D2.2 Realization and Testing of Proximity Sensor

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MULTISENSEAF

Credits

Disclaimer

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Content

Tables & Figures

List of abbreviations

Abbreviations	Explanation
RINA-CSM	Registro Italiano Navale – Centro Sviluppo Materiali
EAF	Electric Arc Furnace
FFT	Fast Fourier Transform
KPI	Key Performance Indicator
MFC	Microsoft Foundation Class
SCL	Serial Clock Line
SDA	Serial Data Line
TOF	Time of Flight

Executive Summary

This deliverable encompasses all development phases of the proximity sensor. It details the system design along with the subsequent stages of fabrication, assembly, preliminary laboratory testing, and final validation performed in a semi-industrial heating furnace. Finally, the test data are analysed, and the system's critical issues are identified, together with proposed future developments to address them.

Based on the test results, the overall design of the measurement system can be considered robust—particularly with regard to air purging, internal lance cooling, and data acquisition. However, several limitations emerged in relation to the sensing elements, especially for prospective deployment in an electric arc furnace.

The camera performed adequately in the re-heating furnace, but its use in an electric arc furnace would require an electro-optical subsystem to attenuate the incident radiant flux and prevent photodiode saturation. A similar limitation was observed for the acoustic sensor, which is likely to experience microphone saturation under electric arc furnace acoustic conditions.

Finally, the TOF sensor proved unsuitable for operation on targets exceeding 800 °C or in proximity to open flames, indicating that the current technology cannot support high-temperature furnace measurements.

The document is articulated in 6 main sections:

Section 1 – Proximity Sensor Design

Section 2 – Proximity Sensor Manufacturing and Assembling

Section 3 – Preliminary lab test and preparation for semi-industrial tests

Section 4 – Sensor Tests at Semi-Industrial Furnace

Section 5 – Data analysis

Section 6 - Future Engineering Challenges

MultiSensEAF: Proximity Sensor

Introduction

This report summarizes the development of the "proximity sensor" measurement system. It details the work done throughout all development phases, from design and assembly to laboratory and near-industrial scale testing. The design, assembly and initial laboratory tests were performed at the CSM laboratories in Rome, while the final tests were conducted in a heating oven at the CSM laboratories in Dalmine.

About the project

The overall objective of the MultiSensEAF project is to develop, implement and test multi-sensor systems for an optimized EAF process control. The improved EAF process performances in terms of reduction of energy demand for melting, power on time, metallic losses and consequently reduced CO_2 emissions.

More specifically, MultisensEAF has the following objectives:

- Development of new scrap proximity sensors integrated in movable head injectors installed and tested at one industrial EAF
- Development and implementation of innovative multi-sensor systems for scrap meltdown monitoring in melting phase, slag conditions, thermal status detection and hot heel in refining phase through merging different principles of detection, OES sensors, camera images, focused radar measurement and acoustic measurements at two industrial EAFs
- Development of innovative soft sensor for scrap characterisation based on a scrap meltdown monitoring using multisensory approach
- Development of soft-sensor approach to determine liquid bath decarburization rate and content of C in the bath through off gas detections.
- Application of improved movable injector operation strategies for optimized scrap meltdown and slag foaming
- Testing and integration of the sensor data into existing KPI and model-based process management systems to optimize EAF operation.

The MultiSensEAF approach

The overall objective will be implemented by a three-step process. Newly developed and additional off-the-shelf sensors will be installed at industrial EAFs to create innovative multi-sensor systems. Data collected by these multi-sensor systems will be used to develop new soft sensors in part based on machine learning and AI methods. The deeper process knowledge created by the multi-sensor systems and soft sensors will be utilized in KPI and model-based process management and optimization. MultiSensEAF considers a holistic approach for the development of the necessary knowledge on sensor technologies and the implementation and use of these measurement technologies for soft-sensors and advanced process control and optimisation to achieve the project goals for the electric steelmaking processes. The project will follow a multi-disciplinary and multi-stakeholder approach, bringing together the expertise of EU steel industry, providers of measurement systems, universities and research groups in the sectors of steelmaking, as well as of sensor and process control system development.

Expected impact of MultiSensEAF

The MultiSensEAF project will contribute to an optimized EAF process control and thereby to improved EAF process performances in terms of reduction of energy demand for melting, power on time, metallic losses and consequently reduced CO_2 emissions. Through execution of effective dissemination and communication measures MultiSensEAF is expected to yield results beyond the immediate scope of the project and contribute to the wider impacts formulated in the European Green Deal. The following key impacts are expected through MultiSensEAF:

Optimization of the charged scrap mix to reduce energy and resource consumption:

- Better understanding of the melting evolution within the arc furnace
- Optimization of the charging schedule and reduction of the electric energy and fossil fuel consumption
- Reduction of the overall CO_2 emission connected with the steel production
- Increased profits due to improved plant productivity

Increasing process efficiency by online monitoring and adaptive process control:

- Improved reliability and stability of the EAF process by optimization of control strategies and model-based decision support systems
- Improved chemical composition of the scrap by achieving a more homogeneous energy distribution and oxidization
- Improved safety and working conditions by advanced monitoring of the process
- Increased metallic yield and energy efficiency
- Reduction of the overall CO_2 emission connected with the steel production

The described pathways include independent measure to improve the stability and safety of the EAF process by upgrading the process monitoring to the current state of the art, including the application of machine learning approaches to exploit the large amount of data generated and identify previously hidden correlations. The described measures can be combined, and their impact will contribute to the common goal of modernization of the EAF process and to a smaller extend to the decarburization of the European steel making by decreasing energy and resource consumption and increasing the metallic yield. Both objectives have been addressed in the European Green Deal: "Energy-intensive industries, such as steel [...] are indispensable to Europe's economy, as they supply several key value chains. The decarbonisation and modernisation of this sector is essential."

With advancing effort to decarburize the European steel making, the share of the EAF route is likely to increase. The current situation on the energy markets puts additional emphasis on the need for an ongoing optimization of process in order to maintain a profitable production.

1 Proximity Sensor Design

The RINA-CSM proximity sensor is a multifunctional device for electric arc furnaces, designed to enhance internal furnace monitoring during steelmaking. Designed for insertion in place of the carbon lance, it can also be readily adapted for installation in alternative housings. This versatile sensor offers three operational modes, each tailored to specific measurement requirements: distance measurement of objects within its range using a time-of-flight detector (proximity sensing), visual monitoring of the sensor's frontal area via an integrated camera, and acoustic analysis through an embedded microphone. The three operating modes cannot operate simultaneously.

The general layout of the proximity sensor system is depicted in **Figure 1**.

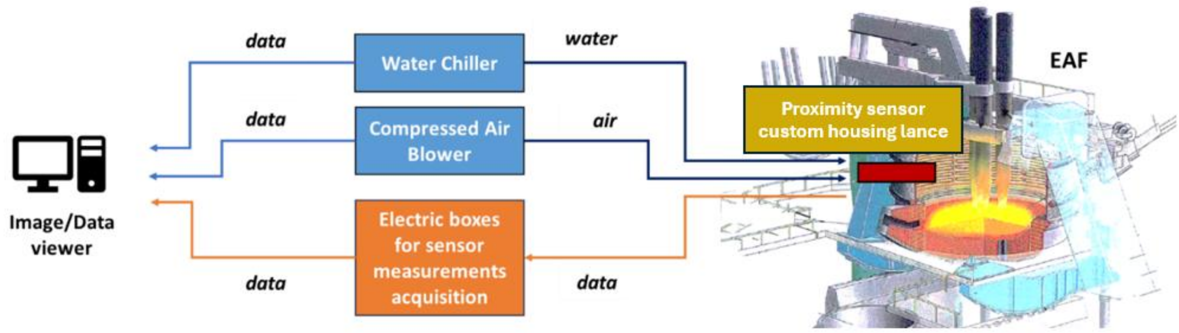

Figure 1 . General layout of the proximity sensor

As illustrated in the **Figure 1**, the proximity sensor system comprises several components:

- a custom housing lance (highlighted in red), containing the sensors directed towards the electric arc furnace,
- a water chiller, responsible for cooling the closed-loop water circuit that regulates the temperature of the electronic components within the custom housing lance.
- a compressed air blower, which generates compressed air to maintain the optical clarity of the lance output,
- three electric boxes for sensors data transmission and conditioning,
- a computer for data acquisition and image processing,
- three sensors located into the custom housing lance.

The custom housing lance is positioned within an EAF's cooling jacket, replacing a standard carbon-oxygen lance. This allows the sensors at the lance tip to face the scrap and steel bath directly, ensuring better measurements. Due to the small internal diameter of the custom housing lance, it can host only one sensor at a time. The design of the Proximity Sensor was performed considering Feralpi EAF use case where the carbon-oxygen lance cooling jacket has an internal diameter of 60 mm and is water-cooled. The carbon-oxygen lance cooling jacket is produced by HTT partner.

1.1 Custom Housing Lance Design

Maximizing the optical aperture and minimizing sound losses requires the sensors to be positioned close to the custom lance housing tip. This placement, however, directly exposes the sensors to a very harsh environment.

In particular, the custom housing lance design must face three main challenges:

1. ***Radiation heat***: the sensor, placed close to the custom housing lance tip, looks directly at high temperature scrap and steel bath and receives the radiation heat they transmit.

The custom housing lance is then designed with a water-cooling circuit able to keep the sensors' temperature in the correct working range.

2. ***Liquid slag***: the liquid slag level can be higher than the custom housing lance tip during the process. Therefore, the slag can enter the custom housing lance and burn the sensor. The custom housing lance directs a compressed-air flux in front of the sensor, out of the custom housing lance tip into the furnace, to keep the slag out of the custom housing lance. The pressure of the slag at the custom housing lance tip can reach 1bar due to its height and density. Therefore, the pneumatic circuit was designed to withstand such pressure at the outlet port.
3. ***Steel drops***: steel drops and other impurities from the furnace can reach the sensor, for example during scrap loading. Again, compressed air flow keeps the sensor clean and the view angle free. The pneumatic circuit was designed to have an air speed of 50-60 m/s at the outlet port in front of the sensor.

Figure 2 illustrates the general design of the proximity sensor custom housing lance. It includes:

1. An ***external tube*** made of stainless steel. It has an external diameter of 60 mm and a thickness of 1 mm. When the custom lance housing is placed inside the carbon-oxygen lance's cooling jacket, its external tube comes into contact with the inner surface of the water-cooled injector. This surface can reach temperatures of up to 250°C at the tip. Compressed air flows from the back to the front of the external tube and exits into the furnace directly in front of the sensor. The rear of the external tube is sealed, with two connectors for the pneumatic circuit serving as the compressed air inlet. The front is open, and its diameter is reduced from 60mm to 30mm. This narrowing increases the air speed to 50-60 m/s.
2. An ***internal assembly*** made up of:
    a. A group of three copper tubes welded together. The central tube allows the electric cables of the sensor to be brought outside of the external tube. The two lateral tubes are part of the water-cooling circuit, one is the delivery pipe, and the other one is the return pipe. The water tubes are welded to the tube of electric cable to keep it at low temperature. Indeed, the temperature of the compressed air, provided by a blower, increases with the pressure drop in the pneumatic circuit and can become higher than the maximum allowed by the electric cables.
    b. A sensor small housing made of stainless steel. It is connected to the three copper tubes and allows the heat exchange between the sensor and the cooling water. This small housing is equipped with a thermocouple to constantly monitor the process sensor (camera, microphone or TOF) temperature and to check the effectiveness of the designed water-cooling circuit in EAF application.

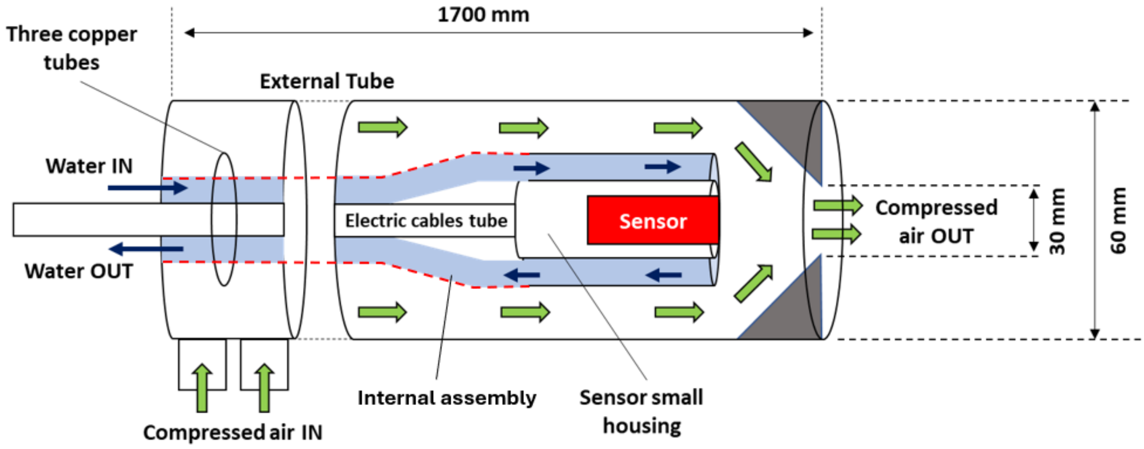

Figure 2. Custom housing lance functional scheme

1.2 Fluid Dynamic Simulations

A fluid dynamics simulation program was implemented to facilitate the precise dimensioning of the air pump and the air passage cross-sections within the lance.

FEM simulations have been performed to estimate the pressure drop within the custom housing geometry. The chosen blower is a claw pump which works at constant angular speed. It keeps the flow rate almost constant in the pressure range between 0.5 bar(g) and 2.3 bar(g). At 0 bar(g) the flow rate is maximum, equal to 140 m^3/h. While the pressure increases, the blower flow rate decreases, reaching the value of 110 m^3/h at 2.3 bar(g). The 2.3 bar(g) maximum pressure, that the blower can withstand, allows to face the pneumatic circuit pressure drop and the possible maximum slag pressure.

Sample of these simulations are presented in **Figure 3** and **Figure 4**.

