

Ultra-Low-Power Wireless Temperature Measurement for High-Temperature Rotating Equipment

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Abstract

This paper presents a wireless, energy-autonomous temperature measurement system for a rotary aluminium melting furnace. The system is designed for temperature acquisition at locations where wired sensors are difficult to install due to rotation, thermal load, and limited accessibility. It consists of photovoltaic-powered wireless sensor nodes, BLE-based communication, and a Linux-based edge gateway for data processing and integration into downstream systems.

The sensor nodes use thermocouple measurement electronics and supercapacitor-based energy storage. Stainless-steel fixtures and thermal shielding enable mounting on the rotating furnace while limiting the thermal load on the electronics. Industrial measurements demonstrate long-term temperature acquisition at the furnace core, outer surface, and exhaust gas path. The results demonstrate the feasibility of cable-free temperature monitoring on rotating high-temperature equipment and identify energy availability as a key factor for reliable long-term operation. The acquired temperature data provides a basis for process monitoring, forecasting, and digital twin modelling of the melting process.

Keywords: Wireless Temperature Measurement, Energy-Autonomous Sensor Nodes, Rotating Machinery Monitoring, Energy Harvesting, Ultra-Low-Power Industrial IoT

Introduction

Temperature is a key process variable in high-temperature industrial applications. Accurate knowledge of the current process temperature is required to monitor and control the state of the system. This is particularly relevant for metal melting processes, where the temperature directly determines the physical state and quality of the molten material. Precise temperature information enables the identification of optimal process conditions, ensuring material quality while simultaneously minimizing excessive heating. As a result, reliable temperature measurement contributes not only to product quality but also to improved energy efficiency by reducing unnecessary heating time and associated energy consumption.

In many industrial applications, metal melting is performed in rotary furnaces. The continuous rotation enables a homogeneous distribution of temperature and material composition, leading to improved process stability and uniformity of the molten material. However, this rotation introduces significant challenges for temperature measurement. Sensors must operate under high thermal loads, mechanical motion, and limited accessibility. Conventional

wired measurement systems are often unsuitable due to mechanical wear, cable fatigue, and the difficulty of routing and maintaining connections on rotating components. Wireless sensor nodes provide a viable alternative for such demanding measurement scenarios. They enable the acquisition of physical quantities at locations where wired solutions are impractical or infeasible [1], [2]. When combined with energy harvesting, these systems can operate without any wired infrastructure for power or communication, allowing fully autonomous deployment [3], [4]. However, the available harvested energy in industrial environments is typically limited and often discontinuous [5], [6]. This imposes strict constraints on system design, requiring ultra-low-power hardware architectures, efficient sensing strategies, and energy-aware communication protocols and software implementation to ensure reliable operation [7], [8].

This paper presents the application of wireless, energy-autonomous sensor nodes for temperature measurement in an aluminium melting process using a rotary furnace. The measured temperature is used to estimate the optimal scrap melting state and time-to-tap approximation, enabling improved process

control and reduced energy consumption. The work describes the overall system architecture of the wireless sensor network, the mechanical integration of the sensor nodes on the rotating furnace including thermal shielding concepts, and the energy harvesting approach. Furthermore, first experimental results are presented, including the performance of the energy harvesting system under realistic operating conditions and temperature measurements at different locations on the rotary furnace and within its exhaust gas stream.

Application Scenario and Requirements

The wireless temperature sensor solution was implemented at the premises of a prominent European metal recycling company, dedicated to secondary aluminium smelting, and located in Spain. The refinery's main activities are focused on two production lines, which include high-capacity smelting rotary furnaces (30 t), holding furnaces, and ingot production lines. The company is dedicated to recycling a wide range of waste containing aluminium, predominantly of post-consumption origins. Prior to industrial smelting process, the received aluminium scrap is characterized, and its quality, as well as the obtained yield are evaluated utilizing refinery's pilot scale rotary furnace of approximately 10 kg capacity which is shown in Figure 1. This scrap characterization, quality and yield evaluation step is crucial to estimate an optimal scrap charging mix for the industrial furnaces. Refinery's pilot rotary furnace is retrofitted with a number of different sensors, such as energy meter, gas totalizer, door sensors, etc. (EU project REVaMP, H2020 No 869882) for process control and optimization purposes. Nevertheless, the molten aluminium scrap state evaluation and time-to-tap decisions at current are based on furnace operator's experience – expert knowledge, as no temperature sensors for continuous measurements were previously installed. Thus, the pilot scale rotary furnace was selected as an asset for wireless temperature measurement solution application.

