Breakdown Characteristics of SF$_6$ and Liquefied SF$_6$ at Decreased Temperature

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Abstract – SF$_6$ gas has been used as arc quenching and insulating medium for high and extra high voltage switching devices due to its high dielectric strength, its excellent arc-quenching capabilities, its high chemical stability and non toxicity. Despite of its significant contributions, the gas was classified as one of the greenhouse gas in the Kyoto Protocol. Thus, many researches are conducted to find out the replacement materials and to develop the SF$_6$ gas useless electrical equipment. This paper describes experiments on the temperature change-related breakdown characteristics of SF$_6$ gas (SF$_6$) and SF$_6$ liquid (LSF$_6$) in a model GIS(Gas-Insulated Switchgear) chamber in order to show the possibility of more stable and safe usages of SF$_6$ gas. The breakdown characteristics are classified into three stages, namely the gas stage of SF$_6$ according to Paschen's law, the coexisting stage of SF$_6$ gas with liquid in considerable deviation at lower temperature, and the stage of LSF$_6$ and remaining air. The result shows that the ability of the LSF$_6$ insulation is higher than the high-pressure SF$_6$. Moreover, it reveals that the breakdown characteristics of LSF$_6$ are produced by bubble-formed LSF$_6$ evaporation and bubbles caused by high electric emission and the corona. In addition, the property of dielectric breakdown of LSF$_6$ is determined by electrode form, electrode arrangement, bubble formation and movement, arc extinguishing capacity of the media, difficulty in corona formation, and the distance between electrodes. The bubble formation and flow separation phenomena were identified for LSF$_6$. It provides fundamental data not only for SF$_6$ gas useless equipment but also for electric insulation design of high-temperature superconductor and cryogenic equipment machinery, which will be developed in future studies.

Keywords: SF$_6$ gas, SF$_6$ liquid, Breakdown characteristics

1. Introduction

With advances in industry, there have been ever-increasing requirements for high-quality electrical energy, simplification of operation and maintenance, and assurance of reliability and safety in electrical equipment. As a result, the use of electrical devices using the exceptional insulation characteristics of high pressure SF$_6$ gas (SF$_6$) is being established both domestically and internationally [1].

However, the most famous insulation material, SF$_6$ gas crucial problems on two parts. Firstly, it has been classified as a greenhouse gas and its usages are globally limited. Thus there are many researches in order to find out its replacement materials. One of them, dry-air and N$_2$/O$_2$ mixture gas which have less environmental impact than SF$_6$ are considered to be applied into power equipment. However, knowing that their dielectric strengths are less than 1/3 of SF$_6$ gas, the power equipment which uses these replacement materials has some problems on its safety and insulation level. Secondly, the SF$_6$ gas which is equipped in intense cold regions causes undesirable breakdown accidents. So as these are caused by the process of liquefaction of the gas, it is needed to reveal phenomenon of breakdown in this process [2].

This paper presents the dielectric characteristics of LSF$_6$ in order to show the possibility of the LSF$_6$ usage in electric insulation devices comparing to SF$_6$ gas. At the same time it demonstrates and explains the phenomena of the breakdown in the process of the liquefaction of SF$_6$ gas. To this end, the insulation characteristics of SF$_6$ liquid (LSF$_6$) in a model GIS (Gas Insulated Switchgear) chamber were evaluated on the different forms/arrangements of electrodes into the dielectric materials. This research could also provide the base data for the design of insulation for a high-temperature superconductor and cryogenic equipment.

This paper is organized as follows: Section 2 describes the experimental procedure and the method. In section 3, experimental results are detailed and discussed. Section 4 presents conclusion.

2. Experimental Procedure & Method

The exterior of the model GIS chamber designed and produced to research the insulation characteristics of SF$_6$ is shown in Photo 1. The highest voltage allowed is AC 300
kV. DY-106-Korea (AC 300 kV / 120 mA) was used as the electricity source. In order to observe the inner temperature of the model GIS chamber, a temperature sensor (UNICON, -90~+90 °C) was installed 80 mm away from the vertical central axis, parallel to the electrode at the center of the experimental chamber's interior. A pressure gauge (WISE, 0~1520 kPa) was installed to measure the chamber's inner pressure. The interior pressure of the chamber can be maintained up to 5×10⁴ Torr using a vacuum pump (SINKU KIKO Co. Ltd, GUD-050A, pumping speed 60 l/min) and a heat-insulating vacuum layer was constructed between the interior and the exterior of the chamber. A window (diameter 110 mm, thickness 20 mm) was installed to allow the observation of the temperature sensor and the electrode installed inside the model GIS chamber. The material for this window was transparent acrylic and was installed by fashioning a cylindrical shape.

