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PRELIMINARY INVESTIGATIONS OF THE ULTRASONIC SIGNAL ATTENUATION IN THE LIQUID LEAD USING WAVEGUIDE

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This paper presents the experimental activities carried out within Institute for Nuclear Research from Pitesti for the ultrasonic characterization of liquid lead, candidate as nuclear coolant of advanced nuclear energy systems. An experimental facility for ultrasonic measurements in a stagnant liquid lead environment (up to 450°C) by pulse-echo technique has been developed. In the absence of an immersion transducer able to work in high temperature conditions, an external ultrasonic transducer in acoustic contact with a stainless steel waveguide is used. With the measured data the acoustic parameters (ultrasonic velocity, attenuation coefficient, wetting factor) can be calculated. These acoustic parameters are used for sonic path evaluation, when the operations of the ultrasonic visualization, measurement and nondestructive testing in liquid lead environment are performed.

Keywords: ultrasonic attenuation, ultrasonic waveguide, liquid lead

1. Introduction

For the demonstration of the LFR (Lead Fast Reactor) technology, further facilities (either existing or under construction) are required. Romanian option to host LFR Demonstrator ALFRED (Advanced Lead Fast Reactor European Demonstrator) involves the Institute for Nuclear Research from Pitesti (INR) in future development of technology, in the frame of European projects aimed at Generation IV research activities. For safety as well as for licensing reasons, an imaging method for evaluation of the status of inner reactor parts submerged in the opaque hot liquid metal has to be developed.

The opaqueness, which is common to all liquid metals, disables all-optical methods. There are not many other physical means except ultrasound, which would

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enable us to “see” through liquid metal. Therefore “visual” inspection can be done using ultrasonic waves [1].
To obtain the necessary resolution and accuracy, a good knowledge of ultrasonic wave propagation characteristics in a liquid metal is necessary. There are two main parameters of ultrasonic waves, which need to be determined: velocity and attenuation. The practical use of ultrasound in the liquid lead still needs to be demonstrated by experiments. These require measurement technologies specially adapted to this working fluid. For these reasons, an experimental facility for ultrasonic measurements in a stagnant liquid lead environment by pulse-echo technique has been developed in our institute. This paper presents the methodology for investigation of ultrasonic wave attenuation.

