Effects of Temperature and Pressure on the Breakdown Characteristics of Liquid Nitrogen

Seung-Myeong Baek*, Jong-Man Joung* and Sang-Hyun Kim*

Abstract - For practical electrical insulation design of high temperature superconducting (HTS) power apparatuses, knowledge of the dielectric behavior of both liquid nitrogen (LN_2) and subcooled liquid nitrogen (SLN_2) are essential. To achieve SLN_2 at atmospheric pressure, cryostat was designed and constructed. By pumping up the LN_2 in the outer dewar, the temperature of LN_2 in the inner dewar at atmospheric pressure can be controlled. The breakdown characteristics of LN_2 in quasi-uniform and non-uniform electrical fields for temperatures ranging from 77 K to 65 K at atmospheric pressure and pressure ranging from 0.1 to 0.5 MPa were investigated experimentally. The experimental data suggested that the breakdown voltage (BDV) of LN_2 is both highly temperature and pressure dependent. We also carried out statistical analysis of the experimental results using the Weibull distribution. The Weibull shape parameter *m* for the sphere-to-plane electrodes in SLN_2 was estimated to be 11 to 18.

Keywords: breakdown characteristics, subcooled liquid nitrogen, HTS, insulation design

1. Introduction

For many years, research and development of high temperature superconducting (HTS) technology has shown rapid progression in a variety of research areas. This is due to the fact that application of HTS technology to electric power apparatuses such as generators, power transformers, fault current limiters, energy storage and power transmission cables will give rise to enhanced efficiency and capacity of the power supply [1, 2]. Recently, research and development concerning application of the high temperature superconductor are actively moving ahead by the Applied Superconductivity Technology of the 21st Century Frontier R&D Program in Korea. Electrical insulation under cryogenic temperature is a key and an important element in the application of these apparatuses. Particularly, cryogenic liquid such as liquid nitrogen (LN_2) is used not only as a coolant but also as an electrical insulating material. However, LN_2 is susceptible to vaporization that could lead to breakdown in a lower electric field. A number of studies have been carried out in this area. In a recent paper by Gerhold [3], the properties of cryogenic electrical insulation materials are well summarized. Basic investigations of breakdown initiation in cryogenic liquids, including LN_2, are described by J. Gerhold [4]. Hayakawa et al. [5] developed relationships between area and volume effects on the breakdown mechanism of LN_2. The authors have been investigating the breakdown characteristics of LN_2 with bubble [6]. Here, the advantages offered by "subcooled cryogenic liquid" have been noted by several authors. Influence of liquid temperature and electrode size on the breakdown characteristics in superfluid helium have been reported by M. Hara et al. [7]. Experimental investigations of surface flashover in LN_2 with a temperature near 68 K have been noted by M. Butcher et al. [8]. More detailed description of the problems in previous studies is required. It is important to obtain the working characteristics over a wide temperature change from near 63 K to 77 K because we are going to use subcooled liquid nitrogen (SLN_2) to maintain the thermal and electrical stability of the HTS apparatus. The HTS transformer and the HTS fault current limiter that are supported by the Applied Superconductivity Technology of the 21st Century Frontier R&D Program in Korea were particularly designed to be operated in 65 K. Thus, we must investigate the breakdown characteristics of SLN_2 prior to the insulation design of these equipments.

In this paper, we present an improved cryostat for SLN_2 acquisition and an experimental investigation of the breakdown characteristics of LN_2 in the uniform and the non-uniform electrical field for pressure and temperature ranging from 0.1 MPa to 0.5 MPa and 77 K to 65 K at atmospheric pressure, respectively. And by using Weibull distribution functions, the results of the measurements are statistically analyzed.

2. Experimental Apparatus and Procedures

Fig. 1 shows a schematic illustration of the experimental setup used in the experiments. The experimental setup con-

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sists of LN_2 tank, vacuum pump, cryostat, measuring equipment and so on. To achieve SLN_2 we have manufactured a cryostat. The cryostat, composed of an inner dewar, outer dewar and vacuum dewar was used for measuring the breakdown characteristics of SLN_2. The cryostat is thermally insulated by using the vacuum insulation and super-insulation. The outer dewar is filled with liquid nitrogen, and its pressure can be decreased below atmospheric pressure in order to adjust the temperature between 65 K and 77 K. The outer dewar is operated by installing a rotary pump with an exhaust speed of 600 l/min. The temperature of LN_2 in the inner dewar is reduced by heat conduction, and the pressure of LN_2 in the inner dewar is atmospheric pressure due to the inner dewar and the outer dewar being separated from each other. The pressure of the inner dewar and the outer dewar is significantly different. The outer dewar with a dimension of ID=300 mm and length=1000 mm is made of stainless steel (SUS 304). However, in order to enlarge the heat transfer, the inner dewar with a dimension of ID=180 mm and length=80 mm is made by Al steel.

