Energy Consumption Characteristics of Pulsed Arc Discharge in High Pressure Carbon Dioxide up to Supercritical Phase

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***Abstract*— Energy consumption of pulsed arc discharge *E* in high pressure CO_2 up to supercritical (SC) phase was investigated under positive pulsed voltage that was applied to needle-to-plane electrode by a magnetic pulse compression circuit. The gap distance of approximately several hundred µm was set inside a high pressure chamber. The peak current of pulsed arc discharge was in the range of 400-600 amperes at gas and supercritical phases. The *E* was calculated by the dumped oscillatory voltage and current under the post-breakdown. In the gas phase, the *E* increased with medium density up to sub-critical phase. Meanwhile, the *E* was almost stable irrespective of medium density in the supercritical phase. Spectroscopic measurement was also carried out to confirm the local thermal equilibrium of the arc plasma at SC phase. The spectral distribution was characterized by the black body (Planck) radiation and line spectra of atomic oxygen (777 and 845 nm).**

Keywords—pulsed arc discharge; supercritical carbon dioxide; energy consumption; spectroscopic measurement

I. Introduction

Recently, discharges in supercritical (SC) fluids have been attracted attention as a power switch and a new chemical reaction field. SC fluids hold potential as an alternative medium of SF_6 due to its high dielectric strength and excellent physical properties. We studied the dielectric recovery phenomena in liquid CO_2 and SC-CO_2 by a laser shadowgraph technique [1]. The results showed that the shadowgraph image of low density region (LDR) caused by the pulsed arc discharge was quite different between liquid CO_2 and SC-CO_2 phases. The bubble like LDR and thinned LDR were observed in liquid CO_2 and SC-CO_2, respectively. In consequence, the voltage recovery rate in SC-CO_2 was greater than that of liquid CO_2. J. Zhang et al. investigated the characteristics of the dielectric recovery phenomena in SC nitrogen by numerical and experimental approaches [2]-[4]. The literatures indicated that SC nitrogen has high breakdown voltage and fast recovery speed. On the other hand, generation of discharge plasma in SC fluids have been draw increasing attention as new chemical reaction fields. The phenol polymerization and carbon material syntheses were reported by some literatures [5]-[7]. Although, the energy consumption of discharge plasma plays a significant role in the elucidation of the breakdown phenomena and chemical reaction processes, the energy consumption in SC fluids have been incompletely studied.

This study describes the energy consumption characteristics of the pulsed arc discharge and its spectroscopic measurements in high pressure CO_2 up to SC phase. The energy consumption was calculated by the dumped oscillatory voltage and current.

II. Experimental Setup and Procedure

The schematic diagram of experimental setup is shown in Fig. 1. The illustrated high pressure chamber is cross-section diagram (top view). A needle-to-plane electrode with gap distance of approximately several hundred µm was set inside a high pressure chamber. The tungsten was adopted as a material of the needle electrode to minimize the erosion. The high pressure chamber was insulated by the high voltage bushing made of PEEK (Poly Ether Ether Ketone) resin that is excellent at dielectric strength and chemical stress. To reduce the inductance, the high voltage line and the ground line connected to the high pressure chamber were as short as possible. The pulsed voltage was generated by a magnetic pulse compression (MPC) circuit (Suematsu Elect. CO., LTD.). The pulse transformer with ratio of n = 3 was connected to the output of the MPC since it is hard to cause a breakdown in high pressure condition by the MPC with maximum output peak voltage of 30 kV. The capacitor of 50 pF was connected in parallel to the high pressure chamber. The positive pulsed voltage with a few tens nanoseconds rise time was applied to the needle electrode. The voltage and current were measured by a high voltage probe (Pulse Electric Engineering CO., LTD., EP-100K) and a current monitor (Pearson Electronics, INC., Model 6595) and were recorded by a digital oscilloscope (Tektronix, DPO4104B-L). The sapphire window was installed in the side of the high pressure chamber due to its broad spectrum characteristics. Optical emission spectra (OES) were obtained with a multi-channel spectroscope (B&W Tek INC., Glacier X). The calibration of irradiance was done in advance. The light

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emission between needle-to-plane electrode was measured by convex lends that is connected to the optical fiber.

The detailed operation system of temperature and pressure inside the chamber was explained by the previous study [8]. The illustration of phase diagram of CO_2 based on the equation of state of Helmholtz free energy is shown in Fig. 2. The critical temperature and pressure of CO_2 are 304.1 K and 7.38 MPa, respectively. The experiments of E were carried out at 306 K in the wide range of medium density up to SC phase, as shown in Fig.2.

