In-flight particle measurement of glass raw materials in hybrid heating of twelve-phase AC arc with oxygen burner

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Abstract. The high temperature provided by a 12-phase AC arc plasma is beneficial to finish vitrification reaction in milliseconds. Another heating method called “hybrid plasma” combines multi-phase AC arc and oxygen burner are expected to improve glass quality and increase productivity with minimum energy consumption. In this study, recent works on the development of in-flight particle measurement in hybrid plasma system are presented. Two-colour pyrometry offers considerable advantages for measuring particle temperatures in flight. A high-speed camera equipped with a band-pass filter system was applied to measure the in-flight temperatures of glass particles. The intensity recorded by the camera was calibrated using a tungsten halogen lamp. This technique also allows evaluating the fluctuation of the average particle temperature within millisecond in plasma region.

1. Introduction

Current glass melting technology is based on the typical Siemens-type melter fired in air with heavy oil or natural gas as the fuel. This type of melter has been used over 140 years because of its good large-scale performance and continuous melting system with minimal financial or technological risk. Fine-grained ingredients, closely controlled for quality, are mixed to make a batch, flows into the furnace that is heated to 1600 ºC. Several processes - melting, refining, homogenising - take place simultaneous in the 2,000 tonnes of molten glass in the furnace, lasting as long as 50 hours. The melting and refining process is key to glass quality but it is energy-intensive and time-consuming.

Many innovations in industrial glassmaking have been explored during the second half of the 20th century as glassmakers have sought to solve critical industry problems. Few of these innovations have been commercialized. The British Glass Industry firstly used plasma in place of traditional electrical firing in glass melting in 1994. The high melting efficiency of soda-lime-silica glass was demonstrated [1]. Similarly, a two-year program began in 2003 by Plasmelt Glass Technologies, LLC, used a small skull melter with all electrodes above the glass batch [2]. However, both of the two programmes have the principle limitations that torch materials and design is not yet quite satisfactory. Recent years, our research group has successfully developed an innovative “in-flight melting” technology to reduce the vitrification reaction of glass batches. The glass raw materials are injected above the furnace and penetrated though the plasma region to be melted and vitrified within milliseconds. This totally changes the traditional radiation heating and improves the thermal efficiency considerably.

A stable 12-phase AC arc plasma furnace has been successfully developed to melt granulated glass raw materials. The particle diagnostics during the in-flight treatment was also studied in order to
understand the plasma-particle energy exchange dynamics [3]. Furthermore, a hybrid heating combined the oxy-firing with the multi-phase AC arc was under research. This new kind of heat source was expected to enhance the energy efficiency and the in-flight glass productivity. However, the in-situ measurement of in-flight particles by hybrid plasma has not been studied yet. Thermal spray particle temperature is most often measured by two-colour pyrometry, also spectroscopic techniques have also been used [4]. An advantage of a two-colour pyrometry is in circumventing the need to know the emissivity of the body in order to determine its temperature. Greybody conditions, however, are often an unwarranted assumption. This paper present the works on the development of particle diagnostics based on the two-colour pyrometry principle.

2. Experimental

2.1. Raw Material

The raw materials of alkali-free glass were supplied by Asahi Glass Co., Ltd., Japan. Reagents of H$_3$BO$_3$, Al$_2$O$_3$, BaCO$_3$, and SiO$_2$ (quartz) were mixed in appropriate mass ratio and dispersed in water to form slurry. The slurry was sprayed from an atomizer into a heated air chamber at 200 ºC to form spherical powders. The average grain size of the raw materials was 135 µm. The target composition of alkali-free glass is 15B$_2$O$_3$-10Al$_2$O$_3$-25BaO-49SiO$_2$ in wt%.

