Estimation of metal state in molten production processes using electromagnetic tomography with fast integrated processing

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Abstract
This paper presents imaging of copper slag solidification processes using electromagnetic tomography (EMT). It describes key components of the measurement system including a sensor that can operate in the harsh temperature environments. An integrated process tomography system is detailed that includes the main processing unit, i.e. a field programmable gate array and other front end circuitries. It is capable of delivering a wide excitation signal frequency ranging from 0.1 Hz to 500 kHz and a fast speed of 131 frames s⁻¹ with a typical signal-to-noise ratio of 66 dB–95 dB. Measurement trials were conducted on a molten converter slag solidification process where the copper slag changes from the molten state to solidification state during the cool-down for more than an hour. The phenomenon in which the disorderly distributed metal gradually forms solid and permeable object was observed, which can indicate the status of the process. This is the first report of observing such a process using an EMT system. Moreover location-based convergence analysis has been carried out in the imaging space and useful new insights have been gained for the copper production process, which would be difficult to obtain otherwise. Verification and calibration using x-ray diffraction and scanning electron microscope indicate the viability of the EMT-based measurement method.

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(Some figures may appear in colour only in the online journal)

List of abbreviations

| Acronym | Description                          |
|---------|--------------------------------------|
| EMT     | Electromagnetic Tomography           |
| I/Q     | In-phase and Quadrature              |
| GUI     | Graphical User Interface             |
| SNR     | Signal-to-Noise Ratio                |
| ADC     | Analogue-to-Digital Converter        |
| DAC     | Digital-to-Analogue Converter        |
| LBP     | Linear Back Projection               |
| SVD     | Singular value decomposition         |
| PS      | Processing System                    |
| SoC     | System-on-a-Chip                     |
| PL      | Programmable Logic                   |
| PGA     | Programmable Gain Amplifier          |
| DMA     | Direct Memory Access                 |
| XRD     | X-ray Diffraction                    |
| SEM     | Scanning Electron Microscope         |

1. Introduction

Electromagnetic tomography (EMT) is an imaging modality for the purpose of industrial process monitoring and medical imaging, which has been intensively studied and developed due to its low cost, non-destructive, non-invasive and convenient properties [1]. It has been applied in a range of applications, such as multi-phase flow imaging which requires visualisation and control during steel production process [2–7].

Many efforts have been made to utilise the EMT system to visualise and monitor the molten metal flow. An EMT system was presented which was applied in the steel industry for imaging the molten steel flow profile in continuous casting through a pouring nozzle with a six-coil EMT sensor array and an impedance analyser [5, 8]. Later on, hardware and software design of an EMT system with an eight-coil sensor array for molten steel flow profiles imaging was reported [9]. The conditioning circuits were integrated and the system was equipped with a LabVIEW-based user interface. The maximum image capture rate is 10 frames s⁻¹. However, there are still limitations in these works as the real flow profiles such as central stream and annular flow were simulated by applying conductive objects which had higher conductivities than most liquid metals in the imaging area. An application of EMT for imaging the molten steel solidification process was demonstrated [1]. Phase changes were observed experimentally of the liquid zone and detected by the EMT sensor array when the wood alloy state changes from liquid to solid at 68 °C–70 °C.

In industrial processes, there are growing number of important applications that require a contactless method for monitoring an object surrounded inside a metallic enclosure [1]. Imaging copper slag melting-solidification process is an example. It can be regarded as a complex multi-phase process, which should be monitored in real-time [10–12]. In-situ monitoring of solidification processes in metals and alloys has been carried out with methods utilizing x-ray exposure, infrared or gamma-ray [13–17]. However, the high temperatures of metals under inspection limit the viability of these methods [13]. For this particular process, there are very few reports on in-situ and real-time measurement, however, this information is critical for plant to further understand the solidification process for optimisation and develop new processes. Therefore, it is important to develop new non-intrusive, non-contact and real time methods capable of visualising the in-situ solidification process continuously for process and quality control in metal production industry. The field programmable gate array (FPGA) based EMT technology is a suitable candidate as it provides real-time measurement and high temperature tolerance. So far, EMT systems have been intensively applied in imaging multi-phase flows such as molten steel flow in metal production industry. However, there is no report on the use of an EMT system to monitor the copper slag melting-solidification process as the temperature of the molten flow can reach to 1260 °C. To withstand high temperature during the process, a high-temperature EMT sensor array and stable EMT system are necessary.

