Flow monitoring in molten glass by means of ultrasonic Doppler method

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This paper described fundamental techniques for flow monitoring in molten glass by means of ultrasonic Doppler method. In order to transmit ultrasound into the glass, buffer rod technique was employed. The buffer rod was made of mullite ceramic bar. Taper shape and cladding layer were introduced to suppress spurious echo. Broadband signal processing technique was proposed to improve noise tolerance in velocity estimation. The proposed methods could be implemented without significant increase of calculation load. Using the buffer rod and the signal processing system, ultrasonic Doppler method in molten glass was demonstrated.

Keywords: Molten glass, high temperature measurement, buffer rod, phase difference method

1 INTRODUCTION

Glass melting techniques have been developed in industrial scale to dispose of nuclear high-level radioactive waste. Clarification of thermal hydraulic behavior in the melter is important in the quality control of products. However, experimental flow investigation has not been done since no velocimetry technique is capable of measuring in molten glass. Flow monitoring in the melter is restricted by high temperature, opaqueness, high corrosive property and high radioactivity of the glass. Ultrasonic Doppler method (UVP) is one of the applicable velocimetry techniques for the glass owing to penetrative property. In this paper, we established UVP technique for molten glass and demonstrated a preliminary experiment of flow monitoring.

The largest issue of high temperature ultrasonic measurement is durability of ultrasonic transducer. For direct contact with the glass, piezoelectric material must possess higher Curie temperature than 1200°C. However, materials with high Curie temperature is not readily available and cannot provide sufficient ultrasonic transduction efficiency unlike conventional transducers. In addition, there are manufacturing restrictions of a transducer e.g. casing or wiring [1-2]. To solve this issue, buffer rod was employed to transmit ultrasound into the glass. Another consideration goes to large attenuation of the glass. Broadband signal processing method was proposed in order to comply with the attenuation. Proposed method relies on broadband property of echo signal from modern ultrasound transducer. Subsequently, application of UVP to molten glass was attempted combining the developed buffer rod and signal processing system. Maximum measurable range of UVP is of interest on practical aspect since ultrasound is strongly attenuated in the glass. Therefore, measurable range was evaluated by analyzing the moving wall echo signal.

2 MEASUREMENT SYSTEM

2.1 Buffer Rod Technique

Due to unavailability of high efficiency ultrasonic transducers for high temperature condition, buffer rod technique was used. A buffer rod is equipped between a transducer and high temperature specimen as a waveguide and temperature buffer. A buffer rod usually has a thin and long shape to provide buffer functions. Clamping a cooling jacket on the rod near the transducer end enables to utilize a room temperature transducer. Therefore, high-efficiency ultrasonic measurement can be performed. Echo signal from specimen exists after rod end echo since both the rod end echo and echo from specimen are transmitted in the same path. Although there is a temperature distribution along the rod in high temperature measurement, the effect of the distribution can be neglected in the measurement by this transmission mechanism.

It is also known that spurious echo arises during the propagation of ultrasound from the transducer end to the specimen end. While longitudinal ultrasound pulse propagates toward the other end, a part of the energy is diffracted on the side wall and converted to the shear wave. Converted wave propagates later than the first emission pulse since the shear wave has slower sound velocity than the longitudinal wave. This diffraction repeats again for the generated shear wave, and thus, another longitudinal pulse is formed after the emission pulse. Consequently, several spurious peaks can be seen in the echo signal, which are called trailing echoes. The problem of the trailing echo is to impair the signal-to-noise ratio because the echo signal of the interest locates after the rod end peak. Many shapes or treatments of buffer rod was proposed to eliminate this by-product [3]. Among them, this study employed the clad taper rod [4].

The buffer rod is made of mullite considering the material durability and wettability. Total length is 300 mm. The rod has a straight section near the transducer end for holding the rod itself and a cooling jacket. The rest part has a taper angle toward the specimen end as illustrated in Figure 1. Diameters of the transducer end and the specimen end are 30 mm and 20 mm, respectively. Porous clad layer is introduced on the side wall to mitigate trailing echoes. The layer is formed by heat-resistant adhesive (Sumiceram S-208B, Asahi Chemical Co., Ltd.), whose main component is alumina. Figure 2 shows a comparison of echo signal between bare and clad rods. Time delay t^* was normalized by the round trip time. Peaks at $t^*=1$ are, therefore, reflected echoes from the specimen end. A transducer employed (2C20I, Japan Probe Co., Ltd.) has a center frequency of 2 MHz and efficient diameter of 20 mm. The trailing echo level is defined as the ratio of the maximum amplitude of trailing echoes to the amplitude of rod end echo. Experimental measured levels of bare rod and clad rod were 8 dB and -14 dB, respectively. The clad successfully reduced trailing echo level by -22 dB. This reduction is due to isolation and absorption of ultrasound by the porous clad layer [5].

