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Adaptation of a high frequency ultrasonic transducer to the measurement of water temperature in a nuclear reactor

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Abstract

Most high flux reactors possess for research purposes fuel elements composed of plates. Their relative distance is a crucial parameter, particularly concerning the irradiation history. For the High Flux Reactor (RHF) of the Institute Laue-Langevin (ILL), the measurement of this distance with a microscopic resolution becomes extremely challenging. To address this issue, a specific ultrasonic transducer, presented in a first paper, has been designed and manufactured to be inserted into the 1.8 mm width channel existing between curved fuel plates. It was set on a blade yielding a total device thickness of 1 mm. To achieve the expected resolution, the system is excited with frequencies up to 70 MHz and integrated into a set of high frequency acquisition instruments. Thanks to a specific signal processing, this device allows the distance measurement through the evaluation of the ultrasonic wave time of fight. One of the crucial points is then the evaluation of the local water temperature inside the water channel. To obtain a precise estimation of this parameter, the ultrasonic sensor is used as a thermometer thanks to the analysis of the spectral components of the acoustic signal propagating inside the sensor multilayered structure. The feasibility of distance measurement was proved during the December 2013 experiment in the RHF fuel element of the ILL. Some of the results will be presented as well as some experimental constraints identified to improve the accuracy of the measurement in future works.

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Keywords: Transducer, high frquecy, high resolution, harsh enviromment

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1. Introduction

The Institute Laue-Langevin (ILL) manages a High Flux Reactor (RHF) to provide, for research, one of the most intense continuous fluxes of thermal neutrons, about 1.5*10^{15} neutrons per second per cm². The reactor core is made

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of 280 aluminum plates containing uranium (^{235}U) and maintained between two concentric ferrules. The fuel plates of 1.27 mm width and 903 mm long are curved and equidistant. The core is cooled through 1.8 mm width water channels existing between the plates.

The irradiation performance of the fuel elements is linked to a plate swelling, usually induced by an unstable behaviour of the fuel (formation of interaction layers and/or huge fission gas bubbles). Therefore, the examination of the irradiated fuel elements is necessary. That's why a non-destructive device based upon high frequency ultrasonic probes is considered. Adapted to the high radiation environment and thinned enough (1 mm thick) to be inserted between two fuel plates, the device allows the measurement of the plate swelling yielding water channel thickness variations. Due to the microscopic structure modification of fuel plates, such measurements must be performed with a microscopic resolution. That is extremely challenging within fuel elements in particular due to limited water channel thickness. To address this issue, high frequency transducers were developed and integrated into a set of high frequency acquisition instruments.

This experimental set-up was described in a previous paper (Zaz, 2015) presenting the distance evaluation through ultrasonic wave time of flight (TOF) *t* measurements (Jackson, 2013). Experimental constraints were also identified and the temperature dependence of the ultrasonic velocity has been considered as a crucial parameter. To ensure the reliability of the distance measurement, the present paper then deals with the development of a device allowing the measurement of the water channel temperature. While contact (Rajendran, 2002) or optical (Crandal, 1968) methods can be found in the literature, we propose a new technique based upon the analysis of the spectral components of an acoustic signal that propagates inside the transducer structure, the dimensions of this latter varying with thermal expansion.

To allow distance measurements, the second step deals with the identification of the ultrasonic velocity in the water of the cooling channel. Various methods have already been successfully proposed to determine the ultrasonic velocity dependence to the temperature (Kuo, 1990). They require the knowledge of the thickness of the tested solid or liquid or other information from which the thickness can be derived. Then, from the time-of-flight measurements, the sound-speed can be deduced at a given temperature. Based on a similar principle, an ultrasonic method is here being developed.

2. Temperature measurement

No standard systems can be used to perform temperature measurements along the water channel between two high-irradiated fuel plates with difficult access constraints. To this aim, a specific device has been developed (see (Zaz, 2015) and Fig. 1(a)). When immersed into the water channel, the sensor temperature variation leads to a thermal expansion of its multi-layered structure, yielding in particular modifications in its piezoelectric element and silica delay line thicknesses. On the proposed temperature range (from 30°C to 40°C), the thermal expansion coefficient (α) of the silica is 4.1 10^{-7}/C° (Bell, 2014) and that of the piezoelectric element is equal to 14.5 10^{-6}/C° (Wong, 2002). These values show that it is possible to neglect the thermal expansion of the silica, that of the piezoelectric element being mainly responsible of a change of the transducer resonant frequency (Fig. 1(b)).

