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Practical Acoustic Thermometry with Acoustic Waveguides

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Abstract Acoustic thermometry is capable of phenomenal accuracy, but is a difficult technique to apply in many practical situations. Here, we describe a modification of the technique, which permits robust temperature measurements to be made, potentially with millikelvin resolution, over a temperature range extending from cryogenic temperatures to over 1000 °C. The technique uses measurements of the time of flight of acoustic pulses in tubes, usually filled with an inert gas such as argon. The tubes—typically made of stainless steel with an outer diameter of 6 mm—act as acoustic waveguides and can be several meters long and bent into complex shapes. The time of flight is determined by the average temperature along the entire length of the tube. Local temperature information can be inferred in several ways. Typically a second shorter tube is used and the difference in time of flight reflects the temperature in the region at the end of the first tube. If the measurement length is sufficiently long—typically 1 m of tube—then a measurement resolution of less than 1 mK is achievable. The technique is well suited to measurements in harsh environments in which conventional sensors degrade. Results from early tests are shown, which highlight the strengths and weaknesses of the technique.

Keywords Acoustics · Harsh environments · High accuracy · Speed of sound · Temperature · Thermometry

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1 Introduction

The accurate measurement of moderately high temperatures (~1000 °C) in harsh environments is a continuing challenge. Many industries, including aerospace, nuclear, automotive, military, and materials processing require reliable measurements over an extended period of time. In such environments, the temperature sensor may be exposed to thermal shock, physical shock, electromagnetic fields, ionizing radiation, high pressures, and physical or chemical contamination. Ideally, a sensor is needed that does not drift with time or thermal cycling and does not degrade or fail during service. In this article, a technique we will call *practical acoustic thermometry* (PAT) is described, which is capable of long-term driftless operation in harsh environments.

The PAT technique measures the speed of sound in tubes usually filled with an inert gas, such as argon, by measuring the time of flight of short acoustic pulses over a known distance. The speed of sound, c, in an ideal gas is given by [1]

$$c = \sqrt{\frac{\gamma RT}{M}} \tag{1}$$

where γ is the ratio of the specific heats C_P/C_V, R is the molar gas constant ($\mathrm{J \cdot mol^{-1} \cdot K^{-1}}$), T is the absolute temperature (K), and M is the molar mass of the gas ($\mathrm{kg \cdot mol^{-1}}$). If the acoustic pulse travels a distance l in a time τ, the temperature is given by

$$T = \frac{Ml^2}{\gamma R\tau^2} \tag{2}$$

It is worth noting briefly that the temperature measured by PAT is strictly correct only when the tube temperature is uniform. If the temperature varies along the tube then the time delay determines an estimate of the average temperature, but with a weighting biased by the $1/\tau^2$ term in Eq. 2.

The idea of acoustic thermometry in a waveguide is not new [2]. Apfel [3] used a resonant acoustic cavity and Zeigler and Spieker [4,5] used a design similar to one of the designs we described here (Fig. 3b). They worked extensively on a feedback scheme for digitally altering the shape of the initial pulse to overcome the alterations of pulse shape caused by dispersion [6] in their 3 mm diameter waveguide. In principle, either a resonance technique or a pulse time-of-flight technique could be used to extract temperature information from an acoustic waveguide. For example, the shape change in the pulses observed by Zeigler and Spiker is related to the finite widths of the acoustic resonances used by Apfel. However, there are also subtle differences between the techniques. For example, the large pressure fluctuations associated with the standing waves at a resonance peak couple strongly to parasitic mechanical resonances. Thus, it is possible that if a resonant frequency happens to coincide with a parasitic resonance, the frequency could be strongly perturbed in a particular range of temperatures. In contrast, the time-of-flight technique is less affected by coupling to parasitic mechanical resonances because the pressure oscillations are much lower amplitude and the measurement is over before mechanical resonances can build up.

Additionally, a resonance technique requires construction of a "resonant sensor" and an additional waveguide to couple the sensor to the instrumentation. In the time-of-flight technique, it is possible to avoid the need for a separate sensor. These facts, coupled with the conceptual simplicity of the time-of-flight technique allows for a simple interpretation of results.

