Progress in Nuclear Energy 82 (2015) 176–183

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Development of the ultrasonic buffer rod for the molten glass measurement

Tomonori Ihara*, Nobuyoshi Tsuzuki, Hiroshige Kikura

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1-N1-7, Ookayama, Meguro-ku, Tokyo 152-8550, Japan

A R T I C L E I N F O

Article history:
Received 15 November 2013
Received in revised form
15 July 2014
Accepted 27 July 2014
Available online 22 August 2014

Keywords:
Buffer rod
Molten glass
Sound velocity
Attenuation coefficient

A B S T R A C T

Design and demonstration of an ultrasonic buffer rod for high temperature fluid especially for the molten glass were studied. Material selection guide for glass melts was established focusing on high temperature strength, attenuation and acoustic impedance. Durability and wettability of ultrasonic buffer rod have been tested for several materials. Frequency of the ultrasound was chosen considering the transmission characteristic of the buffer rod which was investigated employing three dimensional FEM code. The buffer rod tested has tapered shape and cladding on the side wall as a further suppression of trailing echo. Sound velocity and attenuation coefficient measurements in a temperature range of 1000–1200 °C were then demonstrated utilizing the designed buffer rod. Signal processing technique to eliminate remained trailing echoes was also performed. Applicability of the ultrasonic measurement using the buffer rod is discussed.

1. Introduction

Flow measurement technique for high temperature fluid is demanded in controlling and monitoring the nuclear energy plant. In particular, a vitrification melter for high level radioactive waste (HLW) handles very high temperature (exceeding 1000 °C) molten glass. Japanese type vitrification melter is operated with internal Joule heating and natural convection. Thus, flow behavior in the melter is notably affected by the subsidence of the platinum group metals and other substances. Several numerical researches were performed to investigate a thermal hydraulics behavior (Matsuno et al., 2008; Yang et al., 2012). However, their validities in the melter were not confirmed because of difficulties in high temperature flow measurement. Application of conventional flow measurement techniques such as laser Doppler velocimetry and flow visualization is difficult due to opaqueness of melts and high thermal radiation. In contrast, ultrasonic measurement, namely ultrasonic velocity profiler (UVP) is one of the applicable methods in this severe environment. The UVP is based on the pulsed echographic technique and widely applied including duct flow and opaque flow such as liquid metal (Takeda, 1987) due to nondestructive property of ultrasound. Consequently, we focused on the UVP technique and we developed the measurement technique for the molten glass flow (Ihara et al., 2011; Ihara et al., 2013). This paper discusses two points: design of the buffer rod and demonstration of high temperature measurement.

In order to transmit ultrasound into high temperature media, a buffer rod technique has been widely used due to unavailability of high temperature transducer (Breeuwer et al.,; Greenberg et al., 2008; Nagata et al., 1987; Prasad et al., 2008; Sather, 1968; Jen et al., 1997; Burthan et al., 2005). Many of them employed a through transmission method to comply with low signal-to-noise ratio (SNR) (Breeuwer et al.,; Greenberg et al., 2008). This study investigated the design procedure of buffer rod with high SNR. The design involves the selections of material, shape and frequency. After the design of buffer rod, we demonstrated the measurement of basic ultrasound characteristics of molten glass. In the UVP, sound velocity is required since both flow velocity and position of the echo are calculated using sound velocity in the fluid. In addition, temperature dependence of sound velocity is also important because large temperature variation is expected in the industrial melter. If temperature dependence of sound velocity is large, sound velocity varies along the measurement line and ultrasonic beam is bended by Snell's law. The UVP cannot be applied to the conditions where ultrasonic beam is strongly bended. Besides sound velocity, attenuation coefficient of ultrasound is required. Ultrasound is attenuated in viscous fluid during the propagation. Especially, in molten glass, with high viscosity, attenuation coefficient would be large and influence measurable distance. Thus, sound velocity and attenuation coefficient in molten glass were measured to evaluate

---

* Corresponding author. Tel.: +81 3 5734 3059; fax: +81 3 5734 2959.
E-mail address: ihara@us.nr.titech.ac.jp (T. Ihara).

http://dx.doi.org/10.1016/j.pnucene.2014.07.041
0149-1970/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

D	Transmission coefficient
L	Length of buffer rod
R	Reflection coefficient
R^2	Coefficient of determination
t	Time delay after the pulse emission
t^*	Normalized time delay by transit time
T	Temperature
V	Sound velocity
x	Traverse distance of buffer rod
Z	Acoustic impedance

Greek letters

A	Attenuation coefficient
H	Viscosity
P	Density

Subscripts

L	Longitudinal wave
S	Shear wave

the applicability of the buffer rod technique to the flow measurement.