Table 1 demonstrates the components of converter slag, which contains conductive/permeable elements and hence can be measured by EMT method.

A typical EMT system comprises of a sensor array, conditioning electronics and a host PC. The sensor array is a set of coils distributed around the imaging area which can sense the magnetic coupling between each other. One of the difficulties in EMT is to measure relatively small signal changes under a large background signal [19, 20]. Alternative active elements such as TMR sensors have been applied in EMT systems to substitute coils, which are frequency-independent unlike the coils [21]. However, it is not applicable in high-temperature environments such as during the copper slag melting-solidification process.

Also, with the development of programmable digital processing units such as digital signal processors and FPGA, EMT systems tend to be integrated and digitalised, which provides better stability and high-speed data transmission. An FPGA-based digital EMT system was reported, which was believed to be the first system of this kind [22, 23]. This system is capable of delivering data at 200 frames s⁻¹, which is preferable for real-time application. However, no further studies have been conducted to date. Thus, there is still a lack of digital EMT systems which are not only highly integrated but also capable of providing fast response, high signal-to-noise ratio (SNR) and real-time data for applications such as the copper melting-solidification process.
This paper describes the latest developments in a digital EMT system for monitoring the copper smelting process in the metal production industry. This system was integrated in a standard 19 inch rack instrument with a size of 250 mm × 330 mm × 155 mm, which makes it portable and usable under different environmental conditions. The proposed system applied digital excitation signal and digital signal demodulation in FPGA to improve the data speed and SNR, which are essential for many industrial applications that require online imaging such as fast molten flow imaging. The fast data speed (up to 131 frames s$^{-1}$) and relatively high SNR (typical 66–95 dB) would contribute to stable real-time imaging of metal flows during the copper smelting process. Using the proposed system, the flow regime can be monitored to ensure the quality and composition of copper during production. The solidification process was observed and analysed for more than 1 h.

2. System description

The proposed EMT system consists of three main elements: a host PC, conditioning electronics and an eight-coil EMT sensor array. The cornerstone of the entire system is the Zynq-7020 system-on-a-chip (SoC) which includes a processing system based on an ARM dual Cortex-9 processor and a Xilinx 7-series FPGA which is also called programmable logic. The Zynq-7020 SoC is responsible for generating of the digital excitation signal, in-phase and quadrature (I/Q) for receiving the signal, digital filter implementation and data communication between the instrument and the host PC. The conditioning electronics include the Zynq-7020 SoC and front-end circuits, which are connected to eight coils of the sensor array.

2.1. Sensor array

Generally, the design of a sensor array involves choosing the number of coils, materials used to construct the sensor and operating frequency, which influence the system performance in different ways. Typically, if the number of coils increases when the diameter of the sensing section keeps the same, the size of coils will reduce accordingly. The reduction of coil size will result in a smaller inductance and therefore a weaker received signal. When the signal is too weak, the SNR will not be acceptable anymore. Generally, the number of coil can be 8, 12, 16 and 24 as described in [20, 24–26]. With more coils in a sensor array, there are more projections from different angles. However, the increase of coil number may also result in a larger ill-condition number, which may not improve the spatial resolution. In addition, it will also increase the complexity of hardware design. After many research in EMT, there is a consensus that eight-coil generally provides a better results.

In the proposed system, an eight-coil sensor array was applied to the system, which was evenly spaced along the circular imaging area. Therefore, the interval between each coil pair was 45°. During the measurement, the coils were excited in turn and the signals were received from the rest of the coils individually. For example, when coil 1 is excited, coil 2–8 works as the receiving coils. The received signals from coil 2 to 8 are multiplexed, and controlled by the FPGA. Therefore, the sequence would be Ex1-Re2, Ex1-Re3, ..., Ex8-Re1, ..., Ex8-Re7 which gives 56 coil pairs in a single data frame for an eight-coil sensor array.

In order to operate at high temperature, coil formers were made of aluminium oxide, which could be operated at a maximum of 1500 °C for imaging the copper slag melting-solidification processes. In addition, the wires and cables were thermally insulated, allowing the EMT sensor array withstand the high temperature. A photograph of the sensor array and the geometry parameters of the sensor coil are shown in figure 2. The diameter of the imaging space is 100 mm; The number of turns of the coils is 90.