In this article, we report on a series of investigations carried out to determine the feasibility of PAT including the effect of bending the tubes; optimization of the tube configuration to localize the measurement region; and the performance of the thermometer at temperatures up to 1000 °C.

2 Sensitivity

Measuring temperatures accurately using PAT involves determining the time of flight of short acoustic pulses with sufficient resolution. Examination of Eq. 2 shows that for a given timing resolution, $\Delta\tau$, the sensitivity of the thermometer is given by

$$\frac{\Delta T}{T} = \frac{2\Delta\tau}{\tau} \tag{3}$$

For a data acquisition system operating at 1 MHz, $\Delta\tau = 1\,\mu\text{s}$ which yields $\Delta T \approx 1.7\,^\circ\text{C}$ at 1000 °C for a flight path of 0.5 m in argon gas, falling to less than 0.024 °C at −200 °C. However, in practice, pulse timing measurements are achieved by fitting a polynomial to the data points to find the position of peaks in the signals. This interpolation improves the timing and temperature resolution of the measurements considerably, typically by a factor of 10.

3 Bending Test

Preliminary measurements were made in ambient air to determine the effect of bending the acoustic waveguide (15 mm diameter copper tube, 2 m long). A short acoustic pulse (duration: 2 ms) was launched into the copper tube using a piezoelectric transducer (placed against one end of the tube) excited by a square-wave signal from a function generator. A small microphone, connected to a digital oscilloscope, was placed at the other end of the tube to measure the arrival of the pulse. The tube was then bent through successively larger angles and the measurements repeated. In total, the bends add up to an angle of 720 ° (see Fig. 1).

Figure 2 shows the arrival time of the acoustic pulse versus bending angle. In (a), the full dataset is given, and in (b), a magnification of the region where the signal is first detected is shown. A delay in arrival time of 49.5 μs (0.81 % of transit time) between the unbent and the fully bent tube is evident. Before bending, the tube had a length of 200.0 cm. In its fully bent configuration, averaging the outer and the inner length of the tube yielded a new length of 201.6 cm (an increase of 0.80 % in length). The lengthening of the tube on bending fully explains the increased delay in the arrival

