Guided Wave Testing (GWT) of High Temperature Piping

Jimmy FONG 1, Mark EVANS 1
1 Guided Ultrasonics Ltd., Brentford, UK
Contact e-mail: jimmy@guided-ultrasonics.com, mark@guided-ultrasonics.com

Abstract. Process piping in the petrochemical industry often operates at temperatures as high as 400°C (750°F). This creates a challenging environment for NDT inspections in general, including hostile operating temperature for equipment, access limitation due to piping insulation and high level of in-service mechanical vibrations frequently found on many high temperature (HT) lines. Moreover, corrosion under insulation (CUI) remains a significant issue for many plants in operation. GWT offers a cost effective solution for HT applications where long lengths of piping can be screened from a single location. With our HT guided wave equipment, site inspections are regularly performed on the HT lines operating at temperatures up to 350°C (650°F).

In recent years, a high profile incident in a refinery caused by sulfidation corrosion re-emphasized the importance of HT line inspection. Although GWT is not exclusively used to inspect for this type of corrosion, it is used as part of a boarder inspection program to identify pipe features so that local inspection tools, such as positive material identification (PMI), can be subsequently applied at appropriate locations.

In this paper, the capability of the HT guided wave equipment and challenges encountered during testing are discussed. New developments in transducer technology and ring design have been tested on pipes operating at temperatures up to 400°C (750°F), and the experimental results are also presented.
1. Introduction

Guided Ultrasonics Ltd. (GUL) specialises in the development of GWT equipment using piezoelectric technology. Over the past years, much effort has been made to develop equipment capable of testing pipes at elevated temperatures. During GWT, an array of piezoelectric (PZT) transducers is coupled onto the pipe where a toneburst signal is generated to propagate along the axial length of the pipe. As the frequency used for GWT is relatively low compared to standard UT and is typically in the tens of kHz, it is therefore possible to establish coupling in the form of mechanical force between the transducers and the pipe surface without the use of any couplant or bonding layer. Furthermore, a typical GWT using the GUL system takes around 3-5 minutes. For these reasons, piezoelectric technology has a potential advantage over magnetostrictive technology in terms of practicality. Figure 1 shows this high temperature equipment being used in a routine GWT inspection on an insulated pipe operating at 518°F (270°C).

![Image of high temperature equipment performing GWT](image)

**Fig. 1.** a high temperature (HT) ring performing GWT.

This paper discusses two specific areas of development which have been addressed with the aim of providing solution for the difficulties posed by piping operating at high temperatures, namely:

- Modification of transducer design and materials to allow data collection to be carried out effectively without damage to the transducers or degradation of their performance.
- Calibration and compensation which has to be applied to the processed results to account for the changes in guided wave propagation caused by changes in the pipe temperature.

These areas are discussed in detail in the following sections including the results of a trial carried out using the HT transducers over a range of temperatures up to 700°F (370°C).

2. HT Transducer design

The PZT transducers are directly coupled to the pipe during data capture. This is a fundamental part of the GW system as the transducers are used to transfer the energy to and from the hot pipe in the form of mechanical stress waves. Being in direct contact with the structure, heat is transferred from the pipe-surface to the transducer by conduction and radiation. A piezoelectric transducer typically comprises a wear plate, a piezoelectric ceramic and a backing mass. The main challenge using such transducers in a high temperature environment is to prevent depolarisation of the active piezoelectric ceramic. Depolarisation occurs at approximately 70% of the Curie temperature (critical temperature)
of the piezoelectric material. This is an irreparable process where the efficiency of piezoelectric ceramic gradually degrades until it is ineffective. During the patented development of the HT transducer, a number of methods have been investigated with the aim to ensure the temperature of the active piezoelectric ceramic remains well below the Curie temperature, including the following:

- Utilizing advanced piezoelectric ceramic with high Curie temperature
- Thermally shielding the piezoelectric ceramic
- Actively cooling the piezoelectric ceramic

Common piezoelectric materials that are suitable for GWT transducers typically have a Curie temperature of between 530F (275C) and 610F (320C). Although there are commercially available HT piezoelectric materials with a Curie temperature of above 1000F (540C), the cost of such material is extremely high. So unless there is specific requirement for an ultra-high temperature application (i.e. >750F (400C)), using this type of advance piezoelectric material for GWT may not be commercially viable. An alternative solution was found to maintain the temperature of piezoelectric ceramic below the critical temperature by using wear-plate made from a material with low thermal conductivity, such as zirconium dioxide (ZrO$_2$): This creates a thermal barrier for the piezoelectric ceramic. The table below shows the thermal conductivity values of carbon steel, ZrO$_2$ and Al$_2$O$_3$. Of the two ceramics materials, the ZrO$_2$ can be as much as ten times less thermally conductive than Al$_2$O$_3$, and together with its hard wearing properties, ZrO$_2$ is well suited for the HT applications. Furthermore, the wear plate can be shaped to cover the entire front face of the transducer with a ridge contact area to provide further shielding from radiated heat as well as conducted heat.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (Wm$^{-1}$K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon steel</td>
<td>36-42</td>
</tr>
<tr>
<td>aluminium oxide (Al$_2$O$_3$)</td>
<td>18-32</td>
</tr>
<tr>
<td>zirconium dioxide (ZrO$_2$)</td>
<td>3-5</td>
</tr>
</tbody>
</table>

Approaches using active or passive cooling systems to the transducers were considered during the investigation. The active cooling system consisted of blowing cool air onto the transducers using either an air compressor or a pressurised air bottle during the inspection. Although this provided effective cooling to the transducers, there are a number of issues which were found. Firstly, this would require additional bulky equipment. Secondly, any use of a pressurised system may be viewed negatively, particularly in the refinery environment. Therefore it is more attractive commercially to adopt the approach of a passive cooling system, such as the addition of heat-sinks.

