S-CO_2 Power Research Activities In Far East Asia

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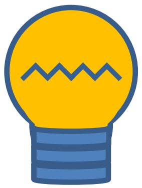
Overview of KAIST NPNP lab

Traditional TH Nuclear Safety+ ML

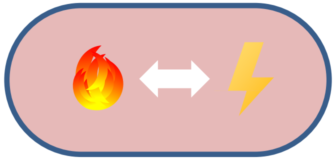
- ✓ Light Water Reactor Safety
- ✓ Big Data generation for Machine Learning
- ✓ Connecting Nuclear Safety with Machine Learning

Next Generation Power Conversion

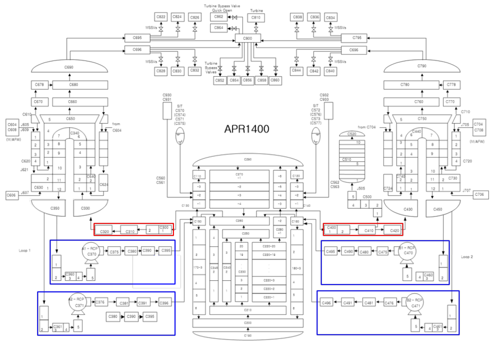


- ✓ Supercritical CO_2 Power
- ✓ Gas turbine for Nuclear Battery
- ✓ Ocean Nuclear
- ✓ Small and Micro Modular Reactor Systems

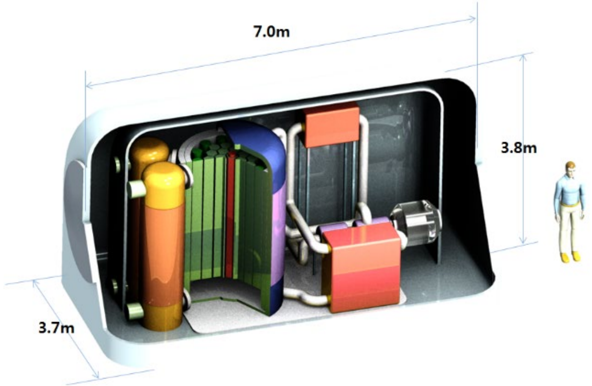
Energy Storage



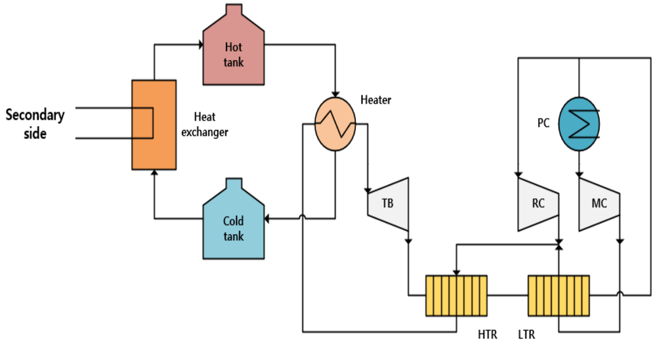
- ✓ Renewable-Nuclear Hybrid
- ✓ Load following with ESS
- ✓ ESS Optimization
- ✓ Grid Simulation



Nuclear Safety Analysis



KAIST Micro Modular Reactor



Thermal Energy Storage

Energy Transition in Maritime Transport

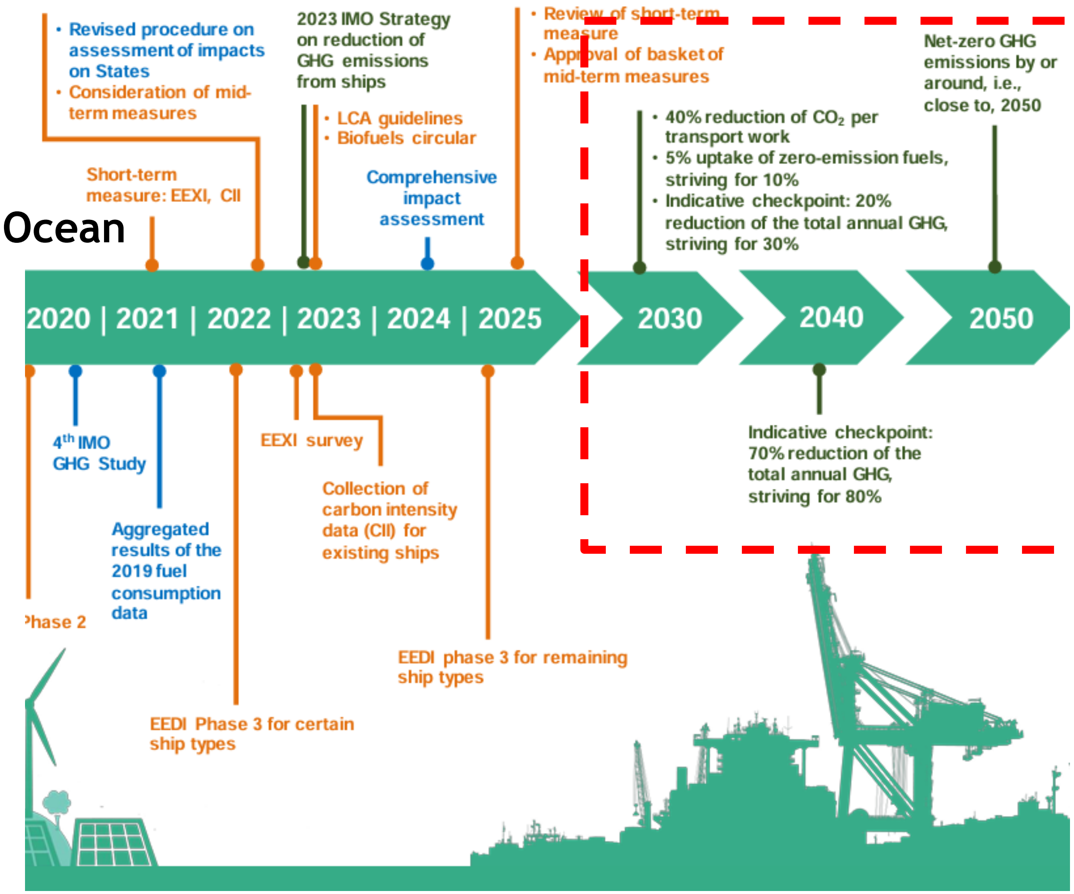
Addressing climate change

Over a decade of **regulatory action** to cut GHG emissions from shipping

Committee outputs

Top 10 Shipbuilding Companies

- Hyundai Heavy Industries Group ➡ **Hanwha Ocean**
- Daewoo Shipbuilding & Marine Engineering (DSME)
- 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



sCO_2 Power cycle benefit: Compact, High Efficiency

Questions: Autonomous (?), Load Following (?), Reliability (?), Nuclear (?)

