Low Velocity Measurement on The Joule-Heating Flow by Ultrasound Velocity Profiler Method

Jiaju Zhou[1], Tomonori Ihara[2], and Hiroshige Kikura[1]
[1] Tokyo Institute of Technology, 2-12-1 Ookayama, Tokyo 152-8550, Japan
[2] Tokyo University of Marine Science and Technology, 2-1-6 Etchujima, Tokyo 135-8533, Japan

A development ultrasound velocity profiler method was tested on the Joule-heating flow in a cubic cavity. The Joule-heating flow was observed in simplify cubic model and also observed in a real glass melter model by UVP method. However, due to velocity resolution of the time repetition method is low, the very slow velocity flow was difficult to measure. A new UVP method named phase difference method was developed for very slow velocity measurement. In this study, the new method was tested on the Joule-heating flow in a cubic cavity for the validation. The Joule-heating cavity is accomplished by passing an alternative current employing a pair of plate electrodes immersed on a facing plane of the liquid in order to generate internal heat source by connecting them with a constant voltage (65V). The electrode surfaces are assumed to be iso-potential and the rest of the boundaries are treated as electrically and thermally insulated. Test section is located in the middle plane between two electrodes. One-dimensional continuous velocity profiles are observed by UVP. As a result, although there are several problems of the phase difference method, the phase difference method can be applied for Joule-heating flow measurement.

Keywords: UVP, Phase difference, Joule-heating, Chaotic flow, Low velocity measurement.

1. Introduction

High-level radioactive waste (HLW) is already produced in all over the world as a waste from nuclear power plants, and the method to reprocess HLW becomes an important issue to solve. In the reprocessing, HLW is dissolved into High-Level Radioactive Liquid Waste (HLLW), and HLLW is poured into molten borosilicate glass in a glass melter to make stable mixture of HLLW and glass for geological disposal. In Japan, Liquid Fed Ceramic Melter (LFCM) type glass melter (Fig. 1) is being developed for the reprocessing.

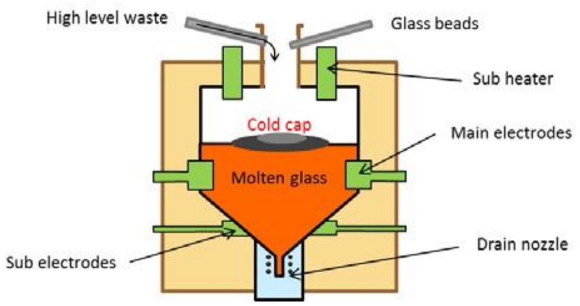


Figure 1: LFCM glass melter.

The glass melter is composed of an upper cubic part and a lower pyramid-shape part. The glass melter applies Joule-heating to generate molten glass, and the melter can mix HLLW and molten glass by convective flow mainly induced by Joule-heating. These volumetric heating in lower part and cooled in the upper part make continuous chaotic flow behavior, named as 'chaotic steady state.' [1] In fact, the chaotic flow behavior in the glass melter is difficult to understand, and the melter operation sometimes aborted when an accident is observed in the melter. Understanding the chaotic flow behavior is important for the effective melter operation, however, there are many effects on the flow behavior: those are electrode cooling, cold cap, platinum group, foaming reagent, etc. Thus, former studies about the chaotic flow behavior was executed using a simple cubic cavity shown on Fig 3. For simplification.

However, the flow behavior depends on the shape of the cavity, it is also important to observe the actual flow in the cavity which has similar shape to the real glass melter. The flow behavior in the sloping bottom cavity was different from the flow behavior in the cubic cavity under several conditions. [2] The most important change from cubic cavity to sloping bottom cavity was the flow in the bottom parts of the cavity. In the sloping bottom cavity, the non-flow area can be observed by 2-D visualization, the flow in this area was very slow. As the velocity resolution of the time repetition method is not enough, the flow in the bottom of the cavity is difficult to measure. Ihara et al developed new UVP method named phase difference method for very low velocity field. [3] To apply the phase difference method, Ihara also developed new system by LabVIEW. [3] However, the Joule-heating flow is affected by thermal field, electromagnet field and flow field. These three field lead flow is completed and the echo of ultrasound signal is difficult to receive. In this paper, phase difference method was tried to apply in the Joule-heating flow and compare with previous study.

