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Sensitivity analysis of vacuum insulation thickness for liquid air tank

Jung Hwan Park [a], Nayoung Kim [a], Jeong Ik Lee [a*]
[a] *Department of Nuclear and Quantum Engineering N7-1 KAIST 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea 305-338, junghwanpark@kaist.ac.kr*
[*] *Corresponding author: jeongiklee@kaist.ac.kr*

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1. Introduction

In order for Small Modular Reactor (SMR) to play an important role in the future electricity market, the load-following capability should be ensured. Currently, the load-following operation of SMR with reactor power maneuvering is possible, but practically, frequent variation of the reactor power can deteriorate the service lifetime of components and economy [1].

To increase the operational flexibility of SMR, a Liquid air energy storage (LAES) system was suggested as a nuclear energy storage option [2]. When electricity price is low, air is liquefied by the transferred energy from steam Rankine cycle. When electricity price is high, the stored liquid air is evaporated and operates air turbines to produce electricity. The reported round-trip efficiency of nuclear integrated LAES is around 40~60% [3]. The energy density of LAES is considerably high, however, the efficiency is still lower than battery storage. Since there is a limit to improve thermal efficiency, reducing the loss of liquefied air can also contribute to the improvement of overall performance.

Liquid air is stored at -196°C, therefore, heat ingress is inevitable from ambient air. The more heat is transferred to the tank, the more loss occurs. The loss of liquid air directly decreases the round-trip efficiency. Thus, it is necessary to evaluate the loss of liquid air according to the thickness of vacuum insulation.

The purpose of this study is to evaluate the effects of insulation thickness on the liquid air tank. This study includes thermodynamic modelling of liquid air tank and compares the insulation performance with insulation thicknesses.

2. Methodology

2.1 System description

Fig. 1 describes the schematic diagram of nuclear integrated LAES and liquid air tank. The nuclear integrated LAES is composed of steam Rankine cycle part and LAES part. When electricity price is low, air is liquefied by the transferred energy from steam Rankine cycle via steam-turbine-driven-air-compressor. The liquefied air is stored at cryogenic tank with high degree of insulation.

