

Discharge mechanisms in liquid nitrogen with thermally induced gas bubbles

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Abstract. Discharge voltages of a sphere-plane electrode arrangement in subcooled liquid nitrogen stressed with impulse voltages were investigated. Tests were performed with and without thermally generated bubbles between the electrodes. Polarity effects could be observed at higher gaps and lower utilization factors. These effects are explained by the occurrence of positive and negative streamers, which have different propagation mechanisms. The measured discharge voltage with thermally generated bubbles is compared to calculated values using Paschen's law.

1. Introduction

Liquid nitrogen (LN_2) is often used as coolant and electrical insulation of superconducting fault current limiters (SFCL) [1]. During the current limitation phase of a resistive SFCL heat is transferred into the LN_2 . This heat input can produce bubbles, which weaken the electrical insulation. In pure insulation liquids it is assumed that the discharge starts due to emission currents from the electrodes [1-2]. With thermally induced bubbles the initiation process of the discharge changes due to the lower dielectric strength of the gas. In [3] the discharge in LN_2 with thermally induced bubbles was investigated in a homogeneous field. At higher pressures and gap distances a polarity effect was observed due to the bubble on the electrode. In this paper the influence of bubbles in the inhomogeneous field on the discharge voltage is analysed.

2. Experimental setup

The measurements were performed with a sphere-plane electrode arrangement, immersed in LN_2 at 78.5 K and 5 bar_{abs}. The setup can be seen in figure 1. The electrodes are made of stainless steel. The sphere (a) has a diameter of 12 mm and the plane (b) of 100 mm. The bobbin of the resistive heater (c) is within the lower part of the sphere electrode and thermally connected to the sphere via a copper rod (d). The heater was supplied with a constant voltage of 11.2 V and a current of 3.6 A. The gap distance can be adjusted by moving the sphere electrode arrangement via a steel cable. The insulation was tested with 1.2/50 lightning impulses using the up and down method. A precise description of this method is given in [3].

The shape of the gas bubbles is dependent on the gap as can be seen in figure 2. Until a gap of 2 mm the bubbles coalesce and reach from the top of the sphere electrode to the surface of the plane electrode (figure 2, 2 mm). At higher gaps discrete bubbles are formed between the electrodes. These bubbles have a diameter of approximately 0.5 mm and are located at the top of the sphere electrode (figure 2, 7.5 mm).



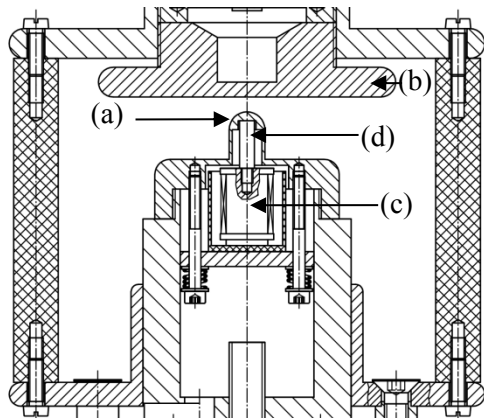


Figure 1. Sphere-plane electrode setup with heater bobbin in the lower electrode.

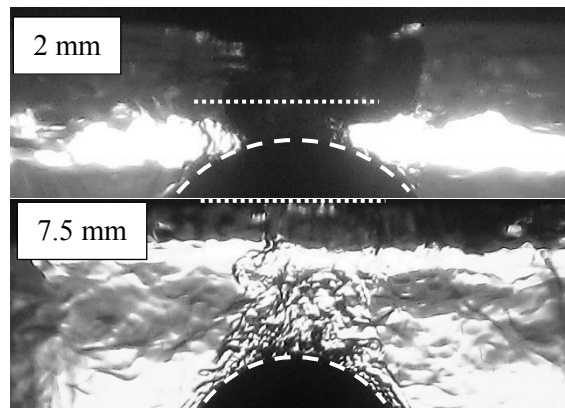


Figure 2. Bubbles at different gaps. Dotted line surface of plane electrode above the sphere, dashed line surface of sphere electrode

3. Results and discussion

The measured discharge voltages without bubbles can be seen in figure 3. If the discharge is triggered by emission currents from the cathode, then the discharge voltage should yield a constant field strength at the sphere surface for different gaps. Up to 3 mm gap, the discharge voltage can be calculated by assuming a constant maximum field at the sphere tip of 82.5 kV/mm and is in good agreement with the measurements (figure 3, dot-and-dash line). But above 3 mm gap the measured values differ from the calculated ones. Additionally the graphs show a polarity dependent change in the discharge voltage, which could be explained by the appearance of positive streamers for the positive sphere and negative streamers for the negative sphere [2]. Positive streamers are faster than negative streamers and can bridge large gaps easier [1]. Therefore the formation of a breakdown at large gaps is more difficult for negative streamers yielding higher discharge voltages [1-2]. It was observed that the negative streamer needs a constant mean field for propagation [4, 5]. For the measured values in figure 3 it is in the range of 50 kV/mm (figure 3, dashed line).

