Development of an Automated Modular System for High Temperature Ultrasonic Testing and Longitudinal Wave Attenuation at High Temperatures

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ABSTRACT

High Temperature Ultrasonic Testing is an unexplored area of non-destructive testing with lots of interest for the industry. The ability to carry out inspections in certain sections of the plant without the need of an outage can save lots of money to the industry. The sectors that would most benefit from this type of inspection are: power generation, petrochemical, offshore, steel, among others. This type of inspection allows the reduction of the frequency and/or duration of outages due to the possibility of on-line monitoring of the defects or degradation of components. Enabling a better planning of the action to take.

Due to this market niche, the elaboration of an automated system for inspection of pipes at high temperatures, up to 450ºC, was approved. A modular system has been designed to be carry out ultrasonic and eddy current tests. There is also a challenge in finding a couplant that allows proper acquisition of results under these conditions.

The automated and modular system developed was tested at temperatures of 450ºC, under more adverse conditions than those found in factories, allowing the inspection of pipes of variable diameter with the aid of an orbital guide where it travels.
Thickness measurement tests were also performed at high temperatures in order to verify the attenuation of longitudinal waves emitted by the ultrasonic probes modified for high temperature. Common oils were used in order to employ an economically viable and easily available couplant, having been reliably employed up to 370 °C.

KEYWORDS: High Temperature Ultrasonic Testing (HT UT); Non-destructive testing (NDT); Automated modular system; Signal attenuation; Couplants.

1. INTRODUCTION

Non-destructive Testing (NDT) is continuously improving and changing. The employment of new techniques or the inspection of new materials is continuously pushing and developing new ways to perform non-destructive testing. One of the most prominent and flourishing techniques is ultrasonic testing. It's continuously gaining ground and becoming as common as radiographic testing, being more economical and safer for the operator than the later.[1] One of the fields that's gaining attention and still has a long road to travel is High Temperature Ultrasonic Testing (HT UT). Its ability for performing on-line inspection without the need for shutting down or paralyzing part of a factory while assessing defects can change the way companies plan their factory stoppages. Commonly, outages must be made to allow the inspection area to cooldown for inspection as plant operating temperatures are usually higher than existing contact inspection technologies.

High Temperature Ultrasonic Testing is a continuously developing technique with a lot of interest in the industry. HT UT struggles with finding a suitable couplant as well as an enduring probe. High temperatures are demanding conditions for most commonly used materials for probes and probes' wedges, as they tend to quickly degrade and damage the materials. High temperature couplants are available but there isn't an optimal solution, specially concerning price, ease of use and corrosive properties.

Following this industry need the Hi2Tust project was created with the aim to develop an automated system for inspection and continuous monitorization of critical components in operating conditions at high temperatures, up to 450ºC. This project continues the work previously started in 2013 with the HiTrust project and aims to tackle the hardships found before, related to the limits of the inspection technique used, the EMATs and problems with the initial prototype.

In partnership with ISQ, an automated system capable of enduring this harsh environment was developed with the bonus of being able to perform ultrasonic testing as well as eddy current Testing (ET). Many concepts were drawn before choosing to develop a module system with a toothed gear to run along an orbital track, illustrated in Figure 1. After lots of simulations run on SolidWorks, the prototype was assembled and compressed air and water cooling was chosen for keeping the inspection system up and running.

Besides developing an automated system capable of enduring high temperatures, ultrasonic testing was also explored and high temperature probes and couplants had to be developed. Most common probes have operating temperatures up to 60ºC so it was necessary to find a way to keep the probe cooled and seek materials with low thermal expansion and resistant to thermal degradation. Two polymers were used to keep the probe insulated from temperature and a water channel was developed to cool the probe and perform the inspection.

Concerning the actual ultrasonic testing, it was also analysed the effect of high temperature on the sound waves, measuring the changes in sound velocity and attenuation. An effort was made to employ economical and easily accessible couplants in a way to find suitable couplants for HT UT and these were compared with a gel paste usually employed by the industry.

Finally, conclusions and propositions for future work were suggested to further developments on the field.

