An Ultrasonic Sensor For Pressure And Fission-Gas Release Measurements In Fuel Rods For Pressurised Water Reactors

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ABSTRACT

A sensor for measurement of the fuel rod internal pressure and fission-gas release is developed for nuclear applications.

The measurement of acoustic velocity and attenuation of the gas allows to calculate both pressure and composition of a mixture. The small acoustic impedance of gas compared to solid one induces a strong insertion loss which prevent propagation of ultrasonic waves inside pipes. We proposed a method to reduce the acoustic impedance mismatches to ensure sufficient wave propagation inside the gas.

Out-of-pile test have been carried out : PZT materials have been tested under gamma irradiations. Temperature behaviour was also studied.

INTRODUCTION

The problem to be solved relates to the measurement of the fission gas pressure and composition measurement in fuel rod by a non destructive method. Fuel rod internal pressure is one of the safety criteria applied in nuclear power safety analysis made by EDF. This criterion is related to the cladding gap reopening and the consequent risk of clad ballooning. Apart from the safety implications, this parameter is also a fuel behaviour indicator and reflects the overall fuel performance and the power history. Rod internal pressure is one criterion among others, like cladding corrosion, against which the acceptable fuel burn-up limit is set.

Besides, the in-situ measurement of fission gas release inside nuclear fuel rods is a key parameter for advanced irradiation programs in Material Testing Reactors (in-pile applications). CEA has been conducting studies for 4 years on acoustic fission gas release measurements for in-pile applications, in the field of the INSNU project (Instrumentation for irradiations and experimental in-pile programs). The online knowledge of fission gas release is particularly relevant for scientific expertise on PWR fuel rods and to update data bases for nuclear safety.

We propose a method based on acoustics to determine, via the speed and the amplitude of ultrasounds, the pressure and composition of a gas mixture from the outside of the pipe and thus propose an answer to this non-destructive evaluation application. We will describe the experimental set-up used to achieve those measurements. We will recall the principle of the specific sensor we designed in order to transfer energy through the pipe wall, which is the first step before performing time of flight measurements. Several thesis or publications have been released on this work [1, 2, 3].

1. EXPERIMENTAL SET-UP AND METHOD

Some authors have already described a technique using echography to measure ultrasonic velocity in gases in a vessel [4]. But this method requires the introduction of sensors inside the pipe, which is not possible in the case of nuclear fuel rods. An experimental methodology needs then to be defined.

The method is based on the measurement of a signal emitted and reflected in a cavity. The signal and its echoes are recorded and the time of flight and its attenuation are measured. From this measurement the composition of the gas mixture and the gas pressure can be deduced The measurement are performed on 10 or 15 echoes to increase the accuracy.

