Deliverable D 1.6
INSTRUMENTATION TOOLS FOR MEASUREMENTS ON INDUSTRIAL DEVICES

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Primary Authors	**João Pereira, jpereira@civil.uminho.pt, UMINHO**
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Project Coordinator	**Marc Huger, marc.huger@unilim.fr, UNILIM**
Document Contributors	**Rafael Oliveira, rafael.oliveira@uc.pt, UMINHO** **Marc Huger, marc.huger@unilim.fr, UNILIM** **Sido Sinnema, sido.sinnema@tatasteeleurope.com, TATASTEEL** **Pratik Grajjar, pratik.gajjar@civil.uminho.pt, UMINHO** **Diana Vitiello, diana.vitiello@unilim.fr, UNILIM**

Change log

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1. Introduction

The present document summarizes the available techniques for the instrumentation of industrial devices. This document refers to "Task 1.5 - Devices for validation on masonry and vessels" within "WP1 - Improvement of measurements tools". Besides this introductory section, three additional sections are presented in this report.

Section 2 describes the pilot steel ladle. The basic project and the general arrangement of the pilot vessel developed inside WP1 and WP4 are being presented. The materials used in the pilot ladle and the layers of the refractory lining and insulating board are detailed.

Section 3 describes techniques that may be used for the instrumentation of industrial devices. This section is divided in three parts: i) Measurements of geometry, ii) Strain Instrumentation; and iii) Thermal Instrumentation.

Section 4 summarizes the conclusions and considerations to be taken while preparing and performing the instrumentation of industrial devices.

2. Description of the pilot scale steel ladle

A 3D pilot scale steel ladle is being developed for thermomechanical experiments, as presented in Figure 1. The pilot ladle consists of a cylindrical steel shell with a welded bottom. The refractory linings will be arranged in concentric layers and the bottom will also be coated with refractory materials.

The aim of the pilot steel ladle is to study some effects in a reduced scale of an industrial vessel:

i) The effects of joints in the effective total heat resistance,

ii) The thermomechanical behaviour of mismatched joints;

iii) The effects of joint thickness and brick geometry in the thermomechanical stresses;

iv) The effects of creep and plasticity under service conditions;

v) How the hoop stress in the ring transforms into radial compression of the insulating layer;

vi) The damage effects after thermal cycles of heating and cooling.

In order to evaluate these phenomena, it will be necessary to measure the temperature distribution across the thickness of the wall, the heat fluxes, the displacements, the stresses and strains in the steel shell and in the refractory linings. This data will be used for feeding and validating numerical models that are under development.

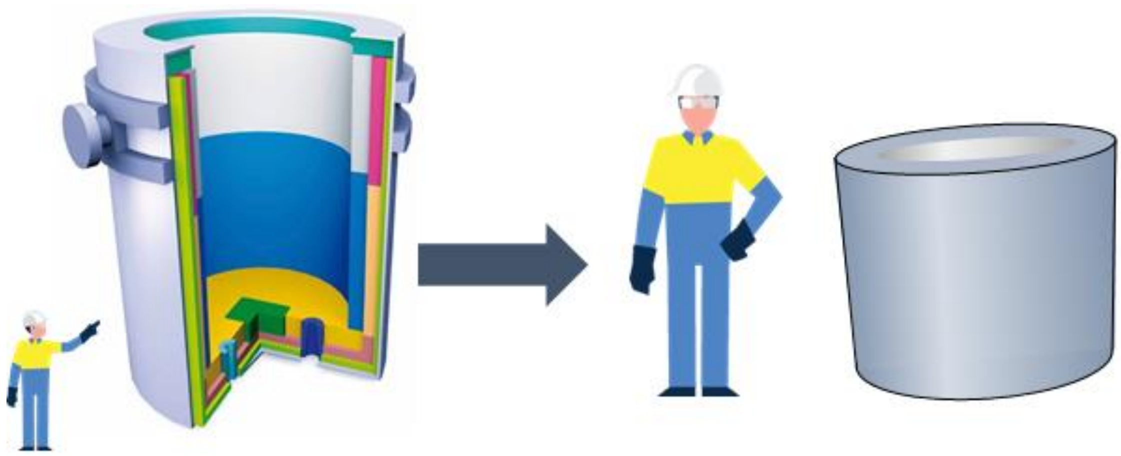

Figure 1: Pilot Steel Ladle.

