Ultrasonic Evaluation of Status of Nuclear Reactors Cooled by Liquid Metal

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Abstract. In new type nuclear reactors, the core is cooled by means of liquid metal. The use of heavy liquid metal for reactor devices under development possesses problems with the required inspection and maintenance due to the opaque nature of the medium. In contrast to water-cooled reactors there are no any other means except ultrasonic, which would enable to inspect inner reactor parts submerged in the hot liquid metal. For safety an ultrasonic imaging method for evaluation of status of a reactor has thus to be developed. The imaging system used for such purpose must operate in very harsh conditions including high temperature (160 - 400 °C), chemical activity of the liquid metal and strong radiation (up to 30kGy/h). These conditions significantly restrict the possible architecture of the visualization system and materials, which can be used.

For solution of this task, first it was necessary to develop ultrasonic transducers, which are able to operate in a heavy liquid metal in the temperature range from 160 to 450^{o}C. The main problems are acoustic coupling of a piezoelectric element to a protector and wetting of the transducer by a heavy liquid metal. The best performance was obtained using the bismuth titanate piezoelectric transducers. The experiments have shown a reliable continuous operation of the proposed transducers in the liquid Pb/Bi alloy up to 1000 hours.

The analysis of different imaging and image reconstruction techniques (such as SAFT and reflection tomography) has shown that for the selection of an optimal technique it is necessary to define very strictly the imaging tasks or at least to separate them into a few different groups. The investigations were carried out using modeling and measurements on mock-ups of reactor components of complicated geometry.

1. Introduction

One of the most important concerns for the nuclear energy industry is the radioactive waste management. For this purpose, the accelerator driven system MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) will be used to study the effectiveness of the minor actinides transmutation. The underlying idea is to transmute long-lived fission products and minor actinides leading to reduce the burden on the nuclear waste geological disposal. The MYRRHA is not intended as an industrial transmutator, but as a first research tool for this process.

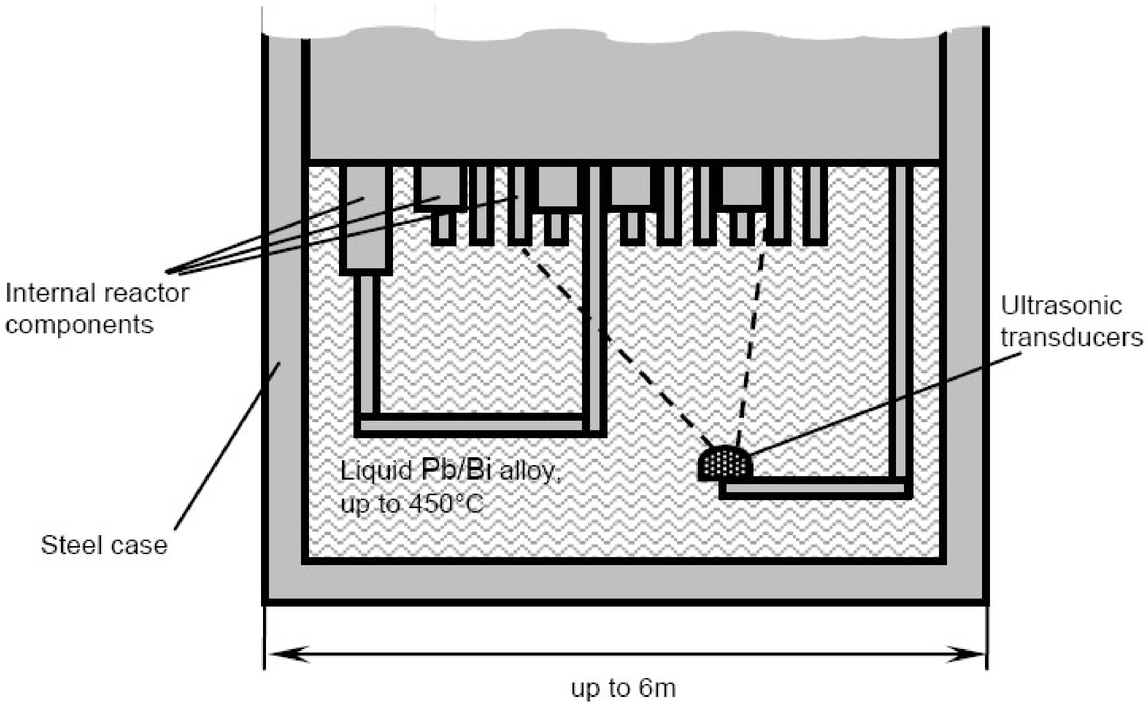


Fig. 1. Approximate geometry of MYRRHA reactor

In the MYRRHA reactor the core is cooled by liquid lead bismuth eutectic (LBE) (Fig. 1). The use of LBE possesses problems with the required inspection and maintenance due to the visually opaque nature of the medium [1, 2]. In contrast to water-cooled reactors, it is not possible optically inspect the submerged reactor parts. In order to solve this inspection issue the Belgian Nuclear Research Centre SCK•CEN and the Ultrasound Institute in Kaunas, Lithuania are collaborating on the development of ultrasonic ranging and imaging techniques for operation in liquid metal environments [3].

