Fundamental study on quenching technique and decaying processes of arc plasmas using solid and gas media

学位論文要旨

気・固相消弧媒体を利用したアークプラズマ冷却手法と減衰過程に関する基礎研究

FUNDAMENTAL STUDY ON QUENCHING TECHNIQUE AND DECAYING PROCESSES OF ARC PLASMAS USING SOLID AND GAS MEDIA

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Abstract

Circuit breakers play important roles for secure electric power transmission. The most important duty of a circuit breaker is to interrupt a fault current, which may cause serious damages to humans or equipment. Circuit breakers use arc quenching media for rapid and smooth current interruption. Arc quenching media made of polymer are often used in low voltage circuit breakers. For a high voltage circuit breaker, gas is usually used for arc quenching. The author investigated arc quenching media in solid phase and gas phase with experiments and numerical approaches. In the first research, a unique phenomenon which occurs only from polyamide materials was investigated. The author discovered that small particles were ejected from a surface of a polyamide specimen when it was irradiated by a thermal plasma, and then named this phenomenon as "spallation" phenomenon. Secondly, fundamental arc quenching characteristics of gas media were investigated. Various gas-blast arcs were intentionally decayed and re-ignited using a power semiconductor switching with time accuracy in micro seconds. Waveforms measurement and high speed videocamera observation were conducted. Furthermore, a sequence of electron density from decaying to re-ignition of the arc was obtained and compared tendency of the blast gas. Dielectric recovery properties for different gas were obtained under the same condition in the same device. The author obtained valuable data for consideration of arc re-ignition process.

1 Introduction

Circuit breakers play important roles for secure electric power transmission. One of the important functions of circuit breaker is arc quenching using pertinent media to make the interruption easier. Arc quenching media made of polymer are often used in low voltage circuit breakers. For a high voltage circuit breaker, gas is often used for arc quenching. The author investigated arc quenching media in solid phase and gas phase with experiments and numerical approaches.

In the first research, the effect of water absorption in polyamide material irradiated by thermal plasmas on the occurrence of spallation phenomena was investigated. The results showed that the polyamide specimen with water absorption ejected a large number of spallation particles. Cooling effects of spallation particles ablation were also estimated in hot air to assess the arc quenching ability from the spallation particle inclusion. This estimation showed that spallation can be useful to enhance arc quenching in circuit breakers.

Secondly, the arc quenching abilities of various gases were studied using a power semiconductor switching technique. Arcs in free recovery condition after a 50 A steady state condition were investigated in SF_6, CO_2, O_2, N_2, air and Ar gas flows. Furthermore, at a specific time high voltages of about 1.1 kV and 1.7 kV μs^{-1} were applied to the residual decaying arcs to elucidate the arc re-ignition process. The results showed a direct relation to the interruption capabilities of the respective gases.

Finally, thermally arc re-ignition processes in various gas flow in a nozzle was focused on by a voltage application at 20 μs delay time from initiation of free recovery condition. Through these experiments, the electron density at the nozzle throat was measured using laser Thomson scattering (LTS) method together with a high speed video camera observation. In addition, detailed dielectric recovery properties were measured under the same condition except gas kinds.

These 3 approaches to investigation of arc quenching techniques firstly propose a new promising method for arc quenching in low voltage circuit breakers. In addition, reliable data of arc quenching ability of various gas flow in a nozzle is given. The author believes that the obtained results are useful for future development of smart grids and eco-friendly energy transport.

2 Spallation occurrence from polyamide materials irradiated by thermal plasma with water absorption

The author discovered a phenomenon that small polymer particles are ejected from the polymer material surface during a high heat flux irradiation to the polymer. This phenomenon was named "spallation". Fig. 1 depicts 7 kinds of polymeric materials under irradiation of an Ar-thermal plasma with a high heat flux. As seen in this figure, PA66 and PA6, kinds of polyamide materials, eject spallation particles from their surfaces. It was also found that occurrence of spallation can be engendered by water absorption into the polyamide materials. If polyamide is installed in a circuit breaker as an arc quenching medium, the arc ignited in the circuit breaker can contact the polyamide and at that time, spallation particles can jump into inside of the arc and quench the arc effectively. In this way, spallation phenomena can be expected to be applied to arc quenching especially in a low voltage circuit breaker.

