Cycle analysis and economic evaluation of heat pipe cooled micro-reactor and comparison with other power generation systems

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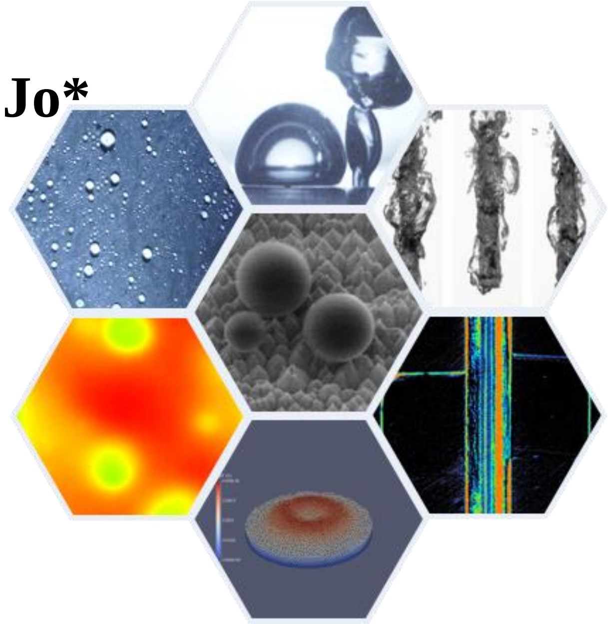
POSTECH

May 19, 2023

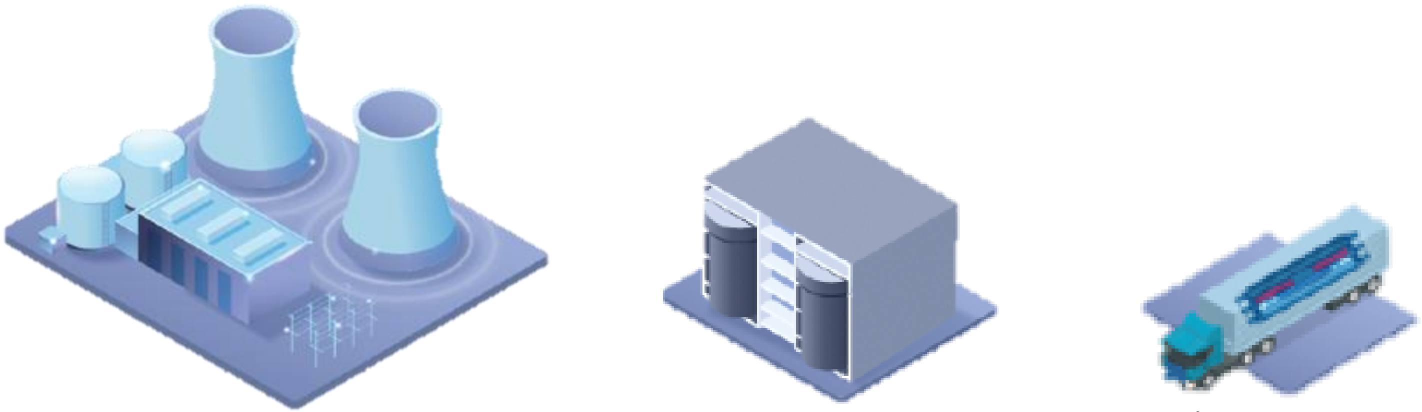


Contents

1. Introduction

● What is the SMR and micro-reactor?

[1]



<Large-scale NPP> <SMR> <Micro-reactor>

	Large-scale NPP	SMR	Micro-reactor
Power generation	300~1000MW$_e$	30~300MW$_e$	~30MW$_e$
Volume	Large (100-1000)	Medium (10-100)	Small (1)
Safety	Low	Medium	High
Construction cost and time	High	Medium	Low
Application	Power generation system	Power generation system	Power generation system, aircraft carrier, space reactor, and submarine, hydrogen production, and mining

[2]

Characteristics of micro-reactor

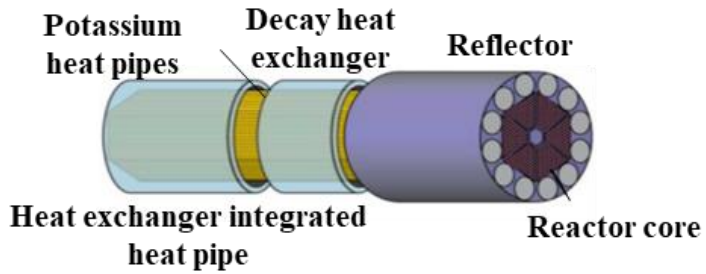
- Low construction cost and time (Modularization)
- Ability to be "grid independent" (Micro-grid)
- Low heat transfer rate & High inherent safety
- Market size: 30~40 trillion won[2]

[1] https://www.iaea.org
[2] David, Global market analysis of microreactors, DOE (2021)

PCS: Power Conversion System
KRUSTY: Kilo-power Reactor Using Stirling Technology

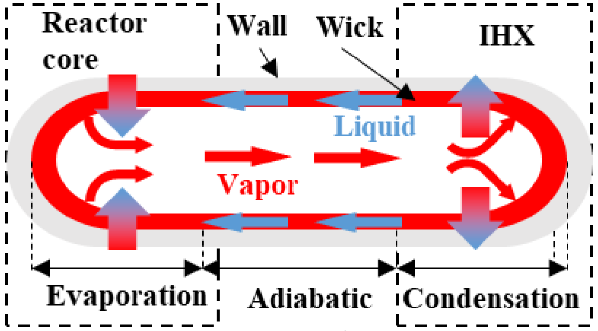
1. Introduction

- What is the heat pipe cooled micro-reactor?

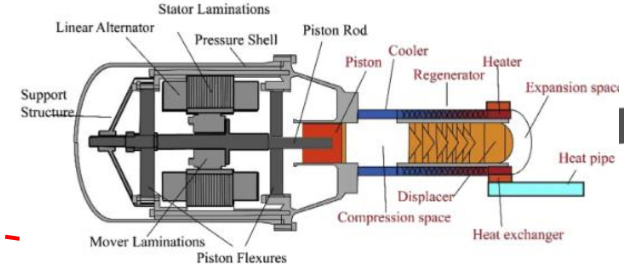


<Heat pipe cooled micro-reactor>

[3]



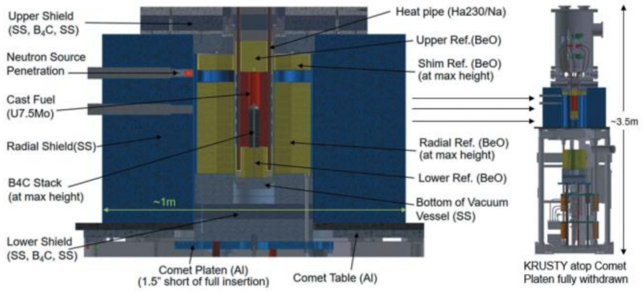
<Heat pipe>



<Stirling cycle>

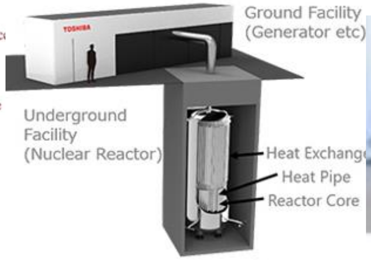
<KRUSTY>

[4]

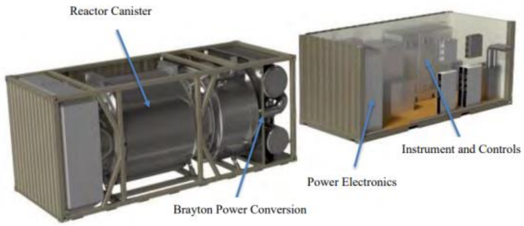


Research trend

<MoveluX> <Aurora> <Evinci>



Buried type



Transportable type

Heat pipe cooled micro-reactor

- Primary system and PCS: heat pipe and stirling cycle
- Advantages: strong negative feedback, long life, and robustness
- Cost and volume are lower than typical NPP (primary cooling system does not require)

