Prompt response and durability of polymer ablation from synthetic fibers irradiated by thermal plasmas for arc resistant clothes

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Abstract. Interactions between thermal plasmas and synthetic fibers such as polyamide, polyester, phenol and aramid were investigated by thermal plasma irradiation technique. Understanding the above interactions is crucial to design effective flame retardant synthetic fiber clothes with arc resistance to protect a human from arc flash accidents. To investigate the interactions, an Ar inductively coupled thermal plasma (ICTP) was used instead of the arc discharge because the ICTP has high controllability and no contamination. The ICTP irradiation raises polymer ablation in case of polyamide and polyester. Two features of the polymer ablation such as prompt response and durability were fundamentally investigated from viewpoint of shielding the heat flux. It was found that polyamide fiber has both a high prompt response and a long durability.

1. Introduction
According to statistics compiled by CapSchell Inc., Chicago, there have been 5–10 arc flash incidents in a day in the United States [1]. The arc plasma is established around the accidental portion between high voltage conductors. This arc plasma usually has extremely high temperature more than 5000 K. It also generates brilliant flash of light involving a large noise. Thus, such arc flash can result in considerable damage to electrical equipments and serious injuries to nearby personnel. To protect personnel workers, it is greatly important to develop protective clothing with a sufficient arc resistant ability.

The National Fire Protection Association (NFPA) has developed a leading internationally recognized safety standard for electrical safety in workplace as NFPA 70E [2]. This standard defines a set of safe requirements for personnel working on electrical equipment. To comply with the standard, employers must carry out a hazard risk assessment and ensure that all employees working in a potential arc-flash hazard zone use appropriate equipment and wear the right protective clothing. The NFPA 70E standard also defines the arc thermal performance value (ATPV) for clothing. This value represents the maximum capability for arc-flash protection of a particular garment. This rating also applies to fabrics. It is presented in cal/cm\textsuperscript{2} or kW/m\textsuperscript{2} through the specified arc exposure test. This arc exposure test needs the arc plasma to create heat flux rates from 84 to 25120 kW/m\textsuperscript{2} exposed to the test clothing. However, this arc exposure test generally requires large test equipments and is also very expensive.
On the other hand, the authors continue to study the interactions between the bulk polymers and thermal plasma, which involves the polymer ablation. This study aims the enhancement in the arc interruption ability of low-voltage circuit breakers by using polymer ablation phenomena [3]. The polymer ablation occurs inevitably by contacting arc plasmas between the electrodes with the polymer wall during the high current interruption performance in a circuit breaker. The polymer ablation creates pressure rise, and then gas flow to enhance the arc interruption ability of the circuit breaker. The polymer ablation is also used for heat protection of a re-entry capsule in aerospace fields [4]. The re-entry capsule with a polymer ablator is exposed to high-temperature air plasma by the aerodynamic effects during re-entry process. The polymer ablator is effectively ablated to generate a heat shield vapor preventing the capsule from being exposed to too high heat flux.

One goal of the present work is to develop a high performance synthetic fibers with arc-resistance ability. The contribution of this paper contains two proposals: (i) to adopt polymer ablation phenomena of the synthetic fiber to protect from the arc plasma heat flux, and (ii) to use an induction thermal plasma irradiation technique instead of the arc exposure test. The contribution also includes fundamental experimental results on the thermal plasma irradiation test to four kinds of synthetic fiber specimens. From the experiments, strong polymer ablations were found for three of the above specimens. To use the polymer ablation for arc protection, two important features such as prompt response and durability of the polymer ablation were fundamentally investigated. The temperature of the ablated vapor was also estimated to obtain the heat shielding ability due to polymer ablation. It was found that polyamide fiber has both a high prompt response and a long durability.

2. Experimental

2.1. Test synthetic fibers

The present work targets the following four kinds of polymer synthetic fibers: polyamide-66, polyester, phenol and para-aramid. The polyamide 66 (PA66) fiber is well known as nylon-66 made of repeating units linked by amide bonds. Its heat resistant ability is relatively low, because it has a lower pyrolysis temperature. The pyrolysis temperature of the test PA66 fiber was actually measured to be 704 K with the thermo gravimetry, the differential thermal analysis and the differential scanning calorimetry (TG-DTA/DSC) method. Thus, it can be easily ablated by the heat flux according to our previous work. This ablation phenomena is expected to be adopted to the heat shielding from arc/thermal plasmas in the present study. The polyester fiber is widely used for textile, and it is also known as the polyethylene terephthalate (PET) fiber. However, in the context of textile applications, PET is referred to rather by its common name, polyester because it contains the ester functional group in its main chain. The pyrolysis temperature of the test PET fiber was measured to be 700 K. From this lower pyrolysis temperature, PET is also expected to be ablated by heat flux. The phenol fiber has high mechanical strength, high wear, heat and flame resistance, and morphological stability. This material fiber is widely used for fire retardant clothes. For this phenol fiber, the pyrolysis temperature could not be measured clearly with TG-DTA/DTG method. The para-aramid (p-aramid) fiber has amide group, and it has various performances similar to a phenol fiber. It is categorized in heat-resistant and strong synthetic fibers. Its applications are in aerospace and military fields for ballistic rated body armor fabric, etc. It is mechanically and thermally stronger than the PA66, because amide bond is combined with benzene ring formula instead of straight chain alkane structures. The pyrolysis temperature of the test p-aramid fiber was measured to be 850 K.