2. SYSTEM DEVELOPMENT FOR HIGH TEMPERATURE ULTRASONIC TESTING

The HI2TRUST project aims to develop an automated inspection and monitoring system for components up to 450ºC. The specific goal is to assess weldments in pipes during its service time, which means there is no need to stop production to inspect the pipeline and will allow for better predictability of scheduled maintenance operations due to emerging flaws.

In order to build such system other components had to be built to simulate the harsh environment found at factories.

2.1. Workstation

In order to achieve the desired temperature, a workstation was developed. There was a need to resort to a kind of oven that could provide safe working conditions for the users, that means it must retain the heat and expel the harmful gas produced by the evaporation of couplants. An *hotte* was used to provide secure working conditions for all experimental work.

Figure 1 Workstation - hotte

This workstation, Figure 1, is made of stainless steel with an interior workspace of 0.3357 m^3. It allows for the placement of the calibration blocks and the assembly of the inspection system.

To trap the heat inside different insulations options were tried but the one which delivered the best results was stone wool covered by aluminium foil. Also, bricks were added to the *hotte* floor for insulation. An exhaustion system was inserted to expel the harmful vapours from evaporating couplants, since some of them could be toxic, and interior lighting and a warning light in the outside were added for safety concerns.

The solution adopted for heating the test pieces was a set of electrical resistances connected to a potentiometer for temperature control.

Figure 2 Heating system assembly

Eight electrical resistances, corresponding to 8 kW, displayed in an annular pattern are connected in pairs to potentiometers with the aid of fiberglassed insulated electrical wires. An internal fan was added for better heat distribution and preventing the resistances to collapse. This assembly heats the test piece up to 457ºC.

Table 1 Correlation between power level and temperature

Level	Temperature (ºC)
1	94
2	147
3	174
4	208
5	257
6	319
7	360
8	397
9	448
10	457

2.2. SCANNING SYSTEM

The inspection of the heated pipe must be made by an automated system resilient to the high temperatures and able to follow a circular path. This system had to be made in metal and the electronical components must be refrigerated to endure the hostile environment.

The scanning system design was inspired by orbital welding machines and many approaches were made to develop the most robust and simple scanning system.

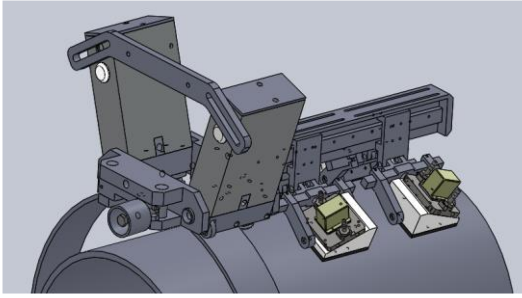

Figure 3 Final prototype for scanning system

The system at Figure 3 resorts to two engines, one in each module, mounted transversally to the orbital track. The motion is assured by a toothed wheel that engages with the orbital track.

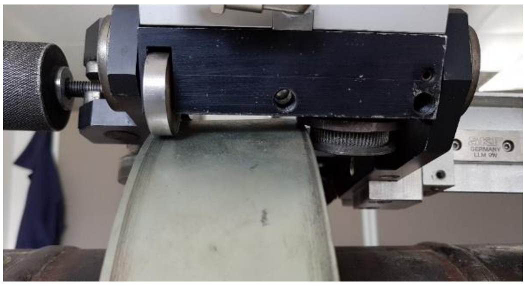

Figure 4 Drivetrain system

The orbital track has a toothed path along the borders of its circumference so it engages with the toothed wheel of the motor. A single ring can be fitted to a range of diameters with the help of screws that adjust to the required dimensions.

The locking mechanism responsible for the union of the scanner system and the orbital track consists of a screwing bolt that forces the scanner toothed wheels to the track. This mechanism can fit different track widths and be adjusted to compensate for slack developed over time.

Figure 5 Fast locking mechanism

The scanner module uses a Maxon® motor that contains the planetary gearhead, the motor and the encoder. The electronics found inside the module are refrigerated through compressed air and water.

