46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA
QNDE2019-1234

MULTI-POINT HIGH TEMPERATURE MEASUREMENT USING LONG ULTRASONIC CERAMIC WAVEGUIDES

Gokul Raja SG[1], Nishanth Raja and Krishnan Balasubramaniam
Centre for Non Destructive Evaluation, Indian Institute of Technology Madras, India.

Abin John
Sr. Product Engineer (NDT Product Development)
Oceaneering International Services Ltd, India.

ABSTRACT

Temperature monitoring at high temperature environments plays an important role in process industries. This paper discusses about using long ultrasonic waveguides for measuring temperatures in high temperature oxidation environments. Use of different ceramic waveguide materials is explored in this study. For this particular study 920 mm long alumina rod of 10 mm diameter with notches at regular intervals across the length is used to monitor temperature from 27ºC to 1100ºC. Torsional mode T(0,1) at 0.25MHz is selected for the experiments because of its non-dispersive characteristics. The ultrasonic signals are transmitted and received using a single shear transducer (0.25MHz) oriented at 90° to the axis to the waveguide. The change in time-of-flight of the reflected ultrasonic signal from the waveguide features (notches and end) is used to measure the local temperature of the surrounding media. This work is of interest in several industrial high temperature process.

Keywords: Waveguide sensors, Multi-point temperature measurement, Ultrasonics.

1. INTRODUCTION

High temperature measurements are very vital for many process industries for monitoring and maintaining the optimum temperature or working conditions. Existing methods use thermocouples and pyrometers, Thermocouple junctions often fail and can measure temperature only at a single point, Pyrometers are known to show inaccurate readings and are largely affected by the emissivity [3]. By the proposed method, one can measure and monitor the temperature at multiple locations and have better control over the process.

The use of ultrasonic waveguide technique has been reported broadly in the literature for different applications that include temperature, density, viscosity, and level of fluids in process control applications [1]. Ultrasonic bulk wave method using modulated continuous wave for air temperature measurement due to change in the speed of sound and phase shift records have been reported elsewhere [5]. The author's group has reported temperature measurement inside a hot furnace using ultrasonic waveguides along with helical and bend features [2]. Here, we explore the transmission and reception of T(0,1) wave modes in a ceramic waveguide made with non-axisymmetric notches. From the reflected ultrasonic guided wave signals from the waveguide features (notch/end), the physical characteristics of the surrounding medium can be determined based on the time of-flight (TOF) as well as amplitude (A) measurements.

2. MATERIALS AND METHODS

2.1 Waveguide Selection

Waveguide can be a metal/non-metal, Rod/wire/tube which supports the propagation of ultrasonic waves.

The following factors are considered for the selection of the waveguide material.

- Melting temperature of the waveguide material.
- Oxidation temperature of the waveguide material.
- Wetting characteristics of the waveguide material.
- Chemical inactivity at normal and elevated temperature.
- Heat conductivity of the material.
- Ultrasonic wave attenuation characteristics of the waveguide material.
- Reliability of the ultrasonic wave propagation through the waveguide.
- Cost and availability of the waveguide material.

However, for this high temperature application a circular waveguide was selected. High density and high purity (99.9%) Alumina (Al_2O_3) is chosen as an ultrasonic waveguide. The dimensions and the material properties are shown in Table 1.

Material Density (ρ) kg/m3	Young's modulus (E) GPa	Poisson's ratio (µ)	frequency (MHz)	Waveguide diameter D(mm) and length L(mm)
3880	350	0.23	0.25	10, 920

TABLE 1: MATERIAL PROPERTIES

---

[1] Contact author: gokulrajasg@gmail.com

2.2 Working Principle

Waveguide sensors can measure changes to surrounding media based on the change in velocity in an ultrasonic waveguide due to the variations in material properties density, young's modulus, shear modulus and coefficient of thermal expansion (ρ, E, G and α) as a function of temperature. In the present work, T(0,1) modes were transmitted and received through the ceramic waveguide using a shear transducer oriented at 90 ° to the axis of the waveguide as shown in figure. The optimized gauge length (l_1=100mm) of the sensor was then employed in the waveguide sensors for distributed temperature measurement. The waveguide sensors were calibrated using δTOF, which is directly proportional to the change in gauge length and moduli of the material as a function of temperature. The δTOF at a given temperature compared to the δTOF at room temperature helps us to measure the temperature within the gauge length of surrounding media.

The properties of the waveguide (Table 1) were used to obtain the phase velocity dispersion curves for the L(0,1) ,T(0,1) and F(1,1) modes of ceramic alumina waveguide as shown in Figure 1[9]. In order to limit the level of dispersion, an operational frequency of 250 kHz was selected for this work.