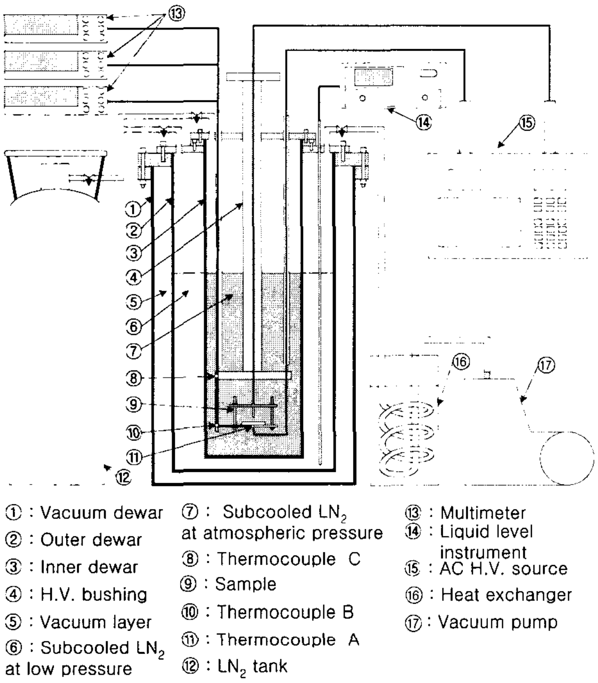

Fig. 1 Experimental setup.

The temperatures along the test section were measured with Chromel-CuFe (0.15%) (Lake Shore Co.) thermocouples calibrated by the saturation temperature of LN_2. The axial temperature distribution of the cryostat was measured with 3 sets of thermocouples on the electrode system in the inner dewar. Thermocouple B and C were 10 mm and thermocouple A was 80 mm away from the inside wall of the inner dewar. Thermocouples A and B were of the same level and thermocouple C was set above B with a distance of 100 mm. During the experiments at significant temperature, we observed temperature fluctuation. The LN_2 level in the inner dewar was monitored using a liquid level instrument (AMI model 185).

The electrode configuration is plane, sphere and needle. The plane electrode was 80 mm in diameter. A sphere electrode 8.8 mm in radius and a needle electrode 0.025 mm in tip radius were made of SUS (304). Measuring electrode geometries are constituted by needle-to-plane and sphere-to-plane electrodes. The electrode geometries used in these tests were immersed in the inner dewar. High voltage, up to 100 kV AC, is supplied by an AC power supply (BAUR, DTA E) with a voltage rise rate of 1 kV/sec. At least ten times, breakdown voltages were measured for the same test condition. The average, maximum and minimum breakdown voltages are illustrated as a point with a vertical bar in the Figures.

3. Experimental Results and Discussion

3.1 Characteristics of Cryostat

Fig. 2 shows the change of the temperature and the level of SLN_2 in the inner dewar at atmospheric pressure as a function of pumping time. The right side in Fig. 2 shows the level of LN_2 in the inner dewar. The temperatures of the electrode system were measured with three thermocouples attached onto the glass fiber reinforced plastic (GFRP) supporting the electrode, as indicated in Fig. 1. It is shown that the temperature of the LN_2 decreases with the increase of the pumping time. When the pumping time is decreased to 187 minutes, the temperature at the thermocouple C is decreased to 63 K. Of course, the cool-down time dependent on the cooling power available and the mass is involved in the increase in the temperature. In the experiment, when the temperature is decreased to 63 K, the level of LN_2 in the inner dewar is decreased from 459 mm to 446 mm.

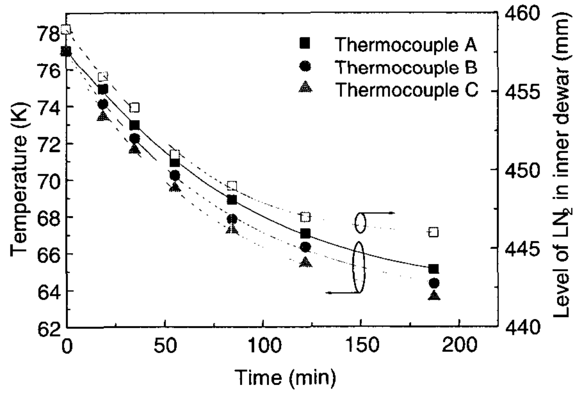

Fig. 2 Dependence of temperature and level of LN_2 in the inner dewar on pumping time at atmospheric pressure.