In terms of operating frequency, the system is capable of providing an excitation frequency in a wide range from 0.1 Hz to 500 kHz. The selection of an effective excitation frequency mainly depends on the coil configuration and physical test setup. For the proposed system, it was implemented to monitor the copper slag melting-solidification in real-time, which is a complex multiphase process. Hence, relatively high frequency was required to provide a fast response.

To determine the optimal operating frequency, the frequency-swept response was measured from 100 Hz to 500 kHz using the instrument. The copper slag sample was measured using a single coil pair of the EMT sensor array and the relative inductance change was obtained by subtracting the frequency response in free space, which is shown as follows

$$\Delta L = \frac{Z_{\text{sample}} - Z_{\text{free space}}}{j\omega}$$  \tag{1}
where $\Delta L$ is the relative inductance change, $Z_{\text{sample}}$ is the impedance of the EMT sensor with the sample, $Z_{\text{free-space}}$ is the impedance of the EMT sensor in free space, $\omega$ is the angular frequency and $j$ is a complex number operator.

The resultant inductance measurements are shown in figure 3. As indicated, the inductance change remained relatively stable from 100 Hz to 500 kHz. However, there is more noise from 100 Hz to 1 kHz while there is a resonance frequency of the EM sensor at higher frequency range. Given that the presence of noise and resonance frequency, an operating frequency of 10 kHz was chosen, which provided a better SNR and avoided the resonance frequency of the sensor array.

The SNR at different coil pairs is shown in figure 4, which largely depends on the distance between the coils. The minimum SNR is 66 dB and the maximum SNR can reach up to 95 dB, which meet the demand of this application.

2.2. Hardware design

The hardware consisted of front-end circuits, AD/DA circuits and an FPGA board (Zynq-7020 SoC), all integrated in a standard 19 inch rack case with a size of 250 mm $\times$ 330 mm $\times$ 155 mm. Front-end circuits are responsible for the amplification and multiplexing of analogue signals. The AD/DA circuits are applied for digital-to-analogue converter (DOC) of the digital excitation signal and analogue-to-digital conversion for the received induced voltage signal. The FPGA generates the excitation signal with a direct digital synthesiser (DDS) IP core, implement I/Q demodulation for receiving signals, and configures of frequency and/or gain, and controls the process during experiments. Figure 5 shows the overall EMT system which includes a host PC, a sensor array and a customised EMT instrument.

The Zynq-7020 SoC is the cornerstone of the proposed EMT system, as shown in figure 6. The selection of FPGA is due to its flexibility as it contains both programme logic and programmes system. This SoC architecture allows easy interfacing with hardware and flexible programming with data process at the SoC level. A 14-bit sinusoidal digital excitation signal was generated using an integrated direct DDS and fed...
The received signal was converted to a digital signal using AD/DA board. The 14-bit received signals were digitally demodulated, which contributed to stable data and high performance against noise. The I/Q demodulator was digitally realised in an FPGA program. The data of both the real and imaginary parts were demodulated, which are necessary for EMT applications. It is worth nothing that the reference sine and cosine waves for I/Q demodulator were from the same DDS IP generating the excitation signal, which were 14-bit as well. After demodulation, the signal was fed into a digital filter, which further filtered the high frequency harmonics. The data consist of 32-bit. These data were then transferred between the program logic and processing system parts with a direct memory access controller and Ethernet communication was implemented between the instrument and the host PC. All modules were synchronised by a 10 MHz internal clock generated by the FPGA. In addition, the FPGA was responsible for switching between coil pairs by controlling the analogue switches on multiplexing circuits, and selecting a programmable gain amplifier (PGA) gain.

The excitation circuit was applied to drive the coils in the EMT sensor, which mainly consisted of a power amplifier and power resistor. The receiving circuit contained eight identical detection channels and was connected to the EMT sensor via an RJ45 connector. Each channel detects the induced voltage at the receiving coils using an instrumentation amplifier, which is followed by amplification and filtering circuits. The multiplexing process between the coil pairs was realised using analogue switches. The analogue switches were controlled directly by the FPGA to drive the excitation coil and multiplex the received signals. A schematic of the excitation and detection channels is illustrated in figure 7. It is worth noting that only one coil pair was demonstrated.

