Paper

# Transient and Continuous Glow Discharges in He, $H_2$ and $N_2$ at Sub-Atmospheric Pressure


Member Tamiya Fujiwara (Iwate University)
Non-member Jyunya Sekikawa (Nagoya University)
Member Emi Ebisu (Iwate University)
Member Tetsuya Sato (Tohoku Electric Power Co., Inc)
Member Hiroshi Yamada (Iwate University)



Durations of transient glow discharge after static and overvoltage breakdowns have been investigated in helium, nitrogen and hydrogen at sub-atmospheric pressure. The result shows that the glow duration is much larger in helium than that in other used gases. The duration of transient glow after static breakdown is rather shorter than that after overvoltage breakdown. Furthermore a continuous glow discharge with a large cross-section was produced in a high frequency range of 25 kHz-100 kHz at sub-atmospheric and atmospheric pressures. The length of transient glow duration is correlative with the ease of production and stability of the continuous glow discharge.



**Keywords**: Glow discharge, Glow-to-arc transition, Atmospheric pressure glow, Electric breakdown


## 1. Introduction

Recently glow discharge at atmospheric pressure has been of great interest in applications to surface treatments, ozone production, reduction technology of nitric oxide in flue gases and so on[1][2]. A glow discharge has a large cross section and is stable at low pressure. The discharge, however, becomes filamentary and changes to an arc discharge in high pressure region. From this fact, it has been considered that it is hardly possible to produce glow discharge at atmospheric pressure. Recently, however, an atmospheric pressure glow discharge has been produced by Kanazawa, *et al.*[1]. They reported that the insertion of a barrier (or barriers) between the electrodes and the dilution of gas with helium are effective to stabilize the glow discharge at atmospheric pressure. There are still few reports on the requirements for production and the characteristics of the atmospheric pressure glow discharge. The purpose of this report is to investigate the transient glow discharge at sub-atmospheric and atmospheric pressures. Furthermore, our final goal is to produce an atmospheric glow discharge in air and its mixture with other gases based on data of the transient glow discharge.

## 2. Experimental method

In this work, two experiments were performed: one was the experiment on transient glow discharge, and another was that on continuous glow discharge. In both experiments, the uniform field electrodes of 50 mm overall diameter were employed. The geometry and dimensions were the same as those described in the previous papers[3][4]. Aluminum and nickel were used as the material of electrodes. In the study of the transient glow discharge, the electrodes were connected with a 2 μF capacitor and a circuit resistor in series. A discharge current flowed from the charged capacitor into the circuit resistor by electric breakdown which took place between the electrodes by static or overvoltage breakdown. When the transient glow discharge occurs preceding the arc discharge, there appears a plateau in the rise of the current to the final value. The duration of the transient glow $t_g$ can be obtained from that of the plateau. In the case of the static breakdown, the capacitor was charged up to the voltage which was equal to the static breakdown voltage between the electrodes. In the case of the overvoltage breakdown, another gap was used between the capacitor and one electrode. The use of the gap made the charging up to

overvoltage possible. Overvoltage ratio $\Delta V$ is given by

$$\Delta V=\frac{V-V_S}{V_S}\times 100 \quad \cdots\cdots(1)$$

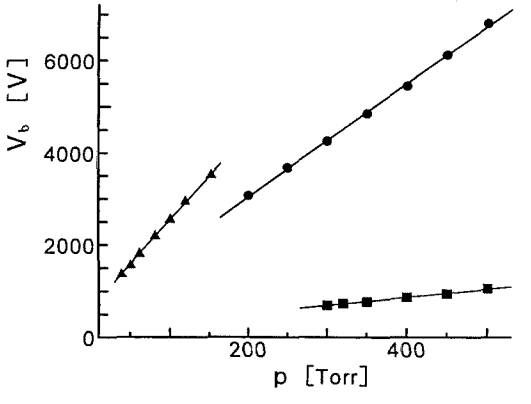
where $V$ and $V_S$ are the applied voltage and the static breakdown voltage, respectively. In regard to the continuous glow, the discharge was produced by the barrier discharge method where a soda-lime glass was put on one electrode as a barrier. In order to maintain the discharge, AC voltage was applied to the electrodes up to 7 kV in peak to peak value in a frequency range of 25 ~100 kHz. All measurements were made after the discharge vessel was evacuated up to $10^{-3}$ Torr by a rotary pump and was filled with test gases to the desired pressure.

