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Abstract	This deliverable describes furnace tests made for developing the sensor technique and evaluate the performance of the sensors in steel industrial environment. Tests were made at 1250°C in a laboratory electrical furnace and also inside a bed of pellets heated to 950°C. The tested wireless sensors did operate and survive 25 minutes in the 1250°C furnace and for 30 minutes in a hot (900°C) pellets bed environment. Even though the full process time last hours lasts longer the duration of the tests made inside furnaces is of large value. For a walking beam furnace several sensors can be used simultaneously or in sequence since it is possible to drop sensors at more than one position. Measurements can increase the understanding of the process and can be used for the tuning of existing models or for the development of new ones.

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List of Acronyms

ABBREV	Explanation
BF	Blast Furnace
EBF	LKAB's Experimental Blast Furnace
WBF	Walking beam furnace
MPC	Model predictive control
PAT	Process Analyze Technology

1 Introduction

Steel is predominantly manufactured in integrated steel plants stages normally starting with the Blast Furnace (BF-) or the direct reduction process. In the BF raw material (for example iron-ore, coke and limestone) is chemically reduced into liquid iron and the non-usable part of material (gangue) is collected in a slag. In the BF the raw materials are loaded at the top, preheated air is blown in the bottom. The iron ore and the slag are both tapped from the bottom of the BF. The molten iron needs a number of following heavy process stages as well as a final adjustment of the steel composition with additives to be cast into cast product. Cast products are slabs, billets or blooms which are further treated in rolling mills. The strands are often pre-heated before further processing and are finally rolled down to intermediate parts such as plate, sheet, strip, coil, billets, bars and rods. These products are used for several other manufacturing operations such as for instance metal working, stamping, forging, wire and drawing, extrusion, and machining.

The whole process chain of steel making consisting of numerous energy intensive processes which also are related to high emissions of CO2, and an extensive work are related to lower the energy consumption and emissions of greenhouse gases to lower production costs and reduce impact on the environment. Many efforts has been done as changing the composition of ingoing raw material and further improved process control, the later often dependent of more sophisticated solutions for measurements in the hot and dusty environment as steel process stages to extract valuable process parameters to operators and control systems.

Measurements are important but often complex in the harsh steel manufacturing environment involving high temperatures and dust, steam, and poisonous gases. Often important information is out of reach. New low-cost sensors developed for harsh environment can supply information that can improve the understanding and knowledge of a process. New sensor technique is interesting for instance for the heavy blast furnaces as well as for usage in the steel strip and plate processes for instance in the walking beam furnaces of for heat treatment applications. In this project advanced sensor solutions are evaluated in steel production environment. Still it remains a challenge to make process modifications, control models have to build upon robust technique and trusted measurements and models. Safety is important as well as efficient production resulting in a high quality steel product. The process control must handle all kinds of process variations in a safe and efficient manner.

1.1 Summary (abstract)

This deliverable describes furnace tests made for developing the sensor technique and evaluate the performance of the sensors in steel industrial environment. Tests were made at 1250°C in a laboratory electrical furnace and also inside a bed of pellets heated to 950°C. The tested wireless sensors did operate and survive 25 minutes in the 1250°C furnace and for 30 minutes in a hot (900°C) pellets bed environment. Even though the full process time last hours lasts longer the duration of the tests made inside furnaces is of large value. For a walking beam furnace several sensors can be used simultaneously or in sequence since it is possible to drop sensors at more than one position. Measurements can increase the understanding of the process and can be used for the tuning of existing models or for the development of new ones.

1.2 Purpose of document

This deliverable will report on the evaluation of inline sensors tested in the steel industry. This evaluation includes the requirement analysis for the cases of material handling and BF processes, applicability of sensors in different materials, sustainability of sensors against temperatures and gas atmospheres, and wireless methods for establishing data connections. The application strategy towards the implementation of the proposed sensors in the experimental BF is presented.

1.3 Partners involved

Partners and Contribution	
Short Name	**Contribution**
Mefos	WP leader
LKAB	Owner of experimental blast furnace
LTU, Electrotec	Provider of measuring equipment and sensors

2 Steel industry processes

In this project most of the focus has been to sensors aimed for blast furnaces and walking beam furnaces aimed for increased process control. In both processes the temperature distribution and gas composition are of importance and location of the measurement point.

