Dynamic Characteristics of Pressure Build Up Tank for HTS Power Cable Refrigeration System

Dongmin Kim a, Heecheol Parka, Seokho Kim a*, Hyunman Jang b, Yanghun Kim b

a Changwon National University, Changwon, Korea
b LS Cable&System, Changwon, Korea

Abstract

HTS power cables are cooled by the forced circulation of sub-cooled liquid nitrogen to remove heat loss and maintain a cryogenic temperature. The refrigeration systems used consist of cryocoolers, a pressure build-up tank, heat exchangers, and circulation pumps.

Liquid nitrogen expands or shrinks according to the temperature variation inside the fixed volume of the refrigeration system and the cable cryostat. The system pressure also changes depending on the volume change of the liquid nitrogen. The pressure of the liquid nitrogen should be kept above a certain level to ensure its dielectric strength. In addition, the pressure should be kept below the allowable pressure level considering the mechanical strength of the refrigeration system.

To enhance the pressure controllability, external heating and cooling should be possible in the pressure build-up tank. For the precise modeling of the pressure build-up tank, thermal stratification and axial thermal conduction are considered. An analysis of such a refrigeration system is performed using the commercial code ‘Sinda/fluint’, a comprehensive finite-difference, one-dimensional, lumped parameter tool.

This paper presents the transient thermo-hydraulic characteristics of an HTS cable refrigeration system according to a variable heat load. The results suggest the design directions of the pressure build-up tank and its control algorithm.

Keywords: HTS Power Cable; Pressure Build Up Tank, refrigeration system, thermodynamics and fluid dynamics of cryogen, pressure control

1. Introduction

Recently, there have been many research efforts to commercialize HTS power cables, and stable cryogenic refrigeration systems have become among the most important components related to this issue [1]. For the stable
operation of the HTS power cable used in these systems, the temperature and pressure of the system’s subcooled liquid nitrogen should be controlled within a specified range. The temperature can be controlled by changing the cooling capacity of the cryocooler and the flow rate of the liquid nitrogen. However, pressure control requires a suitable control method because large variations of pressure can be induced by slight changes of the temperature at a fixed system volume. To control the pressure, a pressure build-up tank (PBT) is used. A simple method involves the use of a heater inside the tank and a relief valve. To increase the pressure, the heater is used to evaporate the liquid nitrogen, while the pressure can be lowered by discharging the gaseous nitrogen through the relief valve, which is located in the PBT. This method is simple but shows a slow response time. It also requires replenishment of the liquid nitrogen corresponding to the amount discharged.

To address these issues, gaseous nitrogen or liquid nitrogen from the refrigeration system itself can be used. To increase the pressure, a small amount of the liquid nitrogen from the exit port of the circulation pump is heated up to room temperature and is induced into the PBT. To decrease the pressure, chilled liquid nitrogen is directly induced into the PBT. In this case, the gaseous liquid nitrogen inside the PBT is rapidly condensed and the pressure thus drops.

This paper describes pressure variation and control characteristics using the commercial code ‘Sinda/fluint’, a comprehensive finite-difference, one-dimensional, lumped parameter tool. The results are compared with experimental results and the optimum design of the PBT and its control algorithm are suggested [2].

2. Modeling of refrigeration system

Fig. 1 (a) shows a schematic diagram of the refrigeration system used with the HTS power cable. The PBT has stratified gaseous and liquid volumes. This design can mitigate pressure variations induced by the thermal expansion or shrinkage of the liquid nitrogen [3 -5].

![Fig. 1. (a) schematic diagram of HTS power cable system, (b) 1D network modeling of the refrigeration system Sinda/fluint](image)

The refrigeration system can be modeled using a 1D network diagram using ‘Sinda/fluint’ considering an energy and momentum equation for all components, as shown in Fig. 1 (b). In particular, the PBT is modeled as a single tank composed of separated gas and liquid volumes in what is termed a ‘twin tank’. This design also allows descriptions of the variation of the liquid-to-gas ratio considering a thermodynamic state and the heat transfer between different phases. The PBT is connected to the exit port of a circulation pump via two different paths.