S-CO_2 Test Rig at KAIST

ABC Test Loop

- **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

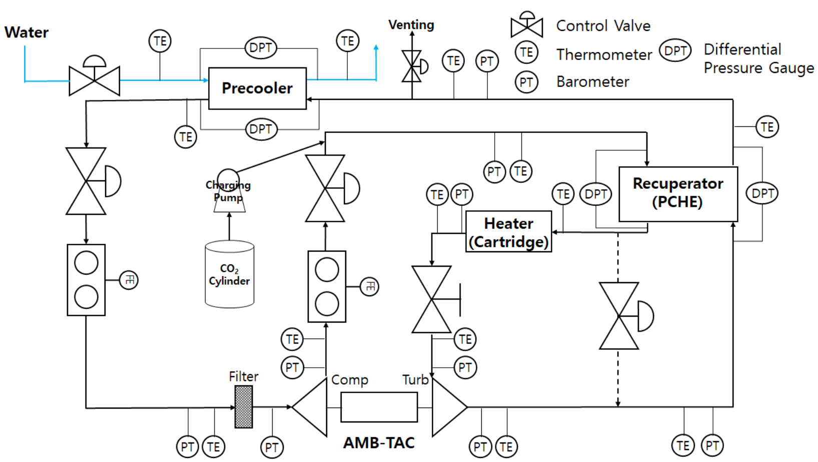


Fig. P&ID of ABC Loop

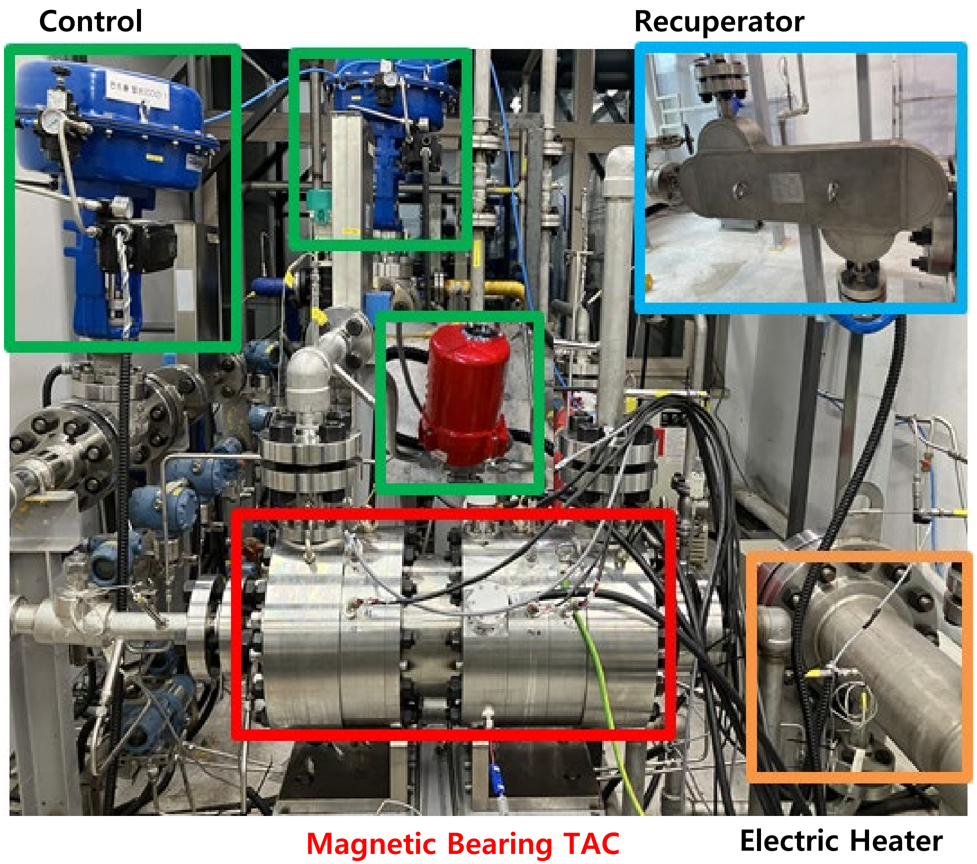
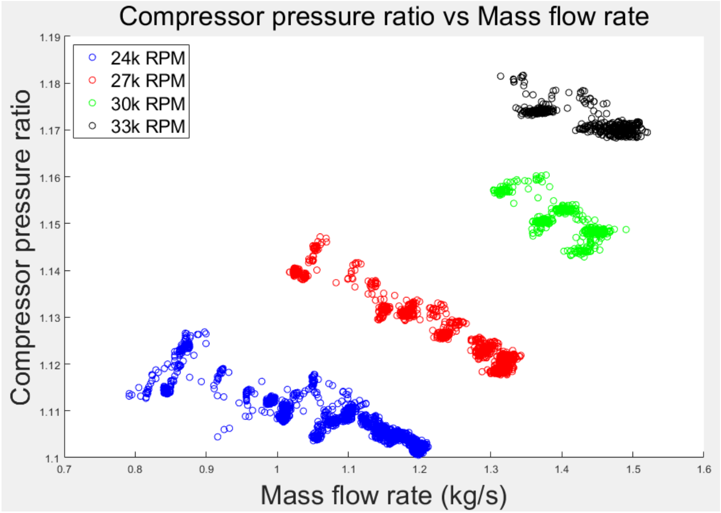


Fig. Overview of ABC Loop

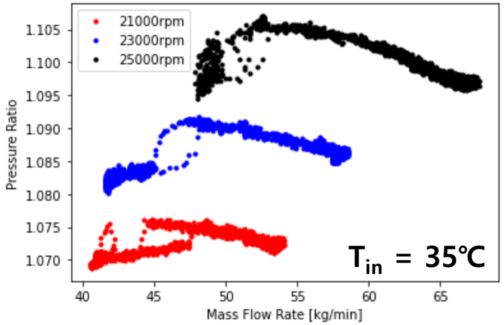
$S\text{-}CO_2$ Compressor Research at KAIST

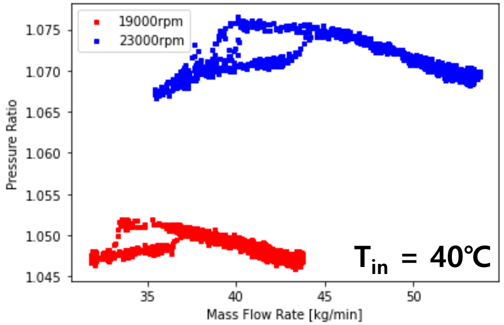
Map and surge behavior

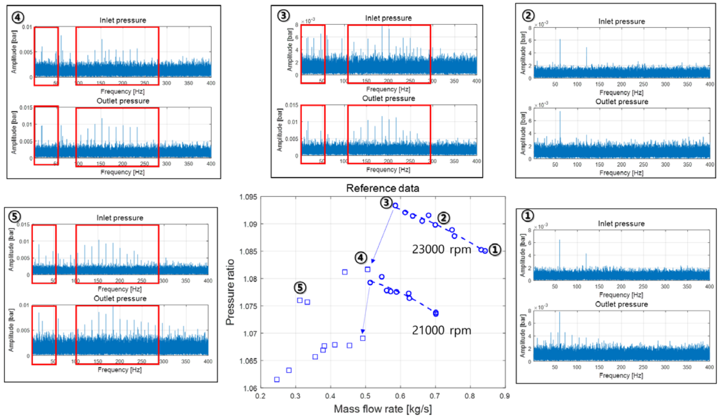
- **Obtaining a compressor map**
  - Based on the test result of a newly installed $S\text{-}CO_2$ TAC compressor
  - No experiments were performed to precisely steady-state the compressor inlet conditions to reflect real gas effects
  - Plan to obtain a dimensionless performance curve of the compressor with precise valve regulation
  - Scheduled to experiment with compressor with inlet conditions inside phase dome



- **Surge and post-surge behavior**
  - Compressor surge and post-surge behavior is studied experimentally
  - Post-surge pressure frequency and recovery process is investigated
  - Inlet temperature and system CO_2 inventory affect surge behavior of compressor



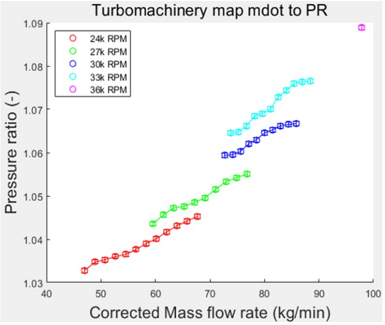


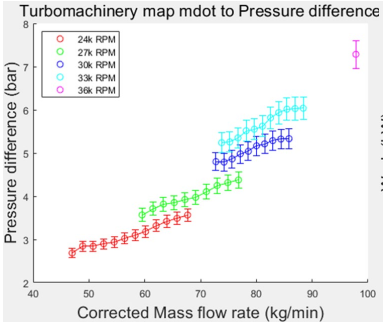


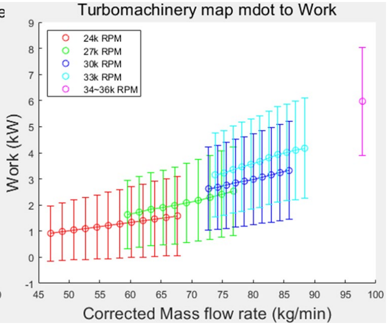
$S\text{-}CO_2$ Turbine Research at KAIST

