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Enhancing signal to noise ratio by fine-tuning tapers of cladded/uncladded buffer rods in ultrasonic time domain reflectometry in smelters

Håkon Viumdal [a,b,*], Saba Mylvaganam [b]

[a] Tel-Tek, Kjølnes Ring 30, 3918 Porsgrunn, Norway
[b] Telemark University College, Faculty of Technology, Kjølnes Ring 56, 3918 Porsgrunn, Norway

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ABSTRACT

Buffer rods (BR) as waveguides in ultrasonic time domain reflectometry (TDR) can somewhat extend the range of industrial applications of ultrasonics. Level, temperature and flow measurements involving elevated temperatures, corrosive fluids and generally harsh environments are some of the applications in which conventional ultrasonic transducers cannot be used directly in contact with the media. In such cases, BRs with some design modifications can make ultrasonic TDR measurements possible with limited success. This paper deals with TDR in conjunction with distance measurements in extremely hot fluids, using conventional ultrasonic transducers in combination with BRs. When using BRs in the ultrasonic measurement systems in extreme temperatures, problems associated with size and the material of the buffer, have to be addressed. The resonant frequency of the transducer and the relative size of the transducer with respect to the diameter of BR are also important parameters influencing the signal to noise ratio (SNR) of the signal processing system used in the ultrasonic TDR. This paper gives an overview of design aspects related to the BRs with special emphasis on tapers and cladding used on BRs. As protective cladding, zirconium oxide–yttrium oxide composite was used, with its proven thermal stability in withstanding temperatures in rocket and jet engines up to 1650 °C. In general a BR should guide the signals through to the medium and from and back to the transducer without excessive attenuation and at the same time not exacerbate the noise in the measurement system. The SNR is the decisive performance indicator to consider in the design of BR based ultrasonic TDR, along with appropriate transducer, with suitable size and operating frequency. This work presents and analyses results from extensive experiments related to fine-tuning both geometry of and signals in cladded/uncladded BRs used in high temperature ultrasonic TDR with focus on overall performance based on measured values of SNR.

1. Introduction

In several industrial applications, ultrasonic transducers (UT) cannot be directly placed in contact with the process media, due to harsh environments, high temperatures or rough surfaces. By utilizing ultrasonic waveguides in the form of buffer rods (BRs), such challenges may be overcome. In such applications, the BR functions simultaneously as a waveguide and protecting element for the UTs. Fig. 1 illustrates a simplified overview of transducer content, and demonstrates how the system can be arranged to determine interfaces in molten bath.

The demand, and hence the research on techniques for utilizing acoustic transducers in high-temperature environments arose in conjunction with non-destructive material testing in the period of extra-terrestrial travels involving rockets and airships, [1]. Acoustic BRs have successfully been utilized in the detection of small particles in molten metals, e.g. aluminium [2,3], and in detecting the solid–liquid interface in solidification of e.g. molten aluminium [4]. Acoustic BRs in longitudinal, shear and torsional modes, operating as delay lines [5], in staggering dead-bands and other applications are discussed in [6]. Level determination in industrial electrolysis processes using BRs, such as in magnesium and aluminium production facilities, have also been tested [7,8]. Ultrasonic online monitoring during polymer extrusion and curing processes of graphite/epoxy has been used with acoustic BRs [7]. Determination of reliable temperatures up to at least 3000 °C has also been possible by using BRs in combination with UT [1]. Methods for estimating liquid densities from reflection coefficients, using acoustic BRs are described in [9,10]. The BR used in [10] has a rather large diameter to avoid spurious reflections from its

* Corresponding author at: Telemark University College, Faculty of Technology, Postboks 203, N-3901 Porsgrunn, Norway. Tel.: +47 35 57 51 64.
E-mail address: hakon.viumdal@hit.no (H. Viumdal).

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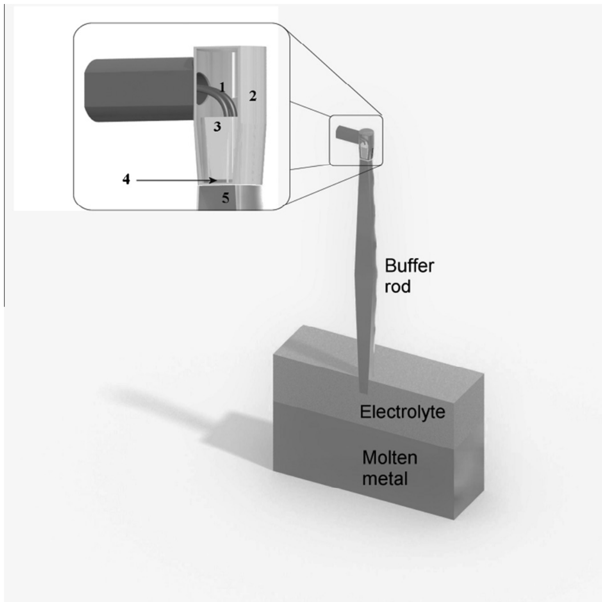

