condition control is required.



Introduction

- Previous compressor inlet temperature control research has been mostly code-based and lacked experimental validation.
- The organic Rankine cycle (ORC) is well studied for control because the nonlinearity of the system prevents classical PID methods from working well.
- S-CO_2 passing through a precooler also exhibits nonlinear thermophysical properties, requiring an ORC-like approach.

Compressor Inlet Temperature Controller Researches

Organization	Controller Type	Experiment or code	Year
SNL	Manual Control	Experiment	2010
ANL	PI; Trial and Error	Code	2015
KAIST	PID; Ziegler-Nichols	Code	2016
Rolls-Royce	PID; Transfer Function	Code	2018

Summary of Control Techniques for ORC Systems

Control technique	Linear/Nonlinear	Development effort	CPU effort	Performance
PID (empirical)	N/A	+	+++	-
LQ	Linear	-	+	++
Adaptive	Linear/Nonlinear	-	---	+++

Introduction

- In order to generalize the process, system modelling and controller design are carried out using simulation code only.
- The designed controllers are evaluated using the S-CO_2 experimental loop.

System Modeling
- Modeling precooler based on simulation
- Achieve transfer function of the precooler system

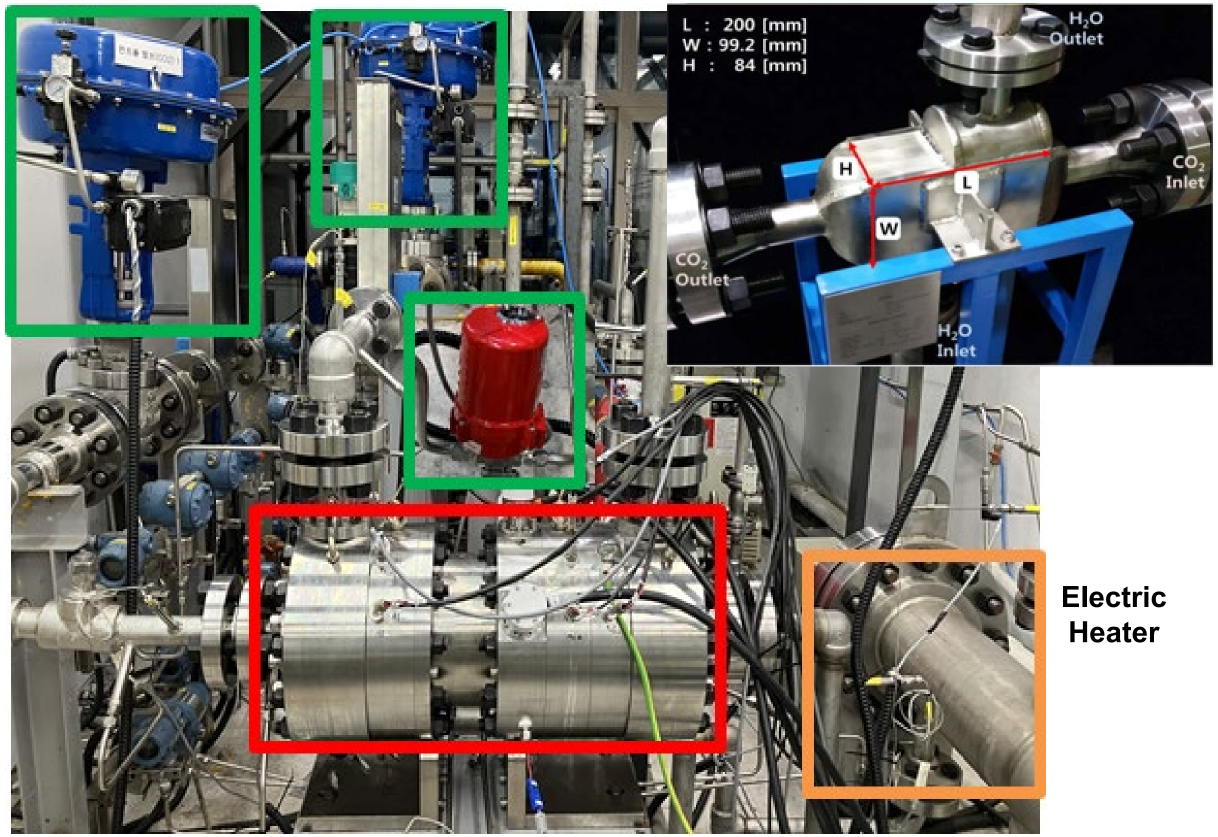
Controller Design
- Choose controller candidate
- Design controller based on precooler system model

Controller Evaluation
- Adopt designed controller to the experiment system
- Evaluate controller based on scenario

Introduction

ABC Test Loop

- Designed for an integrated experiment on the simple recuperated S-CO_2 cycle
- Enables I/O of data using programmable logic controller and computer using LabVIEW
- Control valves for turbine bypass control and compressor experiment
- Magnetic Bearing Turbo Alternator Compressor (TAC)
- PCHE type precooler and recuperator