Map and loss model

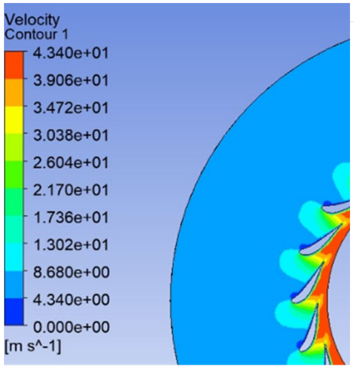
- **Obtaining a turbine map**
  - Based on the test result of a newly installed $S\text{-}CO_2$ TAC compressor
  - Pressure ratio, pressure difference performance map was obtained.
- **Stator (Turbine nozzle) computational simulation**
  - For independent nozzle loss calculations, utilize ANSYS fluent and the REFPROP database providing precise thermal properties of $S\text{-}CO_2$
  - Performing simulations on the turbine nozzles used in the experiment
  - Verify applicability of an enthalpy-based model of nozzle loss to $S\text{-}CO_2$
- **Correlating rotor passage loss based on experimental results**
  - Based on the Benson model, calibrating loss coefficient
  - Appling the newly obtained coefficients of the turbine's rotor passage loss model to the KAIST-TMD code and comparing the results

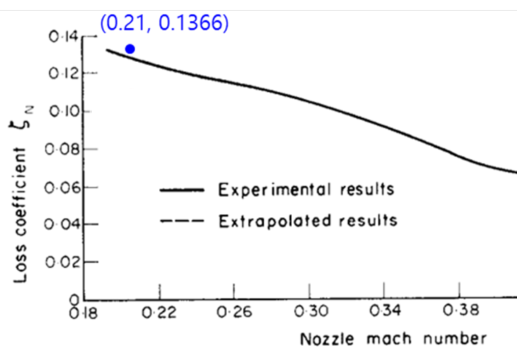


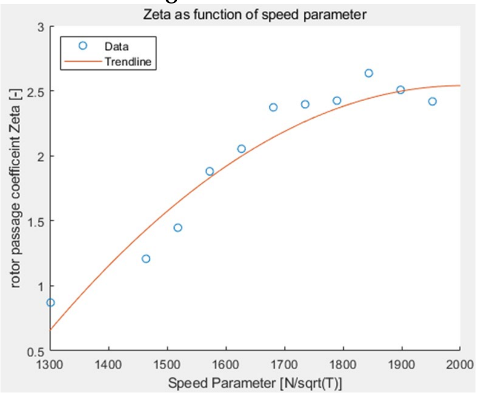


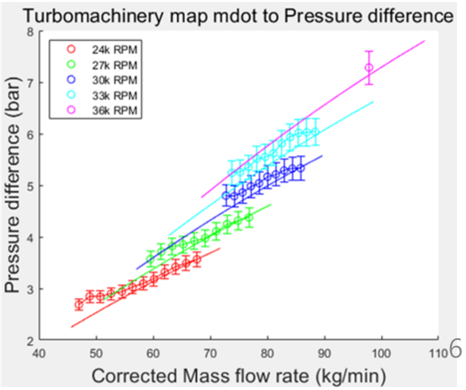


$$h_{passage\ \ loss} = \frac{\Phi^{1.75}(1+K_I)^2}{8}\zeta_I U_4^2 \qquad \zeta_I = -3.79 * 10^{-6} * N_P^2 + 1.52 * 10^{-2} * N_P - 12.7$$





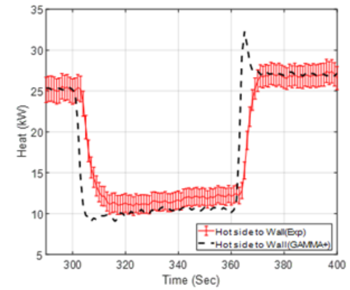




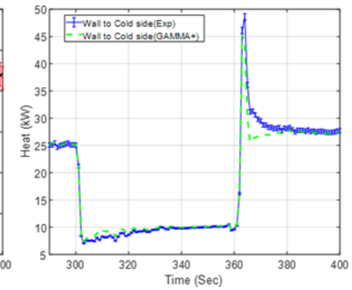
$S\text{-}CO_2$ Heat Exchanger Research at KAIST

Transient Analysis of Precooler

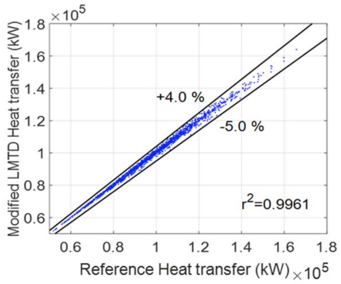
- **Precooler transient analysis**
  - Based on the nuclear system analysis code (e.g. MARS-KS and GAMMA+), precooler transient analysis model is modified.
  - Effect of fluid properties change and heat exchanger component thermal resistance is added.
- **Development of fast heat exchanger transient model**
  - Design model based on LMTD method with correction factor for control the precooler
  - Build model based on precooler mechanism
- **Precooler system analysis for $S\text{-}CO_2$ system control**
  - Validating the developed model with experimental results and system analysis code
  - Off-design model developed based on on-design model and correction factor

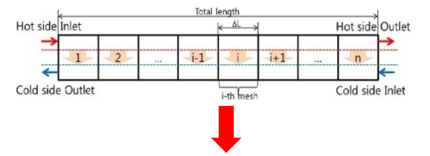


CO_2 side heat of the pre-cooler

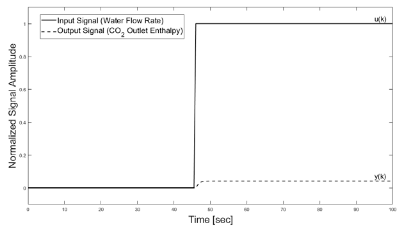


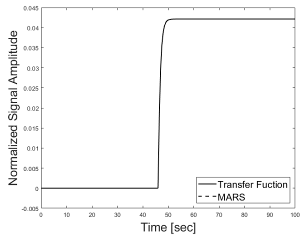
Water side heat of the pre-cooler

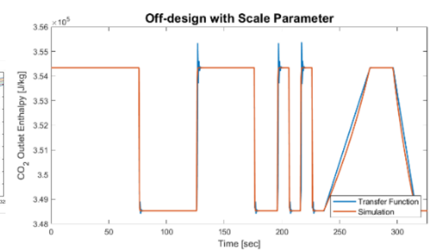


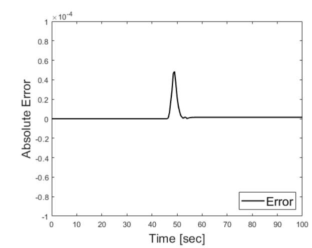


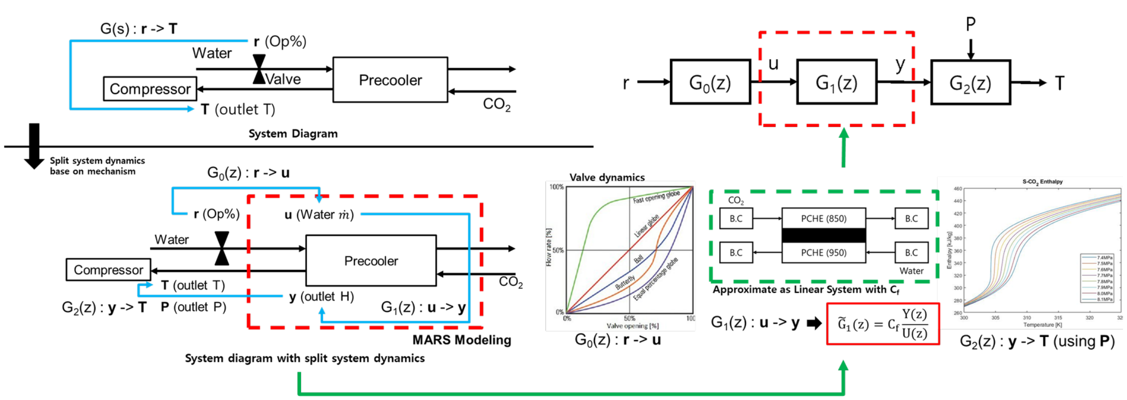
$$\tilde{G}_1(z) = C_f \frac{0.01989\,z + 0.004617}{z^2 - 0.3074\,z - 0.1112}$$