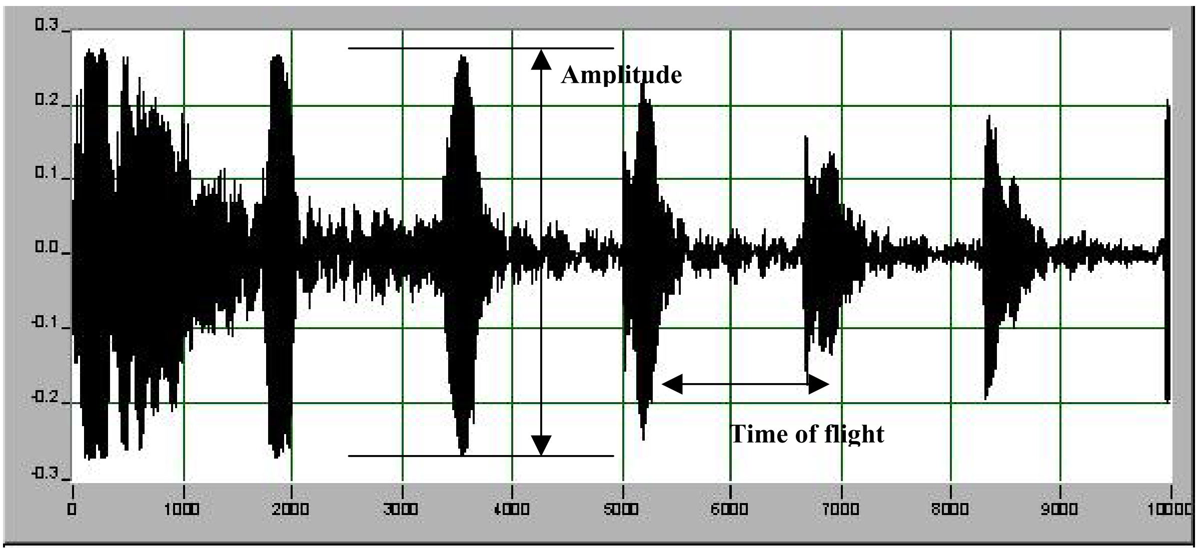

FIGURE 1 : TYPE OF SIGNAL OBTAINED

The main problem, before measuring precisely the amplitude and the time of flight of an acoustic wave in a medium, is to make the wave propagate in the medium.

The gas is contained in a 1 cm Zircaloy pipe or in an equivalent vessel. The thickness of the rod is 570 µm. Small acoustic impedance of gas compared to solid one induces a strong insertion loss which could prevent any propagation of ultrasonic waves inside pipes. Indeed, in the case of a Zircaloy/Helium-Xenon mixture interface, the coefficient of refection (defined as below) is pretty equal to 1.

$$R = \frac{Z_{Zirc} - Z_{gaz}}{Z_{Zirc} + Z_{gaz}} \qquad (1)$$

where $Z_i = \rho_i.v_i$, Z_i is the acoustic impedance of medium i, ρi the density and v_i acoustic waves velocity.

For this reason, we proposed to adapt the piezoelectric sensor frequency to the 570µm wall thickness of these rods and to the water thickness layer (figure 2) to reduce the different acoustic impedance mismatches to ensure sufficient wave propagation inside the gas.

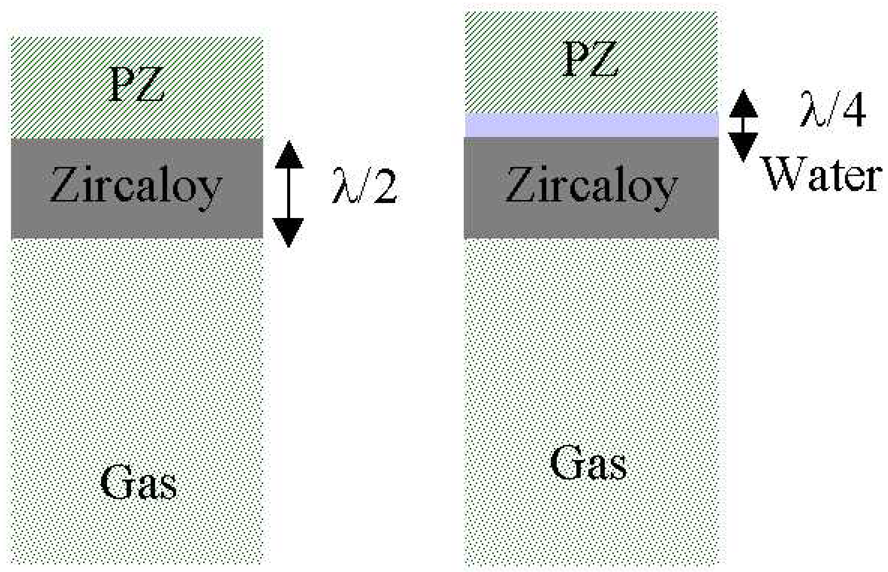

FIGURE 2 : ADAPTATION OF THE PIEZOELECTRIC SENSOR FREQUENCY TO THE 570µm WALL THICKNESS OF THE RODS AND TO THE WATER THICKNESS LAYER

We chose a frequency of 4MHz in order to let the ultrasound go through the pipe wall. Indeed the pipe wall being 570µm thick, it is half wave for this frequency. The Zircaloy layer is then transparent. Then impedance matching concerns piezoelectric material and gas. A quarter wavelength water layer allow to increase the transmission.

The device allows to reduce the reflection coefficient at the Zircaloy/gas interface so that performing amplitude and time of flight measurements is possible without the use of signal processing developments. We realised a half-cylindrical sensor for this purpose, which is described on figure 3. The pipe is immersed in water. A specific mechanical holder has been designed to fix this transducer to the external surface rod. Then we use the relative position of the echoes in order to perform time of flight measurements.