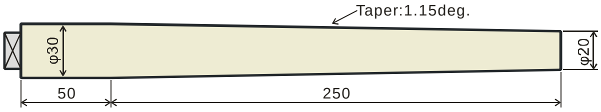


Figure 1: Schematic illustration of bare buffer rod and a transducer (left).

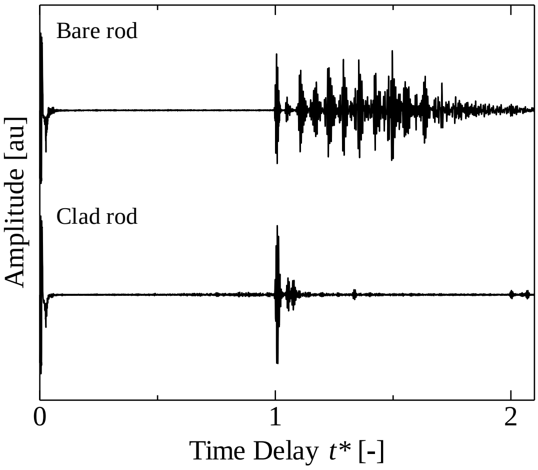


Figure 2: Comparison of echo signals between bare taper rod and clad taper rod.

2.2 Signal Processing

In UVP measurement for the molten glass, large attenuation and trailing echo decrease signal-to-noise ratio. Consequently, velocity estimation error arose as speckle noise. On the other hand, modern ultrasound transducer usually has a bandwidth of 50-100%. Main idea of speckle noise reduction is to use the information of broadband frequencies. Phase difference method is employed to estimate velocity in order to implement broadband signal processing method. In the original phase difference method, velocity is calculated from the phase difference between two successive echo signals [6]. FFT is computed for each measurement volume. Then, the phase of the center frequency is selected and the velocity is obtained. In the broadband phase difference method, velocity is obtained from phase differences of frequencies around the center frequency of the transducer as well as that of the center frequency. Frequency resolution of spectral analysis is determined by AD sampling speed and number of data points in a channel, namely channel width. For instance, channel width is 1 µs and frequency resolution of FFT is 1 MHz when the signal is acquired at 60 MS/s and 60 points are clipped as a channel. This resolution is typical value in phase difference method and it is rather coarse to calculate averaged velocity among frequencies. Moreover, frequency resolution is increased when channel width is decreased to achieve higher spatial resolution. In order to satisfy both high frequency resolution and spatial resolution, we introduced interpolation of the spectrum by zero padding. The zero-padding factor of 4 (in above example, 180 points of zero are appended after windowed original data points) yields the frequency resolution of 250 kHz. Subsequently, velocities of a channel can be derived by the following equation.

$$\boldsymbol{V}(f)=\frac{cf_{\mathrm{PRF}}}{4\pi f}\angle\left(\boldsymbol{X}_i\cdot\boldsymbol{X}_{i-1}^{*}\right) \tag{1}$$

where $\boldsymbol{X}$ is the successive Fourier transform coefficient of a channel. c is the sound peed, f_{PRF} is the pulse repetition rate. $\boldsymbol{V}$ and $\boldsymbol{X}$ are the function of the frequency f. Then, the velocity is obtained by averaging velocities among the center frequency with magnitude weighting.

$$V=\frac{\sum_f \boldsymbol{V}(f)\left\|\boldsymbol{X}_i\cdot\boldsymbol{X}_{i-1}^{*}\right\|}{\sum_f\left\|\boldsymbol{X}_i\cdot\boldsymbol{X}_{i-1}^{*}\right\|} \tag{2}$$

The advantage of the broadband phase difference method is reducing speckle noise and the less calculation load when the Doppler signal processing is implemented full digitally. For example, IQ demodulation is the heaviest process in autocorrelation method. Therefore, the number of averaging frequencies is directly connected to the calculation time when the same technique is applied to autocorrelation method. On the other hand, there is relatively small increase of calculation time in the proposed method when the number of averaging frequencies increases. Although computation load on Fourier transform increases due to the zero-padding, resulting increase can be minimized by choosing proper FFT algorithm for the data length of a channel.