This work further investigated the occurrence of spallation. From the results of N_2 and O_2 included Ar-thermal plasma irradiation, O_2 was confirmed to enhance the occurrence of spallation when O_2 is included in the irradiating thermal plasma. Fig. 2 represents superimposed 100 pictures of water-absorbed PA66 took from 0.9 to 1.0 s after the initiation of thermal plasma irradiation. It can be seen that the number of spallation particles were increased by inclusion of O_2 into the irradiated thermal plasma. In most cases, the low voltage circuit breaker works in air, and thus an air-arc can be ignited in current interruption process. If an air-arc contacts the quenching media made of polyamide, spallation occurrence will be enhanced by O_2 in air, resulting in further high arc quenching performance.

The cooling effects of thermal plasmas by spallation PA66 particles were also estimated numerically. Suppose that spallation particles made of PA66 with a radius of 100 μm are ejected into hot air of 10 cm^3 volume with initial temperature of 10 kK. This estimation shows that 10 and more PA66 particles inclusion might decrease the air temperature by 3000 K. This temperature drop arises mainly from the energy consumption for dissociation reactions in polyatomic species in air-PA66 ablation vapour. These results suggest that spallation phenomena can be useful to enhance arc quenching in circuit breakers.

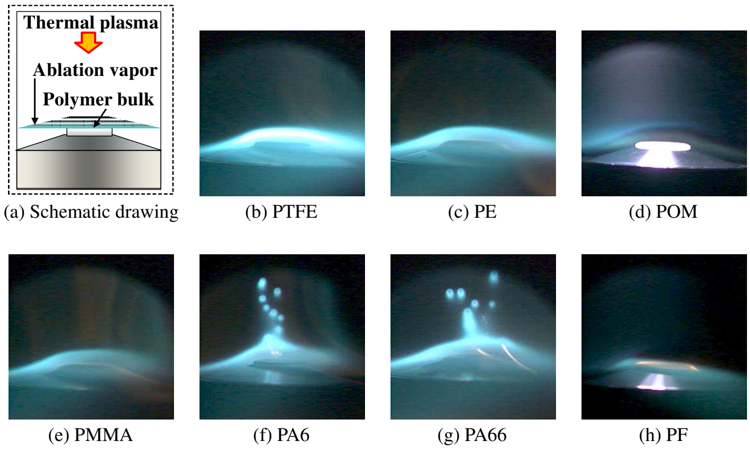

Fig. 1: Ar-thermal plasma irradiation on (b) PTFE, (c) PE, (d) POM, (e) PMMA, (f) PA66, (g) PA6, and (h) PF, (a) is a schematic image.

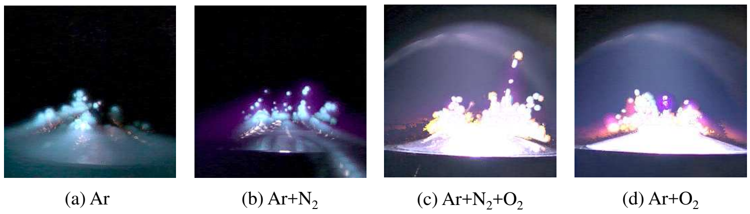

Fig. 2: Ar+N_2/O_2-thermal plasma irradiation on water absorbed PA66

3 Evaluation of arc quenching characteristics of various gases using power semiconductors

Gaseous arc-quenching media are usually used in a circuit breaker. SF_6 gas is widely used due to its extremely high arc-quenching performance in a high voltage gas circuit breaker (GCB). However, use of SF_6 is unfavourable because SF_6 has 22800 times higher global warming potential than that of CO_2. Much efforts have been made to date for development of alternatives or reduction of SF_6 use. Recently, CO_2 based alternatives such as g^3 (mixture of CO_2 and perfluoronitrile) have been developed and it was said that these alternatives have comparable dielectric strength. In spite of that, there are still uncleared physics especially in transient phase on arc extinguishment.

