**Numerical simulation of the temperature measurement by ultrasonic method in an environment representative of the core of SFR**

S. **BENJEDDOU**<sup>a</sup>, J. **MOYSAN**<sup>a</sup>, N. **MASSACRET**<sup>ab</sup>, M. A. **PLOIX**<sup>a</sup>, J. P. **JEANNOT**<sup>b</sup>

<sup>a</sup>Aix-Marseille Université, CNRS, LMA UPR 7051, site LCND, 13625 Aix-en-Provence, France

<sup>b</sup>DEN/DTN/STPA/LIET, CEA Cadarache, Saint Paul Lez Durance, France

**Abstract:**

We develop a modeling of acoustic waves propagation in liquid sodium environment under conditions similar to those present in a Sodium-cooled Fast Reactor (SFR). Our goal is to propose a new Structural Health Monitoring (SHM) tool dedicated to the monitoring of the nominal operating temperature above the core of a reactor. Using ultrasonic time-of-flight, local temperature measurements would be possible. For this, we investigate the computational aspects related to the use of the simulation code named SPECFEM, initially dedicated to the propagation of seismic waves in arbitrary configurations 1D, 2D or 3D. In our study case, the spatial and temporal scales are very different from those used for seismic waves. The data used for this work are derived from tests simulating the thermal-hydraulic characteristics of the core output of SFR.

**Keywords:** Non Destructive Testing, Structural Health Monitoring, Ultrasound, Thermometry, Heterogeneity, SPECFEM.

**Introduction**

French law on sustainable management of radioactive materials and waste is the source of studies on nuclear reactors of new generation technology using liquid sodium for coolant fluid. Practical difficulties related to experimentation in sodium encourage the development of numerical tools for studies around this technology. In particular, the development of numerical methods opens interesting perspectives for the study of new instrumentations and Structural Health Monitoring (SHM) methods based on acoustics.

The starting point of several research works about thermometry for in service temperature measurement is a patent entitled “Remote temperature measurement” [1]. The main idea is to use an ultrasonic beam which strikes the edges of a subassembly which are separated of a known distance. Measuring the time interval between the two points leads to deduce a measure of temperature of the liquid sodium between these two points.

Numerous challenges still exist as several parameters could influence the time-of-flight measurement. The liquid sodium in the core of a nuclear reactor is a turbulent flow and local flow directions can influence ultrasonic propagation. The form of the echoes, depending of the exact fuel subassembly geometry, could also be of primary importance and should be taken into account in the dedicated signal processing method. The proportion of gas could also vary and would modify the relation between celerity and temperature. Specific recent research works exist about evaluating gas proportion in Sodium-cooled Fast Reactor (SFR) [2].

We present in the following sections our modelling steps: media, geometry and source. The numerical method is introduced and the results of our tests are presented using pressure signals recorded by sensors placed in the computational domain.
1 Modelling of the propagation media

We consider the framework of an effective medium for modelling the propagation medium. Density and wave velocity are locally modified to incorporate the effects of a heterogeneous medium due to the sodium flow which implies mainly temperature gradients. Three conditions have to be met to validate the hypothesis of linear phenomena and a plane wave (or quasi-plane) [3]. The first condition corresponds to a weak deviation of the beam. The second condition corresponds to a moderate gradient of the flow velocity relatively to the Mach number. The last condition is satisfied if the inhomogeneities are large compared to the wavelength. These conditions were verified in another study using a ray-tracing code [4]. Other studies on flows in reactors showed that the flow velocities are relatively low [5], the corresponding gradients are also supposed moderate. In particular, characteristics sizes will be large compared to the considered wavelengths of the ultrasonic [6,7]. Finally, the material in which the waves propagate is a liquid metal, its thermal conductivity is very important.

As a first approximation, the assumption of effective medium seems valid and will be implemented in SPECFEM. As the effect of temperature gradient is of primary importance, only temperature gradient effects are studied [4]. The choice of using SPECFEM, originally developed for seismology and based on a spectral element method, rests upon the performance of this code which is well suited to parallel computations. This approach combines the flexibility of a finite-element method with the accuracy of a pseudo-spectral method [8, 9]. This is particularly important given the complexity of the real system that should be eventually simulated. Propagation domains can be simply described by their density and the speed of the compression and shear waves.