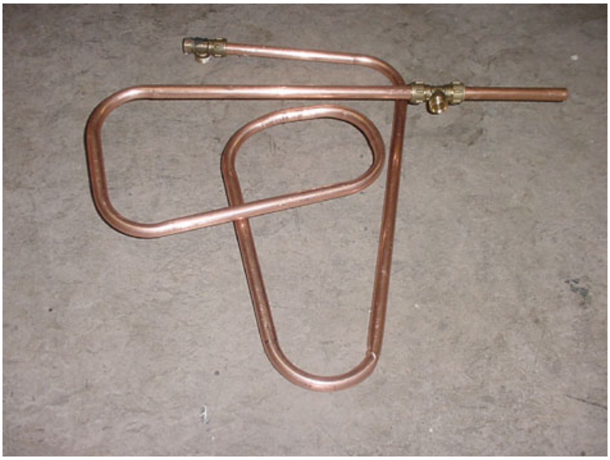


Fig. 1 Tube bending experiment. Eight bends totalling 720°

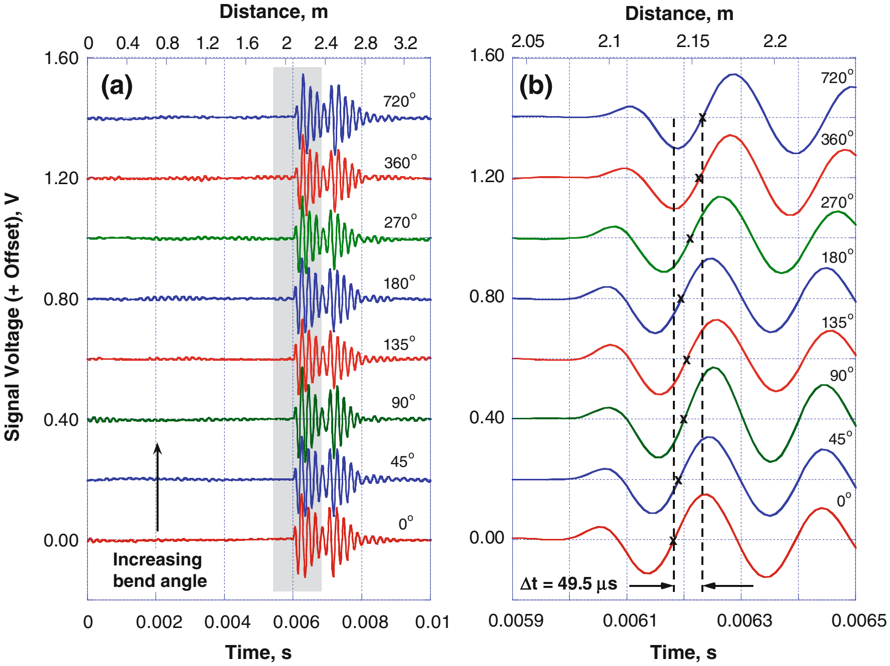


Fig. 2 Tube bending test: arrival time of the acoustic pulse versus bending angle: (a) full dataset and (b) magnification of signal arrival time showing delay in arrival time of 49.5 μs (0.81 % of transit time) between unbent and fully bent tube. Copper tube, 200.0 cm length, 1.5 cm diameter. For clarity, each transient is offset by 0.05 V from the preceding transient

time of the acoustic pulses. Additionally, we notice the amplitude and pulse shape are almost unaffected by the bending.

We conclude that smooth bends in the acoustic waveguide have negligible effect on the amplitude and speed of the transmitted pulse.

4 Localizing the Measurement Region

PAT intrinsically measures the average temperature of the entire waveguide. In order to make a useful PAT thermometer, a method must be employed to localize the temperature measurement region. This can be achieved in a number of ways, but typically involves two acoustic signal paths, one of which involves an additional path length in the measurement region. If one path is longer than the other by $2L_2$, the time delay in arrival of the two pulses at the microphone(s) is given by

$$\Delta\tau = \frac{2L_2}{c_2} \tag{4}$$

where c_2 is the average speed of sound in the measurement region and the temperature is given by

$$T_2 = \frac{4ML_2^2}{\gamma R \Delta\tau^2} \tag{5}$$

Four possible tube configurations were examined (Fig. 3). In Fig. 3a, an acoustic pulse launched into the first tube, enters the measurement region, and is divided at a "T" branch such that a proportion of the pulse passes through a longer path than the other, both eventually returning to be measured by a single microphone. Since a single microphone is used to measure both return pulses, as the temperature increases in the measurement region, the two pulses can become superimposed. This leads to errors in determining the time delay between the pulses as the leading edge of the second pulse is systematically distorted by the "tail" of the first pulse.

In Fig. 3b, an acoustic pulse launched into a single tube, enters the measurement region and is partially reflected by a reduction in the tube diameter. The remainder of the pulse is reflected at the closed end of the tube. Both return pulses are measured by a single microphone. Again, as the temperature increases in the measurement region, the two pulses can become superimposed leading to uncertainty in the time delay between them.

In Fig. 3c, an acoustic pulse is launched into two independent tubes. Both the tubes enter the measurement region, but one has a longer path than the other. Independent microphones measure the *transmitted* return pulses. The benefits of this configuration are that the two pulses are measured independently preventing superposition of the two signals, and additionally the tubes may be purged with pure gas.

In Fig. 3d, an acoustic pulse is launched into two independent tubes. Both the tubes enter the measurement region, but one has a longer path than the other. The benefit of this configuration is that, as with the configuration shown in Fig. 3c, the two pulses are measured independently preventing superposition of the two signals.