Applications of heat pipe cooled micro-reactors

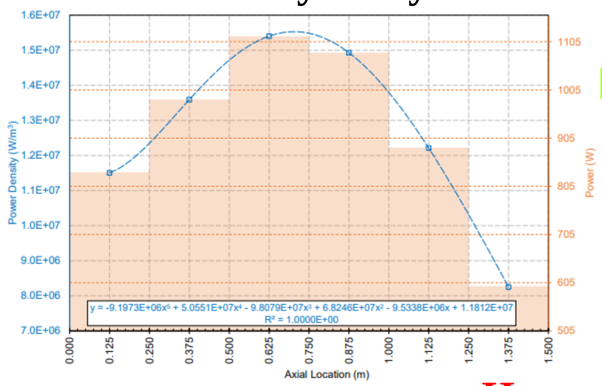
- Space reactors: KRUSTY
- Micro-grid power generation systems: MoveluX, Aurora (buried type), Evinci (transportable type)

[3] Small nuclear power reactors, World nuclear association (2021),
[4] Advances in Small Modular Reactor Technology Developments, IAEA advanced reactors information system (2020)

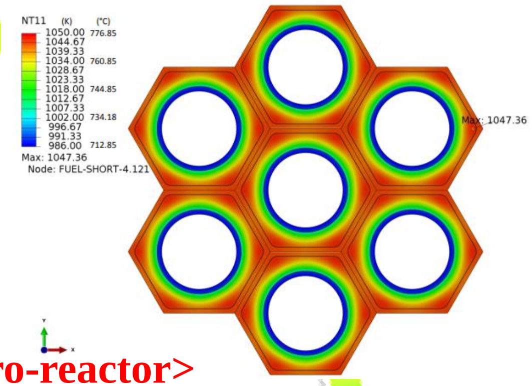
2. Research trend & Research objective

● Research trend of heat pipe cooled micro-reactor

<Reactivity analysis>



<Thermal stress>



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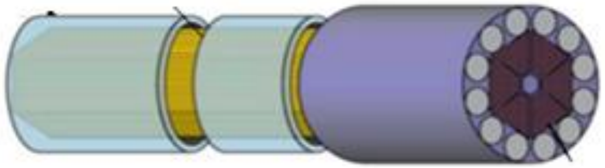
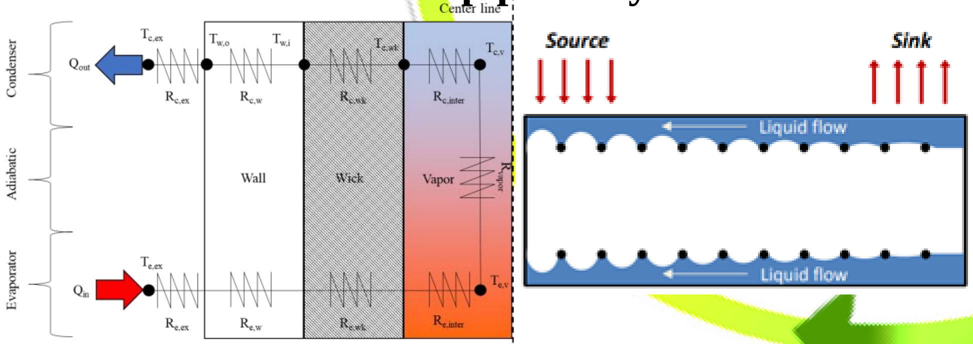
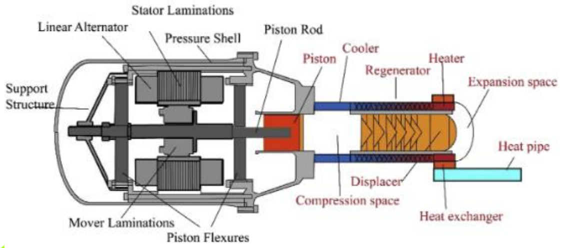


<Heat pipe analysis>



<Stirling engine design>



Heat pipe cooled micro-reactor[5]

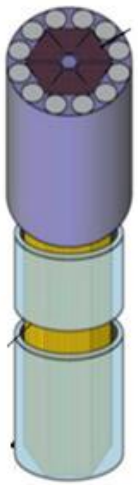
- Most researches for heat pipe cooled micro-reactor were studies of primary system such as **analysis of reactivity, heat pipe, thermal stress**
- The reactor type was used as a **space reactor** and was mostly used as **a stirling engine**
- Research on PCS detailed aimed at generating electricity design is insufficient

[5] Small nuclear power reactors, World nuclear association (2021), https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

2. Research trend & Research objective

● Research objective of heat pipe cooled micro-reactor

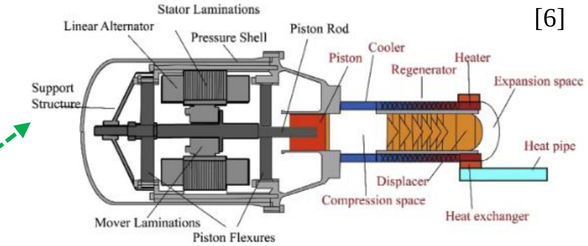
Necessity of research on heat pipe cooled micro-reactor



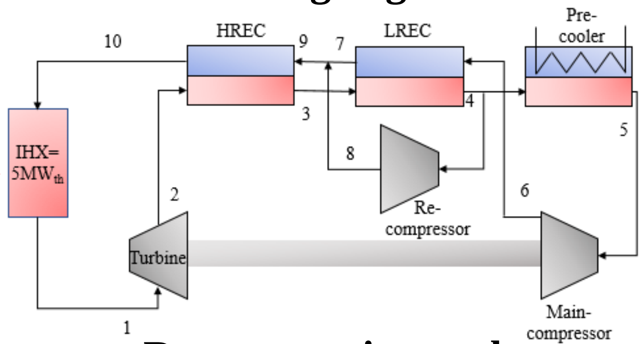
Space reactor

Power generation system

[6]



<Stirling engine>

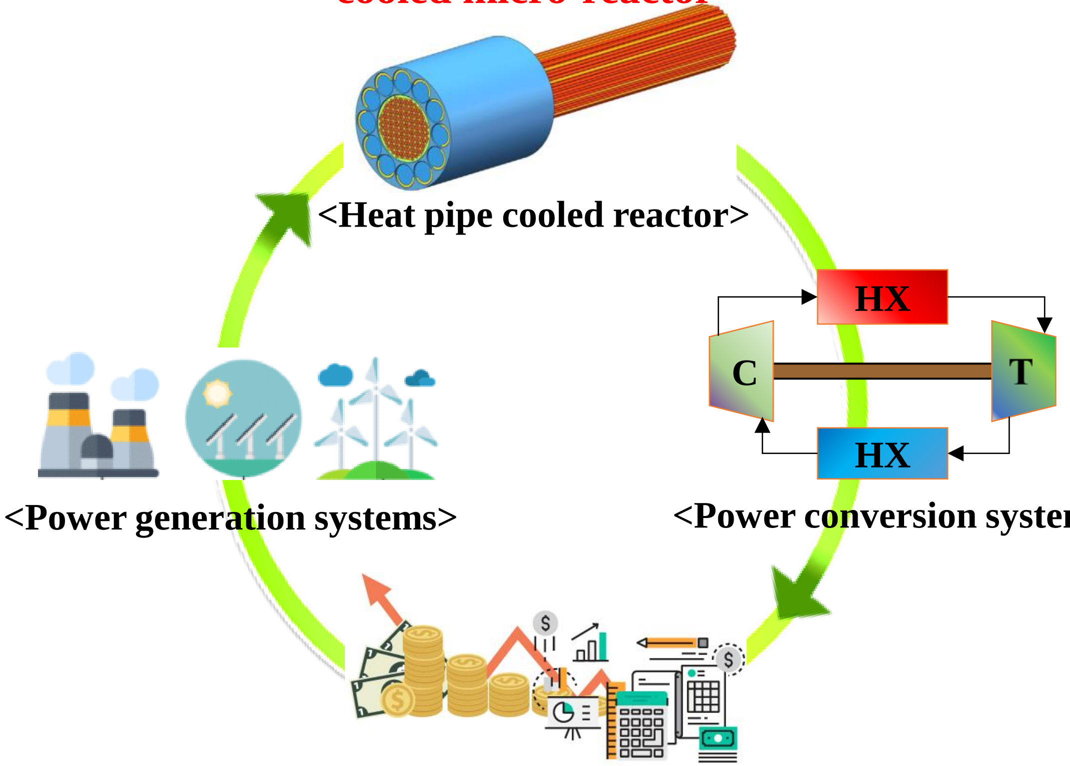


<Recompression cycle>

- Most studies have been conducted on the stirring cycle of space reactors
- Research on the PCS design is needed to develop the power generation system to form a micro-grid

