Noninvasive ultrasonic measurements of temperature distribution and heat fluxes in nuclear systems

Yunlu Jia and Mikhail Skliar
Department of Chemical Engineering, University of Utah, Salt Lake City, United States

Abstract

Measurements of temperature and heat fluxes through structural materials are important in many nuclear systems. One such example is dry storage casks (DSC) that are built to store highly radioactive materials, such as spent nuclear reactor fuel. The temperature inside casks must be maintained within allowable limits of the fuel assemblies and the DSC components because many degradation mechanisms are thermally controlled. In order to obtain direct, real-time measurements of temperature distribution without insertion of sensing elements into harsh environment of storage casks, we are developing noninvasive ultrasound (US) methods for measuring spatial distribution of temperature inside solid materials, such as concrete overpacks, steel casings, thimbles, and rods. The measured temperature distribution can then be used to obtain heat fluxes that provide calorimetric characterisation of the fuel decay, fuel distribution inside the cask, its integrity, and accounting of nuclear materials. The physical basis of the proposed approach is the temperature dependence of the speed of sound in solids. By measuring the time it takes an ultrasound signal to travel a known distance between a transducer and a receiver, the indication about the temperature distribution along the path of the ultrasound propagation may be obtained. However, when temperature along the path of US propagation is non-uniform, the overall time of flight of an ultrasound signal depends on the temperature distribution in a complex and unknown way. To overcome this difficulty, the central idea of our method is to create an US propagation path inside material of interest which incorporates partial ultrasound reflectors (back scatterers) at known locations and use the train of created multiple echoes to estimate the temperature distribution. In this paper, we discuss experimental validation of this approach, the achievable accuracy and spatial resolution of the measured temperature profile, and stress the application of this new method to temperature and heat flux measurements in DSC and other nuclear systems.

Introduction

Process temperature is the primary characteristic that must be monitored in energy conversion processes, such as gasification, nuclear fission and degradation of nuclear waste. In a traditional approach, the measurement of the temperature profile across process containment requires the use of multiple temperature sensors inserted into the structure. The measured temperatures can then be used in process monitoring, assessment of containment integrity and, in nuclear applications, the assessment of radioactive decay and the accountability of nuclear materials. The service and replacement of insertion sensors are difficult and costly in nuclear applications. At the same time, these sensors are often subjected to harsh environment of elevated temperatures, high pressures, continuous radiation, and various physical and chemical stresses, heterogeneities and concentration gradients, all of which tend to shorten their useful service life.

In order to obtain direct, real-time measurements of temperature distribution without insertion of sensing elements into harsh environment of storage casks and other nuclear systems, we are developing noninvasive ultrasound (US) methods for measuring spatial distribution of temperature inside solid materials, such as concrete overpacks, steel casings, thimbles, and rods. This largely non-invasive approach can be used to measure temperature profile in solids and apply the result to estimate the corresponding heat fluxes.

Approach

The physical basis of the proposed approach is the temperature dependence of the speed of sound (SOS) in solids [1-3]. By measuring the time it takes an ultrasound signal to travel a known distance between a transducer and a receiver (the time of flight, TOF), which can be the same device in the pulse-echo mode of operation, the indication about the temperature distribution along the path of the ultrasound propagation may be obtained. In its simplest implementation, consider a sample of a solid material of known thickness L maintained at a uniform temperature. Assuming a pulse-echo method, the measurement of the TOF (return delay) of an ultrasound pulse, created by an ultrasound transducer coupled to one side of the sample and reflected from its distal end, may be used to calculate the speed of sound as:

$$SOS = \frac{2L}{TOF}. \tag{1}$$

The reflection from the distal end occurs due to a change in ultrasound impedances caused by changes in density and the speed of sound at the boundary of the sample. The dependence of the speed of sound on the temperature, $SOS=f(T)$, obtained experimentally or theoretically, would then allow us to estimate the temperature of the sample. However, when temperature of the sample is non-uniform, the overall time of flight depends on the temperature in a complex and unknown way:

$$TOF = \int_{r_h}^{r_c} f(T(t,r))dr \tag{2}$$

and does not provide sufficient information to estimate the temperature distribution across the sample, $T(r)$. By adding constraints on the feasible solution, an estimation of a unique temperature distribution based on measurements in the integral form (2) may be possible. Examples of such constraints may include the requirement that $T(r_c) = T_c$ where T_c is an independently measured surface temperature in the proximity of the ultrasound transducer and $T(r)$ is monotonically increasing, as would be the case for a dry containment of spent nuclear fuel of thickness $L= r_c - r_h$ (with $r_h \leq r \leq r_c$ where r_h and r_c are the coordinates of the hot and cold surfaces of the containment) heated from the inside by radioactive decay, and where T must satisfy the heat conduction model:

$$\rho C \frac{\partial T}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r}\left(r \frac{\partial}{\partial r}\right) T \tag{3}$$

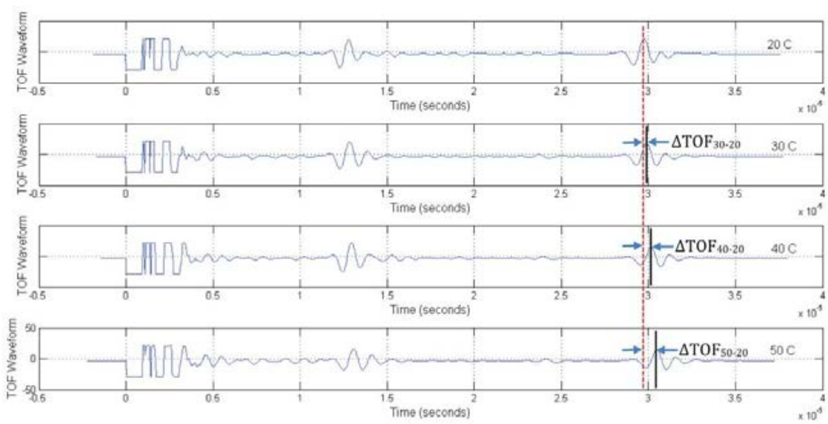
where ρ, C, and k are refractory density, heat capacity, and thermal conductivity, respectively.

The central idea of the proposed method to directly measure temperature in solids using ultrasound pulse-echo testing is to create an US propagation path inside the material of interest which incorporates partial ultrasound reflectors (back scatterers) at known spatial locations. A measurement of the temperature distribution begins with US pulse, generated by an ultrasound transducer. This pulse will be partially reflected from each scatterer in the US propagation path through the solid material and return to the receiver as a train of partial echoes. The TOF of the first echo gives an indication on the average temperature in the 1^{st} zone between the transducer and the first internal scatterer. The next return echo will originate from the second scatterer. By subtracting the TOF of the second and the first echoes, the average speed of sound and the corresponding average temperature between scatterers 1 and 2 can be estimated, and so on until the estimate of the temperature distribution throughout the solid material is obtained. With that distribution known, the temperature of the last (distal) segment can be used to determine $T(r_h) = T_h$, the temperature on the inside of the containment.

In the described approach, the sensitive electronic components are kept away from harsh environments and it is only required that the ultrasound propagation path is engineered to provide multiple internal partial reflectors and the US transducer is acoustically coupled to the outside surface of the containment, representing minor modifications to the containment or other nuclear subsystem. The overall system for measuring temperature distribution: (a) the engineered ultrasound propagation path either embedded as an insert or incorporated into the containment to provide partial ultrasound reflections from predetermined locations; (b) an ultrasound transducer and receiver, which can be implemented as single or distinct components; (c) the analog and digital ultrasound instrumentation used to generate the excitation pulse and then acquire and amplify the return echoes, and (d) the signal processing system that determines the time of flight for each echo and then uses this information to calculate the speed of sound in the corresponding segment of the containment. The temperature in each segment is then obtained using SOS vs. temperature correlation found experimentally or from theory.

In the specific implementation of the described approach, we used the envelope cross-correlation [4] between the echo waveforms obtained at different temperatures to determine the difference in the time of flight, ∆TOF, as a function of temperature. This method uses both the phase and the amplitude of the waveforms to find ∆TOF which makes it suitable for use with dissipative material, including concrete overpacks. The typical results obtained with a cementitious sample are illustrated in Figure 1.

