Effect of Insulation Material on Boil-off Gas in Cryogenic Tank for LAES coupled with SMR

Nuclear Power & Propulsion Lab

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01 Introduction

LAES coupled with SMR

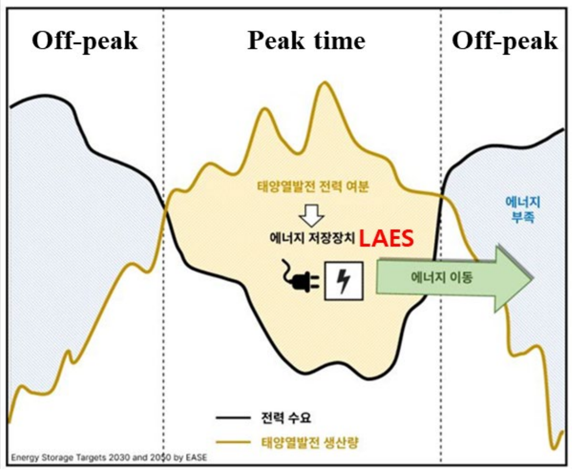

Fig. 1. Energy shift

- Increase in renewable generation → need for flexible operation of SMR
- Suggest LAES coupled with SMR

  → Improve load following by connecting with LAES

- LAES(Liquid air energy storage system) is a large-scale energy storage system
- LAES stores energy by liquefying air with surplus power

  → high energy density, low geographical constraints, eco-friendly working fluid, and long service time

