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Ultrasonic thermometry simulation in a random fluctuating medium: Evidence of the acoustic signature of a one-percent temperature difference

M. Nagaso [a,b], J. Moysan [a,*], S. Benjeddou [a], N. Massacret [a], M.A. Ploix [a], D. Komatitsch [c], C. Lhuillier [b]

[a] Université d'Aix-Marseille, LMA UPR 7051 CNRS, 13625 Aix-en-Provence, France
[b] DEN/DTN/STCP/LIET, CEA Cadarache, 13108 Saint Paul Lez Durance, France
[c] LMA, CNRS UPR 7051, Université d'Aix-Marseille, Centrale Marseille, 13453 Marseille cedex 13, France

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ABSTRACT

We study the development potential of ultrasonic thermometry in a liquid fluctuating sodium environment similar to that present in a Sodium-cooled Fast Reactor, and thus investigate if and how ultrasonic thermometry could be used to monitor the sodium flow at the outlet of the reactor core. In particular we study if small temperature variations in the sodium flow of e.g. about 1% of the sodium temperature, i.e., about 5 °C, can have a reliably-measurable acoustic signature. Since to our knowledge no experimental setups are available for such a study, and considering the practical difficulties of experimentation in sodium, we resort to a numerical technique for full wave propagation called the spectral-element method, which is a highly accurate finite-element method owing to the high-degree basis functions it uses. We obtain clear time-of-flight variations in the case of a small temperature difference of one percent in the case of a static temperature gradient as well as in the presence of a random fluctuation of the temperature field in the turbulent flow. The numerical simulations underline the potential of ultrasonic thermometry in such a context.

1. Introduction

The need for sustainable management of radioactive materials and waste has led to strong and renewed interest for nuclear reactors of a new-generation technology that use liquid metal such as sodium as a coolant fluid (so-called Sodium cooled Fast Reactors, a.k.a. SFR) [1] or liquid metallic eutectics [2]. In the framework of international studies for future Generation IV reactors [3] there is a global need to achieve better, faster and/or more reliable inspection, maintenance, availability and decommissioning processes. Instrumentation requirements to achieve reliable core monitoring and event detection even in the case of accidental events imply diversifying the means of protection and improving instrumentation performance in terms of responsiveness as well as sensitivity [4,5].

Our work aims at improving upon temperature sensors currently used for sodium temperature measurements, such as thermocouples, by resorting to ultrasonic thermometry. Ultrasonic thermometry can be implemented based on several approaches. A first one consists of using an ultrasonic thermometer: by sending an ultrasonic pulse through a thin rod with acoustic discontinuities such as notches or sudden diameter changes, and measuring the time between the initial pulse and the reflections of that pulse, the rod is segmented into a multipoint temperature sensor [6]. For our study however, the starting point regarding thermometry for in-service temperature measurement at the outlet of the core is a second approach described in a 1985 British patent registered by A. McKnight et al. entitled "Remote temperature measurement" [7]. The main idea in that patent is to use an ultrasonic beam that impinges on the two diametrically opposite edges of a subassembly separated by a known distance. Measuring the time interval between the two echoes (and knowing the relation between celerity and temperature) then allows one to deduce the mean temperature of the liquid sodium between these two points.

However, since several parameters can influence the time-of-flight measurement, several challenging issues need to be addressed in order for such a technique to be usable in practice. The liquid sodium exiting the core of a nuclear reactor is a turbulent flow with thermal heterogeneities, and local flow variations can thus influence wave propagation. The shape of the reflected echoes, which depends on the fuel assembly geometry, can also

* Corresponding author.
E-mail address: joseph.moysan@univ-amu.fr (J. Moysan).

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be of importance and should be taken into account in the signal processing method used. In some particular cases, the proportion of gas microbubbles can also vary and modify the relation between celerity and temperature. Recent work has specifically focused on these aspects of wave propagation in a turbulent medium [8] as well as evaluation of gas proportion in an SFR [9].

In this article our goal is to study the development potential of ultrasonic thermometry in liquid sodium and thus to investigate if and how ultrasonic thermometry could be used to monitor the outlet of a sodium reactor core. In particular we want to see if small temperature variations (of e.g. about 1% of the sodium temperature, i.e., about 5 °C) in the sodium flow could have a reliably-measurable acoustic signature. The gas proportion is considered as constant in our study and flow rate effect is also neglected. Since to our knowledge no operating experimental setups would allow us to obtain a precise description of the fluctuating medium, and considering the practical difficulties related to experimentation in sodium, we will turn to highly-accurate numerical modeling based on a full wave modeling technique.