The ultrasonic imaging system, which has to be developed, must operate in very harsh conditions: high temperature (160 - 450 °C); corrosive nature of LBE; strong gamma radiation (up to 30 kGy/h). These conditions significantly restrict the possible architecture of the visualization system and materials. In general, two tasks should be solved:

1) development of high temperature and radiation resistant transducers;
2) the development of a suitable imaging technique.

2. High Temperature Transducers

Ultrasonic transducers, suitable for operation inside the MYRRHA system, have to meet the following requirements:

- continuous operation at high temperatures (up to 450^{o}C)
- corrosion-resistant to LBE;
- pressure resistant;
- radiation resistant (γ and neutron)
- good electro-acoustic efficiency [4]

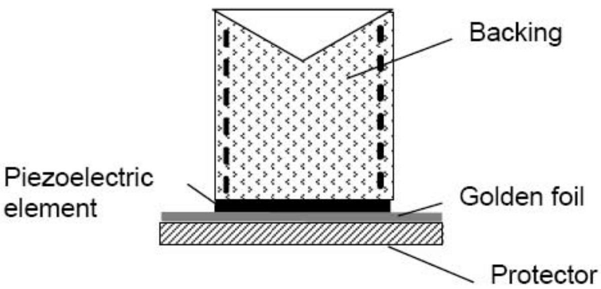
Taking into account these requirements, the following problems had to be solved:

- selection of piezoelectric materials suitable for operation at high temperatures and under a high radiation exposure;

- acoustic coupling of a piezoelectric element to the protector and the backing at high temperatures;
- Durable and stable acoustic coupling between the transducer and LBE.

2.1 General Layout of the Transducer

The design of a conventional ultrasonic sensor must be radically changed for operation in the harsh conditions of MYRRHA. In order to protect the piezoelectric element from the aggressive LBE and a high external pressure, the sensors may be either protected by a buffer rod, or by a thin (~λ/2) or thick (>>λ) metallic membrane. In the case of the sensor with a thin protector (Fig. 2a) the thickness of the metallic membrane is determined according to the frequency and acoustic impedances of the LBE, piezoelectric material and the backing. The metallic backing in this monolithic sensor is bonded to the rear side of the piezoelectric disc. The bonding strength depends essentially on an electrode adhesion to the piezoceramic material, which is not always sufficient. Due to a special concave design of the backing, the multiple reflections inside the backing are suppressed. This sensor possesses an optimal pulse response and is ideal for imaging purposes. The photo of the transducer is shown in Fig. 2b. The piezoelectric elements are bonded to a thin (λ/2) protection layer made of stainless steel AISI 316L, what enables to obtain good sensitivity and bandwidth in liquids.



a

b

Fig.2. a - Sensor with backing and a thin metallic membrane;
b -Transducer with AISI 316 polished λ/2 protector, soldered Pz46 element and serial tuning inductance inside

2.2 Selection of the Piezoelectric Material

The investigation carried out showed that there are only a few piezoelectric materials, which are suitable for a long-term operation in LBE without cooling. At the moment, the best material from the point of view of thermal and radiation robustness is the bismuth titanate ($Bi_4Ti_3O_{12}$) Pz46. The bismuth titanate based ceramic elements may operate up to 550^oC. Other novel materials like aluminum nitride or gallium orthophosphate demonstrate good thermal stability ($GaPO_4$) or gamma radiation robustness (AlN), however, their electro-acoustic efficiency is significantly lower.

2.3 Acoustic Coupling

A special attention must be paid to acoustic coupling between the piezoelectric element, the backing and the protector. It is necessary to point out that a liquid coupling, based on application of high temperature liquids such as silicon oils, is not suitable due to strong γ radiation. A long-term reliable acoustic contact between elements is obtained using a dry coupling technique through an intermediate high purity (99.99%) gold film.

For acoustic coupling of the transducer with LBE, coating of the protector's contacting surface by a diamond like carbon film was proposed. The experiments have shown reliable continuous operation of the transducer in LBE up to 1000 hours.