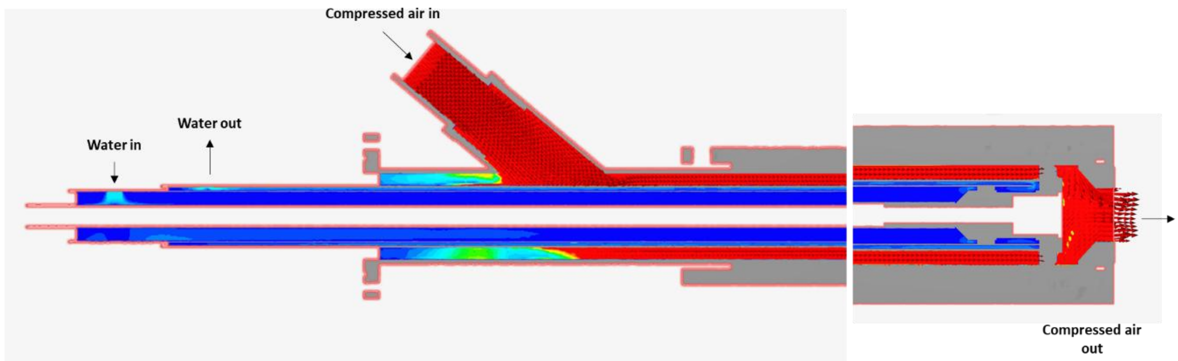

Figure 3. Fluid dynamic simulations of water and air flow inside the proximity sensor lance.

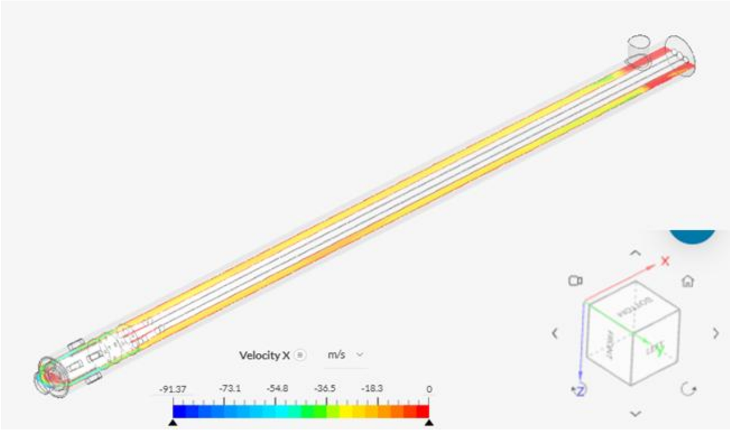

Figure 4. Fluid dynamic simulations to study the pressure drop of compressed air in the Custom Housing Lance

2 Proximity Sensor Manufacturing and Assembling

Once the proximity sensor design was complete, all components were either custom-made using specialized machining or purchased from specialized suppliers. After that, the system's assembly began at the CSM laboratories in Rome.

2.1 Custom Housing Lance

As described earlier, the custom housing lance is comprised of several key components. It has an external stainless-steel tube (proximity sensor external tube) and a separate internal block of three welded copper tubes (copper tubes block), which transport cooling water and electrical data cables. At the tip of the lance is a small stainless-steel head (sensor small housing) that houses the sensor and faces the inside of the electric furnace.

Figure 5 shows the internal parts of the custom housing lance, as they are fully manufactured and ready for assembly with the rest of the system.

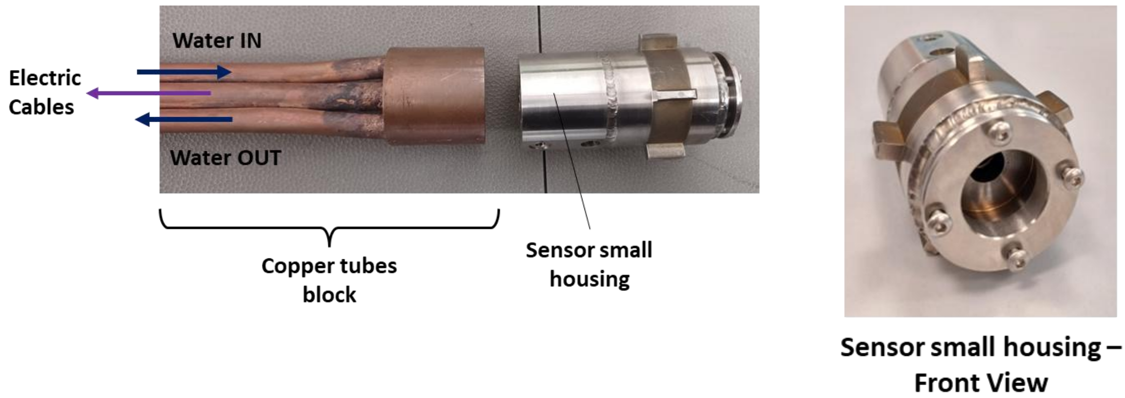

Figure 5. Internal Parts of Proximity Sensor Custom Housing Lance

Figure 6 shows a simple scheme of the mounting procedure of the custom housing. The custom housing of the Proximity Sensor is assembled by inserting the internal block into the external tube. Then the custom housing is inserted into the carbon-oxygen lance cooling jacket which is mounted on the EAF.

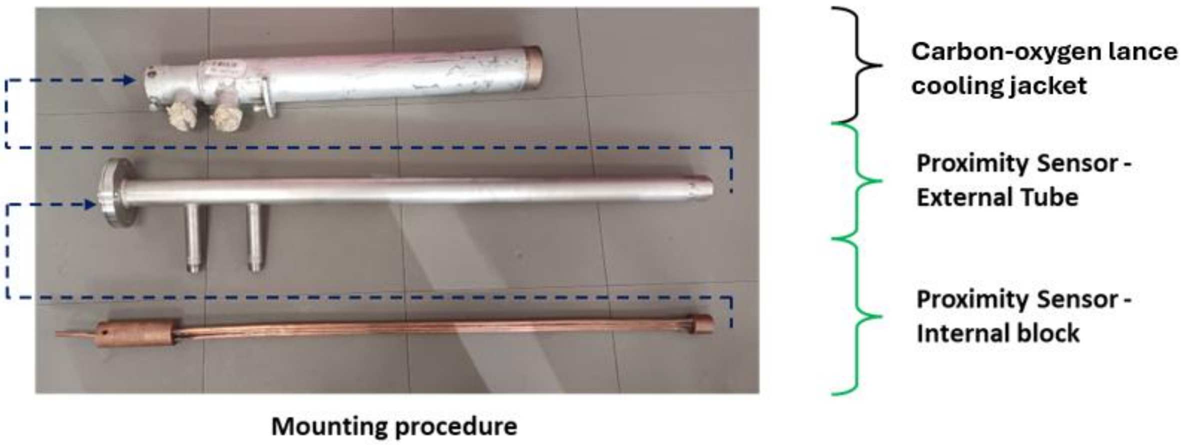

Figure 6. Custom Housing Lance mounting procedure

Figure 7 shows the custom housing lance assembled and inserted inside the carbon-oxygen lance cooling jacket.

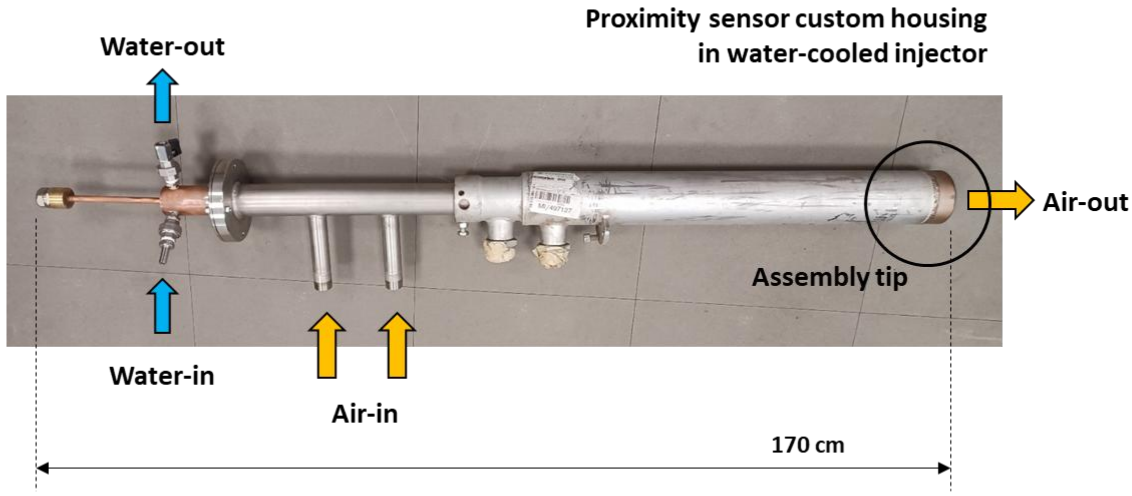

Figure 7. Proximity Sensor custom housing lance within the carbon-oxygen lance water-cooled jacket.

Figure 8 shows a frontal view of the proximity sensor custom housing lance as it sits inside the water-cooled jacket of the carbon-oxygen lance.

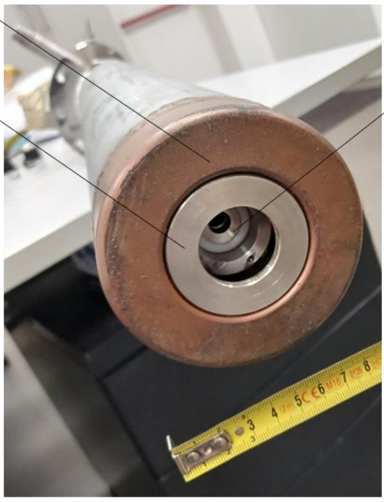

Figure 8. Proximity Sensor custom housing lance frontal view

2.2 Pneumatic Circuit

This circuit includes a blower, tubes to bring air to the custom housing inlet ports, monitoring sensors and pneumatic components:

- Blower. The blower's selection was based on the required air velocity and pressure at the custom housing's outlet, just in front of the sensor. The unit had to deliver an air velocity of 50-60 m/s and tolerate the slag pressure of 1 bar at the injector end. After performing FEM simulations with this data, an Atlas Copco DZS 150 dry claw vacuum pump was chosen.
- Tubes. Specialized canvas and plastic tubing were selected to tolerate both the high pressure and the temperature of the air. Due to the significant compression, the air's temperature is calculated to reach up to 150°C.
- Monitoring sensors. The pneumatic circuit was equipped with two sensors (see the figure below), a thermocouple and a pressure transducer that measure respectively the temperature and the pressure of compressed air at the output port of the blower to monitor its behaviour.
- Other components. A manual valve was mounted at the output port of the blower (see the figure below) to adjust the portion of flow rate that goes into the pneumatic circuit releasing the other portion to the environment.

Figure 9 shows the main components of the pneumatic circuit of the proximity sensor after laboratory assembling.

Figure 9. Pallet with compressed air blower and electric box

2.3 Hydraulic circuit

The hydraulic circuit includes a chiller, an electric box, dedicated sensors (for measuring temperature and pressure at various points in the circuit), hydraulic tubes, and hydraulic components (valves, vents, etc.). The chiller was chosen considering the pressure drop in the hydraulic circuit, calculated through FEM simulation, and based on the heat that the water absorbs near the tip of the lance, where the system experiences maximum heating. **Figure 10** shows the chiller used for the proximity sensor's hydraulic circuit.

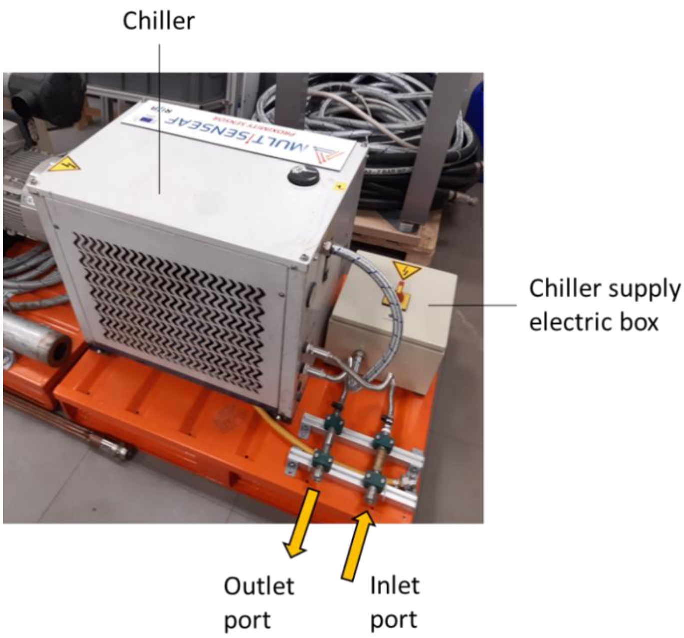

Figure 10. Proximity sensor chiller

2.4 Electric boxes

The measuring system consists of three IP65-rated galvanized steel electrical boxes with the following functions: controlling the chiller's power, supplying three-phase power to the air pump, and managing/transforming the signals from the sensors near the lance.

Figure 11 shows the electrical box that contains the components for turning the water-cooling chiller on and off. **Figure 12** shows the blower electrical box that manages the three-phase power supply for the air pump's on/off control and includes some electronic components needed to power the sensors and transfer data to the acquisition PC. **Figure 13** shows the electrical box that is installed near the lance and is used to transform the sensor signals for transfer over longer distances.