Objective and scope of the research on heat pipe cooled micro-reactor

Detailed design and economic evaluation of heat pipe cooled micro-reactor



<Heat pipe cooled reactor>

<Power generation systems>

<Power conversion system>

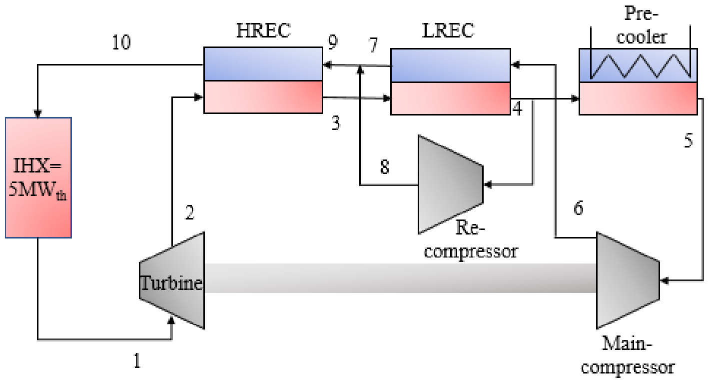
<Economic evaluation>

[6] Kim, M. S., Ahn, Y., & Lee, J. I. (2015). Studies of S-CO2 Power Plant Pipe Selecting Design and General layout for Small Modular Sodium-cooled Fast Reactor. In International Congress on Advances in Nuclear Power Plants.

TIT: Turbine Inlet Temperature
PCHE: Printed Circuit Heat Exchanger
FPHE: Flat Plate Heat Exchanger
BPHE: Brazed Plate Heat Exchanger

3. Research progress

- Determine of power conversion system and components

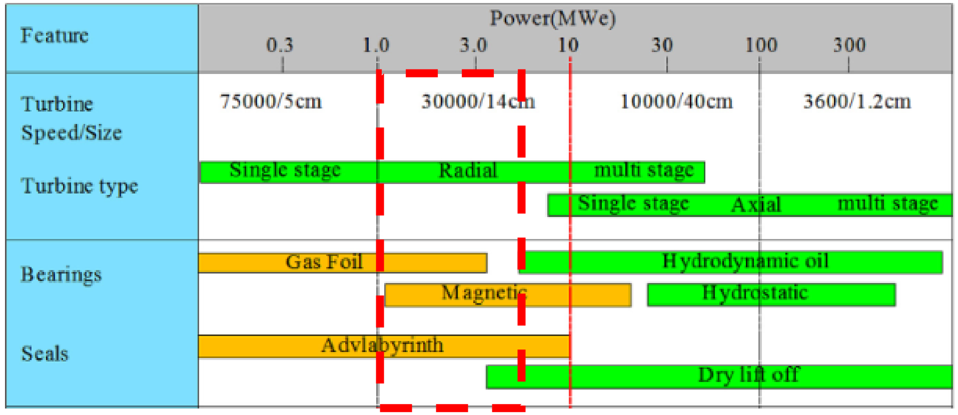


<Recompression Brayton cycle>

Cycle layout and working fluid

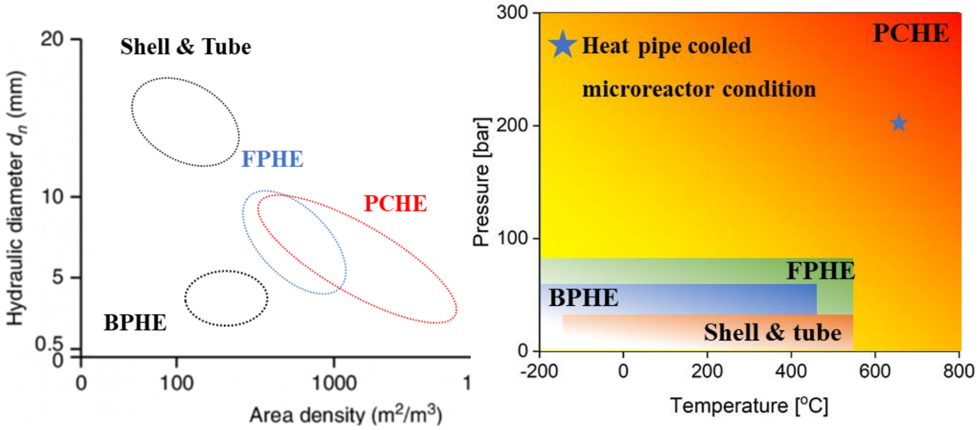
- Working fluid: Supercritical CO_2
- Cycle type: Re-compressor Brayton cycle (High cycle efficiency and compactness)[7]

[10]



<Turbomachinery types>

[8,9]



<PCHE operating condition and area density>

PCHE

- High temperature and pressure conditions
- High heat transfer performance and compactness
- High pressure drop

Radial single-stage turbomachinery

- Power generation of heat pipe cooled micro-reactor: 1 – 5MW$_e$
- Turbine type: radial single-stage turbomachinery
- Speed and size: 30000~ RPM, 5~14cm

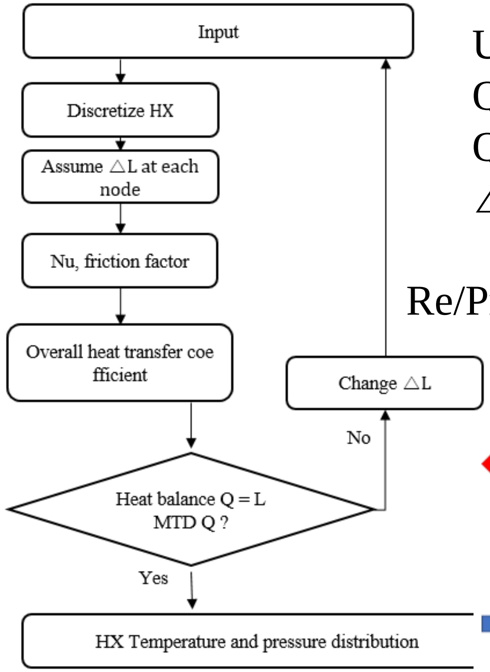
[7] Park J.H, Optimization and thermodynamic analysis of supercritical CO2 Brayton recompression cycle for various small modular reactors, Energy (2018)
[8] Thonon. B, Compact heat exchangers technologies for the HTRs recuperator application (2014)
[9] Xiaoqin, Review on mechanical design of printed circuit heat exchangers, International conference on nuclear engineering (2017)
[10] Yaping Liu, Supercritical co2 Brayton cycle: A-state-of-the-art review, Energy (2019)

3. Research progress

$$N_s = \frac{w\sqrt{Q}}{(H_{ad}g)^{3/4}} \quad D_s = \frac{d(H_{ad}g)^{1/4}}{\sqrt{Q}}$$

$$H_{ad} = \left(\frac{\gamma R T_i}{\gamma - 1}\right)\left\{\left[1 - \left(\frac{P_o}{P_i}\right)^{(\gamma-1)/\gamma}\right]\right\}$$

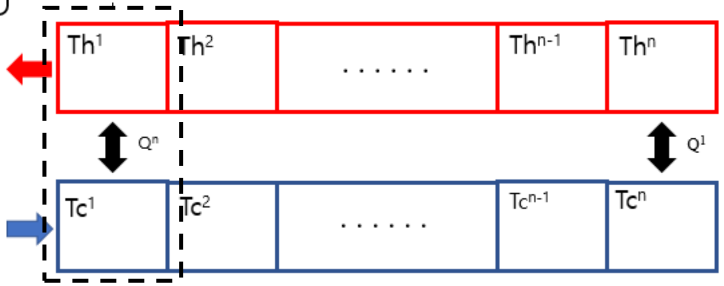
● Development of PCHE and radial single-stage turbomachinery codes



