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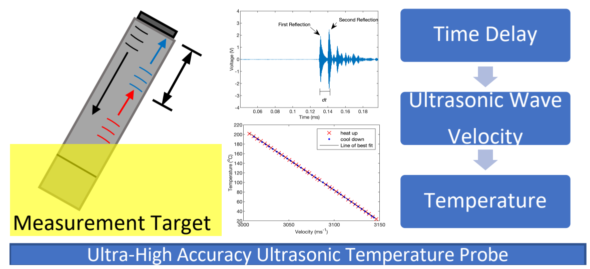
An Ultra-High Accuracy Temperature Measurement Method using Acoustic Waveguide

Ting Yui Wong, Yu Tang, Fangxin Zou, and Zhongqing Su

***Abstract*— This paper presents a very precise approach to measuring temperature in a wide temperature range using ultrasonic waves. A Lead zirconate titanate (PZT) piezoelectric transducer is used to excite ultrasonic shear waves and a solid stainless steel waveguide is selected to confine the ultrasonic wave propagation path. The shape and dimensions of the waveguide were theoretically optimized and numerically simulated to propagate robust, non-dispersive wave, and protect the fragile PZT from high temperature. Ultrasonic wave velocity is highly temperature dependent. The travelling time of wavepacket along the waveguide exhibits a corresponding relationship with the average temperature at measurement zone of the waveguide. Detailed experiment verification and validation processes, together with a calibration stage, were conducted up to 200^{o}C, a temperature that is on par with the operating range of the resistance temperature detector (RTD) used for calibration. Stability test demonstrated that our technique attains a high accuracy (i.e. ±0.1%) which is comparable with the highest precision standard of commercial RTDs along the calibrated temperature range. Temperature tracking test was operated to unfold the temperature measuring and tracking capability of the ultrasonic wave technique in different liquids. This ultrasonic technique is robust and customizable, hence providing a promising alternative for accurate and stable contact thermometry.**



***Index Terms*— Contact thermometry, Piezoelectric transducer, Resistance temperature detector, Shear wave, Temperature, Ultrasonic waveguide**

I. Introduction

TEMPERATURE is one of the most measured physical quantities in industries for process control, such as glass and metal melting plants, nuclear power plants, chemical plants, as well as in laboratories. The temperature sensor market was valued at USD 5.29 billion in 2017 and is estimated to rise to USD 7.48 billion by 2023, reaching a compound annual growth rate of 5.9% [1].

To measure the temperature distribution of a target fluid, the most conventional method is contact thermometry. The most commonly used temperature probes for contact thermometry are thermocouples and resistance temperature detectors (RTDs). Thermocouples work in wide temperature range but its accuracy is relatively low (0.5 to 5^{o}C) [2]. The accuracy problems also include high measurement drifts during long term operations [3]. Hot junction failures cause reliability issues for thermocouples in the hostile environments of process industries. RTDs are the most accurate and stable commercially available temperature probes currently but its working range is rather small. Furthermore, since the sensing elements are fragile, RTDs often require thermowells or other protection and installation methods in industrial applications, causing the fabrication process to be tedious and costly. Hence, the development of alternative contact-type temperature probes is motivated by the demand for more robust temperature measuring technologies.

It has been demonstrated by several researchers [4]–[14] that ultrasonic wave could be applied to temperature sensing. Due to the fact that ultrasonic wave velocity is temperature dependent, temperature could be determined from measurements of ultrasonic wave velocities. The concept of acoustic waveguides has been developed and reported in [5]–[9], [13], [15]–[17] due to the requirement for separating ultrasonic transducers from high temperature measurement zones that would cause conventional, efficient, low cost piezoelectric transducer to depolarize and fail. Piezoelectric transducers are used to excite and receive ultrasonic waves by converting electrical signals into mechanical strains and vice versa. Excited ultrasonic waves travel along the waveguide which acts as the temperature probe contacting the measurement target, and then

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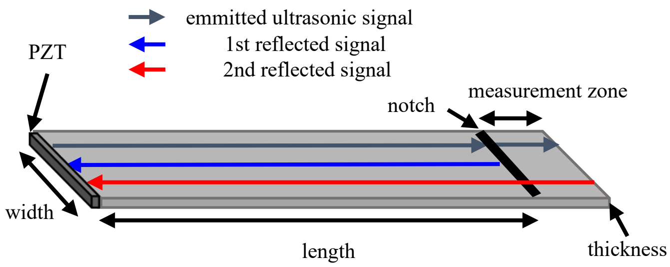


Fig. 1. Schematic diagram of the waveguide including the propagation paths of the first and the second reflection.

are received after being reflected.

The geometric structure of the waveguide is a crucial parameter affecting the signal transmission as strong and non-dispersive signals are desired. Depending on the ultrasonic wave mode and frequency, researchers have presented different structural designs for waveguides. Periyannan *et al.* [5], [8], [9] have presented a helical waveguide sending torsional mode waves as well as a bent waveguide sending longitudinal mode waves. Raja *et al.* [13] have reported the feasibility of using a thin rodlike longitudinal mode waveguide with intentionally designed geometric discontinuities for distributed temperature measurement. Balasubramaniam *et al.* [6] have proposed a buffer rod probe in which shear waves travel for simultaneous temperature and viscosity measurement. Spratt and Vetelino [7] have developed a torsional acoustic waveguide probe for temperature and liquid level measurement. Their waveguide consists of lead-in and sensing zones. The lead-in section is circular in cross section. Rounded rectangular cross section was selected for the sensing zone.

