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Influence of Various Gas Inclusion in Ar Thermal ICP at Atmospheric Pressure upon Plasma Temperature and Impedance

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Abstract—The influence of various gas inclusions upon thermal plasma was investigated from the viewpoint of finding alternatives to SF₆ as an arc-quenching medium in a high voltage circuit breaker. The inductively coupled thermal plasma (ICTP) technique was used to sustain thermal plasma. The effect of SF₆ and six environmental-benign gas inclusions on plasma temperature and impedance was measured. The result indicated that SF₆ causes the plasma radius reduction and plasma temperature decline only with a several percentage inclusion. The similar tendency was found for CO₂, while it was not found for the other five gases. This indicates that CO₂ has a higher plasma-quenching property than the others in the experiment.

Index Terms—Arc-quenching medium, Inductively coupled thermal plasma, Temperature, Radiation intensity, Impedance.

I. INTRODUCTION

RECENTLY, SF₆ gas-blast circuit breakers are widely used in electric power systems, since SF₆ has an attractively high arc-quenching capability[1]. However, release of SF₆ and its product to atmosphere causes an environmental issue because of their high greenhouse effects. To compare the greenhouse effect of different gases, a method has been developed of estimating their global warming potentials (GWP). The GWP is the cumulative enhancement occurring between now and a chosen later time, in relation to a reference gas, CO₂. Because SF₆ has an extremely high GWP of 23900, developed countries were required to reduce the emission of six greenhouse gases including SF₆ in COP3 held in Kyoto, Japan in 1997[2]. Thereby, alternatives to SF₆ have been greatly desired for an arc-quenching medium.

Until now, much effort have been made to search for alternatives to SF₆ for an arc-quenching medium[3-9]. However, no other gas with small GWP and high arc-quenching property has been found. Gas mixtures such as SF₆/N₂ or SF₆/CF₄ are expected to be used for the moment, however, use of these mixtures is not an essential resolution of the environmental issue.

The arc-quenching phenomenon in a circuit breaker is

extremely complicated because it has many simultaneous problems such as very fast transient fluid dynamics, electromagnetic force, turbulence, radiation and non-equilibrium effects. This complexity makes it difficult to understand fully the circuit-breaker arcs. For searching for alternatives to SF₆, it is very important to know the detail in arc-quenching properties of SF₆ and other gases fundamentally.

In this paper, the inductively coupled thermal plasma (ICTP) technique is used to investigate the quenching-effect of gases including SF₆ and other environmentally-benign gases on arc or thermal plasma. The ICTP technique enables us to make a clean thermal plasma free from any contamination. This feature is useful for studying fundamental and inherent properties of gas on thermal plasma, and helps us to understand the arc-quenching phenomena. During various gases injection to Ar ICTP, changes in the impedance and plasma temperature were measured. The result indicated that SF₆ causes the plasma radius reduction and plasma temperature decline only with a several percentage inclusion. The similar tendency was found for CO₂.

II. BASIC IDEA OF USE OF INDUCTION THERMAL PLASMA TECHNIQUE

A. Features of induction thermal plasma

In this paper, high-pressure inductively coupled thermal plasma (ICTP) technique is used to study the arc-quenching effect of various gases fundamentally. Because both a circuit-breaker arc and the ICTP belong to the high-pressure thermal plasma, these have the following similar properties in terms of thermodynamics. (i) They have very high collision frequency between particles, which gives high heavy-particle temperature close to electron temperature. (ii) Their behavior can approximately be described by the thermodynamic and transport properties determined by the temperature and the pressure. (iii) Thermal ionization occurs in them to sustain themselves with having a certain level of electrical conductivity.

Advantages of ICTP technique are clarified as follows: (a) A clean thermal plasma can be made without any impurities because ICTP has no electrode. (b) The ICTP has a good repeatability in its production compared with one-shot circuit-breaker arcs. (c) Injection of gases and/or materials into the ICTP permits a fundamental investigation of their influences

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Fig.1 Schematic diagram of plasma torch.

Fig.2 Plasma impedance measurement system.

on thermal plasma.

B. Parameters for measurement

SF₆ has remarkably high plasma-quenching ability because it seems to have the following properties: (1) SF₆ has a large thermal conductivity around 2000 K due to SF₆, SF₄ and SF₂ dissociations. This high thermal-conductivity at low temperature shrinks the thermal plasma, which leads plasma to have fast transient behavior. (2) SF₆ and its products have large electron-attachment cross-sections, which results in a drastic decrease in the electron density and then the plasma temperature especially at low temperature below 5000 K.

The above properties can be investigated in the steady state ICTP to measure the following points: The first property also results in shrinkage of the ICTP area. This is investigated by measuring the radial distribution of the radiation intensity in the ICTP. The second point is related to the decay of plasma temperature, which is confirmed by the excitation-temperature

Fig.3 Spectroscopic observation system.

estimation from species in ICTP. These changes in plasma radius and temperature also involve plasma impedance.