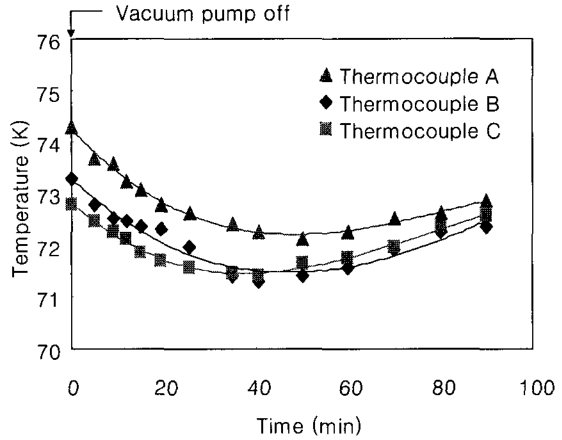

Fig. 3 The temperature gradient as a function of a time after vacuum pump operation is stopped.

Fig. 3 shows the temperature gradient as a function of a time after the operation of a vacuum pump is stopped. The pump was operated for 20 minutes. In this figure, the temperature at thermocouples A, B and C was decreased initially with the time. The temperature at thermocouples A and B was increased after 50 minutes and the temperature at thermocouple C was increased after 36 minutes. However, the temperature behavior of thermocouples B and C is nearly equal because thermocouples B and C are attached at the location that is of equal distance from the inside wall of the inner dewar.

3.2 Temperature and Pressure Dependence on Breakdown Characteristics

First, we measured the breakdown voltage of LN_2 as a function of electrode gap in the non-uniform field and the quasi-uniform field as shown in Fig. 4. The experimental results indicate that the breakdown voltage increased nonlinearly as the electrode gap increased. It is well known that the breakdown voltage of LN_2 is highly related to the electrode shape as well as to the electrode gap. The breakdown voltage of LN_2 in the quasi-uniform field is expressed as $V_B=28.113d^{0.695}$ kV, where d is the electrode gap in mm.

Fig. 5 shows the breakdown voltage of LN_2 at 77 K and subcooled LN_2 at 65 K as a function of electrode gap. A non-linear increase of the breakdown voltage versus electrode gap was observed. The breakdown voltage of LN_2 at 77 K is lower than that of SLN_2 at 65 K. This tendency is considered as follows. The permittivity ε of the bubble is smaller than that of the LN_2, and the electrical stress in the bubble would be greater than in the LN_2. Hence, there is the possibility that partial discharge takes place in the bubble. A life time of bubble rapidly decreases in conjunction with lowing temperature. Consequently, the breakdown voltage of SLN_2 increases. In all cases, the decrease in temperature down to 65 K produces a logarithmic increase in breakdown voltage.

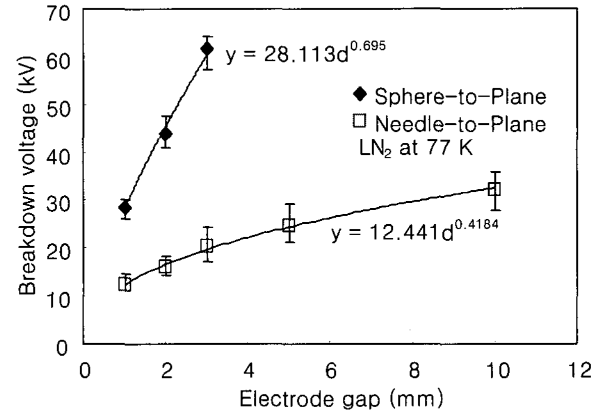

Fig. 4 Effect of electrode gap on breakdown voltage of LN_2 in the non- and the quasi- uniform field.

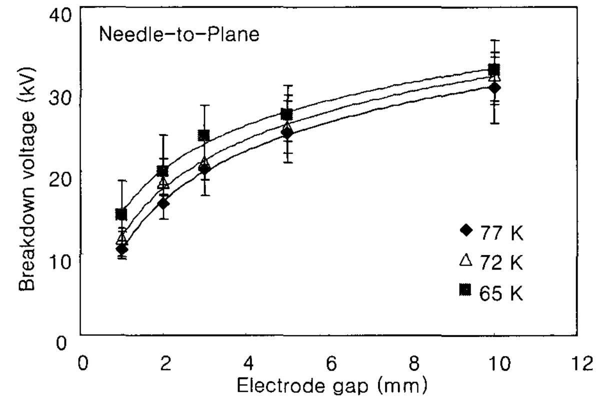

Fig. 5 Breakdown voltage of LN_2 and SLN_2 as a function of electrode gap in the non-uniform field.