Figure 11. Water-cooling chiller electrical box

Figure 12. Blower electric box that manages the three-phase power supply for the air pump's on/off control

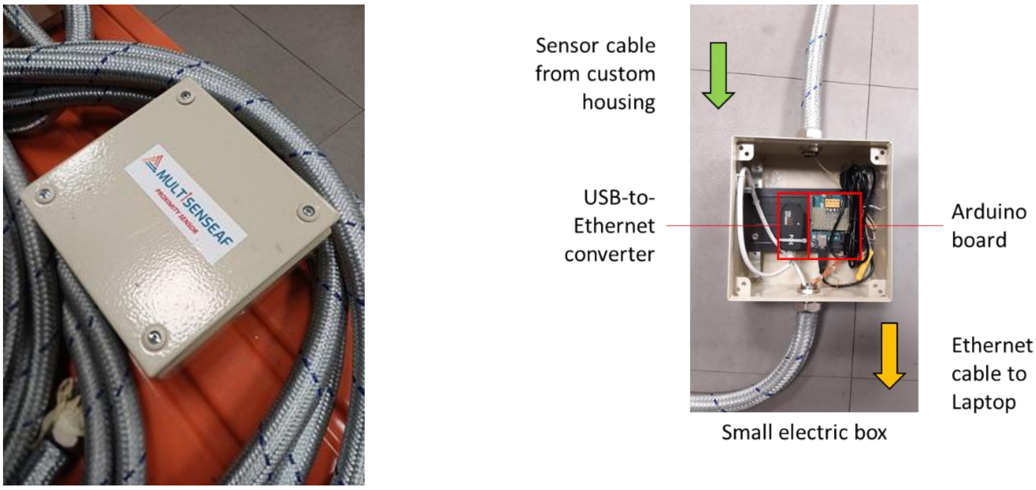

Figure 13. Electrical box installed near the lance used to transform the sensor signals

2.5 EAF Process sensors

As already mentioned in Section 1 on the design, the proximity sensor measurement system can accommodate different types of sensors within the custom housing lance (though not simultaneously). In this project, three types of sensors were tested: a camera, a microphone, and a time-of-flight (TOF) distance sensor.

2.5.1 General data transmission scheme

The three sensors integrated into the custom housing lance utilize several common components for data transmission. The camera and the microphone use the USB standard for data transmission, while the TOF distance sensor communicates via the I²C protocol. For safety reasons, the operator must remain at least 26 meters away from the measurement area, which requires an equivalent cable length for data transmission. Because neither the USB nor the I²C standards can reliably support such distances, an alternative solution was implemented. Data transmission was therefore shifted to CAT5e Ethernet cabling through a USB–Ethernet conversion system composed of two modules: one converting USB to Ethernet, and another converting Ethernet back to USB. The camera and microphone can be directly connected to the USB-to-Ethernet module. The TOF sensor, on the other hand, cannot interface directly via USB; its distance measurements are first acquired by an Arduino Uno (which supports the I²C protocol) and then sent via USB to the same USB-to-Ethernet module.

Both the USB-to-Ethernet module and the Arduino board are housed in a small box (**Figure 13**) located near the custom proximity sensor housing. From this point onward, the three sensors share a common Ethernet transmission line.

A 26-meter CAT5e cable connects the small box to the laptop, where the signal is converted back from Ethernet to USB using the Ethernet-to-USB module. The Ethernet cable runs through the blower electrical box (**Figure 12**), where a female–female RJ45 connector allows the line to be split into two 12-meter segments instead of a single 26-meter cable.

Figure 14 shows the overall schematic of the data transmission system from the proximity sensor custom housing to the acquisition computer (laptop).

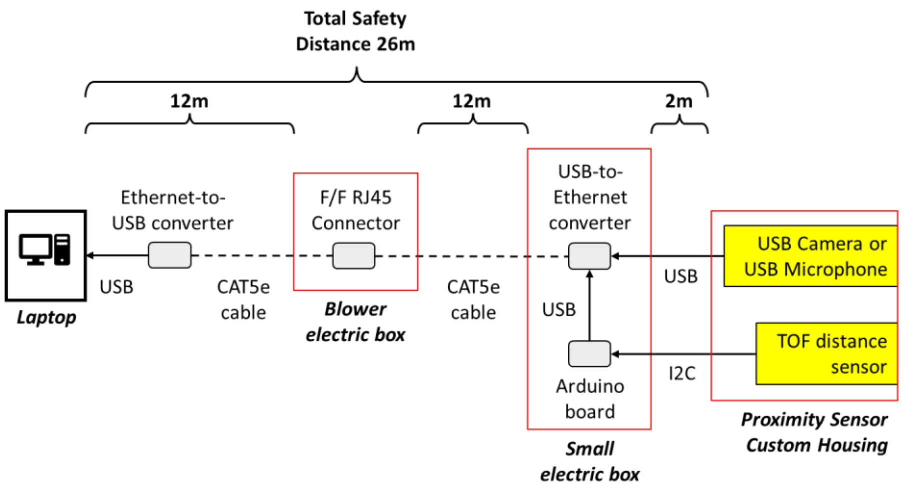

Figure 14 - Transmission scheme of measurements from process sensors (camera, microphone and TOF distance sensor) to laptop

2.5.2 Camera sensor

The chosen USB camera is a borescope due to its small dimensions. Its diameter is only 8 mm. The borescope can focus objects at 10 cm. This distance is too short for the purpose of looking inside the EAF. For this reason, a divergent lens with focal length of –10 cm was placed in front of the borescope to move the focus plane at about 2 m. A sapphire window was placed in front of the divergent lens to protect it. The camera, the divergent lens and the sapphire window are all placed inside the small sensor housing. **Figure 15** shows the borescope camera used for the final tests of the system.

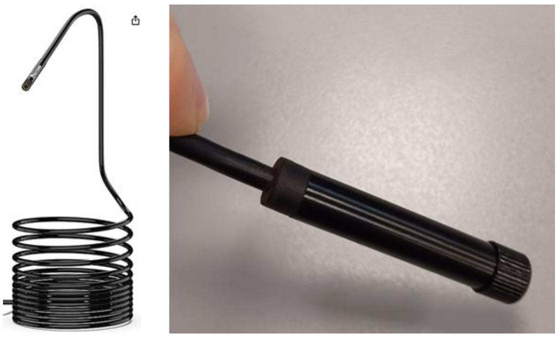

Figure 15 - USB borescope camera to look inside the EAF

2.5.3 Microphone sensor

Among the various sensing options that can be integrated into the proximity-sensor assembly, an acoustic sensor has also been included. This sensor is mounted at the tip of the custom housing lance. The rationale is that the acoustic field localized at the lance tip may carry information about burner operation and/or local phenomena such as water leaks or falling debris. Consequently, it is expected that analysing these localized acoustic signals can yield site-specific information that would otherwise be inaudible from more remote positions. This type of acoustic sensor therefore complements the external furnace acoustic sensor, which instead provides global information on the overall furnace behaviour.

Microphone with 8mm diameter

Figure 16 - USB microphone for audio recordings

The chosen microphone has a diameter of 8 mm. The preliminary tests of the Proximity Sensor assembly, performed in RINA-CSM facilities and described in the following chapters, highlighted a saturation issue due to compressed air and blower noise. An electronic filter was then introduced as countermeasure to tune the voltage measurement amplitude. In particular, the custom filter was introduced between the microphone and the USB connector and placed inside the small electric box that already contains the USB-to-Ethernet module and the Arduino board for TOF measurements acquisition. The electronic filter has a trimmer (variable resistance) which allows to change the filter gain whose reduction could avoid the microphone electronic saturation. A 3D printed custom housing was realized for the filter. Decreasing the variable resistance value R2, the amplitude gain reduces but the filter cutting frequency increases. A trade off must be found. Indeed, a higher cutting frequency leaves possible low frequency noise unchanged. A sapphire window was placed in front of the microphone to protect it in the custom housing. It works also as a sound attenuator against saturation. **Figure 16** shows the microphone used for final system testing. **Figure 17** shows a photograph of all the components in the measurement chain: the microphone, the electronic filter (housed in the 3D-printed enclosure), and the USB connector.

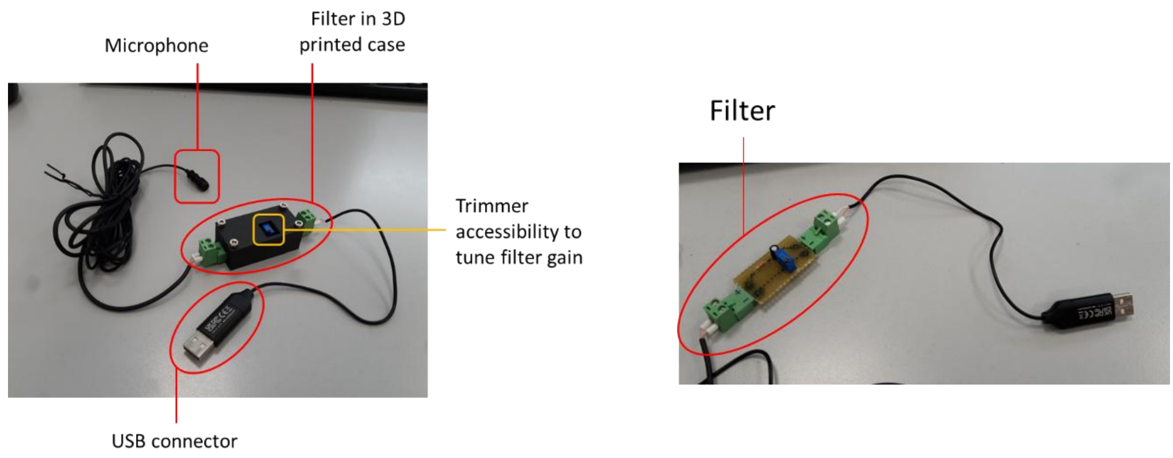

Figure 17 - Microphone measurement chain

Figure 18 presents the electronic circuit scheme of the filter and a detailed close-up photograph of it.

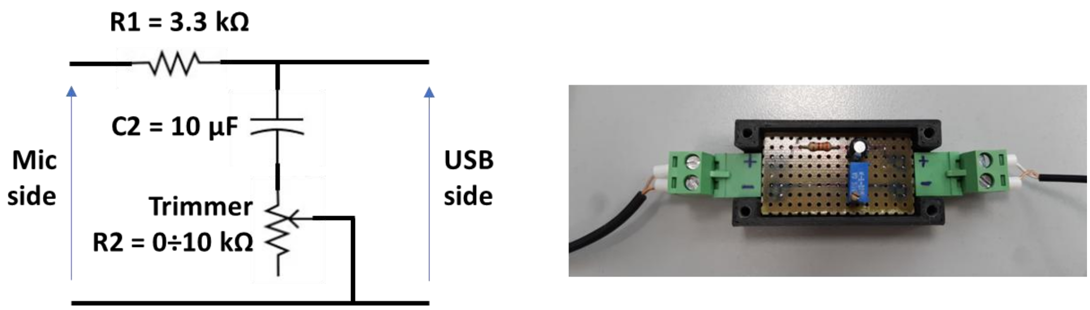

Figure 18 – Filter electronic circuit and detailed photograph

2.5.4 Time of flight sensor

To implement the proximity sensing functionality, a commercial time-of-flight (ToF) sensor was employed, which uses infrared radiation to measure distances of up to 4 meters.

Figure 19 illustrates the assembly of the TOF sensor. The photo on the left shows the complete sensor custom housing lance. The top-centre and top-right images display a detailed view of the injector tip with the TOF sensor inserted inside. The bottom-right image shows the TOF sensor prior to its insertion into the lance.

As visible in this photograph, the TOF sensor was housed in a small 3D-printed enclosure designed to adapt the sensor to the geometry of the proximity sensor tip. The design of the 3D-printed housing was optimized to keep the window sufficiently close to the sensor, thereby minimizing reflection issues that could compromise the measurements. A transparent protective window is positioned in front of the sensor.

The bottom-centre image shows the electronics used for data acquisition from the TOF sensor, built with an Arduino board and housed in the small electrical box (**Figure 13**) located outside, but in close proximity to, the lance.

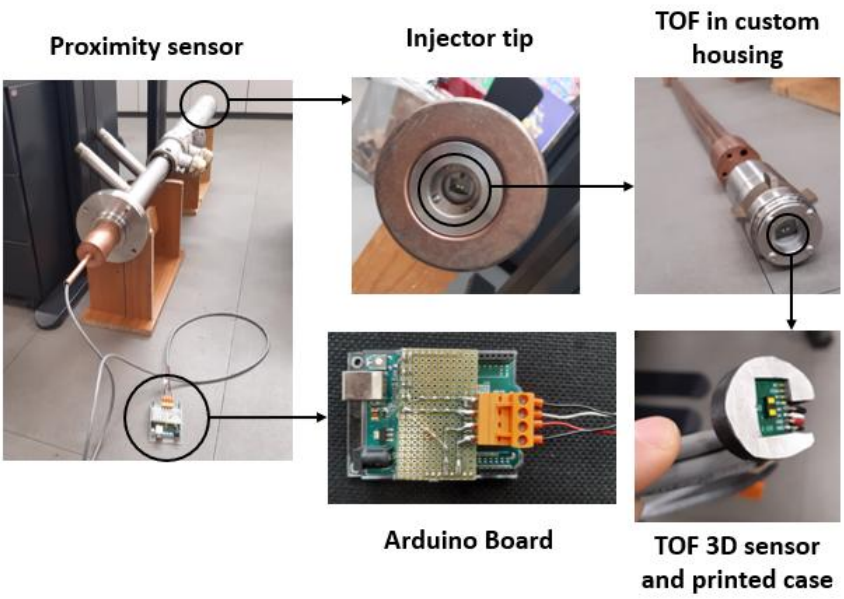

Figure 19 - Assembly of the TOF sensor

The Arduino I2C protocol has its high level at 5V while the TOF board works at 3.3V (recommended range 2.6V – 3.5V). A custom shield was designed to have the Arduino I2C protocol working at 3.3V as well.

First, the pull-up resistors that link by default the SDA and SCL pins of Arduino board to its 5V must be disabled. Then, the custom shield is used to link the SDA and SCL pins to the 3.3V pin through 4.7kΩ resistors.