![Fig. 2. photos of a HT transducer (left) and HT solid ring (right).]
A patent has recently been approved for the HT transducer design, which incorporates some of the ideas discussed above. The photo of such transducer and a fully populated transduction ring are shown in Figure 2. To evaluate the transducer, testing was performed using a set up shown in Figure 3 which consists of the HT transducer loading with a contact force of approximately 44lb (20kg) at the end of a metal strip (30mm x 800mm x 0.5mm) waveguide that is resting on a laboratory heating platform (Fisher Scientific). The temperature of the metal strip can be varied between 70F (~25C) and 740F (400C), and verified using a thermal imaging camera (FLIR T440BX). The transducer was operated in a pulse-echo configuration where a guided wave signal was excited and propagated along the metal strip; the amplitude of the reflection from the end of the strip was then measured to assess the transducer performance. The strip was heated to the target temperature and held for 10 minutes as per the recommended maximum operating time of the HT transducer ring given in the manufacturer’s standard practice.

The process was repeated at temperatures between room temperature (~80F, 27C) and 700F (370C). This was repeated over 30 cycles and the results plotted in Figure 4. It can be seen that the results follow a consistent trend where the amplitude of the signal increases with temperature. This temperature effect is thought to be caused by the softening of the adhesive layers used to manufacture the transducers. Despite this, the stability of the signal is maintained throughout the experiment and as shown later this does not affect the overall quality of the guided wave data. Additionally, there was no sign of permanent damage or degradation of the active PZT ceramic of the transducer following the experiment.
3. **Distance Calibration**

The mechanical properties, such as Young’s modulus, of steel that is used in manufactured pipes vary significantly with temperature. It is therefore evident that the velocity of the guided wave modes is temperature dependent. For GWT on hot pipes, this can result in significant errors in the predicted distance as the velocities used in the data processing are assumed at room temperature. It is therefore particularly important that the velocity of the guided wave is calibrated to compensate for the velocity change. This type of calibration is also known as “distance calibration” and is typically done after data collection as part of the data analysis phase. The simplest method for distance calibration is by comparing the predicted distance to a known feature, such as a weld, to the physically measured distance for the same feature. A correction factor is then applied to compensate for the differences. Measurement to a known feature is not always possible due to the thermal insulation that is used on pipes in plants and facilities operating at elevated temperature ranges. An alternative method is to apply an adjustment factor to the velocity based purely on the measured pipe temperature. To explore this dependency, a simple experiment was carried out using a carbon steel pipe where the temperature was varied and the velocity of the torsional mode ($T(0,1)$) was measured as function of pipe temperature. The results in Figure 5 show that the torsional mode velocity decreases with temperature at a rate of around $0.3 \text{m/s per degree Farenheit}$. Although the precise relationship would also depend on the pipe material properties, it nevertheless provides reference for which the distance could be calibrated to minimise errors.

![Fig. 5. Measured torsional mode velocity as a function of temperature for a carbon steel pipe.](image)

4. **HT Pipe trial**

A test pipe consisting of two sections of 6”, schedule 40 carbon steel pipe (wall thickness 0.28”) was used to demonstrate the stability of the GWT result at high temperatures using the GUL HT transduction system. The pipe was heated using ceramic pad heaters and insulated with silica fabric insulation. The temperature was monitored using K type thermocouples at several locations along the pipe length including the transducer test position. The pipe also included a 6mm hole which represents an approximately 1% cross sectional change (CSC) reflector. The setup is shown in Figure 6.
The guided wave data was collected at three different temperatures: 374°F (190°C), 520°F (270°C), and 716°F (380°C). The results are shown in Figure 7. All three results have achieved a minimum of 43dB SNR sensitivity across the collected frequency range and the 1% defect is easily detected in all of the results. Additionally, on closer examination of the data at the weld location at different temperatures, the misalignment caused by the temperature dependency of guided wave velocity is clearly evident. This effect was then rectified by using the calculated ratio from Figure 5, and the corrected result is shown in Figure 8.

![Fig. 6. Setup for the HT pipe trial.](image)

![Fig. 7. Guided wave data on the HT pipe at three different temperatures.](image)
Fig. 8. Guided wave data before distance calibration (left) and after distance calibration (right).

5. Conclusions

HT guided wave applications are common in many industries, particularly in the oil and gas industry where GWT provides a unique solution to screen for defects or in some cases provides a simple solution to locate pipe features, such as welds. The current range of HT GWT equipment has been shown to produce stable and reliable results, and the development of the HT PZT transducers has led to a patented design which can survive repeated usage in high temperature environments.

The distance calibration is essential in HT guided wave inspection, particularly where the location prediction of the features is critical in certain applications.

References