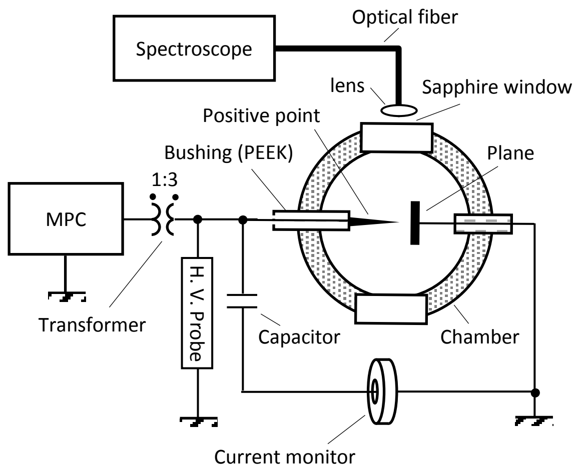


Fig. 1. Schematic diagram of experimental setup. The illustration of high pressure chamber is cross-section (top-view).

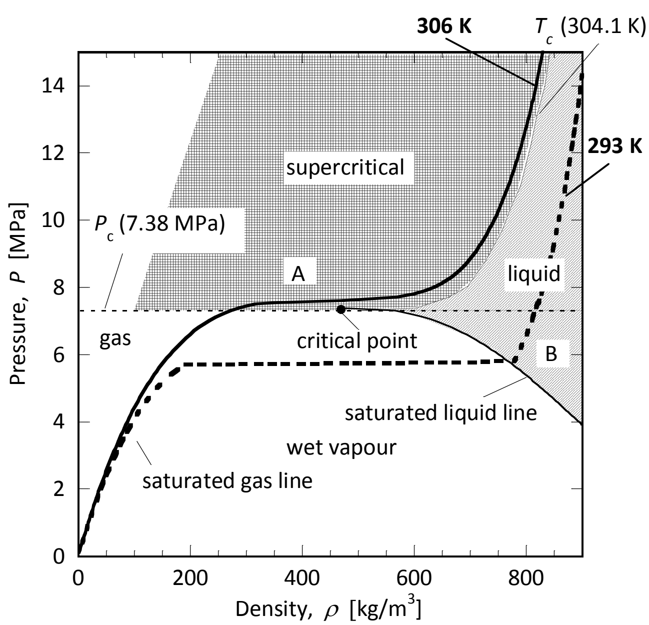


Fig. 2. Illustration of phase daiagram of CO_2.

III. Result and Disucussion

A. Voltage and Current Waveforms and Energy Consumption

Typical voltage and current waveforms are shown in Fig. 3. The rise time of voltage is approximately 57 ns. At the moment of breakdown, the voltage suddenly decreased while increasing current pulse. The dumped oscillatory waveforms are measured in post-breakdown. It is well known LCR dumped oscillation due to pulsed arc discharge with high conductivity. In this study, the energy consumption E was calculated by following equation.

$$E = \int_0^{t_0} v(t)i(t)dt \qquad (1)$$

Where $v(t)$ is applied voltage, $i(t)$ is current and t_0 is the data recording time. The phase difference of BNC cables between voltage and current signals was calibrated in advance. The calculation result of E at SC phase by equation (1) is shown in Fig. 4. The E increases with oscillating by inductance of circuit and plasma in post breakdown ($t > 0$). It should be noticed that the calculation result E includes an energy consumption at the resistance of circuit. Thus, it is inferred that the value of E is greater than that of actual consumption energy of arc plasma.

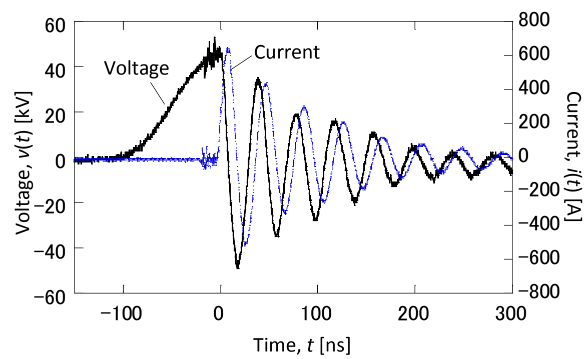


Fig. 3. Typical voltage and current waveforms at SC phase (P = 7.38 MPa, T = 306 K).

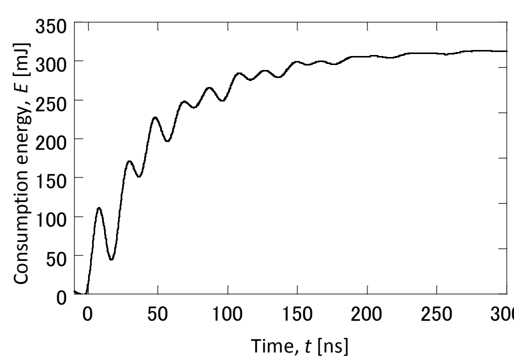


Fig. 4. Calculation result of the energy consumption of pulsed arc discharge at SC phase (P = 7.38 MPa, T = 306 K).

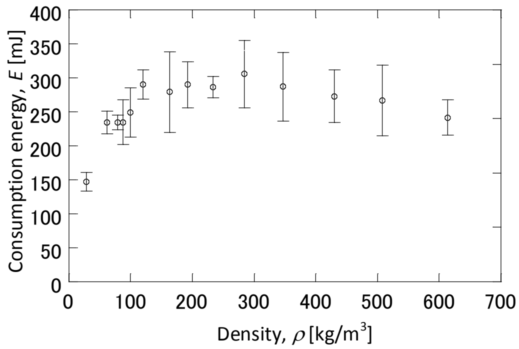


Fig. 5. Energy consumption of pulsed arc discharge as a function of medioun density (T = 306 K).