2. Principle of Phase Difference Method

UVP measurement system inherits advantages of ultrasonic measurement methods such as non-intrusive, applicable for opaque flow and time-series velocity measurement, especially for the unstable flow measurement. On the other hand, this technique has some difficulties such that the ultrasonic velocity depends on the temperature along the measurement line. The UVP method is based on echo signal analysis of ultrasonic pulses reflected by particles suspended in the fluid of each position in the measurement axis and deriving instantaneous velocity. The working principle is depicted in Fig.2.

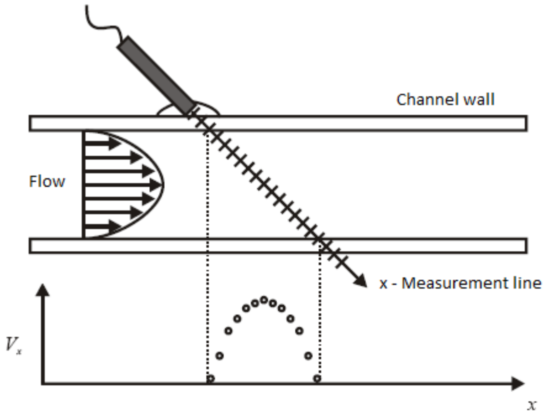


Figure 2: Principle of UVP method.

The transducer emits a pulse and receives the echo signal reflected from the particle suspended in the liquid. The information of position in each channel is extracted from the time delay τ_{prf} or pulse repletion frequency f_{prf} as following:

$$x = c\frac{\tau_{prf}}{2} \quad (1)$$

For the determination of the Doppler frequency, the peak frequency of the spectrogram was chosen. Considering the calculation load and stability, FFT (fast Fourier transform) technique [4] was used for comparison. The echo signal is modeled by the following equation.

$$\begin{aligned} E(t) &= \sin 2\pi f_0 t + A_f \sin 2\pi (f_0 + f_f)t \\ &+ A_b \sin 2\pi (f_0 - f_b)t \end{aligned} \quad (2)$$

where the second term is the forward flow component and the third is the backward component. Stored echo signal is demodulated digitally and Doppler sequences of in-phase and quadrature phase are yield in a repetition order. In the demodulation, a finite impulse response (abbr. FIR) filter is used as a low-pass filter. The length and the repetition interval of the sequences determine the frequency resolution in the spectra. To derive the spectra from these sequences, FFTs are carried out for each channel, and forward and backward power spectra are obtained by the following equation.

$$P_f = (R_e[X_I] - I_m[X_Q])^2 + (R_e[X_I] + I_m[X_I])^2 \, P_b \quad (3a)$$

$$P_f = (R_e[X_I] + I_m[X_Q])^2 + (R_e[X_I] - I_m[X_I])^2 \, P_b \quad (3b)$$

where P_f and P_b are power spectra of forward direction and backward direction respectively. After merging these spectra, the spectrogram is obtained. As the device is based on digitized time domain, this corresponds to the minimum detectable velocity, namely a velocity threshold, which is expressed as

$$V_{\min,DS} = \frac{f_{PRF}}{N_j f_0} c \quad (4)$$

Practically, in order to improve the velocity resolution, the peak of the spectrum is interpolated using a three-point Gaussian curve fit. Nevertheless, this V_{min} could be attributed to a velocity threshold. For example, when a 4 MHz signal is emitted in water at 2 kHz repetition frequency, 128 repetitions yield 5.9 mm/s as the velocity threshold. Although this technique offers high stability, there is a trade-off between time and velocity resolution depending on N_j. The time resolution can be expressed as