During the functional design of the pilot steel ladle, some premises were taken:

i) The pilot steel ladle will not contain molten steel to avoid parasitic effects such as corrosion, penetration, wear, and so on.

ii) The vessel will be heated from the center, probably with a radiation tube in order to prevent oxidation.

iii) The steel shell of the ladle will be equipped with a cooling device to control the thermal gradient.

iv) A lid is being considered for energy saving purposes.

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Refractory layers will be arranged in the same way as in the full scale ladle (Figure 2), however half scale bricks will be used. The following materials are being considered:

- Wear lining: **Fired spinel brick,** which has excellent chemical resistance against the molten steel, but a high thermal conductivity.
- Permanent lining: **Fired bauxite brick** with good resistance against steel and a high thermal conductivity.
- Insulation layers: will be **Grade 26 insulation brick,** temperature resistant up to 1400ºC with a low thermal conductivity and **Microporous insulation** with very low thermal conductivity being temperature resistant up to 1000ºC.
- Optionally a subset of MgO bricks can be inserted to mimic the slag line.

Figure 2: Example of a real linings application.

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3. Instrumentation tools for measurements on industrial devices

This section summarizes the instrumentation techniques that may be used for measurements at industrial scale. The following methodologies will be tested at the pilot steel ladle presented at section 2. This section is divided in three parts:

3.1 Measurements of geometry

3.2 Strain Instrumentation

3.3 Thermal Instrumentation

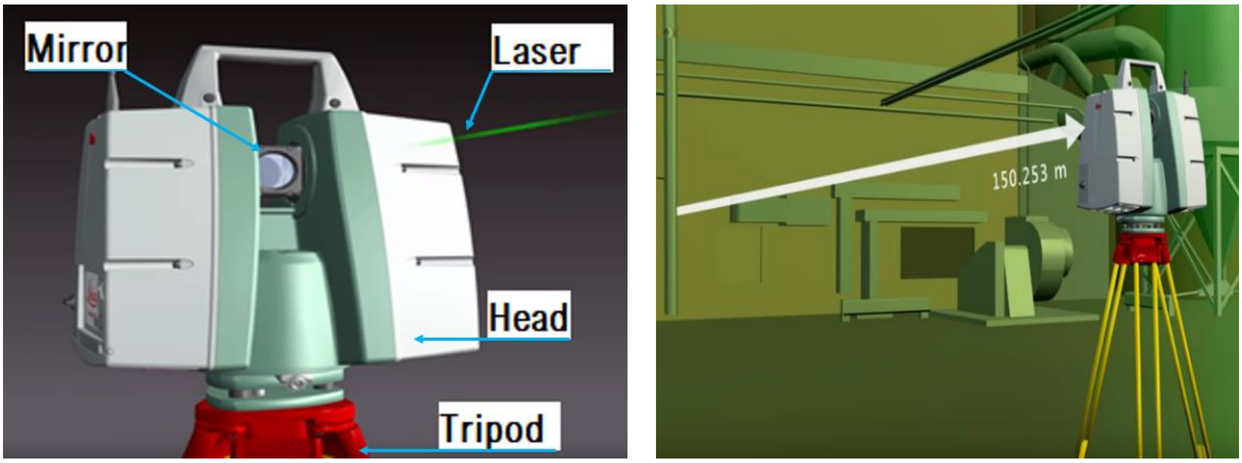
3.1. Measurements of geometry by 3D Scanning

During the fabrication and shipping process, damage may be caused to the composing elements of the pilot ladle leading to an initial geometrical imperfection. The non-circularity of the steel shell and imperfections of the bricks may lead to a non-homogenous stress distribution in the refractory lining and in the shell. Therefore, it is important to have a precise description of the initial geometry of system.

The evaluation of the geometry of industrial devices, aided by digital techniques, will help to track initial imperfections and defects that could induce non-predicted stresses and jeopardize the operation. Based on the three-dimensional scanning of such structures, it will be possible to check the assembly process and find structural failures. Moreover, the scanning can be used to evaluate the geometry of the vessel over its entire lifespan.

The Terrestrial Laser Scanners (TLS), or 3D Scanning, may be used to evaluate the geometry of industrial devices, such as steel ladles. This equipment was originally developed for as-built modelling of architectural and engineering structures, however they can also be used for high-resolution mapping of industrial vessels and equipment.