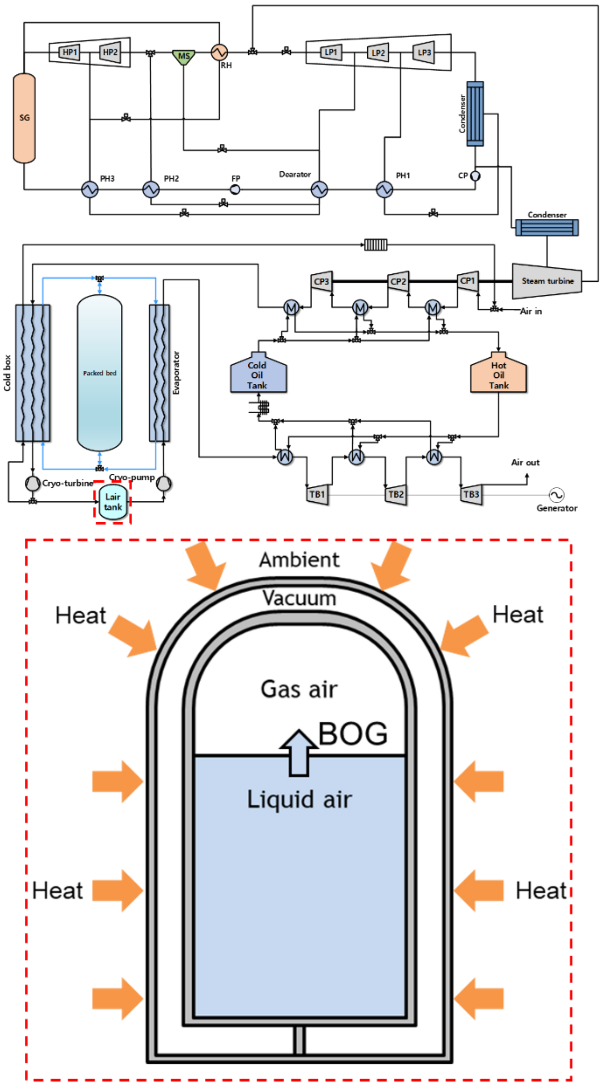

Fig. 1. Schematic diagram of nuclear integrated LAES and liquid air tank

Liquid air is stored at inner chamber and the surroundings are wrapped in vacuum or foam insulation. Due to the low temperature of liquid air tank, heat is transferred from the surrounding ambient air, and heat generates Boil-off Gas (BOG). Therefore, the measurement of BOG is important. The thermodynamic modelling of liquid air tank is introduced in the next section.

2.2 Thermodynamic modelling

For evaluating insulation performance, Partial Equilibrium Method (PEM) is used. PEM is a model that assumes the liquid and gaseous parts are in thermal equilibrium, respectively [4].

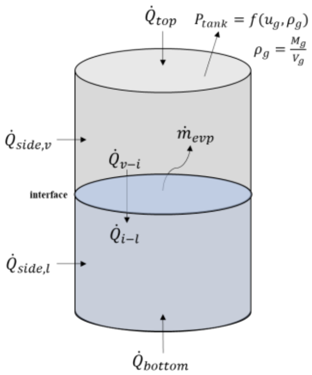

Fig. 2. Schematic diagram of liquid air tank

To utilize PEM, the following assumptions are made as following.

1. Tank is cylindrical geometry.
2. There are three phases: vapor, liquid, and interface.
3. Each phase has a uniform temperature distribution.
4. Wall heat transfer induces only fluid temperature rise.
5. Evaporation is determined by interface heat transfer.

The external heat ingress is modelled by natural convection model.

$$Nu_{wall} = CRa_{wall}^{0.25} \cdots eq(1)$$
$$C = 0.54\ for\ top, 0.27\ for\ bottom, 0.17\ for\ side$$
$$Ra_{wall} = Gr * Pr = \frac{g\beta\Delta T L^3}{\nu^2} * \frac{\mu c_p}{k} \cdots eq(2)$$

where Nu is Nusselt number, Ra is Rayleigh number, Gr is Grashof number, Pr is Prandtl number, g is gravity acceleration, β thermal expansion coefficient, ΔT is wall superheat, L is characteristic length, ν is kinematic viscosity, μ is dynamic viscosity, c_p is specific heat, k is thermal conductivity

Next, interface heat transfer and evaporation rate are modelled. In reality, evaporation and condensation phenomena exist simultaneously. However, in this study, the goal is to simulate the overall behavior of the storage tank, so it is modelled using a simple model.

$$Nu_{v-int} = 0.54Ra_v^{0.25} \cdots eq(3)$$
$$Nu_{int-l} = 0.27Ra_l^{0.25} \cdots eq(4)$$

There are two heat transfer paths at the interface: vapor to interface (*v-int*) and interface to liquid (*int-l*).

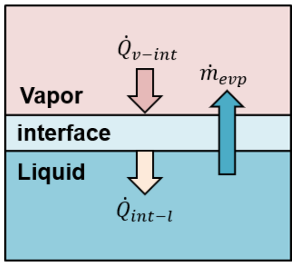

Fig. 3. Heat transfer at the interface

The evaporation rate is calculated from the energy jump model which assumes that the evaporation rate is determined by the net heat transfer rate at the interface [5].

$$\dot{m}_{evp} = \frac{\dot{Q}_{v-int} - \dot{Q}_{int-l}}{h_{fg}} \cdots eq(5)$$

where h_{fg} is latent heat, $\dot{m}_{evp}$ is evaporation rate.

Since air is a mixture, the composition change should be considered with respect to time. In this study, it is assumed that air is consisted only of nitrogen and oxygen. The composition change is modelled by using Phase Equilibrium Constant, K. By considering the equilibrium constant, the composition change is predicted.

$$K(N_2, O_2) = \frac{y(N_2,O_2)}{x(N_2,O_2)} = \frac{\phi_l(N_2,O_2)}{\phi_v(N_2,O_2)} \cdots eq(6)$$
$$\dot{m}_{evp}(N_2, O_2) = K(N_2, O_2) * \dot{m}_{evp} \cdots eq(7)$$

where y is mole fraction of each species at vapor region, x is mole fraction of each species at liquid region, ϕ is fugacity coefficient.