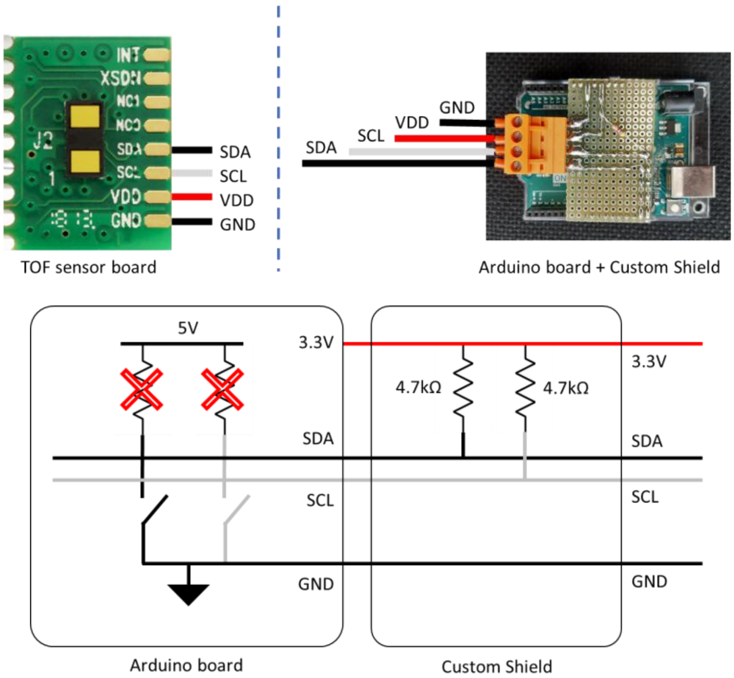

Figure 20 - Custom shield for Arduino board to interact with TOF distance sensor

Figure 20 shows the commercial TOF sensor and its Arduino interface at the top, with the connecting electronic circuit shown at the bottom.

2.5.5 Life check sensors

This group of sensors include the thermocouple to monitor the EAF process sensor temperature while in service, the thermocouple to monitor the compressed air temperature at the output port of the blower and the pressure transducer to monitor the compressed air pressure at the output port of the blower. The two thermocouples are of type K. An Arduino board equipped with a shield for thermocouples acquisition is used to acquire data from the three sensors and is placed in the electric box on the blower pallet. Another USB-Ethernet converter is used to bring data from Arduino Uno Board to the laptop for 12 m.

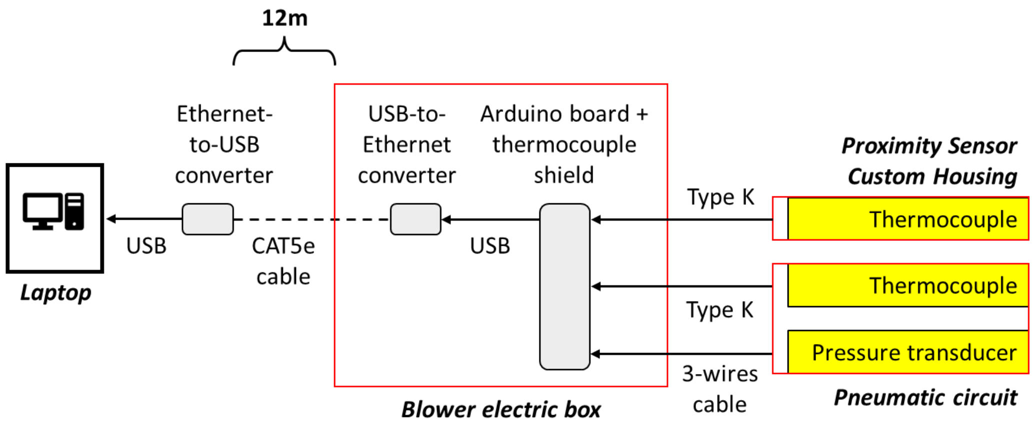

Figure 21 – Transmission scheme of measurements from life-check sensors to laptop

Figure 21 shows the transmission scheme of how the life check sensors are connected.

Figure 22 shows the two boards, thermocouples shield and Arduino Uno, used for life check sensors data acquisition.

Figure 23 illustrates the three sensors utilized as life check sensors.

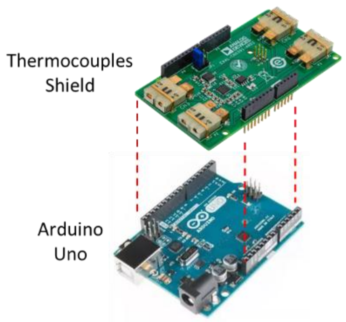

Figure 22 – Boards for data acquisition

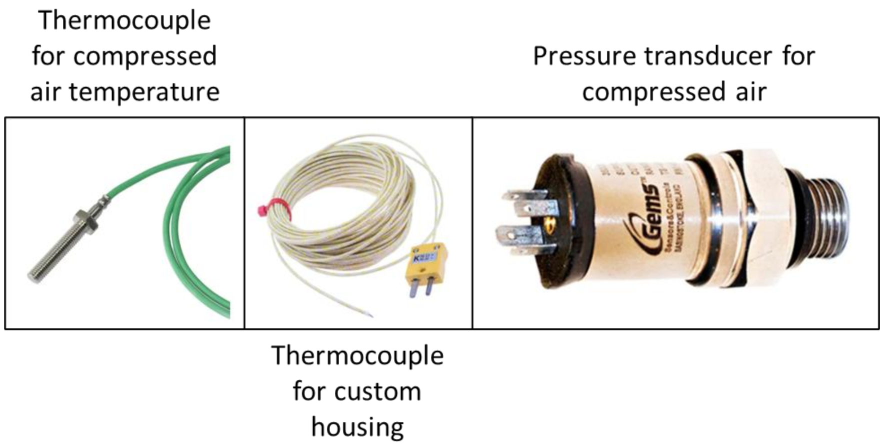

Figure 23 - Sensors used as life check sensors

2.5.6 Software development

Four software have been developed to acquire, save and display data:

- **Arduino code for TOF sensor**: Arduino Uno board reads data and transmits data to the laptop.
- **Arduino code for thermocouples and pressure transducer**: The Arduino Uno board reads data and transmits data to the laptop.
- **Desktop App for distance, temperatures and pressure measurements**: It is an MFC App written in Visual Studio C++: It runs on the laptop, asks Arduino boards for the measurements, saves them in the laptop and displays them in real time.
- **Desktop app for audio recordings**: It is an MFC App written in Visual Studio C++. It runs on the laptop, receives the audio records from the microphone, saves them in the laptop and displays them in real time.

2.5.6.1 App desktop for distance, temperatures and pressure measurements.

The App user interface is shown in **Figure 24**.

User interface description:

1 **Setup**:
   a. Insert database name. The user must insert the name of the test. This name is used in the .txt files where data are saved. Temperatures and pressure measurements (standard measures) are saved in a file titled name_MisStd.txt while TOF measurements are saved in a file titled name_MisTOF.txt.
   b. Select measures. The user can choose to record standard measures and/or TOF measures. The standard measures can always be recorded while TOF measures only when TOF sensor is mounted in the Proximity Sensor.
   c. Save or modify setup. If the User clicks on Save button, fields 1 and 2 are frozen and the Start recording button (2) is enabled. If the User pushes the Modify button, the Start recording button (2) is disabled and fields 1 and 2 become editable again.

2 **Measures acquisition:**
   Start and Stop button allows to start and stop data recordings.

3 **Standard measures:**
   Standard measurements (Camera/TOF/Microphone temperature, compressed air temperature, compressed air pressure) are displayed in real time. The interface tells the User if a communication error between the laptop and the Arduino board occurs.

4 **Time of flight measure:**
   TOF measures are displayed in real time. The interface tells the User if a communication error between the laptop and the Arduino board occurs. The Arduino board sends to the laptop the distance measurement and the measurement status which tells the user if the data is trustable or not.

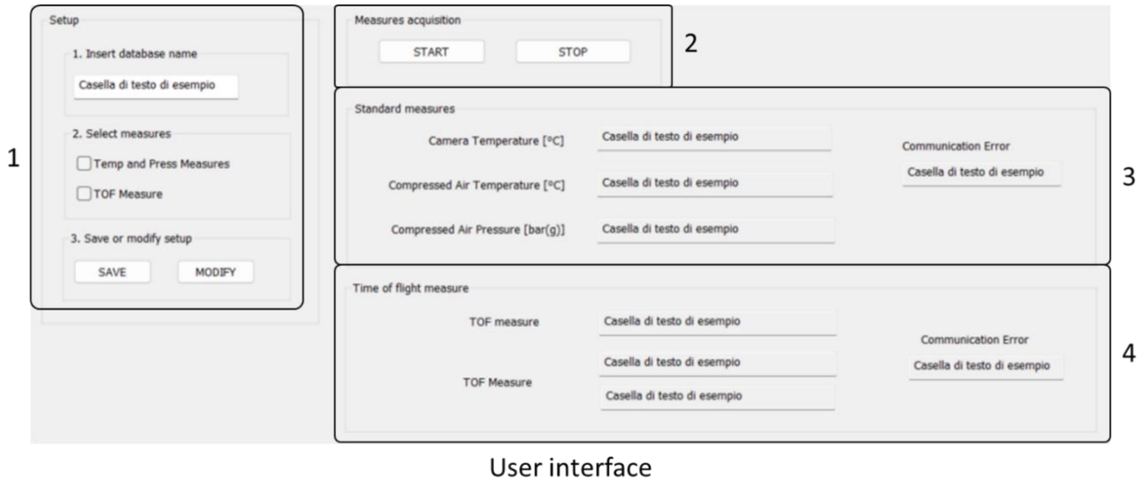

Figure 24 - Software user interface for distance, temperatures and pressure measurements visualization and saving

2.5.6.2 Desktop app for audio recordings.

The App user interface is shown in **Figure 25**.

User interface description:

1 **Saving setup**: It allows the User to insert and save File name, test day and test starting time.
2 **Recording control**: Start and Stop button allows to start and stop data recordings.
3 **Close App**: Ok button allows to exit the application.
4 **Max value graph**: This graph shows the maximum value recorded every 1 second. It allows the User to check if the microphone is saturating (measurement equal to 100) or not.
5 **Average value graph**: This graph shows the average value recorded every 1 second.
6 **RMS value graph**: This graph shows the RMS value recorded every 1 second.
7 **FFT spectrum**: This graph shows the frequency spectrum of 1 second audio recording at a time. It allows the User to check the effectiveness of the electronic filter at different frequencies.

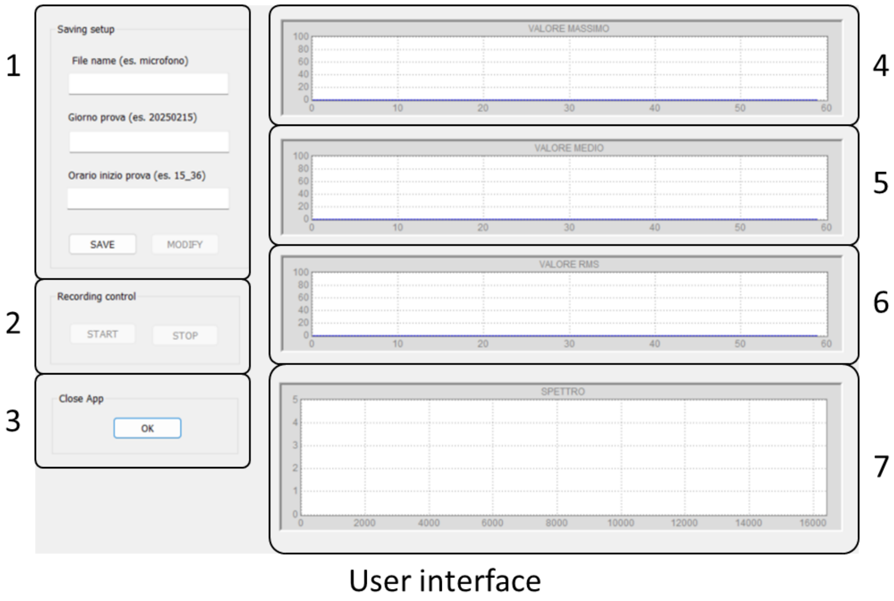

Figure 25 - Software user interface for audio recording and audio analyses

3 Preliminary lab test and preparation for semi-industrial tests

3.1 Preliminary lab test

Preliminary tests were conducted at the RINA CSM facilities in Rome to verify the correct functioning of all proximity sensor components.

In the following pictures, the full assembly mounted in a CSM shed can be seen. It is possible to recognize all the parts of the system: the proximity sensor custom housing lance with sensors inside (**Figure 26**), the cooling water chiller (**Figure 27**) and the compressed air blower and service tubes (hydraulic tubes, pneumatic tubes and flexible metal conduit for electric cable protection – **Figure 28**).