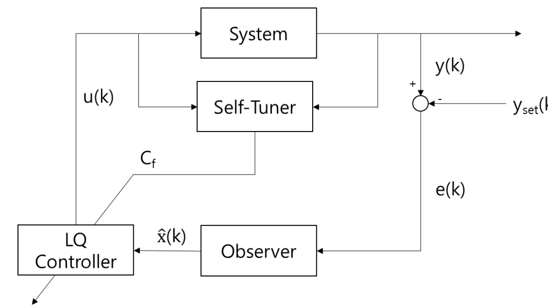


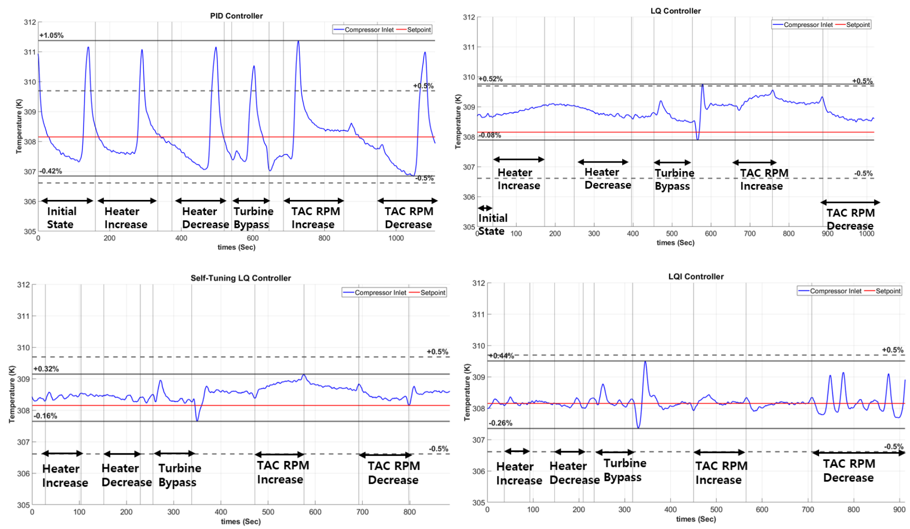


S-CO_2 System Control Research at KAIST

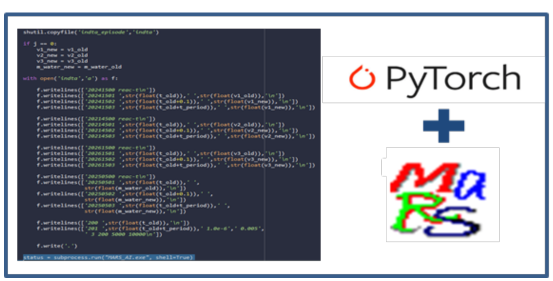
Advanced control

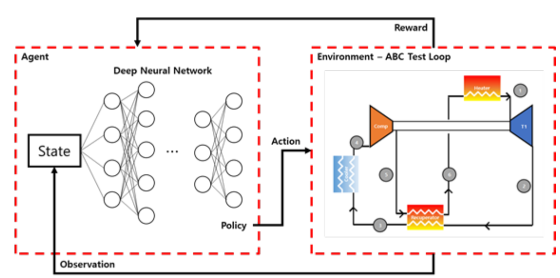
- **Compressor inlet control based on optimal control theory**
  - Compressor inlet temperature controller is designed based on fast precooler model and optimal control theory.
  - Verifying various controller based on control theory by experiment
  - Inlet temperature is maintained lower than 0.5%, which meet the ASME criterion.

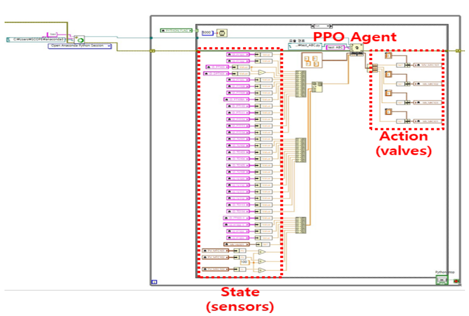




- **Machine Learning based S-CO_2 system control**
  - Reinforcement learning (RL) based control research is being conducted to elevate the level of autonomy of the S-CO_2 system.
  - Time series surrogate model has been established using simulation data produced by the system analysis code.
  - RL agent has been trained based on proximal policy optimization (PPO) algorithm.
  - Trained agent in the simulation environment will be tested and validated on a real hardware facility, the ABC test loop.







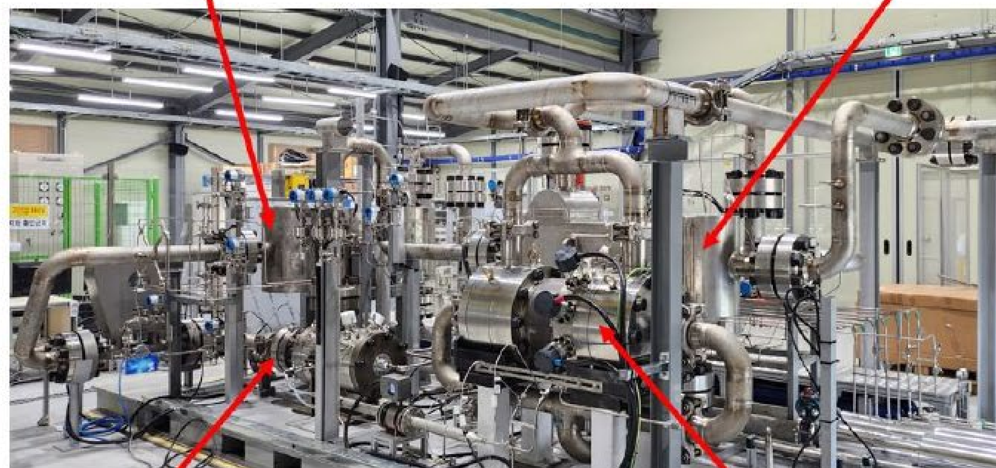
$S\text{-}CO_2$ Power Research in KAERI

❑ sCO_2 Power Generation System pilot plant

Recent progress

- Compressor performance test completed at design point ('20.06)
  (compressor operated at supercritical state)
- Commissioning of power generation completed ('23.12)
  (compressor operated at supercritical state, electric power generated by using turbine)
- Remaining full power test in work, to be completed (~'24.06)

"Precooler" "Recuperator"



"Compressor" "Turbine"

[500 kW sCO_2 power generation system in KAERI]

[Heat source]

[Heat sink]

[Power source]

[NG supply system]

$S\text{-}CO_2$ Power System Commercialization

KEPCO

- Construction of South Korea's first 2MW class supercritical CO_2 power generation demonstration facility infrastructure started by securing 18 billion KRW(~13M USD) in government funds.
- A 32 billion KRW (~23M USD) scale '2MW class supercritical CO_2 power generation demonstration center', the first of its kind in South Korea, will be established in the future innovation district within the Yeosu Industrial Complex.
- The project includes:
  - ➢ Supercritical carbon dioxide power generation cycle design
  - ➢ Construction and pilot operation of supercritical carbon dioxide power generation demonstration facilities
  - ➢ Development of supercritical carbon dioxide power generation performance evaluation criteria and operating procedures
  - ➢ Development of utilization models and discovery of demand companies
  - ➢ Training of specialized personnel and technical support, etc. are planned.