2.3 Simulation condition

For evaluating insulation performance of liquid air tank, simulation conditions are derived. The target capacity is 45tons, but from a conservative point of view, 20% margin is considered. The aspect ratio of tank is set to 3 which is the usual aspect ratio for cryogenic tank. To observe the change of insulation performance, insulation thickness is varied from 0 to 10cm. A 10-hour simulation is performed for each case and the results are described next.

Table. 1. Simulation condition of liquid air tank

Target capacity	45tons (+20% margin)
Tank height	9m
Tank inner diameter	3m
Tank material	SUS304
Tank thickness	2cm
Insulation thickness	0~10cm
Insulation materials Thermal conductivity [6]	Vacuum 5e-4W/m-K @ 10mtorr
Initial temperature	78.8K
Initial pressure	1bar
Initial level	80%
Simulation time	10hr

3. Results and discussions

The simulation code is developed in MATLAB environment and fluid properties are imported from NIST REFPROP.

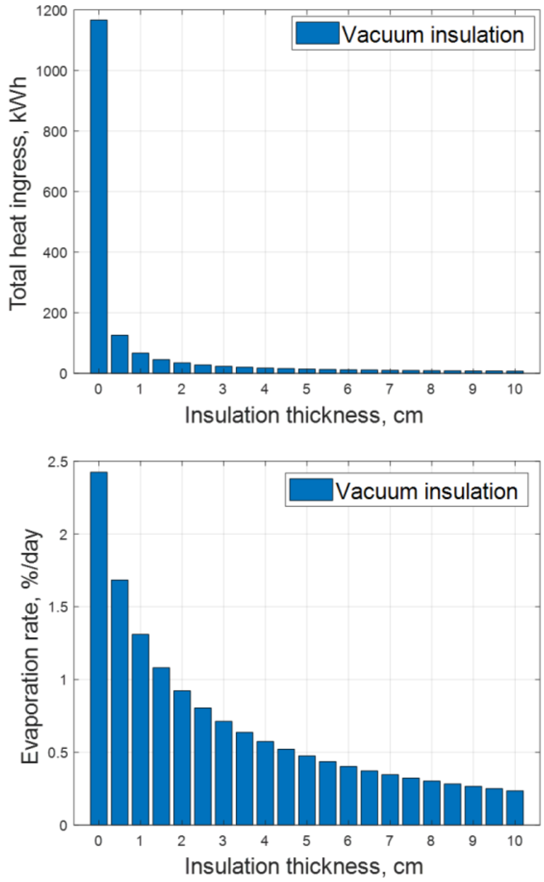

Fig. 4. a) Total heat ingress and b) evaporation rate with insulation thickness

Fig. 4 shows the change of total heat ingress and the evaporation rate of liquid air tank with respect to insulation thicknesses. As the insulation thickness increases, the total heat ingress from ambient air naturally decreases. There is very small heat ingress beyond 2.5cm thick vacuum insulation.

Due to the insulation performance, there is also difference in evaporation rate. In the case of vacuum insulation, the evaporation rate is non-linearly decreased and reaches 0.5%/day after 4cm thick insulation is used.

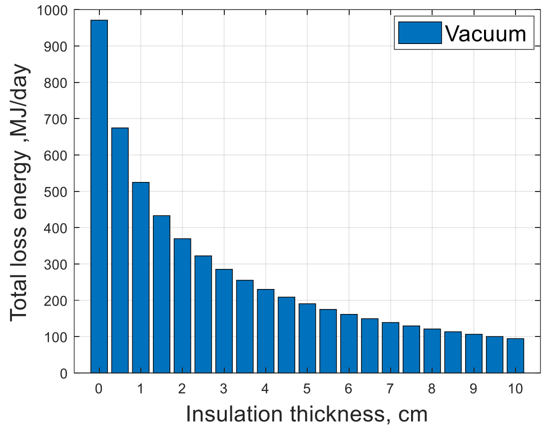

Fig. 5. Total loss energy with insulation thickness

With no insulation, almost 2.5% of total mass is lost in one day. This is very large loss when considering the liquefaction energy of air. By referring to the prior research [2], the liquefaction energy of liquid air is around 901.27kJ/kg (power input is 300MW and air mass flow rate is 386.6kg/sec). Considering the liquefaction energy, almost 1GJ is lost in one day without insulation. When using vacuum insulation, it can minimize the total energy loss down to 100MJ/day.