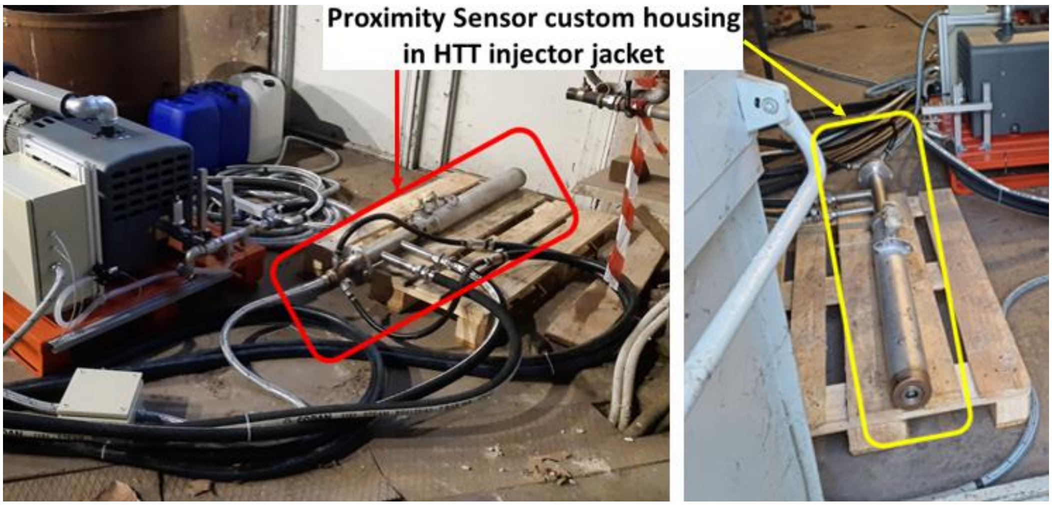

Figure 26 - Proximity Sensor custom housing lance during preliminary tests at the RINA CSM facilities in Rome

Figure 27 - Proximity Sensor cooling water chiller during preliminary tests at the RINA CSM facilities in Rome

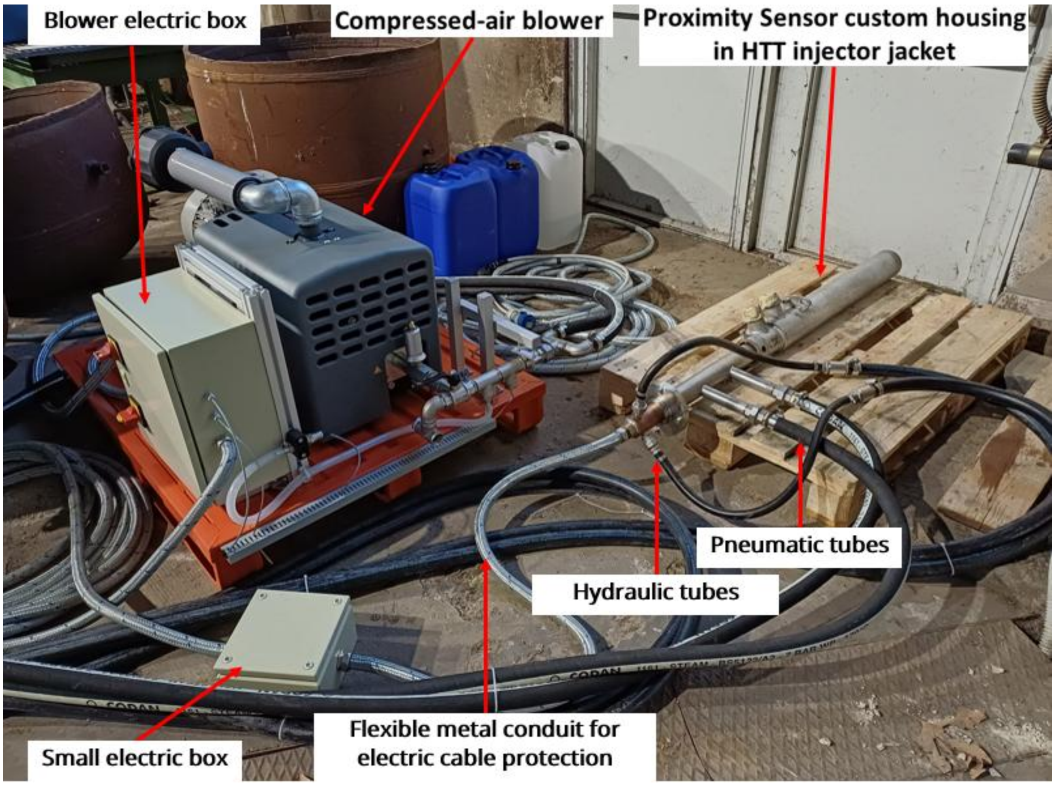

Figure 28 - Proximity Sensor compressed air blower and service tubes during preliminary tests at the RINA CSM facilities in Rome

3.2 Preparation for semi-industrial tests

Once the preliminary tests of the proximity sensor had been completed at the RINA-CSM laboratories in Rome, it became necessary to plan in detail the semi-industrial testing of the entire system at the RINA-CSM laboratories in Dalmine.

To carry out the semi-industrial tests, a preheating furnace located at the Dalmine laboratories was selected. The furnace measures 4 meters in internal length and 1 meter in internal width. **Figure 29** shows two photographs of the selected preheating furnace.

As can be seen in the photographs, several observation windows are distributed along the side walls to allow inspection of the furnace interior: four on the long sides (referred to as *long-side windows* - **Figure 29**, right photograph) and one on the short sides (referred to as *short-side windows* - **Figure 29**, left photograph). Two of these windows were selected for inserting the proximity sensor custom lance housing into the furnace — specifically, the short-side window on the burner side, and the second long-side window from the burner side.

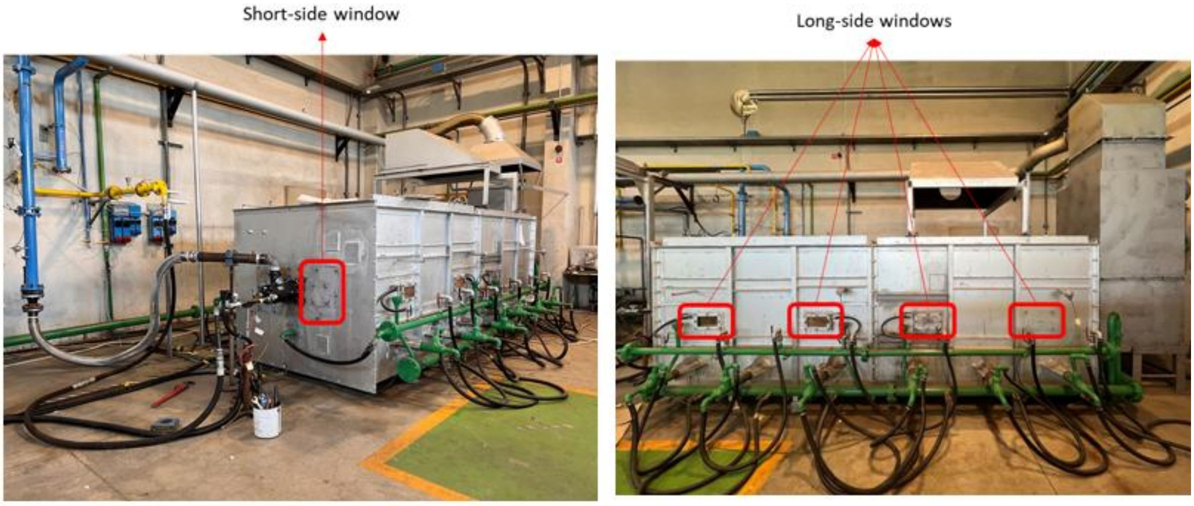

Figure 29 – Semi-industrial reheating furnace at RINA-CSM laboratories in Dalmine

Figure 30 shows the layout of the Dalmine reheating furnace, indicating the furnace dimensions, the locations of the windows used for inserting the proximity sensor during testing, the position of the scrap placed for the tests, and the burner position.

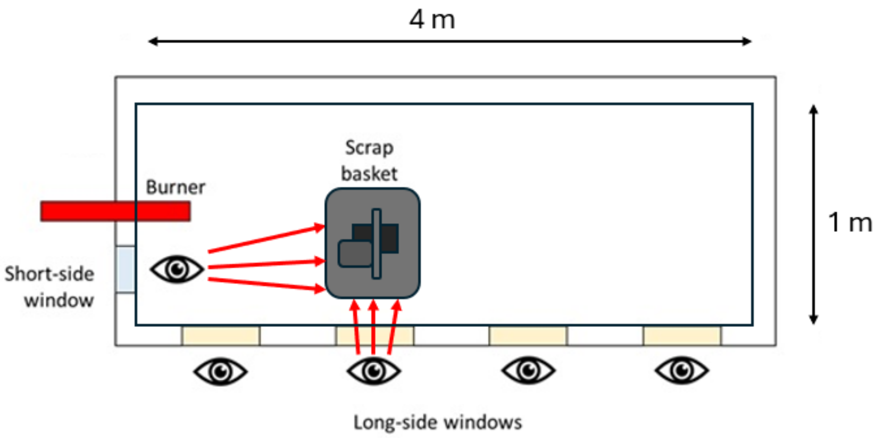

Figure 30 – RINA-CSM Dalmine Reheating Furnace top view

The selection of the observation windows allows for the evaluation of different operating conditions of the proximity sensor. Specifically, the position near the burner (short-side window) enables the assessment of a viewpoint where the flame flows parallel to the sensor’s line of sight, as well as the influence of the burner's proximity on the measurements in terms of noise and vibrations. This configuration most closely replicates the actual conditions that could occur in the electric furnace if the proximity sensor were to be installed on the HTT burner assembly. In contrast, the lateral position (long-side window) provides a completely different perspective, where the burner flame is farther away but more directly visible to the proximity sensor (greater direct radiation), being essentially perpendicular to its line of sight.

To correctly mount the proximity sensor on the furnace windows, a dedicated water-cooled flange was designed to accommodate the custom housing lance of the proximity sensor. In the semi-industrial tests, this component replaces the carbon-oxygen lance cooling jacket that would be used in the electric furnace. **Figure 31** shows the manufactured flange.

Figure 31 - Water-cooled flange for semi-industrial test at Dalmine reheating furnace

To verify that all water seals had been correctly executed, the water-cooled flange underwent a pressurized water leak test. The tests performed are shown in **Figure 32**.

Finally, due to the considerable overall weight and the large overhang of the proximity sensor and the water-cooled flange, which together extend to nearly 2 meters in length, it was decided to use an extendable tripod to support the rear part of the system. **Figure 33** shows this configuration.

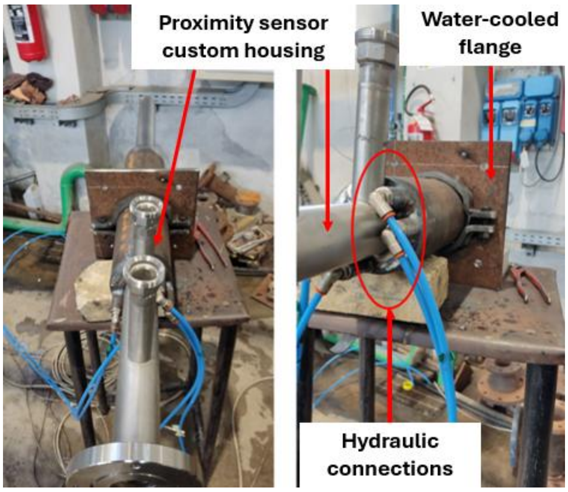

Figure 32 – Water-cooled flange pressurized leak test

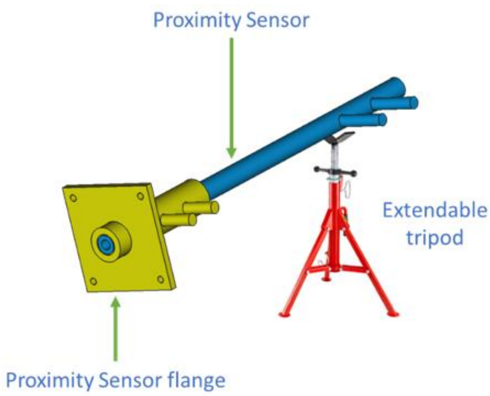

Figure 33 - Extendable tripod to support the rear part of the system

4 Sensor Tests at Semi-Industrial Furnace

In the week 7-11/07/2025, the Proximity Sensor was tested at RINA-CSM laboratory in Dalmine.

As detailed in the previous section, a reheating furnace with a rectangular internal footprint measuring 4 m in length and 1 m in width was selected for these tests. The furnace is equipped with a natural gas/air burner and four thermocouples, which are used to monitor the internal temperature throughout the testing procedure. **Figure 34** shows the plan view of the selected furnace, indicating the position of the burner, the two windows used for the tests (W1 and W2), the location of the four thermocouples (TE01, TE02, TE14, and TE16) and the distances of the scrap basket from the windows. The scrap basket was placed at 1300 mm from the W1 and 200 mm from W2. **Figure 35** displays the control panel used for operating the furnace.

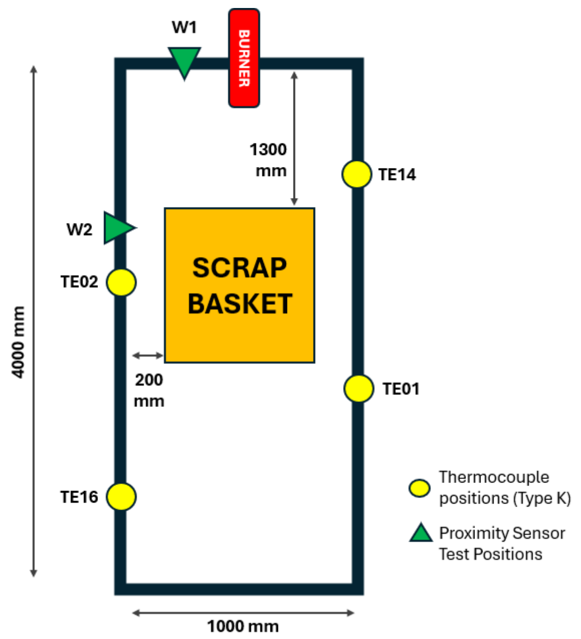

Figure 34 - Plan view of the furnace

Figure 35 – Furnace control panel

Figure 36 provides a photograph of the furnace interior during test preparation.

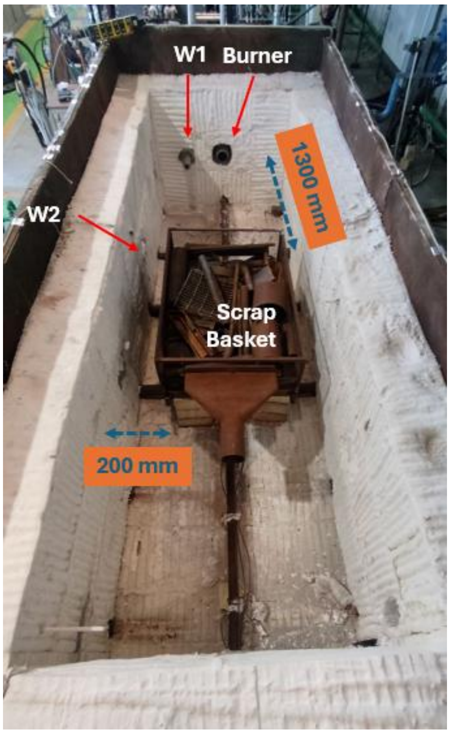

Figure 36 – Internal view of the reheating furnace used for Proximity Sensor semi-industrial tests at RINA-CSM Dalmine

4.1 Test N° 1 - with camera

For the first test, the proximity sensor was equipped with the camera and installed on the side of the burner at Window 1 (**Figure 37**).