Methodology

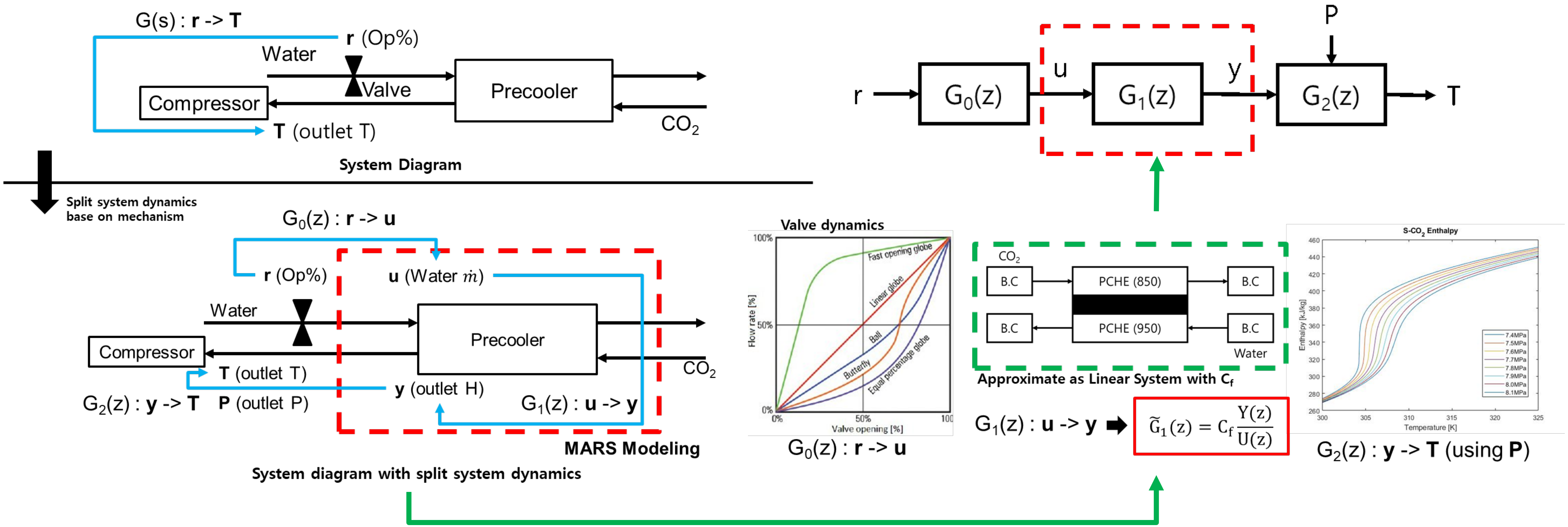
- The Multi-dimensional Analysis of Reactor Safety (MARS) code is a nuclear thermal-hydraulic safety code developed by Korea Atomic Energy Research Institute (KAERI).

- MARS was developed based on USNRC's RELAP5/MOD3.2.1.2 and COBRA-TF to calculate the transient multi-dimensional behavior of thermal-hydraulic systems in light water reactors.

- To conduct MARS simulation for S-CO_2 PCHE system, KAIST research team add two implementations to MARS
  - Precise physical properties of CO_2 based on NIST’s REFPROP
  - Heat transfer correlation of PCHE

- System modelling and controller design only use the data from MARS code.

Methodology



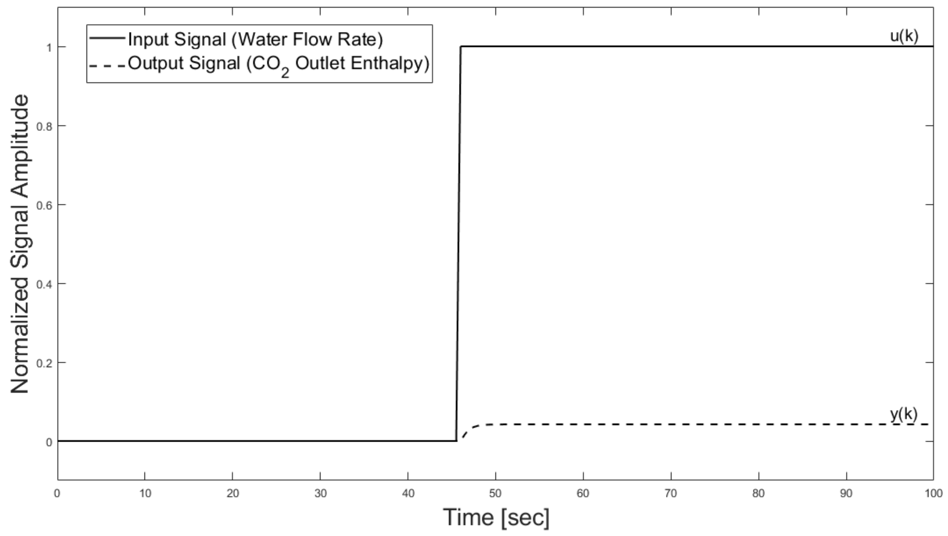
Methodology

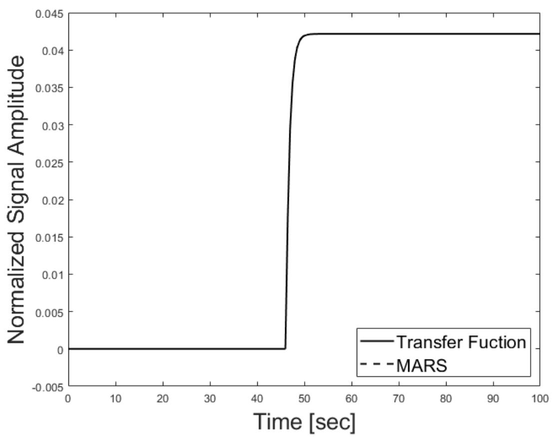
- The input and output signals are used after normalization.

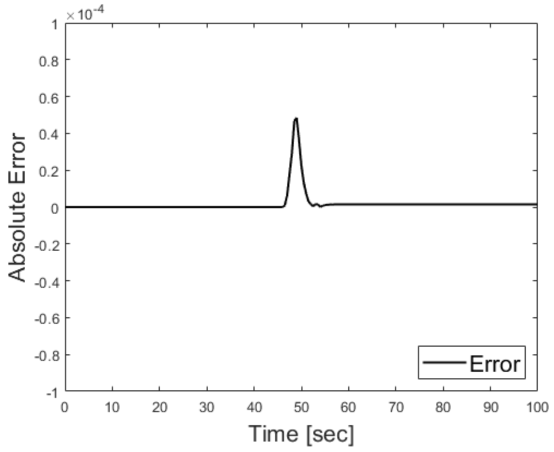
- At the design point, the transfer function is estimated based on the least squares method, using the input and output results of the MARS code.