In the present work a strip waveguide is designed to send shear horizontal (SH) waves, which have been less explored in waveguide-based contact thermometry. Wang *et al.* [1] proved the principle of the concept but did not provide the detailed design process that would be required for applications in higher temperature ranges. The strip waveguide is used to isolate the piezoelectric transducer from high temperature that it cannot withstand and allow steady and uncontaminated ultrasonic wave propagation. The geometries of the waveguide and the excitation frequency determine whether the signal transmission is non-dispersive, so these physical parameters are of great concern in the theoretical investigation of the structural design of the waveguide. Numerical simulations were run to find the suitable length for the waveguide to protect the piezoelectric transducer from hostile environment. The size of the measurement zone was investigated to ensure a clear separation between the reflected wavepackets for accurate time-of-flight (ToF) measurements. A robust signal processing algorithm is used to precisely determine the ToFs of ultrasonic waves. After the dimensions of the waveguide temperature probe were optimized following the design process, it was calibrated against a 1/10 DIN RTD to obtain the relationship between temperature and ultrasonic wave velocity that allows temperature to be deduced from measurements of ultrasonic wave velocity. The calibration was carried out up to the upper limit of the temperature range of the RTD used. Experiments including stability test and temperature tracking were performed to demonstrate the capability and advantage of this robust ultrasonic wave based temperature probe. The measurement uncertainties of the waveguide were proven to be comparable with the accuracy standard of 1/10 DIN RTDs for the calibrated temperature range. Temperatures were successfully measured and tracked by the waveguide within the temperature range of the RTD. The accuracy and stability of the proposed waveguide are the highest among the waveguide-based temperature measurement techniques.

II. Structural Design of Shear Horizontal Waveguide Temperature Probe

Fig. 1 shows the waveguide and the propagation paths of the first and the second reflections. A fraction of the emitted wavepacket gets reflected by a notch bounding the measurement zone. This portion of energy is received by the ultrasonic transducer and recorded as the first reflection. The remaining energy keeps travelling until it reaches the other edge of waveguide and gets totally reflected. This returning energy encounters the notch for the second time, where fractional wavepacket travels through this notch and back to the transducer. The second arrival of wavepacket is detected and recorded as the second reflection. The time difference between the first and second arrivals of wavepacket is the ToF of the ultrasonic wave in the measurement zone of the waveguide, which will be used to deduce the temperature of the measurement zone.

The main purpose of the waveguide is to isolate the piezoelectric transducer from high temperature while transmitting ultrasonic waves with desirable characteristics over a long distance in order to obtain information implying the temperature of the measurement zone. The ultrasonic pulse-echo mode is applied, i.e. a piezoelectric transducer at one end exciting ultrasonic waves that travel along the waveguide and picking up the reflected waves as well. Thus, the structural design of the waveguide takes the following considerations: non-dispersive wave propagation and temperature isolation. The waveforms of non-dispersive waves are conserved so that measurements of ToFs can be more precise and immune to the distances travelled by the waves, i.e. the length of the waveguide. Dispersion curves were calculated to verify that the wave propagation is non-dispersive in the waveguide. Numerical simulations were performed to determine the suitable length for temperature isolation. The length of the measurement zone was determined by the constraint of maintaining a clear separation between reflected wavepackets. The following sections will discuss the determination of each dimension for the waveguide.

A. Width, thickness and excitation frequency

The ultrasonic signal should propagate with as little distortion as possible, i.e. non-dispersive. The waveform of non-dispersive wave would be less distorted so that the determination of ToFs from ultrasonic signals could reach higher accuracy. Researchers [18], [19] have found that strips of large aspect ratio (width $\gg$ thickness) rectangular cross section as shown in Fig. 1 allow a shear-horizontal-type guided wave (SH0*) mode that is very similar to the shear horizontal (SH0) mode in an infinite plate to propagate non-dispersively. Analytic solutions to wave propagation in infinite plates are presented in standard textbooks, e.g. [20], [21]. It was observed that the SH0* mode asymptotically approaches the the bulk shear velocity, at a frequency-width product that is material property dependent. The transition from dispersive to non-dispersive behavior depends on the width of the strip waveguide. Therefore, design criterion can be assigned to the selection of the width, the material and the excitation frequency of the waveguide by looking at the non-dispersive region of the SH0* mode dispersion curve.

The modelling of waveguides with different shapes using finite element (FE) method has been employed by several researchers to trace dispersion curves, e.g. [16], [22], [23]. It is obvious that tracing dispersion curves with finite element method is advantageous for determining the dimensions of the waveguide as the propagating modes and their respective dispersion characteristics can be investigated theoretically. Nevertheless, Cegla [24] proposed that the SH0* mode in a rectangular waveguide with a finite width could be traced with a simple and robust software DISPERSE [25]. The method is employed here to determine the width of the waveguide and the frequency of the ultrasonic wave. In principle, DISPERSE could only trace dispersion curves for infinite plates. Cegla's method works by assuming that the dispersion curve of the interested SH0* mode corresponds to the first higher order anti-symmetric plate (A1) mode in an infinite plate of a thickness equal to the width of the waveguide. The results have been found to be in agreement with that of finite element method. The stated condition for this method to work is that the mode shape of the SH0* mode has to be constant across the thickness of the strip and experiment results have proven the condition to be true for rectangular strips with large aspect ratio (width $\gg$ thickness).

There are additional design criteria on the width, the thickness and the excitation frequency regarding the excitation of SH0* mode in strip waveguide. Jia *et al.* [26] have investigated the critical values about the geometric dimensions of the excitation source by simulation and experiments, that pure SH0* mode can be excited into the waveguide strip by anti-plane shear line loading. For a waveguide with frequency-thickness fd product larger than the first cutoff frequency-thickness product $(fd)_1 = 1.6$ MHz·mm [19], the width w_s and the thickness d_s of the excitation source should be larger than 3λ and equal to the thickness of the waveguide strip d. These critical values should be taken into consideration when determining the width and thickness of the waveguide, and the excitation frequency. Pure excitation of SH0* mode can avoid contamination in the ultrasonic wave signal due to higher order modes that may be dispersive, hence eliminating one of the sources of ToF measurement error.

B. Length

A shear lead zirconate titanate (PZT) piezoelectric transducer will be used to excite shear waves into the waveguide.