S-CO_2 Power System Commercialization

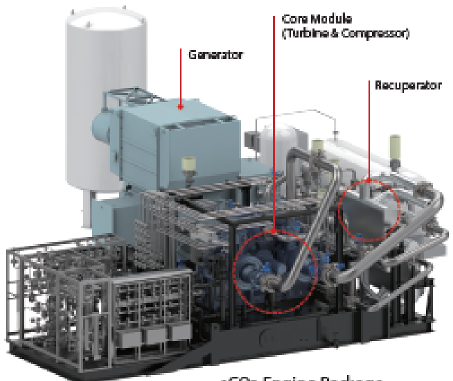
Hanwha Power Systems

Hanwha Power Systems

sCO2 Power Systems

sCO2 Power Systems
Major Scope of Supply by Hanwha

- **sCO2 Engine Package**
- **Heater (Main and Pre-heater) with diverter valve**
- **Air-cooled Pre-cooler**
- **CO2 Management System**



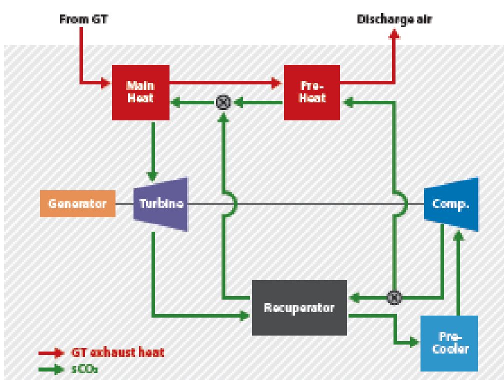
sCO2 Engine Package

Waste Heat Recovery

Industrial processes create exhaust gas streams which are vented and unused and this provides significant wasted thermal energy which can be converted into Fuel-Free electricity.

Our innovative supercritical CO2 technology converts this otherwise unused heat into electricity which can be used on-site or sold into the electric market.

Hanwha Power Systems' sCO2 technology is a perfect fit for use in waste heat recovery applications. This offsets the use of carbon-based generation and provides baseload emission free energy.



Sustainable power solutions provide emission free electricity and valuable ESG benefits

Key Benefits

Sustainability
- Avoids GHG emissions
- Displaces energy from fossil-fuel based generation
- Provides valuable green attributes
- Beneficial ESG value and message for corporations

Money Saving
- Lower installed capital costs
- Lower operation and maintenance costs
- Can supply customer on-site energy requirements
- Unmanned remote operation

Higher Performance
- Superior performance compared to conventional steam and organic Rankine cycles
- Lower on-site power consumption
- Higher operating efficiencies

Module Solution
- Smaller footprint than other Waste Heat Recovery (WHR) technologies
- Conventional components
- Utilizes already proven technology

Cleaner & Eco-friendly
- No carbon emissions
- No air quality concerns
- No water required

S-CO_2 Power System Commercialization

SK Group

BusinessKorea Since 1983 40th

National | Economics | Industries | Stock Market | Finance | Startups | Science/Tech | ESG | Event | K-Culture | Opinion | Who's Who

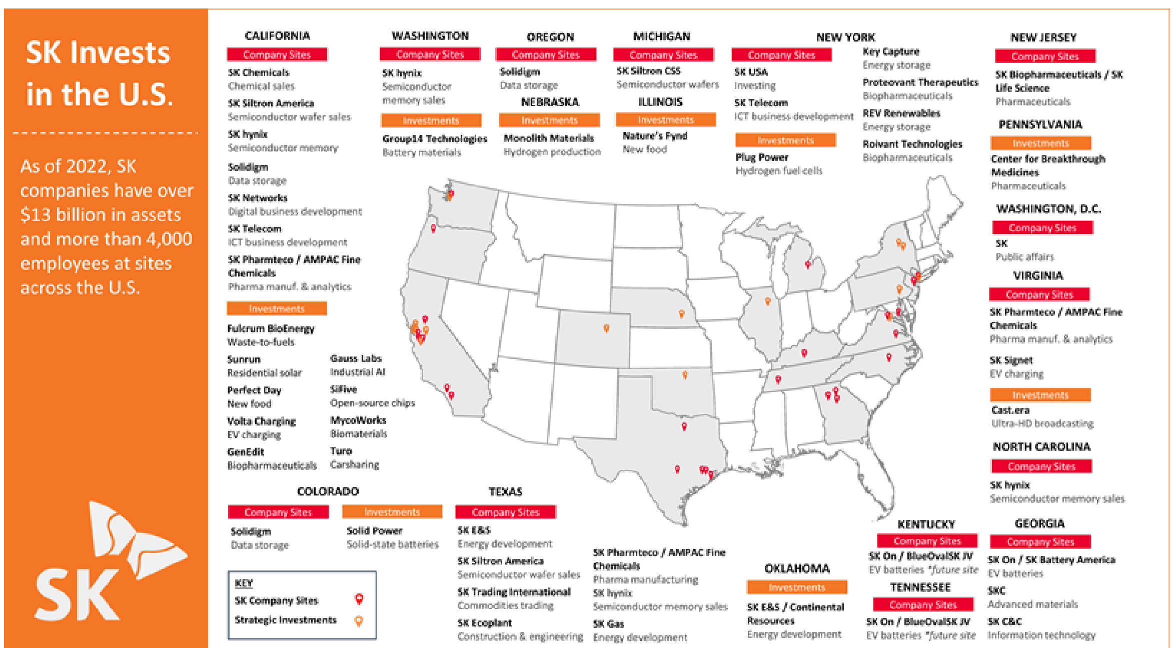
HOME > FINANCE

SK Materials to Acquire Management Rights to 8 Rivers, US CCUS Company by Investing US$300 million

Jung Min-hee | 2023.03.08 12:14 | Edit 2023.03.23 08:47

NET Power And SK Group To Form A Joint Venture

by Petya Trendafilova · May 22, 2023 · 2 minute read



SK Group is South Korea's third-largest conglomerate with more than 120 operating companies that have a combined annual revenue of more than $119 billion. Four major areas: Semiconductors, Telecommunications, Energy and Life Sciences. Three of SK's operating companies, SK Hynix, SK Innovation and SK Telecom are each ranked individually among the world's top publicly traded companies on the Forbes Global 2000.