2.2. Plasma System Description

The schematic illustration of the hybrid plasma apparatus is shown in figure 1. It combines a multi-phase AC arc plasma reactor with an oxygen burner installed over it. The plasma was generated by 12 electrodes, which are symmetrically arranged rotating on the axis and divided into two layers to increase the plasma volume. The angle between the upper six inclined electrodes and the six lower horizontal electrodes is 30°. The electrodes are made of 2%-thoriated tungsten with 3.2 mm in diameter. They are cooled by city water at a flow rate of 3 L/min, and argon shield gas with purity of 99.9% is injected around each electrode at a flow rate of 5 L/min. The AC power supply provides the total current of 320 A and the total voltage of 200 V. The chamber was made of stainless steel and cooled by water. The oxygen burner contains gas supply, powder feeding and cooling system. Propane (C$_3$H$_8$) was used as the fuel at a flow rate of 6 L/min. The primary oxygen and the secondary oxygen were 6 and 24 L/min, respectively. The combustion energy of oxygen burner was 9 kW. The distance from burner nozzle to arc was 300 mm and diameter of arc was 80 mm.

Figure 1. Schematic of hybrid plasma apparatus with diagnostic systems.
2.3. *Particle Diagnostics*

In-flight particle diagnostics were performed at an axial distance of 60 mm down from the lower electrode level and focused on the centre of the plasma plume. According to Figure 1, two diagnostic systems were used for in-situ measurement. One is the optical system DPV-2000 (Tecnar, Canada) which enables to measure single particle velocity and temperature [5]. The spectral regions chosen to provide high sensitivity and low interference from non-thermal background light are \( \lambda_1 = 787 \pm 25 \) and \( \lambda_2 = 995 \pm 25 \) nm, respectively. When use DPV-2000 system, it is inevitable that several non-thermal signals will also be collected by optical lens. The intensity recorded by the sensor was corrected by spectroscopic measurement. The emission spectrum separate the continuum signal emitted by particles and other non-thermal radiations from the vaporized materials and scattered plasma emission [3].

Another implementation of two-colour pyrometry for particle measurement involves the use of a high-speed camera (Photron, FASTCAM SA WTI, Japan). As shown in figure 1, an oscilloscope (Yokogawa, ScopeCorder DL850, Japan) synchronized with high-speed camera measured the current and voltage of the 12 electrodes. The choice of spectral bandwidths used to measure the two-colour particle intensity signal should avoid the direct and scattered plasma light. As the glass particles are low emissivity ceramics, only a limited amount of radiation is available to measure. Figure 2 shows the line emission spectra of the plasma gas species and vaporized particle material (Barium) considered here. For a good sensitivity and to minimum the plasma radiation signal, the camera used a short wavelength band covering 785 ± 5 and 880 ± 5 nm. The optical system observes the plasma plume and splits the single object into two identical images simultaneously, as shown in the figure 3. Histograms of particle properties can be displayed in real time (>10^4 Hz). The technique also indicates how the average particle temperatures change with time due to the multi-phase arc fluctuation.

![Figure 2. Emission line spectrum of hybrid plasma.](image)

![Figure 3. Conceptual diagram of temperature measurement by high-speed camera.](image)
3. Results and Discussion

3.1. Particle Temperature Calculation

Figure 4 gives a sample (dual) image of glass particles streaks. Although narrow band pass filters were used, the fluctuation of the plasma flame can be seen periodically. If the carrier gas flow rate is higher than 30 L/min, the particles fly quickly through the measurement volume and it is impossible to separate the particles one by one. The sensor described here uses a commercially available 12-bit 1024×1024 pixel CCD camera. In a single measurement, up to 1051 images of particle streaks can be recorded at a rate of 5000 frames/s with the exposure time of 200 µs. The camera focused on the centerline at the same height with DPV-2000 but the field of view was much wider. The calculated range of the image was 200×200 pixels which corresponding to the real size of 11×11 mm². Analysis software scans each image to identify individual particle streaks and compute velocity and temperature based on the Planck’s law as in equation (3.1):

$$T = \frac{K_2 (\lambda_1 - \lambda_2)}{\lambda_1 \cdot \lambda_2} \left[ \ln \frac{TR_{\lambda_1}}{TR_{\lambda_2}} + 5 \ln \frac{\lambda_1}{\lambda_2} \right]^{-1} \quad (3.1)$$

where $K_2$ is the second radiation constant in Planck’s law which value is $1.439 \times 10^{-2}$ m · K, $TR_{\lambda_1}$ and $TR_{\lambda_2}$ are the thermal radiations emitted by a particle at $\lambda_1$ and $\lambda_2$, which represents the integrating pixel intensities in the video images. The sensor’s spectral sensitivity was calibrated by a tungsten-halogen lamp.