Rotating furnace temperature monitoring is challenging, as sensors must operate under 1) high thermal loads – typical rotary furnace operating temperatures range from 650 °C to 800 °C [9]-[11], 2) mechanical motion, such as inclination, rotation, and 3) limited accessibility – any cable installation may obstruct the free movement of the furnace. During refinery's pilot rotary furnace operation, the target molten aluminium tapping temperature is around 650 °C, while external backside surface



Figure 1: Application scenario showing the rotary furnace with 10 kg capacity for scrap characterization.

temperatures in a range of 82 °C – 95 °C can be reached (measured by an infrared laser thermometer; HIBOK-77 (DT-8016H/-50 °C + 1600 °C), Ref. 430, Útiles y Máquinas Industriales, S.A.). Regarding the exhaust gas temperature, some measures are periodically carried out in the corresponding filtering systems. However, they are located in a distance from direct exhaust gas flow, and therefore, the reference values may be somewhat lower, in a range of 69 °C – 80 °C (refinery's internal reports data).

For such demanding temperature measurement scenarios, wireless sensor nodes can serve as a viable alternative, which was proposed and applied for the selected asset (the rotary furnace) of the present study.

System Architecture of the Wireless Temperature Measurement System

The wireless temperature measurement system is composed of three main components: distributed wireless sensor nodes, a transceiver unit, and a gateway for data aggregation and processing. The system is designed to capture temperature information at multiple critical locations within the rotary furnace process.

Temperature measurements are performed at three distinct positions: on the outer surface of the rotary furnace, inside the fireclay insulation of the rotary furnace, and at the exhaust gas collection funnel. Accordingly, three wireless sensor nodes are deployed. Two nodes are mounted directly on the rotating furnace, while a third node is installed on the stationary support structure of the exhaust gas funnel,

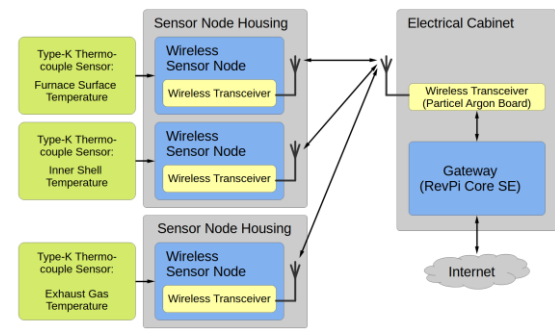


Figure 2: Block diagram of the system architecture showing the three wireless sensor nodes, the gateway with its transceiver.

located several meters away from the furnace. Each sensor node is based on a Nordic nRF52840 microcontroller, which integrates both processing capabilities and a wireless transceiver, enabling compact and energy-efficient operation. The nodes communicate wirelessly with a dedicated transceiver unit implemented using a Particle Argon platform. This transceiver serves as an interface between the sensor network and the higher-level system.

The gateway is realized using an industrial-grade Revolution Pi (RevPi), which performs data collection, preprocessing, and forwarding to external systems. This architecture separates low-power sensing and communication tasks from higher-level data handling, ensuring scalability and robustness in industrial environments. A block diagram of the overall system architecture is shown in Figure 2.

Wireless Sensor Node and Analog Circuitry

Each sensor node is designed as an energy-autonomous embedded system integrating sensing, signal conditioning, processing, communication, and power management within a compact architecture. The node is based on a Nordic nRF52840 microcontroller, which combines an ARM Cortex-M processor with an integrated 2.4GHz transceiver and other peripherals, enabling energy-efficient wireless communication and local data processing.

