Institute for Advanced Engineering
PLANT ENGINEERING CENTER

Institute for Advanced Engineering

A Comparative Experiments for Efficient Operation of Packed Bed Cold Energy Storage System

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0 Contents

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Introduction

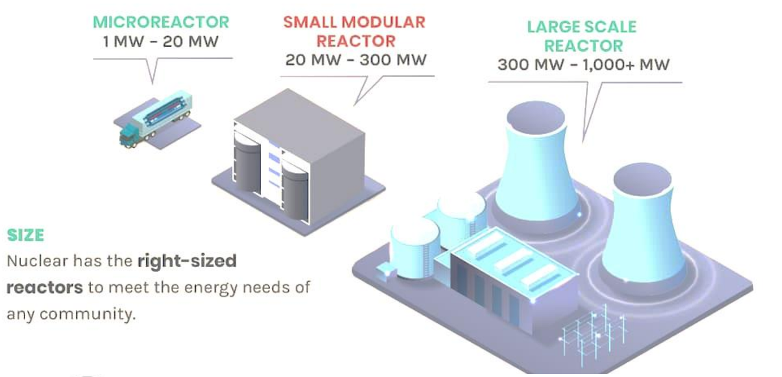
1) Background & Necessity
2) Objective & Procedure

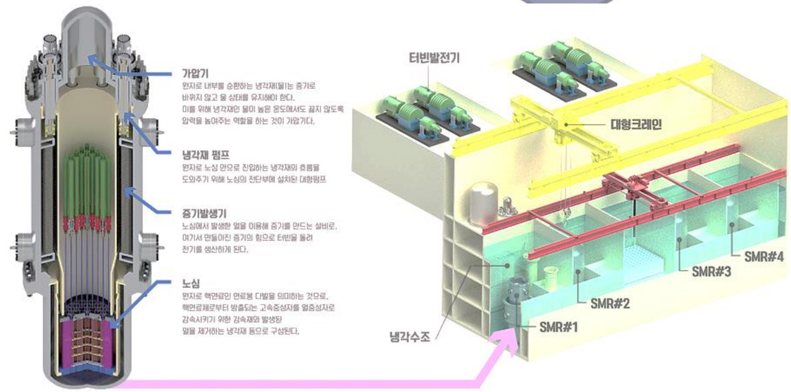
1.1 Background & Necessity

SMR development trend

Strengths of SMR

- Eco-friendly: Decarbonization Energy
- Safety: Low SA possibility, Small site size, …
- Economics: Affordable manufactured, Saving construction time, …





Nuclear-powered Data Centers

(단위:TWh)

구 분	'22년	'23년	'26년
발전량	29,124	29,734	32,694
전력수요	27,080	27,682	30,601
- 데이터센터 전력수요	460		1,050

*국제에너지기구(IEA), Electricity 2024 – Analysis and forecast to 2026

마이크로소프트, 말레이시아에 데이터센터 세운다

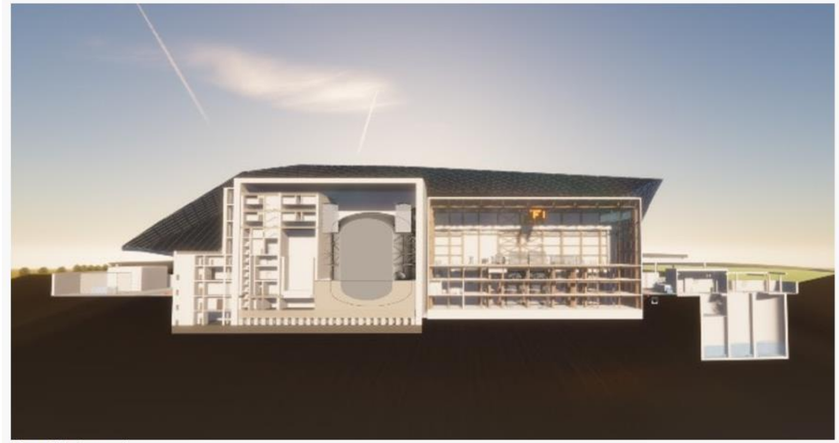
| 클라우드·AI 인프라 구축에 22억 달러 투자…클라우드 컴퓨팅 사업 강화 목표

컴퓨팅 | 입력 :2024/05/03 11:09

김미정 기자 | 기자 페이지 구독 | 기자의 다른기사 보기

Nuclear-Powered Data Centers

A recent DCD post discusses how Rolls-Royce plans to offer small nuclear reactors to US-based cloud operators so their hyperscale data centers can have net-zero emissions and be independent of the electric grid. Small modular reactors (SMRs) are under development by a consortium led by Rolls-Royce. They could potentially power data centers or other infrastructure that needs a steady low-carbon energy supply, which may not be available from the local electricity grid.



[Source: Rolls-Royce.com]

1.1 Background & Necessity

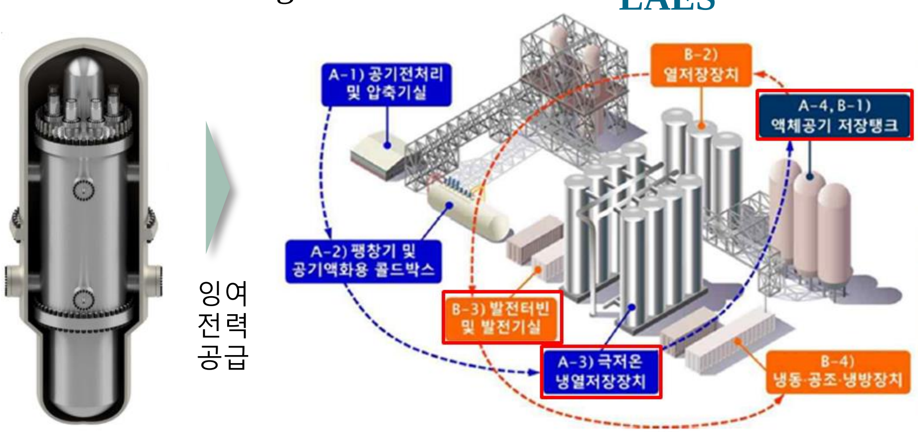
Energy Storage System (ESS)

- It is main concern of nuclear-powered data center to be independent
  - ESS is necessary for load- follow-up operation
  - Essential factors of ESS with SMR are safety, eco-friendly and long life

