In-Flight Particle Measurement of Glass Raw Materials in Multi-Phase AC Arc Plasma

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Abstract: In-flight particle measurement of the surface temperature and velocity is important for understanding of melting behavior of glass particles during in-flight melting by multi-phase AC arc plasma. However, the use of optical pyrometry for particle surface temperature has inevitable uncertainties due to non-thermal emissions signals from the plasma plume. This work presents spectroscopic measurements of the non-thermal signals which were found to be caused mainly by the plasma emissions scattered by the particles and the direct plasma emissions. After that, the accuracy of thermal radiation measurement was estimated and surface temperature of in-flight glass particle was calibrated.

Keywords: In-flight particle, multi-phase AC arc, temperature measurement

1. Introduction

Conventional glass melting use the technology of the original continuous melting furnace developed in Germany by Siemens brothers in 1867. However, slow heat transfer, low thermal efficiency, and severe greenhouse gases emission are still the fatal problems for the traditional technology. Taking into account of the above reasons, an innovative in-flight melting technology with multi-phase AC arc has been successfully developed to melt granulated glass raw materials [1-4]. The high degree of vitrification of prepared powders reveals that the new technology can reduce energy consumption and shorten the production cycle.

Until now, only some diagnosis of the quenched particles has been possible for understanding the melting behavior of glass powders. A plasma-particle interactive modeling was used to simulate the particle trajectories and temperature histories in induction thermal plasmas [5], but the temperature history of particles during the in-flight treatment by multi-phase AC arc has not been investigated yet.

In-flight particle surface temperature and velocity measurement is the first step to understand the plasma-particle energy exchange dynamics and optimize the plasma temperature and residence time during powder treatment. Our objective in this report is to establish a measurement system and study the effect of non-thermal emissions on the temperature measurement of particles.

2. Experimental

2.1 Raw material

Alkali-free glass raw materials with a particle size of 114 μm were prepared by the spray-drying method from the reagents of H_3BO_3, Al_2O_3, $BaCO_3$, and SiO_2. The target of glass composition was $15B_2O_3$-$10Al_2O_3$-25BaO-49 SiO_2 in mass%.

2.2 System description

Figure 1 gives a schematic diagram of the experimental setup for the in-flight particle measurement. 12 electrodes made of 2%-thoriated tungsten were divided into two layers to produce the

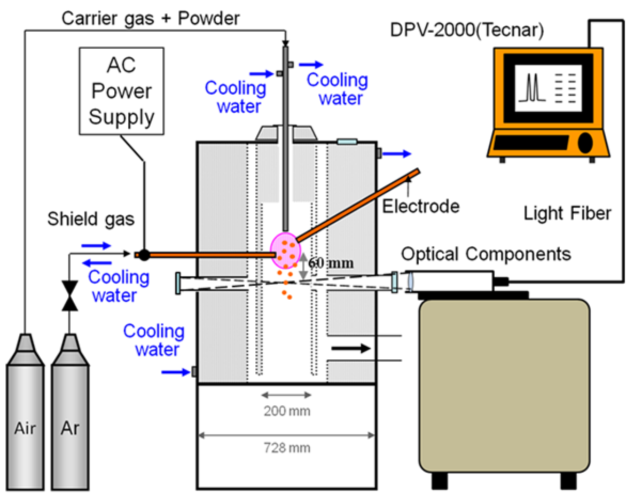

Figure 1. Schematic arrangement of the system setup.

plasma. The angle between the upper six inclined electrodes and the six lower horizontal electrodes was 30°. The host of electrodes, powder feed nozzle and chamber were cooled by water. Argon gas with purity of 99.99% was injected around each electrode at a flow rate of 5 L min^{-1} to prevent it from oxidation. The sensing head was set to focus at a point of 60 mm down from the electrodes to collect thermal radiation emitted by particles.

The high-speed pyrometry system used for particle measurement is DPV-2000 from Tecnar, Canada. The DPV-2000 consists of three main parts [6]: (a) the sensing head collect the thermal radiation emitted by hot particles from the peephole, (b) the detection cabinet contained the photodetectors and optical components of the high speed pyrometry which are needed to filter the particle radiation, (c) a computer equipped with the digitizing and computing boards which are used to compile and display data. An optical two-slits photomask is inserted at the end of the center fiber inside the sensing head. When a hot particle crosses the sensor measurement volume, an image with two peaks is recorded through the photomask. The thermal radiance emitted by a particle is filtered by two wavelength bands, λ_1=787±25 nm and λ_2=995±25 nm, respectively.

