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Ultrasonic Measurements of Temperature Distribution and Heat Fluxes Across Containments of Extreme Environments

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***Abstract*—Extreme conditions are common in energy conversion, material processing, nuclear, airspace, and military applications. In such environments, the most hardened insertion sensors do not perform reliably for long. Ultrasonic measurements, on the other hand, can be acquired noninvasively, with sensitive components kept away from the damaging environment. We have previously developed the ultrasonic method for measuring the spatial distribution of temperatures in solid materials applicable in the cases when large thermal gradients are present. In the developed approach, we use the echogenically segmented ultrasound propagation path, structured to contain engineered or naturally occurring echogenic features, to produce a train of echoes in response to an external pulse of ultrasonic excitation. The delays between the echoes, which encode the information on the temperature distribution in the corresponding segments, is used to reconstruct unknown temperature profile. In this paper, we outline the results of pilot-scale testing of the developed approach and demonstrate its application to the measurements of the temperature distribution across the containment of a high-temperature combustion process. The validation results show that the estimated temperature profile is correctly captured, and the measurement accuracy can be comparable with traditional insertion sensors, such as thermocouples. Overall, the testing has confirmed that the developed approach has matured to become an attractive alternative to conventional sensing in solving challenging problems of long-term temperature measurements in extreme environments. Heat fluxes and thermal stresses in the structure can then be characterized noninvasively using the measured temperature distribution as the basis.**

***Index Terms*—Ultrasonic Sensors, Temperature Distribution, Heat Flux, Industrial Applications**

I. INTRODUCTION

Temperature impacts the time of flight (TOF, t_{of}) of ultrasound waves through a solid medium by changing the speed of the ultrasound propagation c and the propagation length L due to thermal expansion or contraction. By timing t_{of}, the temperature of an isothermal sample can be measured. At non-isothermal conditions the temperature $T(z)$ changes with the position z, $0 \leq z \leq L$. Since the TOF encodes the unknown temperature distribution in a single scalar measurement t_{of}, the unique reconstruction of $T(z)$ is not possible for non-isothermal samples. The difficulty becomes apparent if we consider the following relationship between the TOF measured in the pulse-echo mode and the unknown temperature distribution:

$$t_{of} = 2\int_0^{L(T(z))} \frac{1}{c(T(z))} dz, \tag{1}$$

This integral equation allows an arbitrary number of solutions $T(z)$ that integrate to the same measured time of flight through the sample. Additional measurements or constraints on the admissible $T(z)$ are required to enforce uniqueness.

The method for <u>u</u>ltra<u>s</u>ound <u>m</u>easurements of <u>s</u>egmental <u>t</u>emperature <u>d</u>istribution (US-MSTD) resolves the lack of unique dependence between the measured t_{of} and the unknown $T(z)$ by a) using a structured propagation path with multiple echogenic features which create a train of ultrasound echoes, the TOF of which encodes the temperature distribution in different segments of the waveguide; and b) parametrizing "admissible" temperature distributions within each segment by prescribing a functional form that depends on one or more unknown parameters, which are then found from ultrasonic and other available measurements. The US-MSTD concept was first described in [1]–[3]. Its capabilities to accurately measure temperature distributions on a line and in the volume of cementitious samples were shown in [4], where the measurements of the heat fluxes by US-MSTD method were also demonstrated. The laboratory measurements of the high-temperature distributions in an alumina waveguide were reported in [5].

Here, we describe and analyze the application of the US-MSTD method to the measurements of the temperature distributions across the containment of a 100 kW pilot-scale oxy-fuel combustor continually operated at varying conditions for five days. The comparison of the US-MSTD results with the validation data provided by several thermocouples shows an excellent agreement.