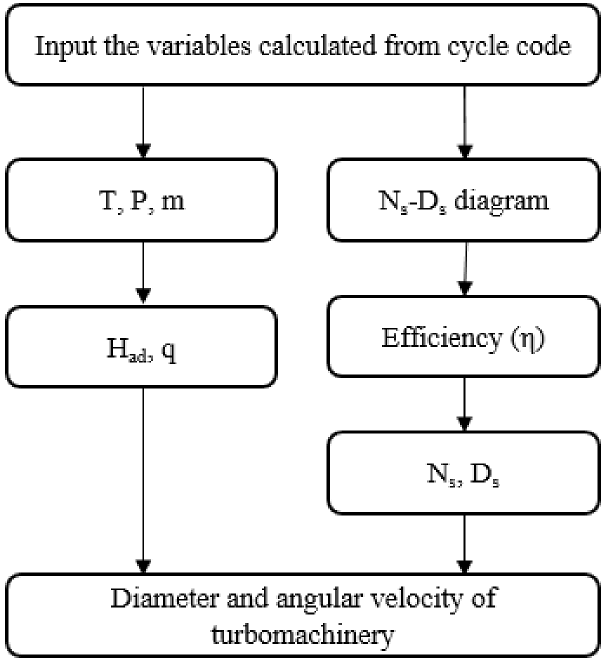
$U = (1/h_h + 1/h_c + k/t)^{-1}$
$Q = UA \triangle T_{LMTD}$
$Q = mc_p \triangle T$
$\triangle h < 0.3$ kJ/kg

$A = Q/(U \triangle T_{LMTD})$
$L = \text{function}(A)$

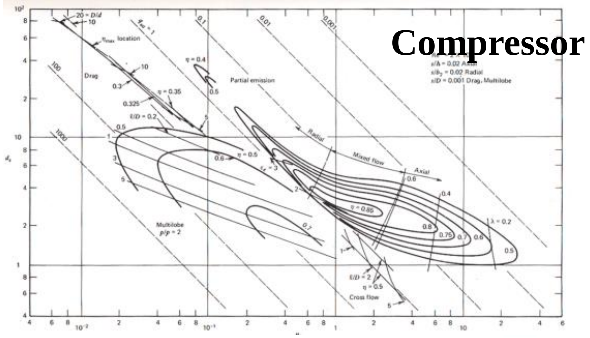
Re/Pr/Nu/f/△P at each node

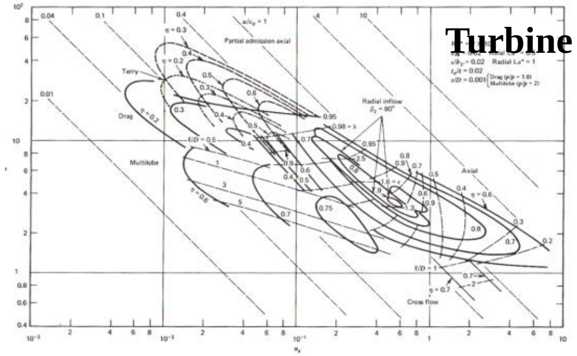


<PCHE code flowchart>



<Turbomachinery code flowchart>





Heat exchanger (PCHE) code

- Method: **Kern's method** **(LMTD and heat balance)**[11]
- Discretization considering change in properties (△h<0.3kJ/kg)
- Results: temperature and pressure distribution, area and volume

Turbine and compressor code

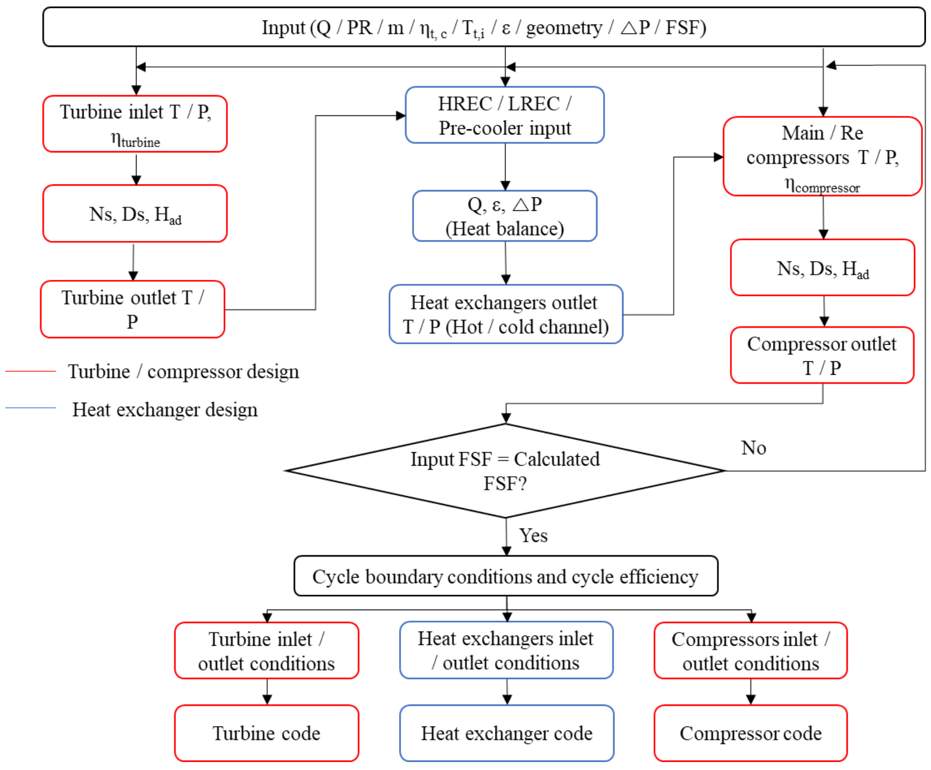
- Ns-Ds diagram[12]

  (Diagram developed through experiment of radial single-stage type)
- Results: Pressure ratio, diameter and angular velocity of turbomachinery

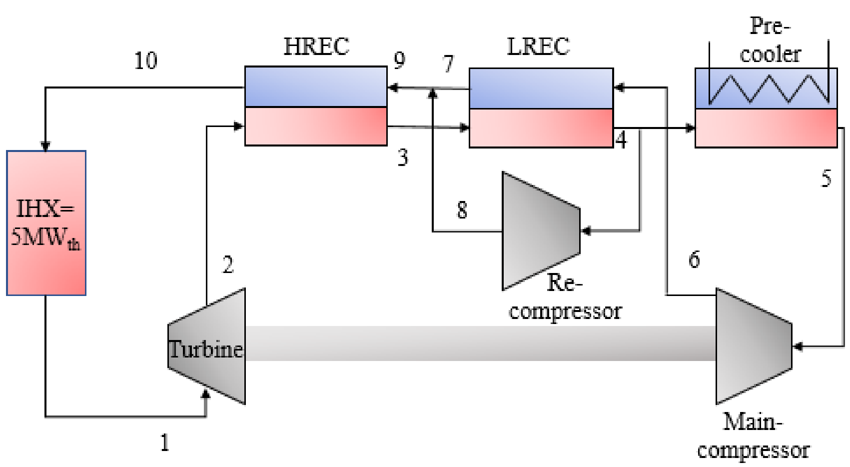
[11] Lee, Evaluation of thermal-hydraulic performance and economics of PCHE for recuperators of Sodium-cooled Fast Reactors (SFRs) using CO2 and N2 as working fluids, NET (2022)
[12] Yaping Liu, Supercritical co2 Brayton cycle: A-state-of-the-art review, Energy (2019)

3. Research progress

● Development of cycle analysis code

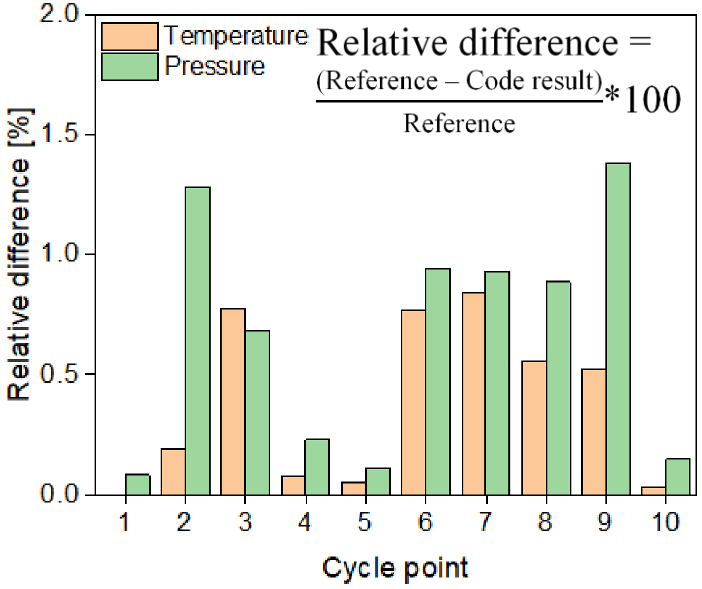


<Turbomachinery code flowchart>



<Recompression Brayton cycle>

[13]