The temperature measurement frontend is designed to support multiple sensor types, including Pt100, Pt1000, and thermocouples. In the presented use case, type-K thermocouples are employed due to their wide temperature range and robustness in harsh environments. The measurement electronics follow a low-power design strategy, where analog components are only activated during measurement phases to minimize energy consumption. The frontend includes a

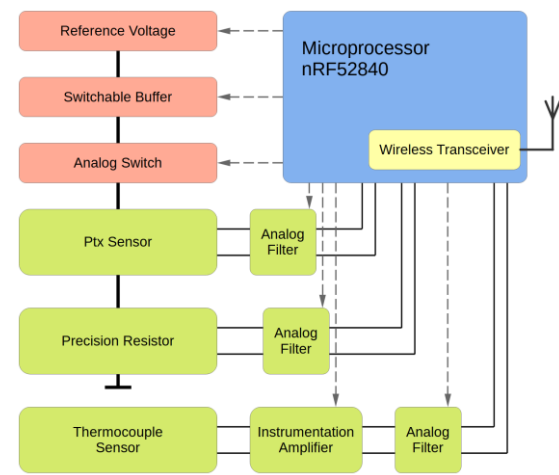


Figure 3: Block diagram of the sensor node's analogue front-end.

precision voltage reference (LTC6652, 2.5 V), signal conditioning, precision resistors, and the internal 12-bit analog-to-digital converter (ADC) of the nRF52840 configured in 16-fold oversampling to reach 14-bit accuracy, enabling low power data acquisition.

For thermocouple measurements, multiple acquisition steps are performed. First, the internal ADC is initialized, and its internal offset calibration is performed. Then, a separate temperature measurement for the cold junction temperature compensation is performed. Therefore, a Pt1000 resistive sensor element is integrated inside the connector of the thermocouple. For each Pt100 or Pt1000 temperature measurement, the reference voltage, the voltage of the reference resistor and the voltage of the Pt100 or Pt1000 resistor are measured. These values are used to calculate the cold junction temperature. After this, the thermocouple voltage is measured, and the corresponding temperature is derived using standardized polynomial approximations. Finally, cold-junction compensation is done using the cold junction temperature measured beforehand. A block diagram of the analogue front-end is shown in Figure 3.

Wireless Communication

Wireless communication is implemented using Bluetooth Low Energy (BLE), which serves both for configuration of the sensor nodes and for periodic transmission of measurement data and status information, including internal supply and harvesting-related parameters. The sensor node firmware is implemented in C/C++ on the Zephyr RTOS and runs on the Nordic nRF52840 platform. It controls the analog measurement circuitry, manages the acquisition of status parameters such as supercapacitor voltage, photovoltaic voltage,

and internal chip temperature, and handles data transmission.

A lightweight application protocol is implemented on top of BLE, supporting both control commands and data exchange. Commands include starting and stopping measurements, reading configuration parameters, and triggering system-level actions such as reboot. Measurement data and status information are transmitted using structured payloads tailored to different sensor types. These payloads are structured into a TLV (Type-Length-Value) scheme and base64-encoded for transport efficiency and compatibility.

The combination of ultra-low-power sensing, duty-cycled operation, and energy-aware communication enables reliable system operation under the strict and fluctuating energy constraints imposed by photovoltaic harvesting in industrial environments.

Gateway

On the gateway side, data acquisition and processing are handled by a Linux-based edge device (RevPi Core SE). The gateway software is implemented in Python and serves as the central interface between the wireless sensor network and the cloud-based data processing systems. It manages BLE scanning and maintains connections to multiple sensor nodes via BLE.

Incoming data frames are received from the sensor nodes, decoded from base64, and parsed according to the implemented TLV-based application protocol. The gateway performs initial data processing by converting raw sensor values into engineering units. This includes the transformation of resistive measurements (e.g., Pt100/Pt1000) into temperature values and the conversion of thermocouple voltages into temperature using standardized characteristics for type K thermocouples.

In addition to data decoding and preprocessing, the gateway provides interfaces for data forwarding and system integration. Measurement data can be transmitted to external platforms via REST-based interfaces for example. Furthermore, time-series data is stored remotely using InfluxDB, enabling continuous monitoring, visualization, and further analysis within the overall data collection architecture.