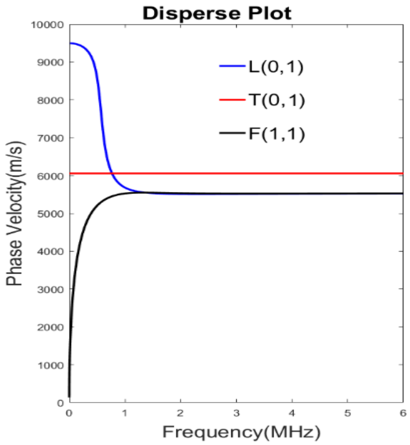

FIGURE 1: DISPERSION PLOT.

2.3 Experimental Setup

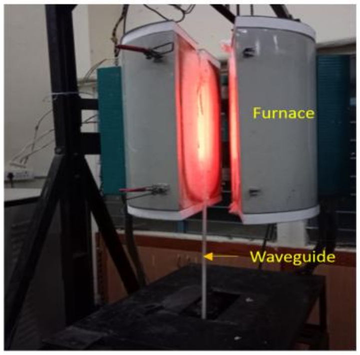

FIGURE 2: EXPERIMENTAL SETUP.

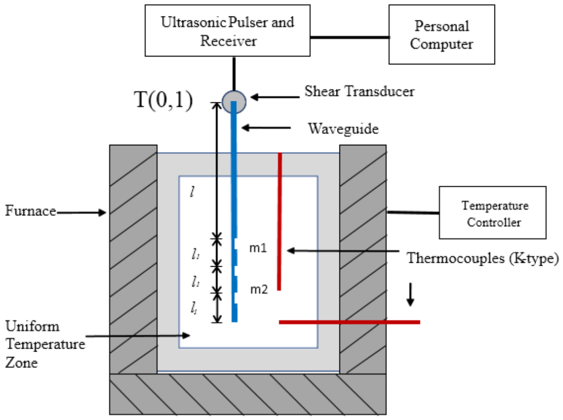

FIGURE 3: SCHEMATIC OF EXPERIMENTAL SETUP.

The diagram in Figure 3 describes the instruments used in the experimental work reported here for measuring the δTOFs of waveguide sensors at different temperatures. A top-access resistant heating-type furnace was used in the laboratory experiments. A Shinko programmable controller PCD-33A was used to control the steady-state heating of the furnace from 27ºC to 1100ºC. The transducer was fixed to the waveguide using the holder and placed above the furnace. The holder temperature was maintained at room temperature. A ceramic waveguide shown in Figure 3 was inserted through a small port from the top of the furnace and placed inside the furnace. Each pair of reflectors (Notch- Notch m1, Notch-End m2) are considered as sensor. The sensor regions of the waveguide were assumed to be in the uniform temperature region of interest. Reference thermocouples (K-type) were co-located near the waveguide sensors to ensure temperature uniformity. These thermocouples were connected to a NI 9211 24-bit card to record the temperature data during the experiment.

3. RESULTS AND DISCUSSION

The reflected T(0,1) signal from each sensor was observed in the A-scans obtained at different temperatures (for example 27ºC to 1100ºC), as shown in Figure 4. The heating experiment was conducted for approximately 180 minutes and simultaneously the δTOFs were collected from all sensors using a peak tracking algorithm [7]. The δTOF data were measured at a rate of one A-scan per 50°C change. The TOFs of the reflected signals from any pair of sensors (notches) can be used to derive the δTOF calibration equation. Here, the TOFs from notch 1 and end, as shown in Figure 4, were used to obtain the δTOFs.

The δTOF of each sensor (pair of reflectors) was measured at various temperatures using Equation (1) [8]. The ceramic waveguide sensor were calibrated using the thermocouple output, as shown in Figure 3. Equation (2) was obtained from the calibration plot (Figure 5) using a second-order polynomial expression, where y and x represent temperature (T) and δTOF, respectively.

$$(\delta TOF_i) = [TOF_{bi} - TOF_{ai}] - [TOF_{bj} - TOF_{aj}] \qquad (1)$$

$$y = -7.7034x^2 + 207.56x + 34.776 \qquad (2)$$

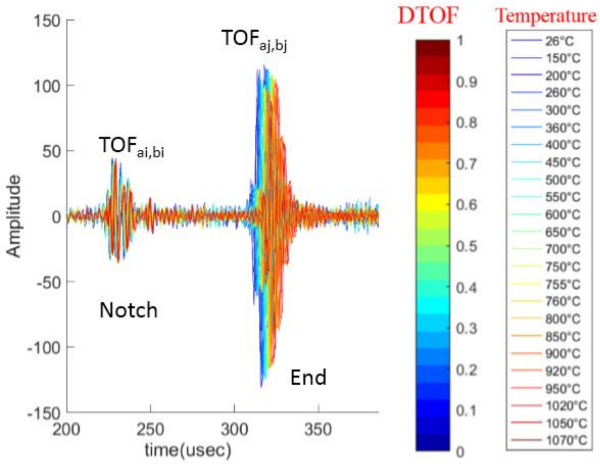

FIGURE 4: OVERLAID PLOT OF A-SCAN SIGNAL.