2.3 Analysis

The gray body assumption $\varepsilon(\lambda_1)=\varepsilon(\lambda_2)$ is used where it is hypothesized that the emissivity of particle surface is not dependent on the wavelength. According to the two-color pyrometry principle, the particle temperature T is obtained from the ratio of the radiation intensity based on the Planck's law:

$$T=\frac{\mathrm{K}_2(\lambda_1-\lambda_2)}{\lambda_1\cdot\lambda_2}\cdot\left[\mathrm{In}\frac{E(\lambda_1)}{E(\lambda_2)}+5\mathrm{In}\frac{\lambda_1}{\lambda_2}\right]^{-1} \qquad (1)$$

where K_2 is the second radiation constant in Plank's law which value is 1.4388 cm K, $E(\lambda_1)$ and $E(\lambda_2)$ are the total energy radiated by a particle at λ_1 and λ_2, respectively. From Eq. (1), the particle surface temperature is calculated based on the ratio. When collecting the particle thermal emission signal, other non-thermal emission signals are also contained in the sensor measurement area. Failure to identify and remove the non-thermal signals leads to errors in calculating particle surface temperatures [7-9].

Since the fluctuation period of multi-phase AC arc is evaluated as about 20 ms, but the detecting time for a particle by DPV-2000 sensor is 150 μs, it is considered that the direct line emission from plasma is not contribute to the total collected energy. The ratio of intensities is affected by the plasma emission scattered by particles. Therefore the theoretical ratio of intensities radiated at two wavelength λ_1 and λ_2 which takes into account of the non-thermal emissions can be written as:

$$\frac{E(\lambda_1)}{E(\lambda_2)}=\frac{TR_{\lambda_1}+SPE_{\lambda_1}}{TR_{\lambda_2}+SPE_{\lambda_2}} \qquad (2)$$

where $TR_{\lambda 1}$ is the intensity of thermal radiation emitted by the particle, $SPE_{\lambda 1}$ is the intensity of plasma emission scattered by the particle.

As described in Eq. (2), the particle temperature obtained by DPV-2000 is not the real surface temperature. To quantify this error, calibration method was investigated by a multichannel spectrophotometer (MD-100, JASCO). The optical fiber was focused at the same position with the sensing head of DPV-2000. The emission spectrum was investigated at the center wavelength of λ_1=787 and λ_2=995 nm which was in accordance with the DPV-2000 detected ranges.

3. Experimental results

Figure 2(a) shows the plasma line emission at λ_1=787±25 nm collected under no powder feeding. When starting the powder feeding at 30 g min^{-1}, line emission from the vaporized particle material was observed as shown in Figure 2(b). Moreover, the emission intensity of Ar I increased compared with no powder feeding. Generally, it is considered that powder injection will lead to lower plasma emission intensity due to temperature decrease by heat transfer to powder from plasma. Therefore the source of this radiation is primarily the scattered light by the particle from plasma. It can be seen that plasma light scattering is not negligible compared with particle emission. In this way, it is assumed that in the spectroscopic measurement, the influence of

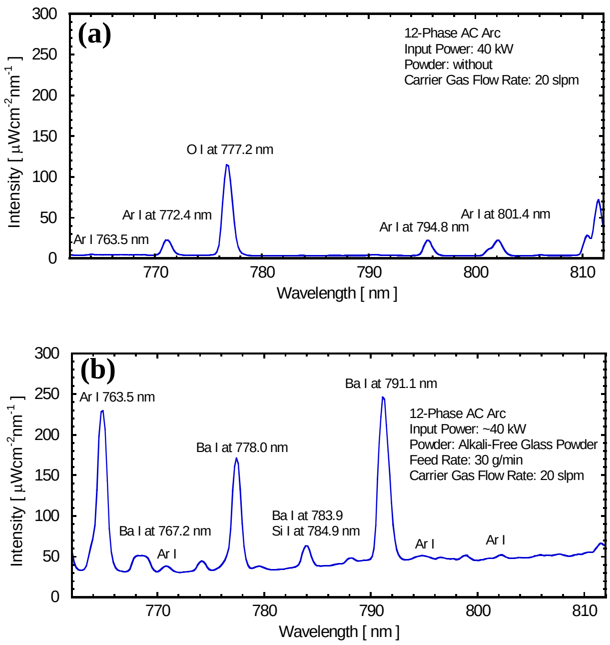

Figure 2. Emission spectrum at λ_1=787±25 nm.
(a) without powder feeding; (b) with powder feeding.

light emitted by plasma is neglected in the measurement position when particles are feeding. The emission intensity ratio $R_{\lambda 1}$ can be given by the following equation:

$$R_{\lambda_1} = \frac{TR_{\lambda_1}}{TR_{\lambda_1} + SPE_{\lambda_1}} \tag{3}$$

where $TR_{\lambda 1}$ is the intensity of thermal radiation emitted by the particle, $SPE_{\lambda 1}$ is the intensity of plasma emission scattered by the particle.

