Bubbly Flow Measurement in High Temperature Molten Salt

Tomonori Ihara[1], Keisuke Tsukada[2], Hiroshige Kikura[2], and Horst-Michael Prasser[3]

[1] Department of Marine Electronics and Mechanical Engineering, Tokyo University of Marine Science and Technology, 2-1-6 Etchu-jima, Koto-ku, Tokyo 135-8533, Japan
[2] Laboratory for Advanced Nuclear Energy, Institute of Innovation Research, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan
[3] Laboratory for Nuclear Energy, Swiss Federal Institute of Technology Zurich, Sonneggstrasse 3, Zurich 8092, Switzerland

Ultrasonic velocity profiler (UVP) was applied for the measurement of bubbly flow in high temperature molten salt. Buffer rod technique was used to transmit ultrasound into the melt. Trailing echo is a typical problem of buffer rod, which cause measurement error in UVP. Customized signal processing technique was presented to suppress noises due to trailing echoes. In addition to the signal processing, post-processing techniques were employed to extract bubbly flow from noisy measurement result. Obtained velocity profile was reasonable result, and it was proven that data processing approach presented was useful to improve measurement quality in UVP with buffer rod.

Keywords: Bubbly flow, Doppler signal processing, Noise suppression, Buffer rod, Post-processing

1. Introduction

Molten salt nuclear reactor is one of advanced reactor systems considered in the generation IV international forum [1]. Nuclear fuel is dissolved in molten salt and circulated in the core and heat exchanger system. Many conceptual designs were presented elsewhere (for example, [2,3]). Fluoride molten salt is used under high temperature (for example, 750 °C) and atmospheric pressure. One of the attractive features of molten salt reactor is online reprocessing; fission products (FPs) can be separated from fuel liquid. Separation of FPs is very important from the safety aspect since inventory of volatile FPs (such as cesium, xenon, etc.) can be reduced from a reactor core, which is recognized as a missing function in the existing light water reactors especially after the Fukushima Daiichi NPP accident. Helium bubbling can be utilized to separate some FPs. From the inlet of the reactor core, small amount of helium is injected as with fuel dissolved molten salt and it is collected at the outlet. Volatile FPs are captured by bubble and are then separated from salt mixture. Noble metal FPs are also captured, which may cause plating on inner structure and then lead damage of the core due to decay heat and high radiation. Optimization of bubble injection is an important task for the realization of helium bubbling. CFD and experimental works have been performed for this purpose [2,4].

Due to very high temperature, radioactivity and corrosive property, measurement and instrumentation techniques are limited [5], Ultrasonic velocity profiler (UVP) has a high potential for the bubble monitoring. The biggest difficulty lies on the emission of ultrasound into high temperature molten salt. We have proposed the buffer rod technique for the application of UVP to high temperature molten glass (up to 1200 °C) [6-7]. One of the drawbacks of the buffer rod technique is noise issue of trailing echoes, which are due to reflection and refraction inside buffer rod. Since trailing echoes overlay on echoes of interest, erroneous velocities are measured in UVP. By optimizing the buffer rod, trailing echoes can be mitigated to a certain level [6,8-10]. Yet, trailing echoes are also amplified and remain as with the signals of interest due to high gain setup of UVP. Consequently, some noise suppression technique should be implemented for the measurement with a buffer rod. There would be two solutions to realize such a noise suppression. First solution is to reject trailing echoes with a standing wall filter. Since trailing echoes are located in the same position like static walls in measurement region, those echoes can be ideally eliminated using a DC filter toward repetition order. This procedure must be implemented before the velocity estimation. Second solution is to distinguish significant velocities in post-processing. Such a procedure can be realized by a statistical approach. Noise suppression techniques are needed to be optimized for buffer rod considering characteristics of trailing echoes. In this paper, signal processing is specially arranged to realize the measurement. Then, bubbly flow measurement in high temperature molten salt is demonstrated using buffer rod.

