OPTICAL DIAGNOSTICS OF DECAY PROCESSES OF Ar/SF$_6$ GAS BLAST ARCS CONFINED BY A NOZZLE

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ABSTRACT

Spatiotemporal evolutions of the electron density (n_e) were measured in decaying SF$_6$ gas-blast arc discharges formed with a long gap (50 mm) in a confined nozzle using laser Thomson scattering. Pure Ar gas and an 80%Ar/20%SF$_6$ mixture gas were used as the arc quenching media at atmospheric pressure. After reducing the current to zero, both the measured n_e and arc radius in the Ar/SF$_6$ gas arc clearly decayed more rapidly than in the pure Ar gas arc.

1. INTRODUCTION

Gas circuit breakers (GCBs) are one of the most important components for high voltage power system [1-2]. For high voltage circuit breaker rated at more than 72 kV, high-pressure SF$_6$ gas is commonly used as the arc quenching media [1-4]. However, SF$_6$ has very high global warming potential, 22,800 times larger than that of CO$_2$. Hence, there is an ongoing search for alternative gases for SF$_6$. For the effective searching and/or development of such alternative gases, the diagnostics of the arc discharges generated inside the GCBs is crucial [5]. Especially, the precise measurements of electron density (n_e) in a decaying arc discharge in a transient state are indispensable since n_e in the arc discharges at current-zero is strongly related to success or failure of arc interruptions [6,7].

In this work, laser Thomson scattering (LTS) has been applied to SF$_6$ gas-blast decaying arcs formed with long-gap movable electrodes and confined by a nozzle, for spatiotemporal measurements of their n_e and electron temperature (T_e).

2.PRINCIPLE

The LTS method can give local values of n_e and T_e in plasmas with high spatial and temporal resolutions [8, 9]. This method has already been applied to wide variety of plasmas[10,11]. However, it has never been applied to the current-zero phase of SF$_6$ gas-blast arcs formed with long-gap movable electrodes and confined by a nozzle, which decay in a time scale of microseconds.

Since the principle of LTS for the diagnostics of plasmas has been described in detail in various references [8], here we describe the principle only to understand the situation of LTS for this study. Thomson scattering is characterized by the parameter α; $\alpha = (\boldsymbol{k}\lambda_D)^{-1}$. Here, $\boldsymbol{k}$ is the absolute value of the differential wave-number vector determined by the incident laser wave-number vector and the scattered-light wave-number vector, and λ_D is the Debye length. Since α was found to be in the range between 0.5 and 2 in this study, Thomson scattering was in the collective regime, where the LTS spectrum consists of an ion term and an electron term. The ion term has a very narrow spectrum (< 0.1 nm) and is quite difficult to detect with a conventional system. On the other hand, the electron term is relatively broad (> 1 nm). Therefore, we observed the electron term to diagnose the plasma. In the range of α mentioned above, the values of n_e and

T_e can be evaluated from the spectral shape and the peak wavelength of the electron term.

3.EXPERIMENT

Figure 1 shows the schematics of an electrical circuit and the longitudinal cross section of electrodes and the nozzle for the arc discharges. An inverter-controlled direct-current source was used as a power supply. It was directly connected to the electrodes, which were made of copper-tungsten. The electrodes were confined by a polytetrafluoroethylene (PTFE) nozzle, and were set inside a vacuum chamber. Before producing the arcs, the tips of the two electrodes were brought in contact. The procedure of arc generation was as follows: After evacuating the vacuum chamber, electrodes were axially blasted by the gases (Ar gas or Ar/SF_6 gas mixture) with a total gas-flow rate of 100 l/min. When the total pressure inside the chamber reached 760 torr, an arc current was applied to the electrodes. After keeping the arc current (50 A) for 200 ms, only the anode electrode was moved and 50 mm long-gap arcs were generated. To move the anode electrode, a high-pressure cylinder was used, which was controlled with an electromagnetic valve. For the interruption of the arc current, a semiconductor switch (insulated gate bipolar transistor: IGBT) was used, which was connected in parallel with both the power source and the electrodes. At a time of 160 ms after generating the 50 mm long-gap arcs, the IGBT circuit was closed and the arc current was removed from the arcs to the IGBT circuit, and the interruption of the arc current was realized. After the current interruption, no transient-recovery voltage was applied in this experiment.