The intensity ratio $R_{\lambda 2}$ can also be calculated from the spectroscopic result at λ_2=995±25 nm with the same method. The effect of carrier gas flow rate on the emission intensity ratio is presented in Figure 3. When increase the carrier gas flow rate, the temperature of particle decrease due to shorter residence time in the plasma region. So the thermal radiation emitted by particle decrease.

Conbined with Planck' law, Eq. (2) and (3), the particle surface temperature can be calibrated using Eq. (4), which has removed the non-thermal radiation:

$$T = \frac{K_2(\lambda_1 - \lambda_2)}{\lambda_1 \cdot \lambda_2} \cdot \left[\text{In} \frac{TR_{\lambda_1}}{TR_{\lambda_2}} + 5\text{In} \frac{\lambda_1}{\lambda_2} \right]^{-1} \tag{4}$$

where the ratio of thermal radiation by particles emitted at each waveleng can be calculated by:

$$\frac{TR_{\lambda 1}}{TR_{\lambda 2}} = \frac{E(\lambda_1)}{E(\lambda_2)} \times \frac{R_{\lambda_1}}{R_{\lambda_2}} \tag{5}$$

Figure 4(a) gives the temperature distribution obtained by the original data from DPV-2000 at powder feed rate of 30 g min^{-1}. The apparent average temperature was 2830°C which did not take into account the contributions of non-thermal radiations. Figure 4(b) shows the true surface temperature distribution modified by Eq. (5) which removed the influence of non-thermal emissions. The average temperature of particles decreases after calibration. Moreover, the shape of the distribution is changed after calibration. This can be explained by the scattered plasma emission at the lower wavelength affects more strongly than the higher wavelength range.

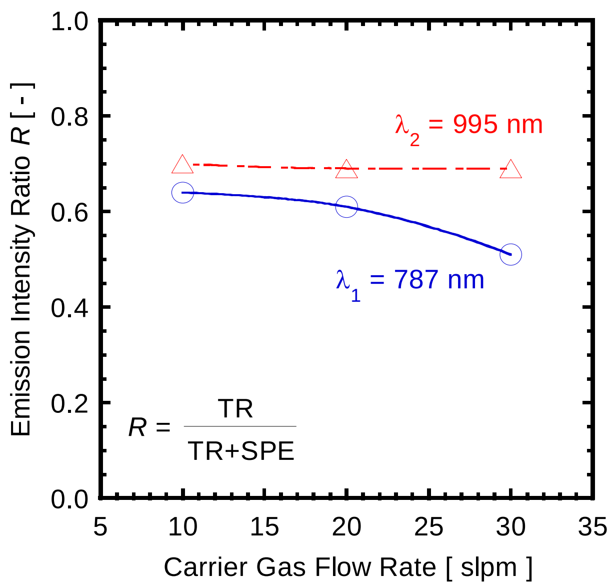

Figure 3. Effect of carrier gas flow rate on the emission intensity ratio.

The measured velocity distribution of particles is displayed in Figure 5. The particles have an average velocity of 9.3 m s^{-1}, which indicates the enough heating time by plasma. Figure 6 shows the relationship of particle velocity and temperature. The wide distribution of temperature means the particles were not heated uniformly during in-flight treatment. The optimization of the process parameters to realize a more uniform heating will be investigated in our future works.