$$\Delta T_{DS} = \frac{N_j}{f_{PRF}} \quad (5)$$

For a single measurement volume in the fluid and when the emission signal contains only one frequency component, the echo signal from tracer particles can be expressed as

$$E(t) = \sin(2\pi f_0 + \theta) \quad (6)$$

where θ is the average phase in the measurement volume. For the second emission, the echo signal is represented using a slightly different value of phase, which reflects the motion of tracer particles inside the measurement volume. Therefore, the main idea of this method is to detect the mean particle displacement from a difference of the phase of two successive signals as

$$\Delta x = \frac{c}{2\pi f_0} \Delta\theta \quad (7)$$

Therefore, the velocity could be estimated using a pulse repetition period T

$$V = \frac{\Delta x}{2T} = \frac{f_{PRF}}{2} \Delta x = \frac{f_{PRF}}{4\pi f_0} c\Delta\theta \quad (8)$$

then the velocities for multiple volumes along the ultrasonic beam axis can be used to form a velocity profile.

The echo signal received and digitized by the receiver is stored in matrix d_{ijk}. This echo signal is described by Eq. (6) substituting

$$t = \tau i + \frac{j}{f_{PRF}} + \frac{k}{f_s} \quad (9)$$

in order to determine the echo phase, a (windowed) fast Fourier transform of d_{ijk} (k=1…,128) is calculated, denoted by X_{ijs}. The phase difference is obtained from the $X_{ijs}X^{*}_{ij-1s}$ as

$$\angle(X_{ijs} X^{*}_{ij+1s}) = \theta_{ijs} - \theta_{ij-1s} \quad (10)$$

The flow velocity V_{ij} can be calculated using Eq. (7) where the frequency index s is selected as it corresponds to the ultrasonic basic frequency f_0.

Since this technique estimates a velocity from two successive repetitions of echo reception, the minimum temporal resolution is given by

$$T_{PD} = \frac{2}{f_{PRF}} \tag{11}$$

The maximum velocity that can be detected, Vmax, is the same as for the Doppler method because the range of $\Delta\theta$ remains between $-\pi$ and π. Numeric simulations suggest that the velocity threshold of the phase difference method can be affected by quantization error. However, its practical performance has not been investigated.

3. Experiment Apparatus

The dimension of cavity is shown as Fig. 3. Two carbon electrode plates are placed on opposing side wall. The cubic cavity is used in former study.

In this experiment, the work fluid was 80wt% glycerin-water solution, and 0.5wt% LiCl was added into the fluid to lead fluid possess the conductivity. After the glycerin-water solution mixed, nylon powder was added into the fluid as a reflected powder. About 1.3 kg fluid was used in the experiment.

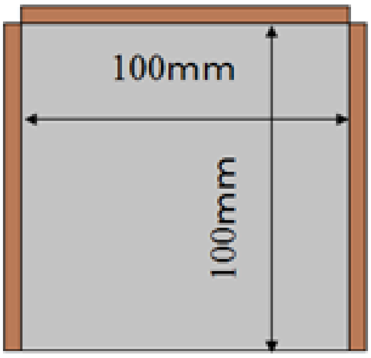


Figure 3: Joule-heating cavity in experiment.