Table 2 Components of the scanning module motor (Part No. 272264) [2]

Encoder	Encoder HEDL 5540	Pulses/N: 500 Channels: 3
Motor	A-max 32 Ø32 mm	Diameter: 32mm Type performance: 20W Maximum torque: 45.5 mNm
Combination Gear	Planetary Gearhead GP 32 A Ø32 mm	Diameter: 32 mm Ratio: 66:1 Torque: 0.75Nm

Once the maximum operating temperature of the motor is 125ºC, there's a need to cool it. A cooling base in aluminium was developed to ensure it stays in operation under high temperature environments.

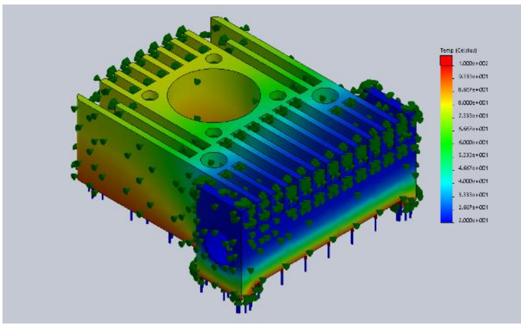

Figure 6 Cooling base under thermal stress

A thermal analysis of the component was made in SolidWorks®. It was assumed a constant temperature of 100ºC in the bottom of the part and it was simulated a constant waterflow along the water channel at a temperature of 20ºC. It was also accounted the influence of the compressed air that cools the piece through convection. A convection coefficient of 200 $W/m^2.K$ of air at 25ºC was used after consulting different sources.

The water channel in combination with the heat dissipaters cools the motor.

In order to control the many electro mechanisms in the system, a control unit was made with connection to a laptop. This enables the control of the motors, the cooling needs and checks the temperatures of the different components.

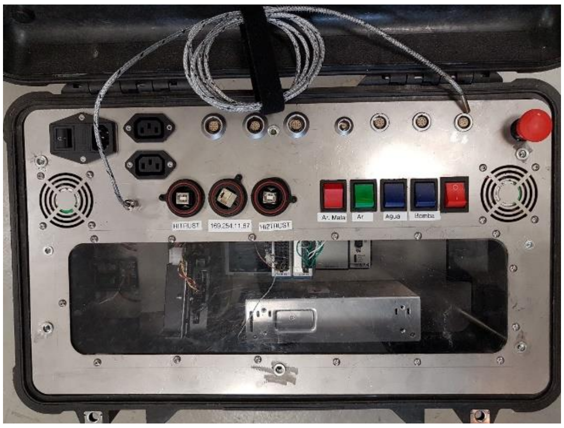

Figure 7 Control unit

This briefcase contains:

- Compact RIO – Lodges modules responsible for the temperature readings of the different thermocouples and PT100 in critical areas.

- EPOS digital positioning controller – Controls the scanners' engines and provides information of their velocity and position.

This briefcase contains a transformer, which converts the 220V AC to 24V DC, powering all the electrical components. The areas controlled by the Compact RIO modules are the left engine, the probes, the cooling water, the transformer and the EPOS digital positioning controller, alongside external thermometers that can be positioned randomly. The control unit is also responsible for actuating the electro valves and pump of the fluidic system and feeding other appliances through the two outlets in the upper left corner. Connections to the laptop are made through USB and Ethernet, and the scanner resorts to LEMO connectors.

The control software for the system compromises of two different programs, one monitors the temperatures and the other moves the scanner.

An initial setup is required for both programs for better accuracy of the data. It's necessary to identify the diameter of the pipe (in imperial units) to be inspected and the over lapse desired by the operator in the scanner's path. The temperature program needs to know which type of thermocouples are going to be used and the parameters of the PT100 probes.

After the setup we can reliably measure temperatures in different points in the system and correctly manoeuvre the scanner, accurately measuring the distance travelled.

The cooling unit developed is responsible for providing the cooling needs of the system through compressed air and water.