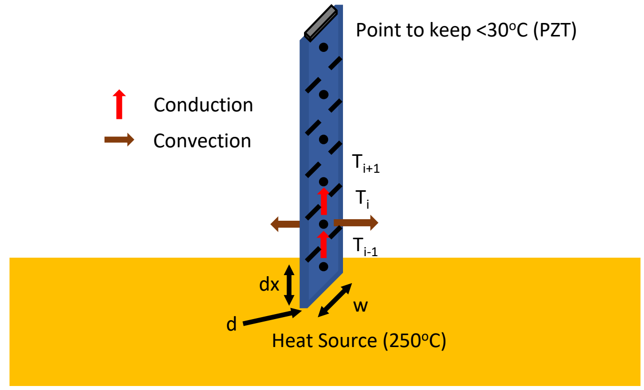


Fig. 2. 1D finite difference model of the waveguide and the heat transfer modes for each element of the waveguide.

Since the PZT cannot withstand high temperature, it is crucial to determine the suitable length of the waveguide to control the temperature distribution along it, therefore ensuring the safety of the PZT as well as keeping the waveguide at reasonable size, and avoiding unnecessary material use and form factor. Assuming that a waveguide is in contact with a constant high temperature source and surrounded by air at room temperature, a 1D finite difference model is set up to solve the heat transfer problem and plot the temperature distribution along the waveguide. The waveguide is designed in a way that length is much larger than width and width is much larger than thickness (length $\gg$ width $\gg$ thickness). Therefore, the heat convection with air on the thin vertical length-thickness surfaces as well as the heat conduction in the width and thickness direction can be assumed to be negligible. Fig. 2 illustrates the model and the heat transfer modes for each element of the waveguide. By considering symmetric heat convection on the two vertical length-width surfaces and heat conduction along the length direction, the heat transfer equation based on energy balance of each element [27] is derived as

$$T_i^{p+1} = \frac{2hdt}{\rho C_p d}(T_a - T_i^p) + \frac{\alpha dt}{dx^2}(T_{i-1}^p + T_{i+1}^p - 2T_i^p) + T_i^p, \quad (1)$$

where T_i^p represents the temperature of the i^{th} element at the p^{th} time step, h is the coefficient of convection, T_a is the ambient room temperature, ρ is the density of the material, C_p is the specific heat capacity of the material, α is the thermal diffusivity of the material and d is the thickness of the waveguide. Solving the temperature distribution along the waveguide after a long period of time allows the length that can sustain enough temperature drop to be determined. The major factors that affect the length of the waveguide are the temperature of the heat source, the environment surrounding the waveguide, and the thermal properties of the material of the waveguide. The length of the waveguide would not be limited by guided wave propagation because the waves excited are non-dispersive and, as such, their waveforms are conserved regardless of the distance travelled.

C. Determination of the Dimensions of Waveguide

The width and the excitation frequency are determined by looking at the non-dispersive part of the dispersion curve obtained by using DISPERSE to trace the A1 mode in an infinite plate with thickness equal to the width of the waveguide. 304 stainless steel ($\rho = 7800$ kg/m^3, $E = 200$ GPa, $\nu = 0.28$) was selected for the waveguide. The bulk shear velocity of 304 stainless steel was calculated as $c_T = 3164.8$ m/s. The phase velocity dispersion curves for the SH0* mode of rectangular 304 stainless steel strips of 10, 15, and 30 mm width are shown in Fig. 3. It is obvious that the frequency at where the SH0* mode transits from dispersive to non-dispersive depends on the width of the waveguide, and above the transition frequencies, the SH0* mode travels at the bulk shear velocity. Thus, the width of the waveguide and the excitation frequency should be determined together from the dispersion curves to allow non-dispersive SH0* mode wave propagation. With 304 stainless steel as the material of the waveguide, a width of 15 mm and an excitation frequency of 2 MHz were selected to guarantee non-dispersive SH0* mode wave propagation in the waveguide. It is worth mentioning that other materials, frequencies and widths can also be selected as long as non-dispersive SH0* mode is allowed to travel.

The practical condition for transmitting anti-plane shear line loading is a waveguide of large aspect ratio (width $\gg \lambda >$ thickness) [28]. By assuming that the SH0* mode travels at the bulk shear velocity of 304 stainless steel at about 3200 ms^{-1}, the bulk shear wavelength of the ultrasonic signal λ can be estimated to be about 1.6 mm. Thus, the thickness of the rectangular strip is selected to be 1 mm to fulfill the condition of large aspect ratio for the desired source characteristic consideration. In addition, a width of 15 mm, which is greater than 3λ (i.e. 4.8 mm), and a thickness of 1 mm allow pure SH0* wave to be excited into the waveguide according to the critical values suggested by Jia *et al.* [26].

The temperature distribution along a waveguide of 150 mm long and 1 mm thick attached to a constant high-temperature source (250^{o}C) and surrounded by air (convective heat transfer coefficient h = 10 Wm^{-2}K^{-1} [29]) at ambient temperature (25^{o}C) is solved using (1). Temperature distribution curves along the waveguide at different time instances are plotted in Fig. 4. The temperature distribution curve of the waveguide at 15 minutes, which is in equilibrium state, shows that a large aspect ratio (width $\gg$ thickness) stainless steel rectangular strip (thermal diffusivity $\alpha = 4.2\times10^{-6}$ m^{2}s^{-1} [30]) waveguide can sustain a temperature drop from 250^{o}C to $<$30^{o}C over a distance of 150 mm under natural convection cooling. The waveguide is extended to 200 mm to include safety factor.