Sir. Rodney Allam Seminar
@ Seoul Dec. 7. 2023

$S\text{-}CO_2$ Power System for Microreactor (Japan)

Mitsubishi Heavy Industry

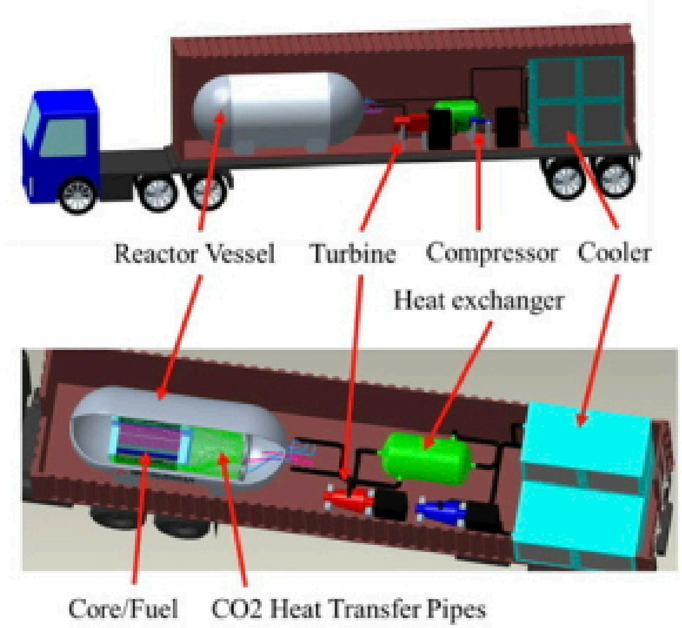
2.Mitsubishi Microreactor Outline(1)

MITSUBISHI HEAVY INDUSTRIES

- The maximum thermal output is 1MWt per module and total power demand is satisfied flexibly combining multiple units.
- Based on "all-solid-state core" concept, the reactor uses a highly thermal conductive graphite-based material that remove heat from core without liquid coolant.
- Transport inside 40ft standard cargo container by conventional transport systems

Conceptual Specifications of the Microreactor

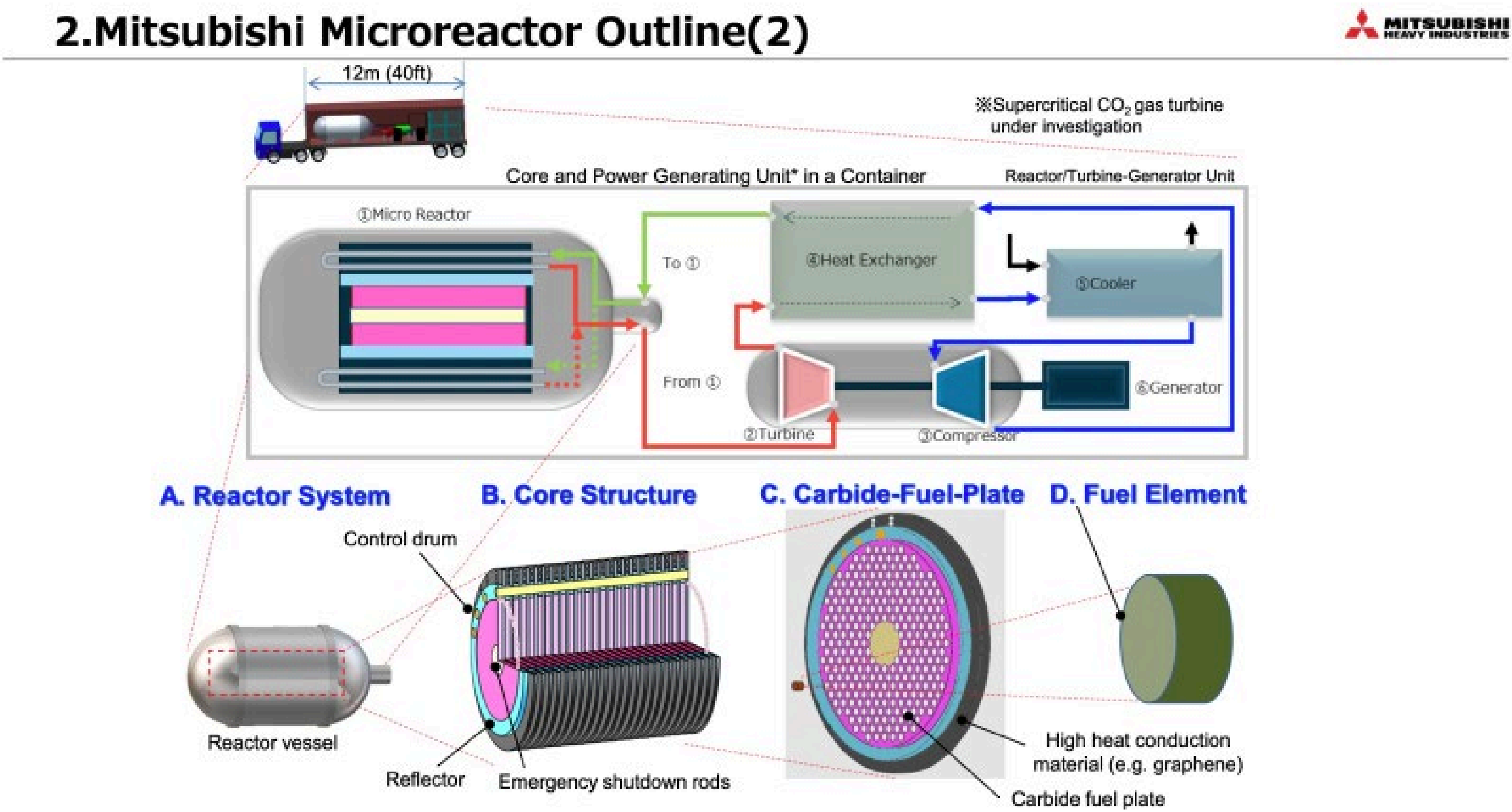
Item	Value
Fuel/Core	HALEU Neutron Spectrum: Epithermal neutron
Core structure	Layer structure with Graphite type material (lighter weight)
Thermal Output	~1MWt
Electric Output	~0.5MWt
Operation/Control	Automated
Safety System	Full passive
Size	Inside Standard 40ft freight container



Source: IAEA technical meeting MHI's R&D project on Microreactor Technology and Development Plan, 2021

S-CO_2 Power System for Microreactor (Japan)

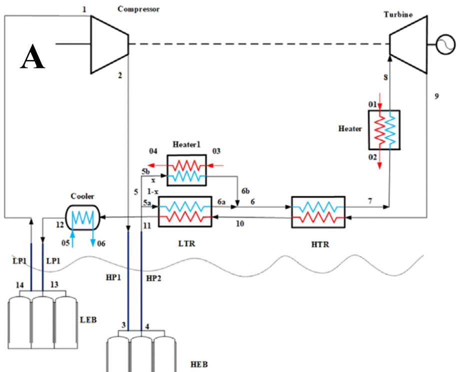
Mitsubishi Heavy Industry



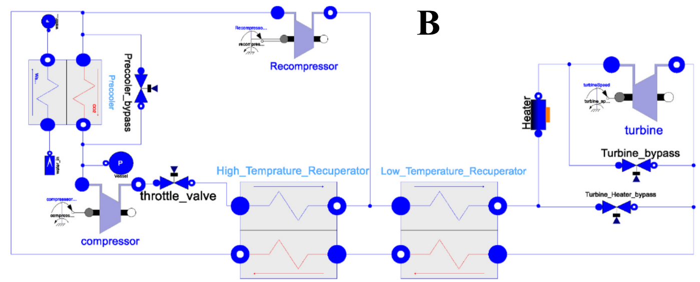
Source: IAEA technical meeting MHI's R&D project on Microreactor Technology and Development Plan, 2021

$S\text{-}CO_2$ Power Cycle Activity (China)

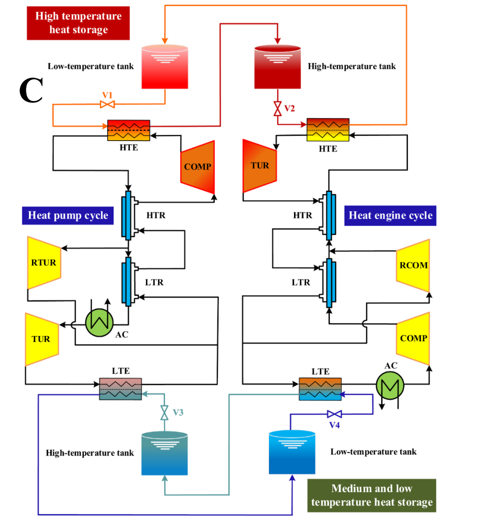
Cycle Development



Compressed $S\text{-}CO_2$ energy storage system
（Xi ‘an Jiaotong University, NPIC）