3. Imaging Technique

For selection of the most suitable approach ultrasonic visualization systems were separated into three groups: the systems used only for determination of a position, the systems, used for visualization of known objects and the systems for visualization of unknown objects. It was shown that for underlined purposes the most efficient are visualization systems based on recognition of the geometry of *a priori* known class of objects.

In spite of all modern automated inspection methods, object recognition (defect classification) is still a difficult task [6]. This is due to a high uncertainty level contained in the information provided by ultrasonic sensors [7]. This uncertainty is caused by variations in properties of the medium, disturbances during the signal propagation process, also diffraction effects, etc., which are very difficult to eliminate.

Methods for object recognition usually are based on the pulse - echo technique [6, 7, 8, 9]. Usually the same transducer for transmission and receiving of signals is used [6, 9], some methods are using separate transducers for transmission and reception of signals [7]. Objects are recognized using different features of the signals received. Classification is performed exploiting features of the received signals in the time and the frequency domains [9]. The most difficult task is to select best features in order to recognize different objects. Sometimes neural networks are used for identification [6, 8].

In the case of the MYRRHA system, the scanning should be linear and the reconstructed image will show the bottom profile of the reactor vessel (Fig. 3). In the image, it would be possible to recognize separate elements and estimate their dimensions and positions. The advantage of such an approach is that the ultrasonic image of the reactor interior will be constructed, in which elements of the construction may be recognized

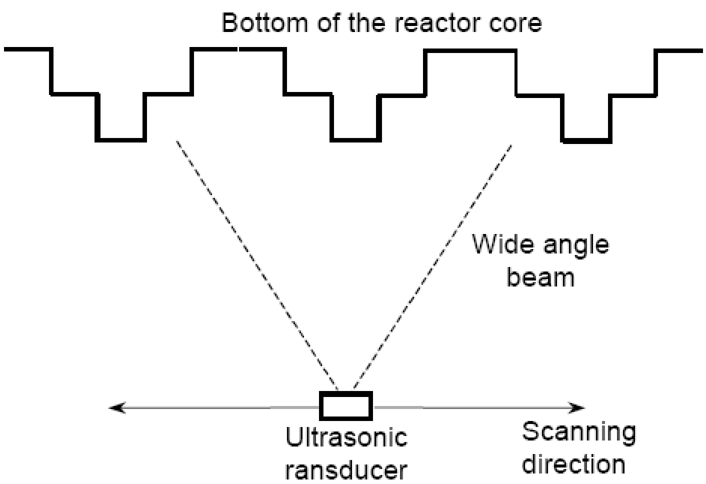


Fig. 3. Possible orientation of wide-angle ultrasonic transducer and scanning directions for imaging of the bottom of the fuel channels

The proposed approach consists of a few steps. During the first step, the ultrasonic images are acquired using mechanical scanning of the set of transducers. After that, the object is recognized using a feature extraction algorithm. From these data, the position and geometrical parameters of the object are calculated.

4. Experimental Investigations

The experiments were performed in a water tank at room temperature, but the used transducers had similar characteristics as the high temperature transducers for use in LBE. A water tank with a scanning system was used for backscattering experiments. Ultrasonic transducer used during the experiments in a pulse-echo mode was a conventional disk shape, 5MHz, 12mm diameter damped transducer.

The shapes of the investigated objects are presented in Fig.4. The triangle prism and L- shape profile were selected for the experiments, because parts of MYRRHA reactor can have such shapes. The test samples are made of aluminum and protected from corrosion by anodic treatment.

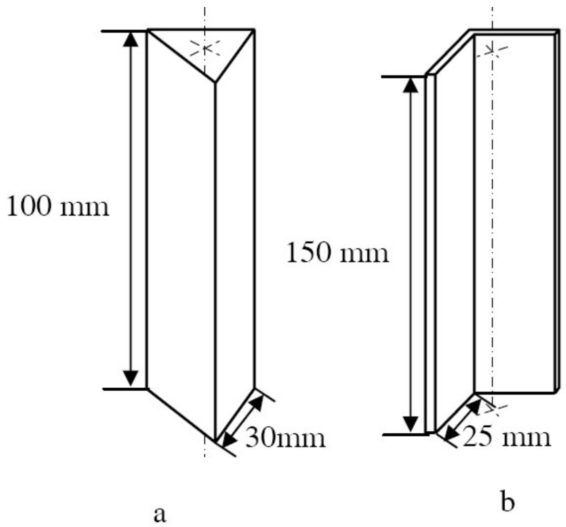


Fig. 4. The geometry of the investigated objects: a - triangle prism, b- L-shape profile

During the experiments the mock-up of the object was rotated with the step 0.5° in the clockwise direction and at each position the reflected ultrasonic signal was recorded (Fig. 5).