- For the off-design condition, model $\tilde{G}_{on}(z)$ at the design point was extended by multiplying it with a lumped correction factor C_f.

$$\tilde{G}(z) = C_f \tilde{G}_{on}(z) = C_f \frac{0.01989\, z \;+\; 0.004617}{z^2 - \;0.3074\, z \;-\; 0.1112}$$

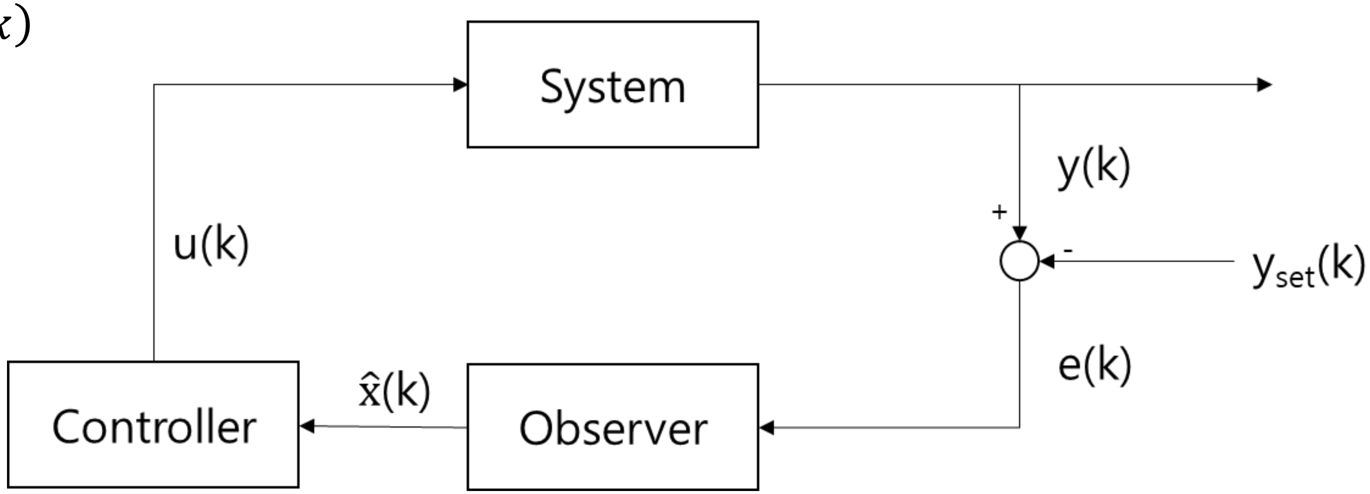






Methodology

- LQ Controller; Optimize control based on the performance index
  - $J = \sum_{k=0}^{n} e^T(k)Qe(k) + u^T(k)Ru(k)$
  - First term penalize errors, second term penalize input.
  - The reason for penalize input is to penalize controller power consumption.
- Feedback parameter K can be obtained using Ricatti equation, which has a proper solution.
- Observer for full state information.

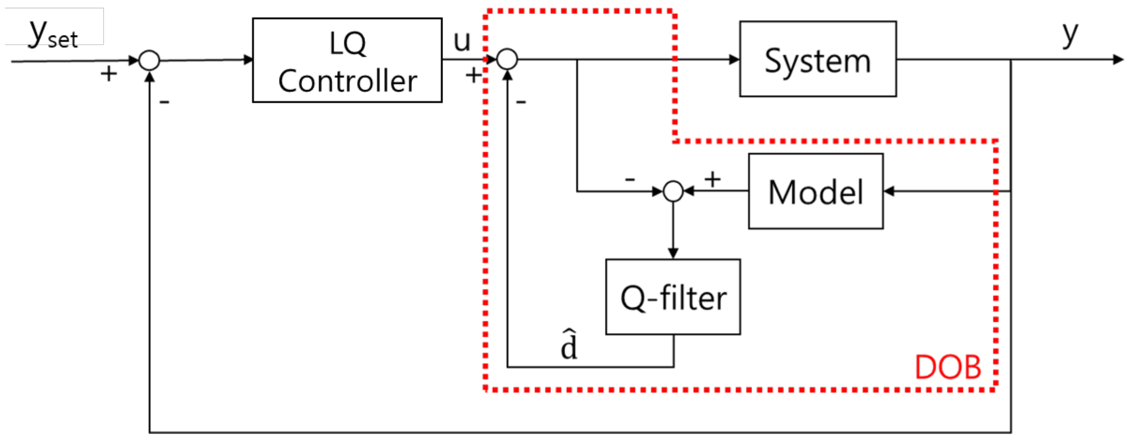


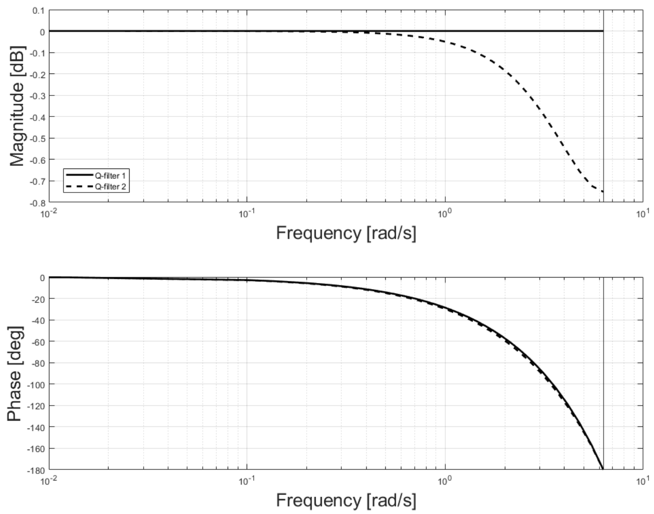
Methodology

- State-state error is likely to occur when use LQ controller directly in the real system.
- Error cause by model uncertainties.
  - Uncertainty in the MARS modeling of the actual system
  - Uncertainty in the estimated transfer function
  - Uncertainty in the lumped correction factor
- Additional controller to reduce state-state error
  - Disturbance OBserver (DOB)
  - Linear Quadratic Integral (LQI)
  - Self-Tuning Controller