The main specification of the experimental chamber is such that the pressurization of 1013 kPa to be on the safe side for pressure variation (203~810 kPa) and maintaining the secrecy within the model GIS chamber is possible for maintaining pressure. In addition, the insulation is designed so that it can allow up to 300 kV for testing the internal insulation force of the SF₆ which has high insulation characteristics, and with which the temperature variation of -90~+90 °C or temperature maintenance is possible.

Following is the experimental method for the breakdown characteristics of SF₆ in temperature decline. The phase transition characteristics and Breakdown Voltage (V_B) were evaluated when the temperature was ranged in -40~+30 °C which is measured by temperature sensor in each pressure after ventilating the inner chamber to 10⁴ Torr before inserting SF₆ with 405, 507, and 607 kPa. The experiment with LSF₆ shows that after ventilating the model GIS chamber up to 10⁴ Torr and maintaining SF₆ at 304 kPa, SF₆ is liquefied until the electrodes are sunk into LSF₆. The resulting Breakdown Voltage (V_B) characteristics were evaluated. For the voltage of the breakdown characteristics, the average value of ten measurements was used. It is measured after about ten times discharges. The voltage was set to the rising speed of 1 kV/s during the V_B measurement.

The next section shows the experimental results following above experimental procedure and the method.

3. Experimental Results & Discussion

3.1 Temperature dependence with the maintenance of a fixed amount of gas, breakdown characteristics and phase transition characteristics

Fig. 1 shows the V_B in specific pressure of SF₆ in N-P electrodes versus temperature. A fixed amount of SF₆ is maintained at 405, 507 and 607 kPa at 30 °C. The purpose of this condition is to identify the inner status of SF₆ and its insulation characteristics according to changes in the power equipments' temperature, using SF₆ in severely cold areas.

In Fig. 1, Pattern I is a phase where pressure decreases according to temperature at a gaseous state toward each pressure. At this time, the pressure gradually decreases as the temperature drops and there is a section where the V_B also drops. In other words, this is a field where Paschen's
Pattern II is a process where the SF₆ is gradually being liquefied in a chamber. The liquefaction of SF₆ is started from the upper part of the chamber where the dry-ice is attached. The liquefied SF₆ surrounds the needle electrode area and inner wall of the chamber and leads the increase of breakdown voltage. The phenomenon of voltage increase at this phase is indicated in Fig. 2. While LSF₆ covers the needle electrode (Fig. 2(b)), it is obvious that there is a great deal of deviation in the $V_B$ value due to the enclosing LSF₆ of the electrode. As increasing the quantity of LSF₆ enclosing the needle electrode (Fig. 2(c)), its drop becomes falling down (Fig. 2(d)). After that LSF₆ is dropped onto the lower part and the plane electrode (Fig. 2(e)), the value of $V_B$ decreases. This is the step where liquefaction is in progress and the insulation media between N-P displays the insulation characteristics of a field where SF₆ and LSF₆ coexist. Finally, LSF₆ is covered on the plane electrode (Fig. 2(f)).

The pattern II is is also figured in Photo 2. SF₆ gas starts being liquefied because of temperature declining. In this temperature range, there is the actual point of liquefaction of the gas. Photo 2(a) shows the behaviors of LSF₆ drops. The upside of chamber is attached to a refrigerant, namely, dry ice. Since the liquefaction has progressed from the upside, the drops of LSF₆ are formed at this place. Then the drops flow both onto the electrodes and the inner wall of the chamber. Photo 2(b) shows the plane electrode which is covered by LSF₆. Moreover, liquefaction occurs at a lower temperature if the gas pressure is low.

**Fig. 2.** The LSF₆ climbs down along to the electrodes: (a) Started liquefaction; (b) LSF₆ surrounds the needle electrode; (c) Set up an LSF₆ drop; (d) An LSF₆ drop; (e) Right after the LSF₆, which was surrounding the needle electrode area, was dropped; (f) Film LSF₆ at the plane

1: The LSF₆, at the upper chamber area, was dropped.
2: The LSF₆ flows on inner wall of chamber
3: The LSF₆ flows on needle

(a) A formation part of the typical LSF₆

1: Needle 2: Plane
3: Formed film LSF₆ at Plane
4: Reflected needle forms

(b) LSF₆ on the plane

**Photo 2.** A process where the SF₆ is being liquefacted in the chamber

Moreover, liquefaction occurs at lower temperatures if the gas pressure is low according to Boyle-Charles's Law and the phase balance. As shown in Fig. 2, the SF₆ exists as gas from 0–20°C, -20–10°C, and -30–20°C at 607, 507 and 405 kPa, respectively. When the temperature of electrode gets lower than 0°C, the liquefaction begins at the highest area of the chamber, which has the lowest temperature in the chamber. The most active liquefaction
occurred when the electrode's temperature was at -20°C. Moreover, the liquefaction began at -30° to -20°C at 405 kPa. Since the chamber’s temperature sensor was installed 150mm from the floor, which is 80 mm away from the horizontal center parallel to the electrode, the actual liquefaction point would occur at higher temperature than measured temperature.