3 APPLICATION OF UVP TO MOLTEN GLASS

3.1 Experimental Setup and Procedure

Figure 3 illustrates experimental apparatus. About 400 g of the glass was melted in a nickel crucible whose diameter is 85 mm. The depth of the molten glass became ca. 40mm. The crucible was set in the test section of electric furnace. Mullite tube was inserted to normalize the temperature distribution in the test section. Thermal insulation blocks were installed to avoid heat leakage from the furnace. The temperature in the furnace was monitored with Type K thermocouple. The buffer rod described in section 2.1 was immersed into the glass. The rod can be moved by PC-controlled automatic stage. Three ultrasonic transducers were employed whose basic frequencies are 2, 3 and 4 MHz. They are made of piezoelectric ceramics and bandwidths are over 50%. Effective diameters are 20 mm for all the transducers. One of the transducers was pressed down to the transducer end by springs. Coupling agent (High-Z LV, Sonotech Inc.) was employed between a transducer and the rod. A cooling jacket was clamped near the transducer end and tap water pass through it to keep the transducer temperature less than 50°C. A PC-controlled pulser/receiver (JPR-10CN, Japan Probe Co., Ltd.) drove a transducer. Two cycles of tone-burst pulse was emitted to improve the bandwidth and the spatial resolution. Pulse repetition rate was set to 100 Hz. Applied voltage and amplifier gain were adjusted in order that the amplitude of the rod end echo is equal to the full scale of digitizer input range. Echo signal was acquired by a digitizer (PXI-5105, National Instruments Inc.) at the sampling speed of 60 MS/s. Velocities were reconstructed offline in order to evaluate the difference of the signal processing methods using the same echo signal.

The rod was firstly moved down until the specimen end touches the bottom wall of the crucible. Then, the rod started to move upward at 1 mm/s. Echo signals were recorded while the rod was moving. Analyzing the signal, the wall speed relative to the rod was obtained. Maximum measurable range was determined when velocity deviates more than 20% from the motion speed. Channel width was set to 0.5 μs to improve the spatial resolution. Zero-padding factor was 3, and thus, the frequency resolution was 667 kHz. Considering the bandwidth, the number of averaging frequencies was set to 5. It leads bandwidths of 133%, 89% and 67% for 2, 3 and 4 MHz, respectively. Experiments were conducted from 1200°C to 1000°C at every 50°C. Measurement was started two hours later after the temperature in the test section reached the set temperature to equalize the temperature variation.

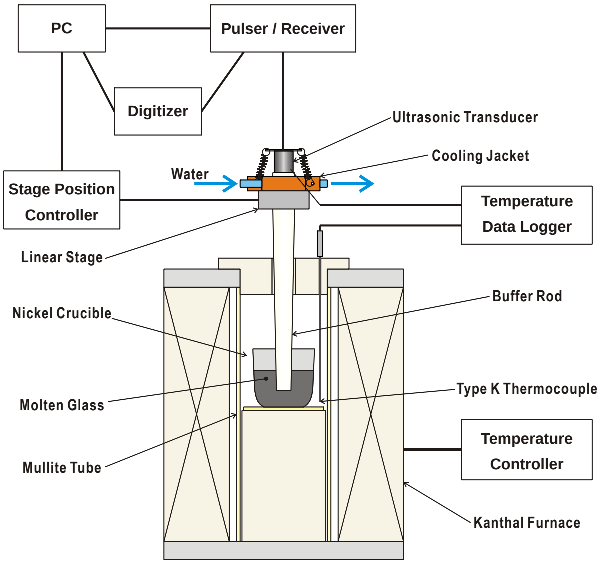


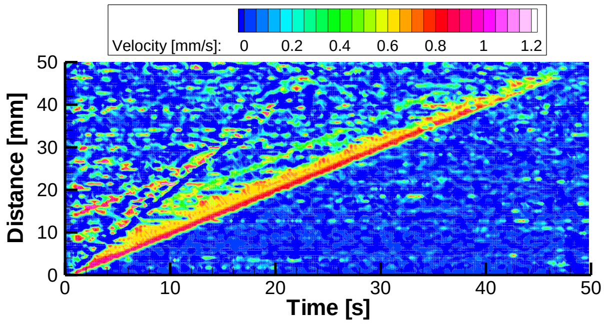
Figure 3: Schematic diagram of experimental apparatus.

Glass composition employed in this study was the borosilicate glass, which contains the simulated waste material. Sound speeds and attenuation coefficients of this glass composition were already investigated [4]. Sound speed in molten glass is almost constant at 2300 m/s from 1000°C to 1200°C. Attenuation coefficient α of the molten glass was fitted well on an exponential function and obtained as the following equation (3).

