Study on the Dielectric Characteristics of Gaseous Nitrogen for Designing a High Voltage Superconducting Fault Current Limiter

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Abstract—The study on the dielectric characteristics of gaseous insulation medium is important for designing current leads of superconducting machines using a sub-cooled liquid nitrogen (LN$_2$) cooling method. In a sub-cooled LN$_2$ cooling system, the temperature of gaseous insulation medium surrounding current leads varies from the temperature of coolant to 300 K according to the displacement between the electrode system and the surface of sub-cooled LN$_2$. In this paper, AC withstand voltage experiments on gaseous nitrogen according to temperature are conducted. Also, AC withstand voltage experiments on gaseous nitrogen according to pressure, size of electrode, and gap length between two electrodes are performed. It is found that there is a functional relation between the electrical breakdown voltage and the field utilization factor ($\xi$). As a result, the empirical formula for estimating an electrical breakdown voltage is deduced by adopting the concept of field utilization factors. It is expected that the experimental results presented in this paper are helpful to design current leads for a high voltage superconducting apparatus such as a superconducting fault current limiter (SFCL) using a sub-cooled LN$_2$ cooling system.

1. INTRODUCTION

There are several technical obstacles such as dielectric, cryogenic, and economic problems to develop and commercialize a high voltage superconducting apparatus such as an SFCL, a superconducting motor, a superconducting transformer, and so on with high reliability. In this paper, a study on the dielectric characteristics of gaseous nitrogen is conducted to design current leads for a sub-cooled LN$_2$ cooling system known to be a most promising method to develop a high voltage superconducting machine [1]. In a sub-cooled LN$_2$ cooling system, the electrical insulation design for current leads is important because the dielectric performance of gaseous insulation medium is inferior to that of LN$_2$ [1]. In Republic of Korea, SF$_6$, CF$_4$, He, and N$_2$ are taken into consideration as a candidate for regulating the pressure of the sub-cooled LN$_2$ cooling system of a high voltage superconducting apparatus [1]. In this paper, dielectric experiments on N$_2$ and analyses using a finite element method (FEM) are performed because N$_2$ is known as the most promising insulation medium for its homogeneity with the coolant as well as dielectric performance [1]. It is known that the dielectric characteristics of gaseous media are deeply dependent on the temperature. Therefore, the electrical breakdown voltage experiments of N$_2$ according to temperature are conducted in this study. This is very important point to determine the electrical insulation design criterion of current leads.

Many papers and reports on the dielectric characteristics of N$_2$ have been published. However, there have not been ever conducted experiments and analysis on the dielectric characteristics of N$_2$ considering $\xi$. Currently, it has been reported that the electrical breakdown voltage of gaseous insulation media such as He, Ne, and SF$_6$, is determined by $\xi$ as well as temperature, gap length between electrodes and pressure [3]. Also, many efforts have been devoted to applying the results to design superconducting apparatuses. This investigation is a part of those efforts.

In this investigation, seven kinds of sphere-to-plane electrode systems with different diameters are designed and fabricated to verify the functional relation between $\xi$ and $E_{max,mean}$ to contemplate the various conditions. The gap length between two electrodes is varied from 10 mm to 60 mm to conduct experiments in wide range of the $\xi$. Also, electrical breakdown voltage experiments on GN$_2$ according to pressure are carried out and functional formulae for calculating the electrical breakdown voltage are derived. This paper presents not only the dielectric experimental results of GN$_2$ according to temperature and pressure but also the electrical insulation design method for high voltage superconducting apparatuses.

2. DIELECTRIC CHARACTERISTICS OF GN$_2$ ACCORDING TO TEMPERATURE

A sub-cooled LN$_2$ cooling system is regarded as a most promising method for its excellent cooling characteristics, thermal conduction, and dielectric characteristics [4]. Therefore, the dielectric characteristics of GN$_2$ considering several conditions for a sub-cooled LN$_2$ cooling system are investigated in this study. A sub-cooled LN$_2$ cooling system is largely composed of liquid part and gaseous part [4]. Fig. 1 shows the schematic sketch of a sub-cooled LN$_2$ cooling system. In Fig. 1, the ellipse with broken line indicates the gaseous part. The current leads are installed at the gaseous part and surrounded by GN$_2$. The temperature gradient of GN$_2$ surrounding current leads is varied from approximately the temperature of LN$_2$ to 300 K because the end of current leads is immersed into LN$_2$ and the other end

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is exposed to the atmosphere. Therefore, the dielectric characteristics of current leads could be quite different according to the displacement from the surface of LN2.