There are different types of laser scanners, but with the same working principle. A laser scanner emits a rapidly pulsing or a continuous laser beam. The head of the equipment rotates around its vertical axis and a mirror rapidly rotates around its horizontal axis (Figure 3a), allowing a continuous sweep of the environment. The result is a systematic swiping of the laser beam over the scanned area.



a) b)

Figure 3: Terrestrial Laser Scanning: (a) Laser emission, (b) Laser return (Source: Leica Geosystems).

When the laser hits an object, part of the laser is reflected back to the scanner. Based on the time between the emission and capture of the beam, it is possible to determine the distance of the object (Figure 3b). The equipment also records the vertical and horizontal angle of the equipment, allowing the calculation of the position of the point in spherical coordinates, as shown in Figure 4. These coordinates are then converted to Cartesian coordinates (X, Y, Z) and recorded.

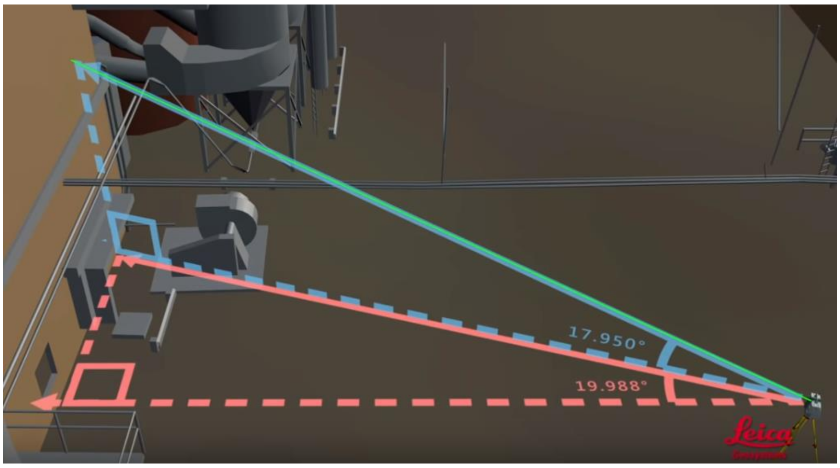
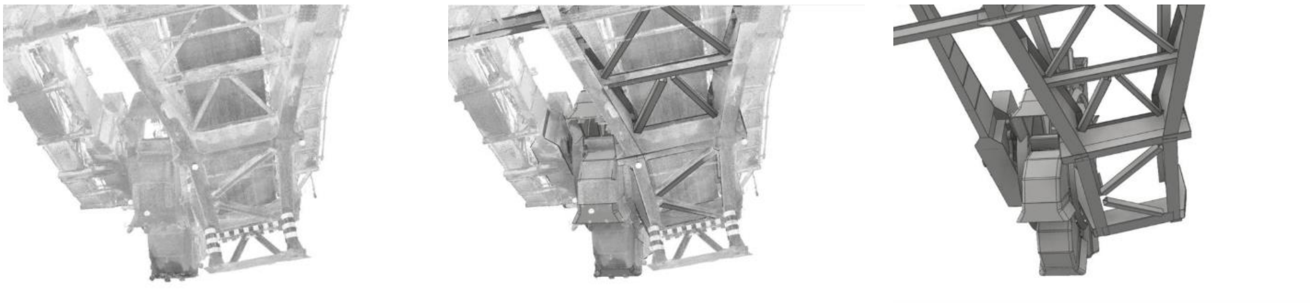
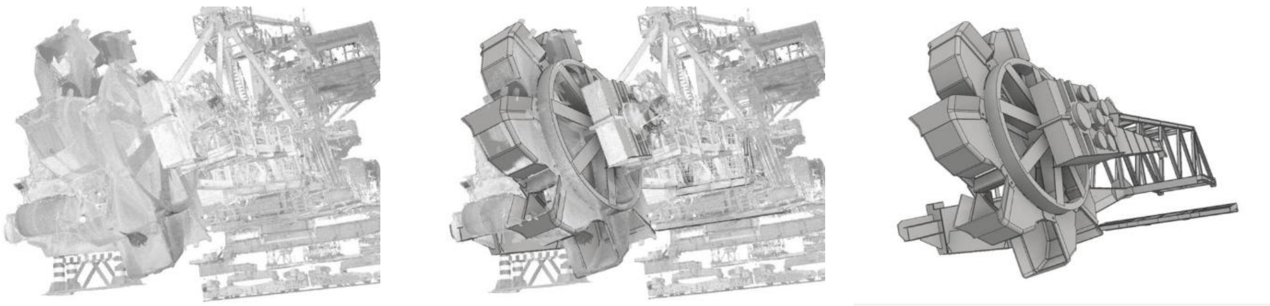


Figure 4: Vertical and horizontal angles (Source: Leica Geosystems).