In this study we analyse the influence of the temperature variation in a directional jet which corresponds to the case of sodium flow at the output of a subassembly. The study of the experience PLAJEST mixing sodium jets [10]; reinforced by its numerical simulation [11], lead us to choose a continuous parabolic evolution of temperature inside the jet. The influence of the presence of gas is neglected in this study. The experimental relation between celerity and temperature is given by the formula (1). The change in density as a function of temperature T (Kelvin) is also implemented (formula (2)). Note that these relations may slightly vary depending of sodium purity [12].

\[ C(T) = 2577.2 - 0.5234 \cdot (T-273) \quad \text{(in m.s}^{-1}\text{)} \]  \hfill (1)

\[ \rho(T) = 1037.1 -0.268. \cdot (T-273) \quad \text{(in kg.m}^{-3}\text{)} \]  \hfill (2)

2 Modelled geometry and ultrasonic source

Figure 1 is a 2D representation of the configuration of the ultrasonic inspection at grazing incidence (7°) over a cylindrical target section whose dimensions are representative of a fuel subassembly. The height of the cylinder is not involved in the measurement of temperature, but determines the size of the mesh. Large dimensions around the tube, not shown in Figure 1, allow a numerical calculation without use of absorbing layers.
SPECFEM offers several types of source; we choose the Ricker wavelet with a central frequency of 1 MHz in accordance with classical frequency, used in inspection. We will record the reflected wave at the source point to simulate a configuration with a single receiver/transmitter, fitted to the ultrasonic thermometry. In Figure 1 ultrasounds will be reflected by the points A and B and the monitoring of the difference of time-of-flight will enable temperature monitoring.

![FIG.1 - Dimensions of the 2D configuration calculation](image)

### 3 Numerical modeling

The equation implemented in SPECFEM can be globally written on the whole area as a linear system matrix corresponding to an ordinary differential equation of order 2

\[ MU + CU + KU = 0 \]  

(3)

\( U \) is a vector containing all of the values of displacement at each node of the interpolated field. \( M, C \) and \( K \) are respectively the matrices of mass, damping and stiffness coefficients that respectively multiply the acceleration, velocity and displacement (unknown system). The finite difference method is then used for the temporal resolution. It is written for different values of \( U \) (that is to say at different discrete times):

\[ U \approx \sum_{k=0}^{\infty} \frac{1}{k!} \frac{\partial^k U}{\partial t^k} \Delta t^k \]  

(4)

Derivatives of displacement are classically deduced from the previous expression:

\[ \frac{\partial^k U}{\partial t^k} = A_k (t, t + \Delta t, t + 2\Delta t) + B_k (t - \Delta t, t - 2\Delta t, ...) \]  

(5)
where $B_k$ is the known terms and $A_k$ the future terms. These expressions are then reinserted into Equation 3. The method of temporal resolution system being based on the formalism of finite differences, convergence diagrams link the discretizations in time and space ($\delta t$ and $\delta x$) via a coefficient called Courant number \[13\] $\alpha$ such that:

$$\alpha = \frac{c \delta t}{\delta x} \quad (6)$$

where $c$ is the wave velocity in the fluid medium.

Standard schema used by SPECFEM imposes a value $\alpha$ less than 0.35. This coefficient is calculated at the beginning of the simulation from the minimum speed which allows adapting the time step value. Spatial discretization is fixed according to the smallest wavelength present in the simulated signals. In the case of SPECFEM \[14, 15\], the minimum number of points (mesh) per wavelength, note $N_{\text{min}}$, is 5.5. We observed that we rather need 11 points by wavelength in order to exploit finely the time-of-flight of the echoes. With these conditions, the time step $\delta t$ equals $2.5 \times 10^{-9}$ second and the number of calculation steps required is set to 80 000. The mesh configuration is built from a script describing the geometry using the tool GMSH \[16\]. The conversion of the mesh for SPECFEM is done via a Python script written for this purpose. Our choice of dimensions of the computational domain allows avoiding the appearance of interference reflections, masking echoes of interest. The characteristics of the steel are: density $7850 \text{ kg.m}^{-3}$, longitudinal wave velocity $5800 \text{ m.s}^{-1}$ and transverse wave velocity $3200 \text{ m.s}^{-1}$.