In this chapter, the author investigated fundamental arc quenching characteristics of various gases including SF_6, CO_2, N_2 and so on. Figure 3 depicts the arc device used in this work. The arc device consists of a vacuum chamber, a moving electrode and a fixed electrode, and a nozzle for gas flow. The outer diameter of the chamber is 200 mm. The upper electrode, which works as the anode, is the moving electrode driven by a compressed air cylinder. The lower electrode works as the cathode. It is the fixed electrode. These electrodes are surrounded by a gas-blast nozzle. Figure 4 presents a schematic diagram of the nozzle and the electrodes, and a photograph of the nozzle made of transparent polymethylmethacrylate (PMMA). The electrode tips are made of copper tungsten (70%Cu-30%W). The moving electrode has 6 mm body diameter and 3 mm tip diameter. The body diameter and the tip diameter of the fixed electrodes are, respectively, 3 mm and 10 mm. The gap length is 50 mm at a full open position. These electrodes are surrounded by the gas-blast nozzle that can blow introduced gas to the arc ignited between the electrodes. The gas inlet diameter is 40 mm, whereas that of the outlet is 18.75 mm. This nozzle has a throat with 10 mm diameter and 10 mm length. We used nozzles made of polytetrafluoroethylene (PTFE) for arc tests. Only for observation of arc behaviour in the nozzle, a nozzle made of transparent PMMA was used. In addition, the arc device can be applied to electron density measurement using laser Thomson scattering (LTS). This work includes measurements of electron density at the nozzle throat.

Figure 5 illustrates the schematics of the experimental circuit. As a power device for arc discharge, an inverter type DC current source was used. This current source can sustain a stable arc between the electrodes for a long time. The experimental circuit has an $IGBT_p$ which is parallel connected to the electrodes. This can translocate the arc current to the IGBT itself at any time by a gate voltage control. Using the system named IGBT-SG, decay processes of SF_6, CO_2, O_2, N_2, air and Ar-blast arcs were fundamentally investigated. Simplified experimental procedure is as follows:

1. Test gas is introduced to the nozzle with a flow rate of 100 or 50 L/min.
2. DC 50 A is provided between the closed electrodes and then the electrodes are opened to ignite a gas-blast arc in the nozzle.
3. The arc becomes steady state after the electrodes opening.
4. The arc current is translocated to the IGBT to start the arc decaying.

Figure 6 represents (a)SF_6 and (b)CO_2-blast arc behaviour in the decaying phase observed by a high speed video camera. SF_6-blast arc decayed rapidly from the whole part of the arc. On the other hands, CO_2-blast arc decayed from the nozzle throat. The other gas-blast arc were confirmed to have a similar tendency to decay from near the nozzle throat.

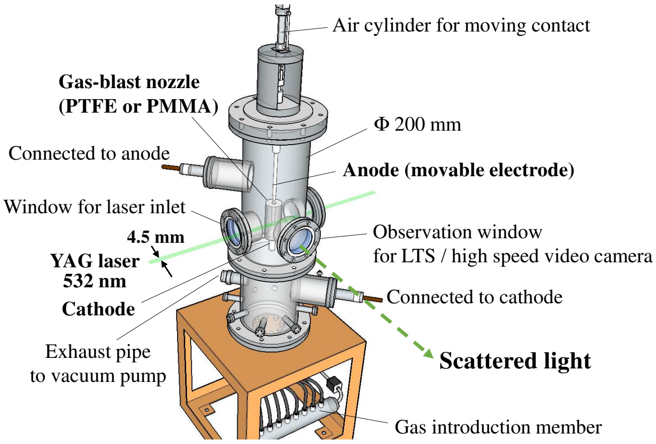

Fig. 3: Arc device

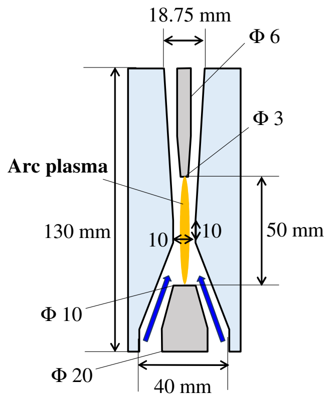

Fig. 4: Cross section of gas blast nozzle and electrodes, and a picture of PMMA transparent nozzle

Figure 7 indicates the decay process of electron density measured by LTS method in the arc at the nozzle throat. As seen in this figure, electron density of SF_6 and CO_2-blast arcs at the nozzle throat decreased in almost the same rate during arc decaying. On the other hands, decrease of electron density in N_2-blast arc was slowly compared to SF_6 and CO_2. The same decay rate of SF_6 and CO_2-blast arc shows no contradiction with the result of arc behaviour observed by the high speed video camera. The results suggest that the nozzle throat plays important roles for arc quenching using CO_2. Further investigation is needed to understand the difference of mechanism of arc decay processes between SF_6 and other gas-blast arcs.

