Study of Automatic Control System for S-CO_2 Power Cycle

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KAIST
NPNP

01
Introduction

Characteristics of $S\text{-}CO_2$ cycles

Compactness and high efficiency

Compact components of $S\text{-}CO_2$ cycle

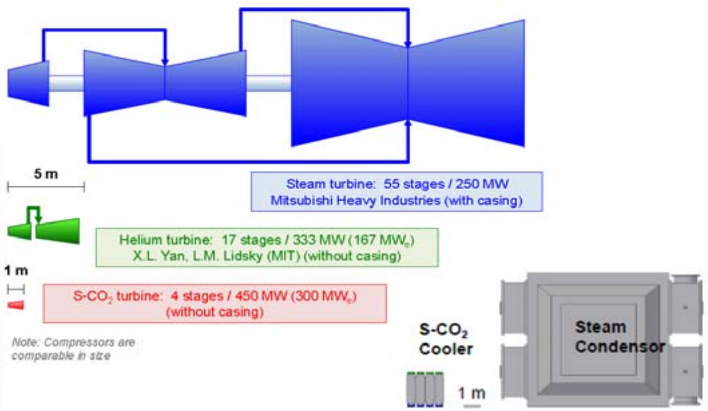
$S\text{-}CO_2$ cycles have compact components

- Compared to steam cycle, no phase change occurs in $S\text{-}CO_2$ cycle → Small volume of cooler
- Compared to conventional gas cycle, $S\text{-}CO_2$ cycles have high density → Small volume of turbomachinery
- These lead to compact and simple cycle arrangement

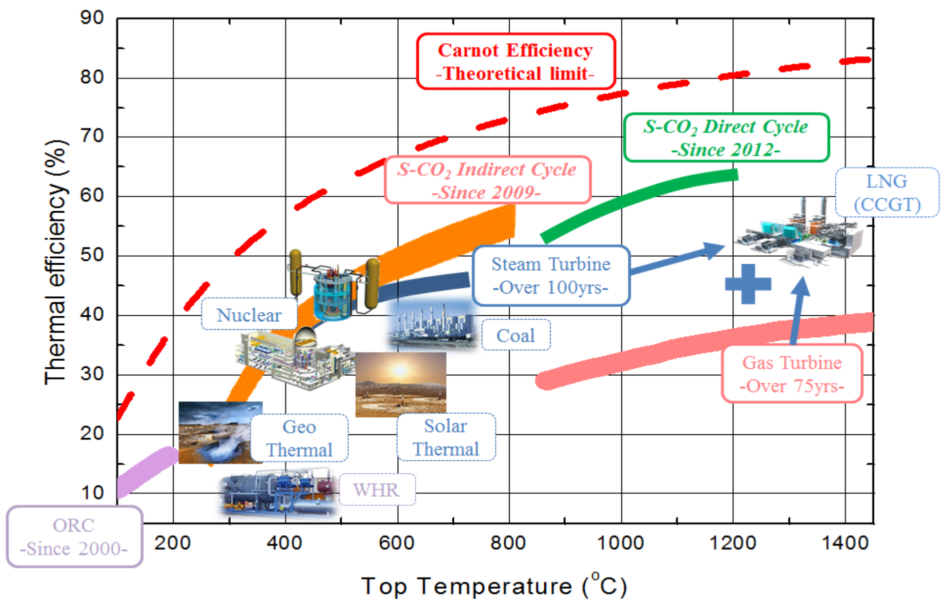
High cycle efficiency in moderate temperature

$S\text{-}CO_2$ cycles have high cycle efficiency in moderate temperature range (400~700℃)

- Compared to steam cycle, $S\text{-}CO_2$ cycles have comparable or superior cycle efficiency (400~700℃)
- Compared to conventional gas cycle, S-CO2 cycles always have superior efficiency



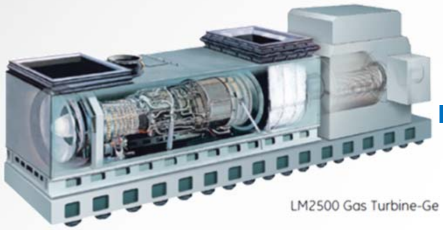
V. Dostal, M. J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT-ANP-TR-100, 2004
Overview Of Supercritical CO_2 Power Cycle Development at Sandia National Laboratories, Steven A. Wright, Thomas M. Conboy, and Gary E. Rochau



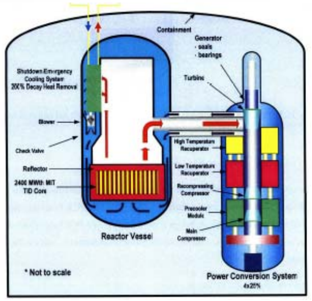
KAIST Micro Modular Reactor

Design concept

Development of Concept



<TM2500-Mobile gas turbine generator, GE>



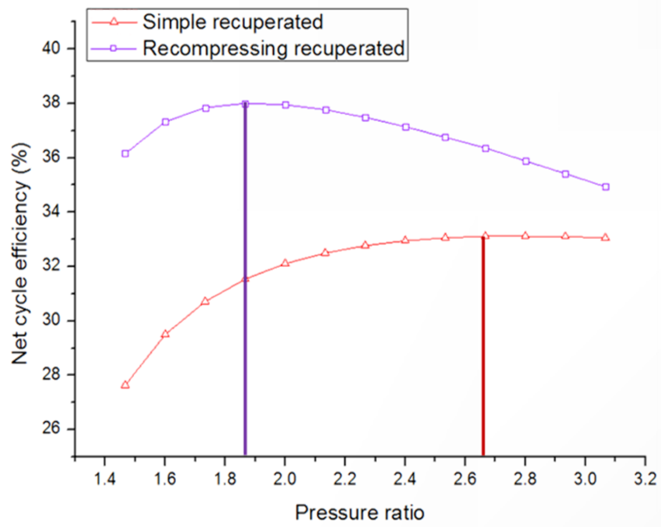
<S-CO_2 MIT GFR, 2400MW_{th}>

<KAIST Micro Modular Reactor, 10MWe>

- Transportable modular reactor.
- Supply of energy to remote region
- Direct Supercritical CO2-cooled fast reactor
- One module contains reactor core, power conversion system.
- Long life core without fuel reloading
- Economic benefit by shop-fabrication

Design Parameters

	Parameters	Comments
External size	7.0 m x 3.9 m, 154 ton	Transportable limit of trailer (260 ton)
Core power / Net Power	36.2 MW_{th} / 12.0 Mw_e	-
Life time (w/o refueling)	20 years	To minimize manual controls by operators in a remote region
Safety features	Autonomous regulation (Reactor power, part load)	
T_{min}	60℃ (Air cooling)	To be independent on places where MMR is operated
Cycle layout	Simple recuperated	For compactness, simple recuperated cycle is adopted



- There are many cycle layout options but simple recuperated layout is selected for comapctness