For the LTS measurements, the second harmonics of a Nd:YAG laser (λ= 532 nm, 10 ns pulse width, laser energy of 50 mJ) were used as probes. To measure the arcs inside the nozzle, two small holes (φ= 3 mm) to inject the laser and an oblong hole (6 mm × 15 mm) to collect the scattered light were made. The oblong hole was made at an angle of 90 degree from the laser path. The laser beam was focused onto a distance of 28 mm above the tip of the cathode electrode through a focusing lens (f = 300 mm). The light scattered from the plasma was focused onto the entrance slit (0.2 mm width and 6 mm height) of a triple-grating spectrometer (TGS) [9] with two achromatic lenses (f = 300 mm, 46 mm effective diameter). The focal length of the TGS was 250 mm and the TGS contains three diffraction gratings (2400 line/mm, 76 mm × 70 mm effective area). The total spectral resolution of the TGS was 0.18 nm and an ICCD camera was used as a detector. By using the TGS, the strong stray light due to reflections of the laser light at the surfaces of the electrodes and the nozzle, were sufficiently reduced. The clear LTS spectra were observed by a single laser-shot measurement when n_e was more than 10^{22} m^{-3}.

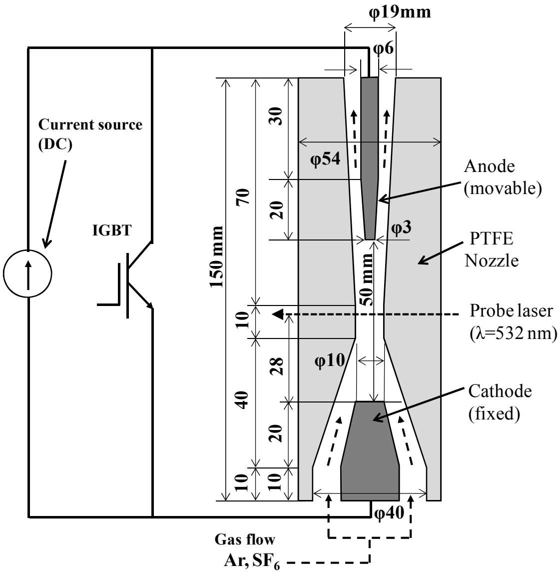

Fig. 1. Schematics of the electricathe electrodes confined by a nozzle for gas-blasted arcs.

4.RESULTS AND DISCUSSIONS

Before the current interruption (t = 0 μs), the applied voltage of the Ar and Ar/SF_6 (20%) arcs were 50 V and 60 V, respectively. After the interruption, the arc current was decreased exponentially.

Unfortunately, when the proportion of the SF_6 gas was higher than 20%, the arcs fluctuated significantly and these conditions were not suitable for the LTS measurements because of the poor reproducibility. Thus, at first, we performed the LTS only on the arcs produced with the Ar gas or the Ar/SF_6 (20%) gas mixture. Figure 2 shows an example of the Thomson scattering spectrum observed from the Ar/SF_6 (20%) arcs at t = 2 μs.

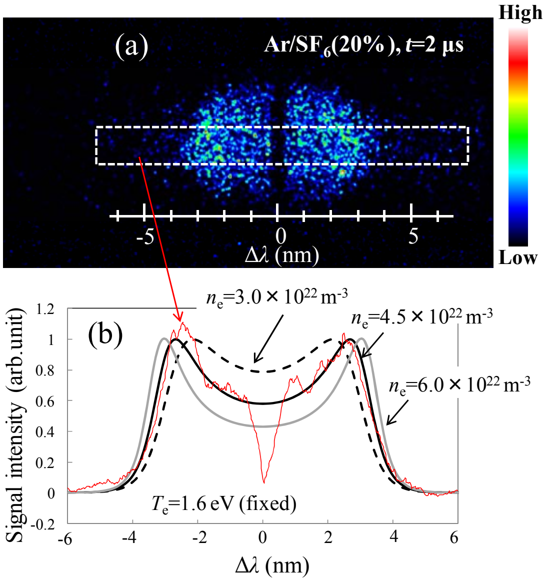

Fig. 2. (a): Two-dimensional LTS image of the Ar/SF$_6$ (20%) arc measured at t = 2 µs, (b): LTS spectrum extracted from Fig. 3 (a) (-0.5 mm < x < 0.5 mm) and theoretical fitting curves. The measured spectrum was smoothed with a moving average method.