![Figure 4. Image of glass particle streaks obtained by two different band-pass filters, 785 ± 5 nm (Left) and 880 ± 5 nm (Right).](image)

3.2. Time-Resolved Particle Temperatures

It is already know that the fluctuation from the 12-phase AC arc causes the temporal non-uniformity of the whole temperature distribution. Considering for the particle velocity and an appropriate estimation, every 5 images (represent for 1 ms) were calculated to obtain the average temperature value of particles. Since the fluctuation period of multi-phase AC arc is evaluated as about 20 ms, the total calculated time for particle temperature was over 5 periodic cycles of 100 ms.

Figure 5 presents the frame-averaged particle temperatures as a function of time under different carrier gas flow rate. Each point was obtained from calculation of all the particles over 5 images. For example in Figure 5(a), the counted particles have a temperature distribution at time of 33 ms. The effect of carrier gas flow rate on the average temperature and particle velocity are summarized in figure 6. The particle velocity is mostly dependent on the carrier gas flow rate. The temperature of particles decreased due to shorter residence time in plasma region. Moreover, a gradual decrease in the temperature fluctuation as a function of carrier gas flow rate can be understood by considering their Fourier amplitude spectra, which is shown in figure 7. The peak around 100 Hz is clearly visible, indicates the periodicity of the temperature evolution. The amplitude decreased with carrier gas flow.
rate increased, which can be explained by the higher gas flow rate decrease the effect of the arc fluctuation on the whole temperature field.

Note that the energy transfer to a particle depends on the input power and its dwell time in the plasma. The particle experienced non-uniform temperature field when it pass through the plasma region. The hybrid plasma decreases the arc fluctuation due to the use of oxygen burner. Moreover, the particles experienced low temperature heating and short residence time in the oxygen flame before they enter the high temperature plasma zone. The particle surface was melted so that the initial void in the granulated raw powders were decreased, thus the diffusivity of the $\text{B}_2\text{O}_3$ vapor can become smaller. Then, the short residence time in the high temperature plasma region can finish the vitrification reaction and inhibits the volatilization.

![Graphs showing temperature fluctuations under different carrier gas flow rates.](image)

**Figure 5.** Fluctuation of the frame-averaged temperature of particles under different carrier gas flow rate: (a) 10 L/min, (b) 20 L/min, (c) 30 L/min.
Figure 6. Effect of carrier gas flow rate on the particle average temperature and velocity.

Figure 7. Frequency spectra of fluctuation of temperatures under different carrier gas flow rate: (a) 10 L/min, (b) 20 L/min, (c) 30L/min.
3.3. Comparison Between DPV-2000 and High-Speed Camera
In our experiment, the lens of DPV-2000 was placed at a constant position so it only focused on the small measurement volume (about 1 mm$^3$) of the center. On the contrary, the calculated range of the high-speed camera was about 11×11 mm$^2$. Figure 8 presents particle surface temperature distribution obtained from DPV-2000 and high-speed camera at carrier gas flow rate of 10 L/min. The comparison of the results is found to be in good agreement. This also confirms the measurement accuracy of high-speed camera. However, increase the carrier gas flow rate cause more smaller-size particles penetrate into the center plasma region, thus the DPV-2000 measured more higher temperature particles. More experiments should be done with DPV system in order to get reasonable data.

![Figure 8. Particle surface temperature distribution estimated by (a) DPV-2000 and (b) high-speed camera.](image)

4. Conclusion
In-flight glass particle measurement in the hybrid plasma heating was firstly introduced in this paper. The influence of the plasma fluctuations on the in-flight particle temperature was evaluated by a high-speed camera with two-colour pyrometry system. Time-dependent particle temperature due to arc fluctuations was observed. Amplitude of the variation in the in-flight particle state decrease with increases the carrier gas flow rate. The particle surface temperature distribution obtained by DPV-2000 analysis shows good agreement with high-speed camera. Using two-colour pyrometry method will help to successfully apply the hybrid heating technique.

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