Methodology

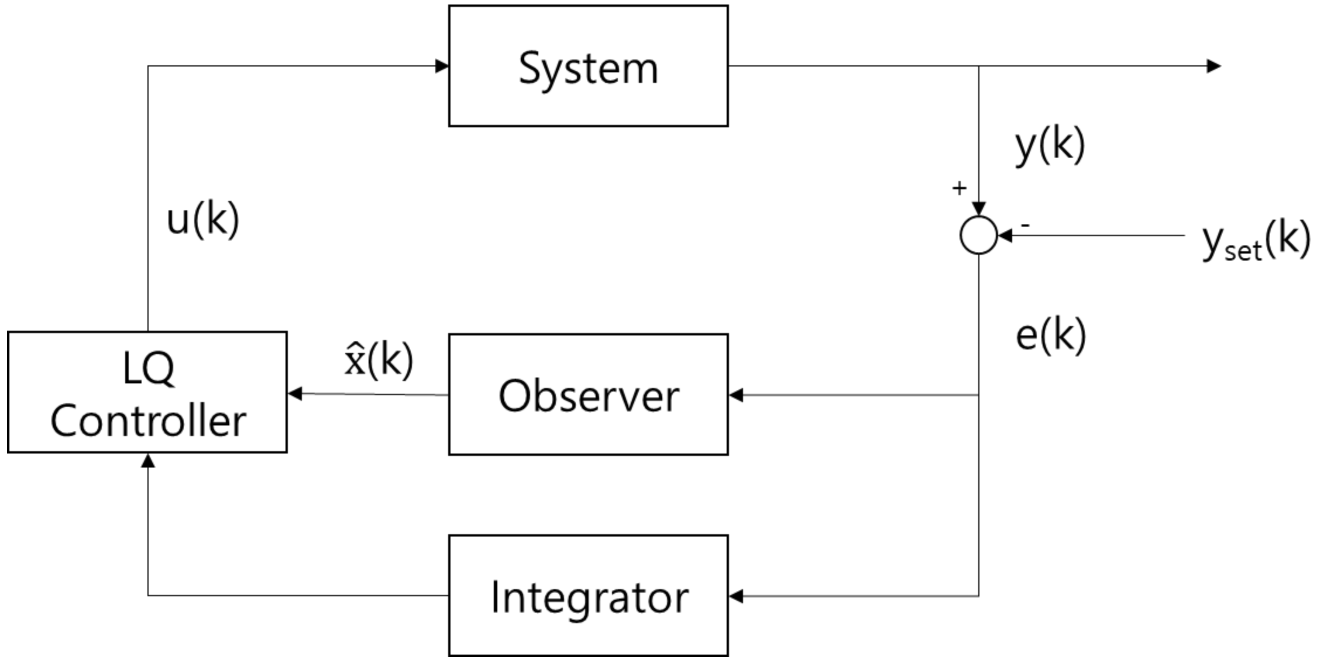
- Disturbance Observer (DOB); force system to follow the model
- Remove the effects of model uncertainty and external disturbances by calculating a lumped disturbance
- Q-filter need to be selected





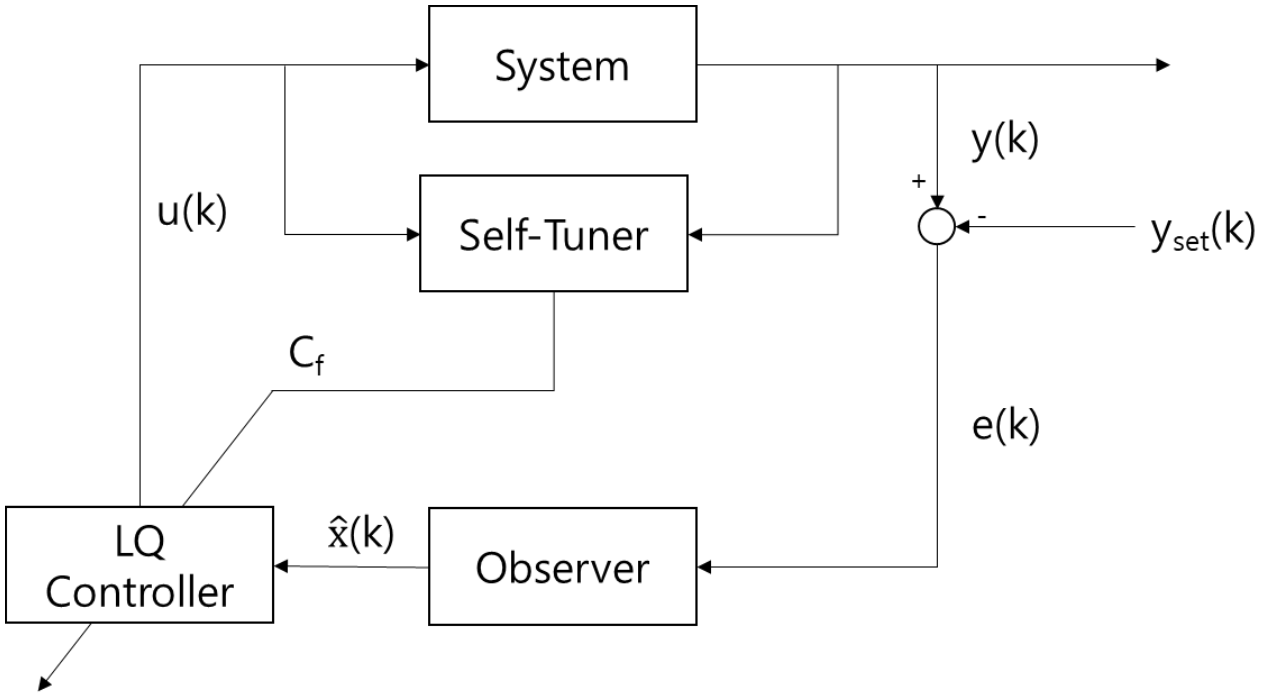
Methodology

- Linear Quadratic Integral (LQI); integrator added to the LQ controller
- The integrator aims to remove steady-state errors due to model uncertainty.