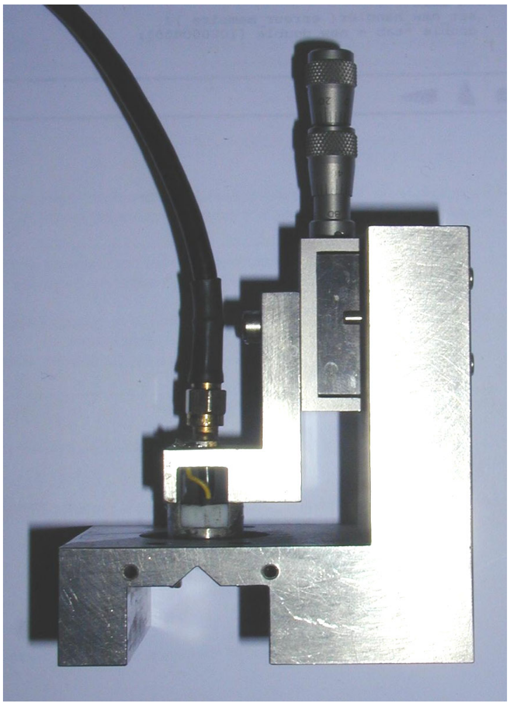

FIGURE 3 : A SPECIFIC MECHANICAL HOLDER TO FIX THE TRANSDUCER TO THE ROD.

An device dedicated to research reactors has also been realized. It consists in a small vessel connected to the gas. The cavity is 1 centimeter diameter and 660 micrometer length. In that case the geometry is plane.

2. EXPERIMENTAL RESULTS AND DISCUSSION

We are going to give the experimental results obtained for one gas (Nitrogen, N2) and for the Helium-Xenon gas mixture

2.1 Pressure determination

Therefore we can represent (figure 4) the propagation speed in gas of the ultrasonic waves versus the pressure for one gas such as nitrogen. Remember that in the case of a single gas, pressure is related to velocity.

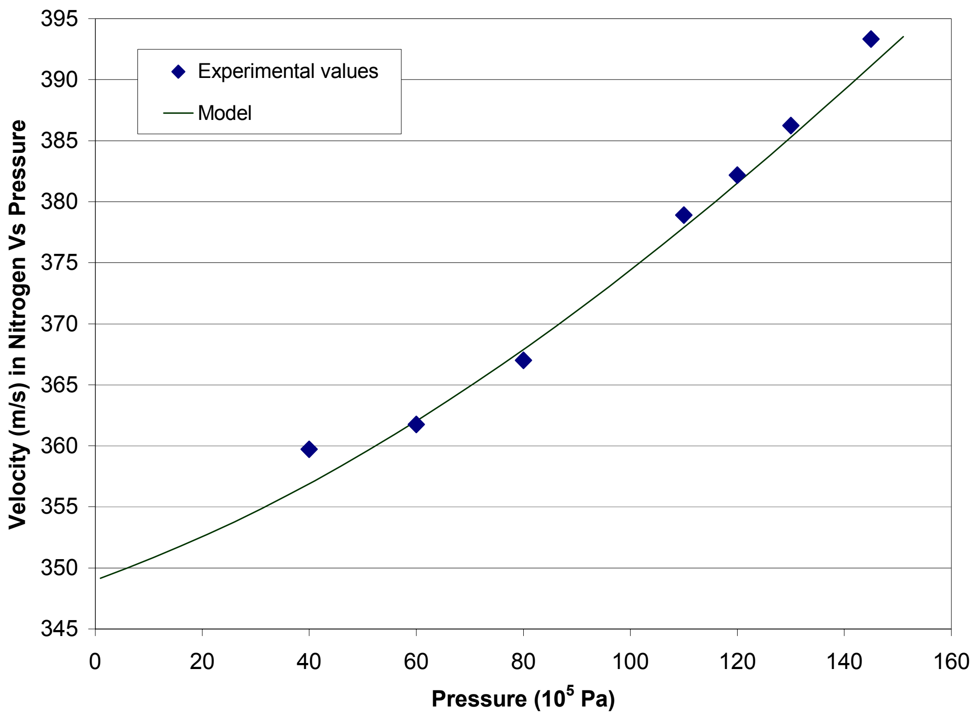

FIGURE 4 : THEORETICAL AND EXPERIMENTAL VELOCITIES FOR NITROGEN, T=300K.