All collected signals, reflected by different objects, where analyzed in a few steps. First off all the dynamic range of the acquired signals was analyzed. This was necessary for selection of suitable signals for further analysis [10]. In the second stage the backscattering diagrams of each object were calculated and analyzed. In the last stage, possibilities of the object shape reconstruction from the measured data were investigated.

It was necessary to measure backscattering diagrams, because from them it is possible to see and to compare the levels of the plane and edge waves signals.

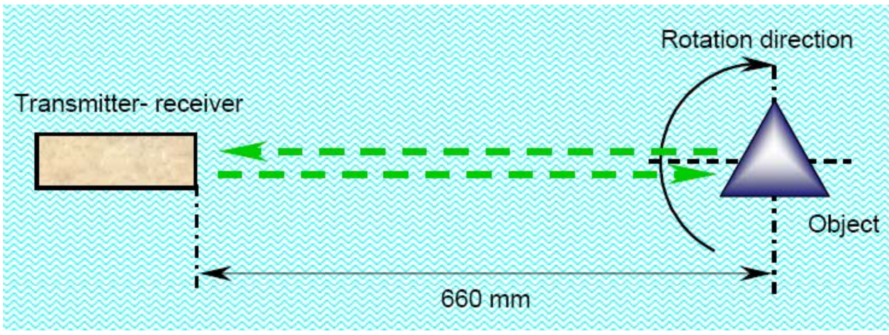


Fig. 5. The set-up of the experiments

4.1. The Backscattering Diagrams of Different Objects

The normalized backscattering diagrams in polar coordinates were calculated as the function $U_{DN}(\varphi) = \frac{\max_t[u(\varphi,t)] - \min_t[u(\varphi,t)]}{K_N}$, where K_N=0.85 is the normalization coefficient, found from the measured reference signal, $u(\varphi,t)$ is the signal measured at the angle φ.

The backscattering diagram of the triangle prism is presented in Fig.6a. For the sake of clarity, the center of the prism is placed at the origin of the polar coordinates. There are three planar reflections. The marginal asymmetry between these reflections can be explained by a small error in transducer orientation with respect to the rotation axis.

Absolutely a different character has the backscattering diagrams of the L shape (Fig. 6b) profile. There are wide angle and corner reflections. As usually, reflection from the rectangular corner has a wide directivity pattern very close to 90°. Another feature of the diagrams is that there are many other sharp lobes which seem to be unexpected.

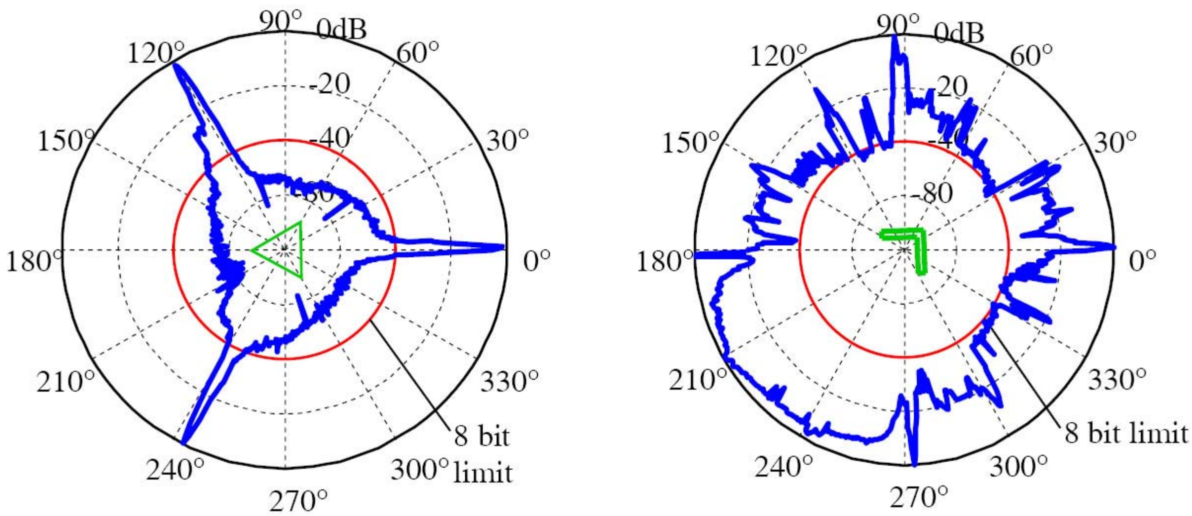


Fig. 6. The backscattering diagrams in a logarithmic scale and in polar coordinates
a - of the triangle prism; b - of the L shape profile

4.2. Reconstruction of the Shape of the Objects using the SAFT Approach

The SAFT (Synthesized Aperture Focusing Technique) was selected as most suitable for demonstration of the possibility to reconstruct a geometrical shape of objects. In the case of the SAFT technique, the signals are collected separately by a single transducer at different positions. The focusing is performed artificially by a software creating the B-scan image, and therefore it operates like a virtual or “soft” transducer array.