구분	안전성/환경성	저장용량	경제성/활용성	수명
 리튬이온	X	△	△	△
 바나듐 레독스	○	△	X	△
 양수	△	○	X	○
 수소저장	△	○	X	○
 공기액화저장	○	○	△	○

- Liquid Air Energy Storage (LAES) system
  - Storing energy in cryogenic liquid air form
  - The cryogenic energy can be used not only for power but also for cooling

LAES

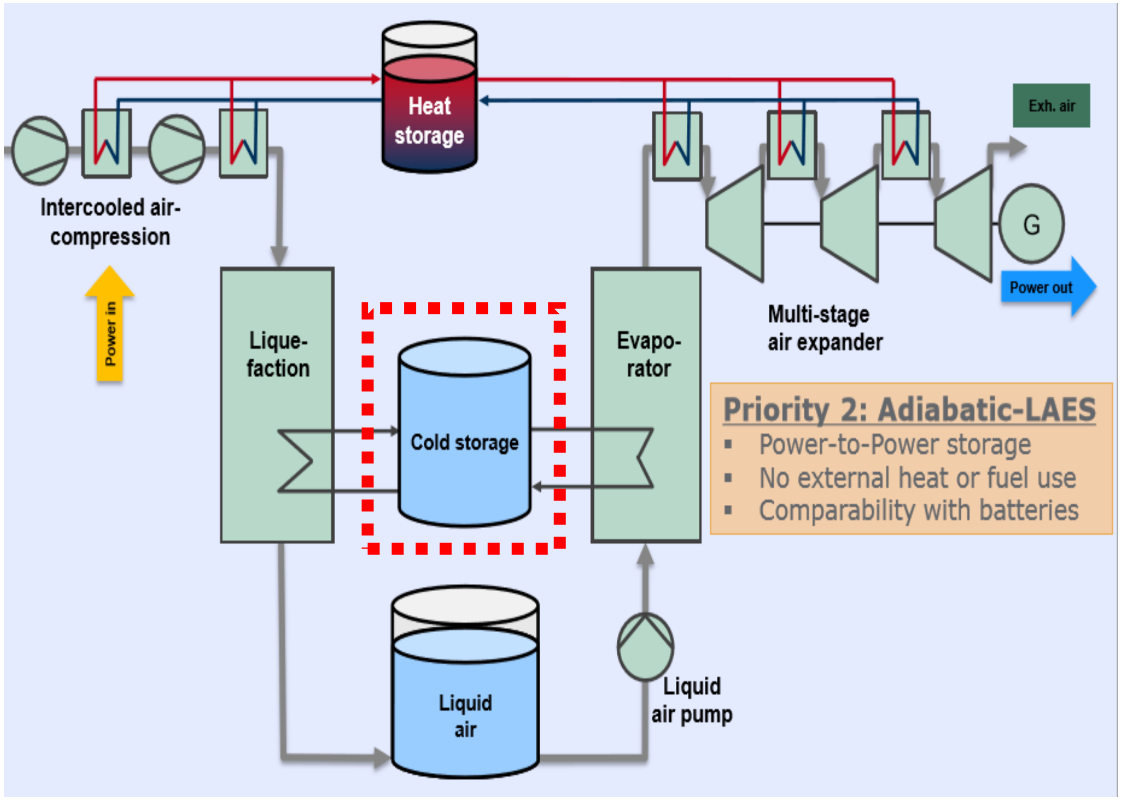


1.1 Background & Necessity

Cold Thermal Energy Storage(CTES)

Importance of CTES

- CTES is a key component that exchange cold energy between the liquefaction process for energy storage and the evaporation process for power generation.
- Its performance determines the round-trip efficiency of LAES system



▲ Process Schematic of Kryolens project in German

1.1 Background & Necessity

Packed Bed CTES

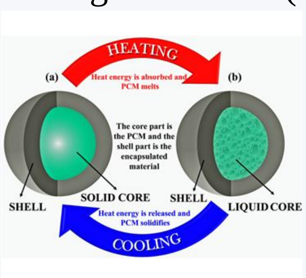
Two types of Packed Bed

- Packed bed is a method of storing thermal energy in a solid so that it has the advantage of high energy density
- Sensible type packed bed is proper for LAES because of its low cost and wide operation range
- But there are several limitations to using and commercializing it.

Thermal Energy Storage

Latent heat: Solid-Liquid

Phase Change Materials (PCM)

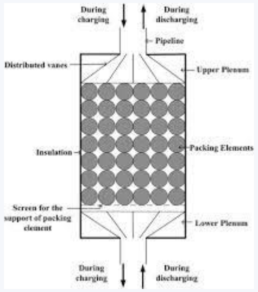


Advantages:
Stable performance,
higher energy density

Disadvantages:
High cost,
Complex mechanism
Limiting operation range

Sensible heat: Solid-Solid

Concrete brick, Pebble, and etc.



Advantages:
Low cost,
Wide operation range,
High energy density

Disadvantages:
Relatively low storage efficiency

Limitation of sensible type

- Hard to increase the size of packed bed for commercializing
  - Difficulty of making that size tank
  - Large size could create significant temperature difference in the heat exchanger, leading to higher exergy loss

Multiple packed bed CTES system is required

1.2 Objective & Procedure

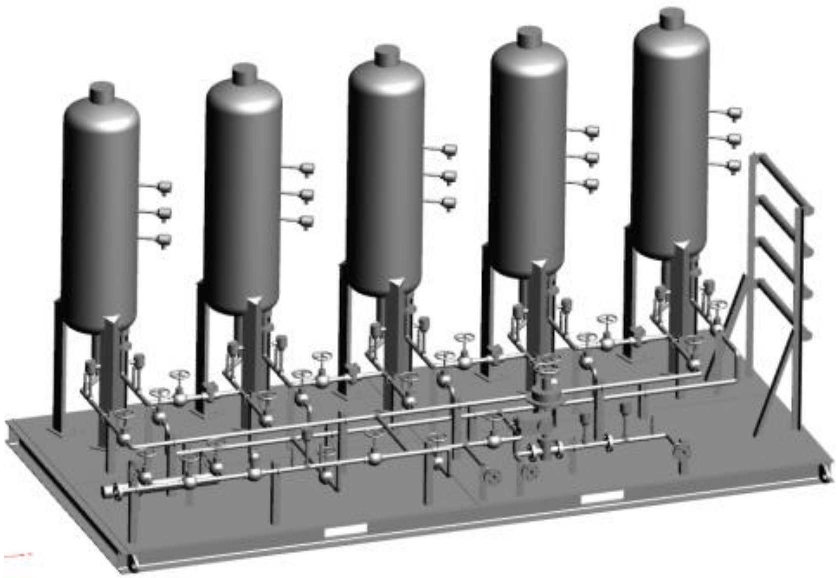
Objective

- Lack of prior study about multiple packed bed CTES system for commercializing
- Unguaranteed performance and proper operation method of multiple system