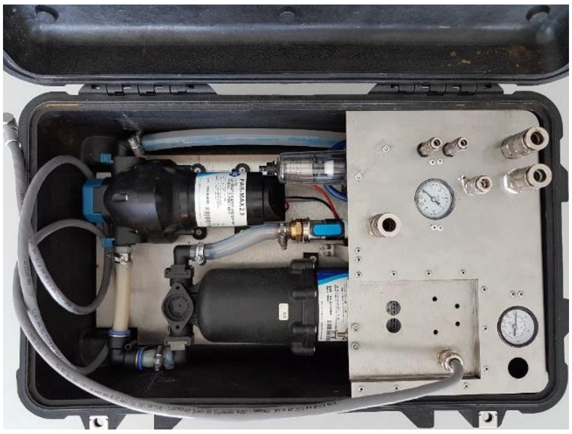

Figure 8 Cooling unit

The hydraulic subsystem incorporates two water intakes in the event that there is no water outlet provided by the grid or it has a low pressure near the inspection location, in that case water is pumped from a cannister. The pneumatic subsystem features an air filter and a flow regulator to control the amount of air passing through the interior of the scanner.

2.3. Ultrasonic testing modules

The ultrasonic testing module can be divided in two key components, the equipment responsible for generating and processing the signal and the probes.

The equipment chosen for this task are the Multix by M2M and the OmniScan by

Olympus. The Multix is the chosen equipment by choice, but the OmniScan is taken into account due to its portability.

Figure 9 MultiX by M2M with a laptop to communicate [3].

MultiX is a versatile equipment which can perform all conventional types of inspection (pulse-echo, tandem, TOFD and so forth), but needs a computer to act as an interface.

Concerning the probes, many simulations were made resorting to CIVA, a NDT simulation software, a select few were chosen but only the probe used later on will be presented.

Table 3 Probe's specifications

Specifications	***Imasonic 12051***
Frequency	3.25 MHz
Bandwith	55%
Nº of elements	20 elts.

The Imasonic 12051 was the selected probe and its main concern is the maximum operating temperature of 60ºC, so a solution was devised by employing active cooling that doesn't allow it to surpass its maximum operating temperature.

A housing for the probe was constructed in order to cool it and provide a water path for the sound beam. Also, wedges of heat resistant materials were used in order to cope with these temperatures.

Flat and angular wedges were developed to enable a greater probability of defect detection. A two-stage wedge was built to keep the probe safe from the heat of the pipes. This assembly consists of two wedges made by heat resistant polymers, one in Duratron® PBI and the other in PEEK. Duratron® PBI has a running temperature service up to 310ºC continuously and 500ºC for short periods of time. It will be in direct contact with the pipes and isolating the heat from the probe. PEEK has a lower operating temperature of up to 250 ºC and is also highly resistant to thermal degradation. This wedge will be responsible for probe assembly, since it connects the probe housing with the wedges. It also has a water channel where the sound beam will travel from the probe to the Duratron® wedge and then to the inspection piece.

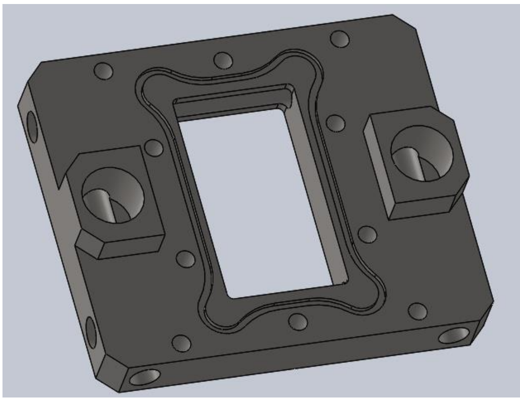

Figure 10 Probe housing for the 5 MHz probe

The probe's housing which will act as a cooling platform has four internal channels for water to circulate and fill the water path for the sound beam.

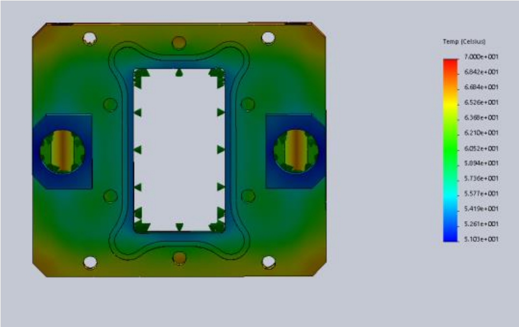

Figure 11 Thermal efficiency simulation of the probe housing

A simulation concerning the thermal efficiency of the cooling capabilities of the probe housing was made resorting to SolidWorks Simulation, it was considered that the water was at 20ºCelsius and the PEEK wedge at 70ºC. The water channels did a good job of cooling the piece, although this simulation doesn't take into account the cooling provided by the water channel inside the PEEK wedge.