2.1 Blast furnace (BF)

The process is an almost continuous process where coke, ore and slag formers are charged at the top of the blast furnace and blast is blown in in the lower part. The slag and hot metal forms and sink to the bottom of the furnace and are tapped approximately every hour.

Additionally to the basic material flow described above, the blast is combined with pulverized coal injection.

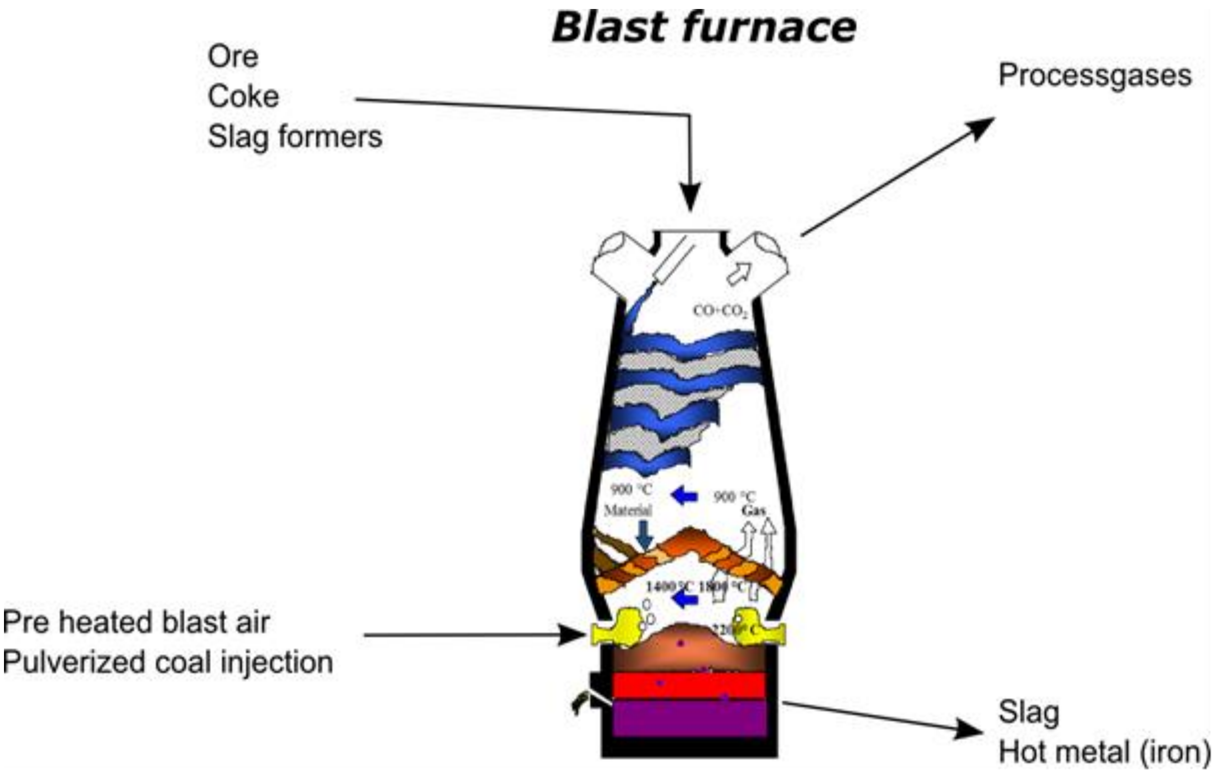

Figure 1: A blast furnace described in the text, blue parts is coke and ore layers, yellow is the blast air, red the liquid slag and purple is the hot metal (liquid iron). The reduction gas is leaving the system in the top of the furnace and slag and iron is tapped from the bottom approximately every hour.

The blast furnace system is regulated to a stable process but disturbed in different ways:

1. The chemical composition of coke and ore varies.
2. Charged material contains alkali metals and Zink which is described more lately.
3. The permeability of the solid layers is not stable and cause different gas distributions in the furnace.
4. Blast air contains different amount of moisture.
5. The charged materials contain different amount of fines, even if fines are screened before charged into the furnace.
6. The charged material contains (or break down to) different amount of fines.

Overall the process is very slow in the meaning: changes in process settings needs a settle time of several hours before the effect of the changes are observed.

Figure 2: Image of LKAB's experimental blast furnace.