Using a thermodynamic model and virial expansion which is not detailled in this paper, a velocity law versus pressure has been obtained and validated experimentally from 40 to 140 bar with our sensor for a fuel rod filled with nitrogen gas. For this pressure range, velocity deduced from flight time measurement varies from 360 to 390m/s.

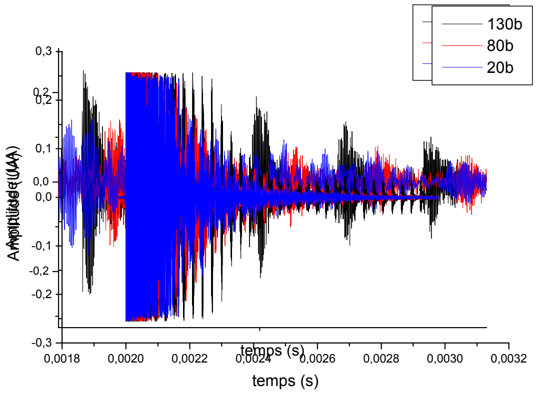

FIGURE 5 : SIGNAL OBTAINED IN THE CAVITY (PALNE CONFIGURATION) FOR A HE-XE (60% HELIUM) MIXTURE AT DIFFERENT PRESSURE

As shown in figure 5, the amplitude of echoes can also be related to pressure of the gas mixture.

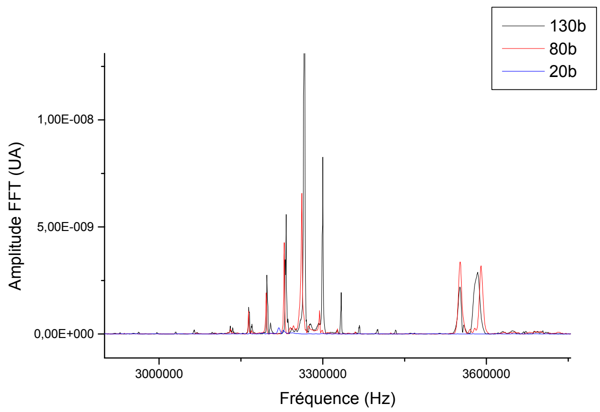

FIGURE 6 : FAST FOURIER TRANSFORM OF THE ECHOES.

Signal processing by a Fast Fourier transform can be a way to increase accuracy of the system (Figure 6).

2.2 Composition determination

The composition can be deduced from velocity measurements with the relations (2) and (3) .

$$v = \sqrt{\frac{\gamma.R.T}{M}} \qquad (2)$$

$$M = x_{He}.M_{\boldsymbol{He}} + \boldsymbol{x}_{\boldsymbol{Xe}}.\boldsymbol{M}_{\boldsymbol{Xe}} \qquad (3)$$

where γ is the ratio of the specific heat of the gas at constant pressure c_p to the specific heat at constant volume c_v. R is perfect gas constant. T the temperature. M is the molecular weight of the gas and x_i the volumic fraction of the gas i.

A virial expansion allows to take into account pressure at second order.

Figure 7 shows that in the case of fuel rods initially filled with pure Helium gas, 10% molar fraction of Xenon decreases velocity from 1050 to 520m/s whereas pressure variation from 50 to 100 bar induces only a 20 m/s increase which means that the ultrasound velocity is very little modified by the gas pressure but sensitive to gas composition. Experimentally measured data points show a good agreement with the theory and as a result a satisfactory determination of the gas composition can be obtained.