Figure 1: The Δ*TOF* between echo waveforms at different temperatures is calculated by cross-correlation with a reference waveform acquired at 20°C



Given the measurements of the time of flight, the speed of sound in each segment between two consecutive backscatterers inside the sample, SOS_i, is calculated at each temperature using the following equation:

$$SOS_i = \frac{2L_i}{(TOF_{refi} - TOF_{refi-1}) + (\Delta TOF_i - \Delta TOF_{i-1})} \quad (4)$$

where L_i are the thickness of each consecutive layer of the sample; TOF_{refi} are the times of fight of reference echoes originating from the three internal interfaces and the distal end of the sample; ΔTOF_i are the differences between time of flights at reference and test temperatures. The overall length of the sample was measured using a micrometer, and the speed of sound at the reference temperature was calculated using equation (1). With known speed of sound at the reference conditions, the thicknesses of each layer Li were calculated at reference conditions using the measurement of TOF_{refi}.

Experimental validation

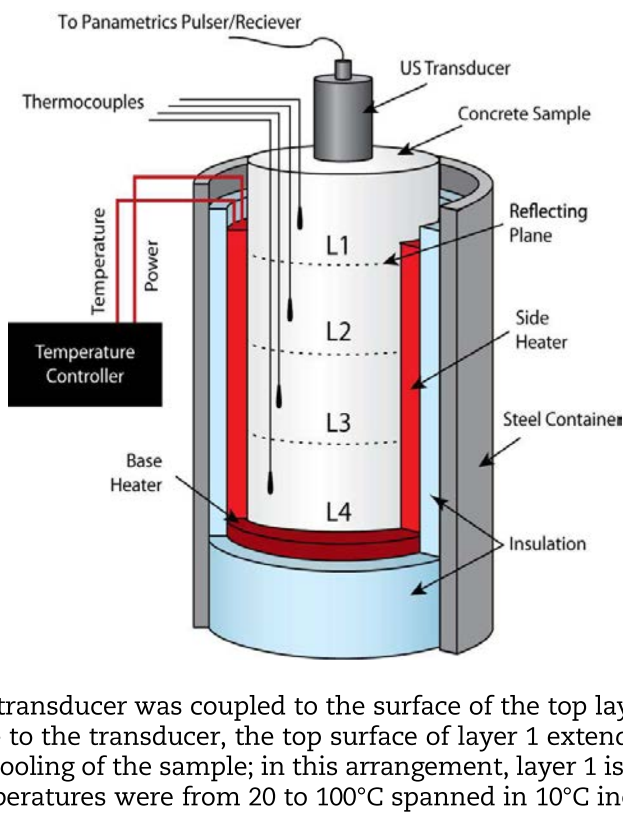
The experimental validation was carried out with a cementitious sample. A 2” I.D. PVC tubing was using as a mold and the water-cement mixture was poured into a vertically oriented mold. Partial internal ultrasound reflections from known spatial locations inside the sample are needed to enable direct US measurements of the temperature distribution. It was found that by casting multiple layers of the same composition and allowing for a partial curing before casting the next layer, enough variation in acoustic impedance is introduced to create partial US reflections at the interface.

A 4” cementitious sample which we used during the experiment was created by sequentially casting four layers (each 1” thick) of a stand Type I/II Portland cement mixture into the PVC form and allowing 30 minutes curing time before casting the next layers. Such implementation of the containment with an embedded partial internal ultrasound reflector is particularly appealing since each layer has essentially identical thermal, chemical and mechanical properties. After removing the solidified sample from the form, it was allowed to cure at room temperature until its ultrasound properties have stabilised.

The ultrasound tests of cementitious samples were carried out using panametrics pulser/receiver (model 5072PR) and panametrics transducer (model V302) with a central frequency of 1 MHz, coupled to a sample using ultrasound gel. The data were acquired using Tektronix oscilloscope (model MSO 2024) interfaced to a computer. The data processing of acquired US waveforms was performed using custom Matlab code.

To establish SOS vs. temperature correlation, the sample was placed inside the fabricated heating fixture depicted in Figure 2, which consisted of a thermally insulated steel container and an internal heating blanket (silicon rubber blanket by BriskHeat®) that tightly surrounded the sample. The temperature of the heating blanket was measured by a thermocouple and controlled by a PID controller. The surface temperature of the sample was measured by four thermocouples attached with high-temperature adhesive tape in the middle of each layer of the sample surface. Two additional thermocouples were used to measure the temperature of the top and bottom surfaces of the sample.