2. Signal processing

2.1 Phase Difference Method

Velocity profile estimation is performed using phase difference method [7,11]. Demodulation is implemented using complex FFT. Let the output sequence for a repetition i be X_i, then average phase difference $\Delta\theta$ can be calculated among certain repetitions N_i.

$$\Delta\theta = \arg \sum_{i=0}^{N_i-1} \left(X_i - \hat{X}\right)^* \cdot \left(X_{i+1} - \hat{X}\right) \qquad (1)$$

Mean value is firstly subtracted and then conjugate products are calculated. This subtraction procedure works as a DC filter (standing wall filter). Averaging is required to increase possibility to capture significant echo signals within one velocity profile estimation and to improve signal-to-noise ratio. Velocity is then estimated as follows.

$$V = \frac{f_{\mathrm{PRF}}}{4\pi f_0} c \cdot \Delta\theta \qquad (2)$$

Doppler amplitude A can be also calculated by the following equation.

$$A = \frac{1}{N_i - 1} \mathrm{abs} \sum_{i=0}^{N_i-1} \left(X_i - \hat{X}\right)^* \cdot \left(X_{i+1} - \hat{X}\right) \qquad (3)$$

Doppler amplitude means amplitude of varying signal during the repetition period since DC component is already rejected from the sequence.

While the DC filter is implemented as described above, erroneous signal practically remains. One of the reasons is a jitter issue due to triggering delay and different clock domains between a pulser and a digitizer. Another reason is the stability issue of an amplifier in a receiver. In addition to those issues, temperature variation in buffer rod may cause a variation of transit time from transducer end to measurement end. As a result, trailing echoes are not eliminated completely. A high-pass filter (HPF) toward repetition order will be one approach to solve this issue. Nevertheless, a filter with a sharp frequency response and a high time response is not available. Under a small number of repetition parameter, low velocity component might be also attenuated and distorted when a HPF is applied. For this reason, a HPF was not employed in this study.

2.2 Velocity Offset

For example, velocity of the measurement end of buffer rod should be always zero since it is a static wall. However, zero velocity cannot be found in some measurements due to jitters and other factors discussed above. In order to solve this problem, offset velocity is introduced. Offset velocity is calculated by averaging velocities among different channels which should ne zeros. Then, it is subtracted through a velocity profile to collect the bias.

2.3 Amplitude Filter

Even if trailing echoes are varying in time, they are more or less stable when they are observed in long measurement time. Erroneous velocity also inherits this characteristic from trailing echo, and they may dwell in almost the same place in velocity and amplitude domains. While a prior information about velocity is unavailable, information about amplitude is clear; amplitude of bubble should be larger than the noise level. Therefore, bubble velocities can be extracted in post processing. Amplitude data is obtained together with velocity data with Eq. (3). Mean μ and standard deviation σ of amplitude for each channel are calculated among long measurement result sequence. By removing velocities whose amplitude is less than $\mu+z\sigma$, significant velocities can be extracted in velocity profiles. In this procedure, one should select an appropriate confidence interval z. Assuming the Gaussian distribution, z=1.28 and 2.33 will lead the data validities of 1% and 0.1%, respectively. In case amplitude are not following the Gaussian distribution, data validity will be different.

3. Bubbly Flow Measurement

3.1 Buffer Rod

Design of a buffer rod is very important since it coarsely define trailing echoes and signal-to-noise ratio. It was found that conical shape is simple and efficient to suppress trailing echoes [6]. In this study, buffer rod with conical shape is used. Considering the bore diameter of the experimental setup described later, diameter of the buffer rod is decided to 27.5 mm. A transducer with efficient diameter of 20 mm was used to transmit ultrasound into the buffer rod. Therefore, designed diameter of measurement end is 20 mm to avoid inadequate diffraction in buffer rod. Overall length is 300 mm. The rod has a straight section of 50 mm and the rest section (250 mm) is tapered to 20 mm. Stainless steel was used to fabricate the buffer rod since stainless steel showed high durability against the molten salt mixture in our preliminary test. On the conical surface of buffer rod, ceramic adhesive was coated to decrease trailing echo level. Echo response from the buffer rod is shown in Figure 1. Rod end echo can be seen at 110 ms. Small echoes are following the rod end echo, which are trailing echoes. Amplitude ratio is 28dB in this figure.

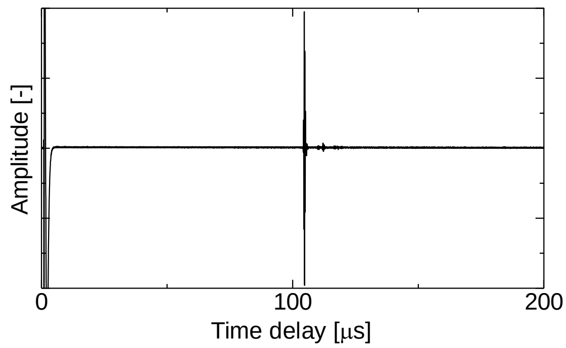


Figure 1: Echo response from the stainless buffer rod used in this study. Trailing echoes can be seen after the rod end echo.