The results of the lightning surge measurements with thermally generated bubbles at an ambient pressure of 5 bar_{abs} can be seen in figure 4. Due to the gas phase, the discharge voltage of these bubbles can be calculated with Paschen's law (1) [3, 6].

$$U_d = \frac{B \cdot p \cdot g}{\ln((A \cdot p \cdot g)/k)} \cdot \eta \quad (1)$$

with p for the ambient pressure, g for the gap, the constant k and the constants for nitrogen gas $A = 510 \text{ bar}^{-1} \text{ mm}^{-1}$ and $B = 19.65 \text{ kV bar}^{-1} \text{ mm}^{-1}$ for $E/p = 2 - 8.48 \text{ kV bar}^{-1} \text{ mm}^{-1}$ and 293 K [3]. In (1) the influence of the temperature on the discharge field strength is not considered. But the density of the gas increases with decreasing temperature. To take the higher density at lower temperatures into account an equivalent pressure is used in (1). This equivalent pressure represents a gas pressure at 293 K with the same gas density as the gas in the bubble at cryogenic temperature and ambient pressure [7]. As a first assumption, the temperature inside the gas bubble is equal to the boiling temperature at ambient pressure. With this temperature for 5 bar_{abs} ambient pressure an equivalent pressure of 17.9 bar_{abs} can be determined [8]. Due to the creation of bubbles at the tip of the sphere, it is assumed that the discharges will start at this point. Therefore the electric field inhomogeneity is taken into account via multiplication with the utilization factor η .

With equation (1) the breakdown voltage can be calculated up to a gap of 2 mm (figure 4, solid line). In this area the breakdown will take place completely in the gas phase. The solid line until 2 mm in

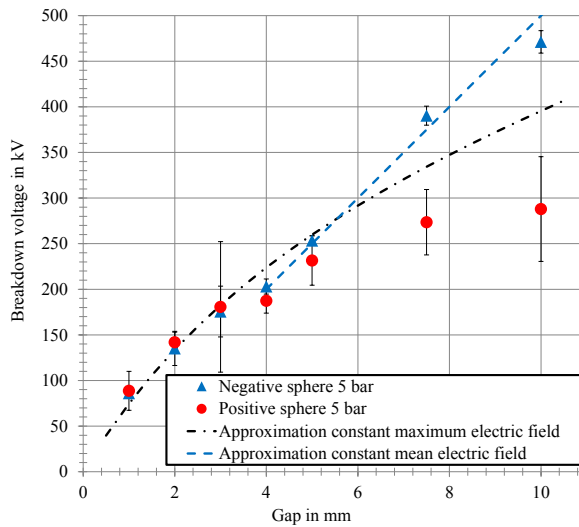
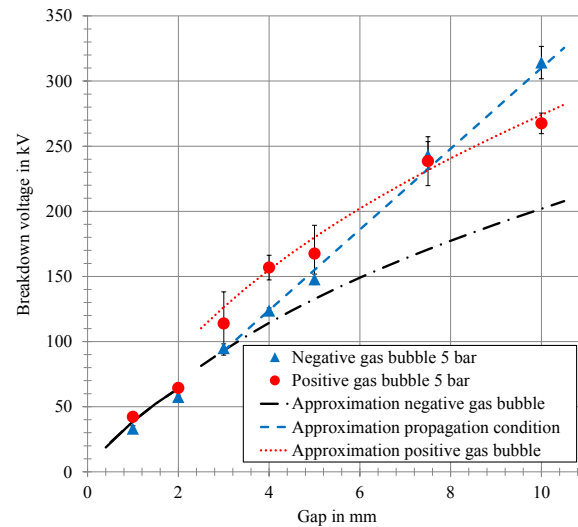
**Figure 3.** Discharge voltages without bubbles.**Figure 4.** Discharge voltages with bubbles.

figure 4 represents the calculated discharge values. The calculations and measurements show a good agreement. Above a gap of 2 mm discrete gas bubbles are formed and the discharge cannot take place in a complete gas phase anymore. But the gas bubble still represents the weak point of the insulation system. It is assumed, that the complete breakdown occurs, if the discharge in the bubble takes place. The discharge field strength is calculated with Paschen's law again. In contrast to equation (1) the first term of equation (2) calculates the breakdown field strength within a gas bubble with the diameter d_b (0.5 mm). Due to different permittivity of liquid and gas, the field enhancement in the bubble has to be taken into account [3]. The field enhancement in a dielectric sphere located in a homogeneous field can be included with the third term in equation (2).