Experiments to identify the efficient charging operation for multiple CTES system

Procedure

- Construction of experimental facility
  - Design of packed bed CTES
  - Lab-scale multiple CTES system
- Experiments (cold charging)
  - Serial operation
  - Parallel operation



02

Experiments and Results

1) Construction of multiple system
2) Experiments of cold charging

2.1 Construction of multiple system

Design of packed bed CTES

- Lab-scale(1.5 kW_{th}) packed bed CTES tank
  - Inner tank and Outer tank(for vacuum insulation):

Inner diameter	250 mm		**Inner diameter**	489 mm
Thickness	9.3 mm		**Thickness**	9.5 mm
Height	1070 mm		**Total height**	1308mm

  - Packed bed: filled with granite pebbles

PB height	760 mm
Pebble diameter	8 ~ 12 mm

  - Temperature sensors (RTD)

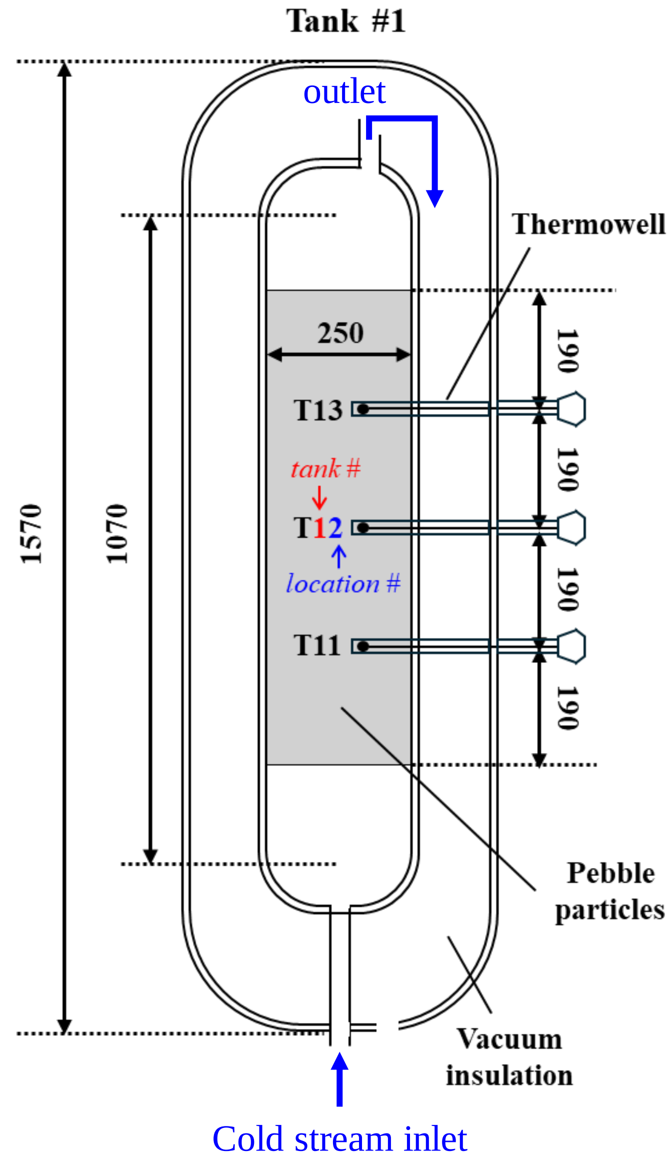
Effective range	-200 ~ 250 °C
Thermowell diameter	1/2 inch

- Pebble properties
  - Density and porosity: 2711 kg/m^3, 0.379
  - Thermal conductivity( ) [$W/(m \cdot K)$]:

$$k = -8.43 \times 10^{-3} \cdot T + 4.869$$

  - Specific heat ( ) [$J/(kg \cdot K)$]:

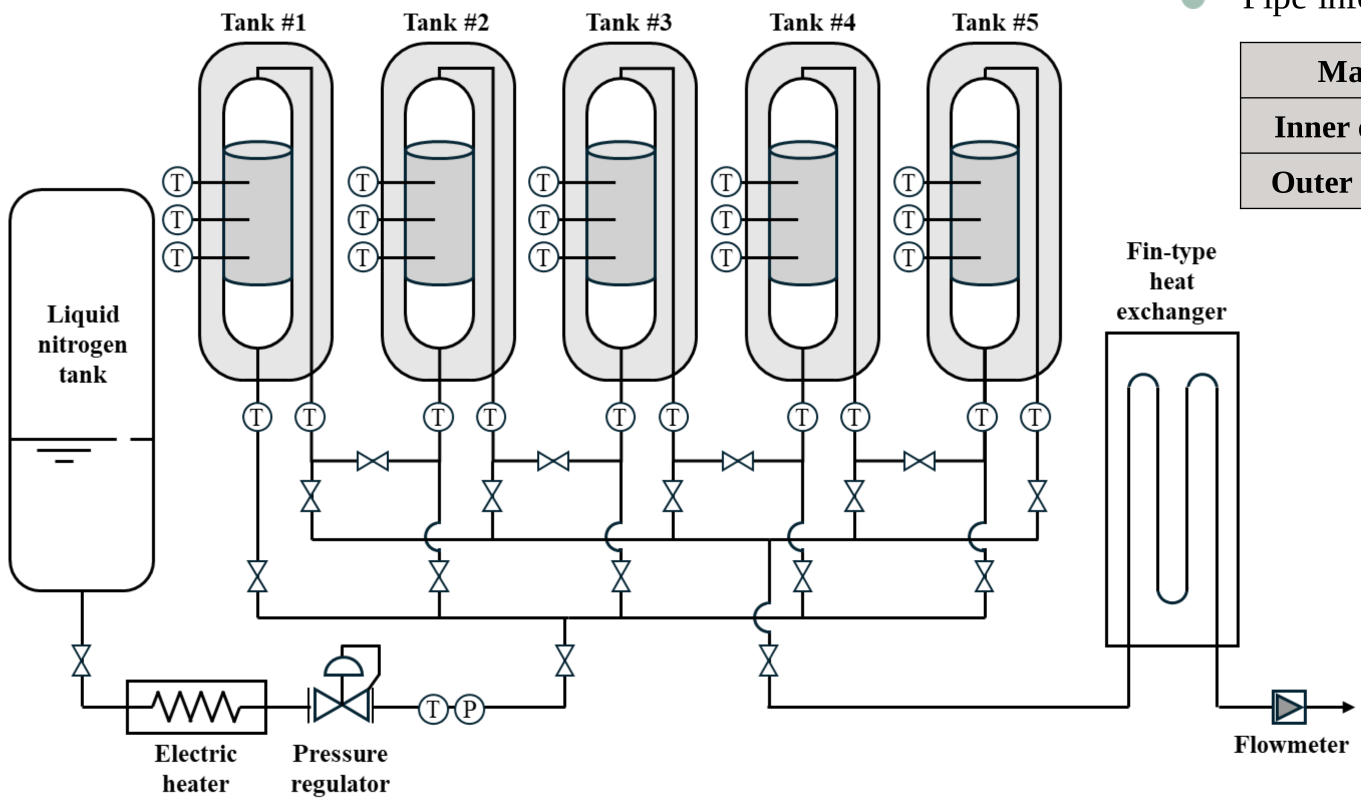
$$c_p = 2.09 \cdot T + 287.1$$



2.1 Construction of multiple system

Lab-scale multiple CTES system

- Connected 5 packed bed CTES tanks
  - In lab-scale, the liquid air was replaced by liquid nitrogen
  - The flow path can be made both conditions of cascaded and branched off by controlling valves
  - Electric heater: vaporization of nitrogen / Fin-type heat exchanger: Exhausting nitrogen in room temperature



- Pipe information

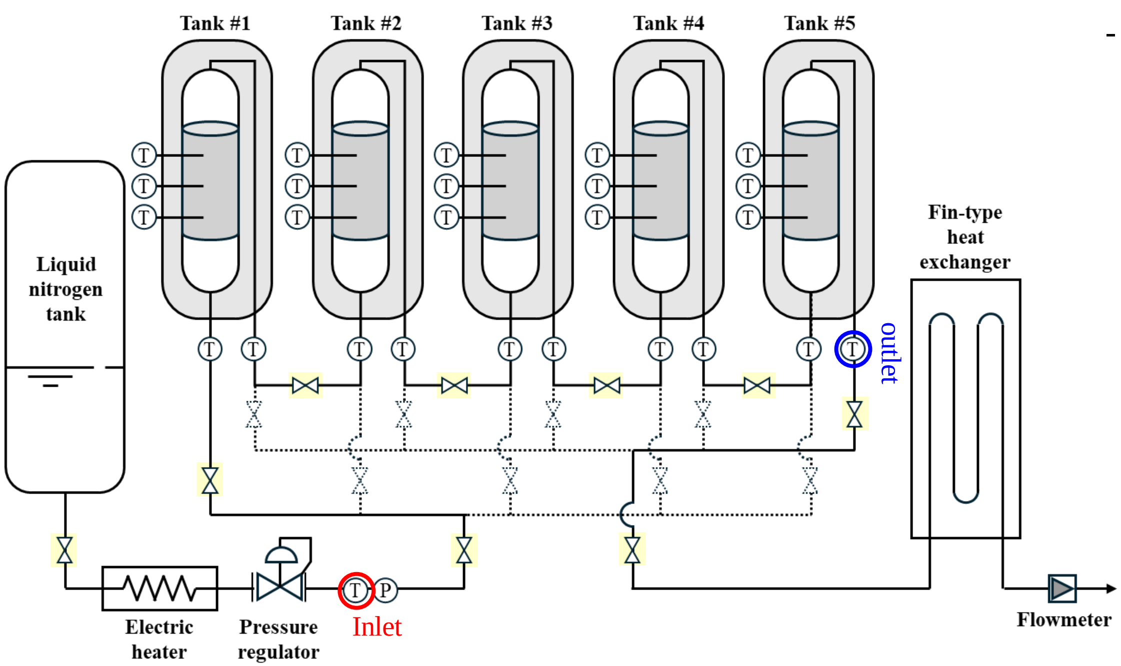
Material	SUS-304
Inner diameter	28.4 mm
Outer diameter	34 mm

2.2 Experiments of cold charging

Experimental conditions

Serial operation

- Cascaded flow path
  - Highlighted valves are opened
  - The cold storage is carried out sequentially from #1 to #5 tanks
  - Nitrogen gas flows packed bed layer from bottom to top in all tanks
- **Main storage tanks: #1 ~ #3 / Buffer tanks: #4 ~ #5**



- Flow condition (common)
  - The mass flow rate was derived by scaling down to 1/200 of 4.5 kg/s, which is the condition of the main product (300 kW_{th})
  - Because of the fin-type heat exchanger, the system pressure at inlet had to be 5 bar-g to achieve the target mass flow rate, 22.5 g/s.
  - The saturation temp. of nitrogen is about -177℃, so that the inlet temp. was set by adding 10 ℃ to the saturation temp.

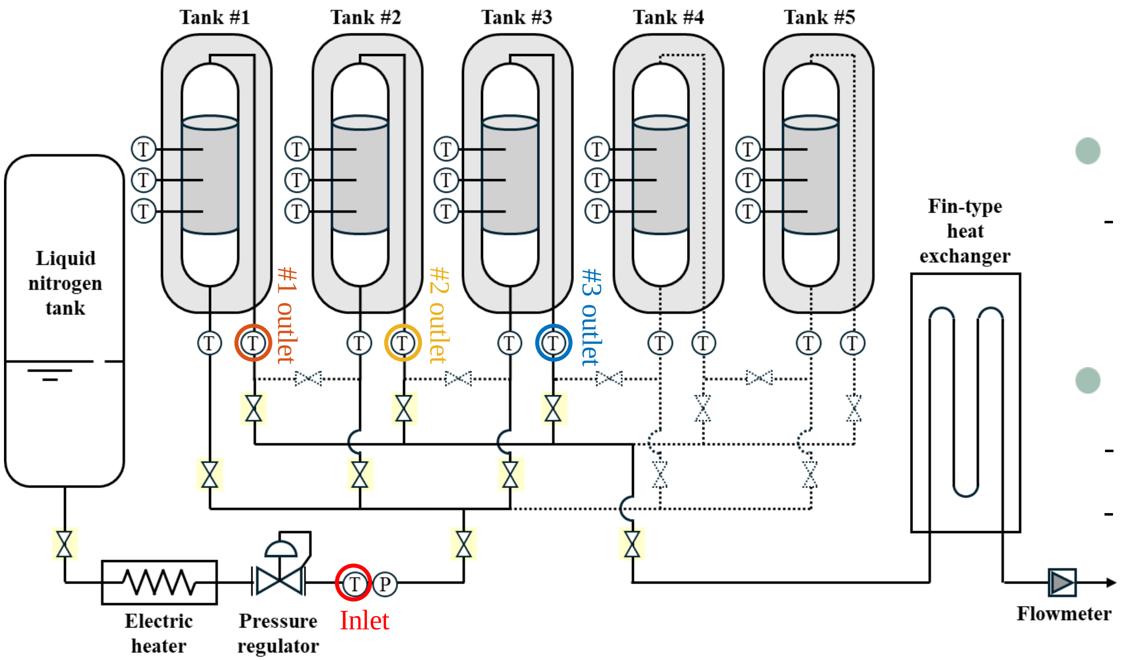
Mass flow rate	22.5 g/s
System pressure (gauge at inlet)	5 bar
Inlet temp. (E.H. setting)	-165 ℃
Charging time	350 min