Energy Harvesting and Power Management

The energy supply is realized through a photovoltaic cell (SM111K09L, IXYS), which converts ambient light into electrical energy. The harvested energy is buffered using a supercapacitor (40F), allowing operation

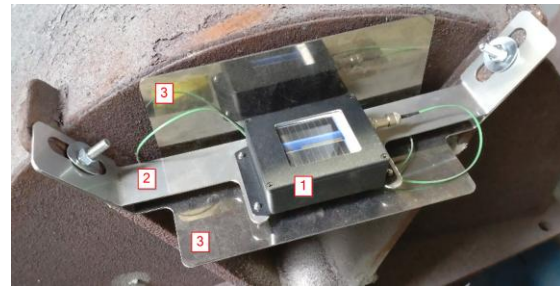


Figure 4: Wireless sensor node housing (1), fixture (2), and heat shield (3) mounted on the rotary furnace.

under intermittently available illumination conditions. A dedicated power management unit, based on a maximum power point tracking (MPPT) concept, ensures efficient energy extraction and regulates the supply voltages for the sensor node electronics. This approach enables fully autonomous operation without any wired power source.

Mechanical Integration and Thermal Protection for the Rotating Furnace

Two wireless sensor nodes were mounted on the backside of the rotary furnace. Both nodes were integrated into a dedicated metal housing featuring a glass window to enable photovoltaic energy harvesting. This housing provides mechanical robustness while allowing sufficient optical access for the integrated solar cells.

The sensor node housings were attached to the furnace using a custom-designed fixture made of stainless steel. Stainless steel was selected due to its relatively low thermal conductivity compared to other metals, reducing conductive heat transfer from the furnace surface to the sensor node. The fixture itself was mounted directly onto the outer surface of the rotating furnace.

To further mitigate thermal exposure, an additional heat shield, also made of stainless steel, was implemented. The heat shield has been bent at a right angle to shield the heat from the two main directions. The fixture and the heat shield are designed as two separate components, creating an air gap between the furnace surface and the shield, as well as between the shield and the sensor node housing. These gaps enable convective cooling and significantly reduce radiative heat transfer from the hot furnace surface to the sensor electronics. The combined effect of conduction reduction, radiative shielding, and convective cooling ensures that the thermal load on the sensor nodes remains within acceptable limits. The complete fixture design is shown in Figure 4.

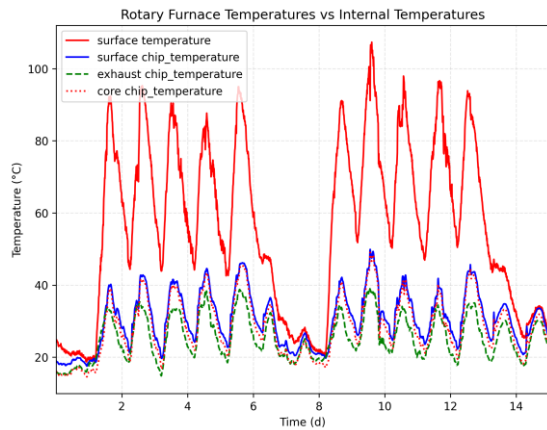


Figure 5: Rotary furnace surface temperature compared to the internal (chip) temperature traces of all three sensor nodes during two of the hottest weeks in the year 2025 (15th to 30th of June).

Figure 5 presents the measured temperature of the furnace surface and the internal temperatures of the three sensor node electronics within the housing. While the furnace surface reaches temperatures of up to 114.4 °C on the hottest day of the measurement period, the internal temperature of the sensor nodes remains limited to 50.25 °C. This reduction demonstrates the effectiveness of the thermal protection concept. The internal temperature is influenced by ambient environmental conditions, as reflected by a third sensor node installed at a distance from the furnace for exhaust gas measurements. This node operates close to ambient temperature and serves as a reference for environmental conditions within the industrial setting. The estimated environmental temperature reached on the same day 39.25 °C. Maintaining a limited internal temperature is critical for reliable system operation. In particular, the employed supercapacitors are specified for a maximum operating temperature of 85 °C. Operating significantly below this limit increases reliability and extends the lifetime of both the energy storage components and the overall sensor node electronics.