D. Measurement Zone

The dimensions of the waveguide have been determined to be 200 mm long, 15 mm wide, and 1 mm thick. An additional part is added to one end of the waveguide as the measurement zone which has to be fully immersed in the measurement target. A notch that is 0.1 mm wide and 0.25 mm deep was manufactured on the waveguide to bound the measurement zone. Fig. 5 shows a typical ultrasonic signal acquired from

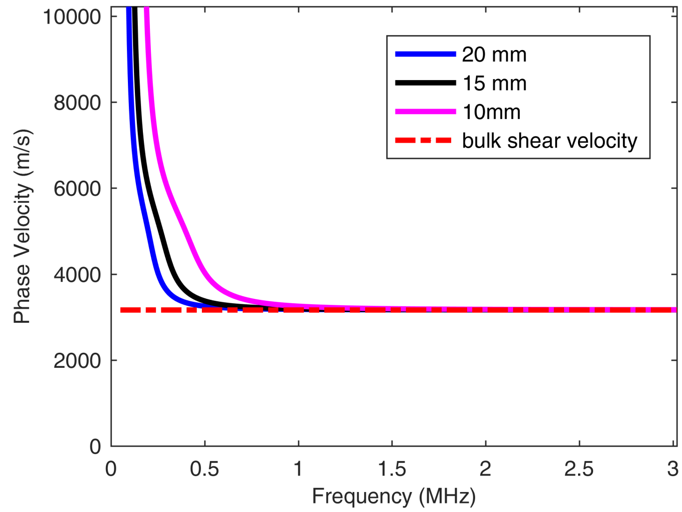


Fig. 3. Phase velocity curves for the SH0* mode in 10, 15, and 20 mm wide rectangular 304 stainless steel strips traced using the DISPERSE software. The dispersion behavior of the SH0* mode wave depends on the width of the strip and the frequency of the wave.

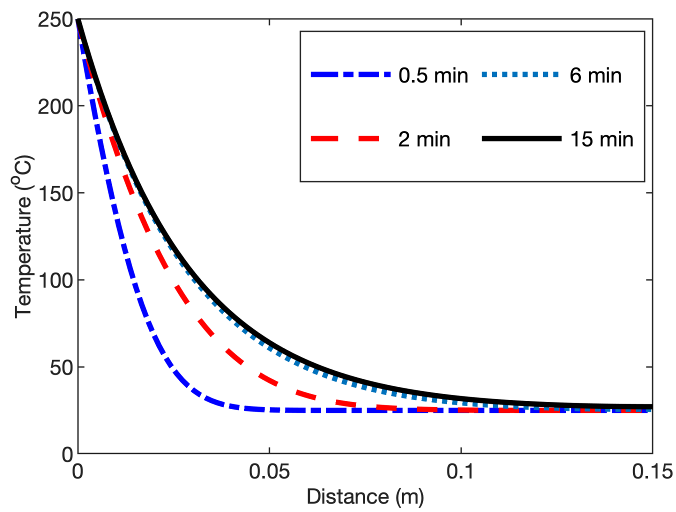


Fig. 4. Temperature distribution curves along a 150 mm long stainless steel rectangular strip at different time instances. The temperature distribution along the waveguide is approaching equilibrium with time and the curve at 15 minutes represents equilibrium state. One end of the strip is maintained at 250^{o}C and the air surrounding the waveguide is at 25^{o}C. Calculation was done according to (1).

the waveguide. The signals after the second reflection are the consequence of reverberating wavepackets in the measurement zone. The ultrasonic shear velocity v within the measurement zone is calculated by

$$v = \frac{2L}{dt}, \tag{2}$$

where L is the length of the wave path in the measurement zone and dt is the time difference between the first and the second reflection.

The length of the measurement zone is limited by the need to avoid overlap between reflected wavepackets, which would compromise the integrity of the time delay measurement. The length of a wavepacket of 5-cycle, 2-MHz Hanning-window sinusoidal toneburst travelling in 304 stainless steel is estimated to be about 8 mm. The first and second reflected

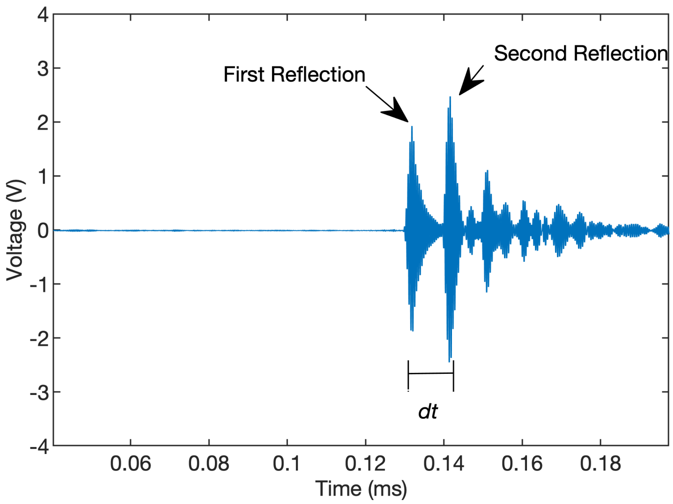


Fig. 5. A typical recorded ultrasonic signal from the waveguide.

wavepackets will need to be separated by a length of $2L$, i.e. 16 mm, so a 15 mm long measurement zone, which equates to a wave propagation distance of 30 mm, is enough for clear separation of wavepackets.

III. Experimental Tests

An SH waveguide temperature probe of 15 mm width, 1 mm thickness, and 215 mm length including a 15 mm measurement zone, was manufactured. A range of experiments were conducted to test the performance of the SH waveguide temperature probe, and hence verify that the design of waveguide is satisfactory and appropriate for the purpose. Fig. 6 shows the experimental setup. The waveguide was calibrated and compared to a commercial 1/10 DIN PT100 RTD (SE012, Pico Technology, UK), which was connected to a platinum resistance data logger (PT-104, Pico Technology, UK). Excitation and acquisition of ultrasonic signals were handled by an oscilloscope (Handyscope HS5, TiePie Engineering, Netherlands) at a sampling frequency of 50 MHz. A shear PZT of 13 mm width and 1 mm thickness with a central frequency of 2 MHz was attached and coupled to the waveguide by epoxy structural adhesive (7300 Two-component adhesive, Ergo, Switzerland). Signals received from the waveguide were amplified by 40 dB by a low noise preamplifier (LNA-EO-3, Ciprian, France). Both PT-104 and oscilloscope were connected to a PC for data storage and subsequent signal processing.