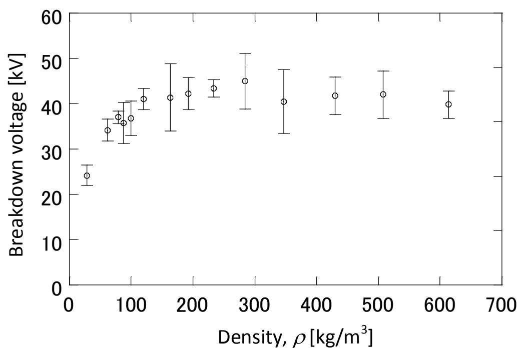
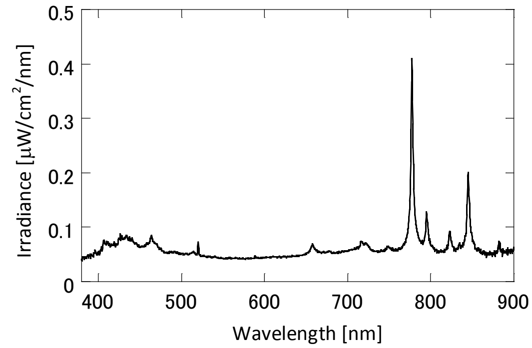
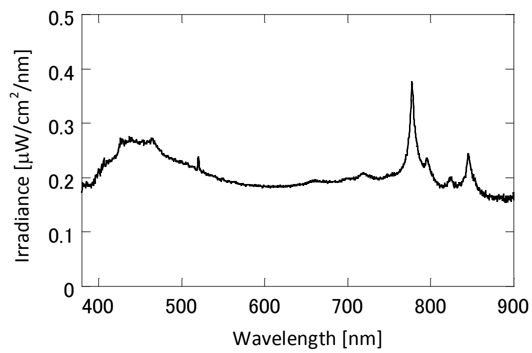


Fig. 6. Breakdwon voltage as a function of medium density (T = 306 K).



(a) gas phase



(b) SC phase

Fig. 7. Optical emission spectra of pulsed arc dsicahrge in pressrized CO_2 (a) gas phase (P = 1.5 MPa, T = 306 K), (b) SC phase (P = 7.6 MPa, T = 306 K).

The calculated E as a function of medium density is shown in Fig. 5. In the gas phase, E increases with increasing medium density up to around 100 kg/m^3. E is saturated with increasing medium density when going from gas to SC phase. On the other hand, the breakdown voltage as a function of medium density is shown in Fig. 6. Breakdown voltage is also saturated irrespective of medium density under SC phase. The saturation characteristics of breakdown voltage were also measured by previous studies of DC and pulsed breakdown [5], [9]. It is supposed that the similar characteristics between E and breakdown voltage correlate to each other. In addition, it was found that the low error bar (standard deviation) of breakdown voltage at 233 kg/m^3 was indicated as shown in Fig. 6. The check of this characteristic is an interesting investigation in the future.

B. Spectroscopic Measurements

OES with 15 accumulations of pulsed arc discharge at gas (1.5 MPa, 306 K) and SC phase (7.6 MPa, 306 K) are shown in Fig. 7. Some bright line spectra are overlapped on the black-body radiation. The condition of pulsed arc discharge is able to assume the local thermodynamic equilibrium because of the black-body radiation. Relatively high bright line spectrum of OI peaks (at 777 nm ($3p^5P$–$3s^5S$), and 845 nm ($3p^3P$–$3s^3S$)) could be observed. On the other hand, some bright line spectra could be observed in the range of 350 - 590 nm. C_2, CO, CO^+ and CO_2^+ are supposed for low spectra [10]. According to [10], [11], high frequency plasma in SC CO_2, C_2 swan bands ($d^3\Pi_g \rightarrow a^3\Pi_u$) were observed in the range of 512-518 nm. In this study, the specific C_2 swan band was not observed.

IV. Conclusion

Energy consumption of pulsed arc discharge in high pressure CO_2 up to SC phase is investigated by analyzing the dumped oscillatory waveforms of voltage and current. Irradiation intensity of arc plasma in gas and SC CO_2 were also measured by a calibrated spectroscope. The results are summarized as follows.

1) A drastic change in the density dependence of energy consumption appeared around the sub-critical phase for the energy consumption characteristics when going from gas to SC phase. The dependence of breakdown voltage on the medium density is similar to the energy consumption characteristics.

2) Planck radiation was measured in the range of 350 – 950 nm. OI peaks (at 777 and 845 nm), C_2, CO, CO^+ and CO_2^+ were observed. Meanwhile, C_2 swan bands in the range of 512-518 nm was not observed at gas and SC phase.

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