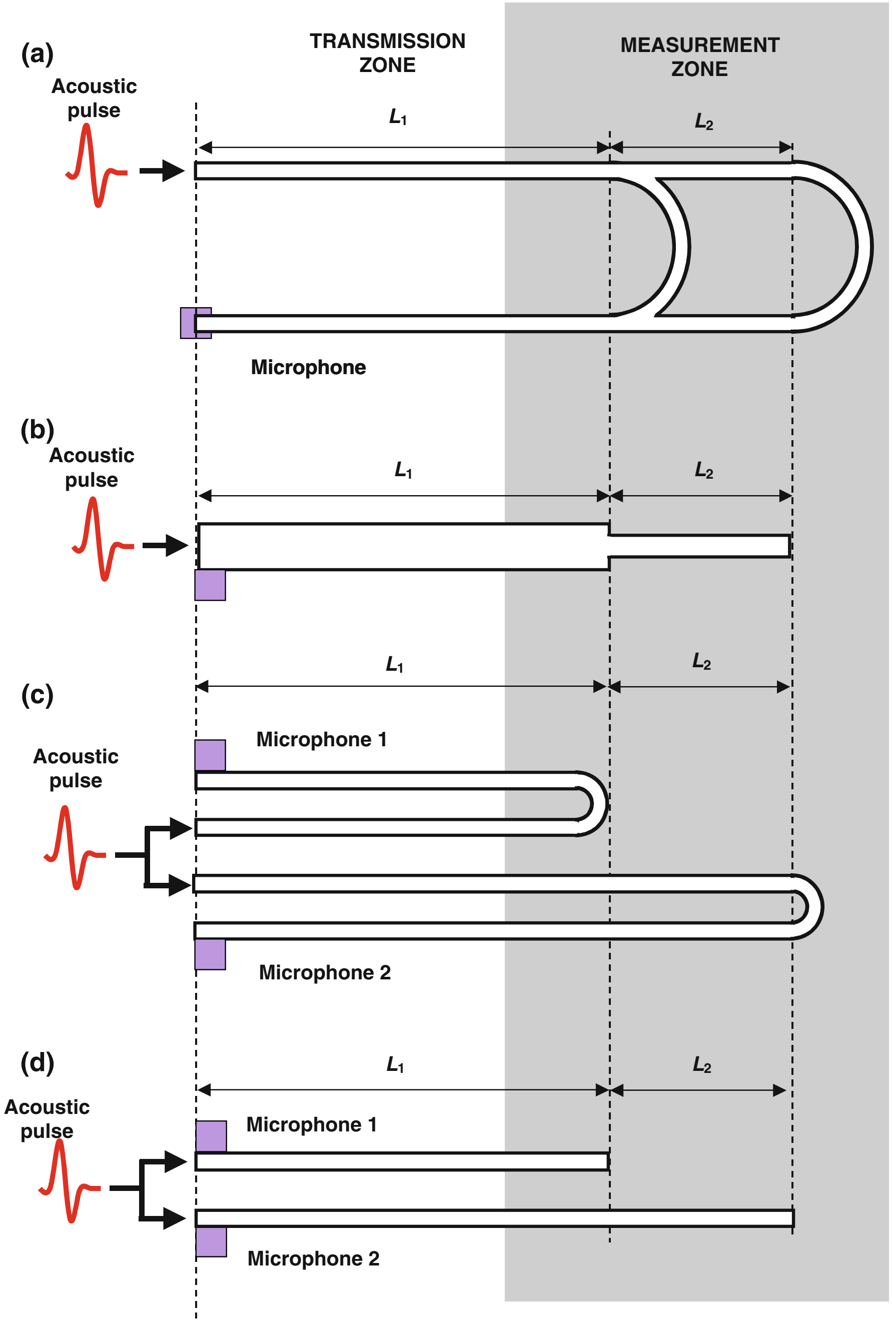


Fig. 3 Four PAT configurations to localize the measurement region: (a) single diameter, two joined tubes-transmission measurement; (b) two diameters, single tube-reflection measurement; (c) single diameter, two separate tubes-transmission measurement; and (d) single diameter, two separate tubes-reflection measurement. In all the configurations shown, the additional path length traveled in the measurement zone is $2L_2$