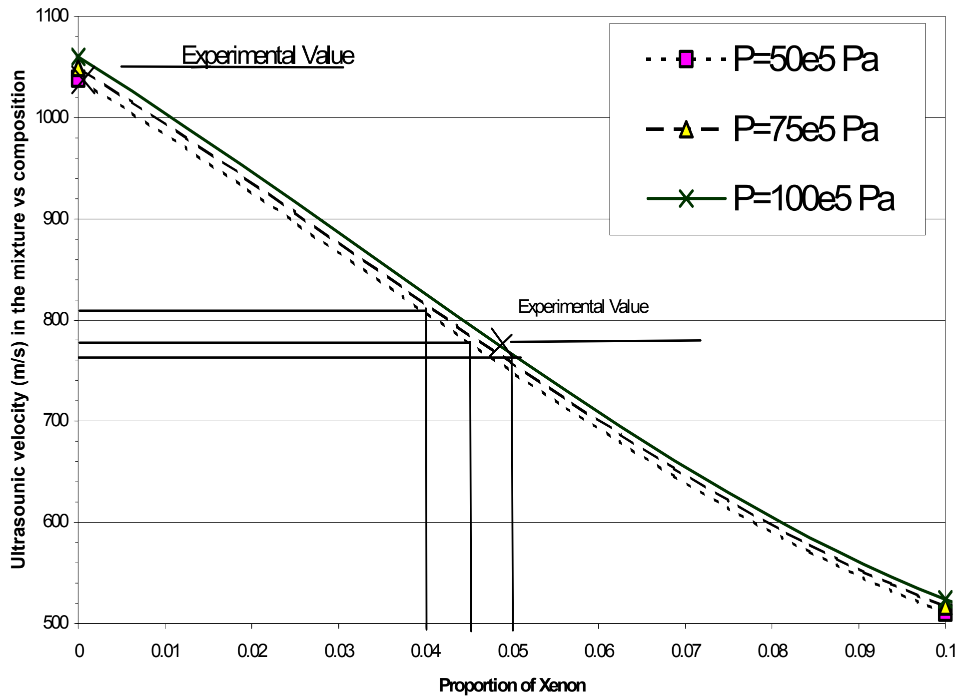

FIGURE 7 : ULTRASOUNDS VELOCITY IN THE HELIUM-XENON MIXTURE AT VARIOUS PRESSURES VERSUS THE PROPORTION OF XENON AT 4MHZ, T=300K.

3. GAMMA IRRADIATION

PZT elements which are often used for ultrasonic sensors were irradiated in air at room temperature using a ^{60}Co gamma source, with doses up to 1,5 MGy at a dose rate up to 20 kGy/h). Different irradiation configurations were proposed to separate cumulative and transitory effects. Similarly, temperature effects are investigated for 10°C variation around ambient.

Frequency impedance measurement was performed by a network analyser to get resonance parameters and to detect PZT properties alterations. Theoretical modelling using Mason circuit allowed to calculate the characteristic parameters of the resonant structure. Analysis was done as function of exposure time, different irradiation configuration and temperature variation.

The study shows a monotonous variation of the resonance frequency and amplitude versus temperature. When PZT are submitted to irradiation, an erratic fluctuation is observed for the amplitude whereas the resonance frequency varies with the dose. But the main result is that, even at high dose, the alteration of the resonance curve is weak. Consequently, such sensors could be used in gamma environment (hot cell) without alteration of their working.

Discussions are engaged between the LAIN, CEA and SCK to perform neutron irradiation before the end of year 2005.

CONCLUSION

We present a specific sensor for online measurement of the fuel rod internal pressure and fission-gas release. Applications concerns the needs of nuclear fundamental research but also for nuclear industry

The measurement of acoustic velocity and attenuation of the gas allows to calculate both pressure and composition of a mixture. We proposed a method to reduce the different acoustic impedance mismatches to ensure sufficient wave propagation inside the gas.

Plane and cylindrical geometry are studied. Frequential analysis (resonance mode approach) allows to improve the sensitivity of the system.

In the case of fuel rods initially filled with pure Helium gas, 10% molar fraction of Xenon decreases velocity from 1050 to 520m/s whereas pressure variation from 50 to 100bar induces only a 20m/s increase. These predictions have been found in good agreement with measurement on Helium-Argon equivalent gas mixtures.

Out-of-pile test have been carried out : PZT materials have been tested under gamma irradiations allowing doses up to 1,5 MGy at a dose rate up to 20 KGy/h. Temperature behaviour is also studied. Such sensors could be used in gamma environment (hot cell) without alteration of their working.

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