The dependence of breakdown voltage on temperature is shown in Fig. 6. The ratio of BDV(65 K)/BDV(77 K) is approximately 1.5 for sphere-to-plane electrode geometry with d=0.5 mm and about 1.2 for needle-to-plane electrode geometry with d=3 mm, respectively. The rising rate of breakdown voltage for sphere-to-plane electrode geometry is higher than that for needle-to-plane electrode geometry because the radius of the sphere electrode is much larger than the tip radius of the needle electrode. It is reasonable that the needle electrode has a larger weak point than the sphere electrode so that breakdown voltage for needle-to-plane electrode is lower than that of the sphere electrode.

Fig. 7 shows the dependence of breakdown voltage on pressure in needle-to-plane geometry for the various electrode gaps. As shown in Fig. 7, breakdown voltage slightly increased with pressure at each gap length. In the case of electrode gap with d=1 mm at 0.5 MPa, breakdown voltage reached 17 kV, which corresponds to about 1.35 times that at 0.1 MPa.

Fig. 8 indicates the dependence of breakdown voltage on pressure in sphere-to-plane geometry for the different electrode gaps. As shown in Fig. 8, the breakdown voltage became saturated while increasing linearly. In the case of the electrode gap with d=1 mm at 0.5 MPa, the breakdown voltage reached 55 kV, which corresponds to about 2.06 times that at 0.1 MPa.

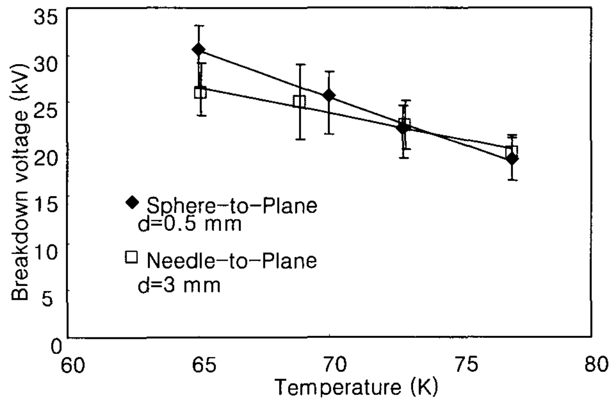

Fig. 6 Effect of temperature on breakdown voltage of SLN_2 at atmospheric pressure in the non- and the quasi-uniform field.

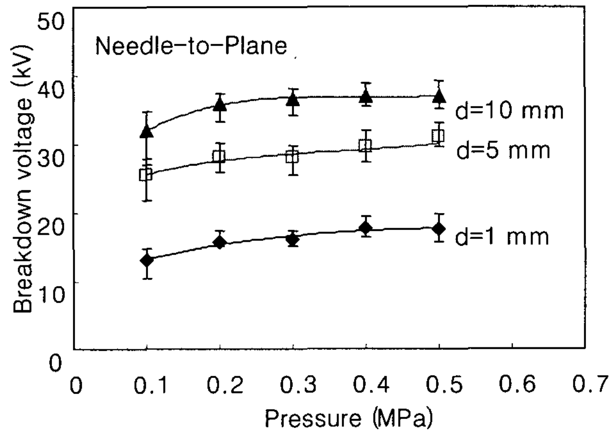

Fig. 7 Breakdown voltage dependence of pressure in the non-uniform field.

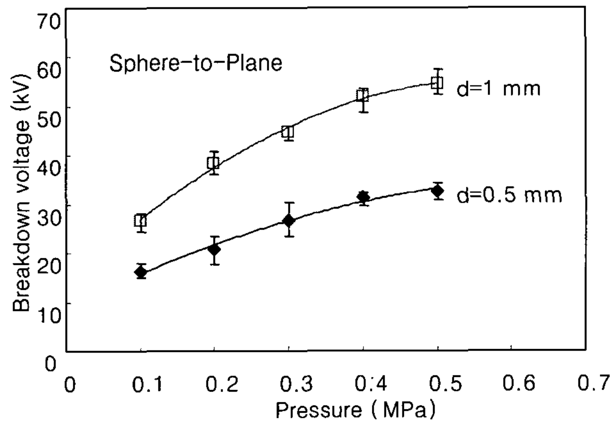

Fig. 8 Pressure dependence of breakdown voltage in the quasi-uniform field.