Figure 2: The experimental setup



The ultrasound transducer was coupled to the surface of the top layer of the sample. To prevent the damage to the transducer, the top surface of layer 1 extended above the fixture to allow for partial cooling of the sample; in this arrangement, layer 1 is effectively used as a delay. The test temperatures were from 20 to 100°C spanned in 10°C increments. After each temperature change, sufficient time was allowed for thermal equilibration to occur before attempting the time of flight measurements. The sequence of temperatures for which the

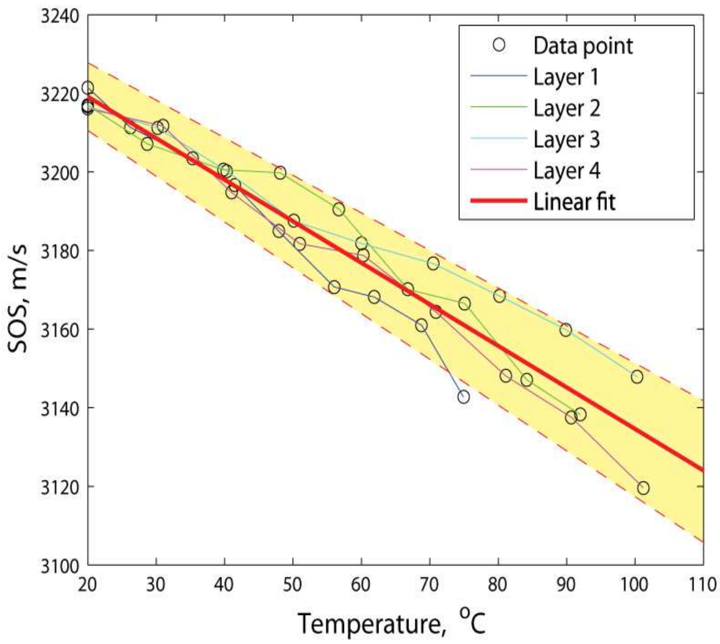
SOS measurements were conducted was randomised. The randomisation included all repeat experiments for each temperature. Such randomisation avoids measurement bias from one experiment to the next. In order to calculate the 95% confidence interval, tests at each temperature were repeated at least 6 times in random order.

To test the proposed method for measuring non-uniform temperature distribution, the sample was placed inside the fixture shown in Figure 2 and heated using the base heater only. After the temperature measurements provided by surface thermocouples stabilised at constant values, an ultrasound excitation pulse was applied to the sample and the four return echoes were acquired. Using the envelop cross-correlation method, the TOF of each echo was determined, and the result was used to estimate the apparent speed of sound in each layer needed to produce the observed time of flight for each echo. Based on the calibration data, thus obtained SOS of each layer provided the corresponding temperature of each layer.

Results and discussion

The speed of sound vs. temperature results for all four layers of the sample, obtained using the described procedure, are shown in Figure 3. The obtained SOS on the vertical axis is plotted as a function of the temperature measured by a thermocouple located at the bottom of the model refractory sample. The data for all four layers were used to obtain a linear fit of the speed of sound as a function of temperature. The obtained correlation is plotted with the 95% confidence interval, shown as the shaded area. The comparison of the thermocouple measurements of the surface temperature in the middle of each layer and the apparent temperature of each layer obtained with the proposed method is shown in Figure 4. Both methods show a similar trend in temperature distribution and an excellent agreement in the estimated axial thermal fluxes, which are proportional to $\frac{\partial T}{\partial r}$.

