Breakdown voltages of cryogenic gaseous helium and in liquid helium

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Abstract. As practical applications of superconductivity have been made in electric power engineering, the breakdown voltage superconductor coolants, such as liquid helium or supercritical helium, have been needed intensively. Furthermore, in our discharge experiment in liquid helium to search for a novel carbon nanotube structure, it was predicted that the breakdown voltage was much higher. So, using the metal spherical electrodes, d.c. breakdown voltages in 4.2K gaseous helium (just above the liquid helium) and in liquid helium have been measured. As a result of the experiment, it was observed that the value is several times larger. Moreover, it was found that there was no difference in the discharge phenomenon before and after the superfluid transition temperature.

1. Introduction

Recent discoveries of ceramics with higher superconducting transition temperatures may make it possible to use liquid helium or liquid nitrogen as the feasible coolant of high current superconducting apparatus. In practical superconducting apparatus, the coolant often also serves as the electrical insulator of the conductor. Therefore, it is important to clarify the electrical breakdown characteristics. For example, the current leads of high-temperature superconducting apparatus immersed in liquid helium may be exposed to gaseous helium. Several works have been reported on this subject. With uniform electric field distribution, the validity of Paschen’s law at low temperatures has been the most interesting and important point.

In addition, we have an experiment to research of the production of carbon nanomaterials using arc discharge in low temperature liquid, such as liquid helium. In this experiment, it was observed many times that no discharge occurred at the breakdown voltage determined by Hara et al. Incidentally, their experimental condition (A sphere-to-sphere electrode system was used, both spheres were 25 mm diameter and made of stainless steel.) and our experimental condition are almost the same.
In the present work, the breakdown voltage of uniform field in 4.2K gaseous helium and in liquid helium are measured and Paschen constants are discussed. Moreover, the breakdown voltages depend on the temperature is discussed.

### 2. Experiment set-up

In our present experiment, original instruments are designed and produced. Fig. 1 shows our experimental instruments. This instrument is vacuum-jacketed structure, and has an evaporation cryostat, which consists of liquid nitrogen dewar and liquid helium dewar in order to prevent evaporation of liquid. So as to remove experimental cells easily, quick coupling method is utilized for the instrument’s top plate. Because most of arc energy is absorbed by the liquid and it causes extraordinary evaporation, the instrument has a leak valve of 10 lit./sec as a solution. Now, the distance between the electrodes is measured with a micrometer (an accuracy of 10 microns) attached to the top of the cryostat. Fig. 2 shows the outline of our experimental system. The metal spherical electrode is set in low temperature area and it is high charged by an outside electric source (Kikusui PWR1600L). In addition, a 500MHz digital oscilloscope (IWATSU DS-5654A) is used so that the current and voltage during discharge can be measured.

An experimental cell is shown in Fig. 3. The upper electrode is made to move up and down. Two electrodes, which are purchased from Nilaco Coro., Japan: 99.9% purity, 10mm diameter brass are perpendicularly placed in or over liquid helium.

In liquid helium experiment, the experiment was performed with two electrodes immersed in liquid helium, as shown in Fig. 3(a). On the other hand, in 4.2K gaseous helium experiment, with the lower electrode dipped in liquid helium, an experiment was performed at a distance of 2 to 5 mm from the helium liquid level, as shown in Fig. 3(b). The liquid level was confirmed visually and by liquid level gage.

For the calibration of the distance between these electrodes, after the thermal contraction of the device settled down, the electrodes were short-circuited, and that point was set to ZERO. This zero calibration was performed before and after a series of measurements, and the error was about 0.001 mm.
3. Experimental Results and Discussion

3.1. In 4.2K gaseous helium

Figure 4 shows of d.c. breakdown voltage versus $\rho g$ measured with gaseous helium, where $\rho$ is gas density in kg m$^{-3}$ and $g$ is gap length in mm. In this experiment, since the experiment is performed several millimeters above the liquid, $\rho$ is 16.9 kg m$^{-3}$, which is the density of a 4.2 K gas. The dashed line is in accordance with Paschen's low in the following equation.

$$V_B = A(\rho g)^B$$

Where $V_B$ is the breakdown voltage. A and B are experimentally determined constants. Almost all measured values of $V_B$, including the present authors’, fall on a line when $A=120 \sim 270$ and $B= -0.02 \sim -0.24$ in the region $0.01 < \rho g < 1$. The constant values from our experimental results are $A=138$ and $B=0.01$. From these facts, it can be seen that our measurement has correctly measured the breakdown voltage.

![Figure 4 Pachen plots in 4.2K gaseous helium](image)

3.2. In liquid helium

Figure 5 shows of d.c. breakdown voltage versus gap length measured in liquid helium. The breakdown voltages and breakdown characteristics in liquid helium have been investigated by many authors$^{1-6}$. Thereby, it is known that the dielectric breakdown voltage in the uniform electric field given by

$$V_B = Cg^{1-D}$$

where C and D are experimentally determined constants. Hara et al. determined $C=21.5$ and $D=0.20$ by their experiment. However, as a result of fitting with our experimental data, these constants are $C = 38.0$ and $D = 0.20$. In particular, the value of C is 1.8 times larger than the Hara et al.’s value.

Although the details of this cause and the sharp peak at 0.2 mm gap are not well understood, it is thought that it can be measured in a more experimentally stable state. The reason is that if it is caused by bubbles or electrode edges, the discharge voltage will drop.
3.3. Temperature dependence

Figure 6 shows that temperature dependence of the breakdown voltage. It is observed below the gap length of 0.160mm, 0.400mm and 0.550mm. Breakdown voltage ($V_B$) increases gradually with temperature. These gradients seem almost same. Fortunately, 0.55mm gap could be measured to the $\lambda$ point.

Fig. 7 shows plots of opening and closing discharge current and voltage in liquid helium as a function of time. Maximum discharge voltages (10 V) and the mean discharge currents are very small, about 0.5–1 A in the experiments. Thus, discharge current can be determined by the impedance of the electric circuit. As the results, all of the discharges are very similar independent for liquid. For these reasons, it seems to be no $V_B$ discontinuity at $\lambda$ point.

4. Conclusions

D.c. breakdown voltages in 4.2K gaseous helium and in liquid helium using the spherical electrodes have been measured. The results of our experiments are summarized as follows.

- Breakdown voltages in liquid helium were measured dependence of gap length. The constant was decided to fit our experimental results, and constant value ($V_B=38.0g^{0.8}$) was 1.8 times higher than constant value of Hara et al.
• Measured values of breakdown voltage fall on Paschen’s law, and the deviation is a few kV at the most.
• Breakdown voltage increases gradually with temperature. It seems to be no $V_B$ discontinuity at $\lambda$ transition temperature

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