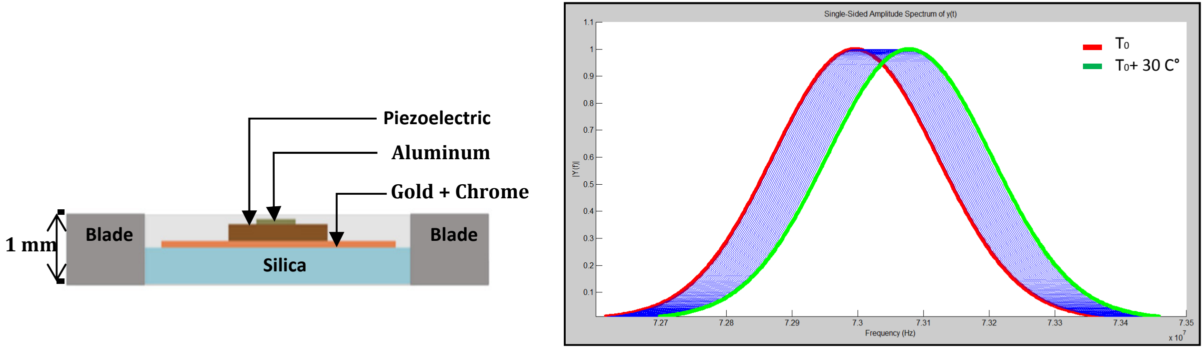

Fig. 1. (a) Transducer multilayered structure; (b) Transducer spectrum at different temperatures ranging between T_0 and T_0+30°C.

The implementation of the measurement system requires the use of an electronic chain of signal acquisition. It includes, among others, the ultrasonic sensor, a thermostatic bath, a thermocouple, and signal processing to plot the sensor frequency as a function of the temperature.

To calibrate the device, the ultrasonic sensor is first immersed in a thermostatic bath that regulates the temperature from 40°C to 30°C by steps of 0.5°C. Each steps is maintained several minutes to ensure temperature stability within the sensor. The transducer is then excited by a home-made pulse. The generated ultrasonic wave radiates in the delay line of silica and then propagates in water. That generates a series of echoes with decreasing amplitude. These echoes are then amplified and sampled. After the stabilization time, signals are stored. To calibrate, the acquisition of the water temperature value is performed thanks to a thermocouple. A series of experiments was developed in deionized water similar to that of the cooling pool of the RHF reactor to evaluate the frequency variation with temperature (Fig. 2(a)). Then while controlling the RHF structure, this experimental calibration law will be used to determine the in-situ temperature of the water channel from the resonant frequency of the sensor.

3. Ultrasonic velocity measurement

To allow ultrasonic telemetry, the second step deals with the identification of the temperature dependence of the ultrasonic velocity of the waves propagating in the water channel. The method proposed here is based on a classical technique where time of flight measurements are performed along known reference distances. During the calibration process, two home-made tanks with controlled thicknesses (3.3 mm and 5.18 mm) are used as reflectors (Fig. 2(b)). Two of the above sensors are set on the opposite sides of a thin steel blade and used to perform the pulse-echo experiments (see Fig. 1(a) and 2(b)). Each transceiver then sends a high frequency ultrasonic wave that radiates in its silica delay line. These radiations generate echoes that propagate into the water channel before being reflected (Fig. 3(a)).