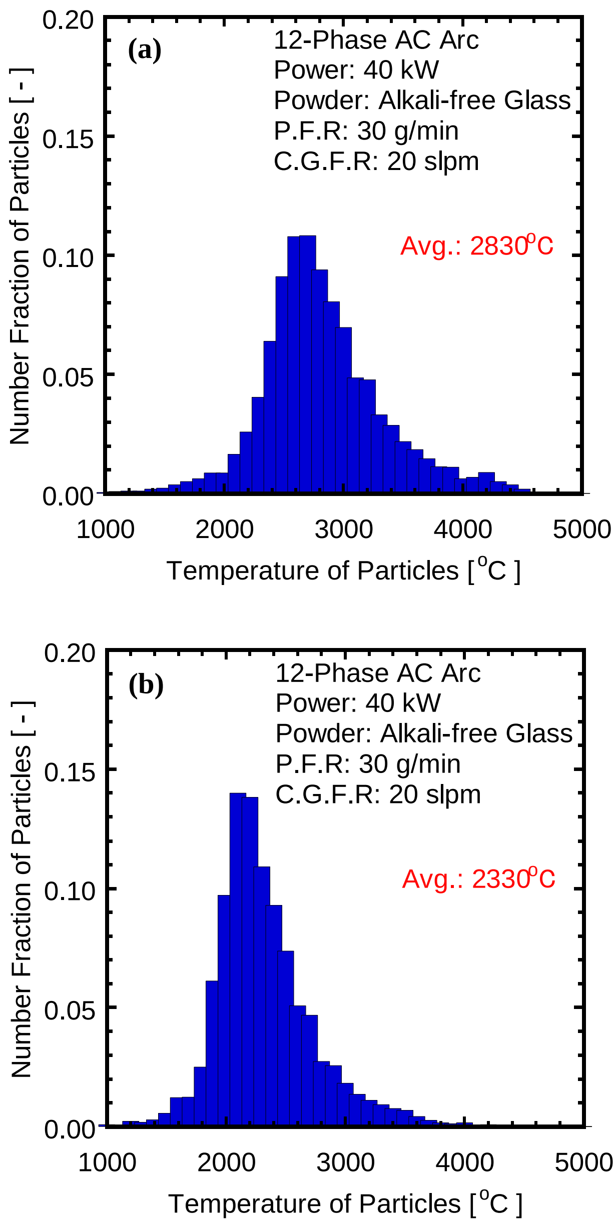

Figure 4. Particle surface temperature. (a) before calibration; (b) after calibration.

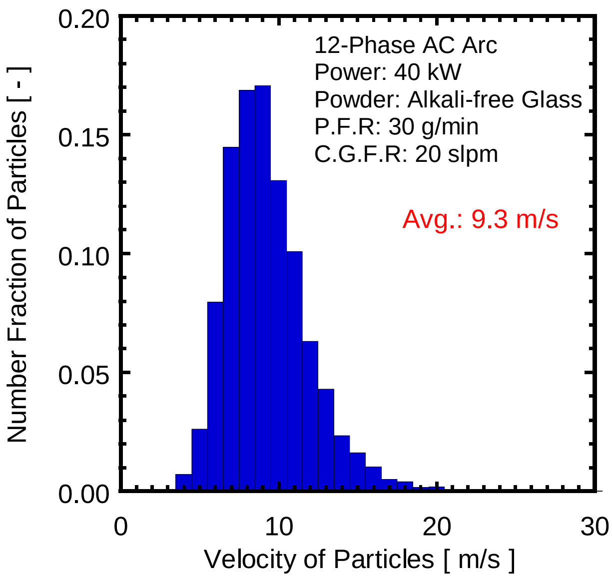

Figure 5. Particle velocity distribution at powder feed rate of 30g/min.

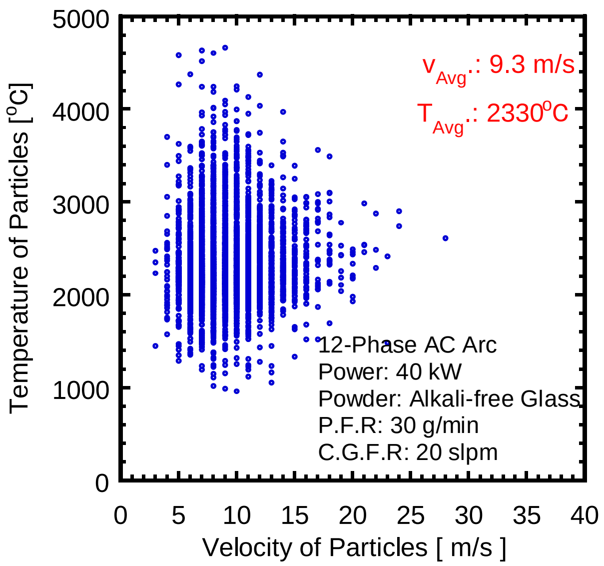

Figure 6. Particle velocity as a function of its surface temperature.

4. Conclusion

This paper pointed out a possible method to determine the influence of non-thermal radiations on the total collected radiations by DPV-2000. From the spectroscopic measurement, the plasma emissions scattered by the particles affect the accuracy of their temperature measurement. The measured surface temperature of the in-flight melting particles by the multi-phase AC arc was about 2330°C and the velocity was 9.3 m s^{-1}.

Acknowledgments

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