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

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***Keywords : Cryogenic tank, Boil-off gas, Insulation**

1. Introduction

In order to increase the load-following capability of Small Modular Reactors (SMRs) in response to the growing contribution of renewable energy sources to power generation, one suggestion is to integrate SMRs with a large energy storage system such as Liquid Air Energy Storage (LAES) [1]. It was suggested that the LAES and the nuclear steam cycle can be coupled mechanically by using a Steam Turbine driven-compressor (STDC) previously [2]. The STDC is used to compress air for the LAES charging cycle. After liquid air is produced for energy storage, maintaining cryogenic temperature for sufficient time in the liquid air tank is essential to achieve good round-trip efficiency of the LAES system. This issue illustrates that the insulation of the cryogenic system is important for the overall system performance.

However, the challenge of maintaining cryogenic conditions makes it difficult to design a system that works well and is economical [3]. The cryogenic system has complex thermodynamic behaviors because the vaporization on its actual interface occurs during the vaporization and liquefaction at the same time.

The Thermo-fluid model for liquid air tank energy storage (LAES) is developed in the previous work [4], JH Park et al. The previous study focused on the thermodynamic analysis model development of proposed liquid air storage tanks and predict composition changes with respect to time. The study used a Partial Equilibrium model (PEM) to model the storage tank. The evaporation rate and inner pressure with respect to storage time were predicted.

The boil-off gas (BOG) occurs in cryogenic tanks that store fluids, primarily liquid natural gas or liquid hydrogen. The BOG has the effect of increasing the internal pressure of the cryogenic tank, and the change from liquid to gas requires heat transfer. Thus, BOG is affected by the heat ingress to the tank and therefore the type of insulation greatly affects BOG. This paper aims to investigate the future structural challenges of cryogenic tank modeling in the relations between BOG and insulation.

2. Methods and Results

Assumptions used for the modeling are as follows

1) The Partial Equilibrium model (PEM) is used for liquid and vapor in the cryogenic tank [4].
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.

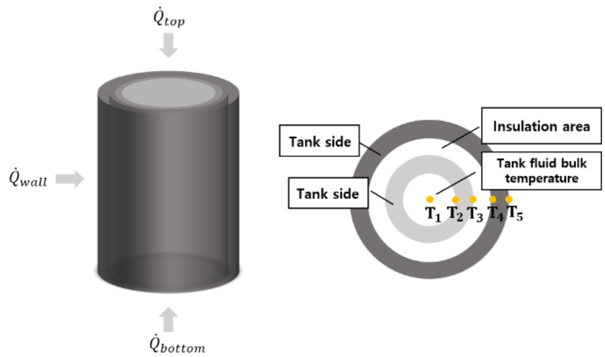

Fig. 1. Schematic diagram of cryogenic tank

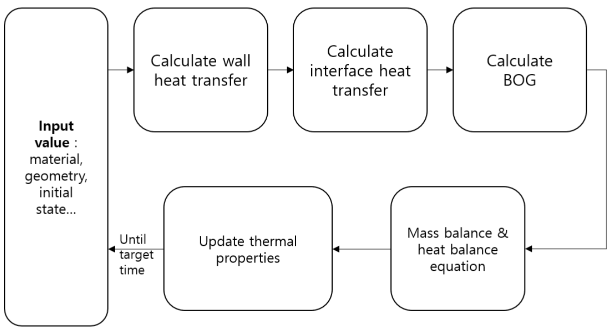

Fig.2. Algorithm of Thermo-fluid model

Table I: Tank geometry parameters

	value	unit
Height	9	m
Diameter	3	m
Side thickness	5e-3	m
Top thickness	5e-3	m
Bottom thickness	5e-3	m
Insulation thickness	4e-2	m

Table II: Thermal conductivity of insulation materials [3]

	type	value	unit
Thermal conductivity	Foam	0.0285	W/m-K
	Vacuum	0.003	

The heat ingress to the tank is divided into three parts, top, bottom and wall as shown in Figure.1. As shown in Figure.1, the cross-section of double tank is divided into four parts, and temperatures in four parts are calculated. Each top, bottom, and wall section is composed of four areas. Fluid, inner tank, insulation, and outer tank. T1 corresponds to the temperature of the fluid in the tank and T2 is the inner temperature of the tank adjacent to the fluid. T3 is the outside temperature of the tank enclosing the fluid. T4 represents the temperature of the insulation. Lastly, T5, denoting the outermost temperature, which represents the exterior temperature of the tank side enclosing the insulation material. The thicknesses of the tank wall and the insulation layer are provided in Table 1. These temperatures are calculated by an algorithm implemented in MATLAB, which is shown in Figure.2. The input data of the tank geometry is summarized in Table I.

