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Breakdown Properties of Coolant for HTS Apparatus Operating at Cryogenic Temperature

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Abstract-- **For the dielectric insulation design of any high temperature superconducting (HTS) apparatus in the electrical power systems, the breakdown properties of cryogenic coolants such as LN_2 are an important factor of the insulating engineering. Therefore, this paper presented an experimental investigation of breakdown phenomena in LN2 under AC voltage. And we studied the breakdown properties of LN2 with decreasing temperature. Also, the Weibull plots of the breakdown voltage of subcooled LN_2 at 65 K for the needle-plane electrode with electrode distance *d*= 10 mm are studied. The dependence of breakdown voltage for needle–plane and pancake coil-pancake coil electrode on temperature is illustrated. The experimental data suggested that the breakdown voltage of LN_2 depend strongly on the temperature of LN_2. The breakdown characteristics of LN_2 under quasi-uniform and non-uniform electrical field for temperature ranging from 77 K to 65 K were clarified.**

1. INTRODUCTION

Since the discovery of HTS materials in 1986, a considerable number of studies have been made on the application of the materials to extensive areas of research. Many reports related to HTS materials in the fields of electrical energy generation, conservation, transmission have also appeared [1]. HTS power apparatuses are expected to be highly efficient for high density and large capacity power transmission systems [2]. In the dielectric insulation design of any HTS apparatus in the electrical power systems, the breakdown property of cryogenic coolants such as LN_2 is an important factor of the insulating engineering. Basic and applied studies on the insulation performance of LN_2 have been promoted eagerly up to now in the world [3-6]. Particularly, LN_2 is used at their normal boiling temperature. This involves phase change and bubble generation much easier than in room temperature liquids. Previous reports concerned with the breakdown properties of LN_2 have pointed out that bubbles and gaseous nitrogen have a treat influence on their breakdown phenomena. Also, researchers are studying method to remove bubble by increasing pressure or decreasing temperature such as subcooled LN_2 [7,8]. However, useful data for practical insulation design of HTS apparatus operated at subcooled LN_2 have not been obtained enough.

From the above viewpoints, we investigated electrical breakdown properties of LN_2 under non-uniform and quasi-uniform electric field. The influence of temperature on breakdown voltage was discussed with different electrodes. And we investigated breakdown characteristics of subcooled LN_2 under non-uniform electric field.

2. EXPERIMENTAL SET UP

The schematic diagram of experimental setup is shown in Fig. 1. The cryostat of a double layered structure was used for LN_2 and subcooled LN_2. The tests at 77K were conducted in the dewar with LN_2, and the testes at 65 K were conducted in the same dewar with subcooled LN_2 at atmospheric pressure. The temperature can be controlled over a significant range by the pumping on the LN_2 cryostat. We put gaseous He to make the 1 atmospheric pressure in the cryostat. A copper-constant thermocouple located on the test section was used for measuring temperature. The voltage across the wires of thermocouple was measured by the voltmeter (KEITHLEY 2002 MULTIMETER). We experimentalized all in situation that is controlled to temperature change 0.5 K.

TABLE I Electrodes for breakdown measurement.

Unit : mm

Shape	Sphere	Needle	Pancake coil
Radious	8.8	0.025	0.24
Material	Stainless steel		Ag sheathed Bi-22 23 tape
Electrode distance	1, 2	1~15	1~5

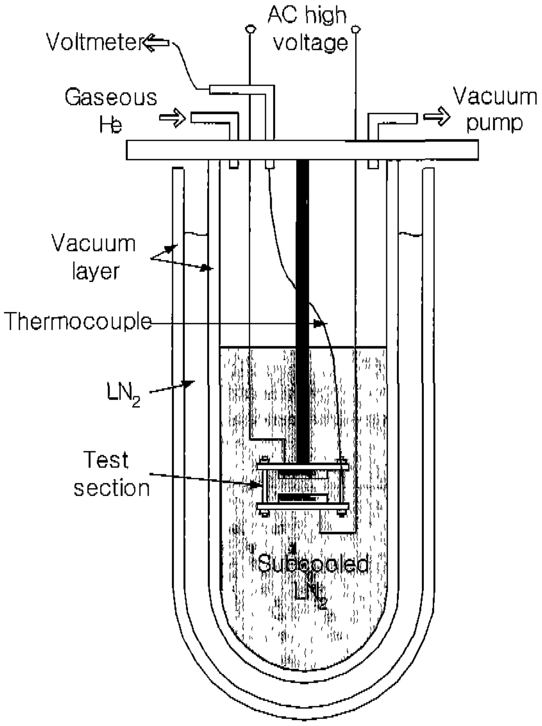

Fig. 2. Fig. 1. Schematic diagram of experimental setup for producing subcooled LN_2 at 65 K.