2.2 Experiments of cold charging

Experimental conditions

Parallel operation

- Branched off flow path
  - Highlighted valves are opened
  - The cold storage is carried out simultaneously in #1 ~ #3 tanks
  - #4 and #5 tanks are not used in parallel operation
- **Only main storage tanks(#1 ~ #3) are used**



- Flow condition (common)
  - Same with serial operation

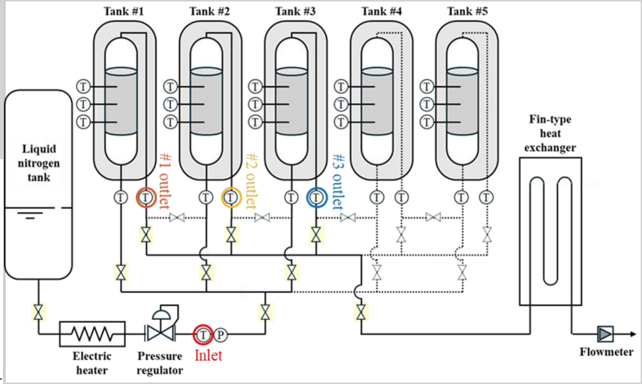
Mass flow rate	22.5 g/s
System pressure (gauge at inlet)	5 bar
Inlet temp. (E.H. setting)	-165 ℃
Charging time	350 min

- Difference of operation with serial
  - If a tank is considered fully charged, the tank is closed to block nitrogen gas entering the tank

$$\frac{\Delta T_{out}\ for\ 1min}{T_{out}} \leq 10^{-3}$$

- Limitations
  - There is no temp. sensor for whole system outlet
  - Mass flow rate of each tank couldn't be measured

2.2 Experiments of cold charging



Results

Summary of experiments

- Serial operation

Mass flow rate	21.15 g/s	
System pressure	4.9 bar-g	
Inlet temp. (100min ~)	-148.9 ℃	
Charging time	350 min	
Average internal temp. [℃]	#1 #2 #3	7.1 → -157.4 6.8 → -157.2 5.4 → -144.0

- Parallel operation

Mass flow rate	22.97 g/s	
System pressure	5.2 bar-g	
Inlet temp. (100min ~)	-151.3 ℃	
Charging time (#1/ #2/ #3)	309/ 345/ 277 min	
Average internal temp. [℃]	#1 #2 #3	2.4 → -145.2 0.8 → -150.6 7.9 → -146.7

Evaluation of charged cold thermal energy in #1 ~ #3 tanks

- Calculation method

$$Q_C = \sum_{i=1}^{T_{end}} c_{p,T_i} \cdot (T_i - T_{i-1}) \cdot m_{PB}$$

- The T is average inter temperature in [K]
- The i is time in [min]
- The c_p is specific heat in $[J/(kg \cdot K)]$
- The m_{PB} is weight of pebbles in tank = 62.3 kg

- Charged cold energy in each tanks

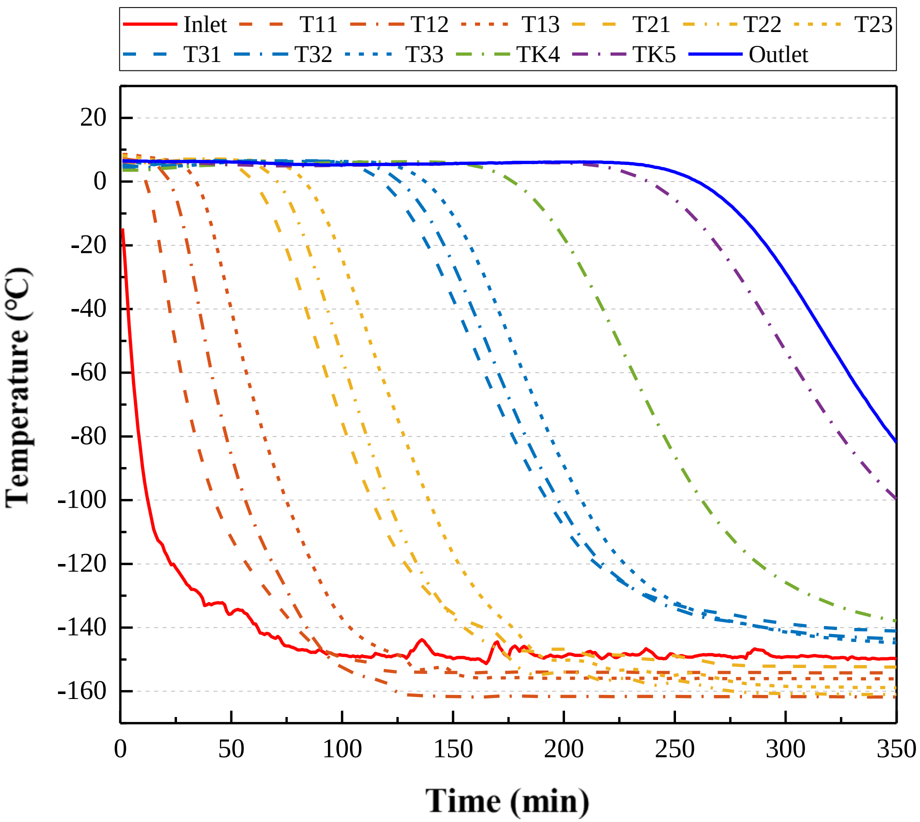
Operation:	Serial [kJ]	Parallel [kJ]
Tank #1	-7,250	-6,518
Tank #2	-7,182	-6,616
Tank #3	-6,637	-6,870