The AD/DA board contained two analogue-to-digital converter (ADC) channels and one DAC channel, as shown in figure 8. It is largely responsible for converting between analogue signals and digital signals. A 14-bit DAC generated an excitation signal with a voltage level of four $V_{p-p}$, which provided a spurious free dynamic range of 84 dB. The excitation signal was then fed into the excitation channel. The received signal from the detection channel was connected to the ADC channel. At present, only one ADC channel is used in the system to measure the received voltage from the EMT sensor. However, the system can be readily extended to measure both the induced voltage and the excitation current, which would provide impedance measurements for the EMT sensor. Both ADCs are 14-bit, which contributes to a high SNR. In the ADC channels, PGAs were implemented to adjust the gain in each channel flexibly. These were controlled directly from the user interface using the FPGA. The selection of ADCs and DACs is mainly determined by performance and price factors. The maximum transfer rate for the ADC is up to 10 MSPS whereas that for the DAC can reach up to 125 MSPS. In the proposed system, the ADCs and DAC are synchronised with the FPGA using a 10 MHz system clock. At 10 MHz sampling rate, the demodulation rate can reach up to 10 MHz/1000 = 10 000 samples/second. In one EMT frame, there are 56 samples for an eight-coil EMT sensor. Therefore, there are 178 frames per second. With some consideration of overheads, the actual frame rate is 131 frames s$^{-1}$, which meets the requirements of real time imaging (less than 10 ms per image).
2.3. Software design

The software is a user interface realised in the LabVIEW graphical programming language (National Instruments). It aims to receive data, combine data, log data and display data in different manners for real-time imaging. It also allows users to control, configure and interact with the instrument during the operation. The PGA gain, excitation frequency and filter width could be configured by the user during the experiment. In addition, the excitation and sensing sequences can be flexibly determined through the user interface, which means that the system can be extended to employ sensor arrays with different coil pairs and structures. The sample speed and SNR were also calculated and displayed in real-time.

In figure 9, the real-time imaging interface is demonstrated. The LabVIEW-based software implemented linear back projection (LBP) algorithm owing to its high speed, which is ideal for online imaging application [24]. However, the LBP algorithm presents a poor performance with respect to complex distributions. The user interface can also log the data simultaneously during the operation, which not only displays the imaging data in real-time but also saves the current dataset in a .tdms file for the offline imaging in the future. Offline imaging allows the use of more complicated, time-consuming and accurate image reconstruction algorithms such as Tikhonov regularisation and singular value decomposition (SVD), in other software such as MATLAB. Figure 10 shows an example of offline imaging in MATLAB using Tikhonov regularisation for image reconstruction.

3. Results

3.1. Experimental testing and image reconstruction

First, the electrical characteristics of the EMT system were tested and validated. As mentioned previously, the system can obtain seven measurements under each excitation coil, which yields $7 \times 8 = 56$ measurements in a single EMT frame.
Typically, it demonstrates a ‘U’ shape in free space as shown in figure 11 which is determined by the spatial distance between coils.

Moreover, the system was preliminary tested in a molten converter slag solidification process, and useful new insights have been obtained during the process, which were difficult to obtain. In this experiment, the proposed EMT instrument, a box furnace, and a crucible were used. The box furnace as high-temperature heating equipment can heat materials to 1600 °C, as shown in figure 12. The box furnace has the advantages of fast heating, high efficiency, light weight, large capacity, energy saving and safety. First, the converter slag was melted by furnace in crucible at 1260 °C, this process lasted 2 h. The crucible has a diameter of 80 mm. After 30 min of heat preservation, it was taken out the crucible from the furnace and put into the EMT sensor, and cooled naturally. The insulation cotton was used to isolate heat to protect the coils and connecting cables. Then the system started recording the data of the converter slag during solidification. The whole record process lasted for 1 h.

The images were reconstructed using three different algorithms: LBP, Tikhonov regularisation and SVD, and the reconstructed images at time of 7 min, 22 min, 37 min, 45 min, 52 min and 67 min were demonstrated, as shown in figure 13.

As can be seen from the figures, initially the voltage change at 7 min had a relatively large value, indicating orderly distributed electromagnetic properties in the imaging area. Disordered flow profiles were observed from 22 min to 37 min. It is worth noting that the voltage change value gradually increased during this time, indicating a stronger signal. After 45 min, a clear object began to appear in the centre of the reconstructed images. The signal continued to increase from 52 min to 67 min until it finally stabilised. As shown, a blue area was observed which was concentrated at the centre of the imaging area. This is believed to be related to the electromagnetic properties of the high temperature copper slag during the solidification process which changes from a disordered distribution slowly and tends to stabilise, suggesting that the material phase in the copper slag from the scattered slowly formed the magnetic material of the organisation.