2.2. Experimental arrangements

Figure 1 depicts the inductively coupled thermal plasma (ICTP) torch used in the experiments as a thermal plasma source. The plasma torch is composed of two coaxial quartz tubes. The inner diameter of the interior quartz tube is 70 mm; its length is 330 mm. Ar gas was supplied as a sheath gas in axial direction and swirl direction along the inner wall of the inner tube. An eight-turns coil is located around the quartz tubes. The coil was connected with an rf power source to supply the coil current. The coil current produces electromagnetic fields to form an ICTP in the plasma torch.
Downstream of the plasma torch, a water-cooled specimen holder was located in the chamber. On this specimen holder, a specimen in a mount is placed to be directly irradiated by the ICTP from the plasma torch. Figure 2 shows the schematic of the specimen fiber, the mount and the water-cooled specimen holder. Specimens used in the present experiment were the polymer synthetic fibers. They are compressed to form a cylindrical shape with a diameter of 11 mm and a thickness of 3.5 mm. The specimen mount is used to fix a fiber specimen. This mount is comprised of two parts: a basement and a cap made of stainless steel. The cap has a hole of 9 mm in diameter. Through this hole, a thermal plasma is irradiated to specimen surface directly. A specimen in the mount was located on the water-cooled specimen holder for thermal plasma irradiation test.

The thermal plasma irradiation to a polymer synthetic fiber specimen may lead to the polymer ablation. The polymer ablation was observed by a color high-speed video camera (HSVC). At the same time, spectroscopic observation was carried out at 2 mm above the surface of the specimen. The optical system is constituted of a quartz lens, an optical fiber bundle, a polychromator and an ICCD detector. The spatial resolution of this observation is about 2.5 mm in diameter. Irradiation was initiated by inserting the movable specimen holder to the position just under the plasma torch.

2.3. Experimental conditions
The total flow rate of Ar sheath gas was fixed at 30.0 L min$^{-1}$. The pressure inside the chamber was controlled at 760 Torr (=101 kPa) with an automatic feedback control for pressure. The distance between the coil end to the specimen surface was set to 200 mm. The input power was fixed at 8.5 kW to the inverter power supply. This input power corresponds to the irradiation heat flux of about 550 kW/m$^2$ from the ICTP to the specimen, according to our numerical calculation result. This heat flux is in the range of the standard test method for determine the arc rating of materials for clothing [5]. The HSVC was used to capture ablated vapor from the specimen. The frame rate was 1000 frames per second.

3. Results for Ar thermal plasma irradiation
3.1. Color high speed video camera observation
Figures 3 shows the irradiating synthetic fiber situation taken by the HSVC. Panel (a) indicates the schematic explanatory view of the video capture pictures; panels (b)–(e) are the images for synthetic fibers irradiated by the ICTP. As seen in this figure, the polymer ablation strongly occurs for PA66, PET and phenol fibers irradiated by the ICTP. For these three materials, the ablated vapor emitting blue-white light was observed over the specimen mount. In particular, the PA66 emitted much more ablated vapor
than the others. Whereas, the p-aramid specimen irradiated by the ICTP hardly generated ablated vapor. This hard generation may be due to its high heat resistance ability.

We are considering the ablated vapor could be rather useful to shield heat flux from thermal plasmas on the polymer surface. For the shielding heat flux by the ablation phenomena, there are two important points that polymer synthetic fibers should have: a high prompt response of the ablation and a long durability of the ablation. From the measurement of the HSVC, these two points were summarized in Table 1 for test four kinds of fibers. The prompt response was judged as ‘yes’ if the ablation initiates in 0.5 s after the ICTP irradiation. The durability was ‘yes’ if the ablation is kept over 10 s.

The PA66 fiber emitted much more ablated vapor. The PA66 ablation was initiated quickly at 0.1 s after the ICTP irradiation, and then the ablated vapor continued to cover the specimen surface after 20 s from the irradiation. The PET fiber required about 0.5 s to initiate the ablation, but continued to generate the ablated vapor. The amount of the ablated vapor was less than the PA66. The phenol fiber also had a quick response to be ablated. However, the phenol finished to emit ablation vapor until 0.4 s after the ICTP irradiation. On the other hand, p-aramid fiber was scarcely ablated by the heat flux although it was damaged after the ICTP irradiation. According to these results, it was found that PA66 has both prompt response and durability of polymer ablation, which is expected to shield heat flux of the arc plasmas.