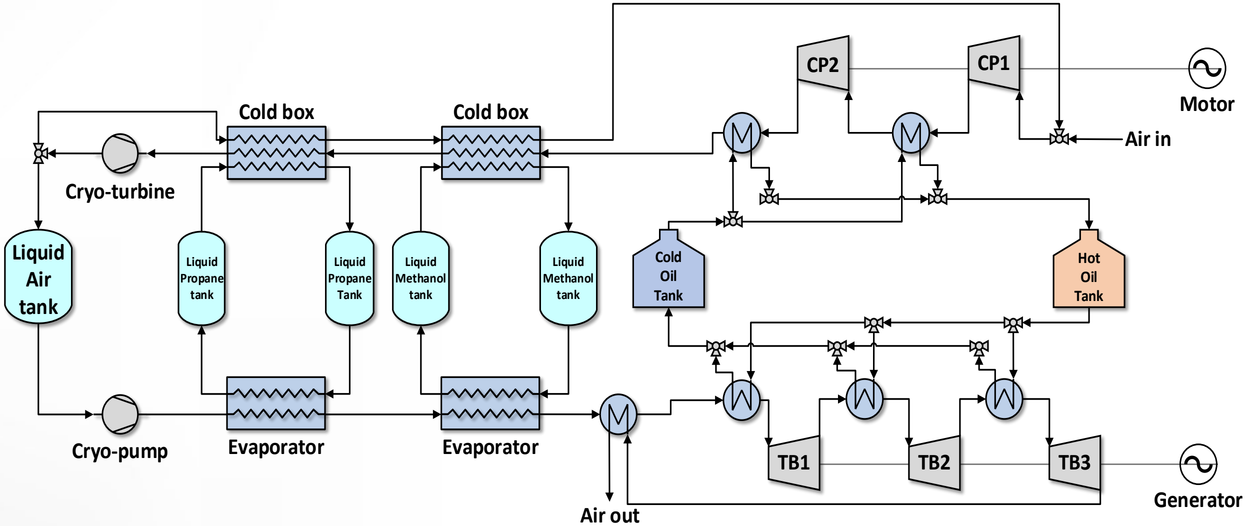

Fig. 2. layout of LAES

LAES coupled with SMR

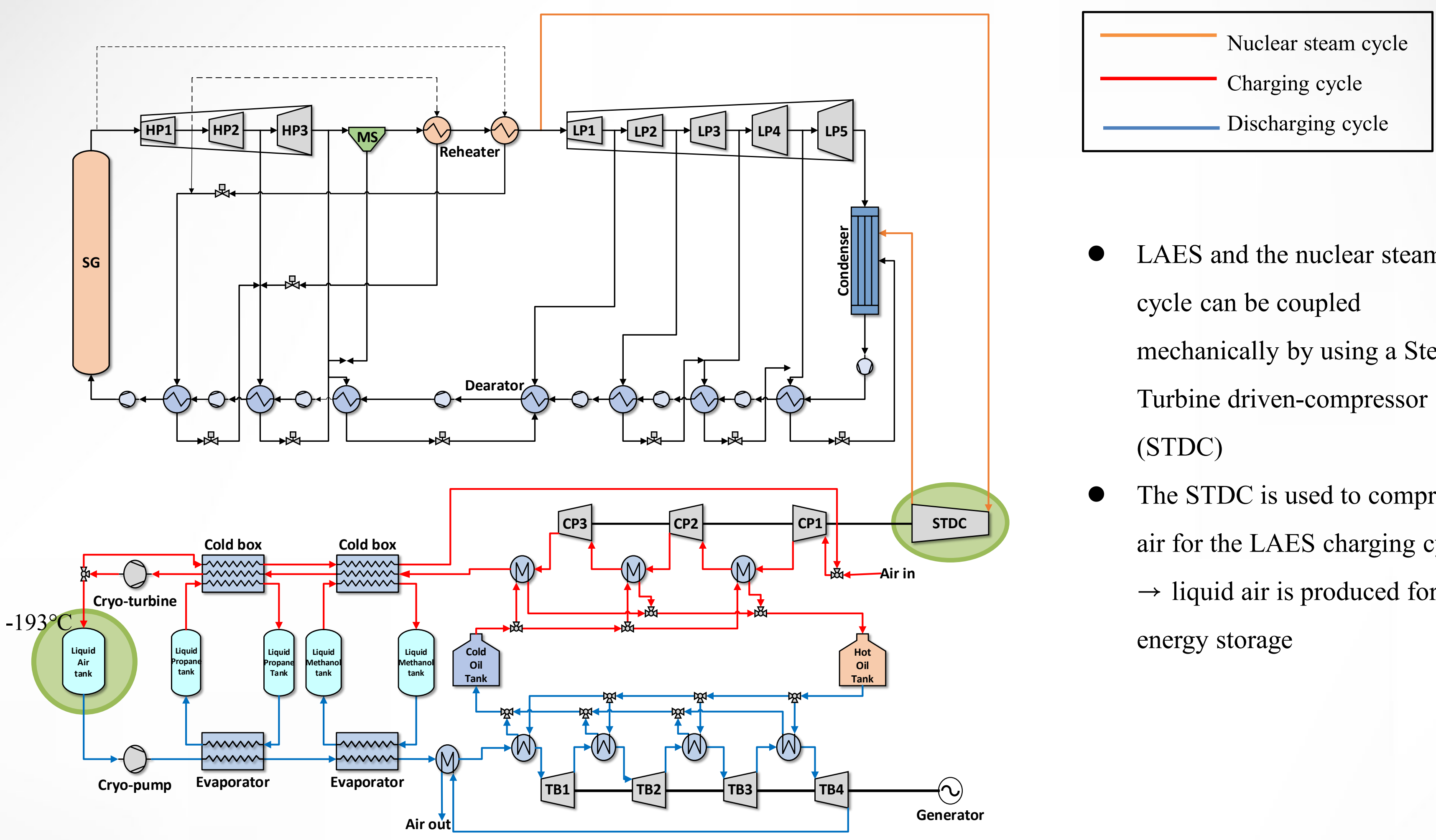

Fig. 3. Schematic diagram of nuclear integrated LAES

- LAES and the nuclear steam cycle can be coupled mechanically by using a Steam Turbine driven-compressor (STDC)
- The STDC is used to compress air for the LAES charging cycle. → liquid air is produced for energy storage

LAES coupled with SMR

- LAES Charging during off-peak, discharging for extra power.
  → (liquid form) high energy density, reducing thermal fluid volume
  → maintaining cryogenic temperature for sufficient time in the liquid air tank is essential to achieve good round-trip efficiency of the LAES