For different image reconstruction algorithms, it can be observed that Tikhonov regularisation and SVD have very similar performance. A similar flow regime was obtained using these two methods. However, LBP has poorer performance when the signal is relatively weak. At 45 min, images obtained from both Tikhonov regularisation and SVD indicated a forming object in the centre. However, the images obtained by LBP showed a strong signal until 67 min. Hence, the object could be identified in advance by using the Tikhonov regularisation and SVD algorithm, as compared with LBP.

3.2. XRD analysis of converter slag

In the XRD sample preparation process, using a vibratory mill sample machine, as shown in figure 14, the cooled converter slag was ground and crushed, then sieved out with a 200 mesh sieve, and the sieved powder was subjected to XRD characterisation. The test results are shown in figure 15.

According to the intensity of each object corresponding to figure 15, it can be seen that the physical phase of copper slag after solidification mainly includes Fe$_2$O$_3$, SiO$_2$ and Cu monomers, while the main elemental composition of converter slag is Fe, Cu, Si, O, S, etc, which is also consistent with the XRD pattern. The XRD characterisation results allowed us to introduce the chemical reactions occurring during the solidification of the copper slag as follows:

$$2\text{CuFeS}_2 \rightarrow \text{Cu}_2\text{S} + 2\text{FeS} + \text{S}$$  \hspace{1cm} (2)

$$\text{Cu}_2\text{O} + \text{FeS} \rightarrow \text{Cu}_2\text{S} + \text{FeO}$$  \hspace{1cm} (3)

$$2\text{CuFeS}_2 + \text{O}_2 \rightarrow \text{Cu}_2\text{S} + 2\text{FeS} + \text{SO}_2$$  \hspace{1cm} (4)

$$2\text{FeS} + 3\text{O}_2 + \text{SiO}_2 \rightarrow 2\text{FeO} \cdot \text{SiO}_2 + 2\text{SO}_2$$  \hspace{1cm} (5)

$$2\text{FeO} + \text{SiO}_2 \rightarrow 2\text{FeO} \cdot \text{SiO}_2.$$  \hspace{1cm} (6)
3.3. Scanning electron microscope (SEM) analysis of converter slag

The SEM sample preparation process, as shown in figure 16, first used the metallographic specimen cutting machine to cut the cooled crucible transversely, after comparing the two different cross-sections of the converter slag samples were selected and made into a cylindrical model, and then used the pre-mill to polish the samples taken for 30 min, and then used the metallographic polishing machine to polish the taken samples before the SEM test was performed. The results of the elemental distribution are shown in figures 17 and 18.

As can be seen from figure 17, the element Zn is uniformly distributed, whereas the other elements form small organisations gathered together. From a microscopic point of view, the dominant elements, such as Fe, Si, Cu, S, etc, all undergo oxidation reactions and agglomerate during the solidification of the copper slag, and it follows that, from the converter slag as a whole, the internal substances also agglomerate and stabilise during solidification. The SEM results also corresponded to the XRD results, which not only verified the chemical reactions occurring during the solidification of the copper slag, but also maximized the accuracy of the
imaging measurements and image reconstruction of the EMT system.

Both table 2 and figure 18 quantify the energy of the main elements in the converter slag, and it can be seen that Fe, Si, and O elements dominate, which also verifies the presence of iron olivine in the XRD characterisation.

4. Discussion

As suggested by the XRD and SEM analyses, the converter slag sample contained elements such as Fe, Si, Cu, and S. These elements tend to gather and form small groups during the solidification process. When elements are scattered, the sample does not exhibit obvious conductivity or permeability. Hence, the detectable change in the imaging area would be relatively low as a result of the low conductivity and permeability. This also corresponds to EMT measurements as shown in figure 13, which demonstrates the relative change in the induced voltages and the image reconstruction results. For the induced voltage, the relative change steadily increased during the solidification process, implying enhanced electromagnetic properties. From the reconstructed images, it can also be observed that initially, the imaging profiles were scattered and kept changing in a disorderly manner. Gradually the reconstructed images presented stabilised profiles after 52 min, which was in good agreement with the SEM analysis showing that the substances stabilised during the solidification process. It is also worth noting that Fe and its oxides take up a large amount according to figure 18. Table 2 and figure 18, which indicates the permeability of the converter slag. Nevertheless, these results demonstrate the potential of the proposed system for imaging changes in the converter slag status during the solidification process.