The LKAB Experimental blast furnace (Figure 2) was built as a unique pilot plant to perform trials of pellets and blast furnace technology prior adaption to production plants.

2.2 Walking beam furnace (WBF)

For the manufacturing of steel products (strip, plate and profiles) steel slabs, billets and blooms are heated in large reheating furnaces. For product quality assurance, energy consumption and safety it is important to accurately monitor and control the furnace conditions. For instance it would be of great value to

a) be able to follow the material temperature through the different furnace zones and b) to in more detail know the furnace atmosphere in the different zones. Temperature measurements inside reheating or annealing furnaces are very complex, the process conditions are tough and the radiation inside the furnace influence IR pyrometer readings. Steel surfaces both reflect and emit infrared radiation and the radiation intensity effect pyrometer measurements. (Outside the furnace the reflected radiation is much lower and a more accurate temperature measurement is possible.)

For tuning purposes accurate temperature measurements are regularly done by using thermocouples drilled into test specimens. The specimens equipped with thermocouples can either have long cables feeding into the furnace or being attached to a capsuled logger that can stand heat for some time. The logger commonly burns after a few tests due to production stops or other problems. These self-contained devices are often too heavy to use on thin material due to the weight. Recently a better and lighter encapsulation has been developed using a phase changing material as insulation, but the cost for the system is high and there is a large risk for burning this system with a higher maintenance cost and the cost for a new investment.

Figure 3 shows a heated slab that is lifted out of Swerea MEFOS WBF at MEFOS during the Disire campaign in November 2015.

Figure 3: An image from the walking beam furnace trials at Swerea MEFOS in November 2015.

3 General considerations for sensors in the steel industry

Steel industry is a harsh environment where for instance high temperature, dust and steam and limited space makes measurements difficult.

A measurement system in steel industry must

- be robust
- provide reliable data on the desired properties to give usable signals intended for the operators the control system and the modeling
- not disturb the production
- have a reasonable size
- be safe
- environmental and process friendly

It is beneficial if the system is

- wireless
- reasonably prized
- simple to use

In-situ sensors are contributing with knowledge of the process status. With additional or improved measurements the control of the process can be refined, product quality can improve and emissions and energy consumption can decrease.

3.1 Properties of interest for the steel process

Even though new DISIRE sensors might not survive the highest temperatures there are several temperature zones below 800°C both in the BF and in the reheating furnaces where DISIRE measurements would generate considerable added value for process improvements.

For the blast furnace a material tracking system could be of large value for particle inner temperature, heating rate etc. for charged material of significant different sizes. Moisture control and drying rates of input material may also be investigated as material movement. Extracted information regarding chemical composition of in furnace gases give information of reduction reactions and reaction zones correlated to position in the furnace, also required training time for operators of a blast furnace may be shortened, today the need of experience is very large compared to many other industrial processes..

In reheating furnaces as walking beam furnaces the temperature distribution is of interest in order to evaluate reheating dynamics of ingoing material (as slabs) in order to heat with a desired velocity and distribution though a symmetric and well controlled heating is of importance. With lack of location precision in a furnace, temperature measurements results in asymmetric temperature profile in the heated material, which influence the following rolling process negatively. Measurements of the furnace atmosphere will assure that the combustion is working properly to a minimum cost and with good quality of the heated material surfaces. In a furnace where O_2, NO_x, CO, CO_2 are produced through the burners and influence the material surfaces in different ways. Gas compounds are commonly measured. It is important to keep the O_2 content on the correct level to avoid excess oxide scale growth ~~and~~ with degraded surface quality.

3.1.1 Temperature

Temperature is a parameter of major importance in hot steel processes. The temperature determines several important properties, the stability of the process the reactions in the material, the energy consumption and is therefore also an important parameter for process control.

In the blast furnace the feedstock is melted and in order to get the process to work continuously and smoothly the temperature in the zones must be controlled and measured accurately. In a blast furnace the composition and physical properties of ingoing material is different and varies at the same time as the in-furnace condition also varies, actions in order to maintain the process stability are required to lower the operational costs and environmental impacts. The different variations in the blast furnace process which influences the stability evaluated using in-situ measurement of temperature in the different layers and at different locations, as the burden is slowly moving downwards in the furnace, is valuable for determining changes in process conditions in real-time.