A hotplate (C-MAG HS7 control, IKA, Germany) was used to heat and stir the liquid from the bottom of the beaker. It was hence assumed that there was temperature gradient along the depth of the liquid only so the waveguide and the RTD were immersed to the same depth in the liquid contained by a beaker. The temperature recorded by the RTD represents the temperature at the tip of the probe. Since the length of the measurement zone of the waveguide is finite along the depth direction, the actual temperature across the measurement zone should slightly variate. For the experiments, the tip of the RTD was at the depth of the mid-point of the measurement zone

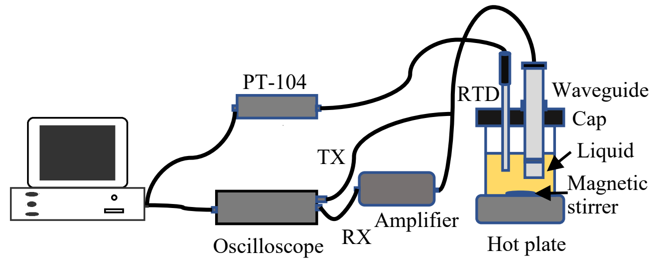


Fig. 6. Schematic diagram of the experimental setup for the experiments conducted in this work, i.e. calibration, stability test and temperature tracking.

of the waveguide because the temperature at that level should represents the average temperature of the measurement zone.

The time difference between the wavepacket arrivals is measured to calculate v so the determination of the arrival times of wavepackets have significant importance to the performance of the SH waveguide temperature probe. The signal acquisition and processing algorithm proposed by Wang *et al.* [1] was adopted in this work to improve the SNRs of ultrasonic signals and hence the precision of ToF measurements. At first, a high signal acquisition rate allowed 300 consecutive signals to be recorded and averaged for each measurement so that the random noise in the signal would be suppressed. The averaged signal was then handled by a 5^{th}-order Butterworth bandpass filter with cut-off frequencies at 1.2 and 2.8 MHz to further reduce the amount of noise in the signal. The filtered signal was next up-sampled to 800 MHz so that the temporal resolution of the arrival times of the wavepackets would be significantly increased. The up-sampled signal was then auto-correlated, and the peaks in the auto-correlation correspond to the arrival times of the wavepackets. In order to determine the exact locations of the peaks as if the auto-correlation was continuous as opposed to discrete, gradient based linear interpolation was implemented to identify the points on the auto-correlation where gradient is theoretically zero. The ToF in the measurement zone dt is the difference between the locations of the first two peaks. Equation (2) can be applied to calculate v once dt is determined.

A. Calibration

The waveguide was calibrated against the RTD to obtain the relationship between temperature and ultrasonic shear wave velocity in the measurement zone. The waveguide and the RTD were immersed in rice bran oil, which is known for its high smoke point of 254°C. Measurements were taken at a 5°C interval from room temperature (~25°C) to 200°C during a complete heating and cooling cycle. Fig. 7 shows the result of calibration. It indicates a linear relationship between temperature T and v that is stable to the direction of temperature change. Linear regression gives the equation

$$T = -1.275v + 4063.3. \quad (3)$$

A R-Squared value of 1 resulted from the linear regression model, showing its high linearity. This agrees with a previous

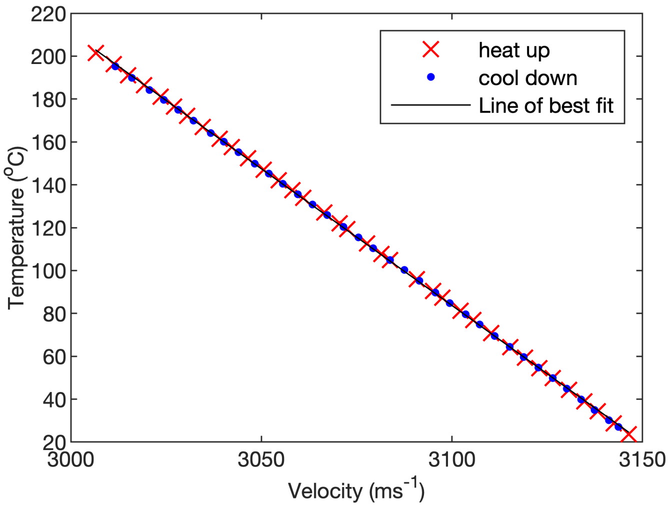


Fig. 7. Relationship between temperature and the ultrasonic shear velocity in a 15 mm wide and 1 mm thick stainless steel waveguide.

study that the linearity remains high within a temperature range up to 400°C [31].

These coefficients are for a 15 mm wide, 1 mm thick rectangular strip waveguide made of 304 stainless steel. Different materials yield different sets of coefficients. It is worth mentioning that slight variations of the coefficients are expected to present for other waveguides of same dimensions, shape and material so calibration has to be done for each individual waveguide for the highest performance in temperature measurement.

B. Stability

The temperature measurement precision of the calibrated waveguide was quantified by repeated ultrasonic and temperature measurements, which were taken by the waveguide and the RTD at some relatively stable temperatures, i.e. 50°C, 100°C, 150°C and 200°C. The result of measurements are shown in Fig. 8. Measurements were taken every minute for a period of an hour at every temperature. The expected temperature measurement uncertainties based on the 97.5% confidence level of the best fitted lines were calculated respectively and compared to the tolerance classes according to the recognized standard for industrial RTDs (IEC 60751) [32]. Table I shows the comparison between the measurement uncertainties of the waveguide and the 1/10 DIN tolerance class per IEC 60751 at each temperature. The precision of the waveguide is on par with that of the highest tolerance class for RTDs.