Fig. 1. Schematic drawing of a level measuring application with a transducer connected to a double taper BR immersed into a molten bath, consisting of two different materials or phases. 1 represents the cables, 2 the transducer housing, 3 the backing material, 4 the piezoelectric material and 5 the buffer rod.

wall and the medium investigated is considerably small to the size of the BR, making this application more suitable for lab based sampling applications. An interesting overview of some of the first applications of ultrasonic BRs is given in [11], where the BR is used to evaluate Young's and Shear moduli and hence Poisson's ratio of materials based on longitudinal and shear wave velocity measurements. In 1965, in nuclear radiation environments, high temperature measurements were performed using BRs based on sound speed dependency on temperatures, [12].

Elasticity measurements in high-temperature applications using BRs for making resonant ultrasound spectroscopy have been reported in [13]. Simultaneous viscosity and temperature measurements in high temperature melts using ultrasonic transducers in combination with BRs is described in [14]. Dispersion phenomena are described in [15] and are exploited to possibly steer the launching direction of ultrasonic waves via a bundle of slender BRs of varying diameters. BRs are used in the measurement of reflection coefficient at interfaces of differing acoustic impedances, density of media, attenuation in the medium of ultrasonic propagation, and as delay lines for signal processing purposes.

The focus in this paper is on the design variations of straight and tapered BRs with and without cladding for improving signal to noise ratio in conjunction with estimating distances and interface levels.

There is a plethora of factors to be considered in the selection of an optimal ultrasonic waveguide for a particular application. The buffer material should match the material of the application, so that the signal is transmitted preferably intact into the actual material. The shape of the BR should match the transducer, and the material of BR should have low attenuation of ultrasonic signals, and facilitate reduction of spurious noise. Finally, the transducer should match the measurement requirements, such as propagation, temporal and not the least, accuracy requirements.

The intended use of the measurement system considered in this study relates to distance measurements and interface detection in conjunction with molten metals. In particular the BRs are designed to detect the level of the interface between two different materials or phases in metallurgical industry, as shown in Fig. 1. A list of symbols and abbreviations used in this paper is given in Table 1.

Table 1
List of symbols and abbreviations.

Symbol	Quantity	Units
TDR	Time domain reflectometry	
NDT	Nondestructive testing	
UT	Ultrasonic transducer	
BR	Buffer rod	
SNR	Signal to noise ratio	dB
c	Sound velocity	m/s
z	Specific acoustic impedance	Ns/m^3
R	Reflection coefficient	
L	Length of buffer rod	mm
d_{Be}	Diameter of buffer rod end	mm
d_{Bm}	Maximum diameter of buffer rod	mm
θ	Taper angle	°
α	Ultrasonic beam spread angle	°
d_{UT}	Element diameter of transducer	mm
f	Frequency	Hz
A	Relative amplitude of reflected pulse	dB
d_N	Near field distance	m
κ	Thermal conductivity	W/(K m)
σ	Electrical conductivity	S/m
L_N	Lorentz number	$Volt^2/K^2$
T	Temperature	K

2. Buffer based ultrasonic TDR

BRs are ultrasonic waveguides used to protect the ultrasonic transducer from corrosive and/or high temperature environments, as in e.g. molten metals. Conventional piezoelectric UT can then be placed on top of the BR with appropriate bonding liquids/pastes, where the temperature is, or can be kept below the critical Curie temperature of the piezoelectric crystal used in the UT [16]. The transducer connected end of the BR might be cooled by cooling pipes wrapped around the BR or by dipping intermittently in the hot fluid, just before the measurements are taken. Nitrogen, water and air are typically used as cooling medium, but water is not allowed to be used in the vicinity of molten metals due to explosion hazard caused by expanding steam.

2.1. Material properties of BRs

In order to achieve consistent high-quality ultrasonic measurements and prevent equipment failure, several properties of the core material of the BR have to be considered, especially in the case of employing these BRs in corrosive environments. In the context of the present study, the physical properties of the BR have been divided into five main groups:

2.1.1. Acoustic properties

The basic acoustic properties to be considered are the acoustic attenuation, the sound velocity c, the specific acoustic impedance z, and the reflection coefficient R. The acoustic attenuation describes wave guiding property within a uniform material, whereas the reflection coefficient describes the reflection of acoustic waves, and hence indirectly the transmission between two materials. Both properties are important in choosing a proper acoustic BR.

As the attenuation of the ultrasonic signal increases with increasing transit distance, the attenuation could be a decisive factor, particularly for longer BRs. However, identifying the source of the attenuation and reducing it and hence the physical modelling of its causes, can be very complex and very often demanding tasks [17]. For metals, the attenuating properties are particularly dependent on the processing method used in the production of the material [18]. The grain size and the casting technique used are essential factors affecting the acoustic guidance property of the BR [19]. However, tabulated values of attenuations for different