2.1. Temperature distribution of a gaseous part

The temperature gradient at the gaseous part of a sub-cooled LN2 cooling system is measured by attaching five K-type thermocouples on a GFRP rod like Fig. 2. The explanation on the structure of a sub-cooled LN2 cooling system is described in another paper in detail [4]. The saturated 77 K LN2 is poured into a cryostat and then the GFRP rod with thermocouples is installed. After the stabilization, the temperature distribution of GN2 in the gaseous part is measured and shown in Table I. As shown in Table I, it is found that the temperature of GN2 next above the surface of LN2 is about 80 K and the temperature of GN2 beneath the top flange is about 300 K. The difference of dielectric performance is caused by this temperature gradient in the gaseous part.

2.2. Dielectric experiments according to temperature

In the gaseous part of a sub-cooled LN2 cooling system the temperature gradient is distributed according to the displacement from the surface of coolant. The variation of dielectric characteristics according to temperature is confirmed by performing AC breakdown voltage experiments. The dielectric experiment is conducted by using an electrode system with a sphere electrode of 50 mm in diameter. The gap length between a sphere electrode and a plane electrode is varied from 1 mm to 10 mm. The temperature of experiment was regulated by controlling the distance between the electrode system and the surface of coolant and the temperature was measured by K-type thermocouples which are installed near the electrodes like Fig. 3. The experimental results are plotted in Fig. 3. As shown in Fig. 3, the electrical breakdown voltage at 80 K is definitely more than two times superior to that of 300 K in case of a 0.1 bar pressure condition. For this reason, the dielectric characteristics at 300 K should be a criterion to design current leads for a high voltage superconducting apparatus considering safety factor Therefore, every dielectric experiment on GN2 according to gap length, size of electrode, and pressure is conducted at 300 K temperature and 0.1 bar pressure condition. In this paper, all of the described pressures mean the absolute pressure.

### Table I

<table>
<thead>
<tr>
<th>Temp. sensor</th>
<th>Temp. (K)</th>
<th>Distance from the surface of LN2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>77</td>
<td>-80</td>
</tr>
<tr>
<td>K2</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>K3</td>
<td>150</td>
<td>60</td>
</tr>
<tr>
<td>K4</td>
<td>220</td>
<td>150</td>
</tr>
<tr>
<td>K5</td>
<td>300</td>
<td>380</td>
</tr>
</tbody>
</table>

![Fig. 1: Structure of a sub-cooled LN2 cooling system.](image1.png)

![Fig. 2: Temperature measurement by using thermocouple sensors.](image2.png)

![Fig. 3: Temperature dependency of AC breakdown voltage according to gap length at 0.1 bar pressure.](image3.png)

3. EXPERIMENTAL SET-UP AND CALCULATION

In this paper, AC breakdown voltage experiment on GN2 was performed under the condition of pressures: 0.1 and 0.4 bar with seven kinds of electrode systems. GN2 is injected into a test chamber after vacuumizing it until the pressure reaches down to $10^{-3}$ Torr by using a rotary pump with a capacity of 192 liter/min in order to minimize the adverse effect of impurities.

3.1. Sphere-plane electrode system

Seven kinds of electrode systems with different diameters are designed and manufactured to understand the AC electrical breakdown characteristics of GN2. The gap length between a sphere electrode and a plane electrode is varied from 10 mm to 60 mm. The specifications of electrode systems are shown in Table III. AC voltage is
## TABLE III

<table>
<thead>
<tr>
<th>Gap Length (mm)</th>
<th>Diameter of Sphere Electrode (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>0.1016</td>
</tr>
<tr>
<td>30</td>
<td>0.0350</td>
</tr>
<tr>
<td>50</td>
<td>0.0226</td>
</tr>
<tr>
<td>60</td>
<td>0.0193</td>
</tr>
</tbody>
</table>