2.2 Experiments of cold charging

Results

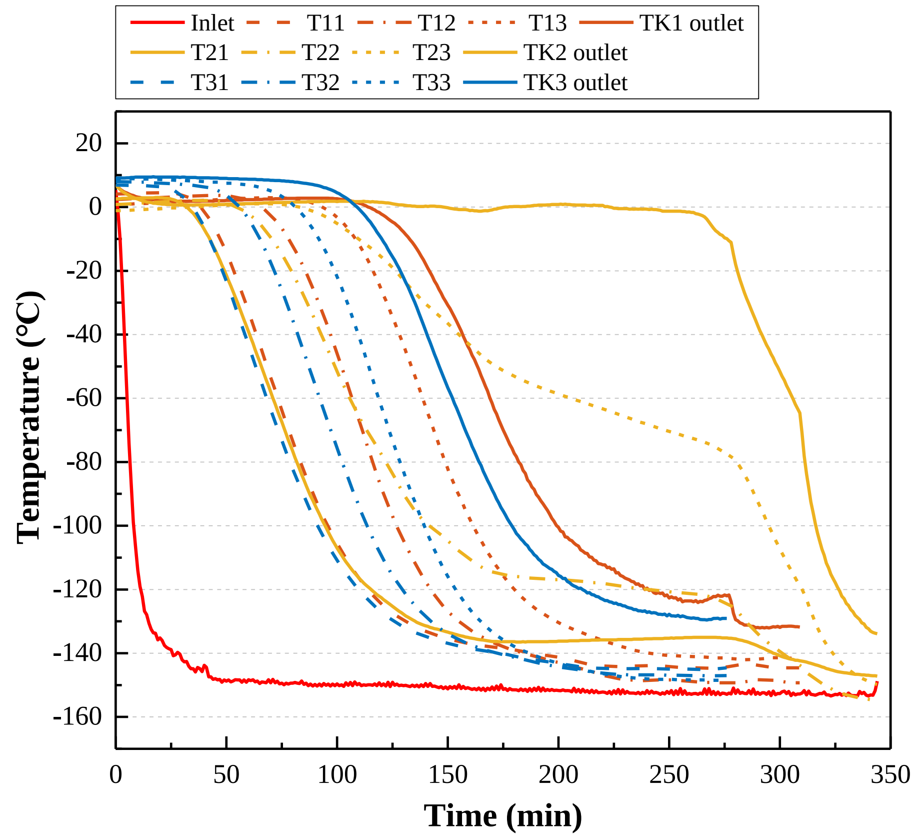
Transient axial temperature distribution

- Serial operation



- The last #3 tank did not satisfy the full charging condition, but the internal temperature converged to -140°C

- Parallel operation



- #3 and #1 tanks were fully charged, but the #2 tank was not and also was not converged.

03

Conclusion

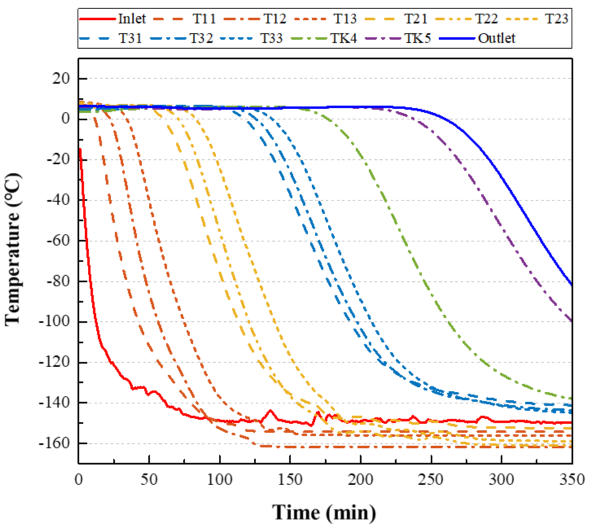
1) Summary
2) Future works

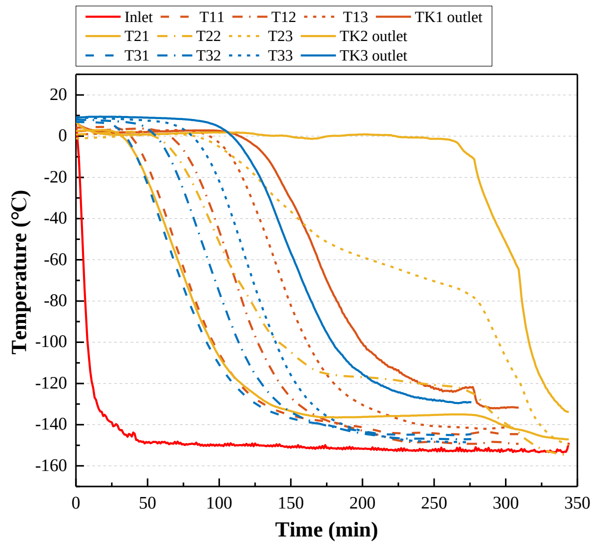
3.1 Summary

Proper operation method for multiple PBCTES system

Adjusted serial operation

- Efficiency of charging energy is better in serial operation.
- But it also presents an energy imbalance issue between the last #3 tank and others.
- The imbalancing did not arise in parallel case, possibly because of the action of closing the fully charged tank.
- A combination of the two methods is required to achieve high energy efficiency while avoiding imbalance energy





	Tank	Serial	Parallel
Average internal temp. [°C]	#1	7.1 → -157.4	2.4 → -145.2
	#2	6.8 → -157.2	0.8 → -150.6
	#3	5.4 → -144.4	7.9 → -146.7

Operation:	Serial [kJ]	Parallel [kJ]
Tank #1	-7,250	-6,518
Tank #2	-7,182	-6,616
Tank #3	-6,637	-6,870