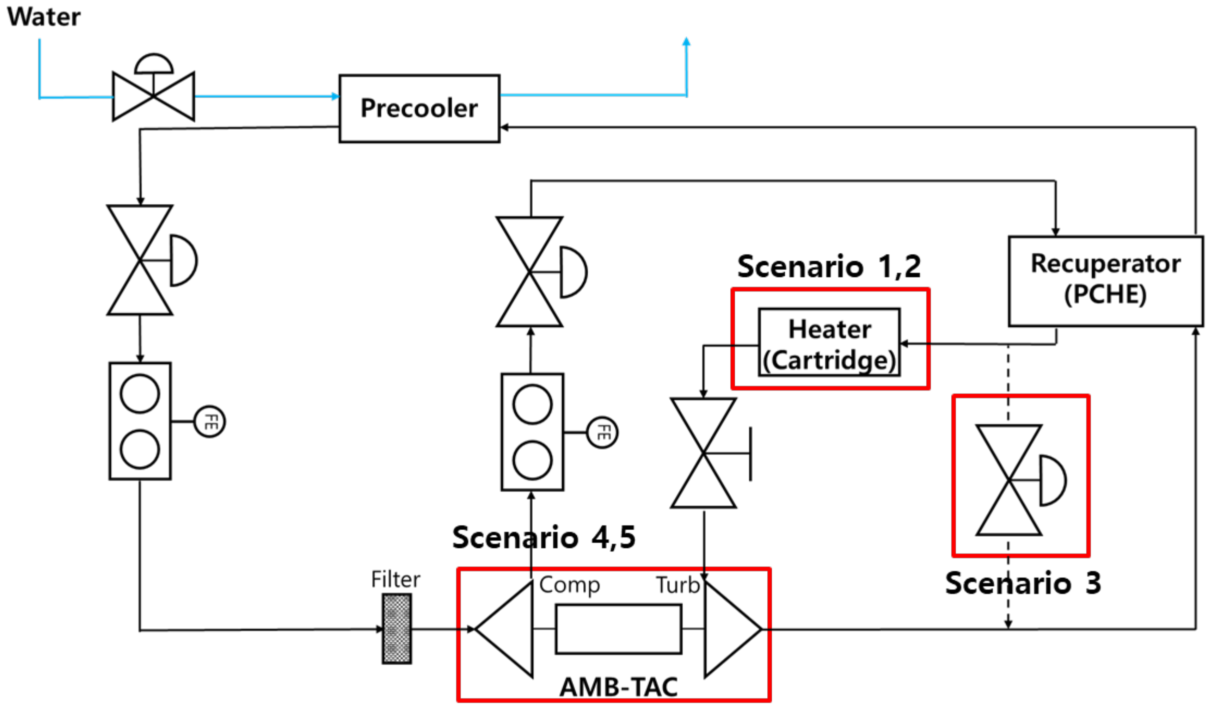
Methodology

- Self-Tuning Controller; based on adaptive control
- Uses online information of input signals and observed outputs
- Update the parameters of the controller over time
- Lumped correction factor is updated over time



Methodology

Scenario	Operation	Temperature	Pressure	Mass Flowrate
Scenario 1	Heater power increase	++	+	X
Scenario 2	Heater power decrease	--	-	X
Scenario 3	Bypass valve open	-	++	++
Scenario 4	TAC speed decrease	+	+	+
Scenario 5	TAC speed increase	-	-	-



Methodology

- According to ASME PTC 10-1997 Section 3, the error range for the compressor inlet temperature cannot exceed 0.5% in absolute temperature.

- As no correlation between a larger input and a larger energy usage for controlling the system, and compensate total operating time, the normalized performance index Jn is selected.

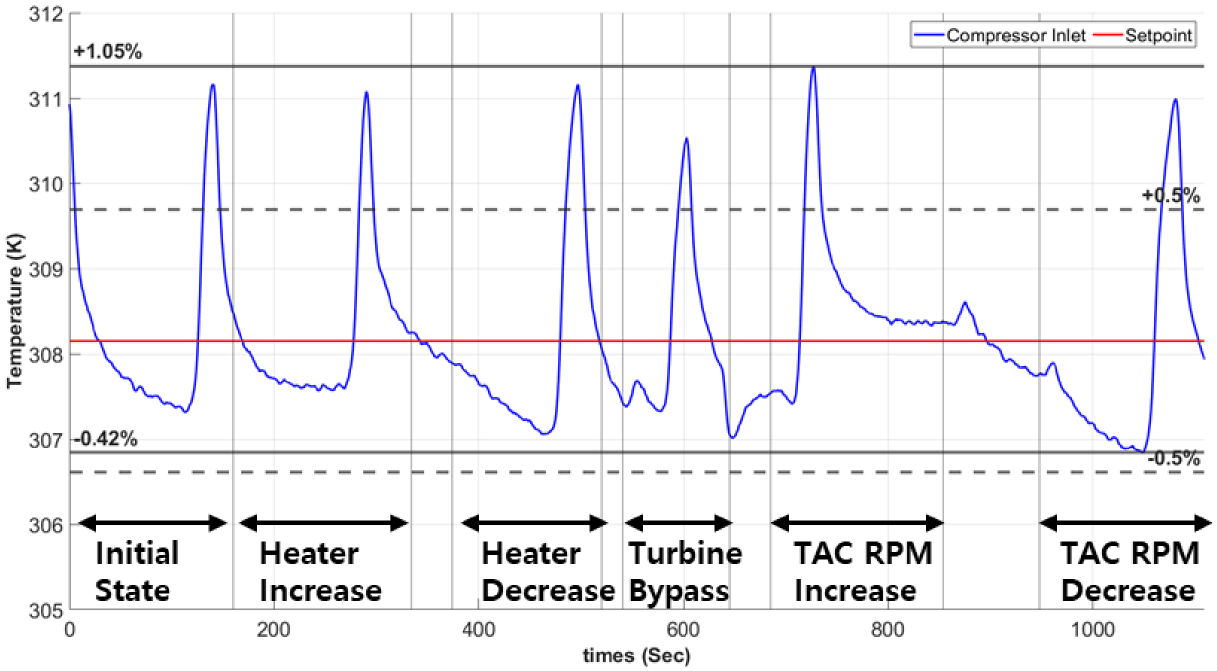
- The smaller normalized performance index, the better controller is.