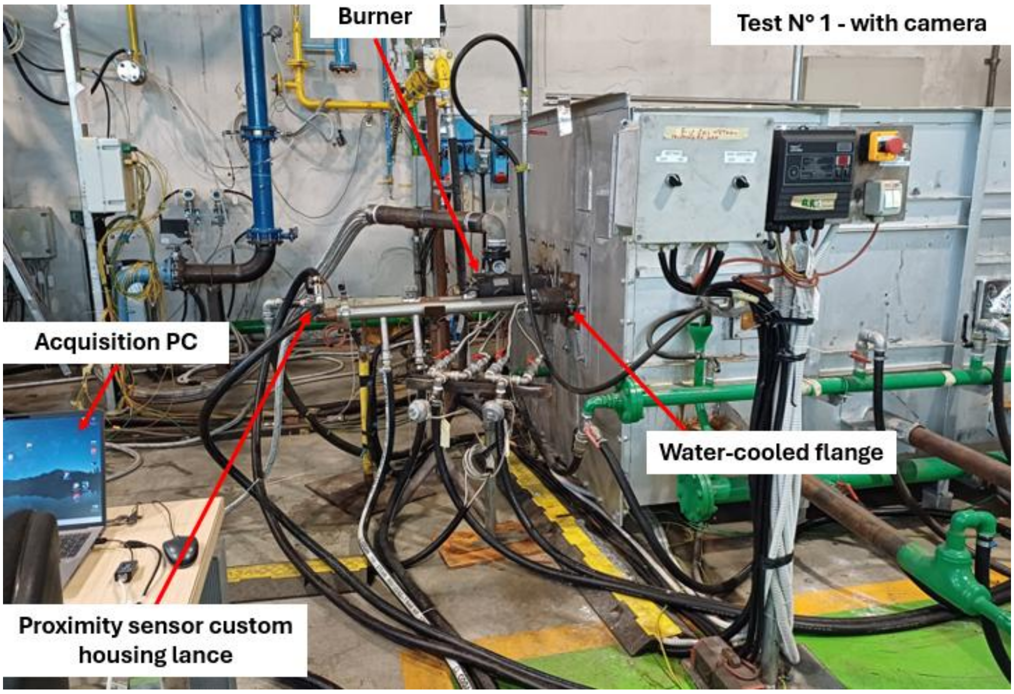

Figure 37 - Proximity sensor equipped with the camera installed in window W1 for Test N° 1

Prior to the test, while the furnace was still open (**Figure 38**), several preliminary checks were carried out. By observing the furnace from the open top, the proximity sensor was positioned such that its tip was flush with the inner surface of the insulating material (**Figure 39**). This configuration ensured that the tip was not excessively exposed to radiative heat.

Figure 38 – RINA-CSM Reheating furnace open before Test N° 1

Figure 39 - Proximity sensor flush with inner furnace surface

Figure 40 shows a detailed view of the custom water-cooled flange mounted on the W1 furnace window. **Figure 41** provides a close-up view of the proximity-sensor lance inserted into the custom water-cooled flange.

Figure 40 - Custom water-cooled flange mounted on the W1 furnace window

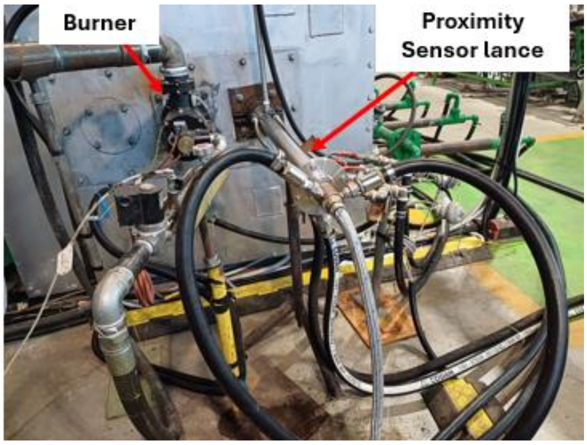

Figure 41 - Proximity-sensor lance inserted into the water-cooled flange

The following figures show the images taken by the proximity sensor camera during Test1.

Figure 42 shows the scrap basket inside the furnace when it was still open, before the test start. Then, the chiller and the blower were activated, and the furnace was closed and turned on.

Figure 43 shows the interior of the furnace, as captured by the proximity sensor camera, when the thermocouples measured a temperature of 600 °C.

Figure 44 shows the interior of the furnace, as captured by the proximity sensor camera, when the thermocouples measured a temperature of 900°C.

Figure 45 shows the interior of the furnace, as captured by the proximity sensor camera, when the thermocouples measured a temperature of 1160°C. This was the maximum temperature reached.

Figure 42 - Scrap basket inside the furnace when it was still open

Figure 43 – View of the interior of the furnace when the thermocouples measured 600°C

Figure 44 - View of the interior of the furnace when the thermocouples measured 900°C

Figure 45 - View of the interior of the furnace when the thermocouples measured 1160°C

The main findings of Test 1 can be summarized as follows:

- The camera sensor remained fully operational and sustained no damage throughout the test.
- The cooling circuit successfully maintained the camera housing at a temperature of 17.5 °C during the entire test, with the chiller outlet water temperature set to 10 °C.
- The maximum water temperature recorded in the chiller tank was 14.1 °C.

Based on these data, it is also possible to estimate the amount of heat absorbed by the water as it circulated through the cooling circuit [1].

[1] This calculation will be reported in the data analysis section.

4.2 Test N° 2 - with Camera

In this test the Proximity Sensor with the camera was moved from window 1 to window W2 on the furnace long side. **Figure 46** shows the proximity sensor custom housing lance and the water-cooled lance installed at window W2 for Test 2.

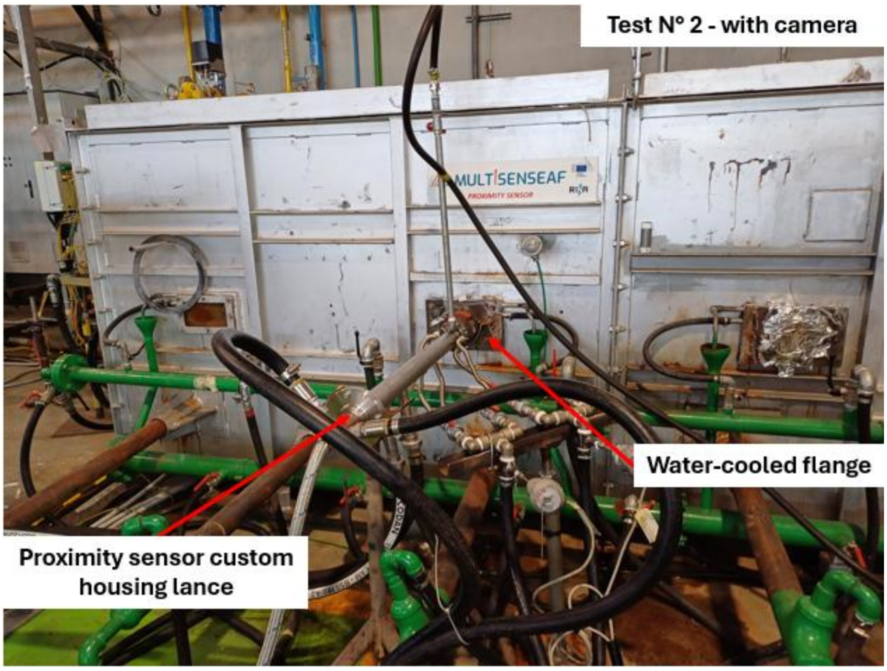

Figure 46 - Proximity sensor custom housing lance and the water-cooled lance installed at window W2 for Test N° 2

Figure 47, **Figure 48** and **Figure 49** present the images acquired by the proximity sensor camera with the furnace operating at 560 °C, 1000 °C, and 1100 °C, respectively. **Figure 50** presents the image as displayed on the Proximity Sensor acquisition PC.

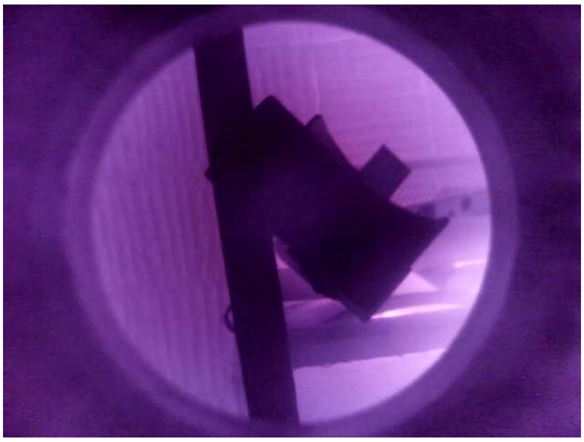

Figure 47 - Image acquired by the proximity sensor with the furnace operating at 560 °C

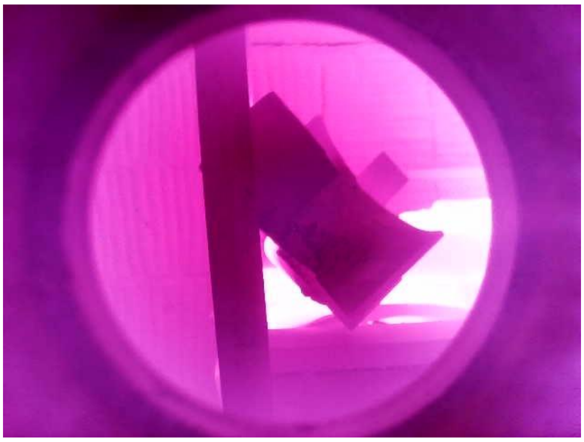

Figure 48 - Image acquired by the proximity sensor with the furnace operating at 1000 °C

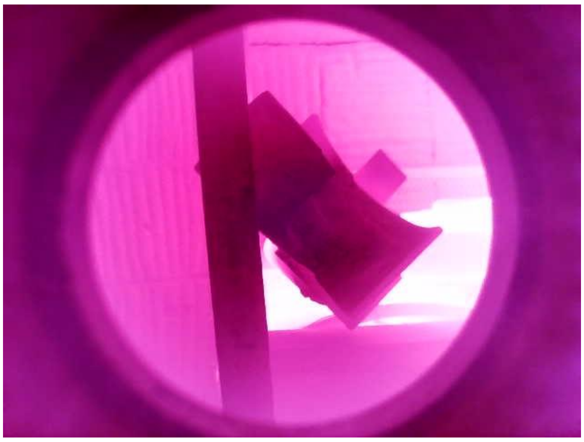

Figure 49 - Image acquired by the proximity sensor with the furnace operating at 1100 °C

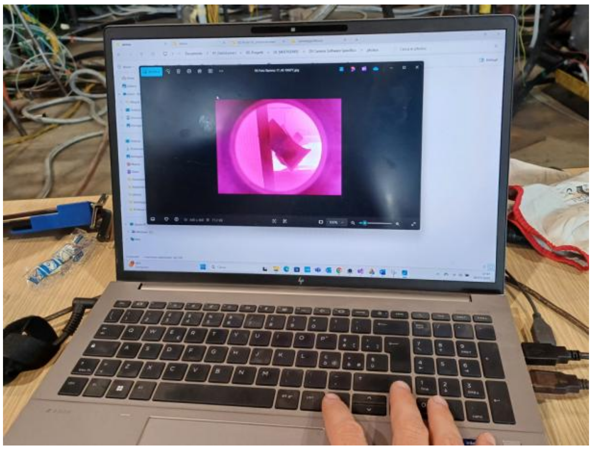

Figure 50 - Image as displayed on the Proximity Sensor acquisition PC

The main findings of test 2 can be summarized as follows:

- The camera sensor remained fully operational and sustained no damage throughout the test.
- The cooling circuit successfully maintained the camera housing at a temperature of 14 °C during the entire test, with the chiller outlet water temperature set to 10 °C.
- The maximum water temperature recorded in the chiller tank was 12 °C.
- At the maximum temperature, the camera exhibited a saturation effect, likely due to direct illumination from the burner.

Because the proximity-sensor camera lacks remotely adjustable brightness-attenuation capabilities, this limitation warrants further investigation, as it confines the camera's usability to a narrow and predefined brightness range.

4.3 Test N° 3 - with TOF

Like the previous test, this one was conducted with the proximity sensor situated at window W2, on the furnace long side, but with the TOF distance measurement sensor mounted inside the custom housing lance. Prior to closing the furnace, the distance between the scrap material within the basket and the insulation's internal surface was measured manually, confirming the value of approximately 200 mm from W2 and 1300 mm from W1.

Figure 51 shows the proximity sensor reinstalled in position W2 and ready for Test 3. **Figure 52** displays the proximity sensor acquisition software, which indicates a TOF measure of 223 mm from the target, the TOF (indicated as Camera) of 24.695°C and indicate the range of measure as "valid".