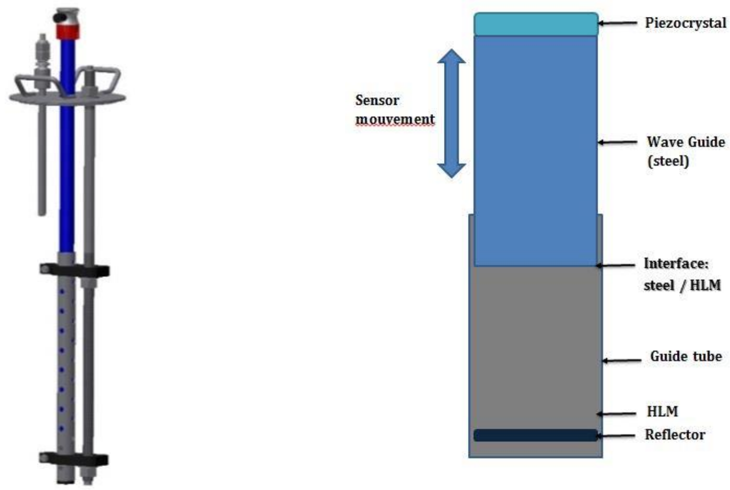
2. Measurement methodology

Ultrasonic pulse-echo technique is often used to perform non-destructive testing and characterization of materials due their simplicity and capability to probe interiors of opaque environments. The main problems which are met in our case are caused by the high temperature (up to 450°C) and the aggressive properties of the liquid lead. Therefore, a single element ultrasonic transducer of large bandwidth, high signal-to-noise ratio, suitable for harsh operating conditions has to be used [2,3]. Because the development of such an ultrasonic transducer for high temperature environments is considered a very difficult problem, the concept of *waveguide* made possible the use of contact ultrasonic transducer in various fields of industry and scientific investigations, inclusiv in Heavy Liquid Metal (HLM) technology [3]. The ideal waveguide transducer must have high efficiency as a transmitter and high sensitivity as a receiver. In practice, the problem of using a waveguide to transmit ultrasonic waves is the presence of spurious echoes resulting from wave dispersion, reverberation, mode conversion, and diffraction within the waveguide. Elimination or reduction of spurious echoes is the main consideration in waveguide development. For ultrasonic measurements the axial ultrasonic wave (longitudinal wave) is of interest. This wave has the largest amplitude and the shortest time-of-flight of the reflected echoes.

A waveguide acts as a buffer that isolates the sensing transducer from a high-temperature and corrosive medium. Thus, an ultrasonic transducer in acoustic contact with a stainless steel waveguide was used. The acoustic coupling between the ultrasonic transducer and the waveguide is an essential problem at high temperatures. To provide acoustic coupling the frontal surface of the transducer is pressed via silicone gel to the surface of the acoustic waveguide (stainless steel AISI 316 rod). Because the wetting of metal surface is low, the frontal contact surface must be flat and well-polished.

For ultrasonic measurements by pulse-echo technique is necessary to have a good perpendicularity between the beam axis and the planar reflector surface. For this reason, we chose to perform the measurements in a *guide tube* equipped with a fixed reflector in the bottom end [3÷7]. The waveguide can slide manually through this guide tube immersed in a liquid environment. In Fig. 1 is shown the experimental set-up for ultrasonic investigation of the high-temperature environment, using waveguide.

The investigation of ultrasonic waves attenuation consists of the evaluation of losses of the signal in propagation path, at various transducer - reflector distances to get quantitative information about the variation of signal amplitude versus a distance. Thus, the distance between the bottom face of the waveguide and the front surface of the reflector must be varied. When the measurement device (fig.1(a)) is immersed in the liquid vessel and the stainless-steel waveguide is moved through the guide tube, the ultrasonic signals reflected by interfaces (bottom face of the waveguide/HLM and HLM/reflector) (fig.1(b)) are exploited. Their amplitudes and time-of-fly values are measured. They are converted into a digital form using the digital oscilloscope. The digital data files are stored and processed on a personal computer.



a) Measurement device - Design

b) The geometry of measurement - Schematic representation

Fig. 1. Experimental set-up for ultrasonic investigation of the high-temperature environment, using waveguide

2.1. Experimental facility description

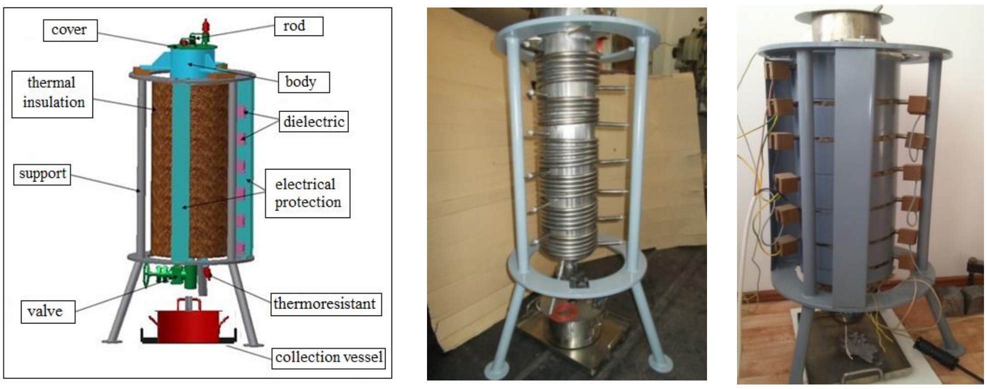
The experimental facility for ultrasonic measurements has the following configuration (Fig. 2) [7,8]:

1) a stainless steel vessel with the accessories used for heavy metal melting and for ultrasonic measurements (Fig. 3);
2) an electrical component used for command and control of the liquid metal heating (range of temperature up to 450^{o}C) (Fig. 3);

3) an ultrasonic component used for experimental measurements in molten lead and data processing (Fig. 4(a)).