II. METHOD

Figure 1 summarizes the concept of the US-MSTD method in its application to the measurements of the temperature distribution across the containment of an energy conversion process. A transducer located outside the containment creates

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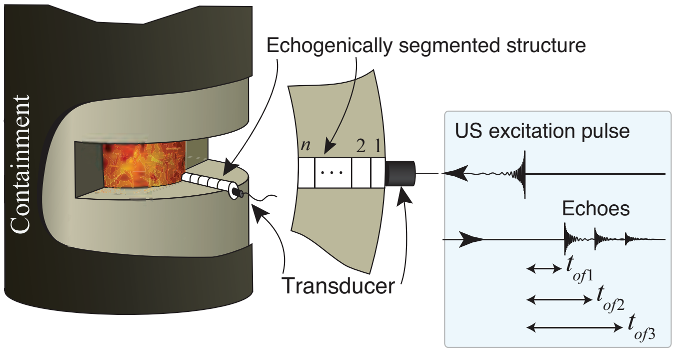

Fig. 1. Excitation pulse created by a US transducer propagates through the structured containment and encounters n echogenic features along its way. The TOF difference between consecutive echoes encodes the temperature distribution in the corresponding segment of the containment.

the ultrasonic excitation pulse. As the excitation propagates through an echogenically-segmented containment, a train of n echoes is produced by echogenic features localized at known positions z_i. The temperature distribution in the i-th segment is found from the segmental time of flight, t_{of_i}, calculated as the difference between the measured TOFs of consecutive echoes produced by echogenic features bounding the segment and located at z_i and z_{i-1}:

$$t_{of_i} = t_{of}^{z_i} - t_{of}^{z_{i-1}} = 2\int_{z_{i-1}}^{z_i} \frac{1}{f(T(z))}dz \tag{2}$$

If we assume a constant segmental temperature, then the velocity of the excitation wave is also constant through the segment:

$$c_i = \frac{2(z_{i+1} - z_i)}{t_{of_i}} \tag{3}$$

The corresponding constant temperature of the segment, T_i, can then be found from the "calibration" equation, $c = f(T)$, obtained experimentally or theoretically. The parametrization (3) was used in [1], where we noted that the resulting piecewise constant approximation of unknown temperature distribution has infeasible discontinuities at the locations of echogenic features. A finer segmentation of the propagation path with a larger number of features improves the accuracy of this approximation.

The piecewise linear parametrization of the segmental temperature,

$$T(z) = m_i z + n_i, \quad z_{i-1} \leq z \leq z_i, \tag{4}$$

enforces the continuity in the estimated temperature distribution but requires an independent temperature measurement in one location (e.g., at the transducer location z_0) [4], [5].

III. Pilot-scale testing

During a week-long campaign, the pilot-scale testing of the US-MSTD method war carried out on a 100 kW down-fired oxy-fuel combustor (OFC) schematically shown in Figure 2. The unit was preheated by natural gas (NG) combustion

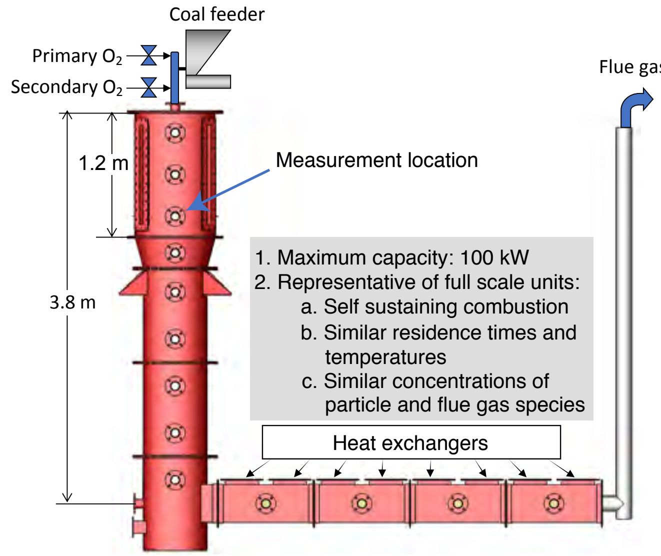

Fig. 2. Pilot-scale oxy-fuel combustor. The echogenically segmented waveguide was mounted to the marked access port located in the ignition zone of the OFC.

until the refractory temperature became high enough for self-ignition of pulverized coal – the primary fuel. NG was also used to keep the OFC temperature high at night during unattended operation. Multiple ports on the OFC provide access to the combustion zone.