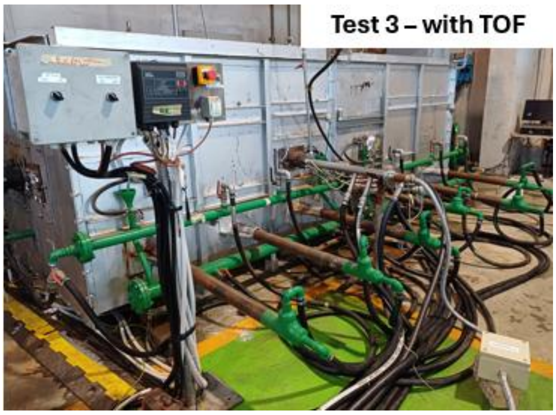

Figure 51 - Proximity sensor reinstalled in position W2 and ready for Test N° 3

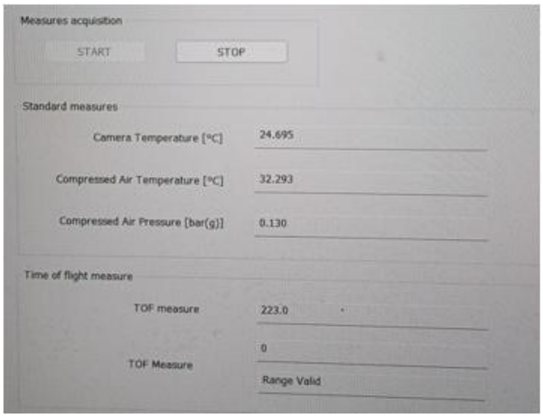

Figure 52 - Proximity sensor acquisition software

The TOF sensor performed accurate measurements until the furnace temperature reached approximately 800°C. Above this threshold, the sensor exhibited measurement anomalies. The test continued, however, to verify the survivability of the measurement system. The trial was sustained for 50 minutes, ultimately reaching a maximum furnace temperature of 930°C.

Figure 53 demonstrates that the TOF sensor temperature was maintained at 16°C, which is well within its maximum operational limits and the absence of communication errors between the sensor and the acquisition system (No Communication Error). So, the measurement problem certainly arises from the measurement methodology employed with hot scrap.

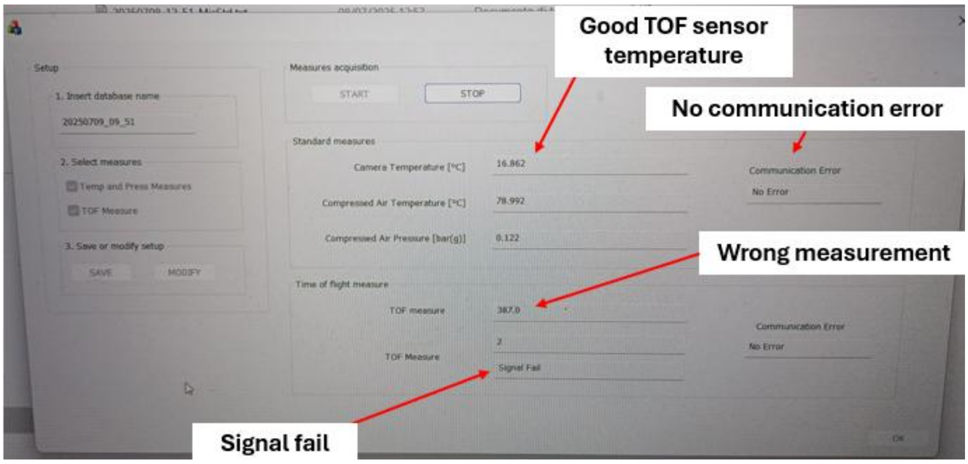

Figure 53 - Proximity sensor acquisition software during signal fault

The main findings of test 3 can be summarized as follows:

- The TOF measurement remained stable for the initial 35 minutes of the test, corresponding to a furnace temperature below the 800°C threshold.
- Exceeding this temperature, the sensor began to yield erroneous readings and subsequently suffered a signal failure.
- The TOF sensor was not compromised by the test; rather, the error was attributed to the measurement methodology employed, which is ineffective at the high target temperature.
- Consistent with prior tests, the sensor cooling system operated effectively, successfully maintaining the sensor at a sufficiently low operating temperature.

4.4 Test N° 4 – with TOF

In this specific trial, the proximity sensor equipped with the TOF sensor was positioned at window W1, adjacent to the burner. The target distance from the sensor tip to the scrap material was 1300 mm. The TOF measurement remained valid for approximately one minute (from the test initiation), subsequently transitioning to an unreliable measurement status. At the point of failure, the furnace's internal temperature was measured at 155 °C. In this instance, the anomaly was attributed to flame interference, which likely disrupted the laser signal. The trial was sustained for 20 minutes, ultimately reaching a maximum furnace temperature of 740°C.

Figure 54 shows the proximity sensor immediately before the start of Test 4. **Figure 55** shows the computer used for data acquisition from the proximity sensor.

Figure 54 - Proximity sensor at window W1 immediately before the start of Test N° 4

Figure 55 – Proximity sensor data acquisition PC

Figure 56 displays the sensor interface prior to the initiation of Test 4. The Proximity Sensor with TOF sensor is in "valid range" and measures 1253 mm, with the sensor temperature recorded at 16°C. In contrast, **Figure 57**, taken approximately one minute into the test, shows that the sensor signal has already transitioned to an error state (Signal fail). The reported TOF measurement is consequently erroneous and measures 1087 mm, despite the sensor temperature remaining optimal at 16°C.

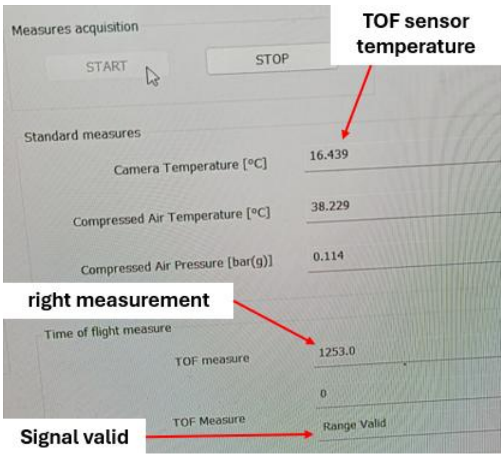

Figure 56 - Sensor interface prior to the initiation of Test 4

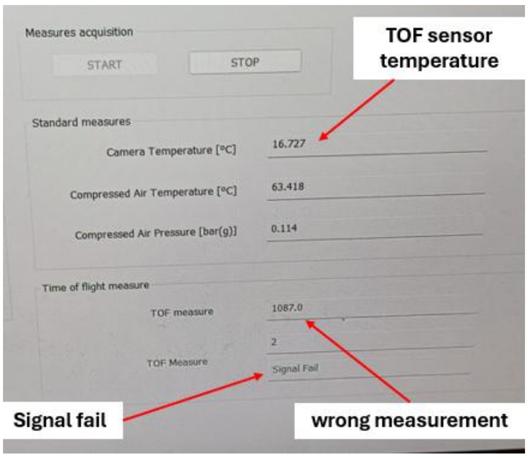

Figure 57 - Sensor interface taken approximately one minute into the Test4

The main findings of test 4 can be summarized as follows:

- Under the conditions of Test 4, with the TOF sensor positioned very close to the burner, interference occurred between the TOF laser signal and the burner flame, resulting in consistently unreliable distance measurements.
- The cooling system of the proximity sensor performed reliably during the test, keeping the sensor temperature within its safe operating range.

4.5 Test N°5 – with microphone

On June 10, 2025, the final proximity sensor test was carried out at the RINA-CSM laboratory in Dalmine. For this test, the proximity sensor was equipped with a microphone and installed in window W1. Because the preheating furnace does not operate at specific acoustic frequencies that would warrant targeted audio analysis, the primary objective of the test was to verify whether the microphone could withstand the furnace's acoustic environment without saturating, and to determine the appropriate configuration needed to obtain high-quality recordings.

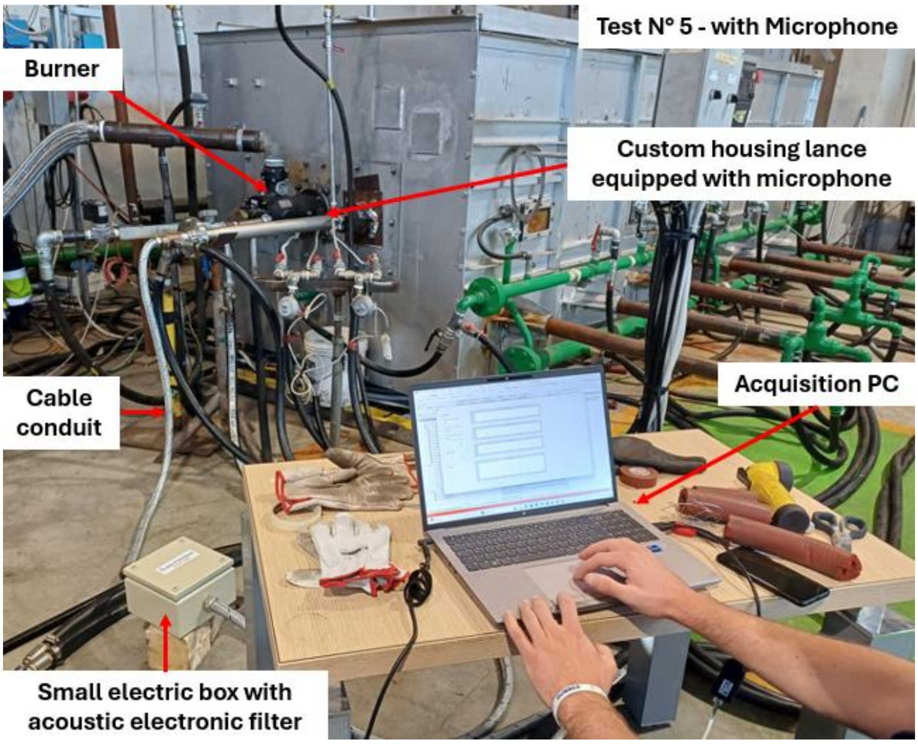

Figure 58 - Proximity sensor equipped with the microphone installed in window W1 for Test N° 5

Prior to installing the proximity sensor in window W1, several preliminary checks and noise-acquisition tests were performed outside the furnace. These tests immediately revealed that the microphone was strongly affected by sound originating from behind the sensor; in other words, it exhibited higher sensitivity to noise coming from the lance and cable conduit than to frontal sound. This issue would have compromised the measurement campaign, as the microphone would have predominantly captured noise generated outside the furnace rather than acoustic signals from inside.

To address this, the protective glass positioned in front of the microphone was first removed, as it acted as an almost impenetrable acoustic barrier to frontal sound (**Figure 59**).

Subsequently, sound-absorbing material (like rubber) was inserted into the cable conduit housing the microphone's electrical cable. The unwanted noise was in fact propagating from the external small electric box, travelling through the cable conduit and the lance, and ultimately reaching the microphone; installing the sound-absorbing barrier effectively eliminated this issue.

Figure 59 - Lance tip without protective glass

Finally, the compressed-air system was activated to assess potential microphone saturation caused by compressed air-jet noise. It was necessary to reduce the gain of the acoustic electronic filter to prevent sensor saturation. The gain was set so that the maximum amplitude of the compressed-air noise reached approximately 40% of the full-scale range. After these adjustments, Test No. 5 was started and conducted until the furnace reached 1030 °C.

5 Data analysis

5.1 Camera Test Data Analysis

Camera tests were conducted on July 8, 2025 (Tests 1 and 2) at the RINA-CSM laboratories in Dalmine. **Figure 60** illustrates the temperature profiles measured inside the reheating furnace by thermocouples TE001, TE002, TE014, and TE016 (refer to **Figure 34** for the thermocouple layout). As the figure shows, furnace preheating was necessary prior to the tests to verify its correct operation. Subsequently, the proximity sensor lance was inserted into Window W1. At approximately 14:30, the burner was reignited to heat the furnace to approximately 1090°C (Test 1). The Test 2 commenced at approximately 17.00 with the proximity sensor lance inserted into Window W2, bringing the furnace temperature to approximately 1070°C.

As described in the previous sections, the camera showed no issues when used inside the lance. However, the strong brightness variations inside the furnace—caused both by the direct view of the flame and by the rising temperature of the scrap—can create saturation conditions for the camera sensor.

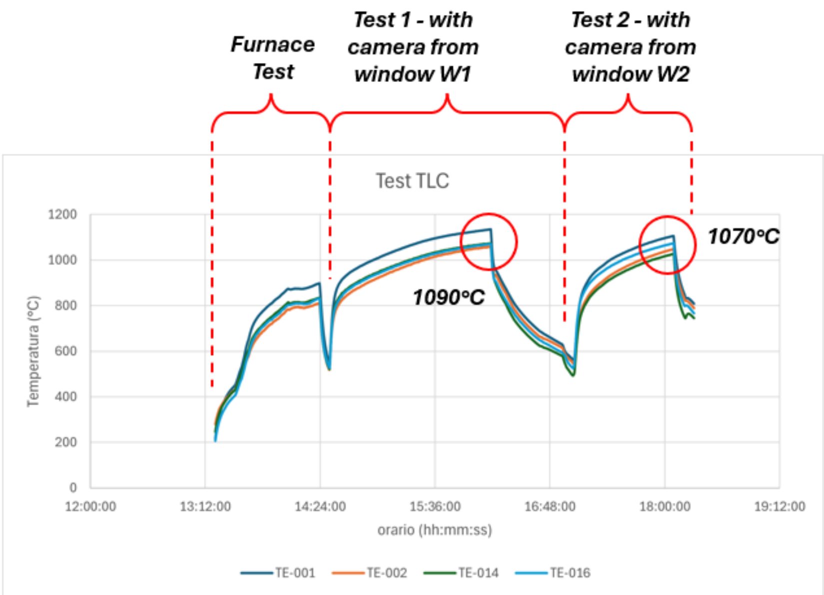

Figure 60 - Camera tests furnace temperature profile

5.2 TOF Test Data Analysis

The TOF sensor tests were conducted on July 9, 2025 (Tests 3 and 4) at the RINA-CSM laboratories in Dalmine. **Figure 61** shows the temperature profiles inside the reheating furnace as measured by thermocouples TE001, TE002, TE014, and TE016 (see **Figure 34** for the thermocouple layout). As the figure indicates, the temperatures reached during these tests were lower than in earlier ones. This occurred because, once it became clear that the sensor was not measuring correctly, the decision was made to shorten the overall test duration.