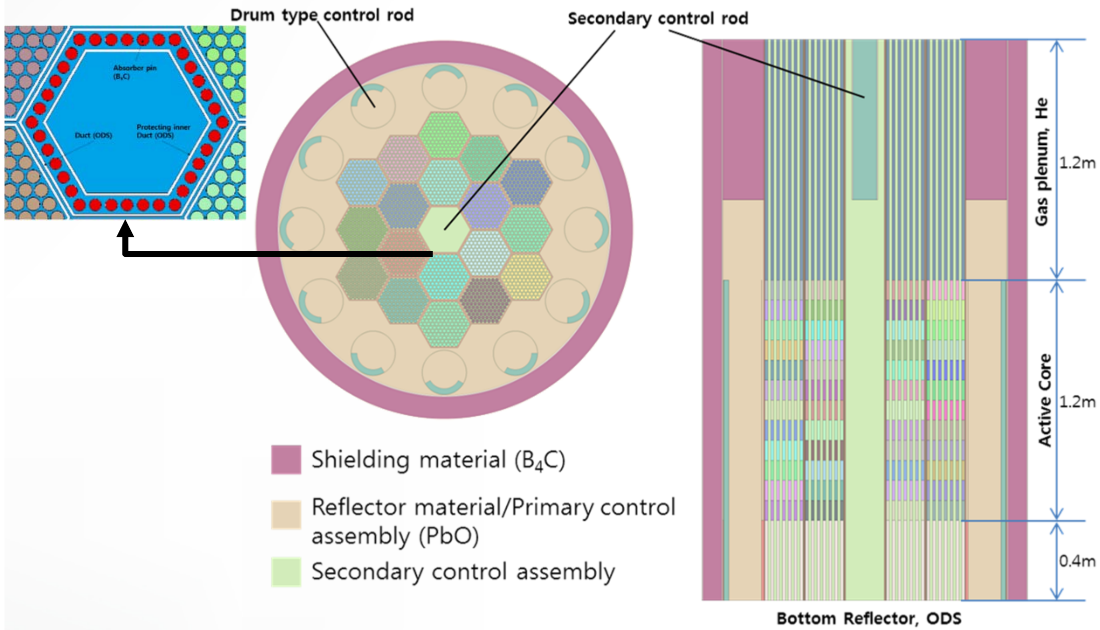
KAIST MMR in Action

Reactor core design

Specifications

Long Life without refueling / Compact core design

- The core consists of 18 fuel assemblies, 12 drum type control rod and secondary control rod, reflector
- The shape of fuel assembly is hexagonal type and 127 fuel pins
- Each channel is swirled by wire wrap to enhance convective heat transfer
- UC is selected as fuel pellets and ODS steel is chosen as cladding material
- The design life time is 20 years without refueling
- Excessive reactivity is regulated by Replaceable Fixed Absorber (RFA)



<Radial and axial configuration of the reactor core>

Design Parameter	Value
Rector Power/Life time	36.2 MWth / 20 years
Number of FAs	18
Active core equivalent radius/height	46.58 cm / 120 cm
Whole core equivalent radius/height	82 cm / 280 cm
Coolant pressure / speed	20 MPa / 6.92 m/s
Coolant inlet / outlet Temp	655.35 K / 823.15 K
Total mass of Core	39.6 ton
Control drum material	98% TD 98w/o enriched B4C (Drum radius = 9.5 cm)
Control rod material	98% TD 98w/o enriched B4C (Radius = 6.0 cm)

Power conversion system design

Cycle layout / Heat exchanger / Turbomachinery

Cycle layout

- Simple recuperated cycle is adopted for simple cycle layout

Recuperator

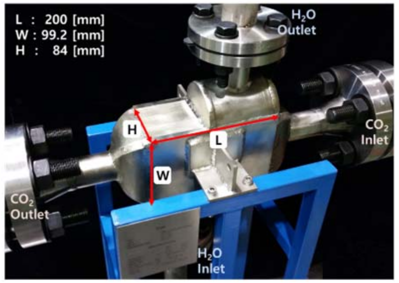
- Printed Circuit Heat Exchanger (PCHE) is selected as a recuperator which is designed by in-house code, KAIST-HXD
- Friction factor and heat transfer coefficient for S-CO_2 PCHE is developed based on CFD and experimental analysis

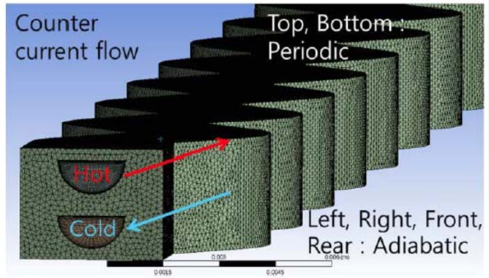
Air cooling-Precooler

- Ultimate heat is rejected through cooling loop to CO_2-Air heat exchanger
- Electric-driven air fans and circulation compressor are used to make forced flow in ambient air and cooling loop, respectively

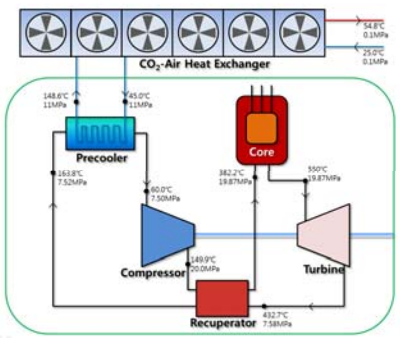
Turbomachinery

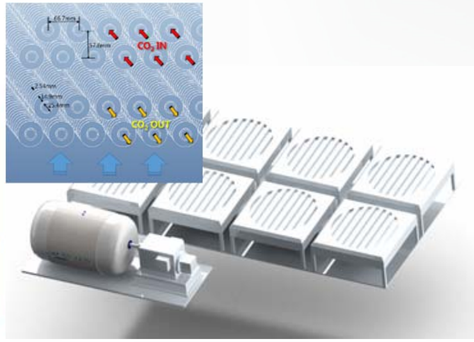
- MMR's turbomachinery is designed by in-house code, KAIST-TMD which adopts 1D mean line method
- Its off-design performance map is validated with KAERI's SCIEL compressor off-design performance map
- From this code, MMR turbomachinery is designed and its performance map is obtained



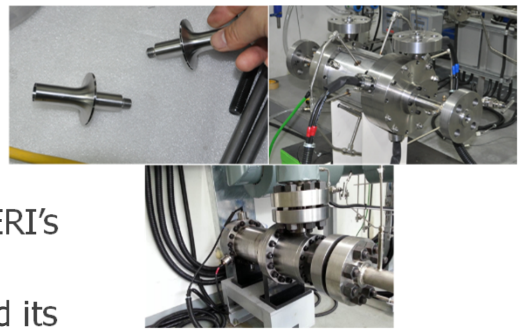


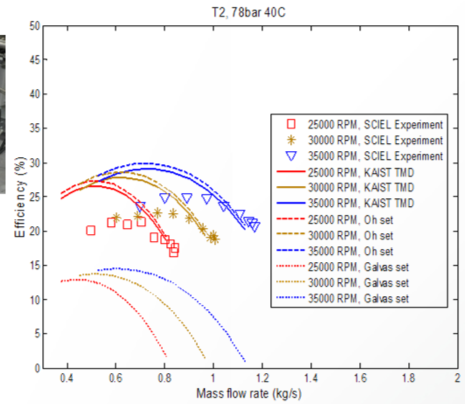
<SCO_2PE PCHE (L) and CFD analysis of PCHE channel (R)>





<Cycle layout (L) bird view of MMR (R)>





<SCIEL compressor (L) and TMD and SNL experimental data (R)>

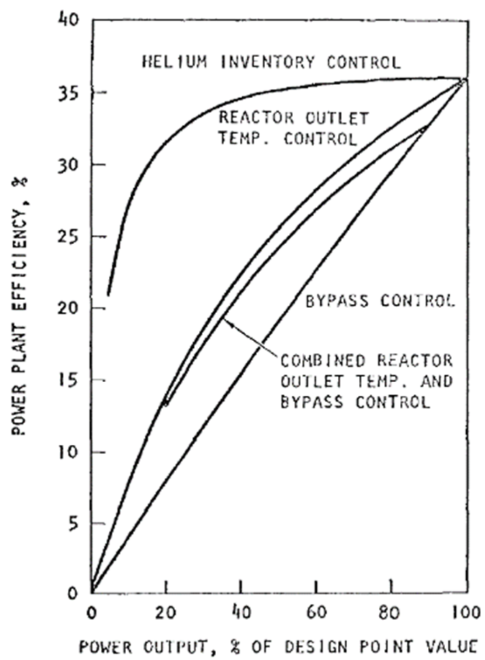
02
Control scheme Analysis

KAIST Micro Modular Reactor

Control strategy list

Control strategy

- For MMR, turbine bypass and inventory control will be considered as a major regulator for maneuvering power
- Inventory control is known as the most efficient control
  but the inventory control is not expected to be used for rapid load
- To compensate its slow characteristic time, turbine bypass control is operated for abrupt load change
- Comparing combinations of turbine bypass and inventory controls, the most appropriate control scheme will be determined