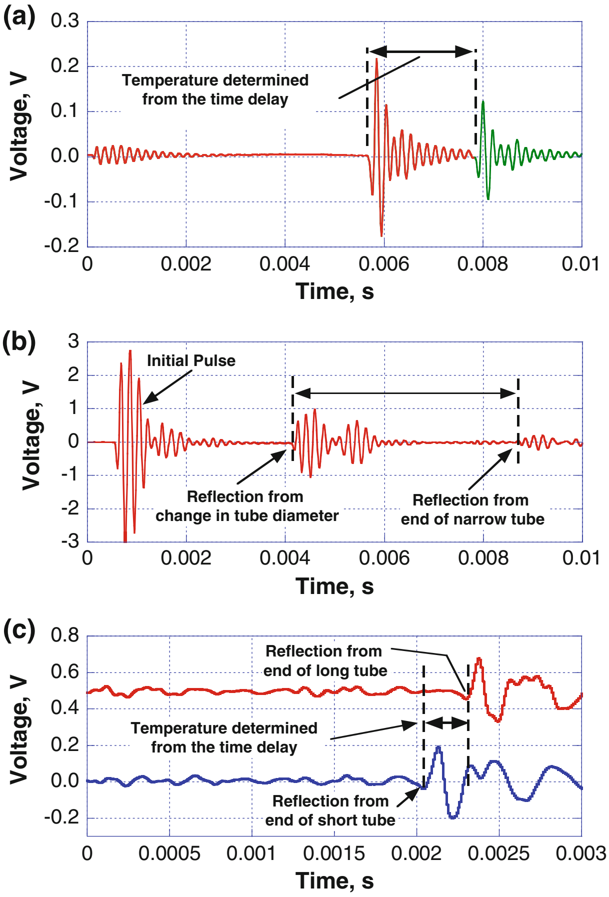


Fig. 4 Measured signals for the four PAT configurations: (a) single diameter, two joined tubes-transmission measurement; (b) two diameters, single tube-reflection measurement; and (c) single diameter, two separate tubes-transmission or reflection measurement

Figure 4 shows examples of the signals measured for the tube configurations given in Fig. 3. Figure 4a shows the signals for the tube configuration described in Fig. 3a with 6 mm diameter stainless steel pipe filled with air at ambient temperature. The time delay between the two pulses determines the temperature, and it is evident that the tail of the first pulse is superimposed on the start of the second pulse. Figure 4b shows signals for the tube configuration described in Fig. 3b with a 15 mm diameter copper tube connected to a 6 mm diameter stainless steel pipe. The combined tube is filled with air at ambient temperature. Again, the time delay between the two pulses determines the temperature. For this example, the two return pulses are relatively separate, but the amplitude of the second pulse is significantly reduced. Figure 4c shows signals for the tube configuration described in Fig. 3c and d with 6 mm diameter stainless steel pipe filled with argon at elevated temperatures. The time delay is greatly reduced at the higher temperature, as are the signal levels.

5 Determination of the Time Delay

In order to determine the temperature, the time delay between the arrivals of the two acoustic pulses must be measured accurately. In addition to the requirement of adequate timing resolution discussed earlier, we need to be confident that we are comparing the corresponding components of each waveform. Due to the variation of temperature along the tubes, junctions and bends in the tubes, the acoustic pulses are seen to disperse. This means that the two return pulses can become dissimilar in shape, making it difficult to accurately determine the delay in pulse arrival times. Three methods to determine the time delay were examined: cross-correlation, threshold-crossing, and first peak location.