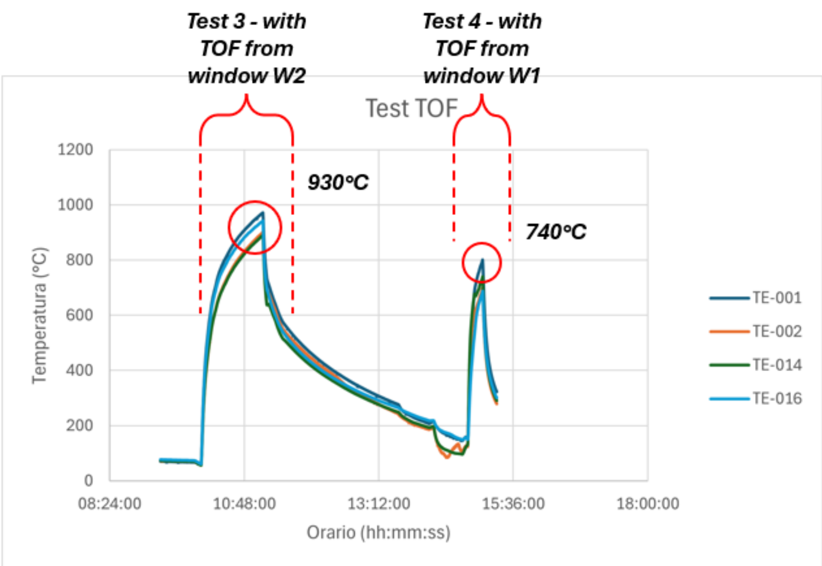

Figure 61 – TOF sensor test furnace temperature profile

Test 3 began at approximately 10:30 with the proximity-sensor probe inserted through Window W2 and concluded when the furnace temperature reached approximately 930 °C. Test 4 began at around 15.00 with the probe inserted through Window W1 and ended when the furnace temperature reached approximately 740 °C.

As described in earlier sections, the TOF sensor exhibited significant performance issues due to the laser operating in an environment heavily affected by infrared radiation. The challenges associated with these TOF sensors are clearly illustrated by the sensor signal data.

Figure 62 shows the TOF sensor signal acquired during Test 3. In this test, the sensor was positioned 200 mm from the scrap. The measurement remained optimal until the scrap reached an approximate temperature of 800 °C after which the strong infrared radiation present severely and irreparably disturbed the TOF signal, as visible in the figure.

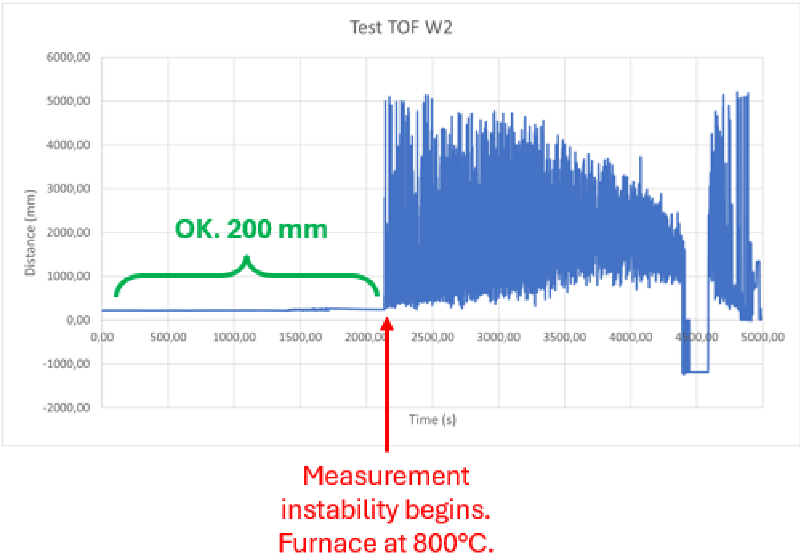

Figure 62 - TOF sensor signal acquired during Test 3

Figure 63 shows the TOF sensor signal acquired during Test 4. For this test, the sensor was located approximately 1300 mm from the scrap. In this scenario, the measurement was immediately compromised by the presence of the burner flame. Specifically, within a few seconds of the burner being activated, the TOF signal became unusable, a disturbance clearly evident in the figure.

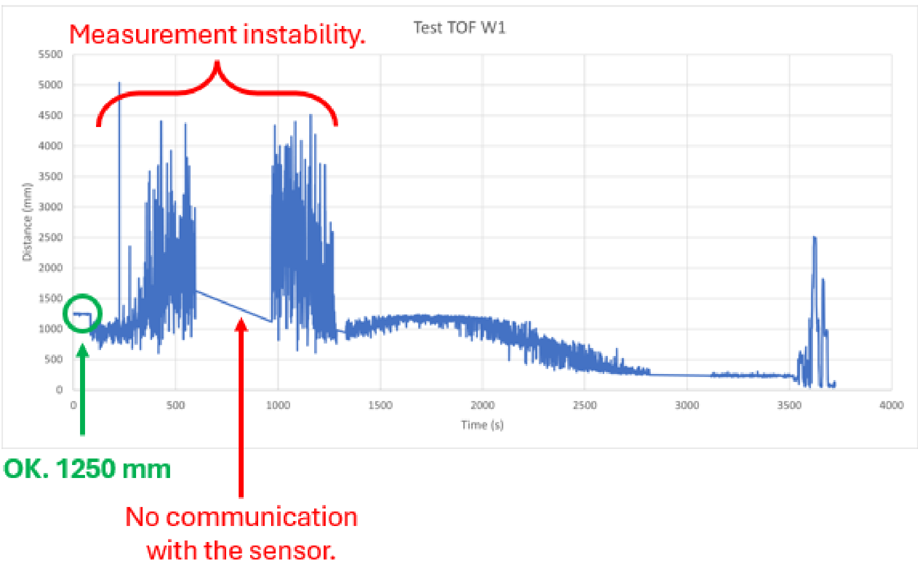

Figure 63 - TOF sensor signal acquired during Test 4

5.3 Microphone Test Data Analysis

The proximity sensor microphone test (Test 5) was conducted on July 10, 2025, at the RINA-CSM laboratories in Dalmine. **Figure 64** illustrates the temperature profiles inside the reheating furnace, as measured by thermocouples TE001, TE002, TE014, and TE016, during this test (refer to **Figure 34** for the thermocouple layout). Test 5 commenced at approximately 11:30 AM with the insertion of the lance, equipped with a microphone, through window W1. The test concluded when the internal furnace temperature reached approximately 990 °C.

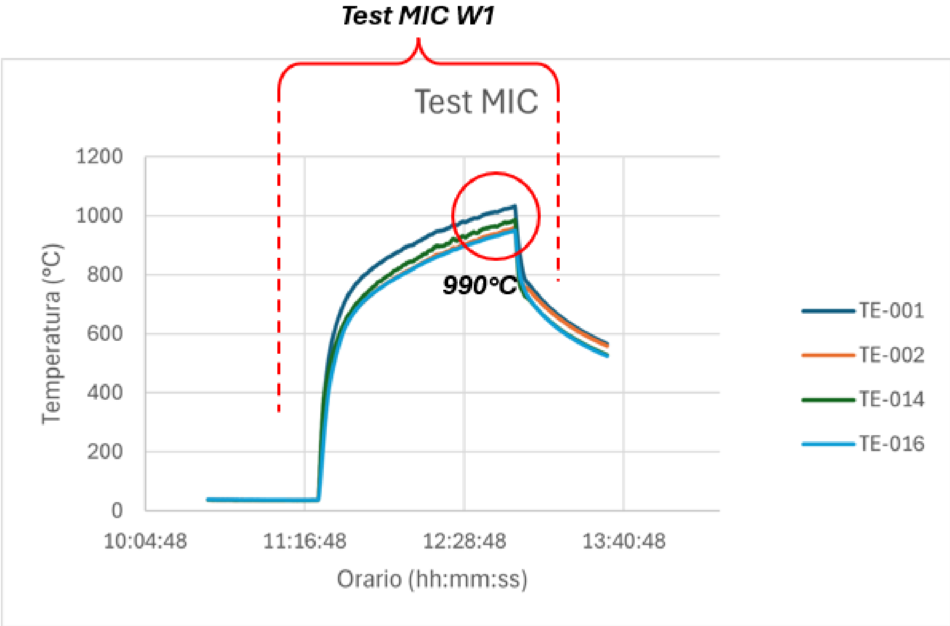

Figure 64 - Microphone test furnace temperature profile

Figure 65 illustrates the microphone signal acquired during the test 5. As is evident, the signal is predominantly stable, showing no significant peaks in sound intensity. The maximum value recorded was 86 db.

It is important to note that a reheating furnace is inherently a much quieter system than an electric arc furnace and exhibits minimal noise variability throughout the process. An EAF, in contrast, generates very intense sound peaks during the initial phases when the electric arc impacts the solid scrap. These peaks gradually diminish as the scrap shields the electric arc noise. Subsequently, the intensity further decreases once the electric arc contacts the liquid metal. This signal variability is entirely absent in the reheating furnace. Consequently, when this sensor will be deployed within an electric furnace environment, specific methods will undoubtedly be necessary to prevent microphone saturation.

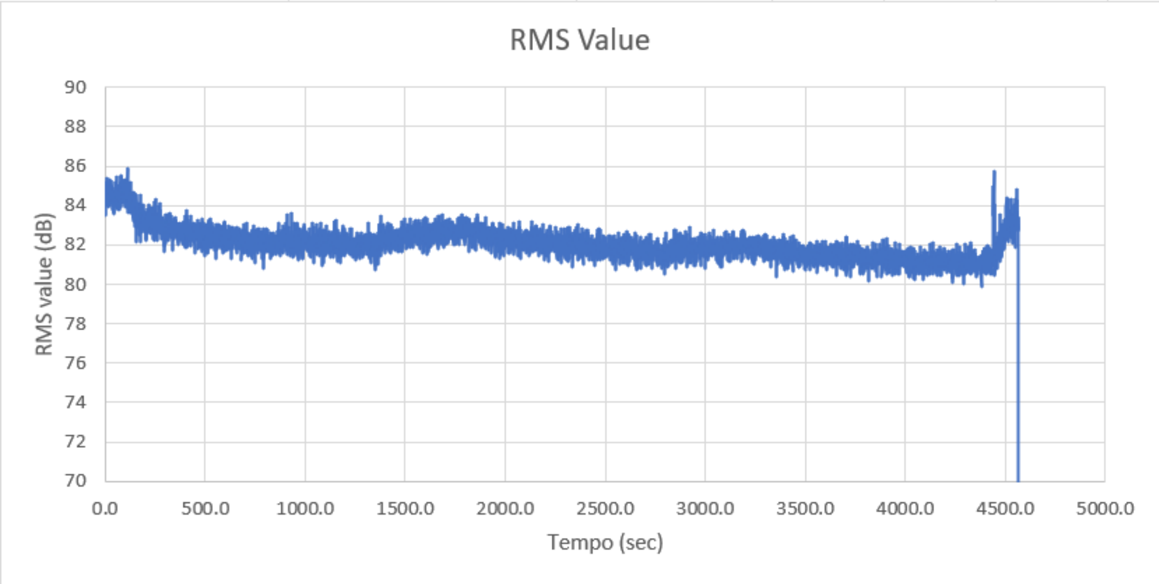

Figure 65 - Microphone signal during Test 5

6 Future Engineering Challenges

Findings from the MultisensEAF research project indicate that, while the Proximity Sensor exhibits a robust and well-engineered architecture, several design adaptations are still required to ensure full compatibility with industrial EAF operating conditions. **Table 1** provides a structured assessment of the sensor's primary functional attributes, identifying those that present outstanding engineering challenges (EAF approved – No) and those that already meet the performance and reliability criteria for EAF deployment (EAF approved – Yes).

Component	Sup-component/behaviour	EAF approved		Issue description	Future Challengies
		Yes	No		
Common part of the Proximity Sensor	Compressed Air Blowing System				
	Sensor Water Cooling System				
	Data transmission system			The current data transmission architecture is overly complex and requires simplification	The data transmission system must be simplified by routing all data transmission via conduit using Ethernet cable.
	Small Electric Box			The small electric box is currently placed on the ground near the launch, making it subject to possible damage.	The small electrical box must be secured to the lance (or probe / boom) and must contain the electronics for the analog-to-digital conversion (ADC) of the temperature sensor located at the tip of the lance.
	Laptop - Acquisition system				
Camera	Camera cooling				
	Camera saturation			Under real-world EAF operating conditions, it is believed that the light intensity may drive the camera's photodiodes into saturation.	It is necessary to develop an electro-optical component capable of attenuating the light incident on the camera, for example by means of mechanical apertures or variable filters.
TOF sensor	TOF sensor cooling				
	TOF mesurement fault			The TOF sensor has been shown to fail to measure targets above 800°C.	Development of a ToF sensor that is insensitive to high infrared radiation flux
	TOF mesurement fault			The TOF sensor has been shown to fail when taking measurements near flames	Development of a ToF sensor that is insensitive to high temperature particles
Microphone sensor	Microphone cooling				
	Microphone saturation			Under real-world EAF operating conditions, it is believed that the sound intensity may drive the microphone into saturation.	It is necessary to develop an electro-optical component capable of attenuating the sound incident on the microphone.
	Back sound			The microphone is susceptible to external noise emanating from the furnace, likely due to poor acoustic isolation.	Optimize the design of the microphone's electrical cable routing, considering acoustic isolation

Table 1 – Proximity Sensor's primary functional attributes

As shown in the table, the common section of the Proximity Sensor is essentially ready for deployment in the electric arc furnace, requiring only minor refinements related to data transmission and the integration of the small electric box on the lance.

The sensing elements, however, still require substantial further development. The camera requires an electro-optical subsystem to regulate exposure to furnace radiation and prevent photodiode saturation. The current TOF sensor is not suitable for EAF measurements due to measurement disturbances caused by the high infrared flux and must therefore be replaced with an alternative sensing technology. The microphone, although it exhibited no particular issues in the reheating furnace, is expected to be susceptible to saturation under electric arc furnace acoustic conditions. Consequently, as with the camera, the development of an electromechanical attenuation system is considered necessary.