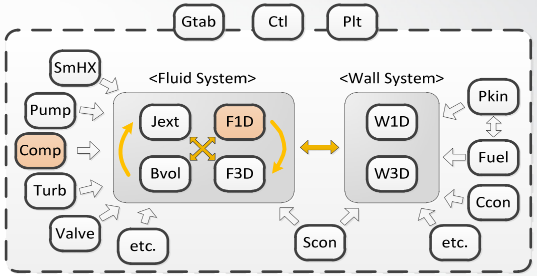
<Part-load efficiency for the various control modes>

Dynamic modeling tool for part load modeling

Validations (1/2)

GAMMA+ code

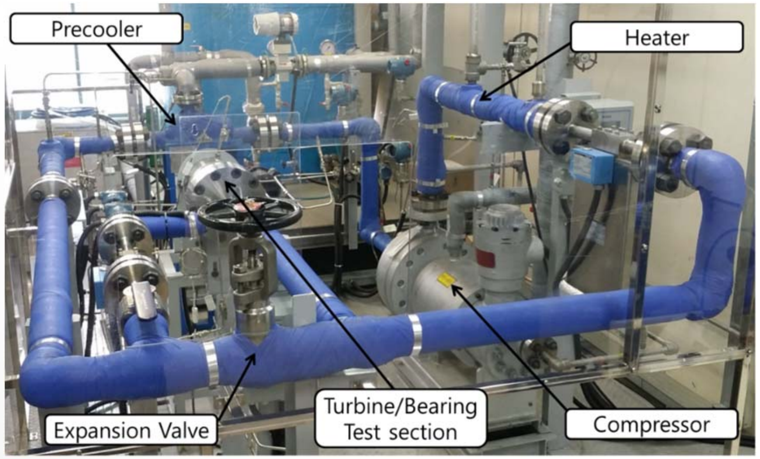
- GAMMA+ code is developed by Korea Atomic Energy Research Institute (KAERI) for predicting transient condition of gas cooled reactor system
- A few component models for S-CO_2 cycle are added in GAMMA+ code (Exact CO_2 property, PCHE correlation, S-CO_2 turbomachinery modeling)



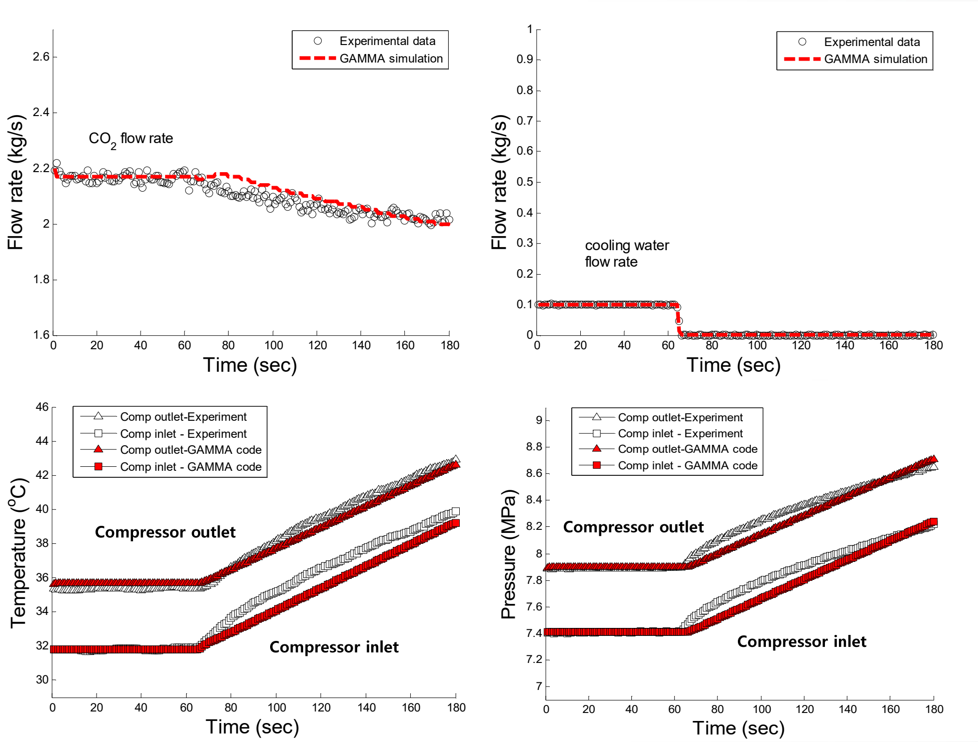
<Code structure of GAMMA+ code>

Validation (SCO_2PE)

- Supercritical CO_2 Pressurizing Experiment (SCO_2PE) is a CO2 compressing experimental loop for testing the S-CO2 compressor and heat exchanger near the critical point



<SCO_2PE device>



< Comparison results of SCO_2PE experimental data and GAMMA+ results >

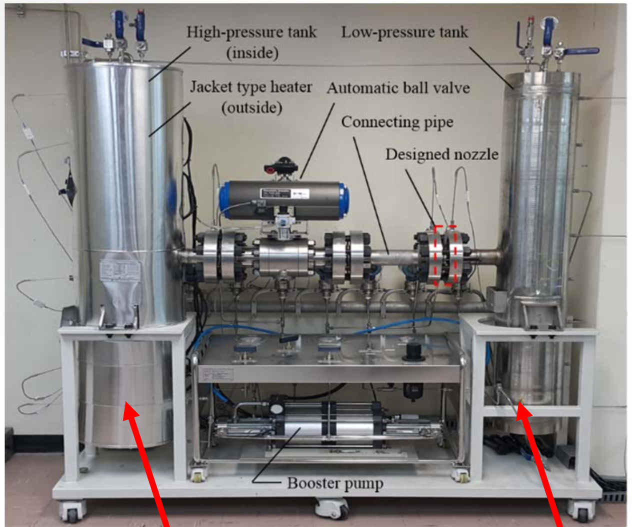
Power Production with SCO_2PE

Dynamic modeling tool for part load modeling

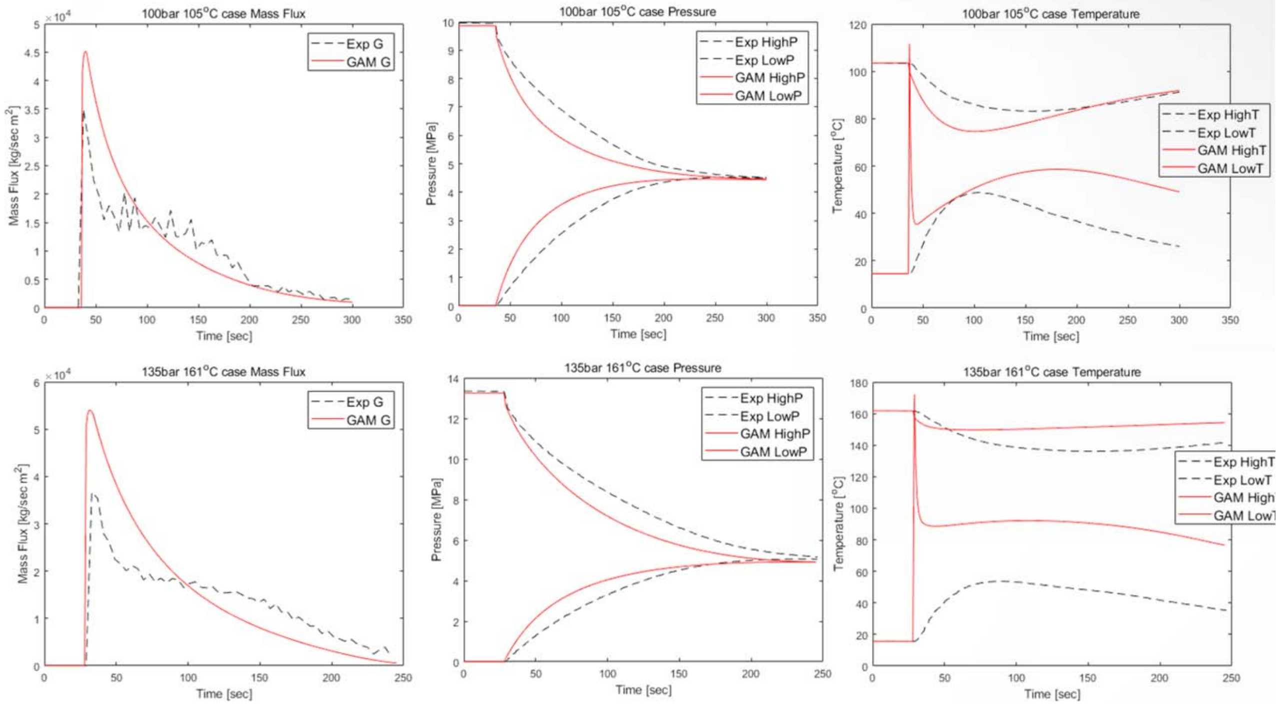
Validations (2/2)