C. Temperature tracking

Temperature is deduced from ultrasonic signals using the equation relating temperature and ultrasonic shear velocity of the measurement zone obtained by calibration. Fig. 9 compares the measurements of temperature of rice bran oil and water every minute using a calibrated SH waveguide and a RTD immersed in the liquid. Calibrations were done prior to the measurements to obtain the coefficients for deducing the temperature of the waveguide. The ranges of measurement were

TABLE I

COMPARISON BETWEEN THE MEASUREMENT UNCERTAINTIES OF THE WAVEGUIDE AND THE 1/10 DIN RTD

	Measurement Uncertainties			
	Waveguide		1/10 DIN RTD	
Temperature (°C)	in °C	in %	in °C	in %
50	±0.050	±0.100	±0.055	±0.110
100	±0.104	±0.104	±0.080	±0.080
150	±0.131	±0.081	±0.105	±0.070
200	±0.142	±0.071	±0.130	±0.065

25-200°C for rice bran oil, which is the temperature range that most 1/10 DIN RTDs work in, and 25-75°C for water. During each experiment, the temperature of the liquid was manually increased at several occasions and then the liquid was allowed to cool naturally. It is observed that the SH waveguide and the RTD measurements were in good agreement. The absolute mean errors between the waveguide and RTD measurements are 0.4318°C and 0.1227°C respectively for rice bran oil and water. This shows a significant improvement in terms of accuracy and stability over other existing waveguide-based temperature probes, whose maximum and mean temperature measurement discrepancies against thermocouples were, respectively, about 4-6°C and 1.5°C with a standard deviation of 0.5°C [5], [8], [13].

Most error could be attributed to the difference in responsiveness to temperature change rather than the intrinsic temperature measurement accuracy as both maximum error values, which are -1.373°C and -0.5686°C respectively, occurred during rapid temperature change. Wang *et al.* [1] experimentally showed that the responsiveness of a waveguide immersed in water is higher than that of a waveguide immersed in oil so the lower absolute mean and maximum error values for the water temperature measurements are expected.

IV. CONCLUSION

This paper has theoretically investigated the structural design of a shear horizontal waveguide temperature probe and experimentally demonstrated the ability of measuring temperature using the designed waveguide. The main purpose of the waveguide is to isolate the PZT from high temperature environment and transmit strong, uncontaminated ultrasonic wave signals that are non-dispersive. In order to apply a strip waveguide as a temperature probe, the physical parameters of the waveguide including its geometric dimensions, the frequency of the propagating guided wave, and the size of the measurement zone should be carefully selected. The dispersion curves of the SH0* mode were calculated using DISPERSE so that the width of the waveguide and the excitation frequency could be selected for propagation of non-dispersive wave. Numerical simulation was performed to determine the suitable length of the waveguide that can maintain the PZT at low temperature. A notch was manufactured on the waveguide to partially reflect the signals for ToF measurement. The dimensions of waveguide are customizable following the above-mentioned analysis. In addition to the physical design of the waveguide that enables stable signals for precise ToF mea-