Three types of electrodes in shape and size were used for measurement of breakdown voltage of LN_2. The dimensions of electrodes for breakdown measurement are shown in Table 1. Needle, sphere and plane electrodes were made of stainless steel (SUS 304). The plane electrodes were 80 mm in diameter and 10 mm in thickness. The surface was carefully polished (roughness < 0.1 μm). The sphere electrodes were in 17.5 mm diameter. The needle electrodes were 25μ m in tip radius. To investigate the basic insulation characteristics of LN_2, a plane-cylindrical needle electrode model was used. The pancake coil electrodes were made by Ag sheathed Bi-2223 tape in width 3mm and thickness 0.25 mm and insulated by a Kapton film between the turns. This electrode is to simulate the type of HTS pancake coil. An electrode system was installed in the inner dewar. All tests were conducted with AC high voltage supply (60 Hz, 100 kV). The applied voltage was raised in all experiments uniformly at a rate of 1kV/s until breakdown. Breakdown voltages were measured under the same experimental conditions at least ten times. The average breakdown voltage and the corresponding maximum and minimum values are illustrated with vertical bars in the figures.

3. RESULTS AND DISCUSSION

The dielectric performance of LN_2 is the key point for application of HTS power equipment. Breakdown voltages of LN_2 are determined depending on voltage waveform, electrode geometry, polarity, impurity, bubble, etc. First, we measured the breakdown voltage of LN_2 as a function of electrode distance under non-uniform field and quasi-uniform field. Fig. 2 shows breakdown voltage of LN_2 as a function of electrode distance d under non-uniform and quasi-uniform field conditions. The experimental results show that breakdown voltage increased non-linearly as the d increased. And breakdown voltage of LN_2 is highly relativive to electrode distance as well as electrode shape. The relation between the breakdown voltage and the *d* can be expressed by the following equation.

$$V_B = kd^m \qquad (1)$$

where, V_B is breakdown voltage. k and m are constants. Breakdown voltage of LN_2 under quasi-uniform field is expressed as $V_B=27.8d^{0.642}$, where d is the electrode distance in mm.

A pressure-temperature curve for LN_2 is shown in Fig. 3. The temperature range from slightly above 77 K down to approximately 65 K is easily available by pumping on the cryostat. The right side of Fig. 3 shows the almost linear increase of voltage of a thermocouple over the same temperature range. The voltage of the thermocouple was measured during pumping. Even if pressure changes rapidly, temperature did not change sharply according to pressure. Thermocouple on the test section is necessary since it is quite easy to establish gradients in the cryostat during pumping.

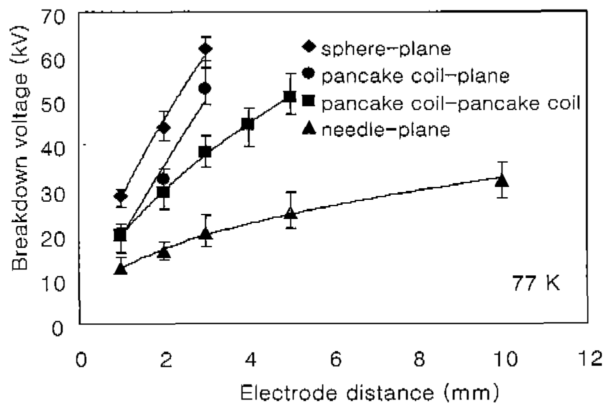

Fig.2. Breakdown voltage of LN_2 as a function of electrode distance under varying field conditions.