Critical flow experimental device

- Critical flow experimental device can validate CO_2 mass transfer between two tanks by pressure gradient
- This device can be used to demonstrate turbomachinery seal, inventory mechanism, and critical flow analyses



	HP tank		LP tank	
	P(MPa)	T(°C)	P(MPa)	T(°C)
Case 1	10	103.5	0.1	14.5
Case 2	13.3	161.7	0.1	15.6



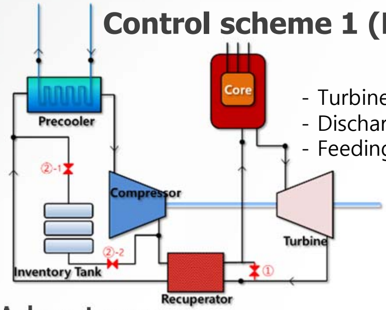
- GAMMA+ code can have ability to predict CO_2 inventory transfer by pressure gradient.
- It is confirmed that inventory tank control modeling of MMR can be designed by GAMMA+ code

Comparison of control schemes (1/2)

Control schemes of MMR

- Four control schemes are listed in terms of advantages and disadvantages
- Part load modeling results with infinite inventory tank will be shown to confirm which scheme is the most proper (100 - 50 - 100% load change)

Control scheme 1 (Reference)

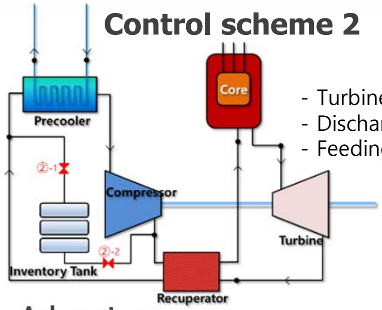


- Turbine bypass (1)
- Discharging: Compressor outlet (2-2)
- Feeding: Precooler inlet (2-1)

Advantages
- With single inventory tank, inventory charging and discharging can be implemented → simplicity
- Compensate response time by turbine bypass

Disadvantages
- Unstable performance in rapid increase of load situation → charged inventory flows in compressor first

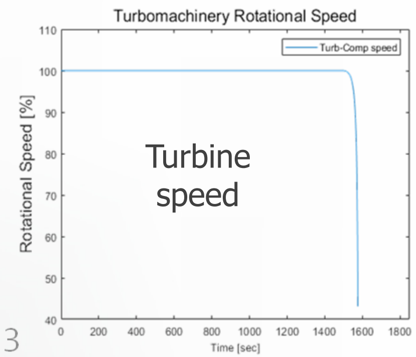
Control scheme 2

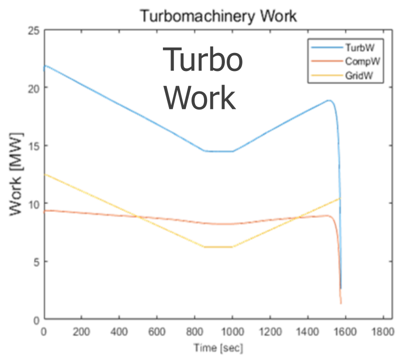


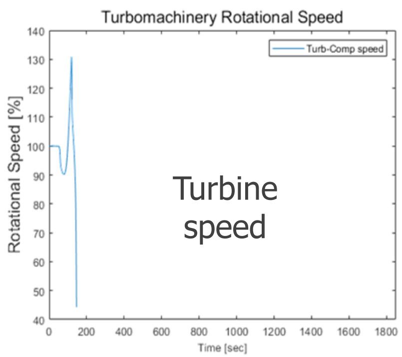
- Turbine bypass (X)
- Discharging: Compressor outlet (2-2)
- Feeding: Precooler inlet (2-1)

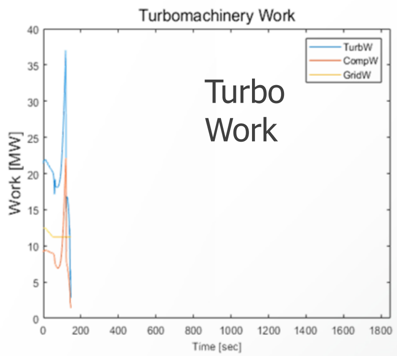
Advantages
- Simpler than control scheme 1 due to absent of turbine bypass

Disadvantages
- Much more unstable, the control scheme makes the system to be very unstable even at 10% load reduction



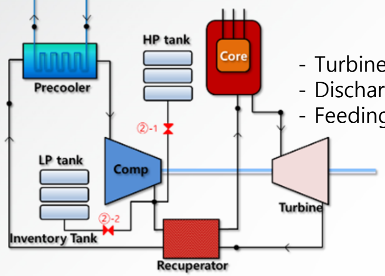






Comparison of control schemes (2/2)

Control scheme 3



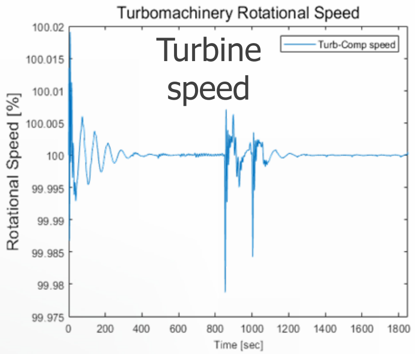
- Turbine bypass (X)
- Discharging: Compressor outlet (2-2)
- Feeding: Compressor outlet (2-1)

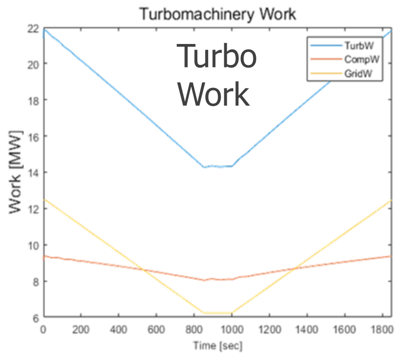
Advantages

- Since inventory charging and discharging are conducted at the compressor outlet, inventory flows turbine first so that generated work is increased first
- Response time is fast enough to regulate turbine rotational speed without turbine bypass

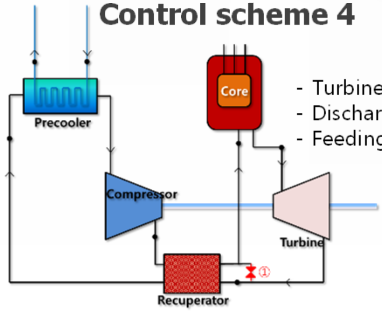
Disadvantages

- Require two inventory tanks both which are located at compressor outlet
  [$P_{comp\_out} > P_{discharge}$ / $P_{comp\_out} < P_{charge}$]
- Oscillation