III. EXPERIMENTAL SETUP

A. Plasma Torch

Fig.1 illustrates a schematic diagram of the plasma torch used in the experiment. The torch is composed of two coaxial quartz tubes with a 161mm length. The inside diameter of the inner and outer quartz tubes are 82 and 100 mm, respectively. Between these tubes, cooling water flows from the bottom to the top-side with a swirl to keep the wall temperature around 300 K. Argon or Argon-additional gas mixture is supplied as a sheath gas along the inner quartz tube wall with a swirl to prevent the plasma from contacting to damage the inner quartz tube. A large chamber with a diameter of 1100mm and a length of 3000 mm is placed under the torch. The plasma in the torch receives power from a 3-turn coil by electromagnetic coupling. The coil is connected with a high-power vacuum tube oscillator with a frequency of 1.67 MHz and a maximum power of 200kW.

B. Measurement System of Plasma Impedance

Fig.2 shows a system for measuring coil-current and coil-voltage to obtain plasma impedance. The coil-current is measured with a 5-MHz-high-voltage Rogowski coil. The two coil-to-ground voltages are measured with two 15-MHz high-voltage C-R potential dividers. Subtracting the voltage from the other yields coil-voltage. Impedance Z, which is related to plasma state, is obtained by the coil-voltage and the coil current.

Fig.4 Measured impedance and phase difference versus additional gas admixture ratio.

Fig.5 Equivalent circuit of induction plasma.

C. Spectroscopic Observation System

Fig.3 shows a spectroscopic observation system. The observation position is adjusted to 10mm below the coil end. The light radiated from the observation position is transmitted through a lens and a mirror to the monochromator. At the focal plane of the monochromator, a multi-channel detector is installed to measure light intensities in the wavelength range of 100 nm simultaneously. Radial distribution of the radiation intensity from the thermal plasma can be measured. The whole optical system was calibrated using a tungsten-halide lamp.

D. Experimental Conditions

In the experiment, the input power was set to 50 kW at the plate terminal of the vacuum tube oscillator. The actual input power to the thermal plasma was estimated to be about 30kW according to the power conversion efficiency of the vacuum tube oscillator. Pressure inside the chamber was fixed at atmospheric pressure 101325 Pa. The total sheath gas flow rate was adjusted to 100 liters/min ($=1.67 \times 10^{-3} \text{ m}^3/\text{s}$) for different kinds of additional gases. The additional gas

Fig.6 Calculated dependence of impedance and phase difference.

admixture ratio X_{add} is defined as follows:

$$X_{\text{add}}[\%] = \frac{Q_{\text{add}}}{Q_{\text{Ar}} + Q_{\text{add}}} \times 100,$$

where Q_{Ar} and Q_{add} are the gas flow rates of Ar and the additional gas, respectively.

IV. INFLUENCE ON PLASMA IMPEDANCE

A. Change in Plasma Impedance by Additional Gas Inclusion

The obtained impedance Z including phase difference between the coil-current and the coil-voltage was affected by additional gas inclusions. Fig.4(a) shows the measured absolute value of the impedance $|Z|$ and the phase difference versus additional gas admixture ratio X_{add} . Pure Ar ICTP has the magnitude of $|Z|$ around 55 Ω. With an inclusion of SF₆ even with a small X_{add} , $|Z|$ remarkably rises, and then reaches to over 100 Ω with 10%SF₆ inclusion. In N₂ case, $|Z|$ increases with X_{add} up to 10%, whereas a further inclusion of N₂ does not increase $|Z|$ considerably. In case of CO₂, $|Z|$ elevates with CO₂ inclusion in proportion to X_{add} .

Fig.4 (b) indicates the measured phase difference between coil-current and coil-voltage. The 100%Ar ICTP has a small phase difference around 4 degree. This value remarkably increases with SF₆ inclusion. However, a further increase in X_{add} from 8 to 10 % causes a decline in phase difference. In cases of N₂ and CO₂, the phase difference increases and then decreases with X_{add} .

As seen in Fig.4, two categories are found in changes of $|Z|$ and the phase difference: the first is that both $|Z|$ and the phase difference increase, the second is that $|Z|$ increases while the phase difference decreases.

Fig.7 Measured radial distribution of radiation intensity of Ar spectral line at 703 nm.