Sequential operation

serial operation with the practice of closing fully charged tanks

Output of research

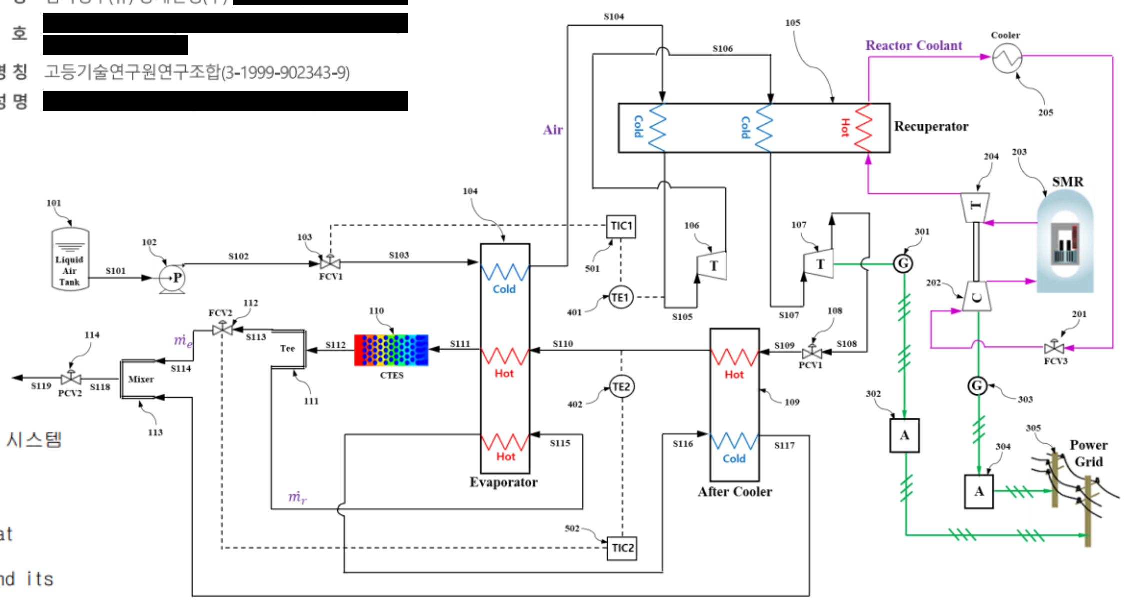
A patent application

- The Name of invention:
  - Liquid air power generation system using the heat source of a small modular nuclear power plant and its control methos

【서류명】	특허출원서
【참조번호】	[redacted]
【출원구분】	특허출원
【출원인】	
【명칭】	고등기술연구원연구조합
【특허고객번호】	[redacted]
【대리인】	
【명칭】	[redacted]
【대리인번호】	[redacted]
【지정된변리사】	[redacted]
【포괄위임등록번호】	[redacted]
【발명의 국문명칭】	소형 모듈화 원전의 열원을 활용한 액체 공기 발전 시스템 및 이의 제어방법
【발명의 영문명칭】	Liquid air power generation system using the heat source of a small modular nuclear power plant and its control method

출원번호통지서

출 원 일 자	2023.12.27
특 기 사 항	심사청구(유) 공개신청(무) [redacted]
출 원 번 호	[redacted]
출원인 명칭	고등기술연구원연구조합(3-1999-902343-9)
대리인 성명	[redacted]

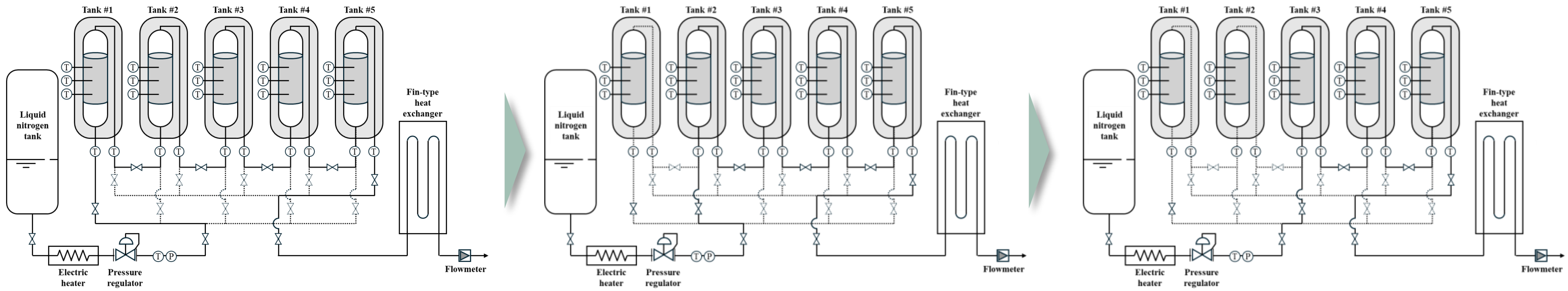


3.2 Future works

Valid sequential operation

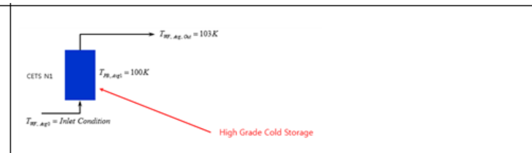
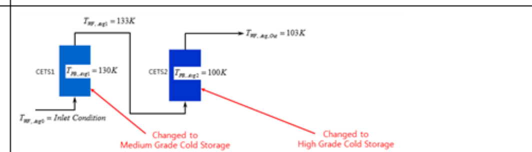
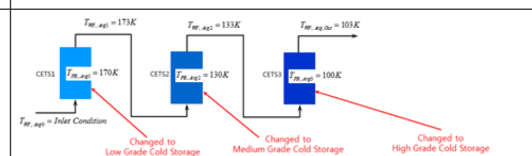
Charging experiments with sequential operation

- Closing the tanks in order



Discharging experiments with sequential operation

- Sequential operation is advantageous for keeping the outlet temperature low for a long time in discharging.

t=t_1		103K
t=t_2		103K
t=t_3		103K

Operation in conjunction with charging and discharging

- When this multiple PBCTES system is operating, The internal temperature of the tanks at the start of charging is not at room temperature, but at the state after the discharge is finished.