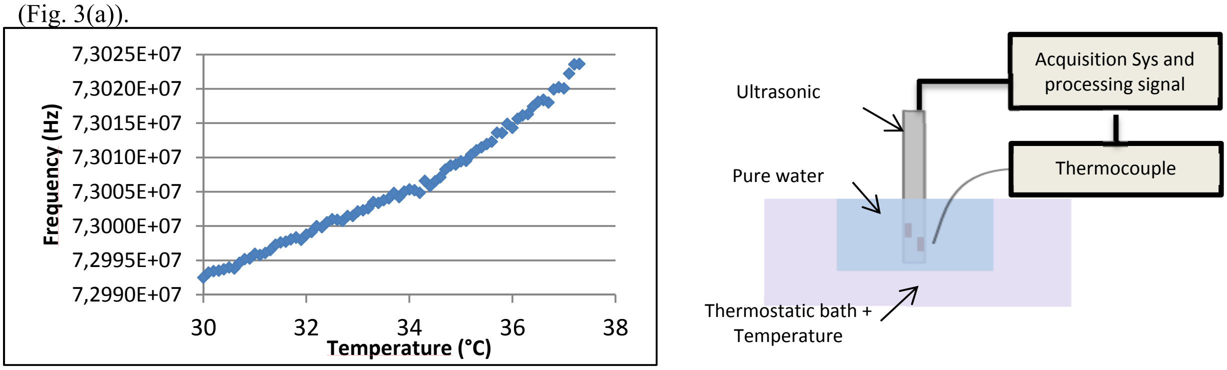

Fig. 2. (a) Variation of the resonant frequency of the transducer as a function of the temperature in the [30°C - 40°C] range; (b) Experimental set-up allowing the speed of sound in water measurement.

To begin, the sensor is placed in the thinnest tank to save a first set of acoustic signals at temperatures ranging from 30°C to 40°C. The same experiment is then repeated in the largest tank. With the known distances and times of flight, the speed of sound in water can then be calculated from the following equation:

$$v = 2 \times \frac{d_{tank} - d_{sensor}}{TOF_{transducer1} + TOF_{transducer2}} \tag{2}$$

where d_{tank} is the known tank thickness, d_{sensor} is the sensor thickness of 1mm and $TOF_{transducer}$ is the time of flight of the acoustic wave measured by each transducer. Results are presented in Fig. 3(b).

The average difference between the experimental speeds of sound measured in the two water channels is equal to 2m/s with a maximum difference value of 4 m/s. These measurement errors can be related to tanks' tolerance of about 20µm. Moreover, errors can also occur due to the thermostatic bath pump which can induce vibrations of the tanks and movement in the water which can affect the ultrasonic signals used for the speed of sound calculus.

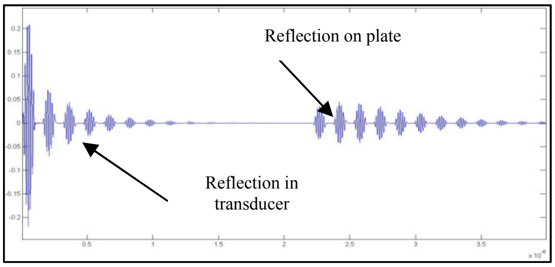

Fig. 3. Temporal acoustic signal

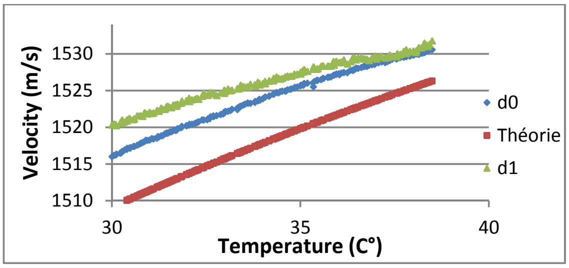

Fig. 4. Ultrasonic velocity in water according to the temperature

To evaluate the accuracy of the measurement system these experimental results were compared with data from the literature obtained for common water (Pignatiello, 2007). The maximum difference between experimental and theoretical value is 6m/s larger than the experimental deviation and indicating differences in the waters' quality.

4. Conclusion

Examination of irradiated fuel elements is crucial to assess their irradiation performance. A device using two ultrasound transducers operating at high frequency (70 MHz), radiation resistant, was developed to control plate swelling. The feasibility of such challenging measurement has already been proved and the experimental constraints attached to measurement procedure have been identified. In particular, temperature measurement of the water channel was among these constraints. To address this issue, a system allowing thermal monitoring from the analysis of the spectral components of our ultrasonic transducer was designed. This system was also used to measure the temperature dependence of the ultrasonic velocity of waves propagating in the cooling water channel of a High Flux Reactor. While being close to those proposed previously in the literature they indicate that the water quality will have to be taken into account when performing High Flux Reactor in-situ controls.

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