Fig. 2. Experimental facility

The **stainless-steel vessel** is an important component during the measurements. It has the following accessories: thermal insulation, electric protection (Fig. 3), measurement device (Fig. 4(b)) [8].



a) Melting vessel – schematic representation

b) Melting vessel – electrical resistances distribution

c) Melting vessel – final form

Fig. 3. Melting vessel with accessories

The **electrical component** allows command and control of the heating by means of two control circuits, each consisting of: an electrical resistance around vessel, a temperature controller, a thermo-resistance [8].

The **ultrasonic component** consists of:

- an ultrasonic contact transducer Olympus V608, unfocused, resistant up to about 100^{o}C, with a resonance frequency of 5 MHz and a diameter of 0.75" (Ø19mm), connected to the pulser-receiver through a high-temperature resistant mineral cable.

- a waveguide (AISI 316 stainless steel bar, Ø19mm, length 600mm), ultrasonic transparent material, without defects. It is acoustically coupled with the contact transducer and allows measurements in high temperatures environments by sliding inside the guide tube ($Ø_{int}$ 21mm).
- a TecScan pulser/receiver system for the transmission/reception of the ultrasonic signal;
- a digital oscilloscope for visualization and digitization of the received signals;
- a personal computer with MATLAB programming language for data processing [8].

The length of the waveguide is set so that the temperature at the contact surface with the piezocrystal is accepted in the operating specification of the ultrasonic transducer. The waveguide is acoustically coupled to the front surface of the ultrasonic transducer and acts as a protector.

A planar stainless steel *reflector* that ensures a stable good quality reflection of ultrasonic waves is necessary. The *guide tube* is fitted with holes to allow the internal penetration of the liquid lead. It is fixed on the circular cover of the top as shown in Fig. 4 (b). This ensemble is called a *measurement device*.

a) Ultrasonic devices b) Measurement device

Fig. 4. Ultrasonic components and accessories

2.2. Mathematical relationships for ultrasonic parameters

For data processing, it is necessary to establish mathematical relationships between the measured (amplitude and time of flight values for monitored signals) (Fig. 5) and the determined parameters (attenuation coefficient and wetting parameter). The transmission and reflection coefficients at the material boundaries are determined by the acoustic properties of materials. The acoustic impedance of a material is $Z = v \cdot \rho$, where v is the ultrasound velocity in material, ρ is the material density. Theoretical transmission T_i and reflection R_i coefficients for acoustic intensity at steel/HLM and HLM/steel interfaces are:

$$T_i\left(steel / HLM\right) = \frac{4Z_{steel}Z_{HLM}}{\left(Z_{steel}+Z_{HLM}\right)^2} = T_i \tag{1}$$

$$R_i(steel / HLM) = 1 - T_i = R_i \, , \tag{2}$$

$$T_i\left(HLM / steel\right) = \frac{4Z_{HLM}Z_{steel}}{\left(Z_{HLM}+Z_{steel}\right)^2} = T_i \, , \tag{3}$$

$$R_i(HLM / steel) = 1 - T_i = R_i \, , \tag{4}$$

where Z_{HLM} and Z_{steel} are the acoustic impedance of HLM and stainless steel, respectively.

a) <u>Attenuation coefficient</u>

In general, overall ultrasound attenuation is characterized by the following exponential decrease of the pressure amplitude p and of the amplitude of the acoustic intensity I with the traveling distance z: $p = p_o e^{-\alpha z}$ and $I = I_o e^{-2\alpha z}$, where p_0 and I_0 are the pressure and intensity at $z = 0$, respectively. The quantity α can be expressed in dB·cm^{-1}, when αz will be in dB. The factor 2 in the exponential term of the intensity equation results from transforming pressure into intensity, as intensity is proportional to the square of pressure.