<Validation>

Recompression Brayton cycle analysis code

- Component type: **PCHE and radial single-stage turbine and compressor**
- **Input**: heat transfer rate of heat source, pressure ratio, mass flow rate, effectiveness of heat exchangers, TIT
- **Result**: temperature and pressure at each point, size of turbine, compressor, and HX
- **Maximum difference** with reference case: about **1.38 %**

[13] Park J.H, Optimization and thermodynamic analysis of supercritical CO2 Brayton recompression cycle for various small modular reactors, Energy (2018)

4. Results & Analysis

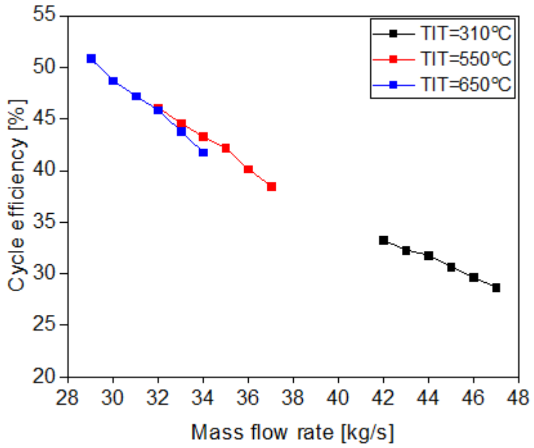
- **Cycle efficiency according to the design parameters**

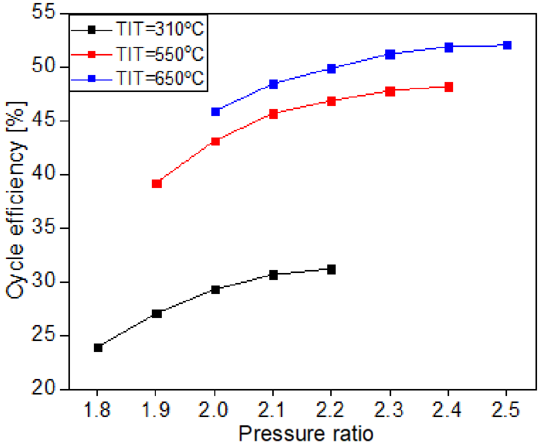
Effectiveness of HX

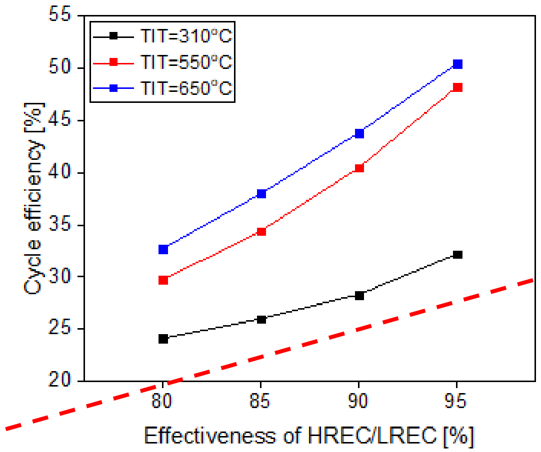
$$\varepsilon = \frac{C_c(T_{c,o}-T_{c,i})}{C_{min}(T_{h,i}-T_{c,i})} = \frac{C_h(T_{h,i}-T_{h,o})}{C_{min}(T_{h,i}-T_{c,i})}$$

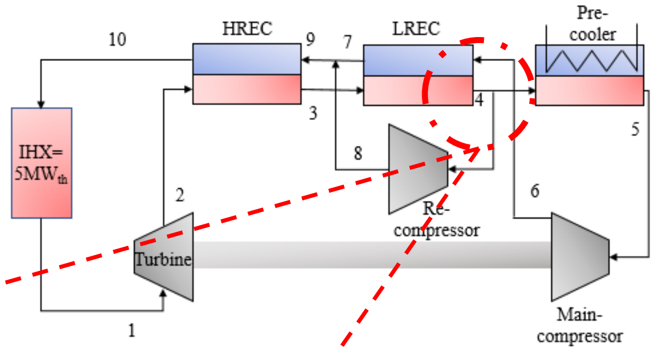
Pressure ratio

$$PR = \frac{Turbine\ inlet\ P}{Turbine\ outlet\ P}$$









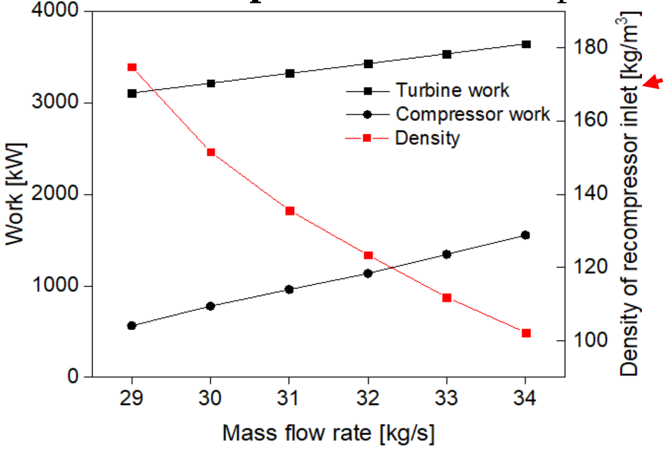
Work of turbomachinery

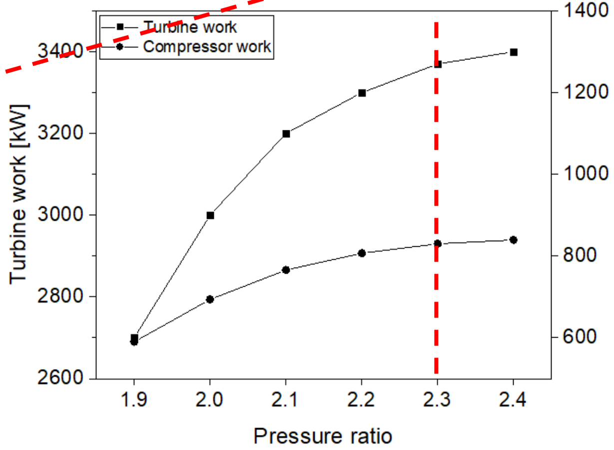
W=(m/ρ)△P

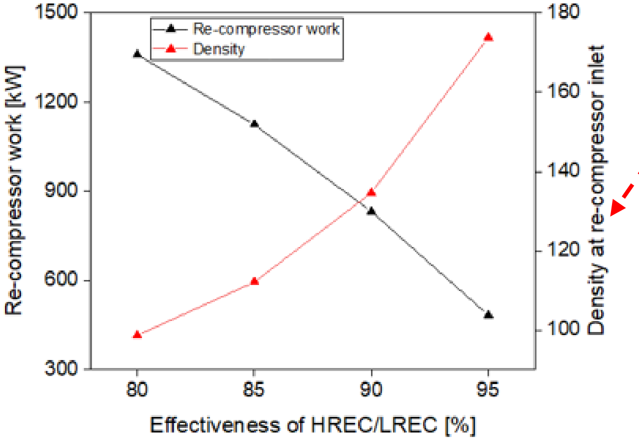
Main compressor inlet T/P are constant

Slope: turbine < compressor

Slope: turbine = compressor







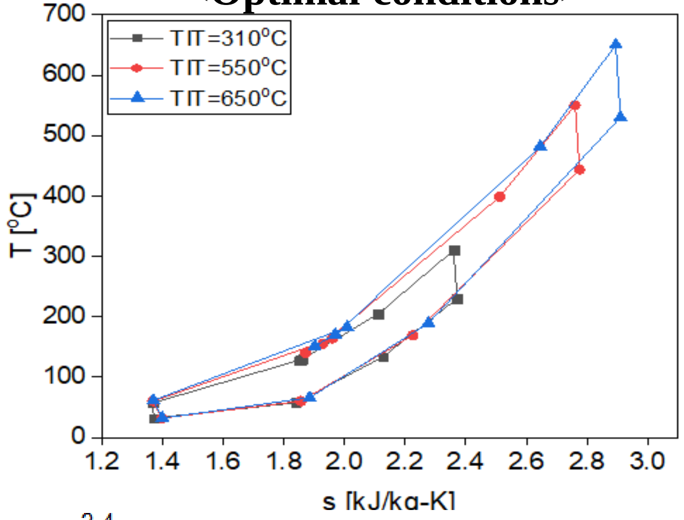
Slope: turbine > compressor

HREC: High temperature recuperator
LREC: Low temperature recuperator
TIT: Turbine Inlet Temperature