Fig. 2 shows the pressure control process using the PBT. When the system pressure increases above its designed

![Fig. 2. Depressurization & Pressurization process by the PBT](image)
value, a de-pressurizing valve is opened to introduce liquid nitrogen into the PBT. The gaseous nitrogen condenses and the pressure decreases. When the system pressure decreases below its designed value, a pressurizing valve is opened. In this case, liquid nitrogen passes through an evaporator and is warmed to room temperature. The warm gaseous nitrogen enters the PBT and this raises the system pressure. Therefore, the pressure control system monitors the system pressure, opening and closing the de-pressurizing and pressurizing valves to keep the pressure in the appropriate ranges [6].

3. Test results of pressure control

There are several test results pertaining to the refrigeration system for the HTS power cable used at the Icheon substation owned by LS C&S and KEPCO. The experiments were carried out using a dummy cable with a heater instead of an actual cable. For the verification of the analysis model, these experimental results can be used here. Table 1 describes the specifications of the tested refrigeration system, which was developed by LS C&S.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value(dummy cable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBT volume [m³]</td>
<td>1.00</td>
</tr>
<tr>
<td>Heat load at PBT [W]</td>
<td>250 for maximum nitrogen level</td>
</tr>
<tr>
<td>Volume of dummy cable [m³]</td>
<td>0.29</td>
</tr>
<tr>
<td>Heat load of dummy cable [W]</td>
<td>30 ~ 5,000 (full load)</td>
</tr>
<tr>
<td>Liquid nitrogen piping volume [m³]</td>
<td>0.016</td>
</tr>
<tr>
<td>Cooling power</td>
<td>5 kW @ 76 K, 2.8 kW @ 72 K</td>
</tr>
</tbody>
</table>

To investigate the effect of the initial liquid level at the PBT on the pressure variation, the level was adjusted to 30% and 50% of the total volume of the PBT by extracting liquid nitrogen. During the level adjustment process, the pressurizing valve was opened to maintain the pressure and warm gas was in-filled at the PBT. After adjusting the initial level, the pressure was slowly increased to 5.2 bar until the de-pressurizing valve opened due to the warm gaseous nitrogen and the background heat load of the PBT. After the pressure reached the high limit of 5.2 bar, a heat load of 5 kW was applied to the dummy cable. From this point, the pressure was controlled by valve operations, holding it within 4.9 and 5.2 bar, as shown in Fig. 3. The pressurizing valve was opened at 5.0 bar and the pressure continuously increased to 5.2 bar according to the background heat load of the PBT. The level of the liquid nitrogen was not changed because the volume of liquid nitrogen was very low compared to that of the PBT.

4. Analysis results of the refrigeration system

The same parameters used with the tested refrigeration system were applied to the analysis model. A transient analysis was conducted for the given initial conditions and valve operations.

Fig. 3. Experimental results (a) pressure variation; (b) liquid nitrogen level of PBT
Fig. 4 (a) shows the pressure variation for the given initial level, and Fig. 4 (b) shows the corresponding variation of the liquid nitrogen level. The analysis results show good agreement with the experimental data. Because the analysis and experiments were performed using a dummy cable, the change of the liquid nitrogen level was negligible. Then, an HTS power cable of 1 km was considered instead of a dummy cable. In this case, the volume of the liquid nitrogen was 4 m³ and the corresponding maximum heat load was 5 kW. Fig. 4 (c) shows the variation of the pressure and the liquid nitrogen level when 5 kW is applied for the first 100 hours with a subsequent reduction to 3 kW. The pressure was controlled by the valve operation and the level increased to 6% in 100 hours. After the level reached 36%, it was reduced from 36% to 33% to absorb the volume contraction of the liquid nitrogen.

5. Conclusion

Using a 1D network analysis, which included the non-equilibrium thermodynamic state of a PBT, a refrigeration system used with an HTS power cable was modeled here, with the results showing good agreement with the experimental results. The pressure control and variations in levels were verified through the analysis of the HTS power cable. For the given constant heat load, the pressure continuously oscillated because thermal equilibrium was not established in the PBT. This was caused by the excessive amounts of chilled liquid or gas entering the PBT.

For a 1 km HTS power cable, the ensuing variation of the liquid nitrogen level was less than 6% at the given volume of the PBT. Considering the level change for the variable heat load, the present volume of the PBT and the opening of the pressurization and de-pressurization values appear to be excessive. For the optimal design of a PBT and related control valve, a 1D network analysis was found to be very useful. For a precise estimation of the pressure and level of the PBT, more detailed specifications of the refrigeration system can be used in future works.

Acknowledgements

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References