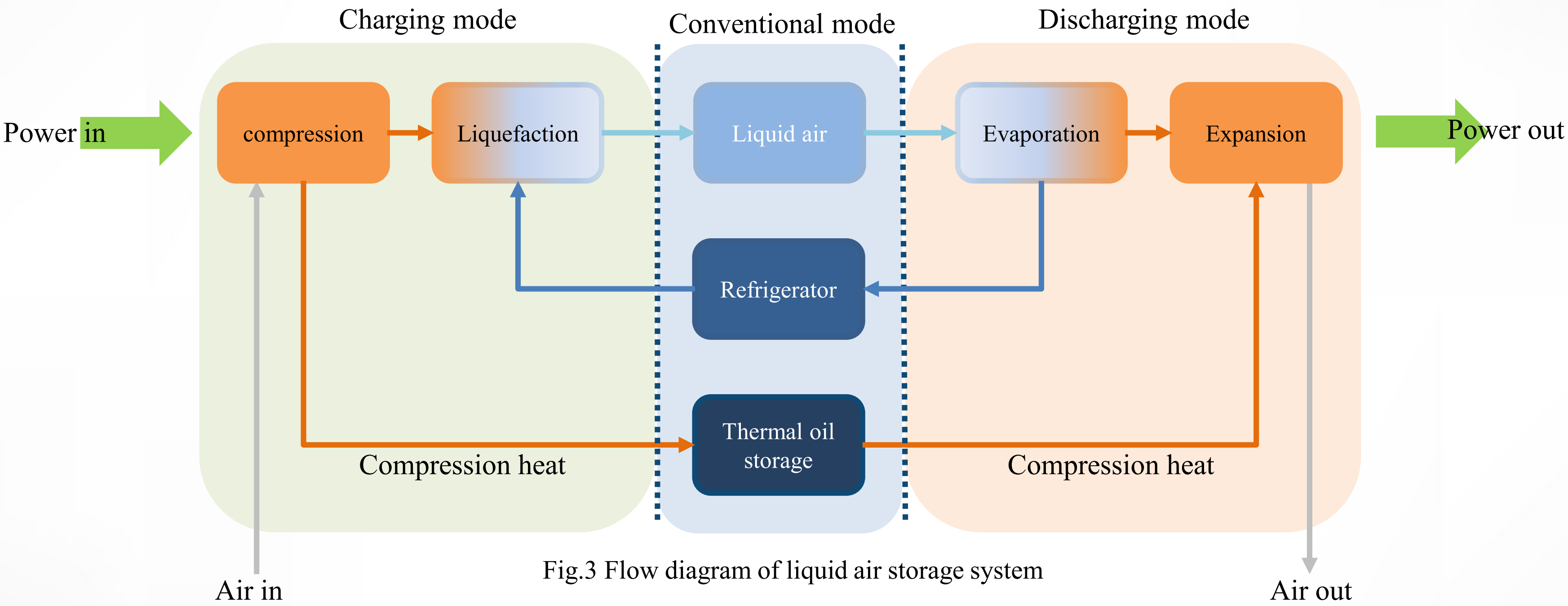

Fig.3 Flow diagram of liquid air storage system

Cryogenic fluid in the tank

- In cryogenic engineering, BOG (Boil-Off Gas) occurs because of heat transfer from the surrounding environment, causing LNG to warm up and turn into gas.

  → potentially raising the tank's pressure

✓ ***"Need for a study on time-dependent BOG variations in liquid air tanks.***

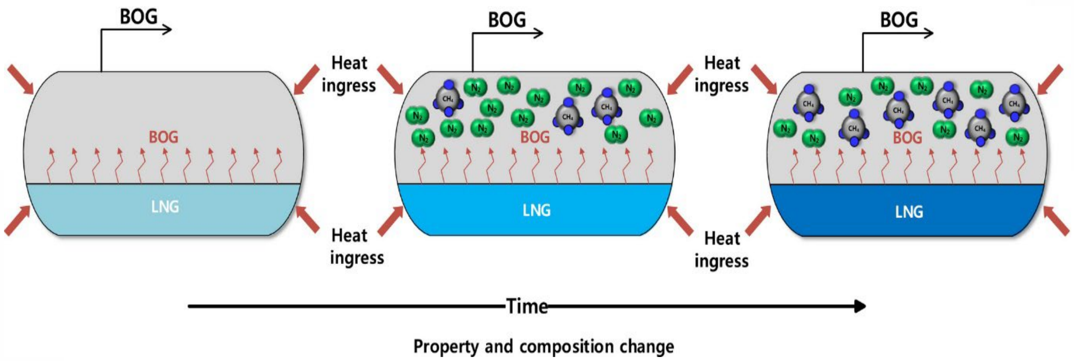

Fig. 4. Property and composition changes in the interior design of LNG tank

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Methodology

Thermal analysis model for a Liquid air tank

- Partial Equilibrium Model(PEM) to model the storage tank
- Evaporation rate, inner pressure