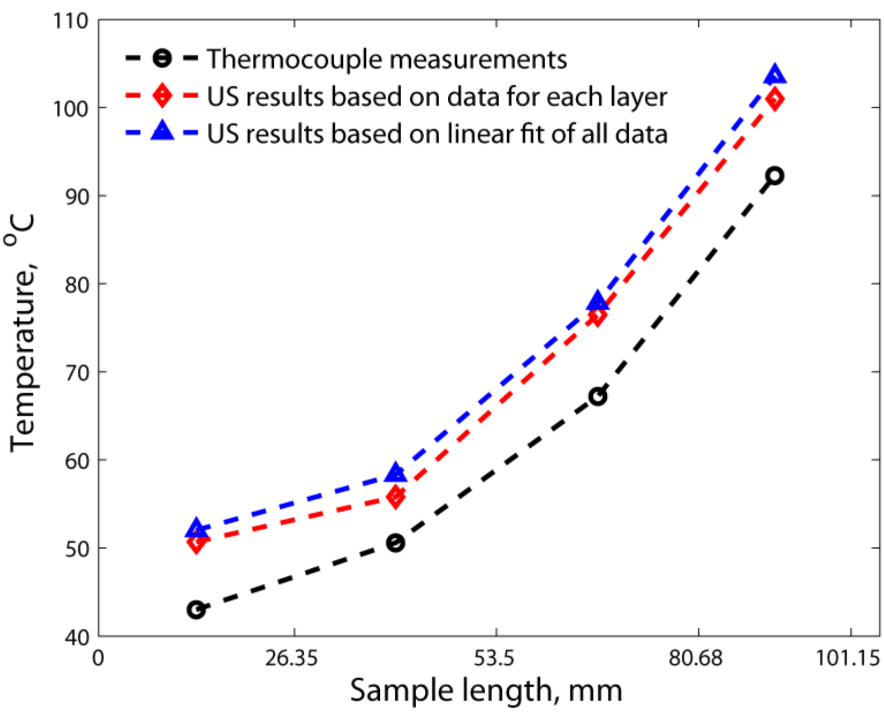
Figure 3: The calibration curves for the SOS as a function of temperature for all four layers of the sample were obtained using envelop cross-correlation data analysis methods. The shown linear fit *SOS=SOS(T)* is based on data for all four layers. The shaded area shows the 95% confidence interval for the obtained linear fit.



Two factors likely contributed to the observed difference in the measured temperature. First, it is reasonable to expect that the surface temperatures of the sample are indeed lower than the internal temperature measured noninvasively by the ultrasound, explaining some of the observed differences. Second, the thermocouples provide essentially point-wise measurements of temperature, while the ultrasound measurements depend on temperature distribution along the entire sample. The results shown in Figure 4 assume a step-wise constant temperature distribution for each layer. A much more accurate estimate of the temperature distribution will be obtained if a more realistic "sub-grid" parameterization is used. For example, we expect that by requiring that the temperature distribution satisfies the realistic heat transport model (e.g. the conduction model of equation (3) supplemented with the boundary temperature condition at the traducer location) the accuracy of the ultrasound measurements of the temperature distribution and the estimation of the hot boundary temperature will improve.

With the known temperature distribution along the path of the ultrasound propagation, the corresponding heat flux through the solid material can be calculates as $q = -k\frac{\partial T}{\partial r}$.

Figure 4: Comparison of thermocouple and ultrasound measurements of temperature distribution in the sample heated from the bottom



Conclusions

This paper describes novel method for measuring temperature distribution in solid materials and its experimental validation. This method is capable of providing an accurate, in-situ, and real-time measurements of the temperature distributions and heat fluxes in solid components of nuclear and other systems characterised by harsh environments.

Acknowledgements

The authors acknowledge support the U.S. Department of Energy's National Energy Technology Laboratory, under award number DEFG2611FE0006947.

References

[1] Jia, Y., M. Puga, A. Butterfield, D. Christensen, K. Whitty, and M. Skliar (2013), "Ultrasound Measurements of Temperature Profile Across Gasifier Refractories: Method and Initial Validation", Energy and Fuels, 27, pp. 4270–4277.

[2] Mi, X., S. Zhang, J. Zhang and Y. Yang 2003 "Automatic ultrasonic thermometry", Presented at 15^{th} Symposium on Thermophysical Properties, 22-28 June 2003, Colorado, United States.

[3] Kychakoff, G., A. Hollingshead, S. Boyd (2005), "Use of acoustic temperature measurements in the cement manufacturing pyroprocess", Cement Industry Technical Conference, 15-20 May 2005, Kansas City, Missouri, United States, Conference Record, pp. 23-33.

[4] Le, L.H., "An investigation of pulse-timing techniques for broadband ultrasonic velocity determination in cancellous bone: A simulation study," Physics in Medicine and Biology 43:2295-308, 1998.