4. Results & Analysis

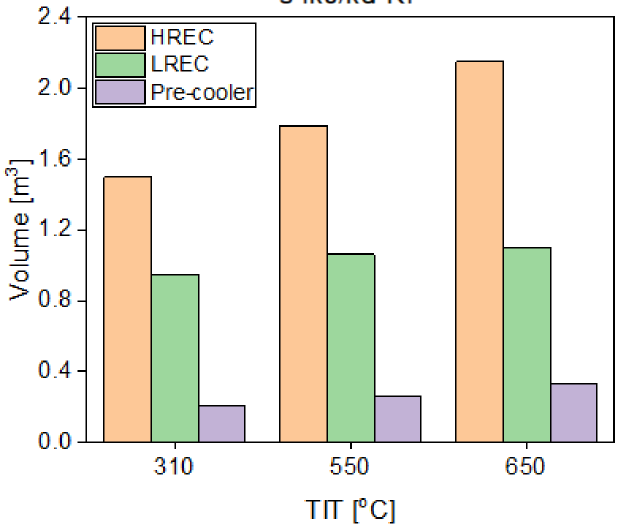
● Optimal operating conditions according to the TIT

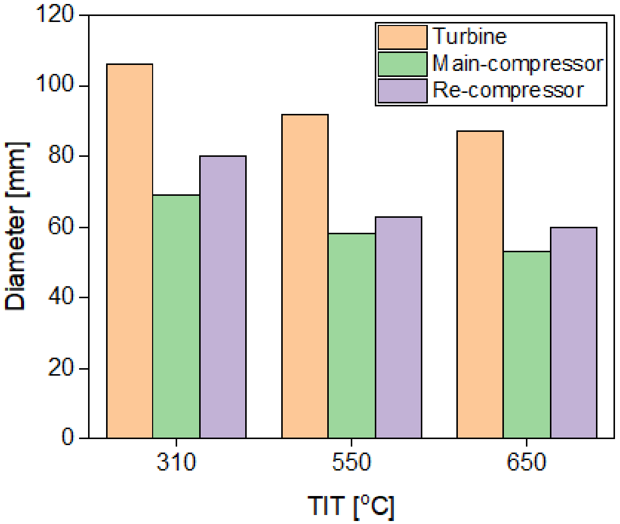
<Optimal conditions>



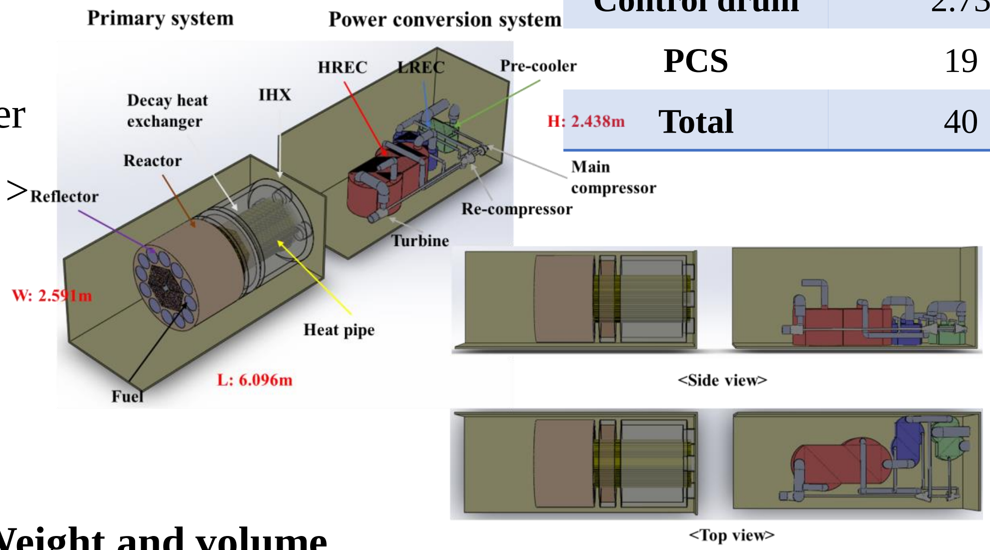
Maximum cycle efficiency

- Cycle efficiency: 31.2%, 47.2%, 52.0% (TIT: 310℃, 550℃, 650℃)
- **Volume** : HREC > LREC > Pre-cooler
- **Diameter**: Turbine > Re-compressor > Main compressor





Component	Weight [ton]
Reflector	8.59
Core	1.95
Fuel	5.83
Heat pipe	1.99
Control drum	2.73
PCS	19
Total	40



Weight and volume

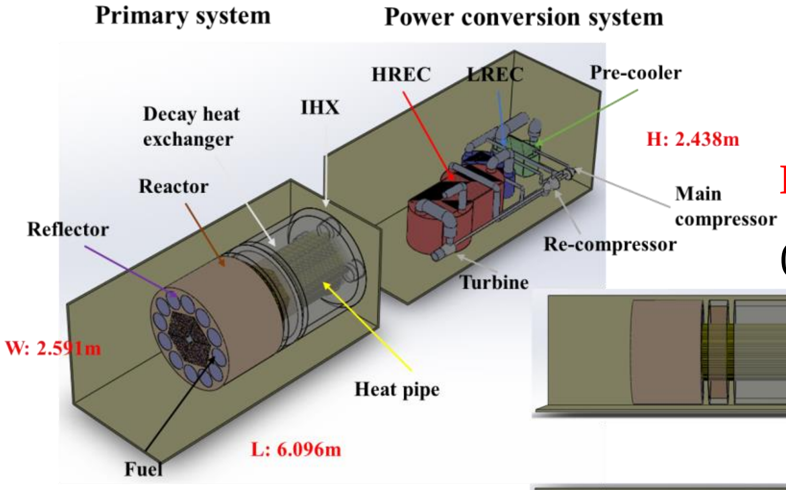
- Primary system was designed by INL (Idaho National Lab)[14]
- PCS was designed by POSTECH
- Container box: 2.591m / 6.096m / 2.438m (W/L/H) (Limitation: 40ton)

[14] Abou Jaoude, A., et al. (2021). An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept, Idaho National Lab.(INL), Idaho Falls, ID (United States).

I&C: Instrumentation & Control
O&M: Operation & Management
LCOE: Levelized Cost Of Electricty

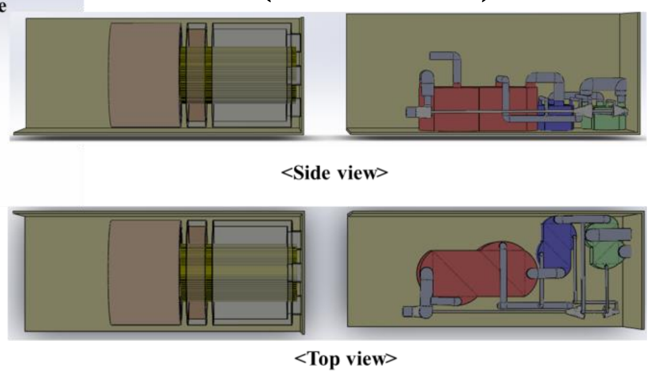
4. Results & Analysis

● Economic evaluation of heat pipe cooled micro-reactor



LCOE=83 USD/MWh

(TIT=650 °C)