  → affected by heat ingress

  → conduction, convection, and conjugate heat transfer

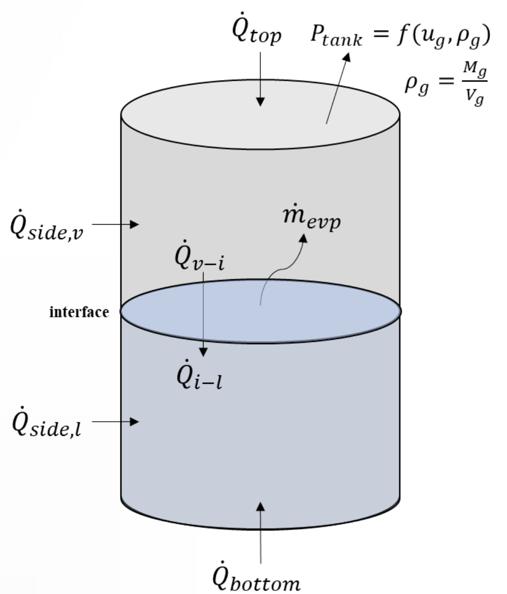

Fig.5 Schematic diagram of cryogenic tank

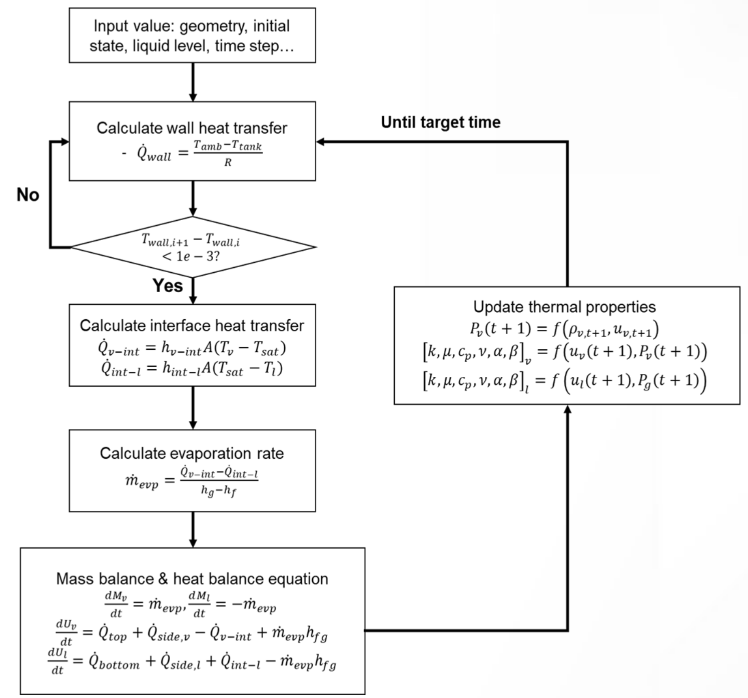

Fig. 6. Process diagram of PEM

Thermo-modeling for a Liquid air tank

- PEM (Partial Equilibrium Model)

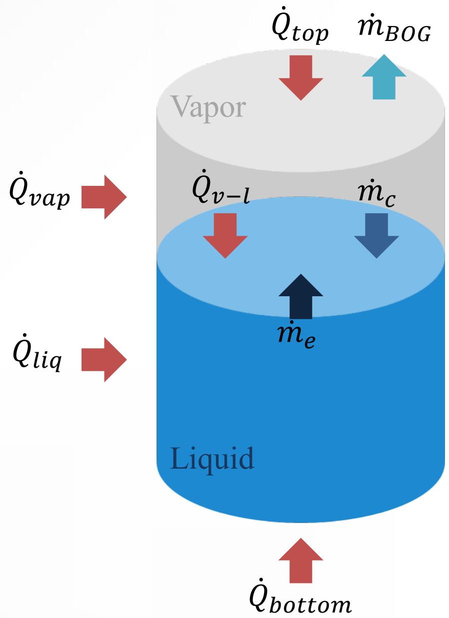

Fig.7 Schematic diagram of liquid air tank modeling

- Mass balance

$$\frac{dm_L}{dt} = \dot{m}_c - \dot{m}_e, \frac{dm_v}{dt} = \dot{m}_e - \dot{m}_c - \dot{m}_{BOG}$$

$$m_L: liquid\ mass, m_v: vapor\ mass, \dot{m}_c: condensation\ rate$$

$$\dot{m}_e: evaporation\ rate,\ \dot{m}_{BOG}: boil-off\ gas$$

- Energy balance

$$\frac{dU_L}{dt} = \dot{Q}_{liq} + \dot{Q}_{bottom} + \dot{Q}_{v-l} + (-\dot{m}_e + \dot{m}_c)h_{fg}$$

$$\frac{dU_v}{dt} = \dot{Q}_{vap} + \dot{Q}_{top} - \dot{Q}_{v-l} + (\dot{m}_e - \dot{m}_c)h_{fg} - \dot{m}_{BOG}h_g$$

$$\dot{Q}_L: heat\ transfer\ to\ liquid, \dot{Q}_v: heat\ transfer\ to\ vapor$$

$$\dot{Q}_{v-l}: heat\ transfer\ from\ vapor\ to\ liquid, U: internal\ energy$$

- Boil-off gas (BOG) rate

$$\dot{m}_{BOG} = \frac{m_v - m_{real}}{dt} + \dot{m}_e - \dot{m}_c$$

$$m_{real} = m_v + (\dot{m}_e - \dot{m}_c - \dot{m}_{BOG})dt$$

$$m_{real} = V_v * \rho_{v-target}$$

$$\rho_{v-target} = f\left(P_{relief}, T_v\right), P_{relief}: relief\ pressure$$