The energy transported in an ultrasound wave is usually characterized by the acoustic intensity I defined as the energy transmitted per unit time (usually 1 s) and per unit area (usually 1cm^2) in the direction normal to the considered area. In the field of ultrasonic inspections, intensity is measured in W·cm^{-2} [4,5].

As shown in the Fig. 5, a balance sheet of the ultrasonic intensity for the waves of interest, over the entire sonic path (propagation media and interfaces) was made. Assuming ultrasonic intensity in sending pulse I_0, we will have:

$$I_\alpha = I_0 e^{-2\alpha_1 L_1} \tag{5}$$

where α_1 is the ultrasonic attenuation coefficient for stainless steel and L_1 is the waveguide length (stainless steel).

It is known that the ultrasonic attenuation by a continuous medium is due to three phenomena: absorption, diffraction and scattering. For liquid lead case there is additional one phenomenon – imperfect wetting of the end of wave guide and steel surfaces. In this situation the ultrasonic absorption and scattering are insignificant, so, the attenuation of ultrasonic wave is mainly due diffraction and imperfect wetting phenomena. At steel/HLM interface, the effect of steel wetting is marked by introducing of a X parameter (wetting parameter):

$$I'_\alpha = I_\alpha(1 - T_i X) = I_0(1 - T_i X)e^{-2\alpha_1 L_1} \tag{6}$$

$$I_{0\alpha 0} = I'_{\alpha} e^{-2\alpha_1 L_1} = I_0 (1 - T_i X) e^{-4\alpha_1 L_1} \tag{7}$$

$$I''_{\alpha} = I_{\alpha} T_i = I_0 T_i X e^{-2\alpha_1 L_1} \tag{8}$$

$$I_{\beta} = I''_{\alpha} e^{-2\alpha_2 L_2} = I_0 T_i X e^{-2\alpha_1 L_1} e^{-2\alpha_2 L_2} \tag{9}$$

where α_2 is the ultrasonic attenuation coefficient for liquid lead material and L2 is the waveguide - reflector distance.

$$I'_{\beta} = I_{\beta}(1 - T_i X) = I_0 T_i X (1 - T_i X) e^{-2\alpha_1 L_1} e^{-2\alpha_2 L_2} \tag{10}$$

$$I'''_{\beta} = I'_{\beta} e^{-2\alpha_2 L_2} = I_0 T_i X (1 - T_i X) e^{-2\alpha_1 L_1} e^{-4\alpha_2 L_2} \tag{11}$$

$$I''''_{\beta} = I'''_{\alpha} T_i X = I_0 T_i^2 X^2 (1 - T_i X) e^{-2\alpha_1 L_1} e^{-4\alpha_2 L_2} \tag{12}$$

$$I_{0\beta 0} = I'^{v}{}_{\alpha} e^{-2\alpha_1 L_1} = I_0 T_i^2 X^2 (1 - T_i X) e^{-4\alpha_1 L_1} e^{-4\alpha_2 L_2} \tag{13}$$

The loss of intensity can be expected to be of the form:

$$\frac{I_{0\beta 0}}{I_{0\propto 0}} = \left(\frac{P_{0\beta 0}}{P_{0\propto 0}}\right)^2 = T_i{}^2 X^2 e^{-4\propto_2 L_2} \tag{14}$$

$$\frac{P_{0\beta 0}}{P_{0\alpha 0}} = T_i X e^{-2\alpha_2 L_2} \tag{15}$$

$$\alpha_2 = \frac{1}{2L_2}\left\{ln(T_i X) - ln\left(\frac{P_{0\beta 0}}{P_{0\alpha 0}}\right)\right\} \tag{16}$$