The scanning process stores all the recorded points and generates the point cloud. This cloud contains the necessary information to describe the geometry of the scanned element. Then, the cloud point is processed using either CAD (Computer Aided Design) or BIM (Build Information Modelling) software and may be used for engineering purposes, as presented in Figure 5.



(a)



(b)

Figure 5: From cloud points to engineering models: (a) Reclaimer Machine: Details of the bucket-wheel (b) Reclaimer Machine: Details of the boom (Source: CT Vision).

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3.2. Strain Instrumentation

One of the main objectives of developing a 3D pilot model of the steel ladle is to validate technologies, equipment and protocols to be used at a later stage in the in-situ measurements of the steel ladle in service conditions. This is in fact a very challenging task due to the extreme conditions in which these ladles operate. Some technologies suitable for application in the industrial devices, that will be tested for use in the 3D pilot model, are presented in this section.

3.2.1. Resistive Strain gauges

Strain gauges are devices used to measure strains in a surface. It was invented in 1938 and the technique is under constant development since then. The gauge is attached to a surface using a suitable adhesive. The strains in the sample lead to strains in the strain gauge, resulting in changes in its electrical resistance. Then, it is possible to correlate the variation of the electrical current passing through the system to the surface strains, these variations are in the order of mV. Some strain gauges are presented in Figure 6. High temperature resistive strain gauges can operate in temperatures up to 300ºC, they are suitable for the instrumentation of some industrial devices.

(a) (b)

Figure 6: Resistive strain gauges: (a) Uniaxial strain gauge; (b) Triaxial strain gauge

Strain gauges provide local measurements of strains in a given direction. In order to determine the principal strains, triaxial gauges shall be used.

3.2.2. Marker Tracking

Marker tracking is a photo-mechanical technique that tracks markers previously installed on the sample´s surface. It may be used to determine displacements and strain fields during a thermomechanical solicitation. It is a powerful technique, as it is simple, fast to use and it requires small computational resources for the data post-processing. Nevertheless, this technique is not suitable to represent discontinuities, such as cracks and ruptures.

The markers are applied on sample surfaces using a felt-tip pen, painted or stamped using a template. A high contrast between the markers and the background (samples surface) is required to increase the accuracy of the method. Stereovision (two or more cameras) may be used to allow measurements of the out-of-plane displacements. Bretagne *et al* [1] have summarized the principles of the technique and the influence of diameter of markers, changes of luminosity, variation of grey level, rotation and out-of-plane displacements and the accuracy of the technique.

3.2.3. Digital Image Correlation

The Digital Image Correlation is an optical full-field measurement technique, it was created at the beginning of the 1980s and has been continuously developed since then, presenting a significant increase in accuracy. It allows the determination of an experimental full-field of strains and displacements, based on the grey level conservation principle [2].

The technique involves recording digital images of a specimen under a mechanical transformation, caused by external forces or temperature variations, and the use of software to apply an image correlation algorithm. The recorded images correspond to two different states: a reference state and a deformed state. A speckle pattern is applied to the sample surface, prior to carrying out the test, generating a stochastic pattern of grey shades on the surface, each pixel of these images then stores information corresponding to a grey value. Some variation of this technique allows inverse identification of a material's properties (I-DIC) [3] and the evaluation of crack propagation (2P-DIC) [4].

3.3. Thermal instrumentation

The evaluation of the temperature fields results in the acquisition of fundamental information that is required to evaluate industrial equipment that operate at high temperatures. The layers of the refractory lining are composed of different materials with specific properties and are submitted to different temperatures in service. This section summarizes the techniques that may be used for the evaluation of temperatures in industrial equipment.

3.3.1. Thermocouples

Thermocouples are widely used for the instrumentation of industrial devices. The most common is the K type, which is composed of Nickel-Chromium / Nickel-Alumel (nickel + aluminium + silicon alloy). This thermocouple is widely used, because it is inexpensive, accurate, reliable and can operate in a wide range of temperatures, up to 1260°C with an accuracy of +/- 2.2°C.

The thermocouples can be installed at the refractory layers (working, safety and insulation) and in the steel shell at different locations (Figure 7). They are inserted in holes drilled into the refractory bricks or welded to steel parts. Marker pens and duct tape assist to keep the thermocouples in place and can be used to indicate where sub level thermocouples have previously been installed. Careful attention should be paid during the installation in order to ensure no overlapping of thermocouples as this could cause crushing of the equipment and change the location of recording.

a) **b)**

Figure 7: Installation of thermocouples* on *steel ladle lining: a) front view; b) top view.