## 3. Experimental results

### 3.1 Duration of transient glow discharge

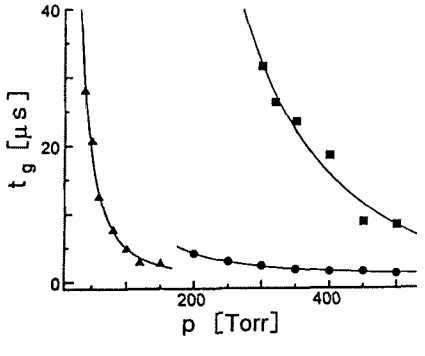
The duration of transient glow discharge $t_g$ was measured in helium, hydrogen and nitrogen for 5.0~7.0 mm gaps at various gas pressures. Fig. 1 shows the plots of $t_g$ against pressure at static breakdown. The transient glow duration decreases with increasing pressure. This reason is due to the fact that energy fed into the discharge increases with pressure. The transient glow duration also depends on the circuit resistance which controls the rate of energy feeding to the discharge. It can be considered that there is no effect of the use of the different resistance upon the order of the duration length among the gases. The authors have previously reported that the duration is in proportional to the resistance[3]. Accordingly the use of the 736~970 Ω resistors results in the difference of the duration within about 30%. The duration of helium is considerably large as compared with that of hydrogen at high pressure more than 300 Torr. It is considered that the large glow duration is attributed to the low breakdown voltage and the large diffusion of electrons in helium. Fig. 2 shows the plots of the breakdown voltage $V_b$ against pressure in helium, hydrogen and nitrogen. It is seen that the breakdown voltage in helium is distinctly lowest among the used gases. In the gas with low breakdown voltage, the discharge current is small because static breakdown takes place at low voltage. In that case, the energy per unit time fed into the discharge will be small during glow phase. The diffusion will make the discharge column large and the flux density of particle impinging upon the electrodes small.

Fig. 3 shows the plots of $t_g$ against overvoltage ratio $\Delta V$ at 500 Torr in helium. It is seen that the duration at static breakdown ($\Delta V=0$) is rather smaller than those at overvoltage breakdown. Such a result has been obtained under a condition of small discharge current in other gases also. This may be caused by the fact that the electrodes are activated by particle bombardment



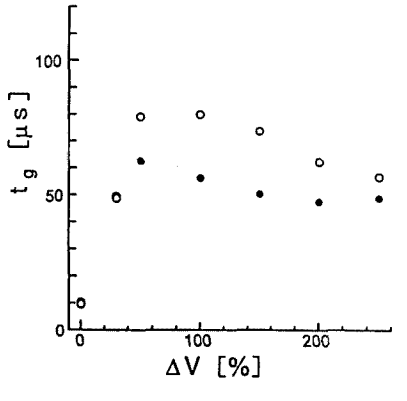

●: hydrogen, 5.0 mm; ▲: nitrogen, 5.0 mm; ■: helium, 7.0 mm.

Fig. 2. Breakdown voltage against gas pressure at static breakdown.




●: hydrogen, 945 Ω, 5.0 mm; ▲: nitrogen, 736 Ω, 5.0 mm; ■: helium, 970 Ω, 7.0 mm.

Fig. 1. Duration of the transient glow against gas pressure at static breakdown.

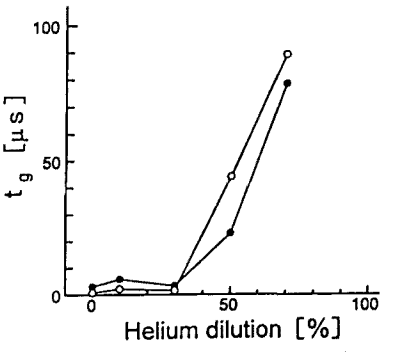



Gap length, 7.0 mm. Circuit resistance, 960 Ω.
○: nickel electrodes; ●: aluminum electrodes.

Fig. 3. Duration of the transient glow against overvoltage ratio at 500 Torr in helium.

during Townsend discharge phase before the static breakdown. It is considered that Townsend discharge has an effect upon decreasing $t_g$ at small overvoltage. The increase of $t_g$ with $\Delta V$ below 50% is caused by that the duration of Townsend discharge decreases with overvoltage ratio. At larger overvoltage, the effect of Townsend discharge is negligible as compared with that of the transient glow discharge. The transient glow duration decreases with the overvoltage ratio above 50%. The decrease of $t_g$ with $\Delta V$, which can been also seen in other author's paper, is caused by the fact that the discharge current during the glow phase increases with the overvoltage ratio[5]. In regard to the electrode material, the duration with nickel electrodes is longer than that with aluminum electrodes. The glow-to-arc transition takes place when thermal electron emission is the dominant process of the discharge[6]. The material with larger work function will require a longer time to induce the thermal electron emission if the energy fed into the electrode per unit time is constant. The experimental result for $t_g$ with different materials is coincide with the fact that the work function of nickel (4.0~5.2 eV) is generally larger than that of aluminum (2.9~4.5 eV).