Control scheme 4



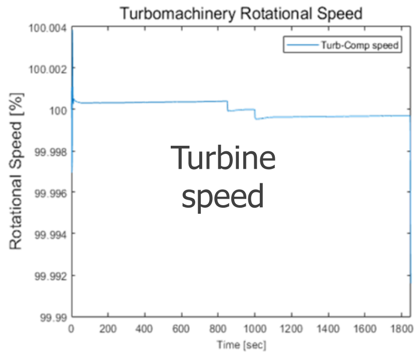
- Turbine bypass (1)
- Discharging: Compressor outlet (X)
- Feeding: Compressor outlet (X)

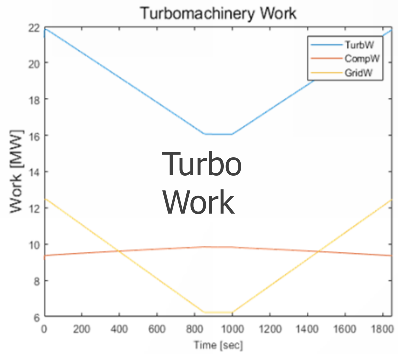
Advantages

- The simplest control scheme (Only turbine bypass)
- The fastest response time

Disadvantages

- The worst part load efficiency



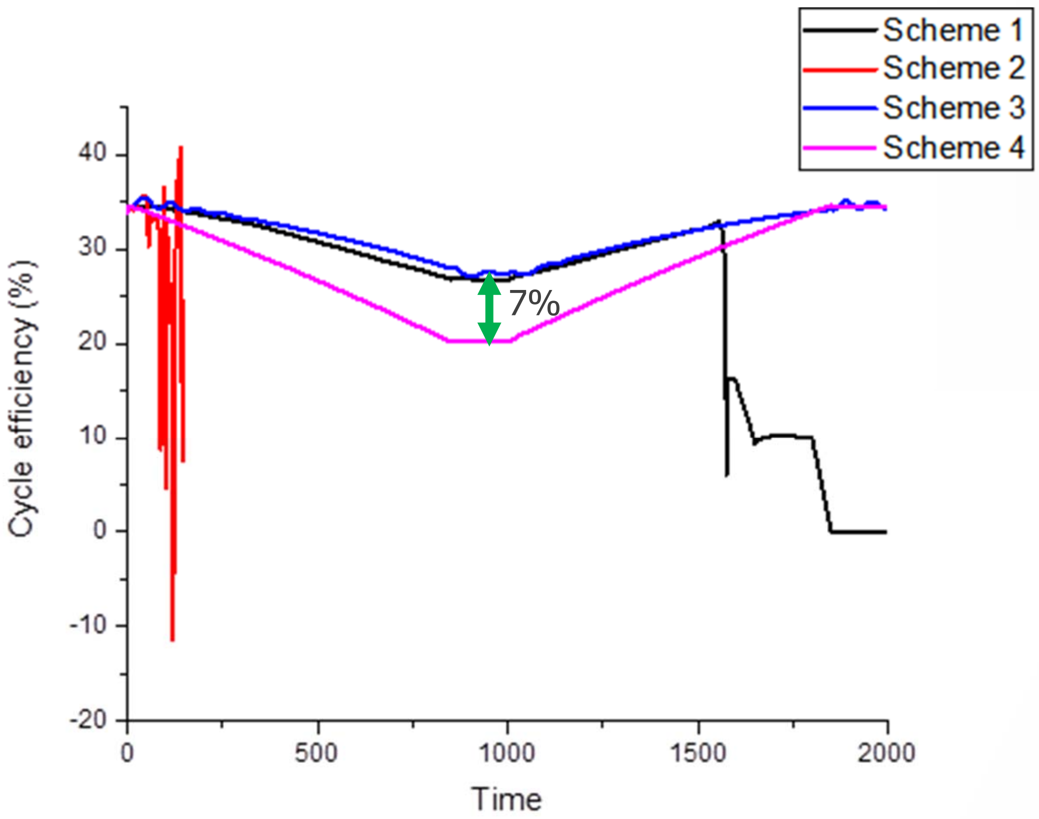


Part load efficiency results

Discussion

Comparison of control scheme options

- To evaluate which control scheme is the most suitable one in an abrupt load change condition, robustness (Response time) and performance (Cycle efficiency) should be viewed as key performance parameters.
- Control scheme 1 & 2: unfit for abrupt load change
- Control scheme 3: The most efficient part load operation
- Control scheme 4: The fastest response time



03

Inventory tank Design

Conceptual Design of Inventory Tanks

Bitsch's work

Finite inventory tank design for closed ideal gas cycle

- Previous part load results are calculated with infinite volume of inventory tanks
- For realistic dynamic modeling, part load modeling should be conducted with finite inventory tank
- According to Bitsch et al. minimum and maximum part load range of loop can be determined by equilibrium pressure of initial tanks and loop after charging or discharging

Lower limit (minimum load)

$$x_{low} = \frac{P_{equil}}{P_{loop}^{high}} = \frac{1 + M_1 / M_o}{1 + yM_1 / M_o}$$

Upper limit (maximum load)

$$x_{upper} = \frac{P_{equil}}{P_{loop}^{high}} = \frac{1 + M_1 / M_o}{1 + \frac{y}{\omega} M_1 / M_o}$$

M_0, M_1: Initial mass of gas respectively in the loop and in the inventory tank

y: Ratio of the cycle HP to the initial pressure of the tank

ω: Pressure ratio of the closed gas cycle

- By using equilibrium between loop and inventory tank, the above lower and upper limit can be obtained

Assumption

1. Ideal gas of Equation of State
2. Isothermal process between tank and loop
3. ratio of P_{high} at part load to P_{high} at full load is equivalent to ratio of part load to full load

$$x = \frac{P_{equil}}{P_{loop}^{high}} \propto \frac{W_{part-load}}{W_{designed}}$$

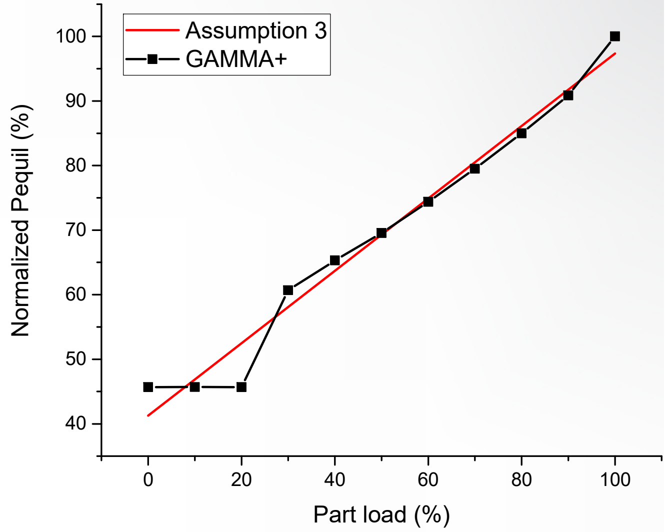
4. Turbomachinery Pressure ratio is constant during part load