3.2 Experimental Setup and Procedure

Experimental setup is shown in Figure 2. Chloride salt was selected instead of fluoride salt for ease of handling in the laboratory. Salt mixture (56wt% KCl and 44wt% LiCl) was melted in the stainless tube whose inner diameter is 78.1 mm and thickness is 5.5 mm. Approx. 3 kg of salt was stored and the depth of the melt was around 450 mm. Two branch pipes are welded on the tube with the angle of 20 deg. Inner diameter of the branches is 27.2 mm. Buffer rod and thermocouple are installed from each branch pipe. Inside the main pipe, baffle plates are placed to divide the flow section into a raiser section (between baffle plates) and a down comer section. Bent pipe (diameter of 6 mm) is used to inject helium gas from the bottom of the melt. Rising bubbles which cross the ultrasonic beam path are observed with the buffer rod technique. A transducer (center frequency of 4 MHz and efficient diameter of 20 mm) is fixed on the buffer rod. The transducer is connected to the signal processing setup. The setup consists of a pulser/receiver (JPR-600C; Japan Probe Co., Ltd.) and a digitizer (APX-5040; Avaldata Corp.) installed in the signal processing PC. 20 cycle burst pulse was repeated at the frequency of 4 kHz. Echo signal is amplified by the gain of +25dB. RF signal is sampled at the speed of 40 MS/s. Channel width of signal processing was 250 ns. Sound velocity of this mixture was 1930 m/s in 500 °C. Subsequently, channel distance was 0.24 mm along beam path and 0.083 (= 0.24 * sin(20)) mm in radial direction. Velocity and amplitude profile set is measured from the end of the buffer rod to 30 mm in radial direction due to the restriction of signal processing system, which will be solved in the future. 8 repetitions (N_i) are used to estimate one profile set. Longer wave cycle and shorter channel width are used to increase the possibility of capturing weak echo signal from bubble. Molten salt mixture was kept at the temperature of 500 °C for two hours before the experiment. Helium gas was injected at the rate of 12.5 ml/s. Measurement was started after a few minutes later the injection starts so that temperature and bubble are stabilized. 200,000 profile sets were acquired in the experiment. Temperature variation during the experiment was less than 10 °C.

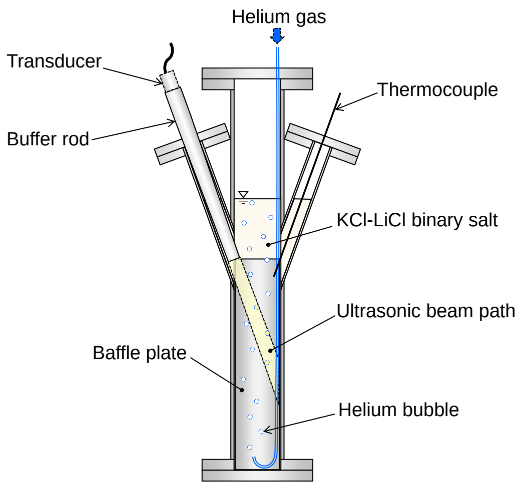


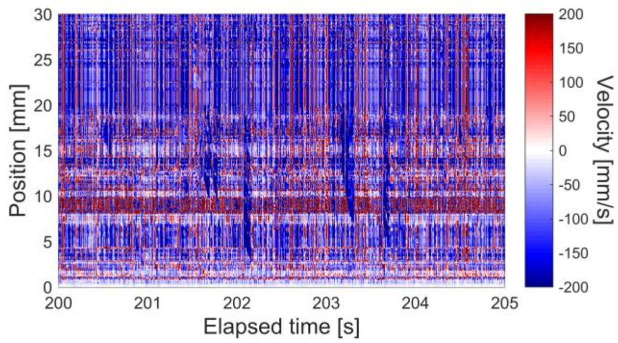
Figure 2: Schematic of helium bubbling experiment apparatus. Chloride salt mixture was melted in the setup. Helium gas was injected through the bent pipe.