An alumina rod (1" OD, 12″ long), which we echogenically segmented by drilling four radial holes located at 1″, 2″, 4″ and 6″ away from the distal end (DE) of the rod, was used as the US-MSTD waveguide. Fig. 3B shows representative waveforms of echoes reflected by the echogenic features (EF) segmenting the waveguide. The waveguide was wrapped with fiberglass insulation which filled the access port in which the waveguide was positioned (Fig. 2). The DE of the waveguide was aligned with the refractory's hot face, while the proximal end extended outside the OFC containment, where it was acoustically coupled to a 5 MHz ultrasound transducer (Fig. 3A). In this arrangement, US-MSTD components are kept away from the harsh OFC environment. Validation temperature measurements were provided by four Super OMEGACLAD™ type K thermocouples (TC1...4; Omega Engineering), which were bent at 90°and inserted into each of the segmentation holes, as seen in Fig. 3C. The first segment between the proximal end of the waveguide (transducer-waveguide interface) and the first hole at z_1 served as a delay line and its temperature distribution was not estimated.

The data acquisition, signal processing, and the estimation of the temperature profile across the refectory were performed by a custom Matlab software. The same software handled the real-time visualization of the estimated temperature profile, the comparison of the US-MSTD results with independent thermocouple measurements, and data archiving. The segmental TOFs were measured using a combination of the envelope cross-correlations [5] and the anisotropic diffusion filter [6],

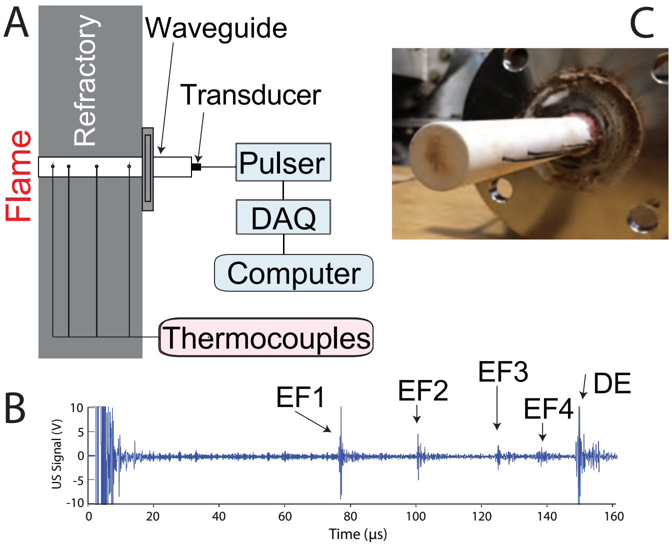

Fig. 3. A: Components of the US-MSTD installation. B: Ultrasound response shows four echoes produced by echogenic features (EF1...4) segmenting the waveguide. The fifth echo is the reflection from the distal end of the waveguide. C: The waveguide extracted from the OFC at the end of the testing campaign is shown after the thermal insulation was removed. Note thermocouples inserted into holes providing ultrasonic segmentation.