Conceptual Design of Inventory Tanks

MMR part load characteristics

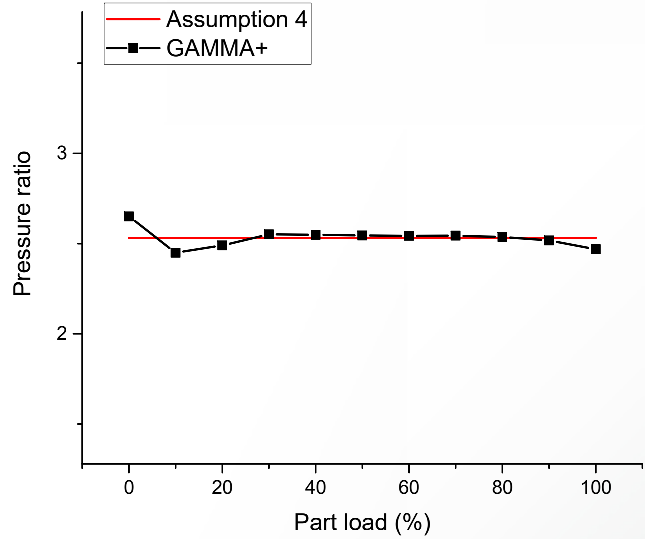
Application of Bitsch's method to MMR

- To apply Bitsch's method to MMR, it should be confirmed that assumption 3 and 4 are also consistence to MMR



Assumption 3 demonstration

- To confirm assumption 3, P_{equil} of MMR is simulated with 8MPa **infinite** inventory tank during 100 to 0% part load operation
  - ➢ Each P_{equil} is obtained from fully steady state results of GAMMA+ code at each part load
- It is noticeable that P_{equil} is linearly dependent upon part load from 100% to 25%
- Assumption 3 is validated for MMR



Assumption 4 demonstration

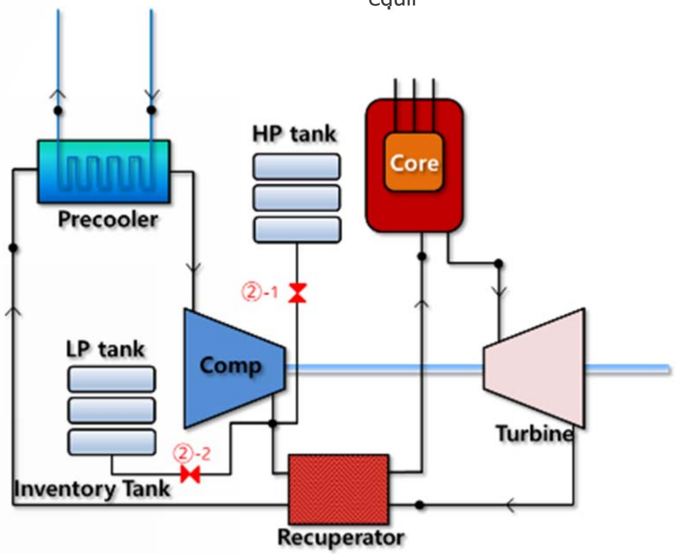
- Pressure ratios of MMR are obtained and constant pressure ratio is shown for <u>25-100%</u> part load
  - ➢ Each Pressure ratio is obtained from fully steady state results of GAMMA+ code at each part load

Conceptual Design of Inventory Tanks

Inventory tank for MMR

Finite inventory tank design for MMR

- From previous results, the upper and lower limit is determined from 25% to 100% load.
- Control scheme 3 whose part load efficiency is superior is selected as the final scheme in MMR
  - ➢ Charging and Discharging occurs at compressor outlet (T_0 = 142°C, P_0 = 20MPa)
- To apply assumption 2, initial temperature of inventory tank is set to the compressor outlet temperature
- From the design specifications, loop parameters are estimated as M_0 = 564kg, V_0 = 1.6435m^3
- MMR cannot introduce ideal gas EOS so that following algorithm is used to calculate P_{equil}



M_0: Initial mass of MMR loop
V_0: Volume of MMR loop
P_0: Initial compressor outlet pressure
T_0: Initial compressor outlet temperature
M_1: Initial mass of inventory tank
V_1: Volume of inventory tank
P_1: Initial pressure of inventory tank
T_1: Initial temperature of inventory tank

↓

Calculate equilibrium density
$\rho_{eq}=(M_0+M_1)/(V_0+V_1)$

↓

Isothermal assumption
$T_{eq}=T_0=T_1$

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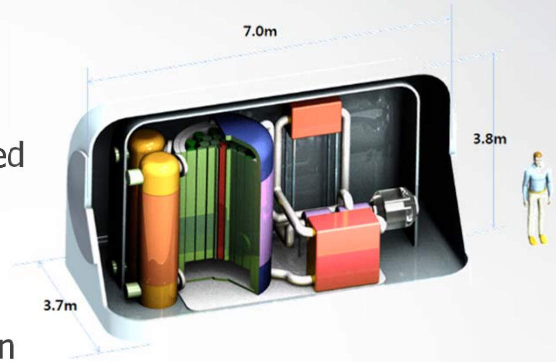
Obtain equilibrium pressure
$P_{eq}=f(\rho_{eq}, T_{eq})$

Conceptual Design of Inventory Tanks

Assessment of tank's Volume and Pressure

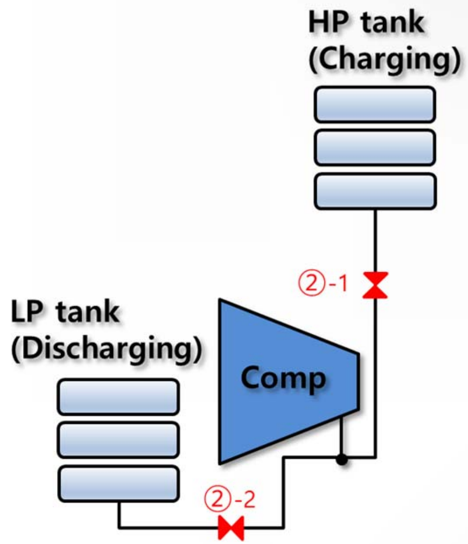


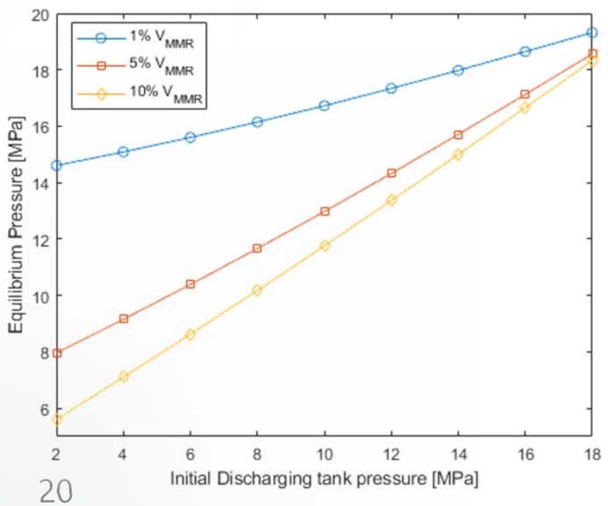
Equilibrium state along with inventory tank's V & P (1/2)

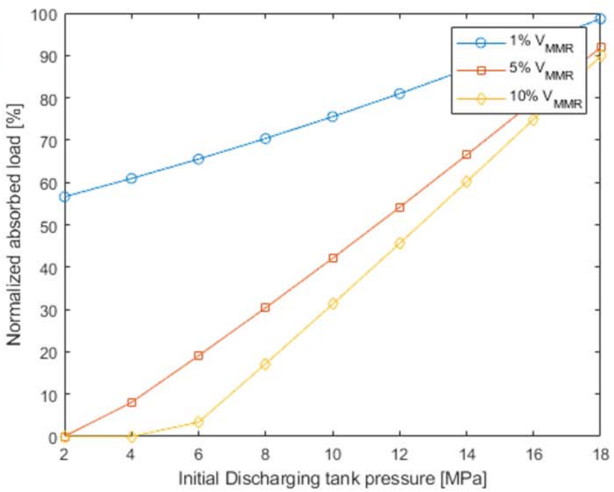
- Volume of containment MMR is 83.6m^3 so that an inventory volume is constrained as 10% of total Volume in this work

Discharging inventory tank (Low pressure tank)