4. Result and Discussions

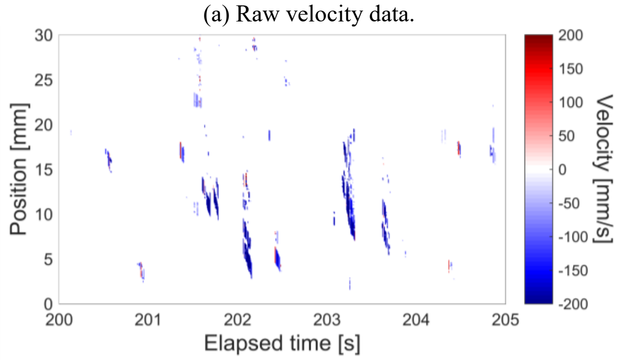
Spatio-temporal velocity plots for a certain time are shown in Figures 3(a). In raw velocity data plot, sign of the velocities are changing randomly. Around 202 and 203 s in elapsed time, there seems to be significant velocities. Velocity offset and amplitude statistics were calculated from the raw data, and offset rejection and amplitude filter were applied. Processed data is shown in Figures 3(b). Velocities mentioned above are successfully extracted in the plot. Confidence factor was set to three in this paper.

Probability density function (PDF) and mean value of velocities are shown in Figures 4. In raw data, mean velocities do not have a meaningful shape due to withstanding trailing echoes. On the contrary, errorneous velocities are successfully rejected in the processed data while the intensity of PDF dropped in two order of manitudes. Boundary layer around the wall can be observed. Velocities are not completely continious where there are strong trailing echoes, for example, around 20 mm in radial position. Nevertheless, high velocity continued toward the end of the measurement depth (30 mm).

Figure 5 shows mean amplitude profiles. Raw amplitudes are indicated by black circle symbols and processed amplitudes are indicated by red square symbols. Raw amplitude profiles outline the trailing echo level. Even after the post-processing, the shape of trailing echo remains in the amplitude profile. Processed velocities (Figures 4(b)) are distorted as well where trailing echo level is higher than its neighboring points (for example, 5 mm in radial position). It means that errournoues velocities are not eliminated perfectly. This velocities cannot be removed by increasing the confidence factor. Amplitude of bubbly flow is almost flat by 20 mm. Strong trailing echoes disturb measurement and amplitudes increased around 20 mm. After 22 mm, amplitudes are decreasing. Number of extracted data points are plotted as data validity in Figure 6. It can be seen that validities after 20 mm are significantly low. It is because of remaining trailing echoes. As confidence interval was set to three, data validity would be 0.13% assuming the Gaussian distribution. However, experimental results are far larger than this value. It can be predicted that amplitude may follow bimodal distribution once a large enough data set is obtained. Therefore, there will be a possibility to extract significant data by appling an advanced filter and adjusting the parameter automatically.

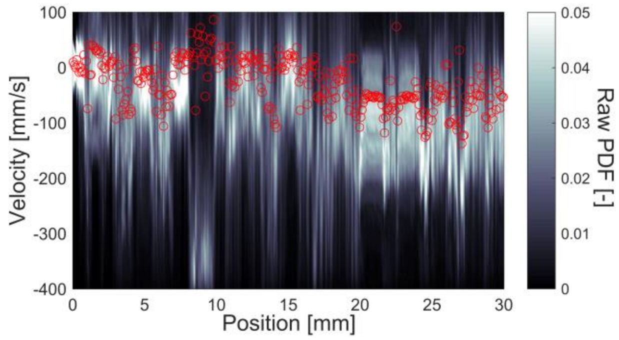


(a) Raw velocity data.

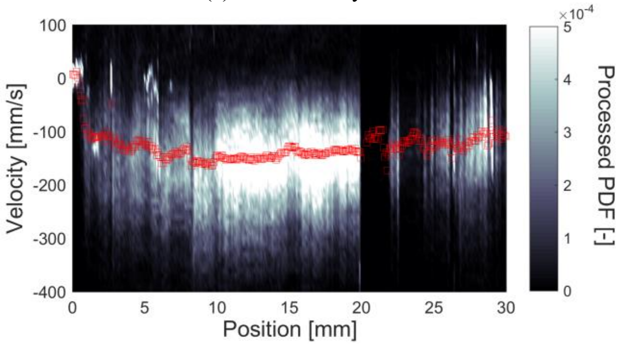


(b) Processed velocity data.

Figures 3: Spatio-temporal velocity plots of bubbly flow in molten salt.



(a) Raw velocity data.



(b) Processed velocity data.

Figures 4: Probability density function and mean velocity (red circle symbols) among 200,000 profiles.