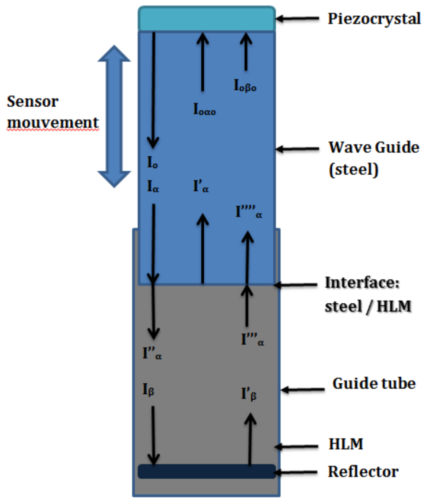


Fig. 5. Schematic representation: signals of interest in the waveguide configuration.

With this relation the α_2 value in nepers per centimeter (Np cm^{-1}) can be obtained. The nepers and decibels (dB) are related via:

$$1\,Np = 20\log_{10} e\ dB = 8.686\ dB \tag{17}$$

Thus, for decibels per centimeter (dB cm^{-1}) we obtain the following relation:

$$\alpha_2 = \frac{20}{2L_2}\left\{\lg\left(\frac{T_i X}{\sqrt{1-T_i X}}\right) - \lg\left(\frac{P_{0\beta 0}}{P_{0\alpha 0}}\right)\right\} \tag{18}$$

So, for ultrasound attenuation measurement in the liquid lead by a pulse echo technique, the explouting of reflected ultrasonic signals from the end of the waveguide ($P_{0\alpha 0}$) and the reflector ($P_{0\beta 0}$) is necessary.

b) Wetting coefficient

The wetting of stainless-steel surfaces submerged in liquid lead can be investigated by pulse echo technique. For these measurements, a ultrasonic transducer with a single piezoelectric element is used. In front of piezoelectric element there is a stainless-steel waveguide protector [7,8]. In order to solve the issue of initial wetting and to get a good acoustic contact between ultrasonic transducer and liquid metal, the oxide layer on the transducer front surface has to be removed. The amplitude of the reflection at the end of a stainless-steel waveguide submerged in HLM is compared with the theoretical one. The discrepancy between theoretical values and measured values can be converted into a "wetting coefficient" as an indication of the wetting efficiency. For this reason it is necessary to find its theoretical formula and experimental values [7,8].

Theoretically, at the waveguide/heavy liquid metal interface (Fig. 6), the transmitted ultrasonic intensity is:

$$I_{Ttheory} = I_O \frac{4Z_{HLM}Z_{steel}}{\left(Z_{HLM} + Z_{steel}\right)^2} \tag{19}$$

where Io is ultrasonic intensity in sending pulse (Fig. 7); Z_{HLM} and Z_{steel} are the acoustic impedance of HLM and stainless steel, respectively; $Z_{HLM} = \rho_{HLM} v_{HLM}$, $Z_{steel} = \rho_{steel} v_{steel}$, ρ = density, v = ultrasonic velocity for longitudinal oscillation mode. By introducing the X parameter (wetting coefficient) in (19), the effect of wetting is taken into account:

$$I_T = I_O \frac{4Z_{HLM}Z_{steel}}{\left(Z_{HLM} + Z_{steel}\right)^2} X \tag{20}$$

Conservation of energy gives the reflected intensity:

$$I_R = I_O - I_T = I_O\left(1 - \frac{4Z_{HLM}Z_{steel}}{\left(Z_{HLM} + Z_{steel}\right)^2} X\right) \tag{21}$$

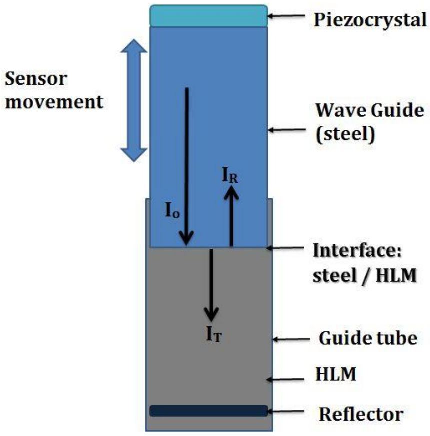


Fig. 6. Schematic representation: ultrasonic signals at waveguide - HLM interface

Translated to pressure:

$$p_R^{HLM} = \sqrt{I_O\left(1-\frac{4Z_{HLM}Z_{steel}}{(Z_{HLM}+Z_{steel})^2}X\right)Z_{steel}} \tag{22}$$

where p_R^{HLM} is the pressure of reflected ultrasonic wave at steel/HLM interface.

