# INVESTIGATION ON SPATIAL TEMPERATURE DECAY OF THERMAL PLASMA WITH POLYMER ABLATION

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Temperature decay of Ar thermal plasmas by polymer ablation was investigated using the induction thermal plasma irradiation technique with experimental and numerical approaches. In the present experiment, the vibrational and rotational temperatures of  $C_2$  molecule in the ablated polymer vapor was estimated to find decaying efficiency of the plasma temperature by the polymer ablation. A numerical thermofluid model was also newly developed including the thermal interaction between polymers and thermal plasmas. Both experimental and numerical results indicate that the plasma temperature at 1–2 mm above polymer surface decays by 2000 K due to the polymer ablation.

Keywords: inductively coupled thermal plasma, polymer ablation, spectroscopic observation, thermofluid model

## 1. Introduction

Polymer materials are widely used for gas flow nozzles in gas circuit breakers (GCB) or for insulation cases in molded case circuit breakers (MCCB). In a current interruption process, an arc plasma is formed between the electrodes in the circuit breaker. The arc plasma can contact the nozzle or the insulation case made of polymer materials, which inevitably causes polymer ablation. The polymer ablation produces a large amount of ablated vapor contaminating the arc plasma. These polymer ablation markedly influences arc interruption processes. Recently, a polymer-ablation assisted type of the lowvoltage MCCB has been developed[1], and a prototype of polymer-ablation assisted high-voltage GCB has been tested[2]. These circuit breakers utilize the polymer ablation phenomena to enhance their interruption capabilities. For improvement of the circuit breaker, it is greatly important to understand effects of polymer ablation on the thermal plasma. However, the interaction between polymer materials and an arc plasma is much complicated involving a large exchange in mass, momentum and energy between them, and it also causes mixing of the ablated polymer vapor and thermal plasma to change thermodynamic and transport properties of the plasmas.

In this paper, we investigated temperature decay of thermal plasmas due to polymer ablation using the inductively coupled thermal plasma (ICTP) irradiation technique [3]. The features of the ICTP are no contamination and good controllability compared to arc plasmas with the electrodes. In the present experi-

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ment, the Ar-ICTP was directly irradiated to the polymer bulk materials located downstream of the thermal plasma. Spectroscopic observation was carried out to obtain the vibrational and rotational temperatures  $T_{\rm vib}$  and  $T_{\rm rot}$  of C<sub>2</sub> molecule in the ablated polymer vapor. The temperature decay due to polymer ablation was estimated from the experimentally obtained temperatures for different polymer materials. Numerical thermofluid modelling was also made to consider thermal interaction between the polymer and thermal plasmas. Both experimental and numerical results indicate that the plasma temperature at 1–2 mm above polymer surface decays in several thousand kelvins by the polymer ablation.

## 2. Experimental setup

Fig. 1 shows a plasma torch, a specimen holder and a spectroscopic observation system used in this experiment. The plasma torch is composed of two coaxial water-cooled quartz tubes. The torch is 345 mm long, and 70 mm $\phi$  in inner diameter. Around the torch, an eight-turn induction coil is located to generate electromagnetic field inside the torch. From the top of the torch, Ar gas is supplied along the wall of the inner quartz tube as a sheath gas. A reaction chamber is installed downstream of the plasma torch. Inside the reaction chamber, a movable water-cooled specimen holder made of stainless steel is located. A cylindrical polymer specimen is mounted on the specimen holder as shown in Fig. 2. The diameter and the thickness of the specimen used here are  $15 \text{ mm}\phi$  and 5mm, respectively. The distance between the induction coil end and the specimen surface is fixed at 200 mm.



Fig. 1 Schematic diagram of RF plasma torch.



Fig. 2 Schematic diagram of specimen.

Spectroscopic observation was carried out to measure emission spectra from C<sub>2</sub> molecule contained in the ablated polymer vapor. The optical system is constituted of a quartz lens, a optical fiber bundle, a monochromator and ICCD detectors as indicated in Fig. 1. The spatial resolution of this system is about 2.5 mm $\phi$  in terms of the observation region. The center of the observation region is set at 1.3 mm above the specimen surface on the axial axis of the specimen.