2. Buffer rod technique

Ultrasound is normally generated with piezoelectric elements. The piezoelectric elements have their Curie temperatures, and the material loses a spontaneous polarization above the temperature. Although some elements possess high Curie temperature, these transducers results worse performance. Consequently, a buffer rod is used for the sound transmission between high temperature specimen and room temperature transducer as a thermal buffer and a waveguide. Echo from high temperature specimen is observed at a transducer end after being reflected from the specimen end. Since both the echo of interest and the echo from specimen end are transmitted in the same path, relative position and amplitude are saved. The advantage of the usage of buffer rod is the capability of utilizing high performance normal transducer cooled down to room temperature while the other end of the buffer rod is heated by specimen. Cooling one end leads to a large temperature gradient along the rod. To comply with the gradient, long rod is usually used and it causes the spurious echo which is called trailing echoes.

Ultrasonic wave in solid media is mainly classified into two kinds: longitudinal wave and shear wave while wave in fluid media is only longitudinal wave. Inside a rod with a finite diameter, emitted longitudinal pulse wave partly impinge on the side wall and is reflected accompanied by mode conversions. Converted shear wave propagates along the rod, and reflection on the side wall occurs again. During the reflection, some waves are converted to longitudinal waves and propagate along the rod later than the emission wave since the velocity of the shear wave is slower than that of the longitudinal wave. These repetitions produce spurious echo, which appears in the midst of the signals of interest, since the signals of interest are after far rod end echo. Consequently, suppression of the trailing echo is the most important task when utilizing the buffer rod with the pulsed echo method.

2.1. Material

Material selection is of significant importance for the ultrasonic buffer rod technique. Firstly, high durability is required. The buffer rod should withstand high corrosive condition as well as oxidization because the glass melt capture other substances into their matrix structure. Naturally, a melting point must be higher than the maximum operating temperature of 1200 °C. In addition, the material must retain high strength at that temperature since ultrasound is the elastic wave. In such a high temperature environment, ultrasonic wave attenuation inside the rod is also the critical problem. There are several high temperature-resistant alloys. In particular, nickel-based alloys offer high strength above 1000 °C and high corrosion resistance. Many vitrification melters adopt them as an electrode. However, these alloys are often solution-hardened and that treatment results in high attenuation of ultrasound due to scattering on grain boundaries. Moreover, dissolution behavior takes place at such a high temperature environment and results huge scattering. Thus, these alloys are not used in this study to avoid complexity for the reason mentioned above. Another problem on the metallic buffer rod is phase transformation. The transformation temperature should be higher, otherwise ultrasound is scattered in the rod. For example, the rod end echo of a titanium buffer rod disappeared at around 900 °C in our test while pure titanium has a transformation temperature from α to β at 882 °C (Davis, 1998). There are few previous reports in which metals such as platinum were employed (Breeuwer et al.,). However, these materials are unsuitable for flow measurement purpose for the reasons of high impedance. Considering above, pure metals and oxides are listed as candidate materials in Table 1.

Other typical criteria for the ultrasonic measurement of glass melt are the impedance matching and wettability. When the ultrasound wave penetrates through the interface between two different media, part of the energy is reflected back. Let the acoustic impedance of the two media be Z_1 and Z_2. Then the coefficients of reflection and transmission of the sound pressure are derived by $R = (Z_2 - Z_1)/(Z_2 + Z_1)$ and $D = 1 - R$, respectively (Krautkrämer and Krautkrämer, 1990). The acoustic impedance Z is defined as $Z = \rho V$ where ρ is the density and V is the speed of sound. Preliminary test (Ihara et al., 2011) revealed that the acoustic impedance of the molten glass was approximately 6 MRayl (1 Rayl = 1 Pa s/m). In contrast, acoustic impedance of solid material is generally larger as shown in Table 1. In the table, materials are listed in ascending order of acoustic impedance. For instance, the transmission coefficient from nickel to glass melt is only 21%. Material, which has the lower Z, is required to achieve high transmission coefficient. Furthermore, material with higher thermal conductivity is undesirable because the use of rod may affects the temperature of the melt. Even though acoustic impedance is low enough, ultrasonic wave sometimes does not penetrate into the glass melt. This wettability problem is observed when the carbon rod is tested in

Table 1
Properties of candidate materials at room temperature which are compiled from manufacturer supplied data and Davis (1998).

Material	Density ρ[kg/m^3]	Sound velocity		Acoustic impedance Z_l [MRayl]	Thermal conductivity [W/m K]
		Longitudinal wave V_l [m/s]	Shear wave V_s [m/s]		
Carbon (Graphite)	1900	2930	1710	5.57	58
Fused quartz	2220	5900	3750	13.0	1.4
Metallic silicon	2330	8430	5840	19.6	160
Zirconia	6000	6800	3570	40.8	3.0
Alumina	3900	10,500	6210	40.9	32
Nickel	8900	5680	2980	50.5	83
Platinum	21,500	3960	1670	85.0	71