The factor K is defined:

$$K = \frac{p_R^{HLM}}{P_R^{air}} = \sqrt{1-\frac{4Z_{HLM}Z_{steel}}{(Z_{HLM}+Z_{steel})^2}X} \tag{23}$$

where p_R^{air} is the pressure of reflected ultrasonic wave at steel/air interface.

$$X = (1-K^2)\frac{(Z_{HLM}+Z_{steel})^2}{4Z_{HLM}Z_{steel}} \tag{24}$$

Assuming that at perfect wetting, X = 1, the theoretical K factor (K_T) can be calculated:

$$1 = (1-K_T^2)\frac{(Z_{HLM}+Z_{steel})^2}{4Z_{HLM}Z_{steel}} \tag{25}$$

and wetting coefficient

$$X = \frac{1-K^2}{1-K_T^2} \tag{26}$$

It can be assumed that:

- in the case of water, the wetting is good (100% wetting) ;
- in the case of air, the wetting is zero (0% wetting).

For these two cases we assigned the following values for X:

$$X = \begin{cases} 1, \ for \ 100\% \ wetting \\ 0, \ for \ 0\% \ wetting \end{cases} \tag{27}$$

For stainless steel/lead interface at 400°C, the values of acoustic impedance Z and theoretical K_T factor are tabulated. The experiments show that a well polished protector surface increases the microscopic contact between liquid metal and waveguide, thus ensuring a better acoustic coupling [7,8].

2.3. Data acquisition and processing

By manual movement of the waveguide, different waveguide surface-reflector distances can be obtained. For every position, the ultrasonic pulse-type signals are received by the piezoelectric element.

The received signals are amplified by the pulser-receiver and visualized on the digital oscilloscope in A-scan representation. This is two-dimensional graphical presentation, in rectangular coordinates, in which the received pulse amplitude [V] is represented as a displacement along one axis and the travel time of the ultrasonic pulse [s] is represented as a displacement along the other axis.

These representations can be saved using the oscilloscope, as .jpg picture format files or .csv data files.

The .csv data files are visualized by MATLAB software application and for each echo of interest (Fig. 7) the amplitude and time-of-fly values can be obtained. These echoes from Fig. 7 are the echoes $I_{0\alpha 0}$ and $I_{0\beta 0}$ from Fig. 5.

Now, entering these values into (18) and (26) relations, the attenuation coefficient and wetting parameter respectively can be calculated [5,8].

The wetting parameter X can be determined according to (24). Firstly, it is calculated the K factor as shown in (23). This needs to determine the reflected waves pressure values (p_R^{air} and p_R^{HLM}) when the stainless-steel waveguide front surface is submerged in air (0% wetting) and liquid lead, respectively. Since the wave pressure value is proportional with wave amplitude, the amplitude of the reflection at the end of waveguide submerged in liquid lead is compared with the theoretical one (in air). It is assumed that the reflection coefficient Ri at the waveguide front surface is *-1* when the waveguide is free (in air).

The amplitude of the signal reflected by the reflector in the case of liquid lead is given in Fig. 8(a). The attenuation coefficient values for liquid lead can be calculated according to (18).