Thermal insulation for a liquid air tank

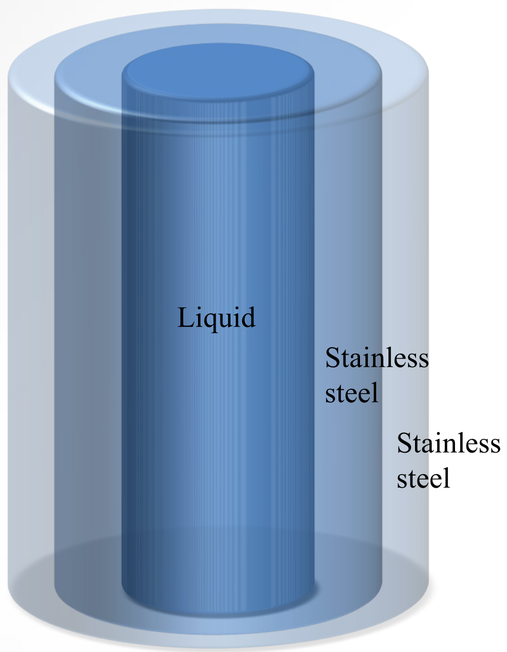

Fig.8 Schematic diagram of a 3D liquid air tank

- Reducing Heat ingress for reducing BOG → well-done insulation
- Double-wall structure (SUS 304) → good for insulation ability
  → searching good insulation material

- Thermal resistance (inside the tank)

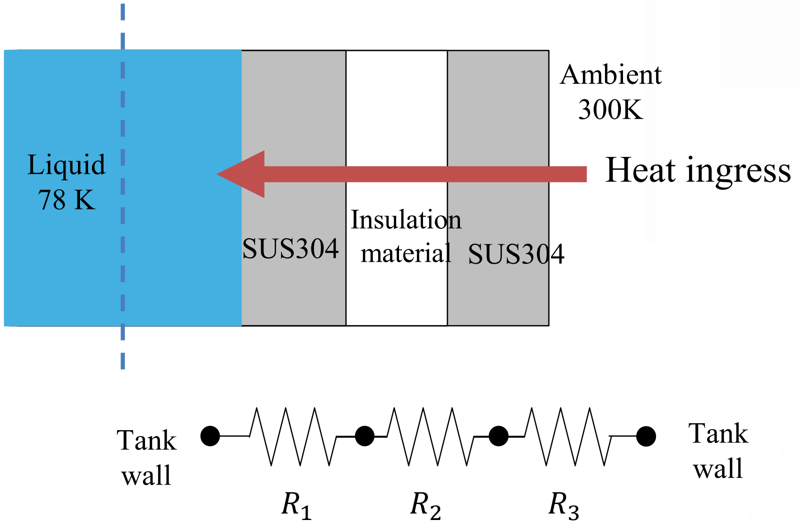

Fig.10 Schematic of the thermal resistance cross-section inside the tank

Thermal insulation type

- Thermal insulation type

1. Foam insulation
2. Vacuum insulation

- Difference of cost & thermal conductivity

→ need thermal insulation ability comparison

✓ In this study, polyurethane foam and vacuum insulation (P=0.01 Pa) were analyzed.