### 4. EXPERIMENTAL RESULTS AND DISCUSSION

AC withstand voltage experiment on GN$_2$ is conducted and the statistical mean value of the electrical breakdown voltage ($V_{BD,mean}$) is calculated. Also, the $E_{max,mean}$ can be obtained by multiplying the $V_{BD,mean}$ by the analytic maximum electric field intensity ($E_{max,1kV}$). The relation of $E_{max,mean}$, $E_{max,1kV}$ and $V_{BD,mean}$ can be represented as follows:

$$E_{max,mean} = E_{max,1kV} \times V_{BD,mean}$$  \hfill (2)

#### 4.1. Experimental results of AC withstand voltage experiments

The electrical breakdown voltage of GN$_2$ with various gap lengths and electrode diameters at 1 bar pressure is shown in Fig. 5. It is revealed that the electrical breakdown voltage increases in proportion to the gap length. Seen from Fig. 5, the saturation tendency of electrical breakdown voltage caused by size effect appears when the sphere electrode is over 40 mm in diameter [5]. This phenomenon is also shown in the experimental results at 4 bar pressure. Fig. 6 shows the electrical breakdown voltage of GN$_2$ at 4 bar pressure condition.

#### 4.2. Discussion

The $E_{max,mean}$ of GN$_2$ at 1 bar and 4 bar pressure could be calculated by the experimental results and Eq (2). Through the calculation, it is found that the graph plots of $E_{max,mean}$ could be fitted by exponentially decaying formula according to the $\xi$ increases. The functional relation between the $\xi$ and the $E_{max,mean}$ under AC experiment on GN$_2$ is shown in Fig. 7. As shown in Fig. 7, the $E_{max,mean}$ decreases as the $\xi$ increases until it reaches about 0.2. When the $\xi$ is over 0.2, there is no drastic variation of the $E_{max,mean}$ and maintain nearly constant value. Especially, this is more obviously observed in 1 bar pressure condition. The empirical formulae for estimating the $E_{max,mean}$ and the AC electrical breakdown voltage could be inferred from trend curves as follows:

$$E_{max,mean,1bar} = f(\xi_{1bar}) = 1.65 \times \xi^{-0.479}$$  \hfill (3)

$$E_{max,mean,4bar} = f(\xi_{4bar}) = 6.50 \times \xi^{-0.412}$$  \hfill (4)

As previously mentioned, the electrical breakdown voltage of GN$_2$ becomes to be saturated near 4 bar pressure. Seen from two equations, it is proved that the magnitude of the $E_{max,mean}$ of 4 bar pressure is approximately more than 3
times larger than that of 1 bar pressure. Therefore, it seems that 4 bar pressure condition is more preferable to 1 bar pressure condition when design a high voltage superconducting apparatus from the viewpoint of the electrical insulation. This pressure condition is not restricted to GN₂ but applicable to other gaseous medium such GHe, GNe, and so on [5]. The experimentally proved fact of functional relation between the ξ and the \( E_{\text{max,mean}} \) means that the \( V_{\text{BD,mean}} \) can be directly estimated by using the calculated ξ and the analytical value (\( E_{\text{max,1kV}} \)) without any dielectric test. The calculated \( V_{\text{BD,mean}} \) by this procedure has high reliability because it is fundamentally based on experimental results.

5. CONCLUSION

In this paper, the dielectric characteristics of GN₂ with respect to temperature variation and the electrical insulation design criteria of GN₂ under AC voltage according to various conditions: gap length between electrodes, size of electrodes, and pressure are dealt in detail. As a result, it is concluded that the insulation design criterion for current leads of a superconducting apparatus should be determined by the experimental results at 300 K considering a safety factor. Furthermore, experiments on the dielectric characteristics of GN₂ according to various pressures should be conducted because this result is limited to the 1 bar pressure condition. Also, the empirical formulae for calculating the electrical breakdown voltage of GN₂ are established and it is found that the \( E_{\text{max,mean}} \) is represented as a function of the ξ. It is meaningful that the results are applicable to the design of current leads for a high voltage superconducting apparatus with a sub-cooled LN₂ cooling system. Also, the empirical formulae are valid not only to a particular model (such as a sphere-to-plane shaped structure) but also to every kind of model because the formulae are originally deduced from the conception of the ξ. Even the results are expected to be applicable to the design of conventional high voltage apparatuses such as the transformer, the motor, the switchgear, and so on.

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