There is a relationship between the transient glow duration and the easiness in production and stability of atmospheric glow discharge. Considering the large duration in helium, it is expected that the effect of adding helium into other gases is to increase the transient glow duration. This effect was investigated by using gas mixture of nitrogen with helium. Fig. 4 shows the relationship between the duration $t_g$ and the helium dilution which is the ratio of partial pressure of helium to the total pressure. It is seen that the transient glow duration increases with the helium dilution above about 30%. The abrupt increase of $t_g$ above this value could be explained by that electron-transport parameters in mixed gas do not vary linearly with mixture ratio. Among the parameters, the diffusion coefficient is important in the transient glow duration because the diffusion makes the flux density of particle impinging upon the electrodes small as above. The product of pressure reduced to 0°C and the longitudinal diffusion coefficient of electrons $p_0D_L$ was measured in gas mixture of nitrogen and helium by Takeda and Nakamura[7]. Their result shows that the values of $p_0D_L$ at helium dilution below 50% make no significant difference from those in pure nitrogen at $E/p_0=7$ V/cm·Torr which is the reduced electric field of Fig. 4. At the dilution of 95%, $p_0D_L$ takes an intermediate value between those of pure




Total pressure, 200 Torr. Gap length, 5.0 mm. Circuit resistance, 960 Ω. ○: $\Delta V=30$ %; ●: static breakdown.

Fig. 4. The relation between transient glow duration and helium dilution in gas mixture of helium and nitrogen.

helium and pure nitrogen. This is caused by that there is the vibrational and rotational levels in nitrogen molecules and the inelastic collisions between the molecules and electrons are dominant in the energy loss of electrons. As the result, the addition of helium with low dilution scarcely has an effect on the increase of the diffusion coefficient. Furthermore, the result shows that at low helium dilution the duration of the static breakdown is slightly longer than that of the overvoltage breakdown. The contradiction with previous statement may be caused by a difference in the discharge current during the glow phase. Under this condition, the glow current in nitrogen is about 4 A and about ten times as large as that in helium. When the glow current is high, Townsend discharge has no effect on the transient glow duration as before. In that case the increase of the energy fed into the discharge would have influence on $t_g$.

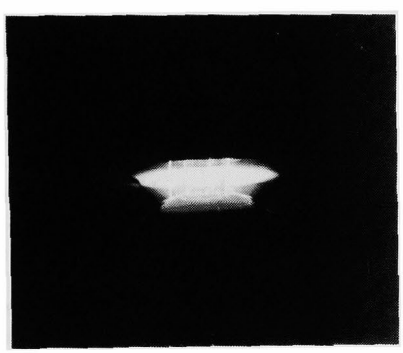
### 3.2 Production of continuous glow discharge

The transition of a discharge from the glow to the arc may be expected to be restrained by alternating the polarity of applied voltage within the glow phase. In helium, the duration of transient glow discharge after static breakdown $t_g$ is about 10 μs at 500 Torr as shown in Fig. 1. If a half period of the voltage applied to produce a continuous glow should be less than the transient glow duration, the frequency of the applied voltage would be above 50 kHz in helium at 500 Torr. In the experiment, however, only a filamentary arc channel was formed between the electrodes at 100 kHz. This fact implies that in the continuous case the glow-to-arc transition takes place by the energy much smaller than that is fed into the discharge during the transient glow phase.

Furthermore, we tried to restrain the glow-to-arc

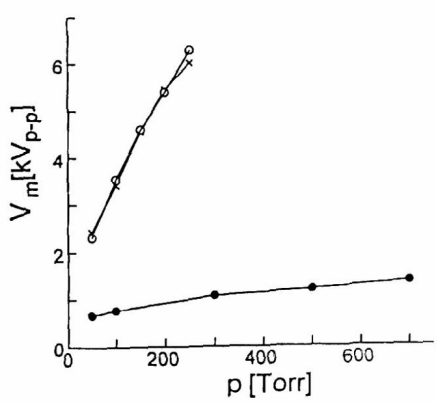
transition by putting a barrier on an electrode. A soda-lime glass of 3 mm thickness was employed as the barrier. This test of the barrier discharge can be considered that the use of a material with large work function cause the transient glow duration long. By this method, a continuous glow discharge was produced stably even in the ranges of frequency and pressure where only a filamentary arc was formed without the barrier. In the case of shorter gap, the radiation from the discharge was almost uniform. However, in the case of longer gap the luminous strings appeared and moved around in the discharge column as shown in Fig. 5.