The room temperature was keep at 20°C. The initial temperature of the fluid was also 20°C. Cooling temperature of the top surface was 20°C as the room temperature by using copper heat sinks and a water circulator at top surface. The electrodes side was adiabatic condition. The experimental apparatus is shown on Fig. 4. AC power was applied in the experiment to generate Joule-heating. A chiller was connected to the heat sink and keep the cooling temperature. UVP transducer was set at the bottom of the cavity. The UVP measurement was shown as Fig. 5. It is composed of three hardware components: an ultrasonic pulser/receiver, a digitizer and a personal computer (PC). The pulser/receiver (JPR-10CN, Japan Probe Co., Ltd.) drives an ultrasonic transducer with square burst signal whose pulse-width corresponds to the transducer frequency. Both of them were connected to the PC and the specialized software control each other. Applied voltages, frequency, burst cycle and PRF (pulse repetition frequency) are controlled by the PC through a USB interface. A low noise preamplifier (PR-40A, Japan Probe Co., Ltd.) is used with the pulser/receiver, and compensates for the attenuation of the ultrasound in the fluid; its gain is +40 dB. To improve the signal-to-noise ratio (SNR), a band-pass filter is integrated into the amplifier. The echo signal is acquired by a 12-bit digitizer (PXI-5105, National Instruments Inc.) and stored in its 128 MB onboard memory. 1-D velocity profile of the Joule-heating flow in the cubic cavity was measured by this system.

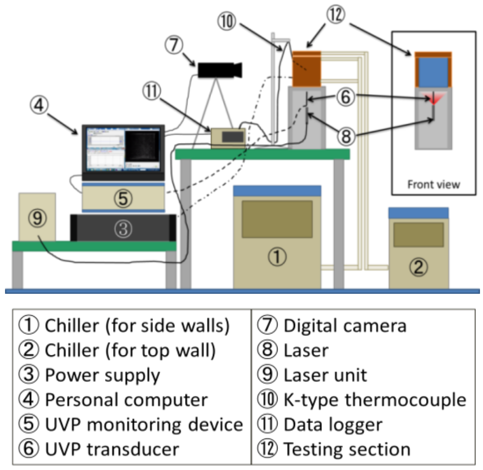


Figure 4: Experimental apparatus.

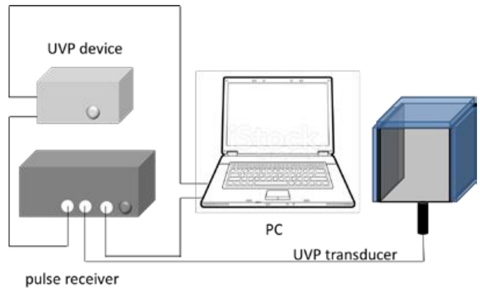


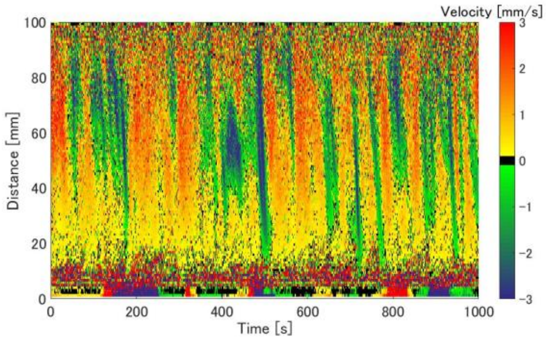
Figure 5: Structure of pulse receiver UVP.

The experiment was started when voltage was applied between the electrodes, it leads Joule-heating occurring in the cavity. After sufficient time from heating started and when the temperature tended to a stable state.

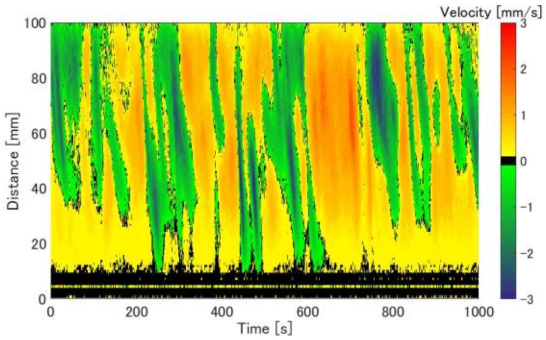
4. Verification of Phase Difference Method

Considering if the electrodes surface was cooling, the flow in the bottom was difficult to measure, the electrodes surface changed to adiabatic. Therefore, just the top surface of the cavity was cooling, and the other surface were adiabatic. Under this condition, the chaotic flow occurred in the whole cavity. Therefore, the reflect powder won't be decreased during the experiment and easy to catch the echo from the ultrasound signal.