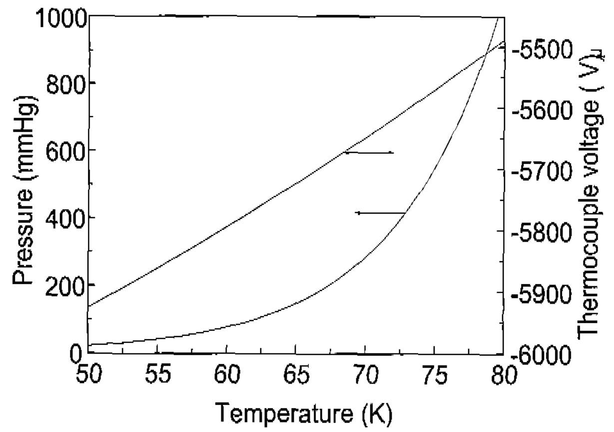

Fig. 3. Pressure-temperature curve for LN_2

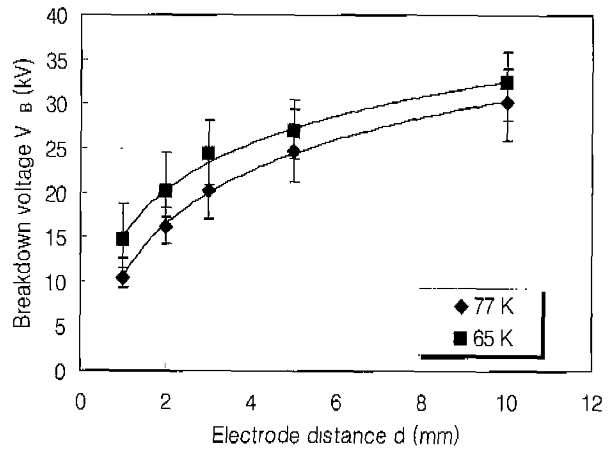

Fig. 4. Breakdown voltage of LN_2 at 77 K and subcooled LN_2 at 65K as a function of electrode distance.

Fig. 4 shows the breakdown voltage of LN_2 at 77 K and subcooled LN_2 at 65 K for needle-plane electrode as a function of electrode distance. A non-linear increase of the breakdown voltage versus spacing d was observed. The breakdown voltage of LN_2 at 77 K is lower than that of subcooled LN_2 at 65 K. The case of the d=1 mm and d=10 mm, breakdown voltage of the subcooled LN_2 at 65 K increased about 42.7 % and 7.8 % compared with breakdown voltage of the LN_2 at 77 K. This tendency is considered as follows. The permittivity ε of 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 bubble life time is reduced if the temperature goes down. Consequently the breakdown voltage increases if the temperature goes down.

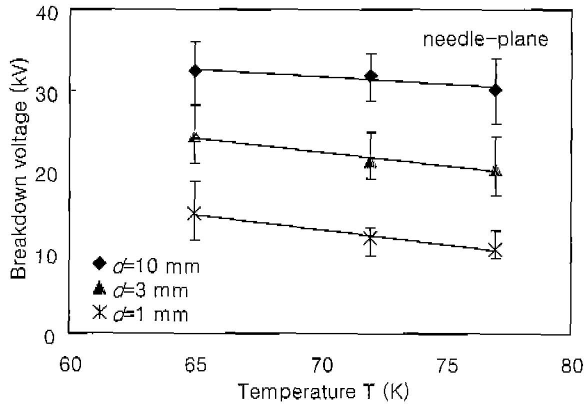

Fig. 5. The temperature dependence of breakdown voltage.

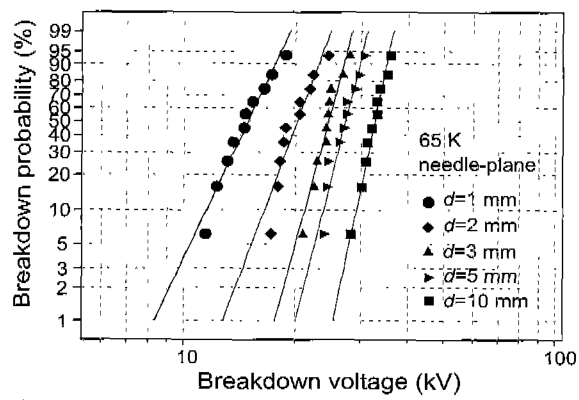

Fig. 6. Weibull plots of the breakdown voltage of LN_2 at 65 K.