The experimental condition was as follows: The pressure inside the chamber was 760 torr. The Ar gas flow rate was set to 30 slpm (=standard liters per minute). The input power to the thermal plasma was 7.5 kW. In this paper, three kinds of polymer materials; PTFE (polytetrafluoroethylene), PE (polyethylene) and POM (polymethylene) were used as a specimen. The PTFE has been used for a gas blast nozzle in the GCB, while the PE and POM were used for various applications. For comparison, a Ti specimen was also used and irradiated as no ablation case.

### 3. Results and discussion

### 3.1 Spectroscopic observation

Figs. 3(a), 3(b) and 3(c) show the emission spectra measured at 1.3 mm above the specimen surface of PTFE, PE and POM, respectively. For all materials, Ar spectral lines were observed in wavelength range of 700–800 nm. Spectra of  $C_2$  Swan system were also observed around 400–600 nm in cases of PTFE and



Fig. 3 Measured spectra at 1.3 mm above the specimen surface.

PE. On the other hand, in POM case, the  $C_2$  spectra were hardly observed. This is attributable to the fact that POM ablated vapor has less  $C_2$  molecules than PTFE and PE ablated vapor according to the calculated equilibrium composition of PTFE, PE and POM ablated vapor[3].

# 3.2 $C_2$ vibrational and rotational temperatures

The emission coefficient of  $C_2$  Swan system can be theoretically calculated as functions of rotational temperature  $T_{\rm rot}$  and vibrational temperature  $T_{\rm vib}$  on the assumption that population of exited molecules follows the Boltzmann distribution[4]. Fitting the calculated  $C_2$  spectra to the measured  $C_2$  spectra can determine  $T_{\rm rot}$ ,  $T_{\rm vib}$ .

Fig. 4 shows  $T_{\rm vib}$  and  $T_{\rm rot}$  estimated from the C<sub>2</sub> spectra in PTFE and PE vapor. This figure also contains Ar excitation temperature  $T_{\rm ex}^{\rm Ar}$  in case of Ti irradiation, i.e. no ablation case for comparison. The  $T_{\rm ex}^{\rm Ar}$  was determined by the Ar atomic spectral lines us-



Fig. 4  $T_{\rm ex}$  of Ar and  $T_{\rm vib}$ ,  $T_{\rm rot}$  of C<sub>2</sub> molecule.

ing the two-line method. However, in case of polymer specimen irradiation,  $T_{\rm ex}^{\rm Ar}$  could not be determined because the intensity of Ar atomic spectral lines was insufficient for the two-line method. In the present experimental condition, the  $T_{\rm ex}^{\rm Ar}$  is considered almost equal to the electron temperature. On the other hand,  $T_{\rm rot}$  seems closer to the heavy particle temperature because the energy transfer rate between rotational energy levels is enough high by collisions with heavy particles. Whereas  $T_{\rm vib}$  can be close to the electron temperature rather than the heavy particle temperature since a difference in vibrational levels is as large as 0.1 eV. Thus, we can roughly investigate the magnitude of temperature decay by comparing  $T_{\rm vib}$  in polymer ablation case with  $T_{\rm ex}^{\rm Ar}$  in no ablation case.

As seen in Fig. 4,  $T_{\rm vib}$  is about 4400 K in any polymer ablation cases, whereas it is 4000 K lower than the  $T_{\rm ex}^{\rm Ar}$  of 8600 K in no ablation case. This implies that the polymer ablation decays the temperature of Ar plasma by 4000 K. This temperature decay may result from the energy consumption for polymer solid ablation and also dissociation of ablated polymer vapor.

# 4. Thermofluid simulation4.1 Calculation condition

Numerical simulation is a powerful tool nowadays to understand complex phenomena such as the interaction between the plasma and the polymer ablation which involves mass, momentum, and energy transfer between them. We newly developed a numerical thermofluid model including the above interactions to elucidate the effect of polymer ablation on temperature decay of the thermal plasma. The developed model takes into account the thermal interaction between the thermal plasma and the polymer materials like ablation and deposition on the surface of polymer materials and the thermodynamic and transport properties of Ar gas and ablated polymer vapor, assuming that local thermodynamic equilibrium condition is established for all calculation space. It calculates the mass flux of ablation gas from the solid polymer using Hertz–Knudsen and Clausius–Clapeyron's equations as shown in Eqs. (1) and (2).