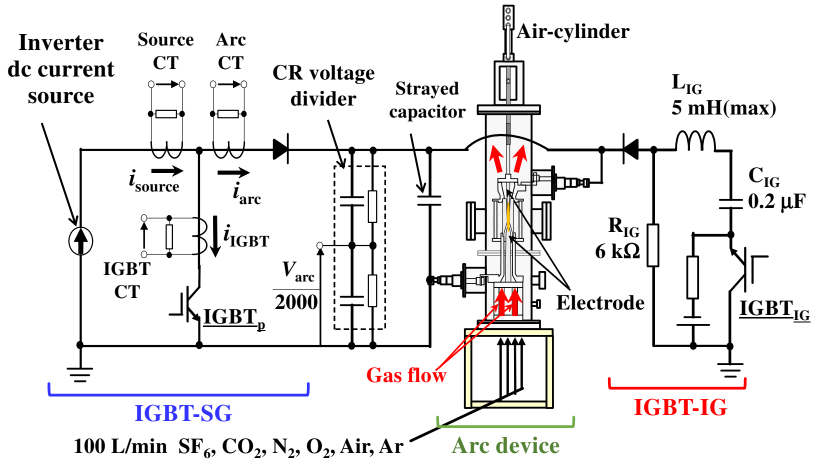

Fig. 5: Experimental circuit

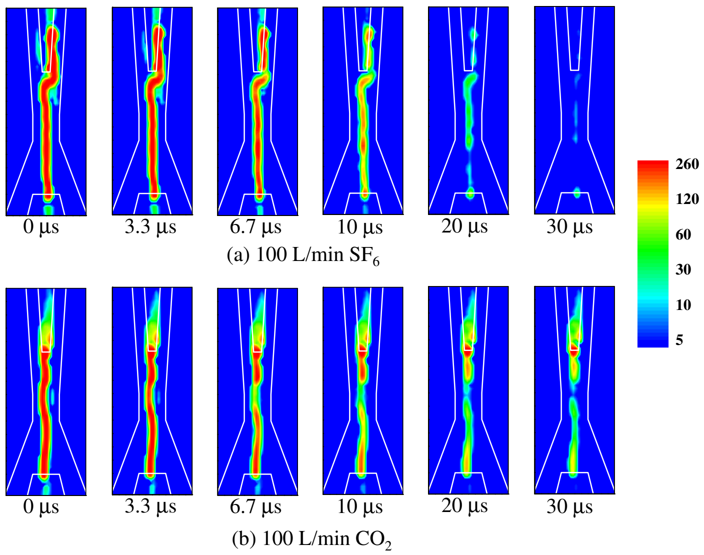

Fig. 6: (a)SF_6 (b)CO_2-blast arc behaviour in decaying phase

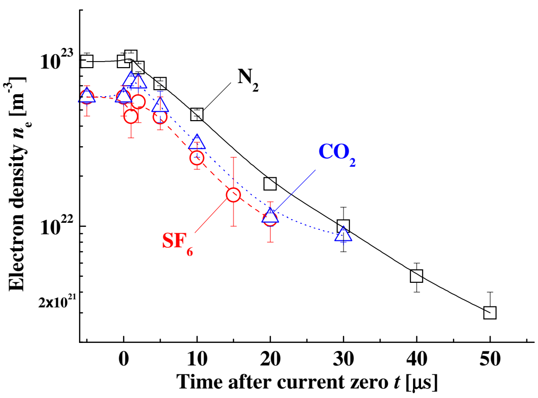

Fig. 7: Measured electron density of the arc at the nozzle throat.