In pattern III, most of the SF₆ inside the chamber is liquefied. LSF₆ is collected at the lower part of the model GIS chamber. Consequently, there exists the extremely low pressure of GSF₆ near the upper part of the chamber. The upper area surrounding the electrode gets filled with mixture of non-liquefied SF₆ gas and the remaining air that could not be ventilated. This is the step where the V_B becomes considerably low. This is the reason of the malfunction of GIS using SF₆ in an intense cold region.

3.2 V_B characteristics of LSF₆

The model GIS chamber used in this research contains a vacuum layer between the inner and outer chambers for heat insulation. Bubbles are created under a certain pressure of LSF₆, and a further increase in the bubbles is followed by the creation of a corona discharge. The flow of the increasing bubbles becomes separated from the boundary by electrodes that are arranged vertically so that a recycling form is created in this field. This phenomenon is called Separation and it is created more easily on the plane.

From the above results which show the liquefied LSF₆ has a strong dielectric characteristic, the different types of electrodes are used for detailed evaluations of the characteristics of LSF₆. The GIS chamber is fulfilled by LSF₆ and the electrodes are also immersed in LSF₆. Fig. 3(a) shows the breakdown characteristics of LSF₆ under the different distances of electrodes according to the types of arrangement of electrodes. The arrangements of electrodes are follows: N-P and S-P, P-P and P-N. As the distance (d) is far, V_B increases for all cases.

When the gap distance is 1mm, V_B for all the types of arrangement are similar, since the short distance leads the uniform electric fields. When d is over than 1 mm, increase of V_B under S-P and P-P arrangements are higher than under P-N and N-P forms. It is also explained by their electric fields. S-P and P-P arrangements keep uniform electric fields in a distance from 1mm to 4mm. In addition, there exists the strong bubble effect under P-P. It is why the V_B under P-P arrangement is lower than V_B under S-P at d=4mm.

Then, P-N and N-P arrangements cause non-uniform fields. Because of this unbalance of the field, the V_B becomes lower. However, the V_B under P-N is higher than under N-P. So as the plane electrode is negative polarity under P-N, it is more difficult to engender the corona discharge because of the feature of electrode. Although it is possible that the bubble is more under P-N arrangement, the bubble of LSF₆ still has good arc-quenching capabilities. Thus, the negative plane electrode would keep being difficult to generate the corona discharge and making V_B higher.

![Fig. 3. The Breakdown voltage characteristics in LSF₆ and LN₂](image)

3.3 The LSF₆ bubble movements

There is a phenomenon that V_B under P-P is higher than the N-P. The authors call this the "Positive Bubble Effect". Under the consideration of bubble generation and the exercise characteristics, the Positive Bubble Effect can be
defined as follows:

1. In the beginning, when the air pressure for the LSF₆ is 406 kPa, the temperature of liquefaction is approximately -20 ~ -30 °C.

2. LSF₆ has natural bubbles and bubbles caused by corona. The SF₆ bubbles in the LSF₆ (BSF₆) have good arc cancellation abilities. Therefore, the corona and arc in the bubbles found in LSF₆ degrade very quickly.

In the results, in the case of the LSF₆, the possibility of bubbles existing inside the chamber degrade. In the LSF₆, the breakdown caused by the electric field is more important than the breakdown caused by the bubble effect. The P-P electrode, which is the sub balanced electrode shape, has a higher Vₖ than the N-P’s, which has an extremely unbalanced electrodes.

![Photo 3](image1)

**Photo 3.** The occurrence and separation of the bubbles (P-N, d=6 mm, V=20 kV): (a) Before voltage connection; (b) Just after voltage connection; (c) 60 s after voltage connection; (d) 120 s after voltage connection; (e) Just after voltage disconnection; (f) 30 s after voltage disconnection

Photo 3 shows the occurrence and separation of the BSF₆. The flow of a liquid is usually separated from its boundary and a recirculation form is produced in its area.

Photo 3(a) is the photograph before voltage connection. The natural BSF₆ elevating from the lower part moves upwards along the surface of the needle electrode. Photo 3(b) shows the bubble separation phenomenon just after voltage connection. In this case, the bubbles are formed in a fan shape, as shown in the photo, due to the heat of the corona at the needle end. The production of bubbles increases at the side of the needle electrode and the needle end with progress of the corona. As shown in Photo 3(c), in terms of bubbles produced by the corona, the bubbles elevating over the plate electrode gradually increased with lapse of voltage connection time. As illustrated in Photo 3(d), when the maximum quantity of bubbles is reached, the elevating speed of the bubbles also becomes maximal.