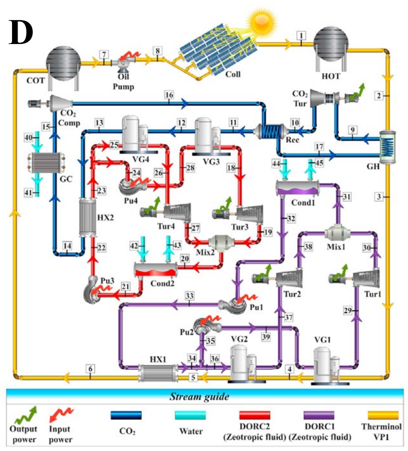


Analysis of different control strategies（Xiamen University）

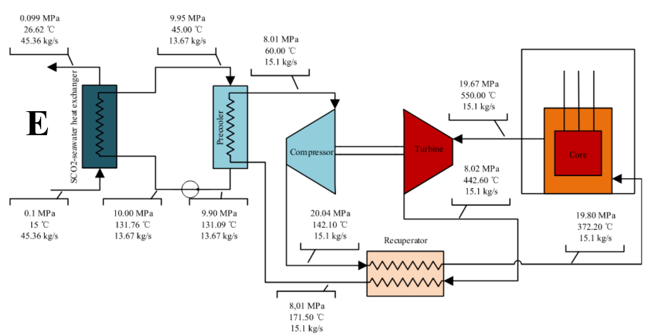


$S\text{-}CO_2$ pumped thermal electricity storage system
（Xi ‘an Jiaotong University, NPIC）

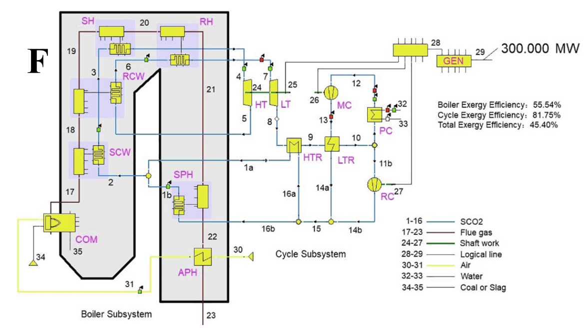
$S\text{-}CO_2$ System design and optimisation



Solar and $S\text{-}CO_2$ (power generation system)
（Harbin Institute of Technology）



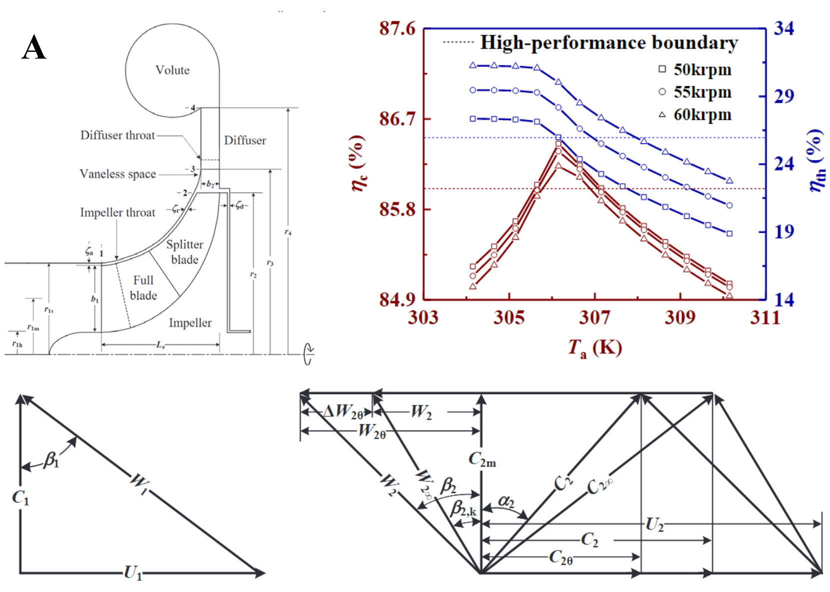
LOCA accident analysis
（North China Electric Power University）



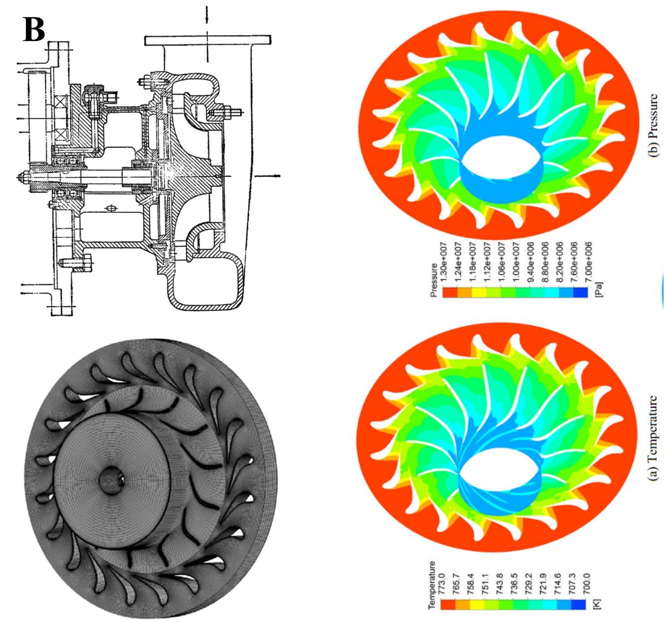
$S\text{-}CO_2$ coal-fired power generation system.
（North China Electric Power University）

$S\text{-}CO_2$ Power Cycle Activity (China)

Turbomachinery



Development and design of compressor models (Beijing University of Technology)



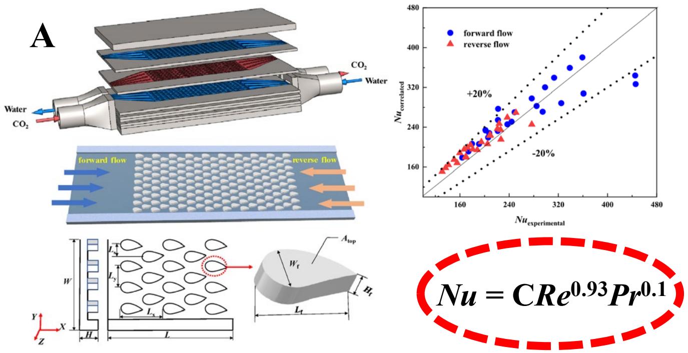
Aerodynamic design and numerical analysis of a radial inflow turbine (Tsinghua University)

(A)discussing the geometric sensitivity of the compressor, the optimisation design of the centrifugal compressor in the S-CO_2 Brayton cycle was con-ducted using a genetic algorithma;

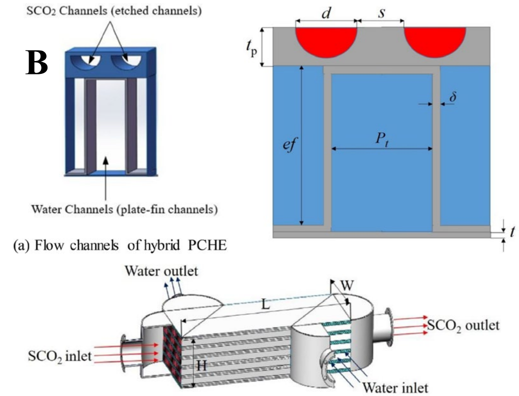
(B)Design method for an S-CO_2 radial inflow turbine is proposed and a 1.5 MW S-CO_2 radial inflow turbine is designed. The three-dimensional (3D) numerical simulation of the designed turbine is carried out by using ANSYS-CFX commercial soft ware, and the results are in good agreement with the design values.