### 4 Results of ultrasonic thermometry

Two reflected echoes are generated by a subassembly at points A and B (see Figure 1). The time delay between these two echoes is then measured. The ratio between the distance of propagation and the time-of-flight leads to estimate the speed of sound and then, from the equation (1), the average temperature at the subassembly outlet. A first numerical test was done to validate our mesh configuration with a medium at constant temperature. With a sodium temperature of 510.5°C, the wave velocity is 2310 m.s$^{-1}$. The time difference between the two echoes is measured from the maxima of the recorded pressure signals. The consideration of the angle of incidence, calculated speed is 2306.12 m.s$^{-1}$ which corresponds to a relative error in speed of 0.17%. The formula (1) gives a temperature of 511.3°C, which corresponds to an error of less than 1°C. This gives information about the final accuracy which will be possible for future applications. In addition, a calculation showed that the consideration of the thermal expansion of the tube does not alter these results.

Then we conducted four simulations: simulation 1 (simul 1), simulation 2 (simul 2), simulation 3(simul 3) and simulation 4 (simul 4). The first considers a single medium, so media 1 and 2 (see Figure 1) are identical with a temperature of 450°C. The second one considers a gradual evolution of the temperature in the medium 2, using a symmetrical parabolic profile between 450°C and 500°C between the edge and the axis of the tube (medium 1 is at 450°C). The third one shows the same kind of profile as second simulation with a global increase in temperature of 5°C. The fourth one corresponds to a simplified temperature ranges: 500°C in the tube and at its output (medium 2) and 450°C for the medium 1. Numerical results are obtained in about 13 hours on a five core processor (3.07 GHZ) laptop with 24 GB RAM memory capacity.

The position of the first echo does not vary as far as medium 1 is identical in the four simulations. That is why we analyse in the figure 2 the variations of the second echo (point B in Figure 1). Table 1 summarizes the results and gives arrival times of the second echo measured at the signal maximum and also the corresponding pressures.
FIG. 2 - Comparison between the echoes from the second edge (point B) for the four simulations.

The signals time of flight in this figure are in accordance with analytic calculations. The intermediate simulation (case 4) demonstrates, as expected, that the wave is only slightly deviated by the temperature gradient. The amplitude of the signal 4 is greater than in simulation 1, the variable density may have an influence on the wave amplitude and this question needs further studies. An important decrease in the amplitude of the second echo should be pointed out in the case of a parabolic profile of temperature (see signals in figure 2). This point has to be further analysed to check the possibility of disappearance of echoes if the signal-to-noise ratio becomes too low. The origin of the loss of amplitude will be studied as the temperature gradient is described with one hundred of discrete media inside the tube (between 450°C -500°C then 500°C -450°C) and that may induce purely numerical attenuation. The continuous slight evolution of wave incidence due to refractive phenomena has to be analysed too.

The analysis of changes in time-of-flight of the second echo provides information on the sensitivity of the method to detect temperature variations. Between simulations 2 and 3 we find that the average elevation of 5°C of the temperature profile leads to a shift of 0.2 µs which is quite accessible in terms of ultrasonic chronometry at 1 MHz. So our numerical approach indicates the sensitivity of ultrasonic thermometry method to a relatively weak discrepancy of temperature.

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Arrival time of the second echo (µs)</th>
<th>maximum amplitude (arbitrary units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. constant temperature (450°C)</td>
<td>182.316</td>
<td>3.818 $10^{23}$</td>
</tr>
<tr>
<td>2. variable parabolic temperature</td>
<td>183.554</td>
<td>0.586 $10^{23}$</td>
</tr>
<tr>
<td>3. variable temperature+5°C</td>
<td>183.766</td>
<td>0.586 $10^{23}$</td>
</tr>
<tr>
<td>4. T: 450°C-500°C-450°C</td>
<td>183.179</td>
<td>5.313 $10^{23}$</td>
</tr>
</tbody>
</table>

Table 1. Results of the four simulations considered in terms of time-of-flight and amplitude.
5 Conclusion

We have presented the 2D modelling of ultrasound thermometry for SHM applications in nuclear reactor with SPECFEM. At this step of the study, considering times of flight, we can conclude that our numerical approach can correctly model the principle of ultrasonic thermometry in the core of a SFR reactor. Predicting signal amplitudes with accuracy, thus assessing the effective detection of ultrasonic echoes, is a more difficult numerical challenge which implies developing 3D numerical studies but also defining finely the acoustical source corresponding to high-temperature transducers.

The thermal heterogeneity of the medium is taking into account considering a simplified medium. We will extend our simulations in order to take into account a more realistic medium from the experimental data PLAJEST [10, 11]. Other issues will be studied as the influence of the edges geometry (right-angles, chamfer…) on the reflected signal. The taking into account the flow rates requires a further development of the code SPECFEM.

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References