The cross-correlation of the two signals is a measure of their similarity. The correlation is calculated by summing the product of the first signal with a time-shifted version of the second. The value of the time shift which maximizes the sum gives an estimate of the delay between the two signals. This technique gives reproducible results for well-shaped Gaussian pulses, but pulses with many "echoes" yield multiple peaks in the cross-correlation function. Changes in shape of the pulses due to dispersion of the pulses leads to inaccurate results and spurious "jumps" in the apparent timing. The threshold-crossing technique compares the points where the front of each pulse first crosses a preset threshold. It has the advantage that the first part of each pulse will have minimum dispersion and thus, better represent the free field speed of sound. However, the inherent noise in the return signals leads to fluctuations in the time delay and poor results. The first peak technique finds the time delay between the first peak in both pulses. The peak-picking algorithm fits a polynomial to a number of points around the peak, reducing the variability of the measured time delay and improving its resolution significantly. Dispersion can cause systematic errors in the time delay, but the benefits of stability and improved signal-to-noise ratio obtained by fitting to the peaks outweighs this. This is the technique used for all subsequent measurements in this article.

6 PAT Temperature Measurements

6.1 Resolution

The practical resolution of a PAT system was investigated by constructing a PAT thermometer according to Fig. 3d with $L_2 = 0.5\,\mathrm{m}$. The 15 mm diameter copper waveguide was coiled inside a stirred liquid bath controlled at approximately 20 °C. A signal generator connected to an amplifier and a high-frequency acoustic transducer were used to launch a short acoustic pulse into the waveguides. Two commercial miniature condenser microphones (RS 242-8911) connected to a National Instruments high-speed two-channel digitizer (Model NI-5122, 14 Bit) measured the return pulses. The digitizer, configured to measure at a sample rate of 1 MHz, was triggered by the signal generator. LabView™ software was written to control the digitizer and determine the average PAT temperature of a number of pulses. The data in Fig. 5a were acquired at two pulses per second, and each point represents the average of 10 pulses. The mean temperature was 19.381 °C with a standard deviation of 0.012 °C. Figure 5b shows

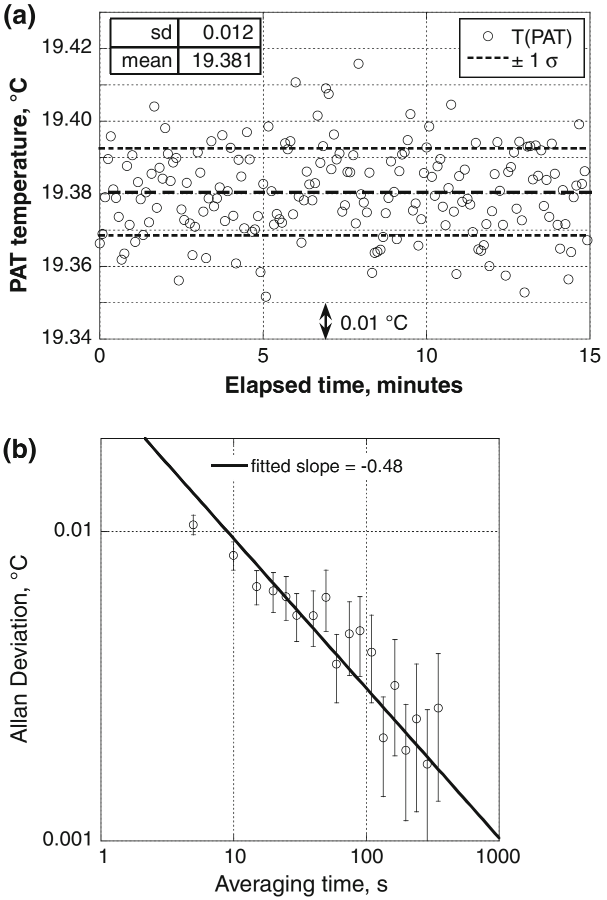


Fig. 5 (a) PAT temperature of a stirred liquid bath at $T = 19.38\,°\mathrm{C}$. Each point is the average of 50 waveform measurements, which gives a resolution of $\sim$10 mK. (b) Allan deviation of the data in (a). The inverse-square-root behavior indicates that the data can be meaningfully averaged to reduce the type A uncertainty of measurement

that the Allan deviation of the data falls as $1/\sqrt{t}$ indicating that further averaging could reduce this to the 0.001 °C level if desired.