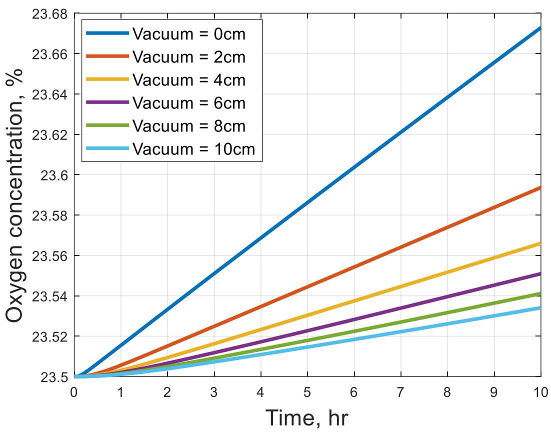

Fig. 6. Change of oxygen concentration with respect to time, insulation thickness

Fig. 6 shows the change of oxygen fraction of the liquid air tank with respect to time and insulation thickness. Since, nitrogen is lighter than oxygen, the evaporation rate of nitrogen is faster than that of oxygen. This is called 'weathering' or 'aging'. High oxygen concentration can cause safety issues on the liquid air tank. Therefore, the change of oxygen concentration should be carefully monitored. The vacuum insulation shows only 0.06%p increases when 4cm thick insulation is used. It seems that the absolute change of oxygen concentration is not large, but additional research is required due to local change of oxygen concentration can be substantially different.

4. Conclusions

In this study, the insulation performance of liquid air tank is evaluated with respect to insulation thicknesses. For the evaluation, the thermodynamic model of liquid air tank is developed in MATLAB environment. By using the developed code, the insulation performance is evaluated. The vacuum insulation shows good insulation performance. After 4cm thick vacuum insulation is used, the evaporation rate is below 0.5%/day. Also, the increase of oxygen concentration is only 0.06%p/day. In terms of overall aspect, the vacuum insulation was found to be excellent due to its low thermal conductivity. However, in terms of economy, high vacuum insulation needs additional cost to maintain high level of vacuum. It means that the capital cost and O&M cost will inevitably increase. Therefore, the economic analysis should be performed for more practical suggestion. In the future, the economic analysis on vacuum insulation will be performed to optimize the overall system.

5. Acknowledgment

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REFERENCES

[1] Locatelli, Giorgio, et al. "Load following with Small Modular Reactors (SMR): A real options analysis." *Energy* 80 (2015): 41-54.
[2] Park, Jung Hwan, Jin Young Heo, and Jeong Ik Lee. "Techno-economic study of nuclear integrated liquid air energy storage system." *Energy Conversion and Management* 251 (2022): 114937.
[3] Yu, Qinghua, et al. "Cryogenic energy storage and its integration with nuclear power generation for load shift." *Storage and Hybridization of Nuclear Energy*. Academic Press, 2019. 249-273.
[4] Seo, Mansu, and Sangkwon Jeong. "Thermodynamic analysis of self-pressurized liquid nitrogen cryogenic storage tank." *JSME-KSME thermal and fluids engineering conference. Sapporo. Japan*. 2008.
[5] Perez, Fernando, et al. "Measurements of boil-off gas and stratification in cryogenic liquid nitrogen with implications for the storage and transport of liquefied natural gas." *Energy* 222 (2021): 119853.
[6] Fesmire, James E. "Standardization in cryogenic insulation systems testing and performance data." *Physics Procedia* 67 (2015): 1089-1097.