- With respect to initial pressure of discharging tank, equilibrium pressure between loop and the tank is plotted along with tank's volume
- As volume of discharging tank is larger, the capacity to absorb inventory from MMR loop is larger → Larger volume leads to extended lower limit of part load
- As initial pressure of discharging tank is lower, density of tank is lower → Lower pressure leads to extended lower limit of part load
- From figures, 5% V_{MMR} (4.19m^3) for discharging tank with 2MPa of initial pressure is selected because it can cover the almost 0% of lower limit, considering margin







Conceptual Design of Inventory Tanks

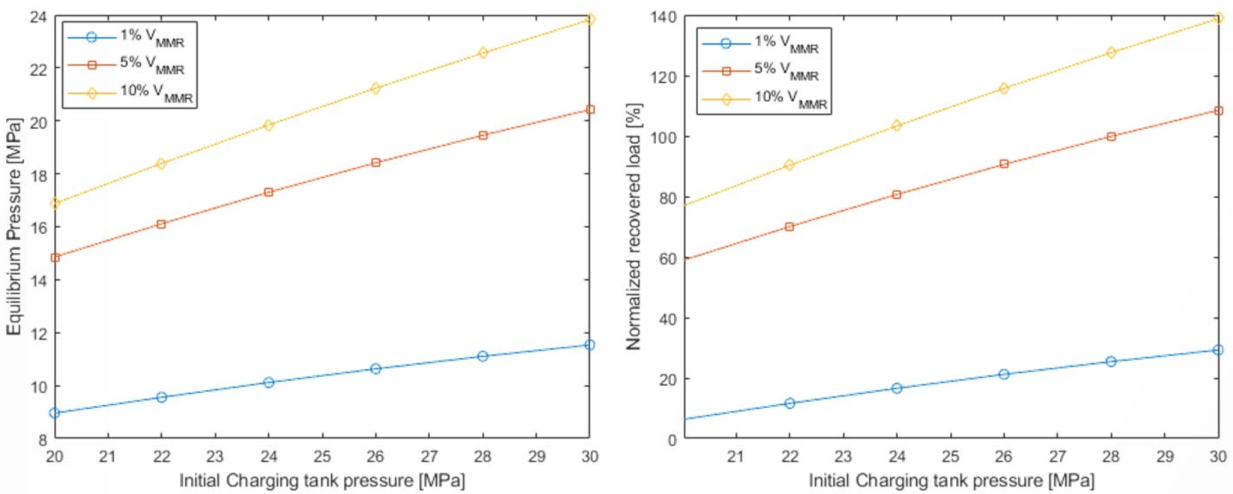
Assessment of tank's Volume and Pressure

Equilibrium state along with inventory tank's V & P (2/2)

- Reaching equilibrium state between loop and discharging tank (2MPa), it should be determined that charging tank's parameter to recover lowest load to full load

Charging inventory tank (High pressure tank)

- With respect to initial pressure of charging tank, equilibrium pressure between loop and the tank is plotted along with tank's volume
- As volume of charging tank is larger, the capacity to supply inventory to MMR loop is larger
  → Larger volume leads to extended upper limit of part load
- As initial pressure of charging tank is higher, density of tank is higher
  → Higher pressure leads to extended upper limit of part load
- From figures, 10% V_{MMR} (8.36m^3) for charging tank with 30MPa of initial pressure is selected because it can cover the almost 140% of upper limit, considering margin

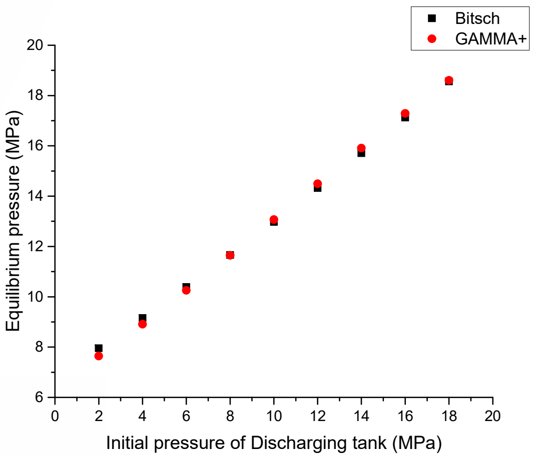


Conceptual Design of Inventory Tanks

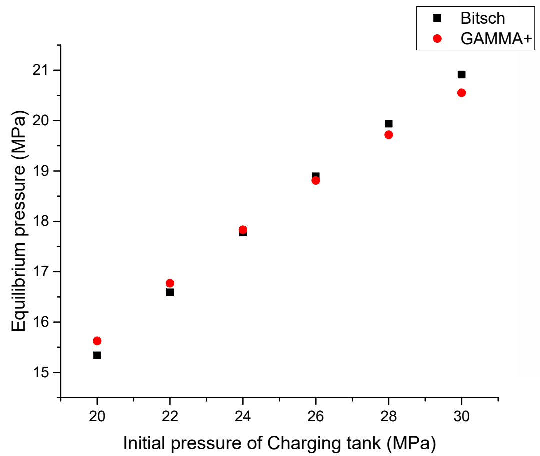
Validation

Validation of charging tank design

- Before apply the designed tanks to MMR, the finite tanks upper and lower limit should be validated whether its results are consistent with transient code (GAMMA+ code).
- With fixed volume of inventory tanks (Discharging: 4.19m^3 / Charging: 8.36m^3), P_{equil} between loop and tanks are plotted with respect to initial pressure of inventory tanks



<Equilibria with discharging tank>



<Equilibria with charging tank>

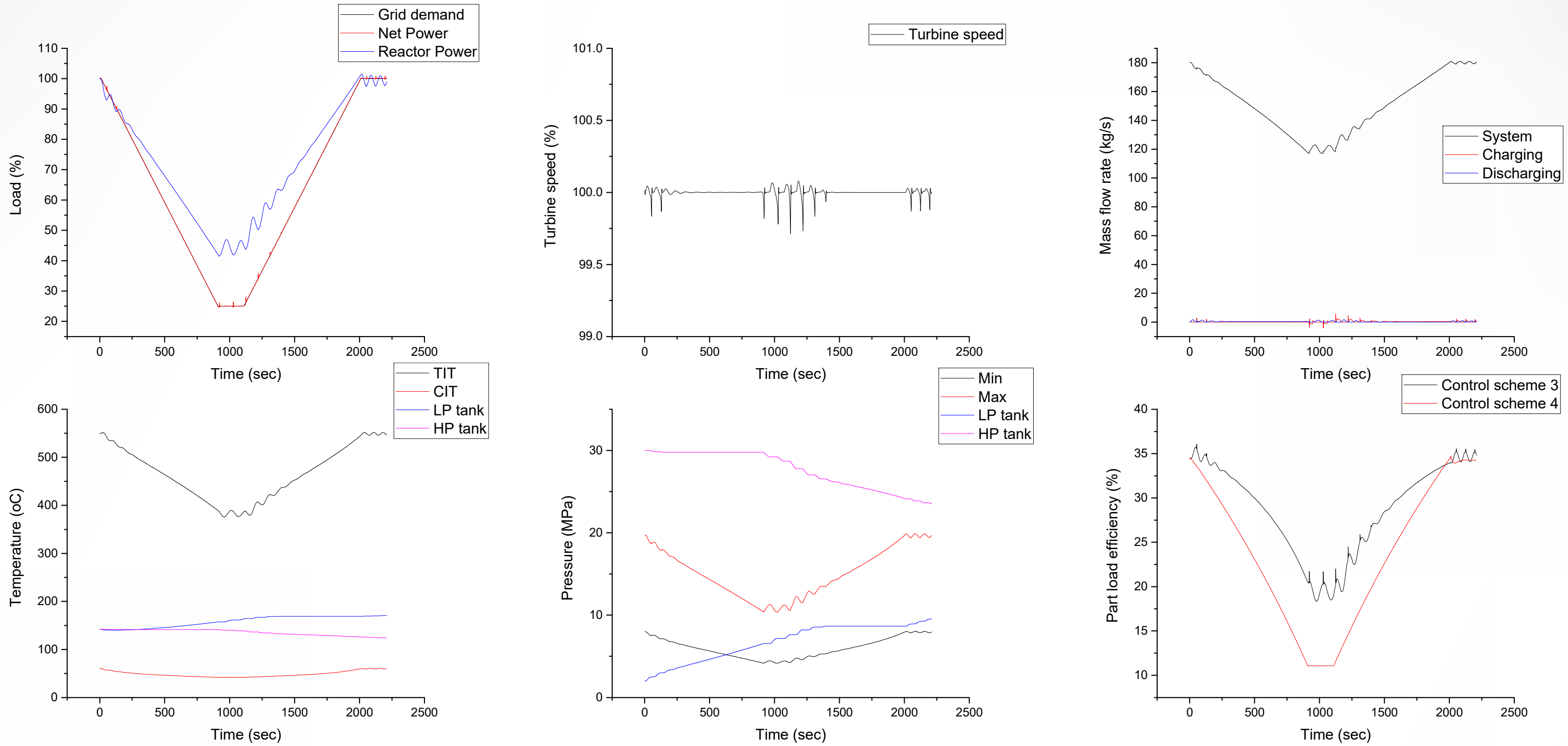
- The P_{equil} between inventory tanks and loop along with P_{ini} of each tank shows good agreement with GAMMA+ code
- Discharging tank is designed as 4.19m^3 with 142oC, 2MPa / Charging tank is designed as 8.36m^3 with 142oC, 30MPa