$S\text{-}CO_2$ Power Cycle Activity (China)

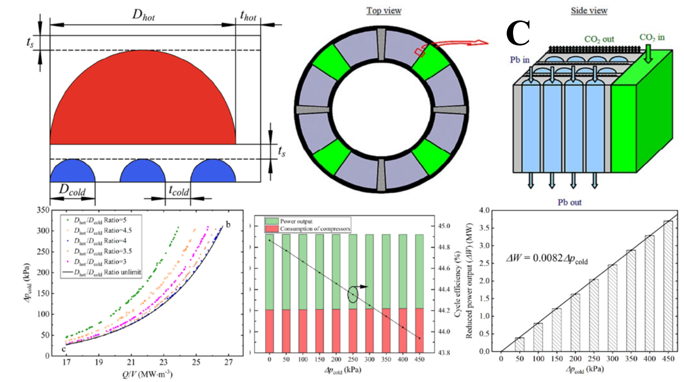
Heat Exchanger



Asymmetric airfoil-fin PCHE（Xi 'an Jiaotong University）



Diffusion-bonded hybrid PCHE（Xi 'an Jiaotong University）



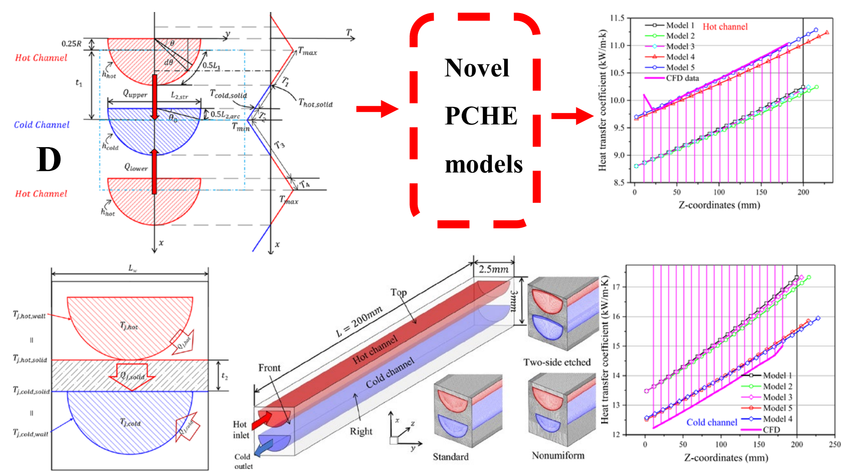
PCHE（CO_2-Pb）(Southeast University)

(A)The effects of working parameters and flow direction on the heat transfer performance are analyzed based on the average thermal-resistance ratio. Meanwhile, the effects of flow directions on the comprehensive performance are quantitatively evaluated.

(B)a diffusion-bonded hybrid printed circuit heat exchanger is put forward as the precooler used for $S\text{-}CO_2$ Brayton cycle.

(C)The channel dimensions of the intermediate heat exchanger were optimized to improve its thermal-hydraulic performance. An in-house code for the thermal-hydraulic design of printed circuit heat exchanger with lead–bismuth and $S\text{-}CO_2$ as working fluid was built.

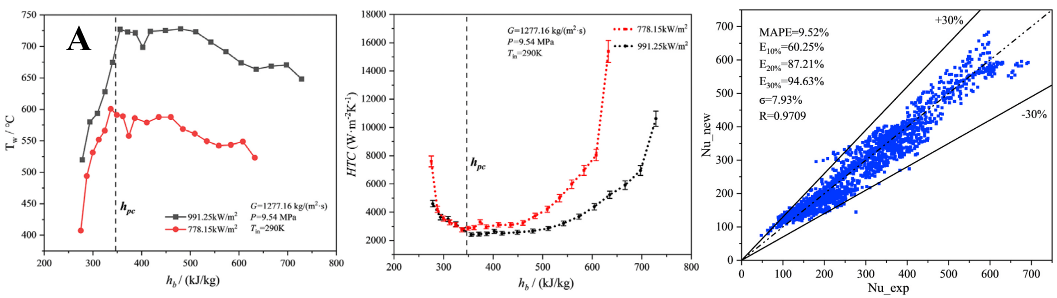
(Northwestern Polytechnical University)



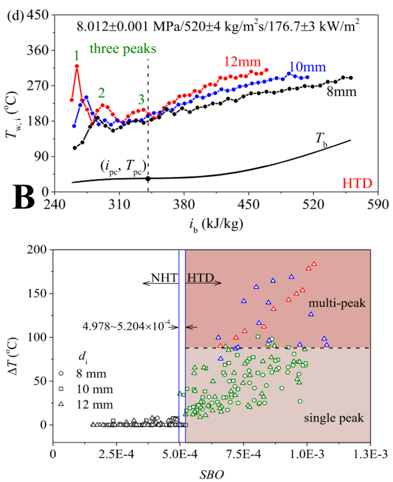
(D)This study addresses the crucial challenge in the design of Plate Heat Exchangers (PCHEs) for $S\text{-}CO_2$ Brayton cycles, caused by inadequate mathematical models and heat transfer correlations. The paper introduce novel PCHE models that surpass existing approaches in accuracy and versatility.

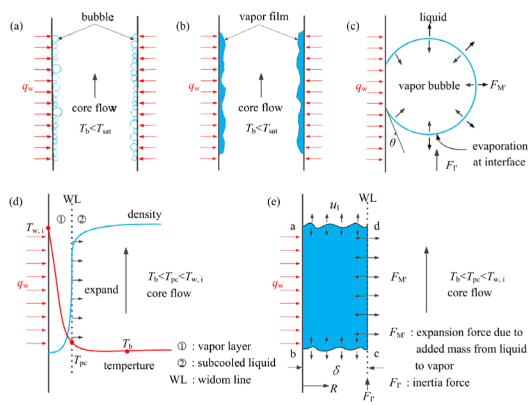
S-CO_2 Power Cycle Activity (China)

Heat Transfer



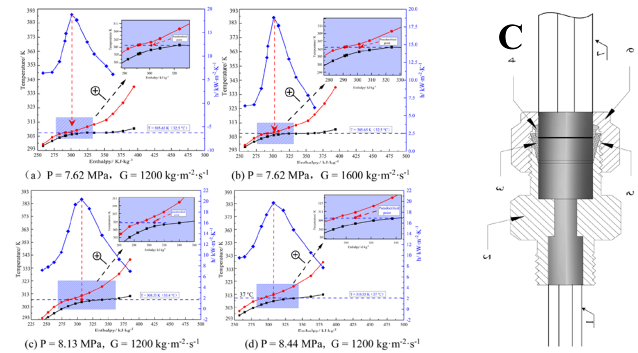
High Heat Flux **>1000kW/m²** **（Xiamen University）**





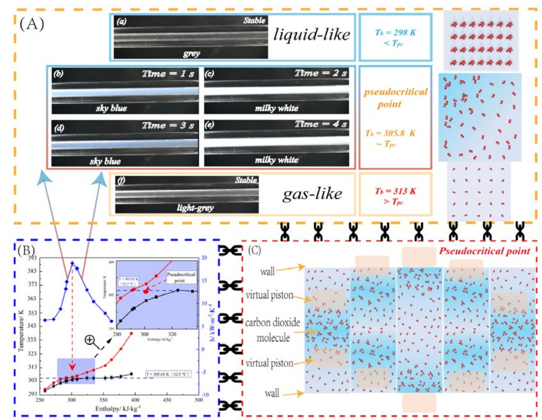
HTD Supercritical pseudo-boiling

（North China Electric Power University）



Visualization experiments and piston effect

（North China Electric Power University）



In the area of flow heat transfer, (A)convective heat transfer experiments of S-CO_2 at high heat flux were investigated, and high-precision heat transfer correlations were proposed in combination with experimental data; (B)The SBO number was proposed based on the pseudo-boiling theory to determine the onset of heat transfer deterioration; (C)The characteristics of supercritical heat transfer and flow pattern visualization are investigated experimentally. The local heat transfer coefficient and visual scenario of supercritical carbon dioxide are presented.

Thank you

Q & A

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