TABLE II Weibull shape parameter and scale parameter

shape	Needle-plane			
source	d (mm)	Temperature (K)	E_l (kV/mm)	m
AC	1	77	10.98	9.31
		72	14.55	12.19
		65	15.67	7.27
	2	77	8.37	13.27
		72	9.88	12.00
		65	10.52	9.21
	3	77	7.11	9.82
		72	7.34	11.45
		65	8.41	12.79
	5	77	5.17	10.13
		72	5.25	15.94
		65	5.59	13.84
	10	77	3.13	13.22
		72	3.26	20.22
		65	3.34	16.51

Fig. 5 shows the effect of temperature on the breakdown voltage of LN_2 with different electrode distance at 77 K, 72K and 65K. In order to examine the temperature effects, we measured breakdown voltage under needle-plane electrode. The case of the d=3 mm, the average breakdown voltages are 20.3, 21.9 and 24.3 at 77, 72 and 65 K respectively. According as temperature goes down, breakdown voltage increases gradually.

Fig. 6 shows the Weibull plots of the breakdown voltage of subcooled LN_2 at 65 K for the needle-plane electrode with d= 10 mm. The breakdown probability of the Weibull distribution for the electric field strength E is given by

$$p = 1 - \exp[-(\frac{E}{E_l})^m] \qquad (2)$$

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

Table 2 lists Weibull shape parameter m and scale parameter E_l estimated from the slope of Weibull plots for each electrode distance in Fig. 6. This table shows that the scale parameter El for the needle-plane increased according as temperature is decreased. For example, the case of the d=1 mm, E_l increased from 10.98 to 15.67 kV/mm according as the temperature decreased from 77 to 65 K. And, the case of the d=10 mm, E_l increased from 3.13 to 3.34 kV/mm according as the temperature is decreased from 77 to 65 K. This result means that subcooling LN_2 decreases the number of vapor bubble in the LN_2, and thereby increases breakdown voltage. Shape parameter m displayed other tendency according to each distance.

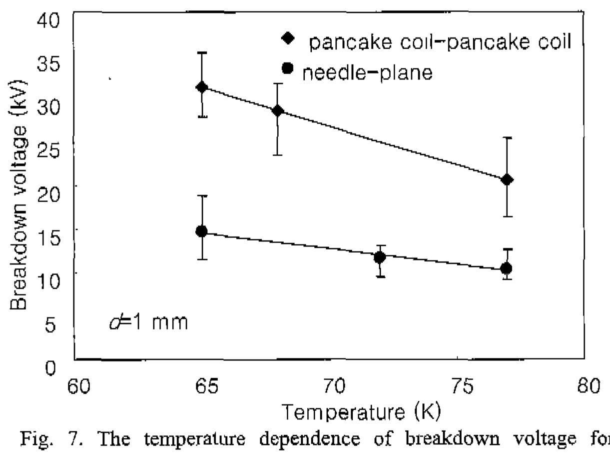

Fig. 7. The temperature dependence of breakdown voltage for different electrode systems.

The dependence of breakdown voltage on temperature is illustrated in Fig. 7 for needle–plane and pancake coil-pancake coil electrode with d=1 mm. The rising rate of breakdown voltage for pancake coil-pancake coil electrode is higher than that for needle-plane electrode. Because the tip radius of the Ag sheathed Bi-2223 tape is about 10 times as large as tip radius of needle. Thus, it is reasonable that needle electrode has lager weak point than pancake coil electrode so that breakdown voltage for needle–plane electrode is lower than that of pancake coil-pancake coil electrode.

4. Conclusion

The breakdown voltages of LN_2 under different electrode system were measured at various temperatures. An experimental temperature range is chosen in the range from above 77 K down to approximately 65 K that LN_2 does not freeze. The experimental results are as follows.

The breakdown voltage of LN_2 increases with increasing d. The breakdown voltage under quasi-uniform field is expressed as V_B=27.8$d^{0.642}$. The breakdown voltage of LN_2 at 77 K is lower than that of subcooled LN_2 at 65 K. According as temperature goes down, breakdown voltage increases gradually. The case of the d=10 mm, breakdown voltage of the subcooled LN_2 at 65K increased about 7.8 % compared with breakdown voltage of the LN_2 at 77 K. The E_l increases according as the temperature goes down. Breakdown voltage for the pancake coil electrode of which the weak point is smaller than the needle electrode increased according as the temperature decreased. In this research, the relationship between the subcooled LN_2 at 65 K and the AC breakdown properties was clarified.

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