Economic evaluation

- Total cost: primary system + secondary system + fuel + construction + decommissioning
- LCOE = $\frac{Sum\ of\ costs\ over\ life\ time}{Sum\ of\ electrical\ energy\ produced\ over\ life\ time}$

$$= \frac{Capital\ cost + \sum_{i=1}^{y}(O\&M\ cost\ +\ Fuel\ cost)/(1+r)^{y}}{\sum_{i=1}^{y}(Electricity\ energy)/(1+r)^{y}}$$

(r: interest rate / y:plant life time)

Primary system

- The cost is calculated normalized cost proposed by INL [15]

Component	Normalized cost ($/kW)
Fuel and moderator	2,334
Heat pipes	2,387
Reflector	650
Reactivity control	1,385
Reactor	7
Decommissioning	1,045
Construction	754
I&C	1,912
O&M	6% of capital cost

Secondary system

- Turbine : C_t=479.34•m• [1/(0.93-η_t)]•ln(PR)•[1+exp(0.036•T_i-54.4)]
- Compressor: Cc=71.1•m• [1/(0.92-ηc)]•(PR)•ln(PR)

  (m: mass flow rate, T: temperature, η:efficiency, PR: pressure ratio)
- Heat exchanger (PCHE): C_{PCHE}=C_M•(V•ρ)

  (C_M: cost per unit mass, V: volume of PCHE, ρ: density of PCHE)

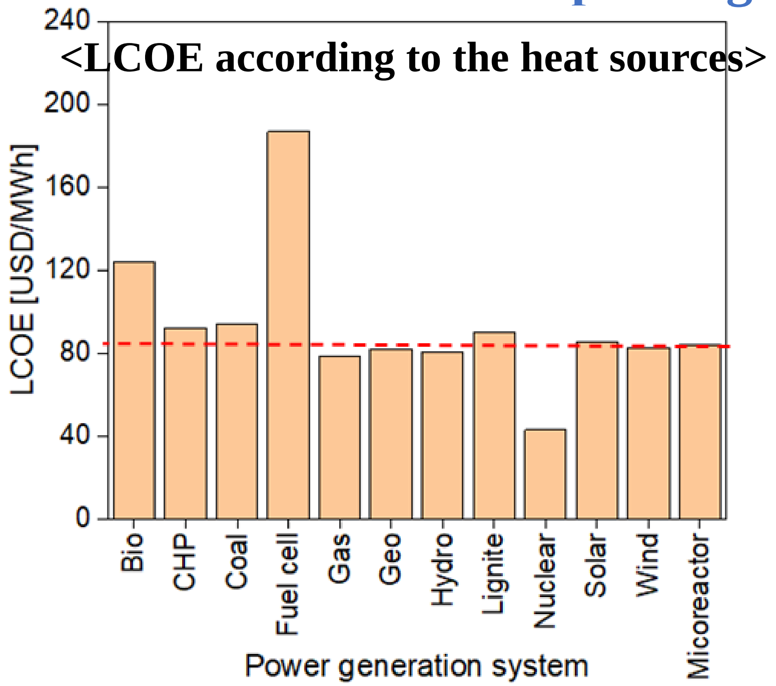
[15] Abou Jaoude, A., et al. (2021). An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept, Idaho National Lab.(INL), Idaho Falls, ID (United States).

LCOE: Levelized Cost Of Electricity
CHP: Combined Heat & Power
NPP: Nuclear Power plant

4. Results & Analysis

● Economic evaluation of power generation systems using various fuels

<LCOE according to the heat sources> [14]



Economic evaluation according to the various heat sources

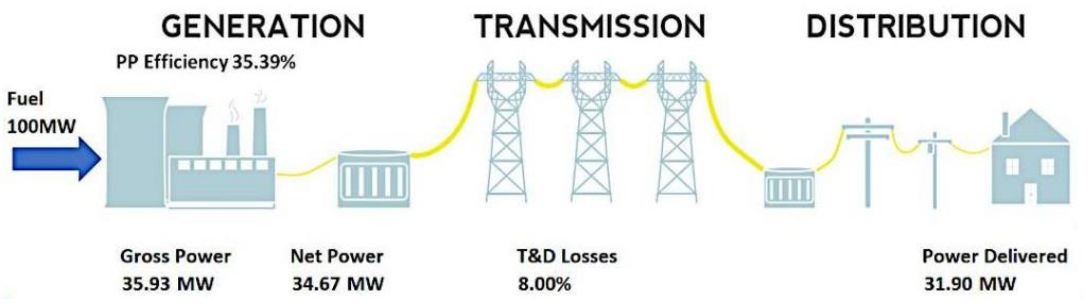
- Average LCOE of various countries
- Discount rate: 5% / Carbon tax: 30 USD/ton
- Carbon emission: Gas, coal, lignite, CHP (Carbon tax)
- Nuclear < Gas, Geothermal, Lignite, Microreactor < Fuel cell, Bio
- **Capital cost**: **Lignite, Gas, Coal** < CHP < Nuclear < Hydro, Solar, Wind < **Fuel cell**
- **Carbon tax**: **Hydro, Solar, Wind** < Nuclear < Fuel cell < **Lignite, Coal, Gas**

Source	**Bio**	**CHP**	**Coal**	**Fuel cell**
LCOE [USD/MWh]	124	92	94	187
Source	**Gas**	**Geothermal**	**Hydro**	**Lignite**
LCOE [USD/MWh]	78	82	80	90
Source	**Nuclear**	**Solar**	**Wind**	**Micro-reactor**
LCOE [USD/MWh]	42	85	83	83

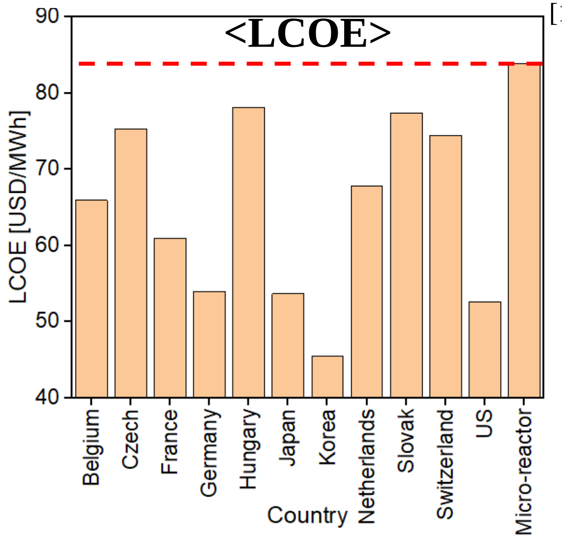
[14] https://www.oecd-nea.org/lcoe/

4. Results & Analysis

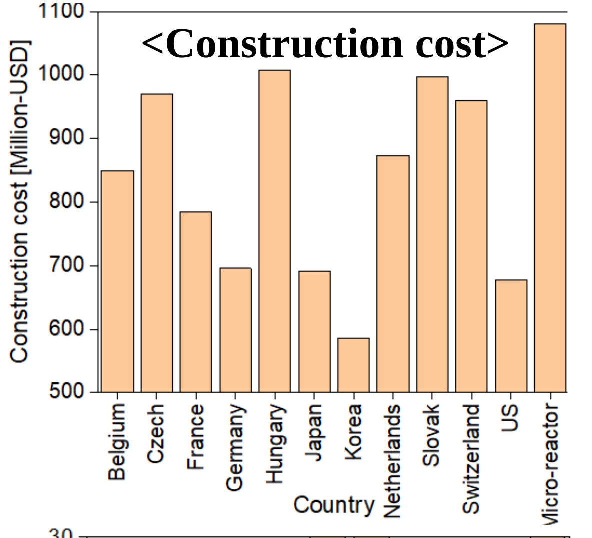
- **Comparison of micro-reactor with large nuclear power plant considering T&D electricity losses**