Name	Evaluation Parameter	Basis	Numerical Form
Criterion 1	Maximum Error	ASME PTC 10-1997 Section 3	Size of Error (%) < 0.5%
Criterion 2	Performance Index	Optimal Control Theory	$J_n = \frac{1}{n}\sum_{k=0}^{n}\left(e(k)\right)^2$

Result

- **PID Controller**

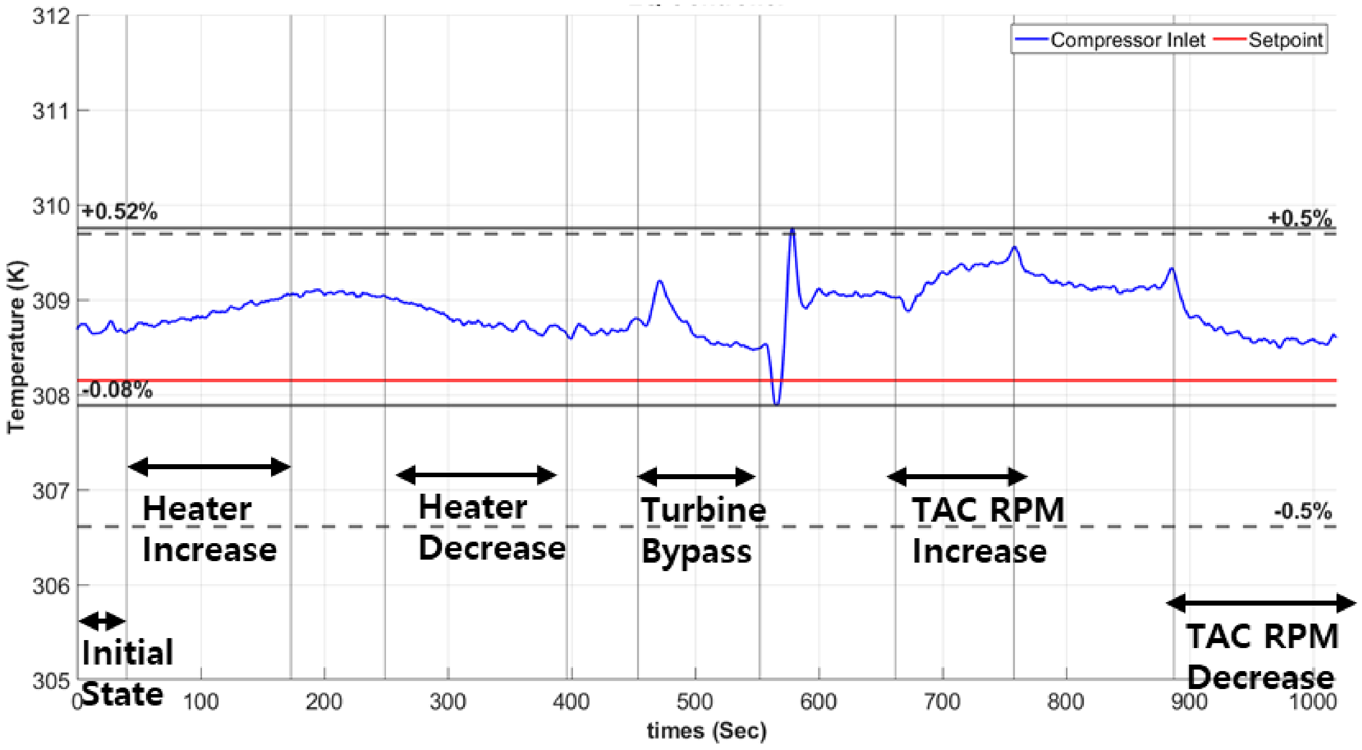
- Excessive overshoot and vibration were observed
- The controller requests to operate valve beyond the control range, which resulted in loosing precision of the control
- The maximum error is 1.05%, which violate criterion 1.



Result

- **LQ Controller**

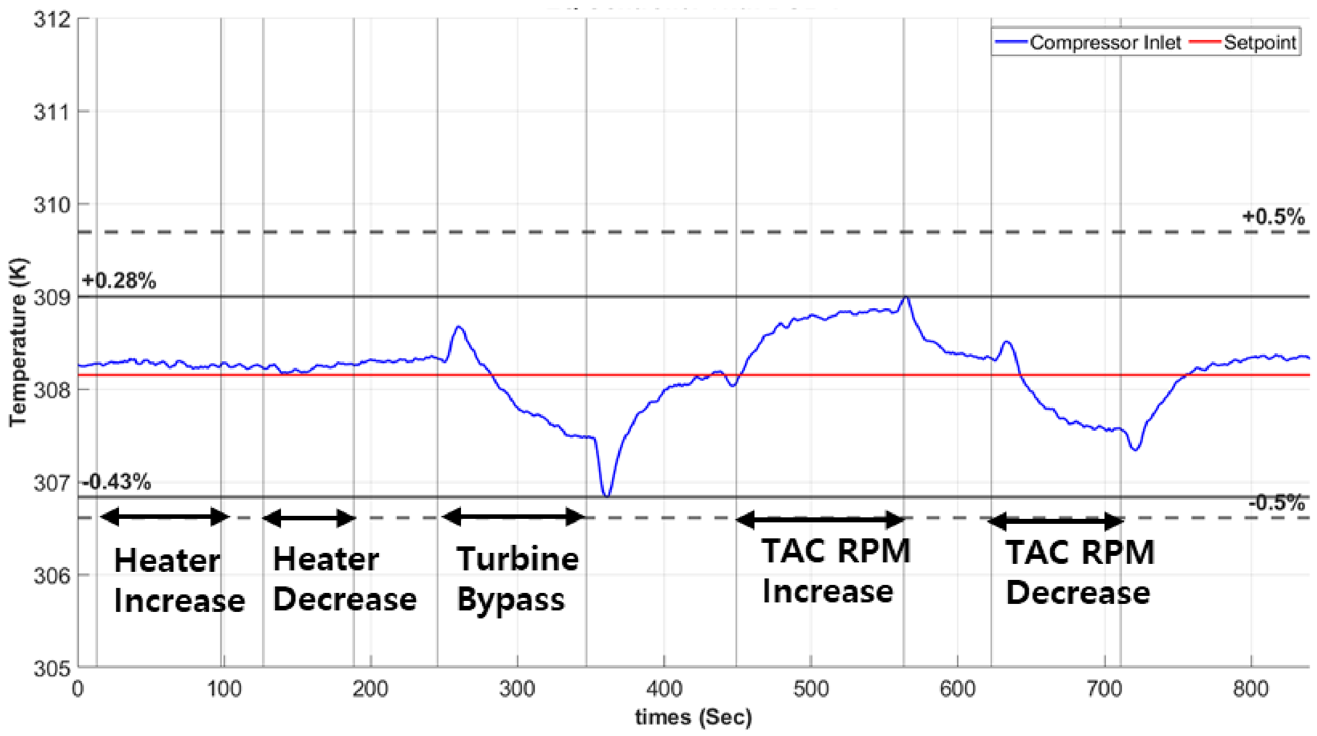
- Steady-state error was observed.
- A steady-state was reached for each disturbance, but a certain deviation compared to the set point temperature was continuously shown.
- Estimated lumped correction factor C_f causes the error
- The maximum error is 0.52%, which violate criterion 1.