Energy Availability and Storage Behaviour

The wireless sensor nodes were originally developed for a different industrial use case. Therefore, it was not known in advance whether the available photovoltaic energy under the illumination conditions of the rotary furnace environment would be sufficient for perpetual operation. Figure 6 shows the supercapacitor voltages (solid) and the solar

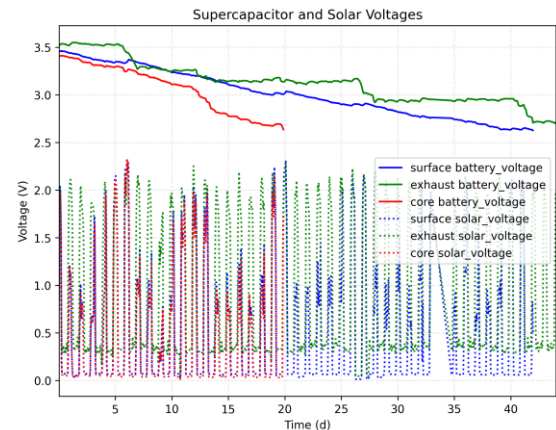


Figure 6: Voltages of the sensor nodes' supercapacitors (solid) and solar cell voltages (dotted) during a six-week period beginning on 21st of October 2024 with insufficient illumination.

cell voltages (dotted) of all three sensor nodes over a six-week period from the end of October to the beginning of December 2024. The supercapacitor voltage traces indicate that the available illumination was insufficient for energy-neutral operation although they receive environmental power every day as can be seen by the solar cell voltage traces. Two of the three sensor nodes discharged progressively and stopped operating after their storage voltage fell below the undervoltage threshold of approximately 2.65 V.

The insufficient energy availability is caused by two main factors. First, the sensor nodes were not originally designed for the low illumination levels present near the rotary furnace, resulting in a negative long-term energy balance. Second, furnace rotation causes the photovoltaic cells to alternate between illuminated and shaded orientations. This strongly time-varying input power can bias the MPPT operating point when open-circuit voltage sampling occurs during low-illumination phases, further reducing harvesting efficiency. As explained in more detail in [12], this effect can reduce the harvested energy by approximately 15 % under comparable periodically varying illumination conditions. Combined with the already limited illumination level in the industrial environment, this additional loss explains the progressive discharge of the supercapacitors and the shutdown of two sensor nodes.

Thus, an artificial light source was installed to illuminate the wireless sensor nodes. During weekend stops, the rotary furnace is positioned so that the sensor nodes face the artificial light source. This allows the nodes mounted on the rotary furnace to recharge during

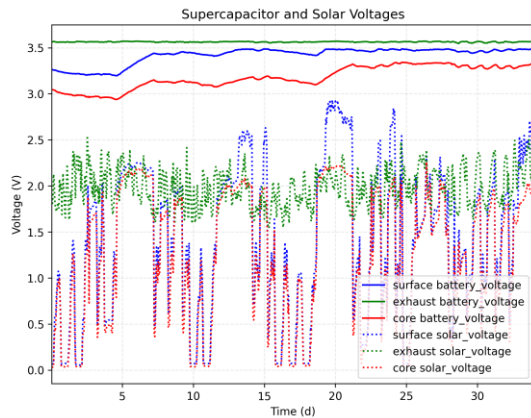


Figure 7: Voltages of the sensor nodes' supercapacitors (solid) and solar cell voltages (dotted) during a five-week period beginning on 26th of January 2026 with artificial illumination during the weekends.

non-operational periods. The stationary sensor node used for exhaust gas temperature measurement is also illuminated by an artificial light source.

Figure 7 shows the supercapacitor voltages (solid lines) and solar cell voltages (dotted lines) of all three sensor nodes over a five-week period starting on 26th of January 2026. The results indicate that artificial illumination during weekend stops is sufficient to enable perpetual operation of the sensor nodes mounted on the rotary furnace. The stationary sensor node receives continuous illumination and therefore remains fully charged throughout the observation period.

However, the harvested power of the furnace-mounted sensor nodes still depends on the exact stopping position of the rotary furnace. If the photovoltaic cells are not optimally aligned

with the artificial light source, the charging performance is reduced.

Temperature Measurement Results

The primary purpose of the wireless sensor nodes is the continuous measurement of process temperatures at three different locations within the rotary furnace system. Figure 8 shows the recorded temperatures over a long-term measurement period starting on 16 Nov. 2025 and ending on 26 Apr. 2026.