Processes using the cast material (slabs, billets, blooms) start with reheating the stocks. The stocks are massive and it takes a long time (hours) to heat a stock efficiently to an even temperature. For the following metal working process (for instance rolling) is very important that the temperature is as even as possible and that the desired temperature is reached since it will determine the final quality and microstructure of the final product. The temperature and the temperature distribution also have a large impact on how the manufacturing stages will function. Proper temperature measurements inside the WBF can assure a homogenous temperature in the material. This is needed for product quality and process stability as well as optimization of energy consumption.

For the steel process with its high temperature the best choice of temperature sensor is a thermocouple sensor. Standard thermocouple types are called K, N, and S. The temperature ranges are for K and N 0-1100°C and for S 0-1600°C.

3.1.2 Oxygen

Oxygen is needed for proper combustion in a combustion furnace. The level of O_2 varies at different positions inside the furnace, depending on the operation, the furnace design and the gas flow pattern. High oxygen levels generate losses due to increased oxide scale growth.

Measurements of the atmosphere in a walking beam furnace can assure that the combustion is working properly to a minimum cost and with good quality of the material surface. It is important to keep the O_2 content on the correct level to avoid excess oxide scale growth and degraded surface quality. The level of O_2 varies inside the furnace. Knowledge of the variation and to know positions of possible unfavoured levels of O_2 are desirable. The O_2 level can for instance be too high due to problems such as leakage. The proper control of oxide content in the various zones in the furnace can minimize losses caused by excessive oxide scale and degraded surface quality and also control combustion and cost for oxygen.

3.1.3 Position

Measurement of position is important since it can tell where a value is measured. Measurements of positions can for instance be used for tracing material or for correlating values with external measurements.

For the blast furnace a material tracking system could be of large value for moisture control of input material and material movement. The BF is loaded with a mixture of raw material with different shapes and sizes and it is not fully known how the material distributes when charged into the furnace. The reactions taking action in the furnace are well known but measurements of temperature combined with locations instantaneously would give valuable information that could be used for process improvements and information to support the process operators decisions during the overall process control.

3.1.4 Moisture

The moisture content in raw material varies. It is interesting to know the amount of moisture if it influences the processes. The blast furnace process is influenced by the moisture content in the burden materials that continuously are fed to the blast furnace. Accurate measurements could improve the recipe calculations in near real time. Moisture is common especially in coke but also other raw materials, which is directly related to the achievable heat level. Moisture becomes steam in hot processes. By frequently measuring the moisture content and tag the particular portion of the feedstock guarantee that the information acquired is correct. For instance measurements can help to identify where the steam can be expected and collected.

4 Evaluation of sensors to be used in the steel industry

To have a sensor applicable for the steel industry it must be sustain the harsh environment and deliver robust and reliable measurements. The demands, development and evaluation of the sensor are done stepwise. The main evaluation steps are

1. Size limitations and construction possibilities
2. Measured properties
3. Temperature and Atmosphere protection
4. Wireless transfer
5. Accuracy

4.1 Analysis for the cases of material handling and BF and WBF processes

For material handling it is interesting to trace how different kinds and sizes of raw material moves through the furnace. This can give improved understanding of the reactions taking place in the BF. For the WBF measurements it would be interesting to follow positions of material inside the furnace but also to be able to follow positions of for instance a measurement probe sweeping through the furnace room measuring the atmosphere.

The plan is to do measurements using measuring bodies with shapes and weight resembling the raw material equipped with sensors. The sensor van also be charged in a group For the WBF and the BF it is interesting to measure for instance position, temperature and atmosphere.

4.1.1 Size limitations and construction possibilities

For the Experimental Blast Furnace the maximum sensor diameter is limited to ~5 cm due to the size of the access way to the top of the blast furnace shaft, the maximum length is 140 mm. Figure 4 shows the basket where the sensor must fit into. The thermal insulation of the sensor will be a combination of boiling water as heat absorbing layer and moulded ceramic insulation.

Figure 4: the encapsulating basket for the sensor. The basket is dropped into the blast furnace through a special locking system.

In the walking beam furnace the size limitations are more open though a quite large sensor arrangement is possible as long as the housing do not affect the measurement.

For the WBF the size limitation is not expected to be an issue. The maximum size is in the region of 0.35x0.35x0.35m. The temperature in the furnace is up to 1300°C. Although the sensor is in the furnace for hours, up to 4h, it is expected that the sensor will survive the whole trial due to proper insulation. The thermal insulation of the sensor will be a combination of boiling water, refractory ceramic fibre blanket insulation and moulded ceramic insulation.