Result

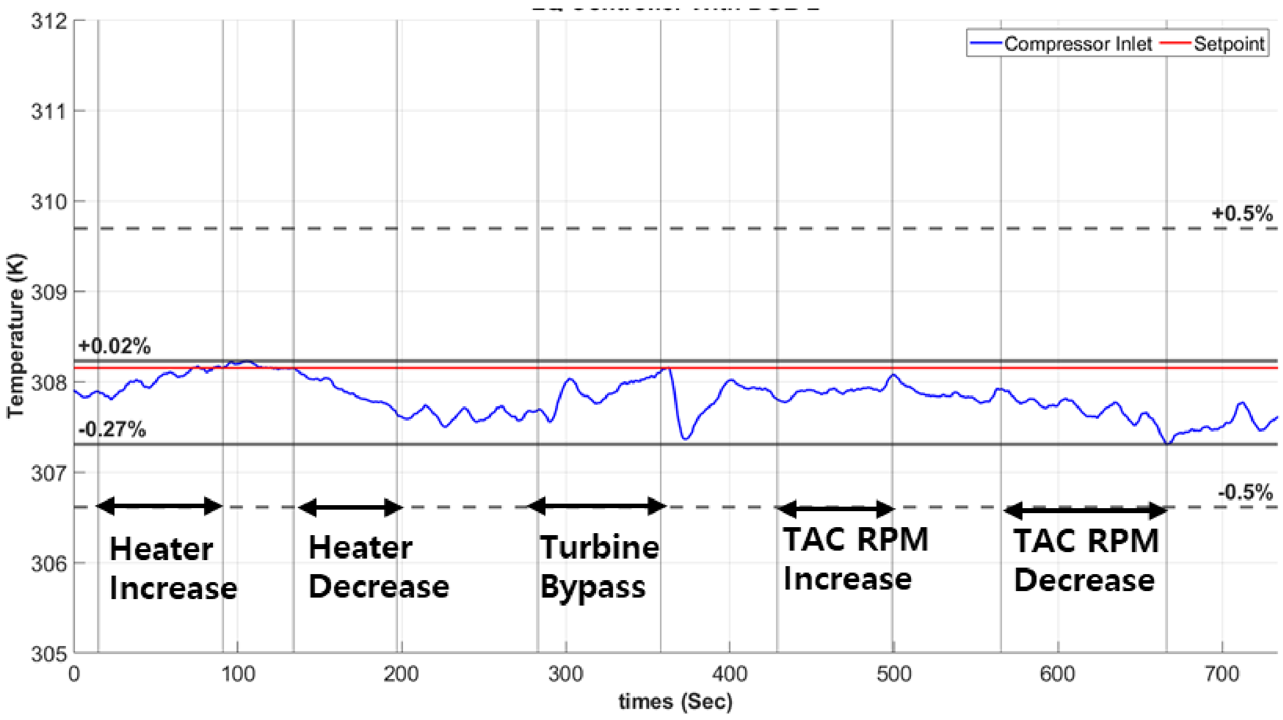
- **LQ Controller with DOB 1**

- Compare to LQ controller, steady-state error was reduced.
- The steady-state error still exists and shows high fluctuation when the turbine bypass valve is open and closed.
- Maximum error is 0.43%, which satisfies criterion 1.
- The overall performance index J_n is 0.153



Result

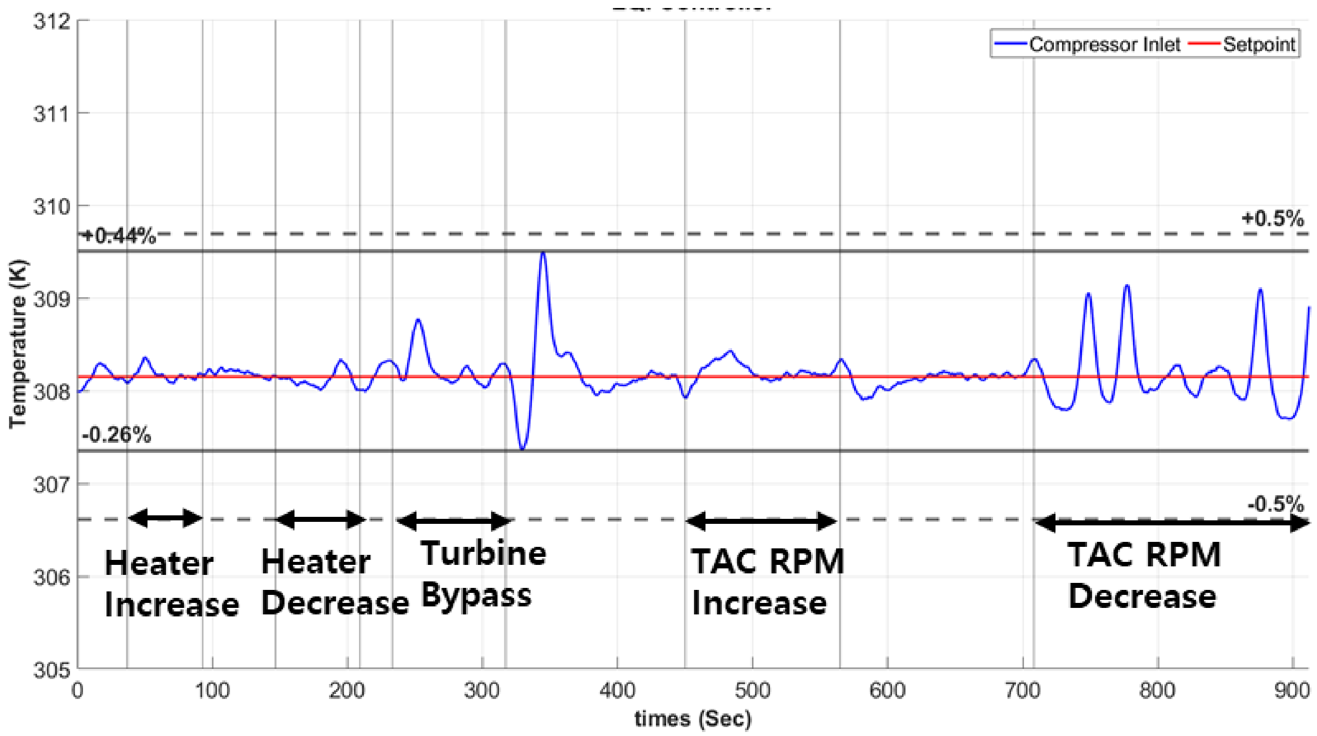
- **LQ Controller with DOB 2**
- Compare to LQ controller, steady-state error was reduced.
- Compare to DOB type 1, the fluctuation when the turbine bypass valve is open and closed is reduced significantly.
- Maximum error is 0.27%, which satisfies criterion 1.
- The performance index J_n is 0.151