In this paper, the insulation material thickness is fixed to observe the effect of the insulation material on the BOG of the cryogenic tank. The insulation materials considered in this paper are foam and high vacuum. Table. II shows the thermal conductivity of insulation material used to calculate the thermal resistance and heat flux of the tank. The heat of the cryogenic tank is calculated with equation (1) at three locations in the tank: top, bottom, and wall.

$$Q = \frac{T_{ambient} - T_{bulk}}{R} \quad (1)$$

$$\frac{1}{R} = \frac{1}{R_{conduction}} + \frac{1}{R_{radiation}} + \frac{1}{R_{ext.convection}} \quad (2)$$

The heat flux is Q, T is temperature, and R is thermal resistance. Thermal resistance consists of three types of heat transfer that occur in the cryogenic tank and is calculated with equation (2). The thermal resistance model is applied to the walls, top, and bottom of the cryogenic tank. With the calculation of heat flux, Boil-off gas is calculated with equation (3).

$$\text{BOG rate} = \frac{M_{boil-off}}{M_{tank}} \times 100 \quad (2)$$

The rate of BOG (%/hr) is defined as the ratio of the mass of boil-off gas per time and the tank bulk mass. BOG will depend on the heat ingress to the tank, and the heat ingress will be determined by the insulating capability of the insulation material.

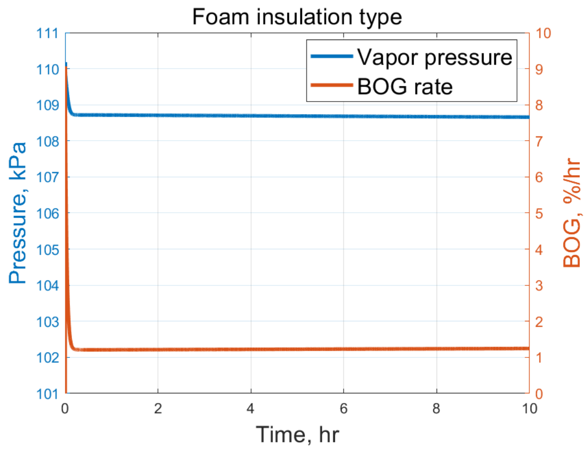

Fig. 3. Boil-off gas rate of cryogenic tank insulated foam

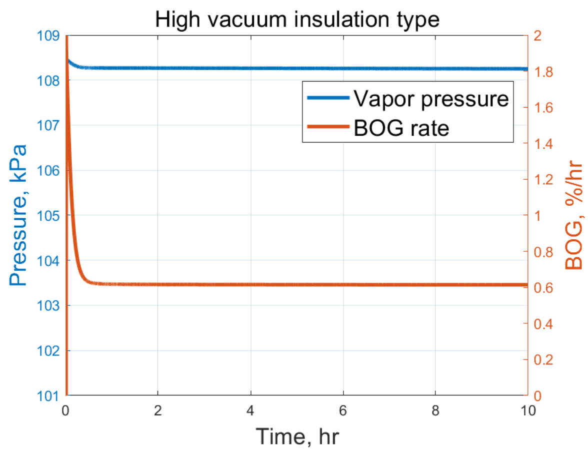

Fig. 4. Boil-off gas rate of cryogenic tank insulated high vacuum

Figures 3 and 4 show the BOG rate for foam insulation and high vacuum insulation, respectively. As the BOG rate converges to the target pressure of 108 kPa, the BOG rate also converges to a certain value. The thermal conductivity of foam and high vacuum insulation is 2 times different as shown in Table II, and the converged BOG rate is 1.23 % for foam insulation and 0.61 % for high vacuum insulation.

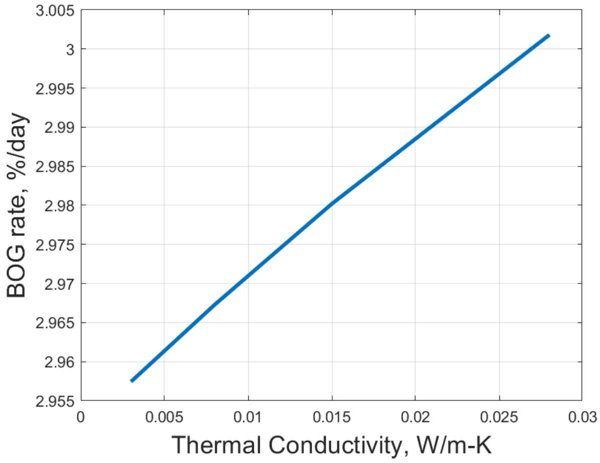

Fig. 5. Boil-off gas rate of the cryogenic tank and thermal conductivity insulated foam

Figure 5 shows the relationship between the thermal conductivity and the converged BOG rate. The calculation is performed while keeping the insulation geometry fixed and changing only the thermal conductivity. Figure 5 shows that the relationship between the two factors is non-linear. The insulation material has to be carefully selected in order to control BOG rate.

3. Summary and future work

This study focuses on the effect of insulation material for the cryogenic tank boil-off gas (BOG). A thermo-fluid model is used to compare effects of different insulation materials on BOG. The Thermo-fluid model simulates the thermodynamic phenomena at the interface of the tank using a Partial Equilibrium Model (PEM). The BOG rate, which is determined by the heat transfer process between liquid and vapor in the tank, is important because it affects the tank pressure. From the analysis of the BOG rate with respect to the thermal conductivity, it is shown that the 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. Therefore, the optimization of tank geometry in conjunction with the insulation method of cryogenic tanks will be performed in the future study.

ACKNOWLEDGEMENT

This work is supported by the Korea Agency for Infrastructure Technology Advancement(KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant RS-2022-00143652).

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