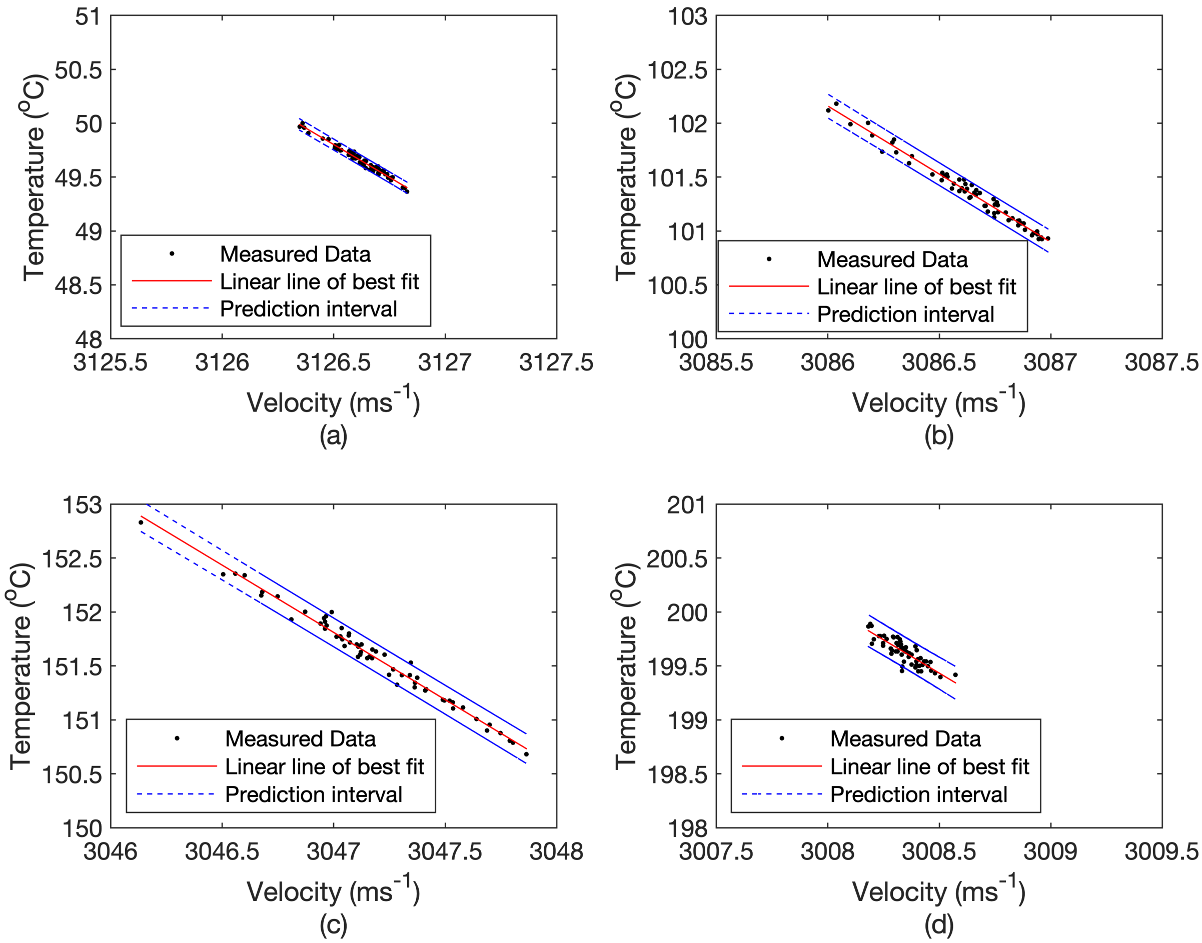


Fig. 8. Temperature measurements and the ultrasonic shear velocities in a 15 mm wide and 1 mm thick waveguide that were recorded at stable temperatures: (a) 50°C, (b) 100°C, (c) 150°C, (d) 200°C. Lines of linear fit and 97.5% prediction intervals are also shown. Same scale is applied to show the variation in measurement uncertainties at different temperatures. The difference in the range of temperature fluctuation is due to the instability of the temperature control of the hot plate. The distribution of measurement points does not affect the calculated uncertainty because the uncertainty is calculated based on the deviation from the line of best fit.

surements, some signal processing techniques, including signal averaging, signal up-sampling, bandpass filter, autocorrelation, and gradient based linear interpolation were applied to improve the SNRs of ultrasonic signals and significantly enhance the precision in determining the arrival times of wavepackets.

Calibration of the waveguide was performed against a 1/10 DIN RTD to obtain the relationship between temperature and ultrasonic shear velocity in the measurement zone from room temperature up to 200°C. The linear regression model demonstrated a high linearity between temperature and ultrasonic wave velocity with a set of specific coefficients which manifest disparate values for different materials. Measurement stability tests were performed from 50°C to 200°C, which is the typical temperature range of 1/10 DIN RTDs. The proposed ultrasonic measurement technique exhibits a high precision of ±0.1%, comparable to that of a 1/10 DIN RTD. Comparisons between real-time simultaneous temperature measurements obtained by calibrated SH waveguide and RTD highlight the ability of the SH waveguide to measure and track temperature across the calibrated temperature range. The relatively small absolute mean errors, 0.4318°C for rice bran oil and 0.1227°C for water, between the waveguide and RTD measurements tenably showcase the good temperature tracking of SH waveguide in both oil and water.

This work presents an attractive alternative for contact thermometry as this ultrasonic temperature measurement technique possesses a number of potential advantages over current resistance-based methods. An inherent superiority of the ultrasonic waveguide temperature probe is its robustness as there is no fragile sensing element or junction that could easily fail. The waveguide temperature probe is easy to fabricate because the geometry of the waveguide is simple. The cost of fabrication is relatively low as affordable materials such as 304 stainless steel can be used. In addition, RTDs are known for its high accuracy but they are limited by operating temperature range. In principle, this waveguide-based temperature measurement technique would work as long as the material used for the waveguide can withstand the temperature range

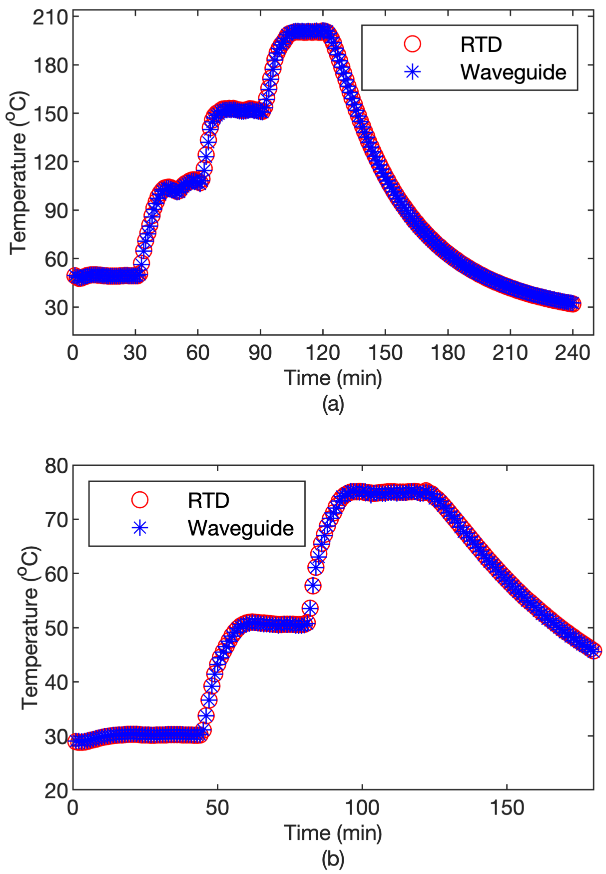


Fig. 9. Comparisons between simultaneous temperature measurements obtained by a RTD and a calibrated waveguide. Measurements plotted in (a) and (b) are for oil and water respectively.

concerned and allow ultrasonic wave propagation. Thus, extended work can be done to study if the accuracy and stability of this SH waveguide temperature probe can maintain at higher temperature where application of RTD is limited. Another possible advantage is that while both RTDs and thermocouples are point measurements, multiple-level temperature measurements with single probe could be achieved using this SH waveguide if more than one measurement zone is manufactured on the waveguide. The SH waveguide temperature probe is robust and easy to customized for the requirements of temperature measurement applications.

References

[1] Y. Wang, F. Zou, and F. B. Cegla, "Acoustic waveguides: An attractive alternative for accurate and robust contact thermometry," *Sensors and Actuators, A: Physical*, vol. 270, pp. 84–88, 2018.

[2] G. K. McMillan, *Advanced Temperature Measurement and Control*. International Society of Automation, 2 ed., 2010.

[3] R. E. Bentley, "Long-term drift in mineral-insulated Nicrosil-sheathed type K thermocouples," *Sensors and Actuators: A. Physical*, vol. 24, no. 1, pp. 21–26, 1990.

[4] W. Y. Tsai, H. C. Chen, and T. L. Liao, "High accuracy ultrasonic air temperature measurement using multi-frequency continuous wave," *Sensors and Actuators, A: Physical*, vol. 132, no. 2, pp. 526–532, 2006.