6.2 High-Temperature Operation

A PAT thermometry system was constructed to evaluate the performance of PAT over the temperature range from 20 °C to 1000 °C. The system followed the basic design shown in Fig. 3c, and was made of two stainless steel tubes with an outer diameter of 6 mm. To prevent degradation of the internal surface of the tubes at high temperatures, a flow of argon gas (100 sccm) was maintained through the tubes with the gas exiting through an adjustable "pinhole" at the end of the tube. The pressure in the tube was not measured, but was probably about 10 kPa above atmospheric pressure. The flow

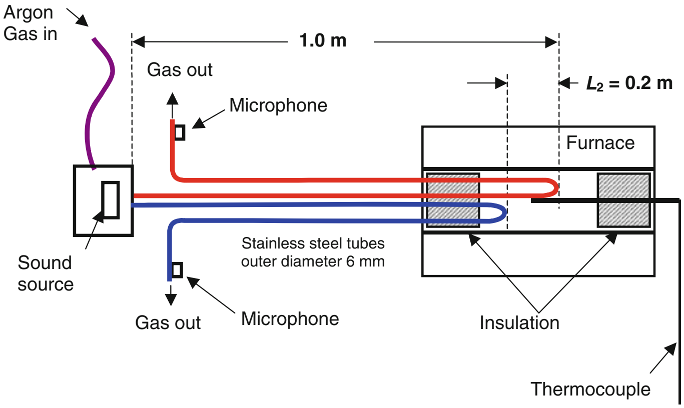


Fig. 6 PAT experimental setup for measurements up to $T = 1000\,^{\circ}\mathrm{C}$

speed through the tube was approximately $4\,\mathrm{m \cdot s^{-1}}$ which will cause an error in the apparent speed of sound. However, as used in this experiment, this error will appear in the apparent length of the sensor region, and additionally, as an error in the temperature dependence of the transit time.

Figure 6 shows the experimental setup. The two tubes of different length were inserted into a horizontal tube furnace such that the PAT system would measure the temperature in the central 20 cm region. A type K mineral-insulated thermocouple was placed such that its tip was positioned in the center of the furnace and was used as a basis for comparison. The ends of the furnace were filled with mineral wool insulation to reduce temperature gradients within the furnace. After an initial measurement around 20 °C, the furnace temperature was increased in the range from 250 °C to 1000 °C in steps of 25 °C. The data were taken while the furnace temperature was drifting at less than 1 °C per minute.

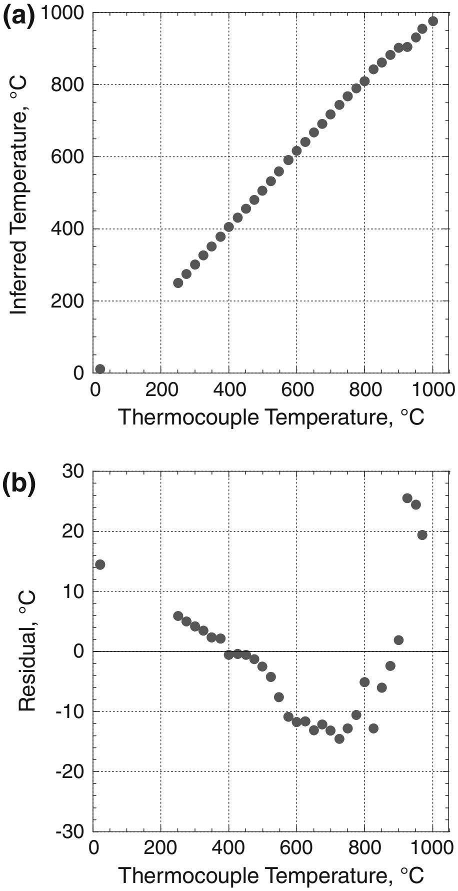
Figure 7a shows a comparison of the PAT temperature with that measured by the type K thermocouple. The time delays from which the temperature data are extracted vary from 1.53 ms at 20 °C to 0.68 ms at 1000 °C. The analysis has two adjustable parameters: the additional length of tube in the furnace; and a compensation for different lengths of tube used to connect the sound source to the furnace. In order not to overfit these preliminary data, we chose not to account for the 1.5 % thermal expansion of the tube or to model the effects of gas flow. Corrections for these effects can easily exceed 10 °C which is typical of the high temperature residuals (Fig. 7b). Our aim here was simply to demonstrate that acoustic thermometry in waveguides can operate at these temperatures.