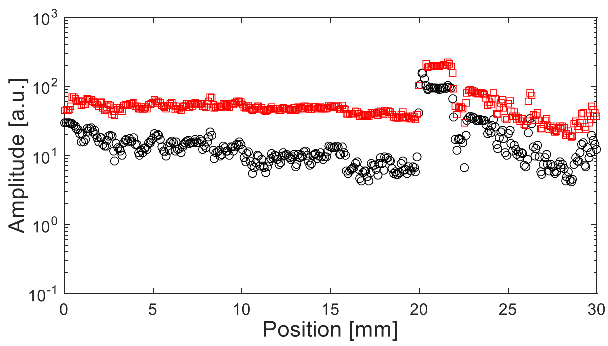


Figure 5: Mean amplitude profiles of raw data (black circle symbols) and processed data (red square symbols).

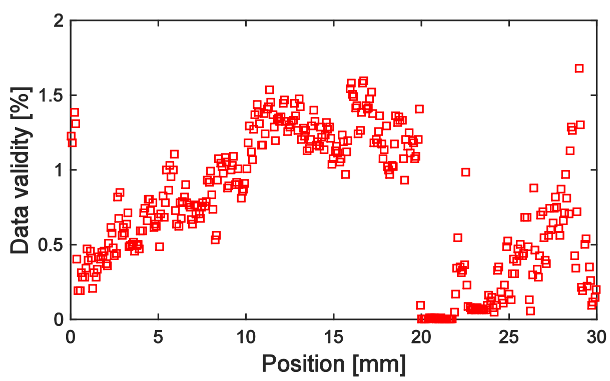


Figure 6: Data validity profile after the post-processing.

6. Summary

Signal processing and post-processing techniques are presented for UVP measurement with buffer rod. Bubbly flow in molten salt was measured at the temperature of 500 °C. Trailing echoes are inevitable problem with buffer rod measurement. Considering the characteristics of trailing echoes, DC filter was applied to eliminate the standing wall echo signal. Phase difference method was applied to estimate velocity and amplitude profiles. Jitter problem was observed due to triggering error, temperature variation and other factors. Offset velocity was introduced to compensate the jitter problem. In order to extract bubble veloicities from noisy measurement result, amplitude filter was used. Velocities with higher amplitude than mean amplitude are extracted. Confidence factor was set to three. Data validity was higher than the value, which can be predicted by the Gaussian distribution assumption. Measured velocity profile was reasonable result considering the experiment condition. It is proven that those procedure was useful to realize UVP measurement with buffer rod even if only classical approaches were used in this study. It was seen that error velocities are not yet rejected completely. Further improvement of post-processing will be required in the future work.

References

[1] Generation IV International Forum, 2014 annual report.
[2] Rouch H, *et al.*: Preliminary thermal–hydraulic core design of the molten salt fast reactor (MSFR), Annal. Nucl. Energy 64 (2014), 449–456.
[3] Serp J, *et al.*: The molten salt reactor (MSR) in generation IV: Overview and perspectives, Prog. Nucl. Energy, 77 (2014), 308-319.
[4] Kedl RJ: The migration of a class of fission products (noble metals) in the molten-salt reactor experiment, Technical Report of Oak Ridge National Lab. (1972), ORNL-TM-3884.
[5] Tallackson JR, *et al.*: Instrumentation and controls development for molten-salt breeder reactors, Technical Report of Oak Ridge National Lab. (1967), ORNL-1856.
[6] Ihara, T, *et al.*: Development of the ultrasonic buffer rod for the molten glass measurement, Prog. Nucl. Energy, 82 (2015), 176-183.
[7] Ihara T, *et al.*: Application of ultrasonic Doppler velocimetry to molten glass by using broadband phase difference method, Flow Meas. Inst., 48(2016), 90-96.
[8] Sather A: Ultrasonic buffer-rod technique for the high-temperature measurement of the elastic moduli of short specimens, J. Acoust. Soc. Am. 43 (1968), 1291-1294.
[9] Jen CK, *et al.*: Fabrication and characterization of continuously cast clad metallic buffer rods, J. Acoust. Soc. Am., 91 (1992), 3565-3570.
[10] Lynnworth LC, *et al.*: Extensional bundle waveguide techniques for measuring flow of hot fluids, IEEE Ultrason. Ferro. Freq. Cntl., 52 (2005), 538-544.
[11] Ihara T, *et al.*: Ultrasonic velocity profiler for very low velocity field, Flow Measurement and Instrumentation, 34 (2013), 127-133.