3.3.2. Infrared cameras

The infrared camera or thermal camera is a useful tool that measures the temperature distribution on the external surface of industrial equipment, such as the steel ladles. The measurement can be made while the overhead crane transports the ladle, this allows the continuous production and the evaluation of temperatures without contact between the measurement device and the analysed object.

All the bodies with a temperature different from absolute zero emit a specific energy caused by the movement of the molecules. This movement is also synonymous of a movement of electrical charges that generates electromagnetic radiation in the wavelengths of the infrared band (from 0.8 to 15 µm). The camera captures this energy and converts it into an electronic signal, which is processed by software and transformed into a thermal image (Figure 8**Erreur ! Source du renvoi introuvable.**). Then, the image is used for temperature calculations and to evaluate the temperatures fields with high accuracy.

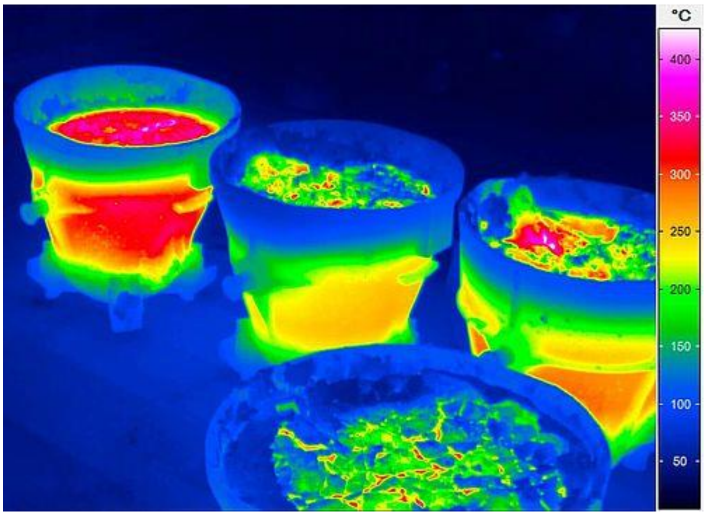


Figure 8: Example of an infrared image of four full steel ladles.

The infrared cameras present some advantages compared to the use of thermocouples. This equipment, provides full field measurement of the temperatures, while thermocouples provide punctual measurements. Therefore, if the problem involves a significant gradient of temperatures or for big structures, a large number of thermocouples would be necessary to evaluate the system, whereas only one IR camera would be required to provide all the necessary measurements in a given surface. A drawback is the limitation on measuring temperatures inside the linings and between the layers, so in such cases, thermocouples are more suitable.

3.3.3. Laser scanning

Laser scanning can also be used to measure temperature. Some systems are also able to measure the reduction of the thickness of the linings, as bricks are continuously subjected to corrosive attacks by hot liquid steel and slag. The laser scanner measurements can be used to evaluate the variation of thickness of the bricks in hot conditions by sending infrared laser pulse from outside the ladle to the wall and the bottom (Figure 9). This monitoring of the brick thickness is really important in order to avoid breakouts which can have serious consequences in terms of production (economical aspect) and general safety of personnel (human aspect).

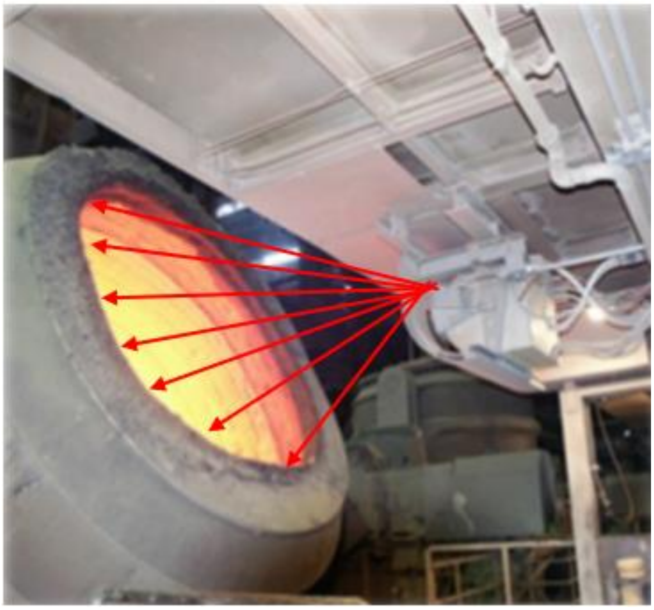


Figure 9: Laser scanner measures on the internal surface of the ladle from the outside the steel ladle