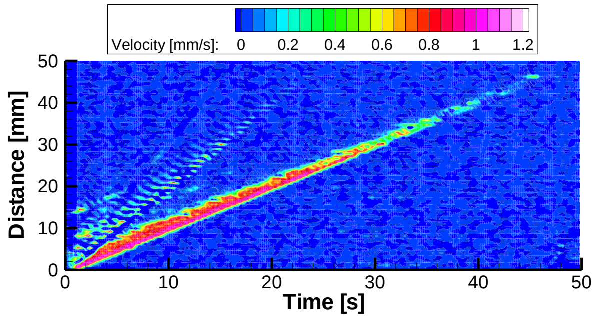
$$\alpha = 2.04\times10^{-6}\exp(-8.87\times10^{-3}T)\,f^{2} \quad \text{[dB/m]} \quad (3)$$

3.2 Estimation of Maximum Measurable Range

Figures 4 show reconstructed spatiotemporal flow maps from (a) a phase of single frequency and (b) phases of five frequencies. Vertical axis indicates the distance from the specimen end. Horizontal axis indicates elapsed time. Legends of the velocity contours are shown above the map. A three-point moving average among horizontal direction (not vertical direction) was applied. The temperature of molten glass was 1200°C and applied ultrasonic frequency was 4 MHz. Sharp diagonal lines mean the wall velocity relative to the rod. Multiple reflections between rod end and the bottom wall of the crucible can be seen as an artifact line, which has larger gradient than sharp original velocity component. Other artifact line running parallel to the original line is due to emission of trailing echo into the glass melt. Many speckle noise can be seen with artifact lines with the original phase difference method in Figure 4 (a). On the other hand, most of them are well eliminated in Figure 4 (b) by averaging among five frequencies, although both maps were calculated from the same echo signal. Computation time to reconstruct flow maps as shown in Figures 4 (a) and (b) were 700 ms and 810 ms, respectively. Thus, increase of the processing times was relatively small.



(a) Reconstructed from a phase of single frequency.



(b) Reconstructed from phases of five frequencies.

Figures 4: Spatiotemporal flow map while the buffer rod elevated at 1 mm/s.

Figure 5 shows maximum measurable range of UVP in the molten glass related to temperature pf the glass. Determined ranges from Figures 4 (a) and (b) were almost the same in ca. 30 mm although the length of the sharp line appears to be shortened in Figure 4 (b). Large difference of values has not been confirmed at other frequencies and temperatures. Therefore, only the data with averaging among frequencies are plotted in Figure 5. Data more than 35 mm in range is neglected since the molten glass was not deep enough than 35 mm. Data for 2, 3 and 4 MHz are plotted with circle, square and triangle points, respectively. The measurable range changes exponentially. In parallel to the experiment, the measurable range was estimated analytically. Discrimination of the wall echo from the trailing echo level may become difficult when the amplitude of the bottom wall echo decreases to the same level of the trailing echo. Consequently, the measurable range can be estimated by dividing trailing echo level (dB) by attenuation coefficient α (dB/m). The estimated lines are also drawn in Figure 5 for each frequency. Experimental data plots and independently estimated lines show good agreement. Based on these discussions, we conclude that measurement can be done within the distance where attenuated ultrasound energy is larger than trailing echo level. It implies that one need to employ lower frequency or buffer rod with improved trailing echo level to measure a longer distance.

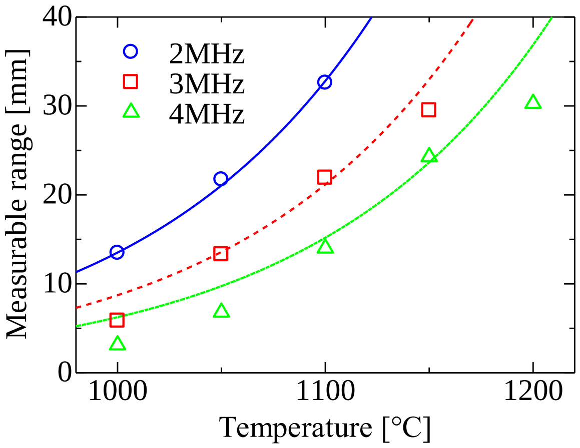


Figure 5: Experimental results of maximum measurable range (plots) and estimated range (lines) for each ultrasonic frequency.

4 SUMMARY

In order to realize ultrasonic Doppler method for molten glass flow, buffer rod technique and broadband signal processing method are presented. The buffer rod was utilized as a waveguide and a temperature buffer. The spurious signal called trailing echo was successfully mitigated over 20dB by taper shape and the porous clad layer. Signal processing method is also discussed to suppress the speckle noise due to large attenuation and remaining trailing echoes. Velocity is calculated from phase differences of several frequencies in this method. Implemented system showed lower speckle noise than the conventional method. Using the buffer rod and signal processing system, maximum measurable range in molten glass was investigated. Analytical method was also examined and it was revealed that the measurable range is determined by the attenuation of ultrasound and trailing echo level. In future work, flow monitoring in molten glass will be demonstrated with the developed system.

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