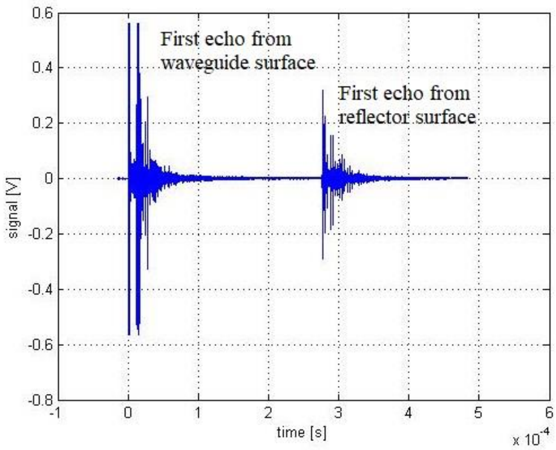
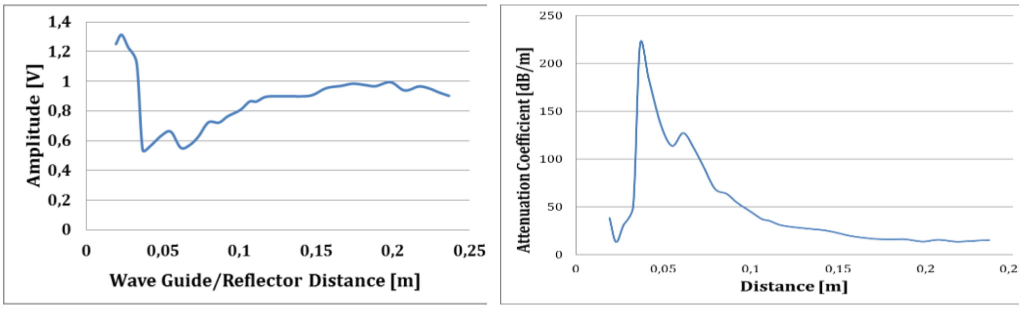


Fig. 7. Viewing data files with the MATLAB software: A-scan representations in amplitude [V] – time-of-fly [s] coordinates

For each value of the waveguide front surface – reflector surface distance, a value of the coefficient is obtained. By graphical representation of these values, diagrams like the one shown in Fig. 8(b) can be obtained.



a) Amplitude of reflector signal b) Attenuation coefficient

Fig. 8. Preliminary results for liquid lead (400ºC)

As is shown in Fig. 8(a), the amplitude of the reflected signal representation is the profile of acoustic field of the transducer - waveguide ensemble, on the axis of the ultrasonic beam. The region close to the front of the waveguide (0 ÷~0,07m in this case) with a system of maxima and minima in intensity is known as the near field (Fresnel zone). The region beyond the near field (>~0,07m) is known as far field (Fraunhofer zone) where the intensity of the beam varies as the square of the distance.

Fig. 8(b) shows the evolution of the attenuation coefficient related to distance from the frontal surface of the waveguide. Its values tend to a constant value.

6. Conclusions

This paper presents the experimental activities carried out within Institute for Nuclear Research from Pitesti for the ultrasonic characterization of liquid lead resulting in an experimental facility with a measurement and data processing methodology. With the measured data the acoustic parameters (attenuation coefficient, wetting factor) can be calculated. These are useful when ultrasonic measurement and visualization techniques for operation in heavy liquid are developed. The preliminary tests of this experimental facility have obtained diagrams like those shown in Fig. 8. The values and the shape of the graph are in good agreement with the theory and the specialty literature [6,9]. For a better accuracy of the results, it is necessary a more rigorous observance of the following aspects:

- a more reliable solution is obtained by estimating signal losses using a larger distance;
- a planar stainless steel reflector that ensures a stable good quality reflection of ultrasonic waves is necessary;
- a liquid metal (lead) with a higher level of purity;
- a good perpendicularity between the beam axis and the planar reflector surface;
- a good acoustic contact between transducer surface and waveguide top surface;
- it is beneficial to use a high temperature resistant ultrasonic transducer suitable for operating long time, immersed in liquid metal;
- an oxygen control system for measuring and adjusting the concentration of oxygen (it allows maintaining the oxygen concentration in the field of interest).

R E F E R E N C E S

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