One of the difficulties in order to get a good model is to define what a liquid-sodium fluctuating medium can be. Its temperature and flow velocity field fluctuate by the interaction of a flow and the core structure composed of various assemblies, and they also fluctuate due to the thermo-dynamical equilibrium of the medium. To the best of our knowledge, no Computational Fluid Dynamics code can accurately generate such media at reasonable cost at a scale compatible with the ultrasonic scale that we want to target. We will thus turn to physical modeling to generate the fluctuating medium. In general, physical characteristics of a heterogeneous liquid medium fluctuate spatially and temporally, depending on its nature and on the environment. Such a heterogeneity is quite complex to model in a deterministic way because of many uncontrolled factors and thus it is common to model them based on a stochastic process. This issue has been addressed in the literature regarding modeling of heterogeneous liquid sodium in the context of wave propagation simulation. Fiorina [10,11] studied this issue and used a ray-tracing code and a Gaussian beam summation method to perform wave propagation simulation and compared amplitude and time of flight fluctuations with known analytical results. Similarities between water and sodium have been well described [12] and it is thus possible to reproduce liquid sodium behavior with hot water experiments. Fiorina [10,11] represents the fluctuating medium by a homogeneous and isotropic turbulent medium: temperature spatial fluctuations are considered in the stochastic domain and modeled by a Fourier mode summation technique. More recently Lü [13] also modeled such media. To reduce calculation time, he first calculated a mean field and then added a phase-variation part that reproduced the medium randomness.

In order to verify the possibility of measuring a small temperature variation in such an environment, which is the main goal of our study, it is necessary to consider the effect of temperature fluctuations caused by turbulent flow. For this purpose, we regard the temperature field as a combination of a static temperature distribution, which is to be measured, and a fluctuation part. Considering that fluctuating part, we resort to the Gaussian random field method, which is a random field generator based on a spectral method introduced by Shinozuka [14].

The article will be structured as follows: In Section 2 we will describe the thermometry concept at the outlet of the fuel assembly. In Section 3 we will then introduce the numerical method, and in Section 4 we will describe the configurations defined for our simulations and the definition of the temperature fields. We will then discuss the results and show that our 2D numerical simulations underline the potential of ultrasonic thermometry.

2. Thermometry at the outlet of nuclear fuel assemblies

Current setups for thermal instrumentation above a reactor core consist of several hundreds of thermocouples assembled in thermowells, one above each fuel assembly that needs to be monitored. However, as indicated above, there is a need for developing more efficient instrumentation for the next generation of nuclear reactors. One important issue to address is the ability to perform faster measurements, as the expected response time of the complete temperature instrumentation in these future reactors is 0.1 s or even less instead of at best about 1 s with sheathed thermocouples. Another interest for the ultrasonic method is that it is less sensitive to sodium jet bending than thermocouples. Additional improvements could consist of reducing the number of electrical wires located above the reactor core, which would open new design possibilities.

Acoustic thermometry based on ultrasonic transducers is a good candidate for such improved monitoring, as such transducers are already under development for instance at French Atomic Commission for various local measurements performed during maintenance operations. For in-service monitoring however, temperature and sodium flow characteristics are not the same as during maintenance operations (temperature is significantly higher, and sodium is flowing instead of idle), but transducers are designed for very high-temperature (up to 600 °C or even more) and should thus still be suitable for that usage.

Acoustic thermometry is based on the dependence of ultrasonic wave celerity on temperature in a given medium. Sobolev [15] has established the following empirical relationship between temperature and wave celerity in sodium:

$$C_{us} = 2723.0 - 0.531\ T_{kelvin} \quad (1)$$

where C_{us} is the celerity of ultrasonic waves in meters per second and T is sodium temperature in Kelvin degrees.

Density is also temperature dependent [14]:

$$\rho = 1014.0 - 0.235\ T_{kelvin} \quad (2)$$

The 1985 patent mentioned above considered the use of an ultrasonic beam as the basic tool for monitoring. As the celerity of ultrasonic waves is about 2300 m s^{-1} in sodium at 550 °C and as the distance between the monitored subassemblies and the transducer in future reactor designs should typically vary between a few tens of centimeters and several meters, using ultrasounds should indeed make measurement with a short response time possible because the time-of-flight will be in the range of milliseconds. The actual response time of an ultrasonic measurement device would then mainly be due to signal processing time in that device. Furthermore, with a single transducer operating at grazing incidence it would then be possible to simultaneously measure the temperature of the sodium flow at the outlet of several fuel subassemblies, allowing for the use of a smaller total number of measurement devices in the reactor.

Our goal in this article is to investigate how to develop a method involving the propagation of an ultrasonic beam toward two surfaces separated by known distance, which will both generate echoes. As mentioned in the 1985 patent the edges of the fuel subassembly heads are good candidates for generating the echoes, i.e., for being these two surfaces. The model to design for such a study must take into account the fact that in-service thermohydraulic conditions above the reactor core may disturb the propagation of ultrasonic waves between the ultrasonic transducer and the subassembly heads in terms of time delay as well as deflection. There are indeed several sources of thermal heterogeneities above the core: the temperature difference between sodium flowing out of two neighboring subassemblies can reach values as high as several tens °C owing to the design of the core; moreover, the sodium