B. Dependence of plasma impedance on circuit parameter and plasma parameter

The above changes in Z are originated from plasma condition related to eddy current path. The circuit behavior of the ICTP is interpreted by an equivalent circuit of a transformer. Fig.5 shows the equivalent circuit, in which Z is expressed as follows:

$$Z = R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} + j\omega \left(L_1 - \frac{\omega^2 M^2 L_2}{R_2^2 + \omega^2 L_2^2} \right) = |Z| \exp(j\phi)$$

where R_1 is the coil resistance, L_1 is the self-inductance of the coil, M is the mutual-inductance between the coil and the plasma, L_2 is the self-inductance of the plasma, R_2 is the resistance of the plasma, ω is the angular-frequency, ϕ is the phase difference. Because the R_1 and L_1 have been obtained to be 0.54Ω and $1.37 \mu\text{H}$, respectively, in another experiment, then Z depends only on three parameters M , L_2 and R_2 . The quantities M and L_2 are considered to be a function of squire value of a plasma radius. The magnitude R_2 depends on the plasma temperature, that is, R_2 decreases with increasing temperature because electrical conductivity of the plasma markedly increases with temperature. Figs. 6(a) and (b) show examples of dependences of $|Z|$ and ϕ on plasma radius and R_2 obtained by the calculation. In this calculation, R_2 is set to a typical value of 1Ω for deriving Z on plasma radius, while plasma radius is set to 25 mm for Z on R_2 . It is seen that decreasing plasma radius increases both $|Z|$ and ϕ , while increasing R_2 involves an increase in $|Z|$ and a decrease in ϕ . These changes are found to agree with the experimental result shown in Fig.4. This agreement indicates that the first change in Z arises from a reduction of plasma radius, and the second is due to plasma temperature decline.

V. INFLUENCE ON PLASMA RADIUS AND TEMPERATURE BY SPECTROSCOPIC OBSERVATION APPROACH

For the purpose of cross-checking and developing the above discussions, spectroscopic observation was carried out to obtain the plasma radius reduction and plasma temperature decline by gas inclusion.

A. Radiation intensity

Figs.7(a)-(c) indicate radial distribution of the radiation intensity of Ar line at 703 nm measured at 10 mm below the coil end. It should be noted that $0.8\% \text{ SF}_6$ inclusion drastically decreases the radiation intensity. Similar tendency can be seen in $10\% \text{ CO}_2$ inclusion case. On the other hand, up to $30\% \text{ N}_2$ inclusion does not cause such a drastic decrease in radiation intensity. Further experiments were carried out for other gas inclusions of H_2 , He , O_2 or air, and the results indicated that up to 10% inclusion of these gases hardly affected the radiation intensity. Selection of other spectral lines leads to the similar dependence on gas inclusion, which means that the radiation intensity decay is attributed to the plasma quenching itself.

B. Temperature

The two-line method was applied to estimate the excitation temperature of Ar on the assumption that the plasma was under the local thermal equilibrium (LTE) condition. Two Ar lines at 703 nm and 714 nm were selected for this estimation. This couple of the lines has a large difference of 1.5 eV in the upper potential level, which facilitates precise temperature estimation. Figs.8(a)-(c) indicates radial temperature distributions for Ar- N_2 , Ar- CO_2 and Ar- SF_6 ICTP. It can be found that N_2 injection scarcely decreases the temperature of Ar ICTP. The H_2 , He , O_2 and air inclusion also keeps temperature high. However, CO_2 inclusion markedly decays the temperature, similarly to SF_6 . For example, $1\% \text{ SF}_6$ and $10\% \text{ CO}_2$ inclusions decline the temperature by over 1500 K . The above decline characteristics of the radiation intensity and

Fig.8 Measured radial temperature distribution at 10mm below the coil end.

Fig.9 Calculated radial temperature distribution at 10mm below the coil end.

the temperature can be considered to indicate the high plasma-quenching capability of gases.

VI. MODELING OF AR ICTP WITH ADDITIONAL GAS

In order to interpret the phenomena obtained in the experiment, a two-dimensional model was developed to simulate flow and temperature fields in an Ar ICTP with an additional gas. On the assumption of local thermal equilibrium, optically thin and laminar flow conditions, the behavior of ICTP in a steady state can be described by solving conservation equations of mass, momentum and energy and Maxwell equation for vector potential and equation of state. These simultaneous equations in a two-dimensional space were solved by SIMPLER method after Patankar [10]. Figs.9(a)-(c) show calculated radial distribution of plasma temperature at 10 mm below the coil end for SF₆, CO₂ and N₂ inclusion cases. SF₆ and CO₂ inclusion remarkably decreases

the plasma radius and temperature, whilst N₂ inclusion causes less decreases in them than the other gases. This approximately agrees with the results of the radiation, temperature and plasma impedance as described in the previous section.

VII. CONCLUSIONS

The influence of various gas inclusions upon thermal plasma was investigated from the viewpoint of finding alternative to SF₆ as an arc-quenching medium in a high voltage circuit breaker. The inductively coupled thermal plasma (ICTP) technique was used to sustain thermal plasma. The effect of SF₆ and six environmental-benign gas inclusions on plasma impedance and temperature was measured. The result indicated that SF₆ causes the plasma radius reduction and plasma temperature decline only with a several percentage inclusion. The similar tendency was found for CO₂, which

indicates that CO_2 is one of the candidates for the environmentally-benign arc-quenching medium.

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IX. BIOGRAPHIES

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