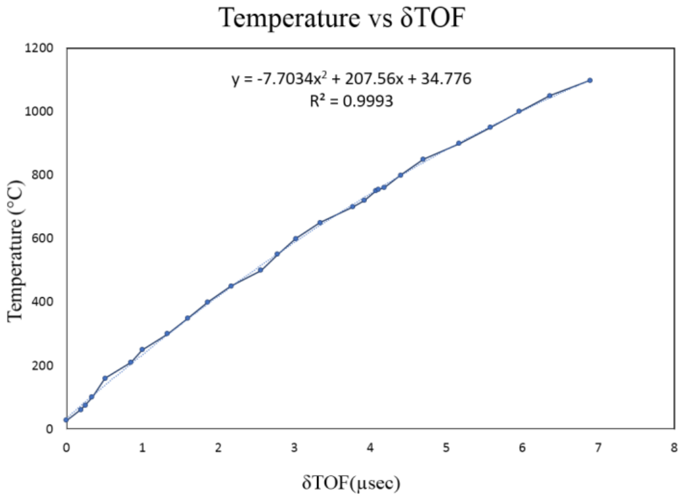

FIGURE 5: CALIBRATION CURVE.

4. CONCLUSION

This paper has reported the design and development of ceramic waveguide sensors for demonstrating distributed temperature measurements from a laboratory test furnace. A long ceramic waveguide with two pairs of notches (m1, m2,) was designed for multi-level temperature measurement. It was also demonstrated that using an experimentally obtained calibration curve, the temperatures at multiple locations in different media could be measured reliably using a single ultrasonic waveguide. These measurements were compared with the co-located conventional temperature sensors output and found to be in good agreement. The maximum difference between the ultrasonic sensor data and the thermocouple output was 4°C-6°C in the temperature measurements. Also, it is possible to increase the number of sensors for distributed temperature measurement at multiple regions over a wide range of applications. The distributed sensors can also be utilized for measurement of changes in the surrounding media of hazardous regions and remote regions, for example, for the measurement of temperature in steel mold process, nuclear industry, and oil and gas industries, etc.

REFERENCES

[1] L. C. Lynnworth, *"Ultrasonic Measurements for Process Control: Theory, Techniques, Applications."* Academic Press, New York, 1989.

[2] Krishnan Balasubramaniam and Suresh Periyannan, *"A novel waveguide technique for the simultaneous measurement of temperature dependent properties of materials"*, US Patent 20160153938 A1, June 2016.

[3] Suresh Periyannan, Prabhu Rajagopal and Krishnan Balasubramaniam. "Ultrasonic bent waveguides approach for distributed temperature measurement."*Ultrasonics Vol.74* (2017):pp.211-220.DOI https://doi.org/10.1016/j.ultras.2016.10.015.

[4] Nishanth Raja, Krishnan Balasubramaniam and Suresh Periyannan, "Ultrasonic Waveguide Based Multi-level Temperature Sensor for Confined Space Measurements.", *IEEE sensors journal* Vol. 18 No. 18(2018): pp. 5699-5706. DOI 10.1109/JSEN.2018.2843531.

[5] Tsai, Wen-Yuan, Hsin-Chieh Chen, and Teh-Lu Liao. "High accuracy ultrasonic air temperature measurement using multi-frequency continuous wave." *Sensors and Actuators A: Physical* Vol. 132 No. 2(2006): pp. 526-532. DOI https://doi.org/10.1016/j.sna.2006.02.025.

[6] Suresh Periyannan and Krishnan Balasubramaniam, "Moduli Determination at Different Temperatures by an Ultrasonic Waveguide Method." *Experimental Mechanics* Vol. 56 No. 7(2016): pp. 1257-1270. DOI 10.1007/s11340-016-0157-y.

[7] Suresh Periyannan and Krishnan Balasubramaniam, "Multi-level temperature measurements using ultrasonic waveguides", *Measurement* Vol 61(2015): pp. 185-191.DOI https://doi.org/10.1016/j.measurement.2014.10.050.

[8] Nishanth Raja, K Lingadurai, Suresh Periyannan and Krishnan Balasubramaniam. "Ultrasonic waveguide-based distributed temperature measurement on a solid surface." *Insight Non-Destructive Testing and Condition Monitoring* Vol. 59 No. 7(2017): pp. 358-363 DOI 10.1784/insi.2017.59.7.358.

[9] Brain Pavlakovic, Mike Lowe, David Alleyne and Peter Cawley. "DISPERSE a general purpose program for creating dispersion curves." *Review of Progress in Quantitative Nondestructive Evaluation* Vol. 16(1997), pp.185–192
URL https://link.springer.com/chapter/10.1007%2F978-1-4615-5947-4_24.