3. SYSTEM VALIDATION

3.1. SCANNING SYSTEM EVALUATION

Following the complete construction of the scanning system it was necessary to test it at the desired temperatures, upwards of 400ºC, to check if it can withstand the harsh environment, taking special attention to the probes and the engines.

The scanning system was assembled inside the *hotte* with the pipe of 323,9 mm in diameter and the heating system was turned on at maximum power. The conditions provided inside the *hotte* are harsher than in a factory due to the oven like atmosphere created compared to a more open space environment.

Figure 12 Fully assembled scanning system

The high temperature test was monitored using the thermocouples provided by the control unit and an infrared thermography camera, a FLIR® T620. Reflective areas, like our probe housing, are hard to record and lead to misleading results, so a calibration is needed prior to inspection.

With the aid of the thermographic camera 4 different points were monitored: the pipe, the orbital track, the base of the scanning system which is in contact with the orbital track and the probe.

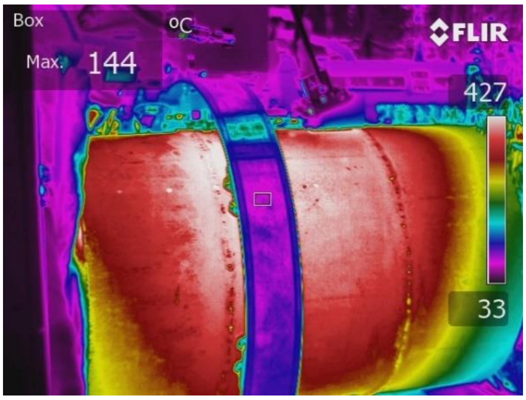

Figure 13 Thermal image of the scanning system

The pictures taken with the thermographic camera appear with a temperature scale, indicating the maximum and minimum temperature found in the photographed area which colour scheme fluctuates between white and dark, for highest and lowest temperature value respectively. The temperature value found at the top left of the image indicates the maximum temperature recorded inside the box in the middle. In Figure 13, it's noticeable the different temperature values found during the inspection.

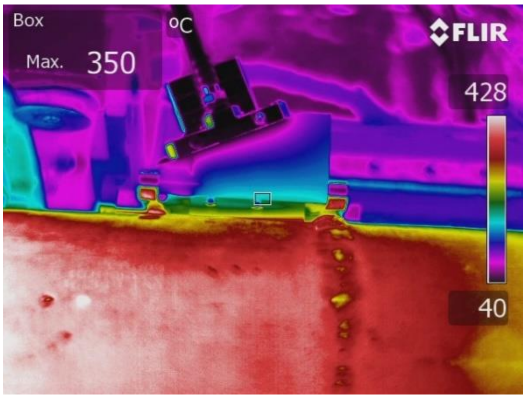

Figure 14 Infrared photography of the probe

In Figure 14 can be observed the temperature variation between the probe, probes' wedges and the pipe. Although the pipe is at 428ºC the probe's temperature around its housing is roughly 40ºC.

Table 4 Temperatures measured at crucial points

	Temperature (ºC)
Pipe	428
Orbital track	144
Scanning system	56
Probe	40

It's noticeable the efficient cooling through compressed air and water of the scanning system, maintaining the scanning system below 60ºC. Also, the orbital track doesn't seem to exceed temperatures of 144ºC, transmitting few heat into to the scanning system.

The PBI and PEEK wedges did a good job at dissipating energy with the aid of water cooling. It's essential that the probe's temperature doesn't surpass 60ºC since surpassing its maximum operating temperature could damage the probe.

This test validates the designed system and proves it can endure temperatures near 450ºC, which means it is able to inspect the areas intended in a factory environment where there is refreshing air around instead of an oven like atmosphere.