Part load simulation

With finite inventory tanks

Part load simulation from 100-25-100% load with 5%/min rate

- With designed finite discharging and charging tanks, control scheme 3 is used to maneuver the grid load



- Q_{core} is autonomously regulated by thermal-reactor feedback effect | W_{net} is well fitted to W_{grid} | N_{turb} is maintained
- The following P, T, and $\dot{m}$ are changed to fit system's net work to the demanded load by tank's PID controller
- The results show slight oscillation at the beginning of load reduction, staying and increase
- Compared to simple turbine bypass control (control scheme 4), control scheme 3 shows superior part load efficiency

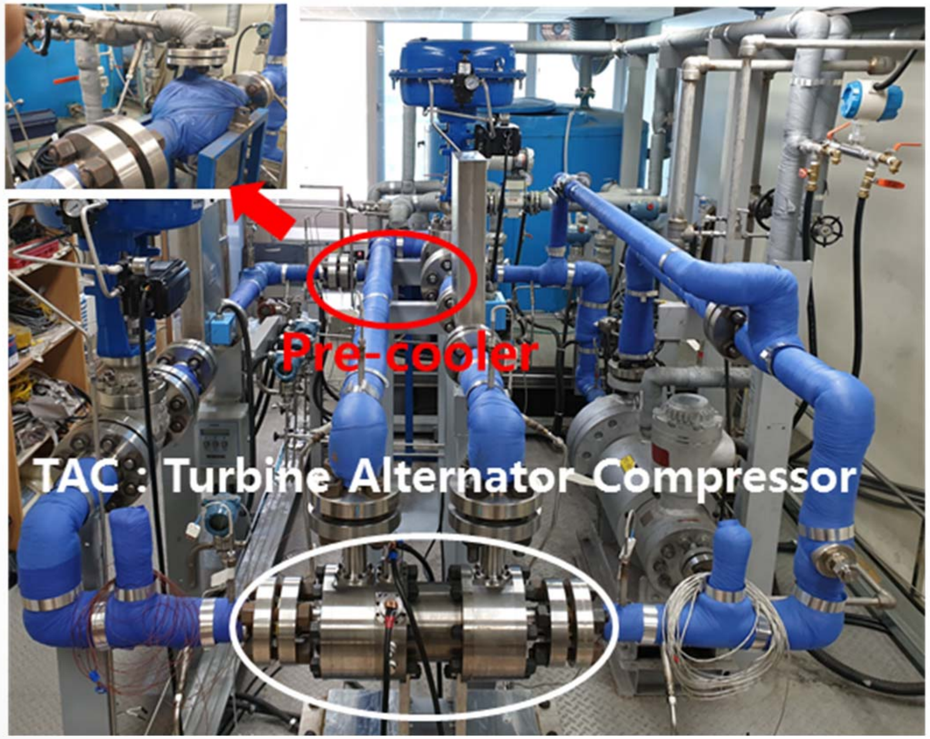
04
Conclusions

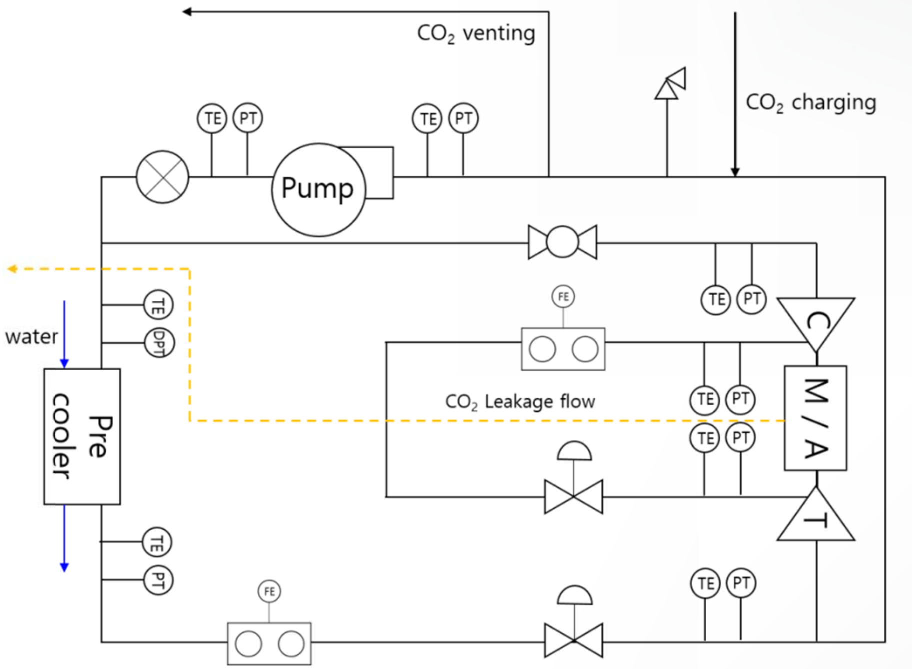
Conclusion

- To supply a remote region for 20 years without reloading, an S-CO_2 cooled KAIST MMR was designed
- To model control procedure or accident conditions, a transient code for S-CO_2, GAMMA+ code is adopted and validated with KAIST SCO_2PE facility
- Since MMR is operated in a remote region with minimal operators, autonomous control ability is important
- For efficient and fast response part load operation, four control schemes are compared with infinite inventory tank first
- Then, for realistic part load simulation, finite inventory tank's are designed by Bitsch's method
- The assumptions of Bitsch's method can be applied to MMR because charging or discharging temperature is far from the critical point (142^{o}C / 20MPa)
  → The method is applicable to other S-CO_2 cycles if charging / discharging location is still compressor outlet
- After equilibrium state between loop and the designed inventory tanks are validated with GAMMA+ code, 100-25-100% part load simulation is implemented with control scheme 3
- It shows some oscillating results during part load operation but its efficiency is superior to simple turbine bypass control

Future work

- SCO_2PE is just updated, equipped with two control valves and adding TAC unit
- With the improved SCO_2PE, automatic controller and control logic for startup, load following and balancing thrust force will be analyzed
- The results of GAMMA+ code are also validated with the measured data to simulate controllability of real scale S-CO_2 system





<Diagram of the S-CO_2 TAC experiment facility>

Thank you