Fig. 5 Calculation space.

$$m_{\rm pol}\Gamma_{\rm abl} = P_{\rm v}\sqrt{\frac{m_{\rm pol}}{2\pi kT}} \tag{1}$$

$$P_{\rm v} = \begin{cases} P_0 \exp\left(\frac{L}{RT_{\rm boil}} - \frac{L}{RT}\right) & (T \ge T_{\rm melt}) \\ 0 & (T < T_{\rm melt}) \end{cases}$$
(2)

where  $m_{\rm pol}$ : mass per polymer molecule,  $\Gamma_{\rm abl}$ : mass flux of ablated gas,  $P_{\rm v}$ : saturated vapor pressure, k: Boltzmann constant, T: temperature,  $P_0$ : standard pressure (=101325 Pa), L: evaporative latent heat of polymer material,  $T_{\rm melt}$ : melting temperature of polymer material,  $T_{\rm boil}$ : boiling temperature of polymer material, R: gas constant.

Fig. 5 indicates a schematic diagram of the cross section of the reaction chamber as a calculation space used in the present thermofluid model. The boundary condition on the reaction chamber inlet was previously calculated using another electromagnetic-thermofluid model for an induction thermal plasma [3]. The calculation condition was set to the same one used in the experiment; Ar gas flow rate was 30 slpm and input power was 7.5 kW. The calculation was made for PTFE, PE and POM ablation cases, and for a fictitious adiabatic material specimen for no ablation case.

#### 4.2 Calculation results

Figs. 6(a), 6(b) show temperature contour distribution in cases of PTFE and PE ablation. On the other hand, Fig. 6(c) shows temperature contour distribution in case of no ablation. The white colored area in these figures indicates the specimen and the water-cooled holder. The Ar thermal plasma from upstream is irradiated to the specimen surface. The temperature distributions are similar among any polymer ablation cases in general. However, a small difference in the plasma temperature can be seen near the polymer specimen surface among different polymer materials. In addition, there is a large temperature decay near the polymer specimen surfaces between ablation case and no ablation case.



Fig. 6 Two-dimensional distribution of temperature .

To clearly find the difference in the temperature decay near the specimen surface, the axial temperature distributions for different conditions were plotted in Fig. 7 for comparison. In this figure, the horizontal axis indicates the distance from the specimen surface on the axis of the torch. In the adiabatic and no ablation case, the plasma temperature is about 6500 K almost independent of the axial distance from the surface. On the other hand, the plasma temperature decreases remarkably in the axial range of 0–3 mm in polymer ablation cases. Especially, near the polymer surface, the temperature drops to about 500-800 K in any polymer ablation cases. This temperature decay is mainly caused by energy consumption for polymer solid ablation and dissociation of ablated polymer vapor. On the other hand, insignificant difference in the temperature decay appears for these three polymers treated here. This little difference occurs because the ablated polymer vapor scarcely mixes with Ar thermal plasma in the present condition, and influence of the ablated polymer vapor is limited just around the specimen surface.



Fig. 7 Axial distribution of temperature.

#### 4.3 Comparison with experiment

We have already estimated  $T_{\rm vib}$  and  $T_{\rm rot}$  of C<sub>2</sub> molecule in PTFE and PE ablated vapors experimentally in the previous section. These experimentally obtained temperatures could be compared with the calculated temperatures at 1.3 mm above the specimen surface. In polymer ablation case, the calculated temperature is about 3500 K, which is similar to experimental results of 3300 – 4400 K. Thus, the calculated temperature provides good agreement with the experimentally obtained temperature.

### 5. Conclusion

Temperature decay of thermal plasmas caused by polymer ablation was investigated experimentally and numerically using inductively coupled plasma irradiation technique. Three different polymer materials such as PTFE, PE and POM were used for ablation materials. Spectroscopic observation was carried out to estimate  $T_{\rm vib}$  and  $T_{\rm rot}$  of  $C_2$  molecule in ablated polymer vapor by fitting the calculated  $C_2$  emission coefficient to the measure one. The  $T_{\rm vib}$  and  $T_{\rm rot}$  were estimated to be 3300 - 4400 K in this experimental condition, while the Ar excitation temperature was 8500 K in no ablation case. This implies that the polymer ablation causes temperature decay of 4000 K near the polymer specimen surface. This temperature decay by the polymer ablation was also deduced by the developed thermofluid model.

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