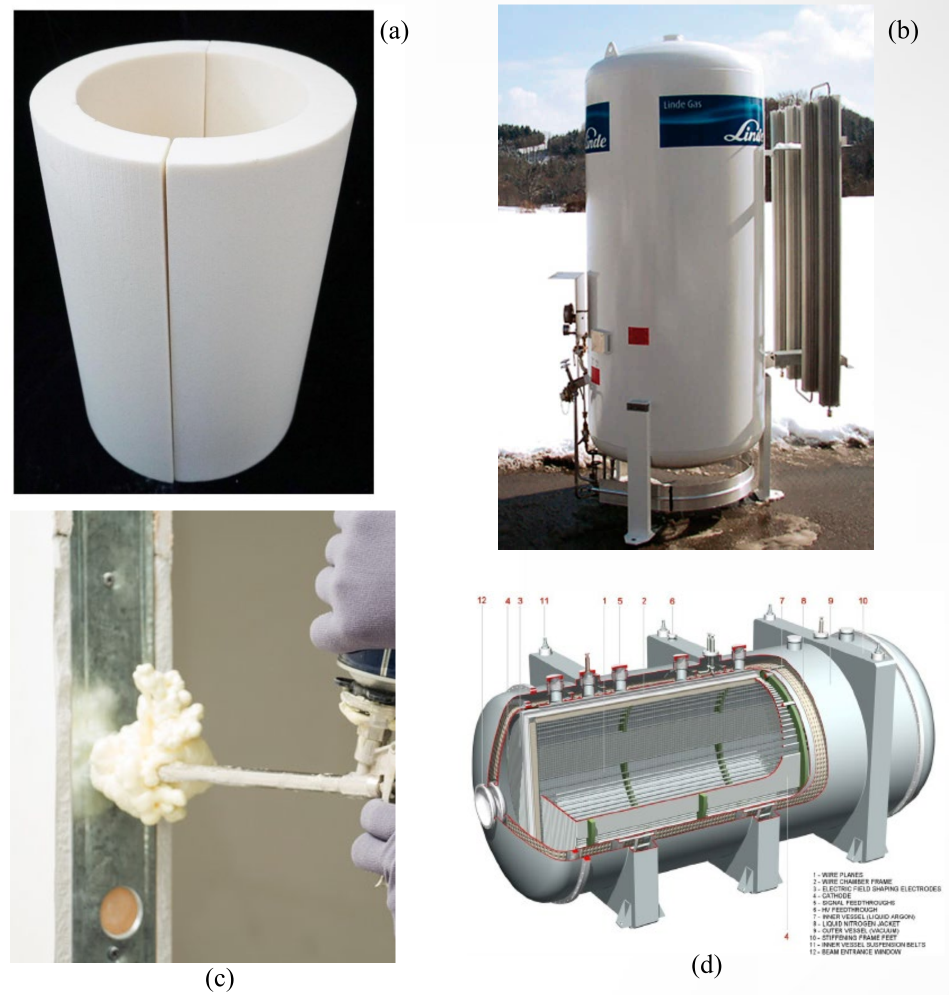

Fig. 11 (a) polyurethane foam (b) foam spray (c) Liquid gas tank insulated vacuum (d) schematic diagram of vacuum insulation tank

Thermal resistance for insulation material

- Heat transfer type : conduction, convection and radiation

  → Apply Thermal resistance model to the top, bottom and wall of the tank

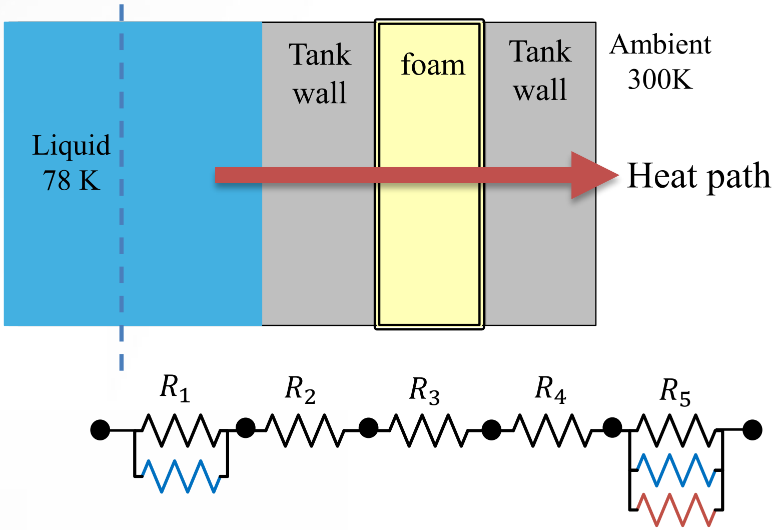

Fig.12 Schematic of the thermal resistance cross-section inside the tank with foam insulation

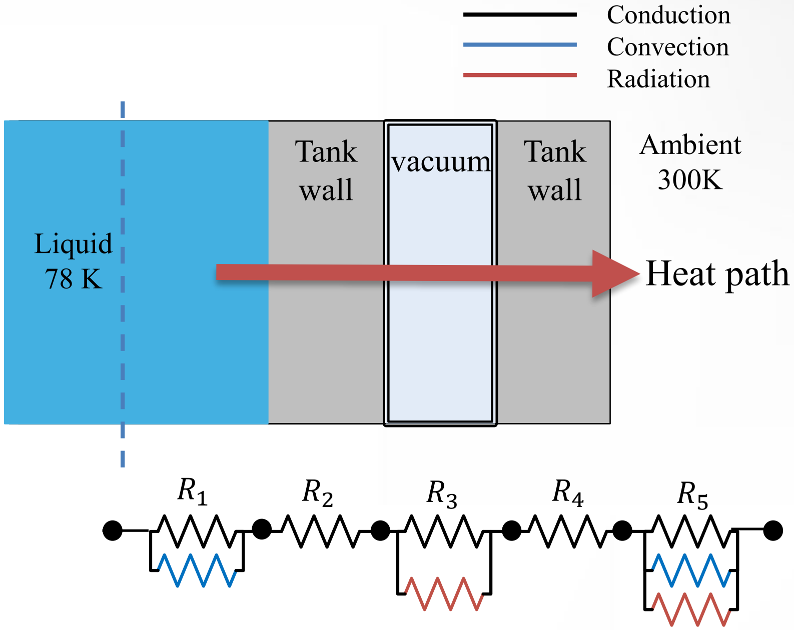

Fig.13 Schematic of the thermal resistance cross-section inside the tank inside the tank

$$R_{total} = R_{conduction} + R_{radiation} + R_{convection}$$

Design for a Liquid air tank

- Tank pressure rises due to BOG

  → vented by the relief valve

  → maintain the inner pressure of the tank
- Insulation thickness is designed using scaling method and fixed the value as 0.04m

  → to observe the effect of the insulation material on the BOG of the cryogenic tank

Table.1 Design parameters for tank modeling

parameters		
Height	9.0	m
Diameter	3.0	m
Side thickness	0.005	m
Top thickness	0.005	m
Insulation thickness	0.04	m

Thermal conductivity		
Foam	0.0285	W/m-K
Vacuum	0.003	W/m-K

- Assumptions used for the modeling

1) The Partial Equilibrium model (PEM) is used for liquid and vapor in the cryogenic tank.
2) The heat flux is calculated for top, bottom, and wall sections of the tank due to the different thermal properties at different location.
3) The total duration of analysis is 10 hours.
4) The temperature of the insulation is determined by thermal conductivity, and the temperature distribution within the insulation is not considered.
5) The BOG is assumed to be vented to maintain pressure at 108 kPa.