To exploit more information during the solidification process, a convergence analysis based on pixel location is presented in the time domain, which helps provide a better view of the flow profiles at different times. As shown in figure 19,
pixels at different locations in the imaging area were selected to observe. The imaging area is a circle with 100 pixels in both the x- and y-axes. Pixels were taken at \( R = 10 \), \( R = 25 \), \( R = 50 \), and right at the centre with equal spacing at the circumference. In this case, Tikhonov regularisation was applied to obtain the pixel value, which provided better results than LBP. The convergence results are shown in figure 20. As indicated, from 0 to 50 min, the values at different pixel locations are close to zero at different radius, which indicate weak electromagnetic properties and a disordered distribution in the imaging area. Changes at all locations were observed from 50 min to 60 min. However, the pixel values at different locations vary in different ways. The closer the pixel is to the centre of the imaging area, the larger the signal change. When the pixel is at the centre, the pixel value changes the most. In addition, for pixels at the edge of the imaging area at \( R = 50 \) and \( R = 25 \), the value changed randomly to either positive or negative, indicating a disordered distribution in these locations. However, the pixel value tended to change only to the positive at \( R = 10 \) and at the centre, indicating that a large signal appeared at the centre of the imaging area. This signal is believed to relate to the presence of the solid converter slag at the end of the process. After 60 min, the signal finally converged and remained stable until the end of the experiment. According to the results, it can be deduced that solidification occurred between 50 min to 60 min and the emerged solid object was close to the centre in the imaging area. The signal increased during the process, suggesting enhanced electromagnetic properties.

5. Conclusion

In this paper, a real-time online EMT system based on FPGA was presented, which aims to monitor the copper slag melting-solidification process. The system is highly integrated in a standard 19 inch rack instrument with a size of 250 mm × 330 mm × 155 mm, which makes it portable and can withstand different operating conditions, such as high-temperature. In addition, the EMT sensor array former was made of aluminium oxide, and wires and cables are thermally insulated to operate in high temperatures. Fitted with an eight-coil EMT sensor array, the system is capable of providing data with high SNR and high transfer speed, which plays an important role in real-time imaging. The data speed can reach up to 131 frames s\(^{-1}\) with a relatively high SNR of 66–95 dB. The

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**Table 2.** Atomic content and concentration of the main elements of converter slag.

| Elt. | Line | Intensity (c/s) | Atomic% | Conc. | Units |
|------|------|----------------|---------|-------|-------|
| O    | Ka   | 1208.85        | 44.698  | 22.214| wt.%  |
| Al   | Ka   | 170.48         | 2.584   | 2.165 | wt.%  |
| Si   | Ka   | 1508.25        | 18.492  | 16.133| wt.%  |
| S    | Ka   | 94.90          | 0.970   | 0.966 | wt.%  |
| Fe   | Ka   | 2490.77        | 30.308  | 52.577| wt.%  |
| Cu   | Ka   | 38.16          | 0.758   | 1.497 | wt.%  |
| Zn   | Ka   | 92.85          | 2.190   | 4.448 | wt.%  |

100.000 100.000 Wt.% Total
system can be configured flexibly to connect to a sensor array with different numbers of coils and structures. Furthermore, the digital design of the system is flexible and therefore the instrument can be expanded readily to 16 channels if necessary by increasing the amounts of channels and switches. Also, the system can be readily extended to impedance measurements instead of conventional voltage measurement in EMT systems.

The system was applied in the solidification process of the copper slag in laboratorial environments, and the performance of the system was verified using XRD and SEM analyses. In industrial, the processes and the temperature conditions are the same as in the laboratorial environment and the main difference is the scale of the copper slag which relates to the size of the sensor array. In [22], a scaling transformation has been reported. When the new sensing system inflates by \( k (k > 1) \), the inductance of the coils will also increase by \( k \) times. This indicates a larger induced voltage and potentially a better SNR performance. Nevertheless, the applicability of the EMT system in the practical metal production process will be investigated in future work.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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