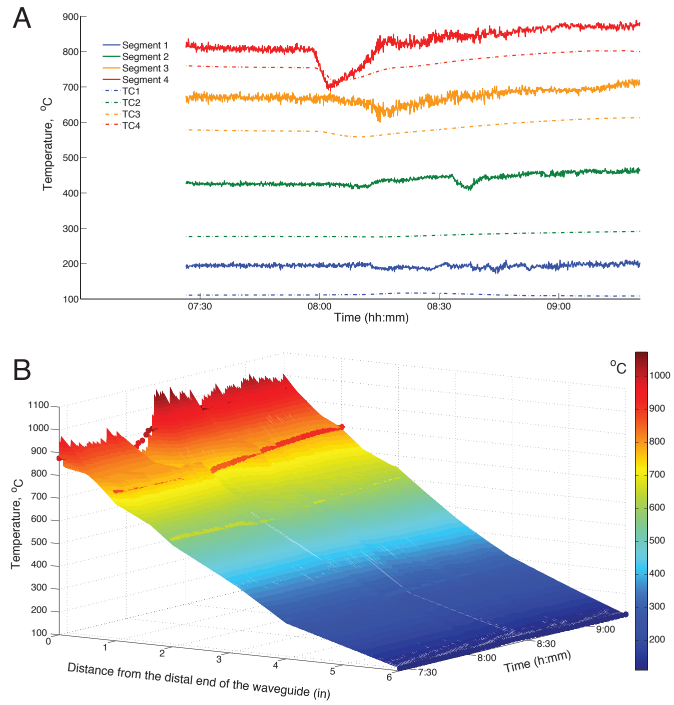

Fig. 4. A: Comparison of piecewise constant segmental temperature distribution and thermocouple measurements during the change from NG to coal combustion. B: The evolution of the piecewise-linear temperature during fuel changeover.

which was applied to robustly the measurements of t_{of_i}. The relationship between the temperature and segmental speed of sound needed to estimate an unknown temperature distribution along the waveguide was obtained experimentally [5].

IV. Results

The pilot testing took place over ∼120 continuous hours during which the US-MSTD system measured the temperature distribution across the containment of the OFC process every 5 seconds. Several notable operating conditions were characterized, including the initial heating of the unit, steady-state combustion of either natural gas or coal, the transition from NG to coal and back, combustion with the transient fuel flow rates, and the final cooldown of the unit. The transition from the stable NG combustion to coal combustion is captured in Fig. 4. The flow of gas was stopped just before 8 AM, leading to a cooling of the hot face of the refractory and the distal end of the waveguide. The piecewise constant approximation of the temperature profile across the waveguide in Fig. 4A shows a rapid decrease in the temperature of Segment 4 after the flow of the NG was stopped and then, after the heat conduction delays, in Segments 3 and 2. The temperature in Segment 1 remained largely unaffected by a short interruption in the combustion. The feeding of coal started about 10 minutes after the NG flow was stopped. The US-MSTD temperature measurements in Segment 4 promptly showed a change in trend from falling to rising temperatures reflecting the resumption of combustion.

Fig. 4A shows similar trends in US-MSTD and TC measurements. However, the ultrasound measurements, which depends on the entire temperature distribution in the waveguide and thus are less impacted by the heat transfer delays, reflect the change in the operating conditions much faster and with higher sensitivity than the point-wise TC readings. Note that the highest waveguide temperature occurs at its distal end. The TC measurements taken in the locations of echogenic features are the lowest temperatures in each segment. As a result, the US-MSTD piecewise constant approximation of the segmental temperatures is always higher than the thermocouple readings at the boundary of the segments. Fig. 4B shows the evolution of a piecewise-linear temperature profile, which gives a more accurate reconstruction of unknown temperature distribution and a better agreement with thermocouple measurements.

Fig. 5 captures changes in operating conditions during a different day of the trial. The shown data begins right after the OFC was switched from NG to coal, causing the rise in temperature which eventually exceeds 1,000° C on the distal end of the waveguide at ∼ 8:40 AM (Fig. 5A) and then stabilizes at that level. At approximately 9:20 AM, the flow rate of coal was slightly lowered, which caused the transition of the refractory temperature to ∼970° C.

The temperature of the waveguide's distal end (refractory's hot face), shown in Fig. 5A, was estimated using piecewise linear parameterization; the thermocouple measurements were not available for this location. Note that the piecewise constant approximation of the temperature in Segment 4 significantly underestimates the hottest temperature of the segment which occurs on the distal end of the waveguide.