<T&D electricity losses>

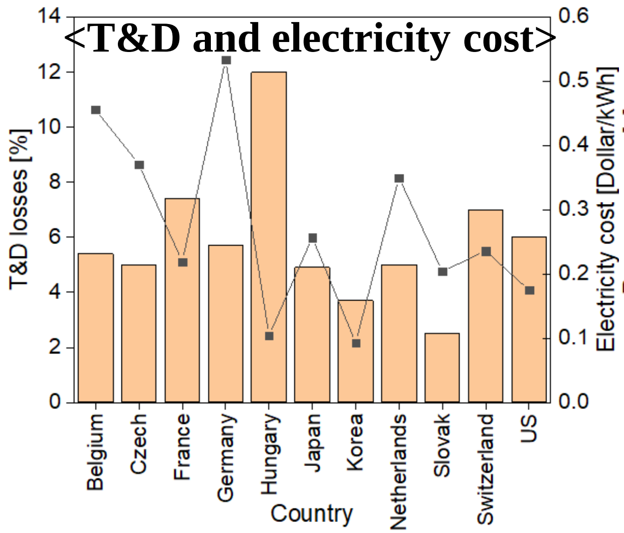


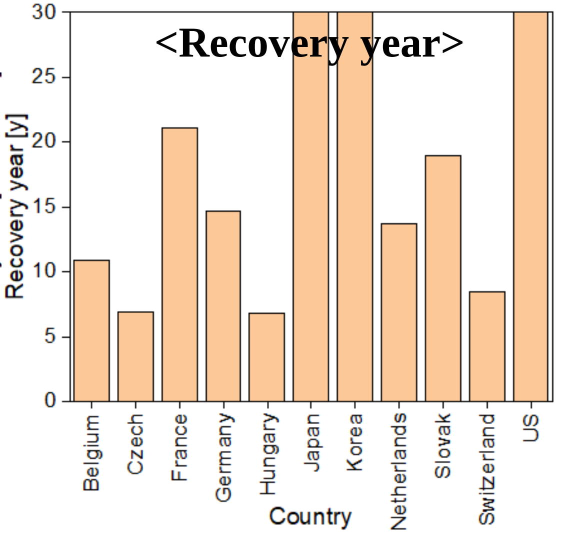
[15]



Economic evaluation according to the various heat sources

- **LCOE**: South Korea (45USD/MWh), Hungary (78USD/MWh), Micro-reactor (83USD/MWh)
- Construction cost was calculated based on the **100MW$_e$**
- Large NPP occurs T&D electricity losses
- Construction difference = Cost due to T&D losses* **Recovery year**
- **Recovery year: Hungary (4.3y), South Korea (More than 60y)**





[15] https://www.oecd-nea.org/lcoe/

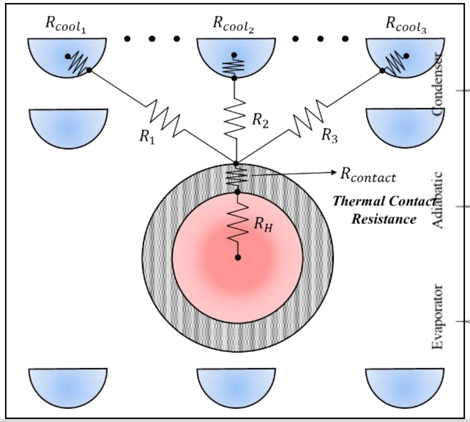
5. Conclusion & Future work

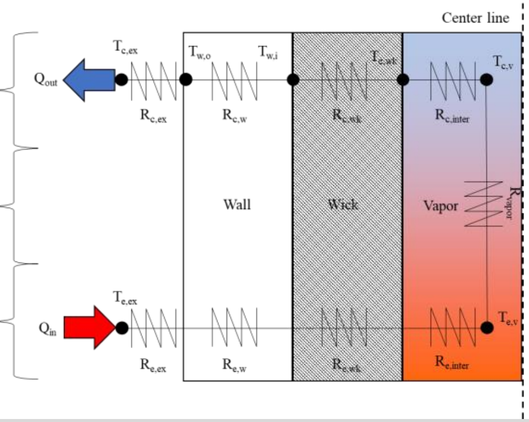
● Conclusion

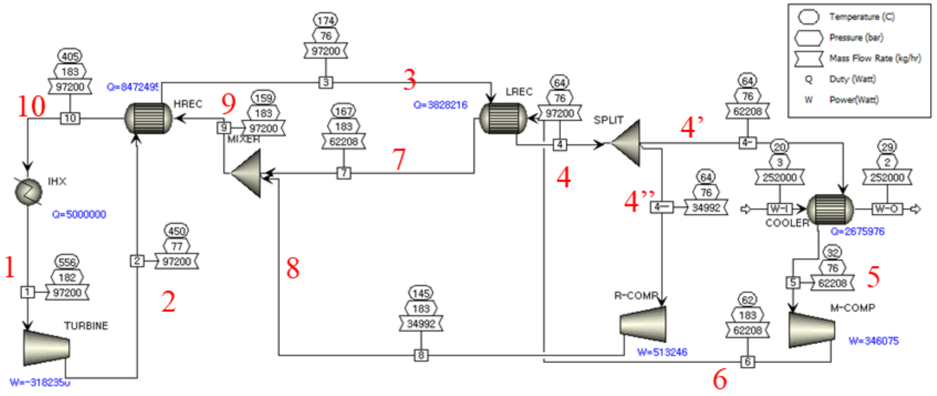
- Cycle analysis code including heat exchanger and turbomachinery sub-codes was developed
- Optimal cycle condition was derived based on the maximum cycle efficiency according to the design parameters
- A power generation system using micro-reactor was compared with the existing fuel system using various fuels
- Economic evaluation was conducted by comparing large nuclear power plant considering T&D losses

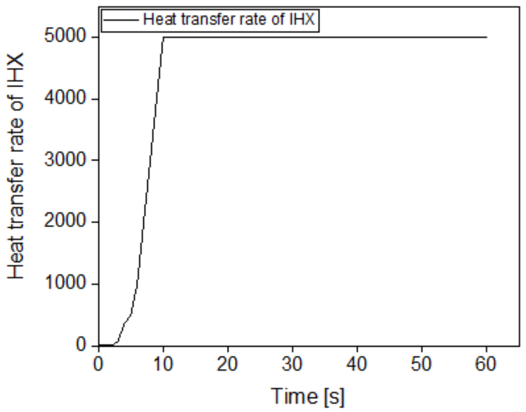
● Future work

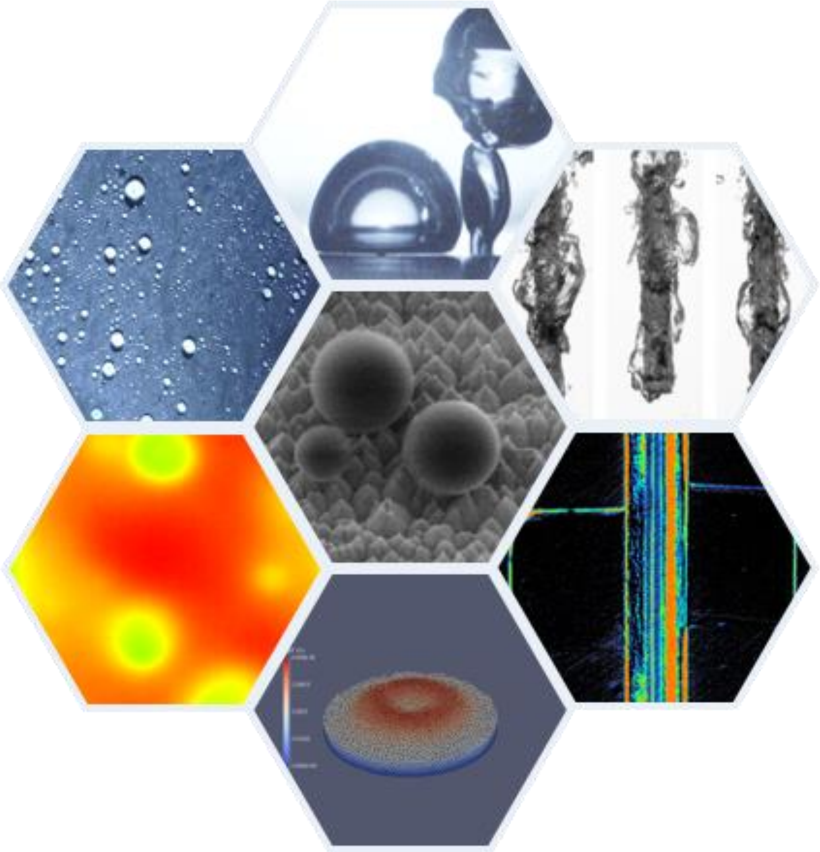
- Heat pipe analysis will be performed to design IHX integrated with heat pipe
- Transient simulation will be conducted to understand the operation of the designed micro-reactor











Thanks for your attention