The measurements clearly reveal the cyclic operating behaviour of the melting process. During active production phases, the temperature of the rotary furnace repeatedly reaches values above 600 °C, while shutdown periods are characterized by a rapid decrease towards ambient temperature. The weekly production cycle is clearly visible, with regular interruptions during weekends. Furthermore, an extended period of inactivity can be observed around the turn of the year, corresponding to seasonal production holidays. The different measurement locations also show distinct thermal characteristics. The highest temperatures are observed directly at the rotary furnace, while the remaining measurement positions exhibit lower temperatures and slower thermal dynamics. The long-term measurements demonstrate stable operation of the wireless sensor network over several months and confirm the capability of the system to continuously monitor the thermal behaviour of the industrial melting process.

Figure 9 shows the same temperature traces during one representative week of continuous operation. The cyclic behaviour of the melting process can be clearly identified. At the beginning of each production day, the rotary furnace is pre-heated before the aluminium

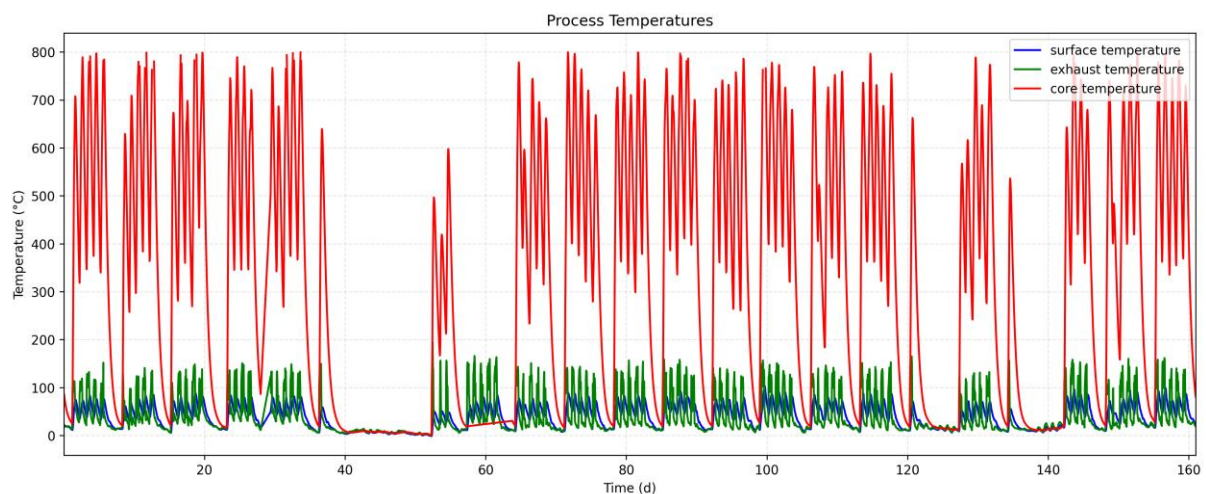


Figure 8: Long-term temperature measurements (furnace core, outer furnace surface, and exhaust gas system) of the rotary furnace process from November 2025 to April 2026 showing weekly production cycles and seasonal shutdown periods.

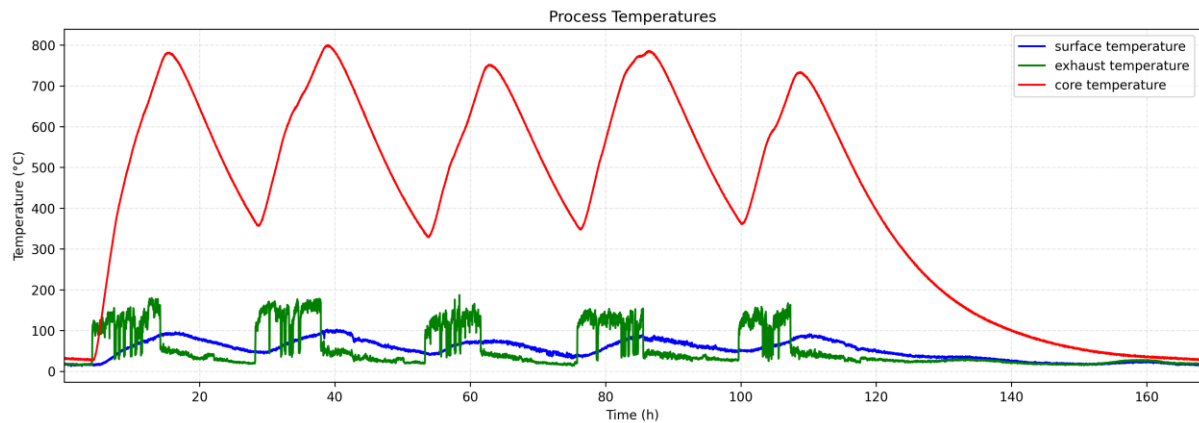


Figure 9: Temperature profiles during one representative production week showing cyclic heating and cooling behaviour of the furnace system.