The minimum value of applied voltages where the continuous glow discharge was produced was defined as $V_m$. Fig. 6 shows the relationship between $V_m$ and pressure in helium, nitrogen and air. It is seen that the variation rate of $V_m$ against pressure is much smaller in helium than that in nitrogen. There is no distinct difference between nitrogen and air in both $V_m$ and their variation rates. It was confirmed that the insertion of the barrier was effective to restrain the appearance of anode and cathode spots and stabilize the atmospheric glow discharge. By the barrier discharge method, atmospheric glow discharges with cross sections of 50 mm diameter and 47 mm×131 mm were produced in helium, air and their mixture.



Gap length, 7.0 mm. Frequency, 50 kHz.
Applied voltage, 5.0 kVp-p.

Fig. 5. A shutter photograph of the continuous glow discharge in helium at 700 Torr.




Gap length, 1 mm. Frequence: 50 kHz.
●: helium; ○: nitrogen; ×: air.

Fig. 6. The relationship of $V_m$ (peak-to-peak value) with gas pressure.

## 4. Conclusions

The duration of transient glow discharge was measured in helium, nitrogen and hydrogen as basic data of atmospheric glow discharge. The transient glow duration of helium is much larger than those of other gases. When AC voltage was applied at the frequency deduced from the transient glow duration, only a filamentary arc channel was formed at sub-atmospheric pressure. The insertion of a barrier was effective to restrain the appearance of electrode spots in high pressure region. By this method, the continuous glow discharges were produced with large cross sections at sub-atmospheric and atmospheric pressures in helium, air and their mixture.

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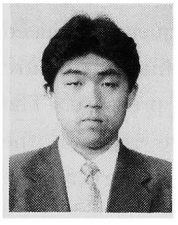
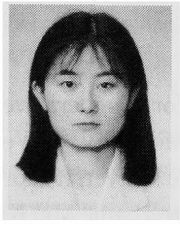
**Tamiya Fujiwara** (Member) He received the M. E. and Dr. E. degrees in Electrical Engineering from Tohoku University, in 1973 and 1986, respectively. He is now a professor of Iwate University. He has been engaged in research of gas discharge, discharge plasma and their applications.

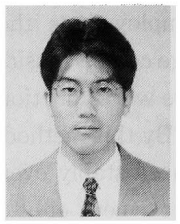
Dr. Fujiwara is a member of the Japan Society of Applied Physics, the Japan Society of Plasma Science and Nuclear Fusion Research.



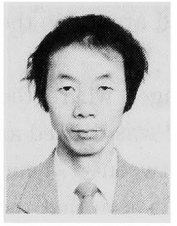
**Jyunya Sekikawa** (Non-member) He received the B. E. and M. E. in Electrical Engineering from Iwate University, in 1993 and 1995, respectively. Since April 1995, he is now a student of the Graduate School (Doctor's Program) of Nagoya University. He has been engaged in research on gas discharge, discharge plasma and their applications.



**Emi Ebisu** (Member) She received the B. E. in 1994 in Electrical Engineering from Iwate University. She is now a student of the Division of Engineering Graduate School (Master's Program) of Iwate University. Miss Ebisu will join Tohoku Electric Power Co., Inc. in April 1996. She has been engaged in research of gas discharge plasma and their applications.



**Tetsuya Sato** (Member) He received the B. E. and M. E. in Electrical Engineering from Iwate University, in 1993 and 1995, respectively. In 1995 he has joined Tohoku Electric Power Co., Inc. His rescarch interests deal with gas discharge, discharge plasma and their applications.



**Hiroshi Yamada** (Member) He received the M. E. and Dr. E. degrees in Electrical Engineering from Hokkaido University, in 1975 and 1979, respectively. He is now a professor of Iwate University. Dr. Yamada has been engaged in research on gas discharge, discharge plasma and their applications.

He is a member of the Physical Society of Japan, the Institute of Elecrostatics Japan.