In general, the speed of flow of a viscous fluid is reduced near the boundary due to viscous resistance compared to the speed of irrotational flow. The speed of bubbles existing at the lower part of the plate electrode becomes near zero (0) and they are shown as static bubbles. Therefore, static bubbles form the SF₆ gas layer at the back of the moving direction (the lower part of the plate electrode).

In addition, at the lower part, where separation is produced, the bubbles at the outside of the separation surface move very rapidly and those at the inside move relatively slowly. As described, the high velocity gradient at the separation surface produces an eddy phenomenon and the eddy of bubbles may clearly be identified at the back side of the plate where the bubbles are most actively produced, as shown in Photo 3(d).

It was noted that when the voltage was disconnected, the production of the corona was rapidly reduced and the elevating speed of the bubbles was also significantly reduced, as indicated in Photos 3(e) and 3(f).

### 3.4 $V_B$ characteristics contrast needle-plane with plan-needle

![Fig. 4](image2)

**Fig. 4.** The bubble-flow to pass at plan

Although the experimental imitation GIS chamber used in this research has placed a vacuum layer between inner and outer chamber for heat insulation, the bubbles are created under certain pressure of LSF₆ and such bubble gets increased even more followed by creation of corona.
4. Conclusions

This paper described the breakdown characteristics of SF₆ liquid (LSF₆) based on the phase change of SF₆ gas (SF₆) under declined temperature. As being progressed the liquefaction of SF₆, the breakdown voltage (Vₜ) increased, because the LSF₆ covered the electrodes of the test chamber. Even though the chamber was not fulfilled by LSF₆, the Vₜ was higher than the one of SF₆ at normal temperature. After that most of SF₆ liquefied and that LSF₆ which was covered the upside electrode kept going on be dropped on the downside electrode, the Vₜ became decreased. It is due to the low Vₜ characteristics of remained air and low pressurized SF₆ gas. These results show good insulation characteristics of LSF₆ comparing to SF₆ gas and the possibility of the LSF₆ usage in electric insulation devices. Moreover, the comparison study with different types/arrangements of electrodes in LN₂ and LSF₆ were also achieved. Due to the positive bubble effect of LSF₆, the Vₜ under P-P was higher than the Vₜ under N-P. This result is contrary to the cases in LN₂ which had not the same effect. The positive bubble effect of LSF₆ helped degrading the corona discharge in the chamber.

This research provides fundamental data not only for SF6gas useless equipment but also for electric insulation design of high-temperature superconductor and cryogenic equipment machinery, which will be developed in future studies.

4.1 The temperature according to the fixed amount of gas-pressure Vₜ characteristics

(1) At the Pattern I of Fig. 1, the characteristics of SF₆ gas follow the Paschen's Law at each pressure.
(2) SF₆ gas gradually liquefies from the needle electrode area and the inner walls of the chamber during temperature declining. As the drops of LSF₆ climbs down to the needle electrode, the Vₜ increases considerably. This phenomenon strongly occurs when the LSF₆ surrounds the needle electrode area. However, there is a great deal of deviation between the highest and lowest Vₜ; the value being low if Vₜ is measured right after the LSF₆ dropped to the lower section (Pattern II of Fig. 1). It shows the dielectric strength of LSF₆ is better than SF₆'s.
(3) If the liquefaction is progressed further, the surroundings of the upper electrode becomes being filled with low density of SF₆ and the remaining air, and the Vₜ becomes considerably lower by being in an extremely low pressure state (Pattern III of Fig. 1). This condition causes the malfunction of a GIS using SF₆ as its insulation gas.
(4) The boiling point where the gaseous SF₆ becomes LSF₆ differs according to pressure, but in the experiment, liquefaction occurred when the electrode's temperature was about -10 ℃. The actual
liquefaction point is the upper chamber, where the refrigerant dry ice is attached. It can be seen that the liquefaction temperature is lower than the temperature in the upper chamber.

4.2 $V_B$ characteristic and LSF$_6$ bubble movements

(1) Dielectric breakdown of LSF$_6$ is determined by electrode form, electrode arrangement, bubble formation and movement, arc extinguishing capacity of the media, difficulty in corona formation, and the distance between electrodes.

(2) The bubble formation and flow separation phenomenon were identified for LSF$_6$.

(3) The dielectric characteristics of LSF$_6$ are determined by the electric fields between electrodes and the bubble movements. It is especially observed that the bubbles are generated by the heat of corona discharge under P-N arrangement and affect to the breakdown voltage.

This research provides fundamental data not only for SF$_6$ gas useless equipment but also for electric insulation design of high-temperature superconductor and cryogenic equipment machinery, which will be developed in future studies.

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References


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