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Results

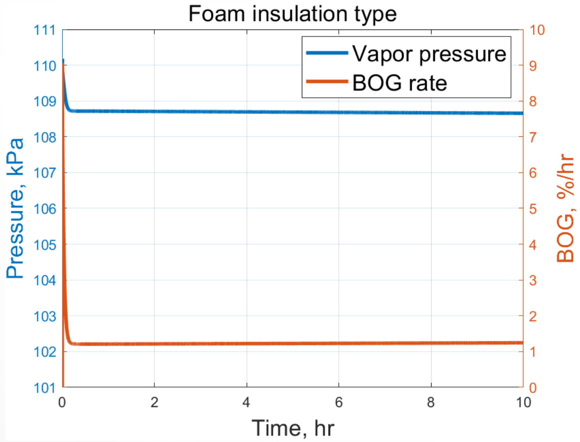
Results

- BOG rates for foam and high vacuum insulation.
- Pressure converges to target pressure of 108 kPa → BOG rate converges to a certain value.
- 10 times difference in thermal conductivity

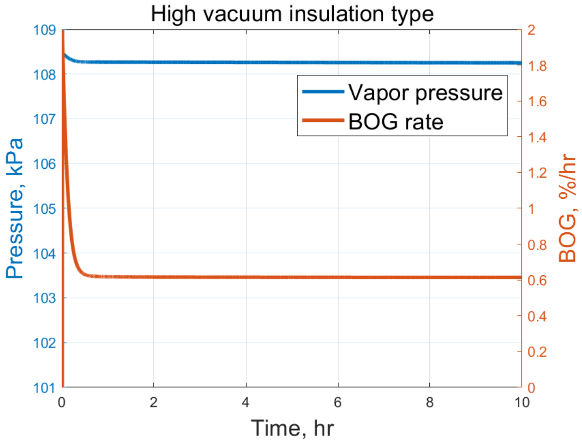
  → foam insulation (k = 0.0285) reaches 1.23%/hr converged BOG rate

  → vacuum insulation (k = 0.003) reaches 0.61%/hr converged BOG rate
- Non-linear relationship between thermal conductivity and converged BOG rate.

  → The choice of insulation material is crucial for BOG rate control.



(a)



(b)

Fig. 14 Boil-off gas rate of cryogenic tank insulated (a) foam and (b) high vacuum

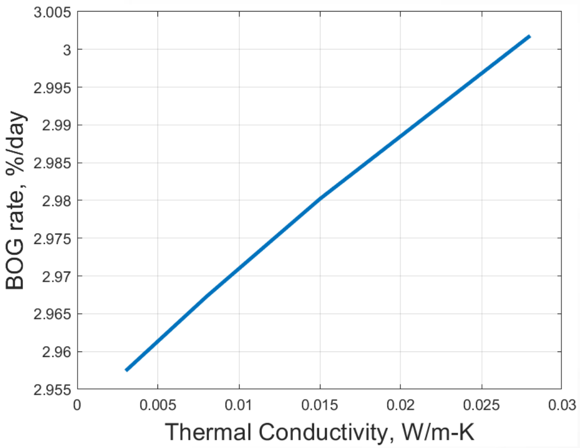


Fig. 15 Boil-off gas rate of the cryogenic tank and thermal conductivity insulated foam

Geometry design for Liquid air tank

- Insulation of the cryogenic tank is important for the tank design and how long the liquid air tank can hold liquid air for storing energy