scrap material is introduced and melted. This heating phase is visible through the rapid increase of the exhaust gas temperature, which reacts first due to its direct exposure to the combustion process and hot gas flow.

The temperature measured inside the furnace core increases with a noticeable delay. This behaviour results from the sensor placement within the fireclay lining rather than direct contact with the molten material itself. Consequently, the measured temperature reflects the thermal inertia of the refractory material. The outer surface temperature of the rotary furnace exhibits the slowest response and lowest absolute temperature due to the thermal insulation provided by the furnace structure.

During operation, the furnace core temperature reaches values above 700 °C, while the outer surface temperature remains below approximately 100 °C. The exhaust gas temperature shows rapid fluctuations caused by changing burner operation and process dynamics. After daily operation ends, all temperatures decrease gradually due to the thermal mass of the furnace system. At the end of the working week, a continuous cooldown towards ambient temperature can be observed over several days, illustrating the long thermal time constants of the rotary furnace and its refractory lining.

Figure 10 shows the temperature profiles during one representative production day in the middle of the working week. In contrast to the beginning of the week, the furnace core temperature is already elevated at the start of the measurement period due to the remaining thermal energy stored in the refractory lining from previous operation cycles.

The detailed temperature traces show that the rotary furnace operates in alternating heating and standby phases rather than being heated

continuously. During active heating, the exhaust gas temperature reacts immediately and fluctuates due to burner operation, while the furnace core and outer surface temperatures respond more slowly because of the thermal inertia of the fireclay lining and furnace structure. During standby phases, no melting is performed and the temperatures stabilize or decrease slowly, indicating that the furnace retains substantial thermal energy for subsequent process cycles.

The presented temperature measurements provide a basis not only for process monitoring, but also for forecasting and digital twin modelling of the rotary furnace. The combination of exhaust gas, furnace core, and outer surface temperatures enables identification of heating, melting, standby, and cooldown phases. Like digital twin approaches for industrial furnace systems, these data can be used to synchronize thermal models with the real process, estimate non-directly measurable thermal states, and predict future

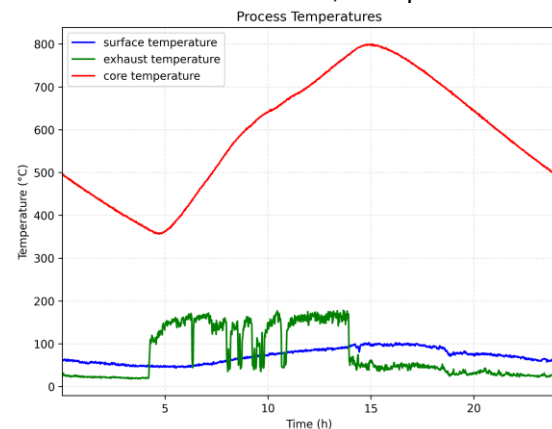


Figure 10: Detailed temperature traces during one production day illustrating alternating heating and standby phases of the rotary furnace.

temperature evolution. This supports model-based process optimization and reduction of energy consumption [13].

Conclusion and Outlook

This paper presented a wireless, energy-autonomous temperature measurement system for a rotary aluminium melting furnace. The results demonstrate reliable cable-free temperature monitoring at multiple furnace locations and confirm that the mechanical fixture and thermal shielding keep the sensor electronics within acceptable temperature limits. Energy availability was identified as the main limitation for long-term autonomous operation, especially under low and dynamically varying illumination caused by furnace rotation. However, additional artificial illumination enabled stable operation over extended periods. The measured temperature data further provides a basis for process monitoring, forecasting, and digital twin modelling. Future work will focus on improved energy harvesting, further power reduction, and the use of the measured temperature data for forecasting and digital twin applications.

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