3.2. Signal Attenuation vs Temperature

Signal attenuation is a major concern regarding high temperature ultrasonic testing and it's very hard to find a suitable couplant which is economically viable and easy to apply, so various experiments were made resorting to common vegetal and mineral oils and compared to a standard gel for thickness measurement.

A thickness measurement test was made to a mock-up of an actual pipe found in a factory, it has 323,9 mm of diameter and a thickness of 7,1 mm.

As observed in Figure 15, the industry standard gel for thickness measurements at high temperatures is the ideal couplant for these inspections providing a clear signal all throughout the tests. But it's not suitable for automated inspections due to its applicability. Regarding the more common solutions, peanut oil provided good signal through this temperature range up to 370ºC but special attention must be taken to probe cleaning since it leaves a lot of residues.

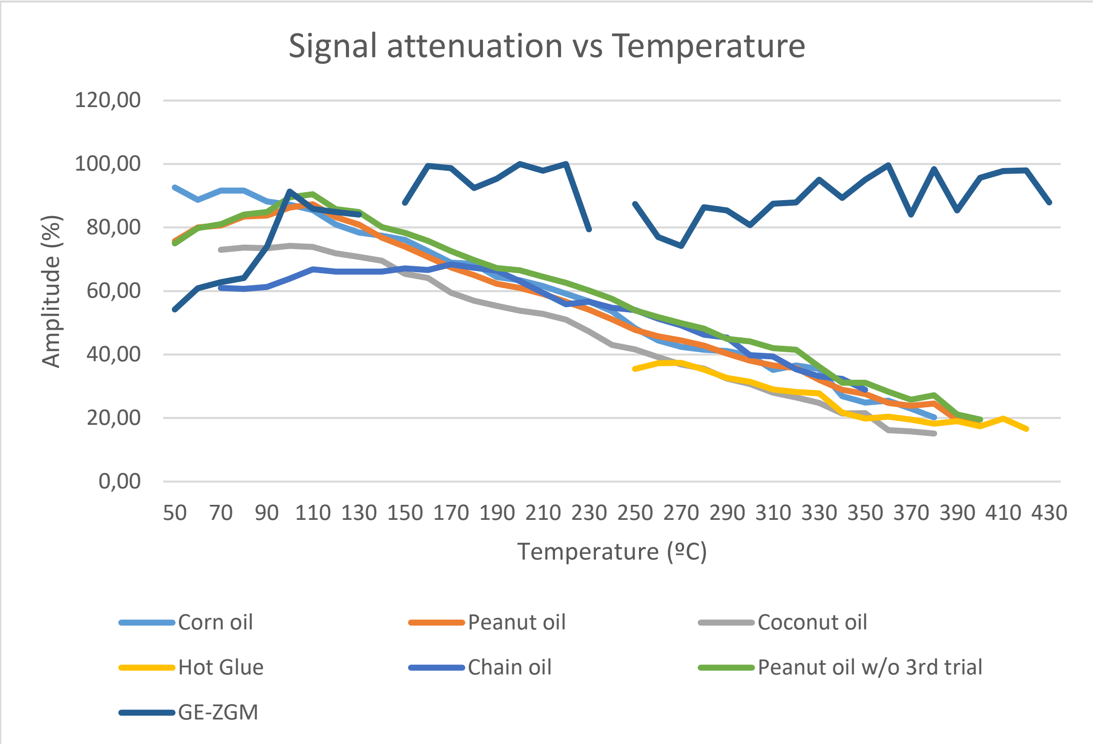

Figure 15 Signal attenuation of longitudinal waves of all tested couplants

Hot glue was a promising couplant since it can endure temperatures up to 420ºC and possibly onwards, but it fell short due to low amplitude values and the amount of residues it leaves.

4. CONCLUSIONS

This work was done in collaboration with ISQ with the aim to develop an automated modular system for HT UT.

The developed system was tested at temperatures up to 450ºC and it's ready to be tested at temperatures higher than 450ºC in a factory.

Signal attenuation of ultrasonic waves was verified and two different couplants were choosed as viable, being more economical and practical than those found in the industry. An automated couplant injection system should be studied in order to obtain better results and further studies concerning transversal wave attenuation and other couplants should be made.

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