Each element (point) in a conventional B-scan image $\mathbf{B}(N, M)$ is $b(k, t_j) = u_k(t_j)$, where $u_k(t_j)$ is the amplitude of the k-th measured signal at the instance t_j. Here $k \in [1, N]$ is the number of the collected ultrasonic signals, $t_j \in [t_{start}, t_{end}]$, N is the total number of signals and M is the number of samples in each signal. Each point of the B-scan image in the SAFT technique is obtained as $b_{\mathrm{SAFT}}(x, y) = \sum_{k=1}^{N} u_k(t_k)$, where $t_k = \frac{2 \cdot d_k(x, y)}{c}$, $d_k(x, y)$ is the distance between the transmitter-receiver and the point (x,y), c is the ultrasound velocity in a medium. Of course, the directivity pattern of the transducer, an exact position of the transducer and many other parameters must be taken into account also.

As illustration of this technique the reconstructed images of the triangle prism and L-shape profile are presented in Fig. 7. It can be seen that the outer profile of the objects is reconstructed correctly except some lines extending the object wall near the edges. This may be explained by the fact that in this case, the image is reconstructed mainly from the signals, reflected form planar surfaces, therefore exact positions of edges cannot be determined. The artifacts inside the object are caused by internal reflections [10].

In the case of L-shape profile (Fig.7b) very strong corner reflections can be seen. These reflections do not project into a single point and possess a butterfly type shape. For reconstruction of corners probably the tomographic approach and more precise selection of parameters should be used [11].

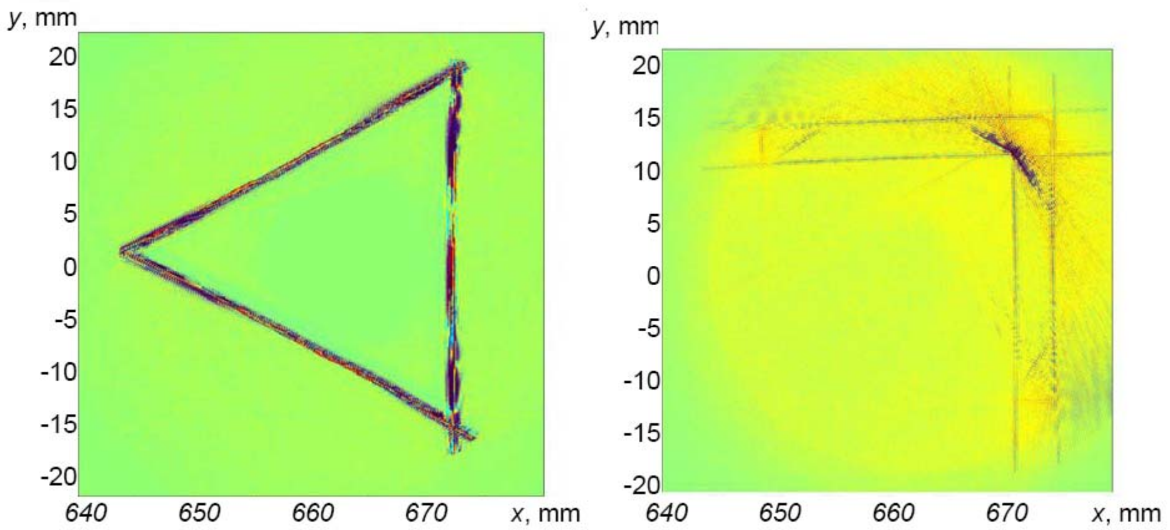


Fig. 7. The reconstructed image obtained from the data with the 30dB gain a - of the triangle prism; b - of the L-shape profile

5. Conclusion

Investigation of the developed ultrasonic transducers in LBE has proven that they are suitable for a long-term operation without cooling in a corrosive environment at elevated temperatures.

The analysis of the image reconstruction techniques, such as SAFT has shown that even from the data measured by a single transducer, when mock-up of the object was rotated and at each position the reflected ultrasonic signal was recorded, it is possible to reconstruct the shape of the different objects (triangle, L-shape profile).

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