7 Summary, Difficulties, and Results

7.1 Summary

PAT offers the possibility of a robust, accurate, and a driftless thermometer. Several configurations are possible, the choice depending on space, geometrical, and gas flow

Fig. 7 (a) Inferred PAT temperature versus thermocouple temperature and (b) residuals of a linear fit to the data in (a)



requirements. Measurements at room temperature have confirmed that the thermometer is capable of excellent resolution, and measurements up to 1000 °C have demonstrated that high-temperature operation is possible. The technique measures the average temperature over a length of tube, and the main focus of our initial experiments has been to use short sensor lengths, typically 50 cm long, bent into a loop, to aid localization of the temperature measurement. However, there may be applications where the averaging over much longer distances would be useful. We have not yet found the maximum practical length but have demonstrated the technique in 25 m of 20 mm diameter plastic tubing.

PAT involves a speed-of-sound determination in a noble gas and so could, in principle, be developed as a primary method of thermometry. However, to do this we would need to develop a parallel technique for determining the length of the measurement section, perhaps using high-frequency microwave pulses. However, we believe the technique offers greater utility as a conventional secondary thermometer suitable for use in harsh environments. Although the thermometer needs calibrating, the simple physics underlying the operation makes it possible to produce excellent interpolation functions.

The hardware and software requirements are modest and PAT systems need not be particularly expensive, and modern acoustic processors offer alternative algorithms for extracting the impulse response function of an acoustic system. The electronic and acoustic sources and detectors must be situated in a region of modest temperature, typically less than 100 °C. Typically, even in harsh environments such as a steel factory, there are regions where control electronics may be located within a few meters of a high-temperature apparatus. The electronics could be coupled to the hostile environment with a standard tube—ideally the same as is used to make the sensor and coupled to the sensor through a standard tube coupling.

7.2 Further Work

At NPL, we will be carrying out further work on this technique over the next 3 years. Our work so far has not relied on acoustic theory beyond that of Rayleigh [2]. We will develop a theory of the pulse propagation taking into account tube bends, boundary layer phenomena, and temperature gradients. Experimentally, we will consider ways of ensuring that both the tubes experience the same temperature gradient and investigate the use of alternative tube arrangements for multipoint temperature measurements.

In this study we used flowing gas, but it would obviously be advantageous if a sealed system could be used. At low temperatures this is possible, but at high temperatures, outgassing from the walls may contaminate any sealed gas. Argon is cheap and available in good purity, but if operated in a cryogenic or radioactive environment, helium may have advantageous properties. One possibility would be to include an internal temperature-controlled resonator or waveguide which could be used to assess the purity of the gas *in situ*.

In practice, acoustic waveguides could be constructed from any substance chosen solely to withstand the rigors of the external environment. Experiments have shown that PAT using steel waveguides is extremely robust. After creating large dents in the waveguide with a hammer, we were unable to detect any delay in the acoustic pulse. Internally the only requirement is for a smooth surface and for tubes with a diameter much larger than the thermal and viscous boundary layers (typically 0.1 mm). Additionally, the radius of curvature of the waveguide must be much greater than its diameter.

The obvious weakness of this technique is its susceptibility to acoustic and vibrational noise, which frequently accompanies harsh industrial environments. It may be that the extent of such interferences provides an ultimate limit to the utility of the technique. However, we see no reason why signal averaging should not be able to recover signals from even extremely noisy environments.

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