Fig. 5B compares the thermocouple measurements with US-

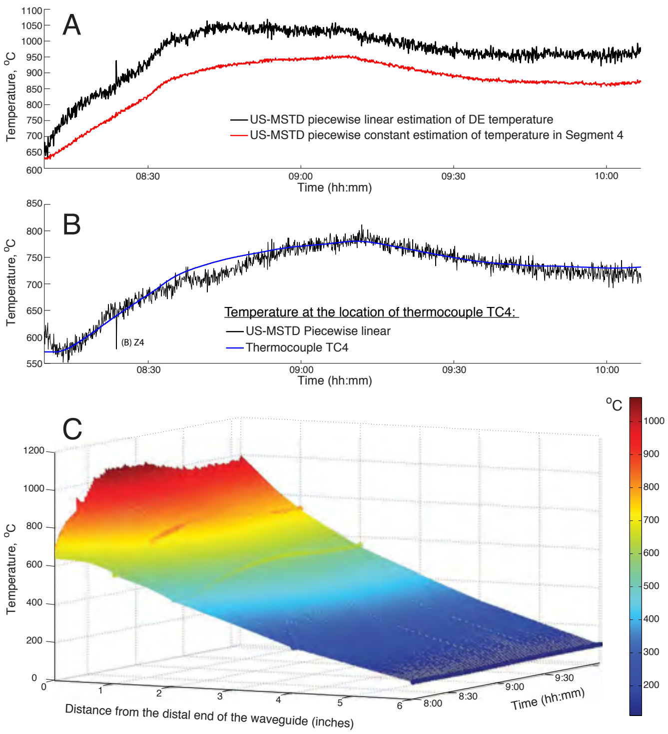

Fig. 5. A: Temperature at the waveguide's distal end estimated by the US-MSTD method during the transition from NG to coal combustion and then the reduction in the coal feed rate. B: Comparison of the thermocouple and US-MSTD measurements at the location of the echogenic feature EF4. C: The evolution of the piecewise-linear temperature distribution along the waveguide during the described changes in the operating conditions.

MSTD results under piecewise linear parameterization at the location z_4, which is the boundary Segments 3 and 4. While the agreement between the two measurements is excellent, a higher "noisiness" of ultrasound measurements is apparent. This increased variability is the feature of the piecewise linear parametrization, which requires the slope of the temperatures in a segment. A small variability in the slope caused by measurements noises translates into a higher variability in point-wise temperatures seen in Fig. 5A and B. The issue can be resolved by low-pass filtering of US-MSTD measurements, which can be acquired with high sampling rates.

Fig. 5C shows the evolution of the temperature profile along the waveguide measured by the US-MSTD method with piecewise linear parametrization. Note the high sensitivity of the DE temperature to changing operating conditions of the OFC, which rapidly diminishes with the distance from the hot face of the refractory. As a result, compared to the thermocouples placed away from the combustion zone to prevent their rapid failure, the US measurements give, both, faster and a more pronounced indication of changing operating conditions.

V. Discussion

The US-MSTD system was successfully tested on the pilot-scale OFC oxy-fuel combustor during $\sim$120 hours of continuous operation. Real-time temperature distributions along the waveguide were captured during all changes in operating conditions. US-MSTD results are in excellent consistency with the independent thermocouple measurements, as was previously observed in the laboratory testing [4], [5].

The test revealed several issues. The alumina waveguide had no visible damage nor surface corrosion after five days of around-the-clock exposure to the high-temperature environment of OFC, and only limited ash deposit was observed on its distal end. At the same time, the TC4 thermocouple, which was inserted into the echogenic feature closest to the flame zone, has lost its functionality after the test. The outer sheathing of TC4 (rated for the use up to 1,335° C) was damaged despite thermal and abrasion protection provided by high-temperature fiberglass insulation used to wrap the waveguide inserted into the access port. The sheath became brittle and exposed the thermocouple wires during subsequent handling.

Though the appearance of the alumina waveguide after the test was normal, a significant and irreversible deterioration in the strength of ultrasound echoes has occurred, indicating that structural changes in the material have occurred as a result of prolonged exposure to high temperatures. Microstructure changes, mainly the growth in alumina grains, are the likely explanation, which was confirmed by SEM imaging. The observed increase in the ultrasound attenuation indicates the need to use a stabilized alumina as the waveguide material in future high-temperature applications.

Overall, the pilot-scale testing confirms that the US-MSTD method has matured to become a new alternative for solving challenging problems of prolonged temperature measurements in energy conversion and heat treatment processes, including gasifiers, combustors, nuclear reactors, and waste incinerators, and other extreme environments where the conventional insertion sensors are impossible or difficult to deploy. The measured temperature distributions provide the information needed to estimate heat fluxes and thermal stresses inside the structures, which is a unique capability of the US-MSTD method.

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