Continuous operation experiments required

Q&A

Thank you

300kW$_{th}$ level PBCTES

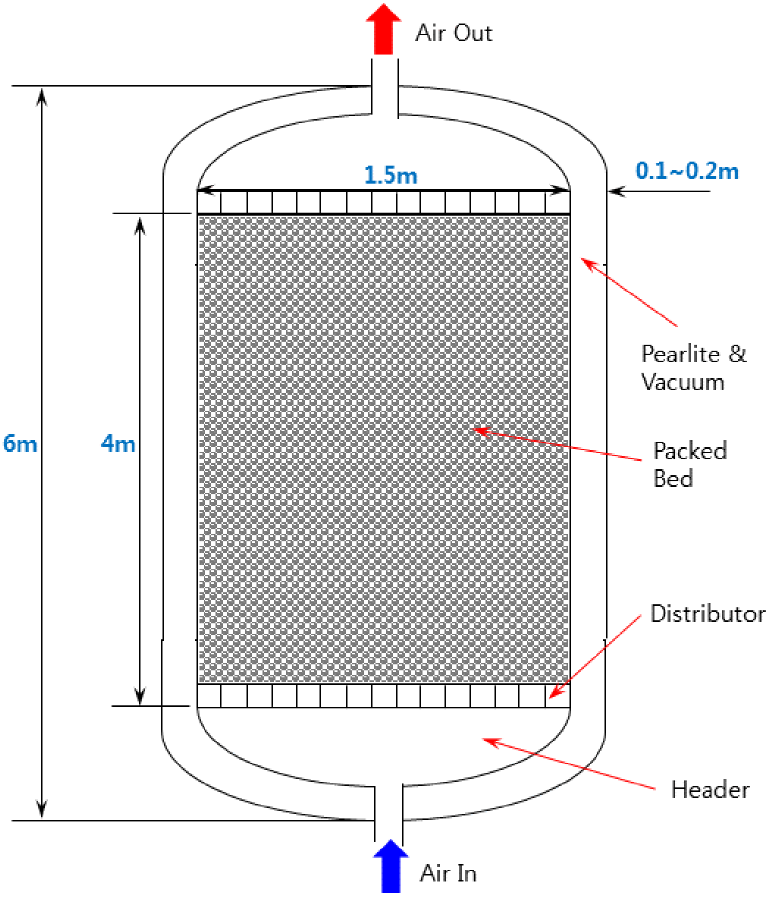


표 4. 300 kWh$_{th}$급 냉열저장 장치의 제원

내 체적	10m^3
자갈층 체적	7.2m^3
재료(내부)	SS304
단열 방식	펄라이트 진공 단열
무게(탱크)	7,000 kg
무게(자갈)	10,800 kg
총 무게(부대설비 포함)	Under 20 ton

표 5. 300 kWh$_{th}$급 냉열저장 장치의 운전 조건

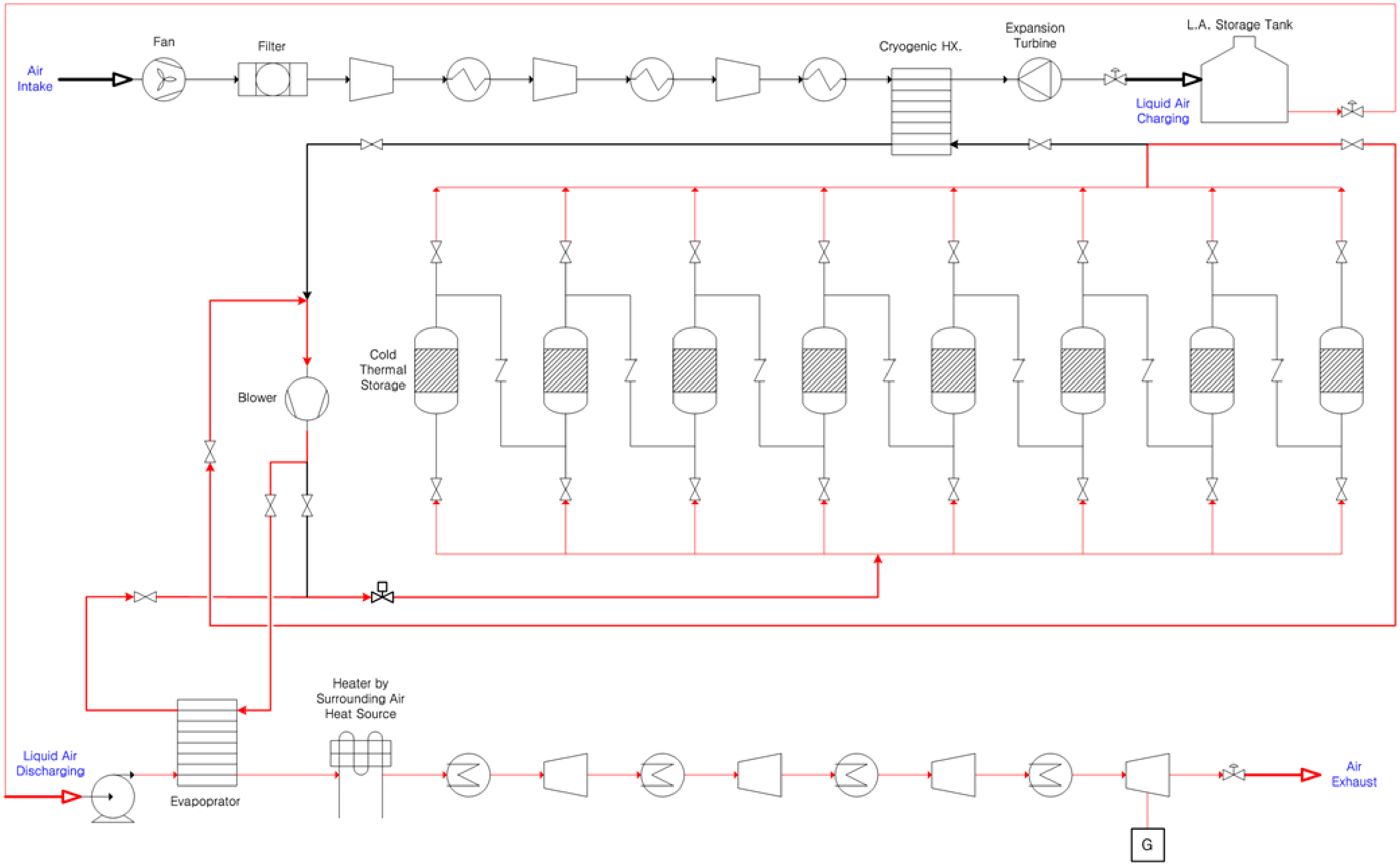
작동 유체	Specific Air, Mole Fraction (N2: 75.72% , O2: 23.20% , Ar: 1.08%)
유량	1~10 kg/s
압력	0 ~ 4 bar-A.
온도	(-185) ~ 40 Degree C.

표 6. 300 kWh$_{th}$급 냉열저장 장치에 적용된 자갈의 조건

밀도	2500 kg/m^3
정압 비열	0.5 kJ/kg K (at 185K)
Void Fraction	Under 0.4
직경	20 ~ 50 mm

Sup. Main product

300kW$_{th}$ level multiple PBCTES system



Sup. Main product

Total process of LAES