Table 1. Prompt response and durability of synthetic fiber specimens.

|                | PA66 | PET | Phenol | p-Aramid |
|----------------|------|-----|--------|----------|
| Ablated vapor  | yes  | yes | yes    | no       |
| Start time of ablation [s] | 0.1  | 0.5 | 0      | no       |
| End time of ablation [s]     | 20   | 20  | 0.4    | no       |
| Prompt response             | yes  | no  | yes    | no       |
| Durability                  | yes  | yes | no     | no       |
3.2. Spectroscopic observation and estimation of vapor temperature
The ablated vapors were observed from some of specimens in the ICTP irradiation experiments. The spectroscopic observation was conducted to analyze the composition of the vapor and then the vapor temperature. Figure 4 shows the emission spectra observed at 2 mm above the specimen surface of four kinds. These spectra were measured at 20 s after the ICTP irradiation. The p-aramid fiber is scarcely ablated, and thus almost only Ar spectral lines were observed as indicated in panel (d). The phenol fiber has a lower durability of the ablation, and thus the spectral intensity from the ablated vapor at 20 s after the irradiation is also weak as depicted in panel (c). On the other hand, strong molecular spectra from C₂ Swan system can be detected in ablation vapor from the PA66 and PET fibers. Especially, the PA66 fiber vapor has a stronger intensity from C₂ compared to the PET fiber. In addition, the vapor from PA66 also has strong intensity from CN Violet system because the PA66 contains nitrogen atoms in it. This implies that the vapor measured is indeed the ablated one from the specimen, and that bluish light from the vapor is mainly due to C₂ molecular spectra.

Use of the molecular spectra enables the estimation of the vibrational temperature and the rotational temperature of molecules. First, the emission coefficient of C₂ Swan system was theoretically calculated as functions of the vibrational temperature $T_{\text{vib}}^{C_2}$ and the rotation temperature $T_{\text{rot}}^{C_2}$ of C₂ assuming that population of exited molecules follows the Boltzmann distribution. After that, fitting the theoretically calculated emission coefficient to the measured spectra yields the both $T_{\text{vib}}^{C_2}$ and $T_{\text{rot}}^{C_2}$ simultaneously. The $T_{\text{vib}}^{C_2}$ and $T_{\text{rot}}^{C_2}$ estimated here has a relatively low accuracy because the Abel inversion was not employed for the radiation intensities. In spite of that, the estimated $T_{\text{vib}}^{C_2}$ and $T_{\text{rot}}^{C_2}$ can be used for an indicator of the temperature with $\pm 500$ K uncertainty at the highest intensity region.

Figure 5 represents the estimated $T_{\text{vib}}^{C_2}$ and $T_{\text{rot}}^{C_2}$ from PA66 and PET fibers. This figure also includes
the Ar excitation temperature $T_{\text{ex}}^{\text{Ar}}$ in case of no specimen. The temperature $T_{\text{ex}}^{\text{Ar}}$ was estimated by the two-line method using Ar atomic lines at wavelengths 703.7 nm and 714.0 nm on the assumption of Boltzmann relation for the excitation population. In this figure, $T_{\text{C}_2}^{\text{vib}}$ is about 4400–4600 K and $T_{\text{C}_2}^{\text{rot}}$ is about 3500 K. Generally, the rotational temperature becomes close to the translational temperature of heavy particles, because the energy level difference for rotational excitation is low of the order of 0.01 eV and thus the energy transfer happens frequently by collision with many heavy particles. Whereas, $T_{\text{vib}}$ is rather close to the electron temperature in a plasma because of the energy level difference for vibrational excitation is on the order of 0.1 eV. However, the most important thing that we emphasize in Fig. 5 is the difference of $T_{\text{C}_2}^{\text{vib}}$ and $T_{\text{C}_2}^{\text{rot}}$ from $T_{\text{ex}}^{\text{Ar}}$. Originally, the Ar ICTP irradiates the heat flux with this $T_{\text{ex}}^{\text{Ar}}$ of about 8300 K. The heat flux leads to the ablation of the synthetic fibers to create cloud of the ablation vapor covering the specimen surface. The vapor temperature is of the order of $T_{\text{C}_2}^{\text{vib}}$ or $T_{\text{C}_2}^{\text{rot}}$. These temperatures are 3000–4000 K which is much lower than $T_{\text{ex}}^{\text{Ar}}$. This may indicate that the ablated vapor with lower temperature covers the specimen surface, reducing temperature gradient between the plasma and the specimen surface, and then reducing the actual heat flux effectively.

4. Conclusions
In this paper, interactions between thermal plasma and synthetic fiber were fundamentally investigated for effective design of the arc retardant textiles and clothes. The arc retardant clothes are desired to protect a human from the arc flash accidents. Four kinds of synthetic fibers were tested: polyamide-66 (PA66), PET, phenol, para-aramid fibers. The Ar inductively coupled thermal plasma (ICTP) was irradiated for this fundamental study instead of the conventional arc discharge because of its controllability and no contamination. It was found that the PA66 and polyester fibers were markedly ablated by the ICTP irradiation, and the ablated vapor covered the specimen surfaces. From this experiment polyamide fiber was found to have both a high prompt response and a long durability. The temperature of the ablated vapor was estimated to be 3000–4000 K much lower than the plasma temperature 8300 K. This implied that covering the specimen surface by a lower temperature vapor may reduce the temperature gradient, resulting in the heat flux reduction on the specimen surface.

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