4.1.2 Measured properties

For the steel industry the sensors that can measure the following physical properties are of interest.

1. Temperature (~300-1300°C),
2. Moisture
3. Gas components (O2, CO, CO2),
4. Position

The main focus for sensor development is on measuring temperature and oxygen content.

It is important that the new sensors reach satisfactory performance since otherwise the sensor system cannot support further improvements to the process.

4.2 Applicability of sensors in different materials

The sensors can be capsuled in different materials. The capsule must withstand the process environment as well as allowing signals to pass. By making the sensor resembling shape and weight of the raw materials, the BF the measurements might give additional information. For instance it is interesting to know material movements and the behavior of different types and mixtures of raw material. This is interesting because in the field of research different not commonly used charging materials are sometimes tested. Materials are sometimes exchanged to more environment friendly products and it is important to evaluate the changes in process conditions in a more rapid way. This may be of large interest in a production plant where disturbances must be avoided.

It is simpler to use sensors inside a WBF than in a BF since the atmosphere in the WBF is not very dangerous and many areas can normally be reached from openings. In the WBF the sensor could be placed on a dummy slab or with some effort it is possible to sweep a sensor around in the furnace room to measure for instance variations in temperature or atmosphere. It is also possible to enter sensors at different stages in the process.

4.3 Sustainability of sensors against temperatures and gas atmospheres

In the steel process the major issue for sensors is the hot environment. The maximal temperature for electronics is approximately 150°C. Since the temperatures in the process reach way over that the protection shield is an important task. The simple rule is the thicker thermal insulation the better protection against the high temperature. However, thicker insulation means larger size. The size can be an issue due to the surroundings and process demands. A commonly used thermal insulation material in the steel industry is Kaowool® due to its low thermal conductivities, resistance to thermal shock and wide range of products.

In a BF the gas atmosphere contain a lot of different gas components and particles. A potential dangerous particle is metallic particles that might influence the function of the sensor. It can create a short circuit and disturb the wireless communication. To completely avoid particles entering the electronics a gas-proof shielding might be used.

4.3.1 Sustainability against temperatures

Figure 5: MEFOS furnace used for test of the temperature protection shield.

Protection sensor shield tests were carried out in a furnace with ceramic lining and steel shell. The purpose of the shield is to protect the sensor electronics from heat and other negative impacts on the sensors. A thermocouple measured the temperature inside the protection shield chamber. The result from the test was promising. The temperature inside the protection shield held a tolerable temperature for 25 minutes at furnace temperature of 1200°C.

A more detailed sensor design is described in deliverable D3.1. In a BF the temperature goes from 300°C to 900°C at the upper part of the BF. It takes hours to reach the 900°C. For the possible application in WBF the tested time period was is too short. However, in a WBF the protection shield can be quite large and it is possible that the sensor can sustain the time period inside the WBF with a thicker thermal insulation combined with more boiling water.

To be able to keep the internal temperature of the PAT low for a long time, a thermal insulation need to be combined with the encapsulation of a material or fluid that will consume energy when heated inside the insulation. To find an upper bound on the feasible life-time of enclosed unit a survey of commercially available insulating materials was made. More information is found in the report of deliverable D3.1

4.4 Wireless methods for establishing data connections

4.4.1 Wireless transfer

A test was made to investigate the wireless transfer capabilities of the sensors at different temperatures and having surrounding conditions resembling the conditions in the blast furnace. In the tests an capsuled sensor was placed inside a bed of hot pellets. This test was made to investigate if the pellets would screen the radio signal.

A box (Figure 6) of the size 70 x 70 cm was built and filled with pellets. A tube was placed in the centre with the purpose of acting as a passage for the sensor into the pellets bed. The box was filled with pellets and was heated to 900°C in an electric furnace and then placed at a cooling table (Figure 7) at distance of four meters from the receiving antenna. Figure 8 shows hot red color radiating pellet box with tube being placed at a table after heated to 900°C. Figure 9 show the antenna. The sensor was placed through the tube to the bottom of the hot pellets (see Figure 7b) and after this the tube was removed. In that way the sensor was covered by hot pellets.