  → Tank geometry is also crucial indicator for modeling

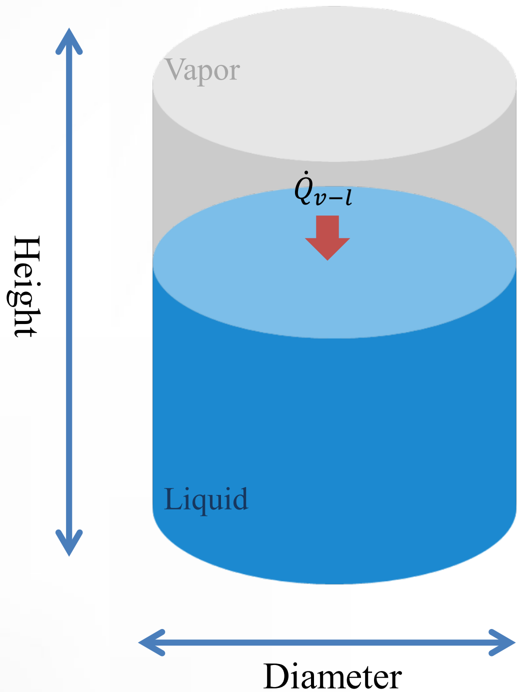


Fig. 16 Schematic diagram of a liquid air tank

- Aspect ratio

$$AR = {}^{H}/_{D}$$

→ Variation of aspect ratio influences Nusselt number

- Vapor-liquid heat transfer

$$\dot{Q}_{v-l} = h_{v-l}A\left(T_{vap} - T_{liq}\right)$$

$$\frac{1}{h_{v-l}} = \frac{1}{h_{vap}} + \frac{1}{h_{liq}}$$

$$Nu_{vap} = 0.54Ra^{0.25}$$

$$Nu_{liq} = 0.27Ra^{0.25}$$

$$Ra = Gr * Pr, Pr = \frac{\mu C_p}{k}, Gr = \frac{g\beta\Delta T D_{eq}^3}{\alpha\nu}$$

Results

- Aspect ratio change

  → interface area change → Nusselt number change

  → heat amount change → BOG rate change

- Total heat ingress into the tank reaches its minimum when the aspect ratio is 1

  → BOG rate also reaches its minimum at an aspect ratio of 1

- Heat ingress to the top, bottom, and walls of the tank varies with changes in the aspect ratio

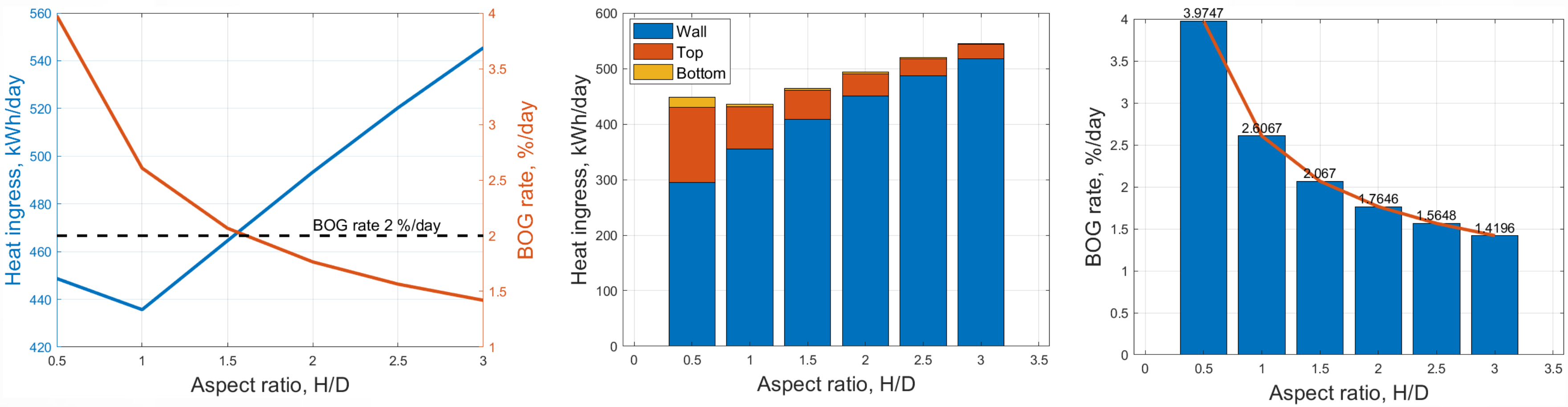


Fig. 17 Heat ingress and BOG rate of cryogenic tank for aspect ratio (*H/D*)

04
Summary

Summary

- Growing renewable energy → SMR flexibility needed
- Propose coupling SMR with LAES → Enhance load-following via LAES connection
- LAES (Liquid Air Energy Storage) charges during off-peak, discharges during high demand.
  - → Liquid form = high energy density, reduced thermal fluid volume
  - → Maintaining cryogenic temps in tank is important for LAES efficiency
- In cryogenic engineering, BOG (Boil-Off Gas) is a critical issue due to rising tank pressure.
- BOG rates for foam vs high vacuum insulation
  - → Converge at 108 kPa target pressure
  - → Foam insulation, 1.23% converged BOG rate
  - → High vacuum insulation, 0.61% converged BOG rate
  - → Non-linear relation between thermal conductivity and BOG rate
- Aspect ratio variation → interface area change → Nusselt number change → Heat amount change
  - → BOG rate change
- Minimum total heat ingress and BOG rate at aspect ratio 1
- Heat ingress to tank top, bottom, and walls varies with aspect ratio changes

Thank you

The Secret to success is to never give up