4 Fundamental study on thermal re-ignition process of various gas-blast arcs using voltage application highly controlled by powersemiconductors

Understanding of not only the decaying process but re-ignition process is necessary for elucidation of arc quenching mechanism. The experimental circuit shown in Fig. 5 can provide various operation of arc current and voltage. In Chapter 3, the same circuit was used for an arc ignition and the arc decaying for investigation of arc decaying processes. In this chapter, an artificial transient recovery voltage (TRV) was applied to the decaying various gas-blast arcs. This artificial TRV was named quasi-TRV. Application timing of quasi-TRV can be controlled precisely in time with less than a micro second time steps. In this work, with a specified delay time t_{d} from initiation of the arc decaying, the quasi-TRV with a peak of 1.2 kV was applied to re-ignite the arc intentionally. Test gases were SF_6, CO_2, O_2, N_2, air and Ar with a flow rate of 100 L/min. As acquisitions, averaged re-ignition voltage was obtained to investigate dielectric recovery properties, a temporal variation in the electron density at the nozzle throat from decaying to re-ignition of the arc. The arc behaviours were observed by a high speed video camera for each gas-blast arcs.

Figure 8 shows the dielectric recovery properties of SF_6 and CO_2-blast arcs in panel (a), and those of CO_2, air and Ar-blast arcs in panel (b). The tests were conducted using quasi-TRV with a RRRV of 2.0 kV/μs. The horizontal axis indicates the timing t from initiation of the arc decaying. From panel (a), the dielectric strength of SF_6 residual arc recovered extremely fast with time. At t=5 μs after from initiation of the arc decaying, the dielectric strength, that is, the averaged arc re-ignition voltage was obtained as 0.3 kV. This value is higher than SF_6 arc voltage in steady state. The dielectric strength increases with time, leading to 0.55 kV at t=20 μs. After t=20 μs, rapid rise of the arc re-ignition voltage was observed with time, and it reaches more than 0.8 kV at t=22.5 μs.

Figure 9 shows temporal variation in the electron density of the arc at the nozzle throat from the arc decaying to re-ignition. In this situation, the arc decayed till 20 μs, and at 20 μs, the quasi-TRV was applied to the arc. The measured electron density of SF_6-blast arc decreased smoothly till 20 μs. Afterwards, the electron density increased quickly because of the arc re-ignition, and reached to almost the same value measured before decaying.

In other gas-blast arcs, the electron density once increased just after initiation of the arc decaying. In addition, the electron density hardly increased to initial value before decaying.

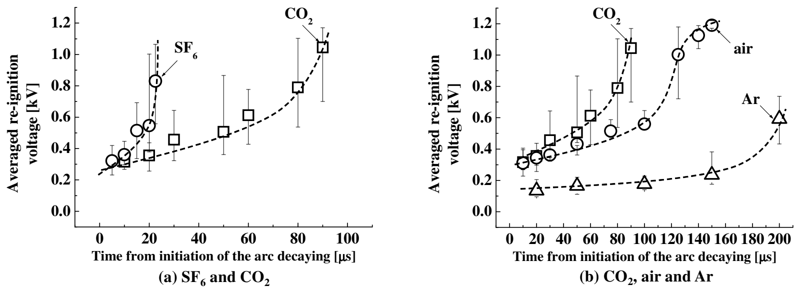

Fig. 8: Dielectric recovery properties of (a)SF_6 and CO_2, and (b)CO_2, air and Ar-blast arc

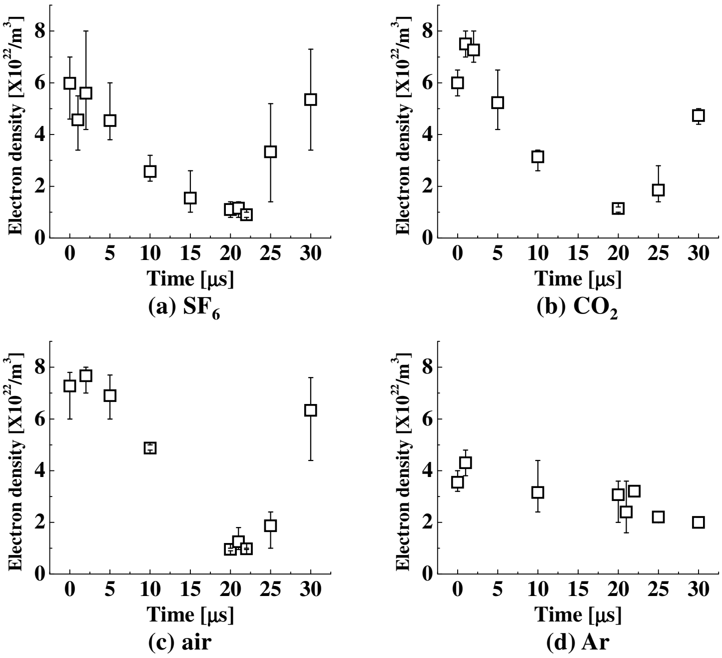

Fig. 9: Temporal variation in the electron density of the arc at the nozzle throat.