Result

- **LQI Controller**

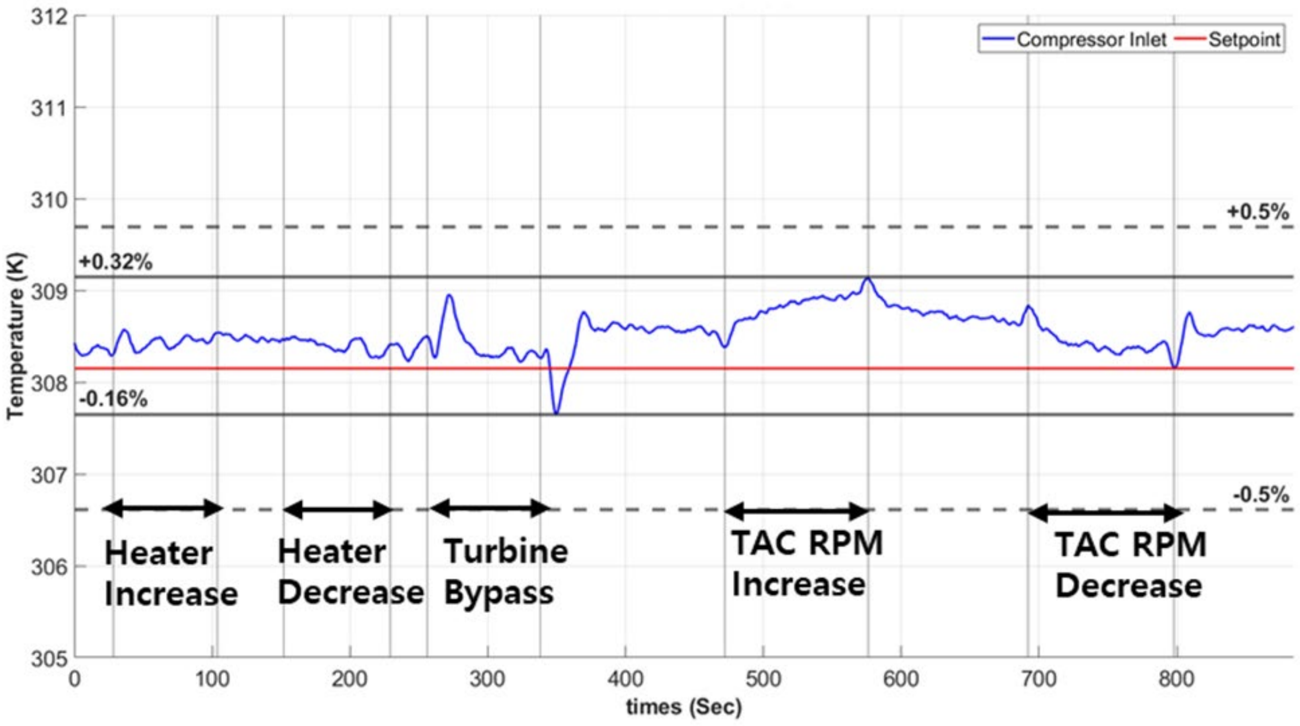
- Compare to LQ controller, steady-state error was significantly reduced.
- The oscillation increased in the case of decreasing TAC rpm scenario.
- Maximum error is 0.44%, which satisfies criterion 1
- The overall performance index Jn is 0.059



Result

- **Self-Tuning LQ Controller**

- Compare to LQ controller, steady-state error was reduced.
- Effect obtained by reducing the inaccuracy of the model itself by using the method of calculating the lumped correction factor C_f
- Maximum error is 0.32%, which satisfies criterion 1.
- The performance index J_n is 0.192



Discussion

Criterion 1: Maximum Error

Controller Type	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Overall
LQI	0.07%	0.06%	0.44%	0.09%	0.32%	0.44%
DOB Q-filter 1	0.06%	0.07%	0.43%	0.28%	0.26%	0.43%
DOB Q-filter 2	0.11%	0.21%	0.25%	0.13%	0.27%	0.27%
Self-Tuning LQ	0.14%	0.11%	0.26%	0.32%	0.22%	0.32%

Criterion 2: Performance Index

Controller Type	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Overall
LQI	0.004	0.011	0.110	0.011	0.126	0.059
DOB Q-filter 1	0.014	0.016	0.235	0.277	0.182	0.153
DOB Q-filter 2	0.019	0.191	0.123	0.078	0.219	0.151
Self-Tuning LQ	0.097	0.065	0.144	0.430	0.098	0.192

Summary & Conclusion

- During the **load-following operation** of S-CO_2 Brayton cycle, **compressor inlet condition is changed**.
- For efficient and safe operation of compressor, **inlet temperature should be maintained**.
- Existing research has limitation that use classical PID method, code-based and lacked verification via experiments.
- **Controllers based on the LQ controller**, designed with a well verified **system code**, can successfully control a physical system **without the need for a further tuning process**.
- **LQI controller** is optimal when the CO_2 mass flow rate **fluctuates less** and **does not go under the design flow rate**.
- **LQ controller with a DOB and a self-tuner** is optimal for **high fluctuation** and mass flow rate **going low**.