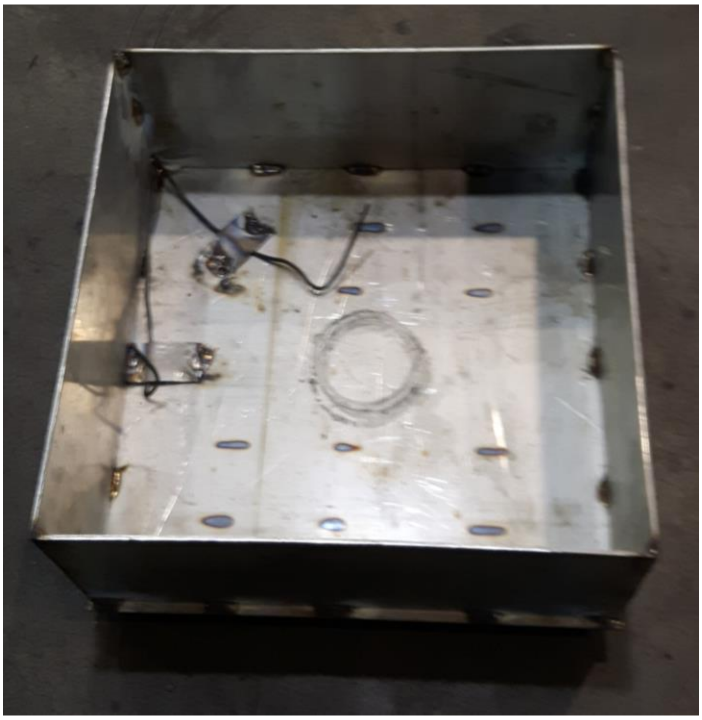

Figure 6: The box containing thermocouple sensors for validation of the new sensor.

a) Pellet box before heating b) Box discharget at 900°C

Figure 7: The box filled with pellets before and after discharge from the furnace. The sensor was dropped into the pellets bed through the pipe. The pipe was then removed and the hot pellets surrounded the sensor and the sensor temperature data was successfully measured and transferred.

Figure 8: Photograph from the wireless test. The pellets box is slowly cooling down on the table.

The receiver was simultaneously recording the radio signal containing the temperature information measured by the sensor. The radio receiver (antenna) (see Figure 10) was placed at a distance of four meters from the sensor which were covered by the pellets bed. The main purpose with the test was to investigate the best frequency for data transmission.

A successful test will require the transfer of data with adequate bit rate and having realistic distance between transmitter and receiver. Good performance results are crucial since if the radio links cannot function satisfactorily the whole sensor system cannot support further improvements to the process.

Figure 9: Antenna used to receive the measured signal.

Frequencies between a 433 MHz up to 3 GHz were tested. The test showed that measurements must be done at low frequencies. The higher frequencies gave a large damping effect. The lowest frequency 433 MHz gave the best results.

4.5 Accuracy

As in many industrial applications it is interesting to reach as high accuracy as possible. In this project the effort focus on limiting the size of the sensors and the sustainability to very high temperatures, both difficult properties to achieve. The resolution of the measurement therefore comes second. To evaluate the results the measured temperature with the novel wireless sensor will be compared with conventional thermocouple sensors already installed at MEFOS facility. The gaseous composition measured by the new sensor will be compared with an existing conventional gas emission analyser. The position test is done by moving the sensor in a predetermined path inside the furnace. The moisture test in the heated gas is compared with a conventional sensor system.

5 Application strategies of the sensors in the experimental BF and the walking beam furnace

5.1 Strategies for application of the sensor

The sensors will be affected by extremely high temperatures from the surrounding furnace in both the blast furnace and walking beam furnace. Wireless communication is needed since signal cables are difficult to protect from the surrounding heat. The sensors also need to be powered by a suitable battery.

The sensors must be shielded properly and it would be beneficial to use some kind of phase changing material that will help keeping the sensor temperature at a moderate temperature level when the electronics is running.

5.1.1 Blast furnace strategy

To be able to prepare and mount antennas in laboratory environment a new special lid (at a size of ≈ 70 cm diameter) has been designed and manufactured. This allows a free offline construction and mounting of required antennas prior installation at the blast furnace. An existing lid will be replaced by the lid built in the DISIRE project.