5 Conclusions

This thesis reported fundamental study about arc quenching technique using solid and gas media.

Firstly, the author has studied contributing factors on the spallation occurrence from polyamide materials, and a fundamental method of ejection frequency control of spallation particles. Water absorption is the simplest method for spallation occurrence. Furthermore, the author is also developing a new other enhancer of spallation phenomena instead of water, because it is hard to keep water in polyamide materials for a long time. Nevertheless, we believe that spallation phenomena can be one of the strongly effective applications for arc quenching or temperature control in various arc devices, including circuit breakers. For the actual use of spallation phenomena for a circuit breaker, it is necessary to conduct further arc quenching tests.

Secondly, the current interruption capabilities of various gases quantified using a newly developed method. The results obtained in this work will support the consideration of the fundamental characteristics of arc discharge and the development of alternatives to SF_6. Additional approaches must be made to ascertain the fundamental properties of current interruption phenomena. We are planning further investigation, such as the influence of TRV peak voltage and rise rate using advanced techniques with power semiconductors.

Finally, a gas-blast arc was intentionally decayed using power semiconductor by producing free recovery condition, and intentionally re-ignited by application of artificial recovery voltage called quasi-TRV. From many tests, dielectric recovery properties of SF_6, CO_2, air and Ar-blast arcs were obtained. Results showed that dielectric recovery of SF_6-blast arc is extremely faster than the other five gas flow in this work. The electron density both in decaying phase to re-ignition phase was obtained for each gas-blast arc using laser Thomson scattering (LTS) method. It was found that electron density in the SF_6-blast arc decreases quickly during the arc decaying phase, and after the arc re-ignition the electron density rises more quickly. The obtained data helps us to consider thermally arc re-ignition process.

The author believes that the obtained results are useful for future development of smart grids and eco-friendly energy transport.

平成３０年　１月３０日

学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

Fundamental study on quenching technique and decaying processes of arc plasmas using solid and gas media

（気・固相消弧媒体を利用したアークプラズマ冷却手法と減衰過程に関する基礎研究）

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３．審査結果の要旨（600～650字）

平成30年1月30日に第1回学位論文審査委員会，同日に口頭発表，第2回審査委員会を開催し，慎重審議の結果，以下のとおり判定した。なお，口頭発表における質疑を最終試験に代えるものとした。

低電圧配線用遮断器の中には，固体消弧材料としてポリマを用い，それにアークを接触させることでポリマを溶発させ，その噴出ガスによりアークを消滅させるものがある。本論文では，ポリマにポリアミド系材料(PA6,PA66など)を用いた場合，溶発だけでなく数百μm のマイクロ粒子が多数噴出するスポレーション現象を発見した。スポレーション現象がポリアミド材の吸水効果により生じること，さらにマイクロ粒子がアークに混入・蒸発することで，アーク温度を数千K低下できることを明らかにした。

高電圧電力用遮断器にはガスが消弧媒体としておもに使用される。現在，SF_6 ガスが消弧媒体として広く用いられるが，温室効果が高くその代替ガスが切望され，その試験方法も求められている。本論文では，SF_6，CO_2，N_2 などの様々なガス吹付けアークに対して，時間制御よくアーク減衰過程を把握するために，パワー半導体をμs オーダで制御しながらアークへの電流注入と減衰アークへの電圧印加を行う新試験手法を提案している。本手法を用い，同一条件で各種ガス吹付けアーク減衰過程，絶縁回復特性を実験的に明らかにした。同時に九州大学との共同研究によるレーザトムソン散乱法を用いた電子密度測定に基づいて，この各種ガス吹付けアーク内の電子密度減衰過程を明らかにした。これらのデータは，SF_6 代替ガス内におけるアーク減衰状態の検討上，極めて重要な基礎データである。

以上，本研究は，低電圧・高電圧遮断器内のアーク減衰過程の解明に対して大きく貢献するものである。そのため，本論文は博士（工学）に値すると判定した。

４．審査結果　(1) 判　　定（いずれかに○印）　○合　格　・　不合格

(2) 授与学位　博　士（工学）