[5] S. Periyannan, P. Rajagopal, and K. Balasubramaniam, "Torsional mode ultrasonic helical waveguide sensor for re-configurable temperature measurement," *AIP Advances*, vol. 6, no. 6, 2016.

[6] K. Balasubramaniam, V. V. Shah, R. D. Costley, G. Boudreaux, and J. P. Singh, "High temperature ultrasonic sensor for the simultaneous measurement of viscosity and temperature of melts," *Review of Scientific Instruments*, vol. 70, no. 12, pp. 4618–4623, 1999.

[7] W. K. Spratt and J. F. Vetelino, "Torsional acoustic waveguide sensor for temperature and liquid level," *2009 IEEE International Frequency Control Symposium Joint with the 22nd European Frequency and Time Forum*, pp. 850–854, 2009.

[8] S. Periyannan and K. Balasubramaniam, "Multi-level temperature measurements using ultrasonic waveguides," *Measurement: Journal of the International Measurement Confederation*, vol. 61, pp. 185–191, 2015.

[9] S. Periyannan, P. Rajagopal, and K. Balasubramaniam, "Ultrasonic bent waveguides approach for distributed temperature measurement," *Ultrasonics*, vol. 74, pp. 211–220, 2017.

[10] G. Sutton, M. De Podesta, R. I. Veltcheva, P. Gélat, H. D. Minh, and G. Edwards, "Practical acoustic thermometry with acoustic waveguides," in *AIP Conference Proceedings*, vol. 1552, pp. 943–948, 2013.

[11] A. N. Kalashnikov, A. Afaneh, S. Alzebda, and V. Ivchenko, "Ultrasonic measurements of temperature in aqueous solutions: Why and how," *Physics Research International*, vol. 2011, 2011.

[12] L. C. Lynnworth, *Ultrasonic measurements for process control: theory, techniques, applications*. Academic Press, 1989.

[13] N. Raja, K. Balasubramaniam, and S. Periyannan, "Ultrasonic waveguide-based multi-level temperature sensor for confined space measurements," *IEEE Sensors Journal*, vol. 18, no. 14, pp. 5699–5706, 2018.

[14] D. Hu, H. Xuan, Z. Yu, D. Y. Wang, B. Liu, J. He, and A. Wang, "Acoustic fiber bragg grating and its application in high temperature sensing," *IEEE Sensors Journal*, vol. 18, no. 23, pp. 9576–9583, 2018.

[15] L. C. Lynnworth, Y. Liu, and J. A. Umina, "Extensional bundle waveguide techniques for measuring flow of hot fluids," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 52, no. 4, pp. 538–543, 2005.

[16] M. Laws, S. N. Ramadas, L. C. Lynnworth, and S. Dixon, "Parallel strip waveguide for ultrasonic flow measurement in harsh environments," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 62, no. 4, pp. 697–708, 2015.

[17] K. Balasubramaniam, N. Raja, and S. Periyannan, "Ultrasonic Waveguide Sensors for Measurements in Process Industries," in *Proceedings of IEEE Sensors*, vol. 2018-Octob, pp. 2018–2021, IEEE, 2018.

[18] F. B. Cegla, "Energy concentration at the center of large aspect ratio rectangular waveguides at high frequencies," *The Journal of the Acoustical Society of America*, vol. 123, pp. 4218–4226, jun 2008.

[19] J. Jia, Q. Wang, Z. Liao, Y. Tu, and S. T. Tu, "Design of waveguide bars for transmitting a pure shear horizontal wave to monitor high temperature components," *Materials*, vol. 10, sep 2017.

[20] D. Cheeke and R. D. Finch, *Fundamentals and Applications of Ultrasonic Waves*. CRC Press LLC, jan 2002.

[21] J. L. Rose and P. B. Nagy, *Ultrasonic Waves in Solid Media*. Cambridge England : Cambridge University Press, 1999.

[22] L. Gavric, "Computation of Progative Waves in Free Rail Using a Finite Element Technique," *Journal of Sound and Vibration*, vol. 185, no. 3, pp. 531–543, 1995.

[23] P. Wilcox, "Dispersion and excitability of guided acoustic waves in isotropic beams with arbitrary cross section," in *AIP Conference Proceedings*, pp. 203–210, AIP Publishing, feb 2003.

[24] F. B. Cegla, *Ultrasonic waveguide sensors for fluid characterisation and remote sensing*. PhD thesis, Imperial College London, 2006.

[25] B. Pavlakovic and M. J. S. Lowe, "Disperse user's manual," 2003.

[26] J. Jia, Z. Liao, X. Cai, Y. Tu, and S. T. Tu, "Critical excitation of the fundamental quasi-shear mode wave in waveguide bars for elevated temperature applications," *Sensors*, vol. 19, feb 2019.

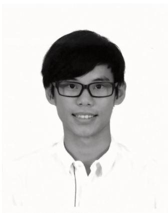
[27] T. L. Bergman, A. S. Lavine, F. P. Incropera, and D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*. John Wiley & Sons, Inc., 7 ed., 2011.

[28] F. B. Cegla, P. Cawley, J. Allin, and J. Davies, "High-temperature (>500°C) wall thickness monitoring using dry-coupled ultrasonic waveguide transducers," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 58, pp. 156–167, jan 2011.

[29] J. H. Whitelaw, "Convective heat transfer," 2011.

[30] M. T. Mustafa, A. F. Arif, and K. Masood, "Approximate analytic solutions of transient nonlinear heat conduction with temperature-dependent thermal diffusivity," *Abstract and Applied Analysis*, vol. 2014, 2014.

[31] A. Gajdacsi, *High accuracy ultrasonic degradation monitoring*. PhD thesis, Imperial College London, 2015.
[32] International Electrotechnical Commission, "IEC 60751," *Industrial platinum resistance thermometers and platinum temperature sensors*, 2008.



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