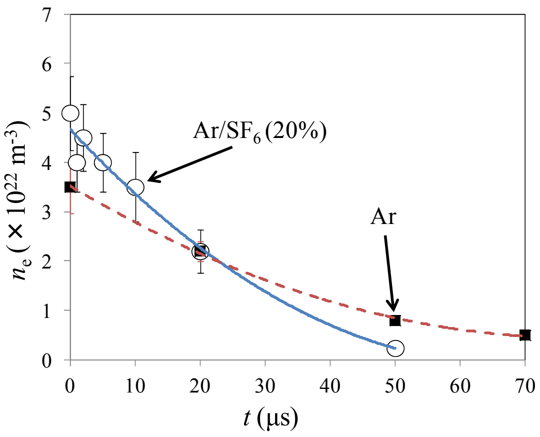

Fig. 3. Temporal evolution of the electron density at the center of the Ar and Ar/SF$_6$ (20%) arcs after the current interruption.

These measurements were performed with a single-laser shot. Since the ICCD camera was used as the detector, the one-dimensional spatial distribution corresponding to the probing-laser path (radial direction: x) of LTS spectra were observed at a same time. Although a part of the LTS spectrum was cut by the TGS around the probing-laser wavelength (531.8-532.2 nm), a clear electron term was observed. Figure 2 (b) shows the LTS spectrum at the center of the discharge (-0.5 mm < x < 0.5 mm) and theoretical curves having different n_e. In Fig. 2 (b), the measured spectrum was smoothed with a moving average method. Through the fitting procedure, n_e and T_e were estimated to be 4.5×10^{22} m^{-3} and 1.6 eV, respectively. The LTS measurements were performed at several times (t = 0, 1, 2, 5, 10, 20, 50, and 70 µs) to obtain temporal evolutions of n_e and T_e. Figure 3 shows the temporal evolutions of electron density of the Ar arc and of the Ar/SF$_6$ (20%) arc at the center of the plasmas. At t = 70 µs, we could not measure the clear LTS spectrum from the Ar/SF$_6$(20%) arc since n_e was too small to measure with this system. The results of the LTS measurements shows clear differences of temporal evolutions for the case of the Ar arcs and the Ar/SF6(20%) arcs. Before interrupting the arc current, the n_e of the Ar/SF$_6$(20%) arc was larger than that of Ar. After the current interruption, however, the n_e of the Ar/SF$_6$ (20%) arc decreased rapidly. At t = 50 µs, the n_e of the Ar/SF$_6$ (20%) arc became much smaller than that of the Ar arc, and at t = 70 µs, the Ar arc still kept n_e larger than that of the Ar/SF$_6$ (20%) arc at t = 50 µs. These results clearly show that the decay speed of n_e in the Ar/SF$_6$(20%) arc after the current interruption was larger than that in the Ar arc.

5.CONCLUSIONS

We have applied LTS to the decaying SF$_6$ gas-blasted arcs formed with a long-gap movable electrode confined by the PTFE nozzle. The LTS signals were detected before and after the current interruption and the temporal evolutions of n_e were measured. After the current interruption, the n_e in the Ar/SF$_6$ (20%) gas arc decayed more rapidly than in the Ar gas arc, although the n_e was larger than that of Ar gas arc before the interruption. In order to investigate the alternative gases inside high-voltage circuit breakers, quantitative characteristics of arcs, especially n_e around current-zero is crucial. The results of this study gave the first quantitative measurements of these parameters and clearly showed that the decay speed of n_e is increased when SF$_6$ is used as the arc quenching media.

As a future work, diagnostics of decaying arcs produced with SF$_6$ (100%) gas are needed. As described before, with SF$_6$ (100%) gas, it is difficult to generate the arcs in a same position. As a result, LTS signals from SF_6 (100%) are not reproducible. In order to overcome this problem, we are developing a new LTS system, in which a cylindrical lens instead of a conventional spherical lens is used to focus the probe laser. With the cylindrical lens, the probing laser is focused to be a sheet-type. This type of laser is convenient to cross the arc column even if the arc position is not stable.

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