$$U_d = \frac{B \cdot p}{\ln((A \cdot p \cdot d_b)/k)} \cdot \eta \cdot \frac{3 \cdot \epsilon_{rF}}{\epsilon_{rG} + 2 \cdot \epsilon_{rF}} \cdot g \quad (2)$$

The second term still represents the inhomogeneity. The multiplication of the first three terms yields the mean electric field strength of the arrangement, if the breakdown field strength in the bubble is calculated with Paschen's law. Therefore multiplication with the gap g leads to the discharge voltage across the electrodes. With equation (2) and the Townsend criterion ($k=2.5$) the dot-and-dash line in figure 4 can be calculated. It is obvious that the measured values do not fit to this calculation.

The discharge voltages for the positive gas bubble on the sphere show a similar tendency as the calculations, but the values are higher. An explanation for this phenomenon could be the required propagation condition for the positive streamer together with the discharge conditions in the bubble on the electrode. If an initiation electron is present in the gas bubble, it will be accelerated towards the anode (figure 5, I). On its way to the anode it will ionize gas molecules. The created ions move to the cathode. At the gas liquid interface the ions can pass into the liquid, but due to their low mobility in the liquid [9] they will accumulate at the interface and reduce the electric field in the bubble but enhance it in the liquid. Additionally the liquid phase on the cathode will hinder the creation of secondary electrons. It is assumed, that the positive streamer propagates through the liquid due to ionization processes in the liquid phase [2]. If the field strength in the liquid is too low for propagation of a positive streamer no breakdown will occur. For the formation of a discharge the charge at the liquid gas interface, produced by an initiation electron, has to be high enough to enable ionization processes in the liquid (figure 5, II). As first hypothesis this situation is considered by applying the streamer criterion ($k=18$) in equation (2). These calculated values are represented in figure 4 by the dotted line and are in good agreement with the measured values.

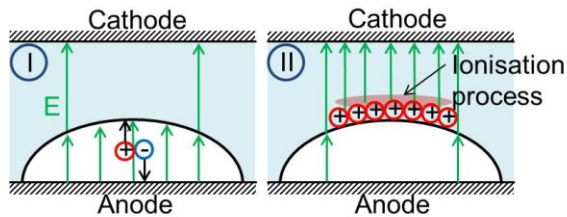


Figure 5. Discharge mechanism in positive bubble

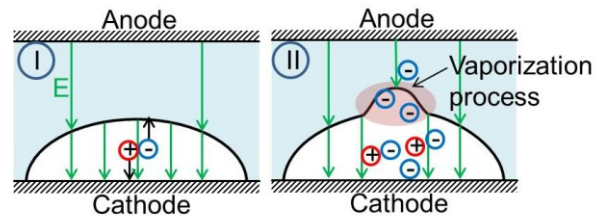


Figure 6. Discharge mechanism in negative bubble

The discharge in the bubble on the negative sphere can still occur after the Townsend mechanism, because secondary electrons can be produced on the surface of the cathode due to its location in the gas phase (figure 6, I). But the measured discharge voltages for the negative gas bubble are also higher than the calculated ones with equation (2) and show a linear dependence of the gap. This effect is similar to the previously investigated propagation condition for negative streamers in LN_2 without gas bubbles (figure 3). The mean field strength, required for propagation of the streamer through the liquid phase, in the measurements with thermal bubbles, is around 31 kV/mm. The propagation of the negative streamer is due to vaporization of the liquid and discharges in the gas phase [1, 2]. In contrast to the ions the electrons have a higher mobility in the liquid. Therefore they will not accumulate at the interface but move through the liquid and will heat it up during their path to the anode (figure 6, II). In the generated gas voids new discharges can occur.

4. Conclusion

In this paper the discharge voltages of a sphere-plane electrode arrangement with and without thermally generated bubbles are investigated. It is shown, that without bubbles, the discharge voltage for small gaps depends on the maximum electric field at the sphere electrode. At higher gaps the field inhomogeneity increases and only streamers with the same polarity as the sphere occur. This yields a polarity effect. Positive streamers have lower discharge voltages than negative ones. The discharge voltage of negative streamers increases linearly with gap due to its propagation condition.

With gas bubbles between the electrodes, the discharge voltage for small gaps can be calculated with Paschen's law considering the Townsend criterion. But at higher gaps polarity effects arise due to different propagation conditions for the positive and negative streamers. For gas bubbles on the positive sphere, the discharge voltage can still be calculated with Paschen's law if the streamer criterion is used. For bubbles on the negative sphere again a linear dependence of the discharge voltage on gap was observed but with a lower slope than for the measurements without bubbles.

5. References

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