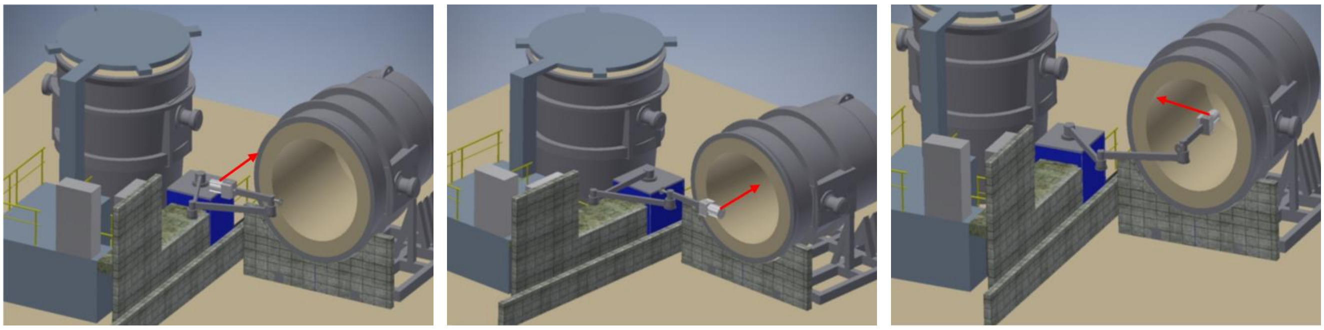
Two problems can be highlighted:

- the accuracy of the measurements depends on the angle of incidence of the laser beam;
- the shadowed area under the mouth is not accessible for the laser beam.

The second disadvantage has an impact on the measurability of the slag zone, a very important area in ladle lining relating to the risk of a breakout. To overcome the above problem, a laser head system has been developed [5]. The entire measurement takes less than 3 minutes and it can be divided in three steps (Figure 10):

a) the laser head is positioned such that the laser scanner sees the outer contour and a part of the mouth of the ladle in order to find the exact position of the ladle by using a "3D – structure finding" software;
b) the second scan is carried out in front of the mouth to measure the area of the bottom of the ladle;
c) the laser head moves completely through the mouth inside the hot ladle and it measures the ladle wall lining with a 360° rotating laser scanner; each scan takes only 20 seconds.

Once the measurement is finished, the head returns at the position zero. The data are collected (generally 3.9 million points with accuracy better than 5 mm) and processed.



a) b) c)

Figure 10: Measurement procedure: a) External measurement; b) Bottom measurement; c) Side measurement

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4. Conclusions and final considerations

This document summarizes the instrumentation methodologies that may be used on industrial vessels, including the suitable acquisition equipment and techniques. This deliverable is the output of the "Task 1.5 - Devices for validation on masonry vessels" inside of "WP1 - Improvements of measurements tools".

Section 2 described the 3D pilot scale steel ladle that is being developed within the scope of ATHOR Project. The general arrangement of the vessel was presented, the materials used and the layers of the refractory linings and insulating board were detailed. Moreover, some details about the conceptual design of the pilot vessel were described.

Section 3 described the instrumentation tools for measurements on industrial devices. The thermal instrumentation, strain instrumentation and optical devices for evaluation of geometry were presented. These techniques are applicable for the measurements of industrial equipment such as steel ladles.

As presented in this document, there are many techniques available for the evaluation of temperatures, displacements and strains in industrial devices. However, when dealing with the service temperatures of refractories, these techniques may not be completely suitable and some improvements will certainly be necessary. The development and experimental research on the pilot steel ladle will allow testing the different instrumentation techniques and equipment, helping identifying the best suited techniques to use in the industrial application. Moreover, the measurements of strains and temperatures with redundant techniques will allow us to perform a benchmark between these techniques.

In conclusion, the improvements of measurements tools performed within WP1, including the "Tasks 1.1 - Thermal instrumentation", "Task 1.2 - Strain Instrumentation", "Task 1.3 – Devices for thermo-physical properties characterization" and "Task 1.4 - Devices for thermomechanical characterization" are increasing the current knowledge and allowing the development and validation of innovative techniques presented in this report that may be used for the instrumentation of industrial devices.

5. References

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