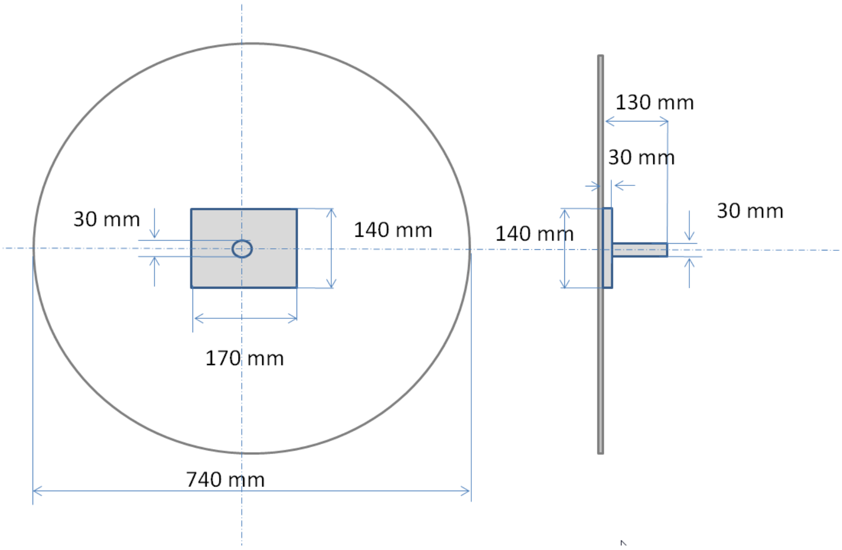

Figure 10: A sketch of possible mounting of antennas on the lid.

The lid will contain two antennas one radio frequency antenna and one magnetic loop antenna in order to receive the radio signal from the in process placed sensors. During the BF campaign, sensors will be dropped though a special gating system. The radio signal from the sensors which sends out recorded monitoring are collected through the antennas installed in the special lid.

5.1.2 Walking beam furnace strategy

The pilot sized WBF is designed for research work and it is possible to quite freely design suitable set-ups for measurements. There are a number of openings where measurement devices can be tested (Fig 11 for possible positioning of antennas). It is also possible to in parallel measure using for instance thermocouples and other devices useful for comparison with and verification of the measurements in this project.

Figure 11: Image of possible position for the receiving antennas on the brick wall in the WBF.

There is a lot of available space inside the furnace beneficial for the wireless sensor. It can for instance be placed on a dummy slab that is mechanically fed through the different zones in the furnace.

5.2 Final industrial demonstration

Both LKAB's EBF and MEFOS WBF are of experimental type. This means that the furnaces aren't a production unit. Hence, the furnaces are only running during special arranged project campaign. Still running the EBF and WBF are large operations near industrial scale. The campaigns are expensive and require detailed planning and a lot of human resources.

5.2.1 Final demonstration in the LKAB experimental blast furnace

The furnace is used for special campaigns lasting about two months where a number of different process variations are tested. During a campaign the developed sensors will be tested in the hot environment inside the blast furnace. The Disire trials will be performed at the end of a campaign. Then it might be possible to excavate remains of the sensor for examination after the furnace has cooled to room temperature. The final test in the blast furnace is done at the end of the project.

5.2.2 Final demonstration in the walking beam furnace

After successful outcomes from the above initial tests, a full-scale test will be conducted in a walking beam furnace at MEFOS. The objective is to evaluate whether the new sensors can manage the environment in a walking beam furnace during the entire movement through the furnace. First, the furnace runs in normal mode. Thereafter, the sensors are sent into the furnace. The information from the sensors are received with antennas and evaluated.

In general, the performance will be evaluated in terms of successful and reliable transfer of accurate measurement data. A comparison with the data gathered from conventional sensors will be performed.

The developed MPC system will also be tested during the same campaigns. This final test in the WBF is done during a WBF campaigns preliminary at the end of the project.

6 Conclusion

The wireless measurements inside an electrical furnace and in the bed of pellets showed positive results for using the sensors in steel industry since the signals could be received through a steel lining and through a hot pellets bed. The test in the pellet bed showed that measurements must be done at low frequencies. Higher frequencies gave a large damping effect. The lowest frequency 433 MHz gave the best results. Even though the life time for the sensor is short in comparison to the full process time these kinds of measurements are of large value. The measurements will increase the process knowledge in several ways. Continued sensor development combined with improved application strategies is believed to increase the feasibility for introducing this kind of small wireless sensors in steel industry.