The flow profile in the cubic cavity was measured by phase difference method and compare with the time repetition method. The flow behavior in the center line of cubic cavity measured by phase difference method is shown as the Fig. 6(a), and the Fig. 6(b) shows the data was measured by the time repetition method. The similar chaotic flow can be observed in almost whole of the cavity. The chaotic flow occurred almost in the whole cavity. However, in the bottom of the cavity, the phase difference method shows more noise than time repetition method. In the time repetition method, the bottom parts just show no flow. However, in the phase difference method, the flow in the bottom parts is complete and difficult to analyze. To know the flow profile in the cavity, 30s average data is shown in Fig. 7.



(a) Phase difference method



(b) Conventional method

Figure 6: Flow behavior at the center line.

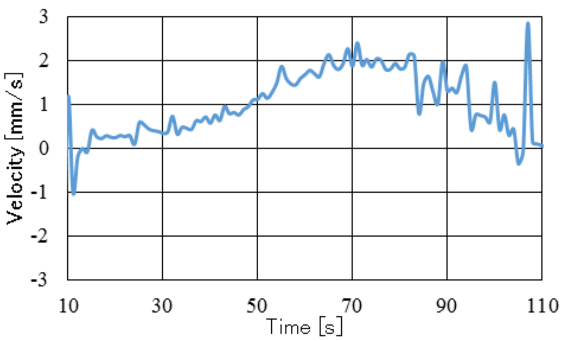


Figure 7: 30s average profile of phase difference method.

It can be find that flow measurement was not start at 0mm position, the noise observed by the phase difference method was the echo from wall. The phase difference method was easy to be affected by the noise near the transducer. However, in the cavity, the echo of ultrasound signal from reflect powder can be recognized well, the chaotic Joule-heating flow was observed by the phase difference method clearly. Therefore, the phase difference method can be applied for the Joule-heating flow measurement. The flow measurement in the bottom of the sloping bottom cavity, which the velocity was very low almost no flow can be expected.2013

5. Conclusion

A new UVP measurement method, phase difference method was developed for low velocity measurement. New soft system and phase difference method was tested for applying to the Joule-heating flow measurement. The Joule-heating flow in a simple cubic cavity was measured by the phase difference method. The electrodes surface under the cooling condition was applied to test the new system, and the electrodes surface under the adiabatic condition was applied to test the phase difference method. The result of phase difference method measurement was compared with the time repetition method. The following conclusions were carried out by the experiment.

The new UVP system can be applied in the Joule-heating flow. When the repetition number of high, few reflect powder field is difficult to measure. However, the velocity profile can be observed by the average data. In addition, If the reflect powder can keep in a high mount, the low flow field can be measured.

The phase difference method has noise near the wall, however, the flow in the cavity can be measured by the phase different method.

The phase difference method can be considered apply in the sloping bottom cavity to observe the flow behavior in the sloping bottom part.

References

[1] Tsuzuki N, *et al*.: The numerical analysis on unsteady flow in the cavity whit Joule-heating, 48th Heat Transfer Symposium of Japan, Volume III, 727-728 (2011).
[2] Zhou J, *et al*.: Effect of Cavity Shape on Chaotic Flow Behavior by Joule-Heating, ISFMFE2014, No. 90196 (2014).
[3] Ihara T, *et al*.: Ultrasonic velocity profiler for very low velocity field, Flow Measurement and Instrumentation, 34 (2013), 127–133.
[4] Chihara K, *et al*.: The microcomputer-based ultrasonic pulsed Doppler flowmeter system, IEICE Transactions, 63 (1980), 351–352.