As the pressure of the LN_2 increases, Fig. 7 and Fig. 8 show that breakdown voltage also increases. Because the bubble volume decreases with increasing pressure, the breakdown voltage increases with increasing pressure.

Fig. 9 indicates the increase rate of both BDV(65 K)/BDV(77 K) and BDV(0.1 MPa)/BDV(0.5 MPa) of the breakdown voltage as a function of electrode gaps in the needle-to-plane geometry. Both BDV(65 K)/BDV(77 K) and BDV(0.1 MPa)/BDV(0.5 MPa) are calculated from Fig. 6 and Fig. 7. In the case of d=1 mm, the rate of BDV(65 K)/BDV(77 K) and BDV(0.1 MPa)/BDV(0.5 MPa) breakdown voltage increases up to 1.4 times and 1.36 times respectively. However, in the case of d=10 mm, the rate of BDV(65 K)/BDV(77 K) and BDV(0.1 MPa)/BDV(0.5 MPa) of breakdown voltage increases up to 1.07 times and 1.19 times, respectively. This may be brought about by the difference in volume ratio of vapor bubbles to the electrode gap. In the case of the smaller gap length, the vapour bubbles that are the weak point of the breakdown occupy a large part of the gap length. By decreasing the temperature and increasing the pressure of LN_2, the volume ratio of vapor bubbles is rapidly reduced. Thus, the breakdown voltage in the pressurized condition of SLN_2 largely increases compared with LN_2 at 77 K under the non-pressurized condition.

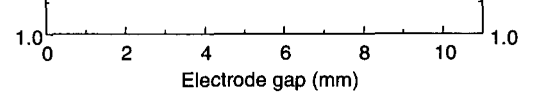

Fig. 9 Increase rate of breakdown voltage as a function of electrode gaps.

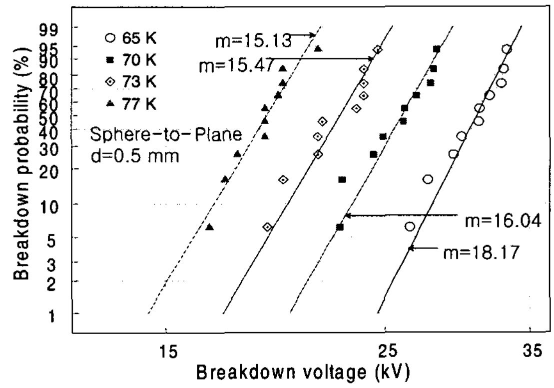

Fig. 10 Weibull plots of breakdown voltage.

Fig. 10 illustrates the results with the breakdown voltage characteristics for SLN_2 under sphere-to-plane electrode with d=0.5 mm. The breakdown probability p in the Weibull distribution for the electric field strength E is given by:

$$p = 1 - \exp\left[-\left(\frac{E}{E_l}\right)^m\right] \quad (1)$$

where m is the shape parameter, and E_l is the scale parameter.

The value of the shape parameter m for SLN_2 at 65 K is higher than that for LN_2 at 77 K, and the values are m=15.13 and m=18.17, respectively. This result signifies that breakdown voltage increases due to the decrease in vapor bubbles as the liquid temperature declines.

4. Conclusions

A cryostat for SLN_2 at atmospheric pressure was developed to investigate the breakdown characteristics of SLN_2. The breakdown voltages of LN_2 in the two-type electrode geometries were measured when the temperature changes from 77 K to approximately 65 K. The following conclusions are obtained:

As the temperature was reduced, the breakdown voltage was gradually increased. By subcooling the LN_2 by about 72 K, the average breakdown voltage with d=1 mm was increased to about 12%. When the LN_2 was subcooled to about 65 K, the average breakdown voltage with d=1 mm was increased to about 41%. In the case of a smaller gap length, the temperature was worked as a potent influence. The breakdown voltage for the sphere electrode of which the weak point is smaller than the needle electrode was increased as the temperature was reduced. As the pressure was increased, the breakdown voltage was gradually increased. In the case of d=1 mm, the increase rate BDV(0.1 MPa)/BDV(0.5 MPa) of breakdown voltage went up 1.35 times. In this research, the breakdown characteristics of LN_2 with both increasing pressure and decreasing temperature were clarified.

Acknowledgements

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