

Thermographic inspection of the movement of metallurgical slag on the surface of liquid metal

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Original article

Abstract

The importance of slag in metallurgy means that issues related to its physicochemical properties and the processes of its formation and movement on the surface of liquid metal are the subject of numerous studies. Two institutes of the Łukasiewicz Research Network have begun collaborating on observing the movement of slag on the metal surfaces using thermal imaging. The results obtained using this method will be used to improve numerical and physical models and optimize metallurgical processes. Initial tests of observing the movement of slag based on recording the change in the position of markers floating on the slag surface with a thermal imaging camera were performed in a laboratory electric arc furnace.

Introduction

Production of metals in pyrometallurgical processes from their ores or secondary components (scrap) occurs at high temperatures, generally higher than the melting point of the metals being produced. Metallurgical slag plays a significant role in these processes. Depending on the technology used and the stage of the smelting process, slag plays a different role in achieving the desired properties of the smelted metal. Metallurgical slag plays a significant role in these processes.

Keywords

- metallurgical slag
- observation
- flow
- mixing
- thermovision

Authors' contributions

A – Preparation of the research project
B – Assembly of data for the research undertaken
C – Conducting of statistical analysis
D – Interpretation of results
E – Manuscript preparation
F – Literature review
G – Revising the manuscript

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Conflict of interest

None declared.

Depending on the technology used and the stage of a given smelting process, slag plays a different role in achieving the desired properties of the smelted metal. Metallurgical slag, which generally has a lower specific gravity than the smelted metal, remains on the surface of the molten steel, creating a layer that chemically influences the metal and also isolates it from the atmosphere, which has chemical and thermal significance [1–4]. Depending on the amount of slag and its degree of foaming, this layer ranges from 150 to 500 mm in an EAF furnace and 80 to 200 mm in a ladle furnace. In a BOF converter, in extreme cases, as a result of foaming, the slag can fill the entire converter and flow out of it. This is an undesirable case. Slag is generally the result of two fundamental processes: the melting of slag-forming additives intentionally introduced into the process and the accumulation of chemical reaction products occurring during metallurgical processing of molten metal. Additionally, slag consists of used refractory lining material and impurities introduced with the charge. The importance of slag in metallurgy and the variability of its parameters mean that issues related to its physicochemical properties, its formation processes, its movement on the surface of the molten metal, and its impact on the refractory lining are the subject of numerous studies and analyses covering various technological processes. For these reasons, two institutes of the Łukasiewicz Research Network located in Gliwice, namely the Łukasiewicz Institute of Non-Ferrous Metals (Ł-IMN) and the Łukasiewicz Upper Silesian Institute of Technology (Ł-GIT), have collaborated on developing a method for monitoring the movement of metallurgical slag on the surface of liquid metal using thermal imaging. The results obtained by this method, in conditions close to real ones, will be used to improve numerical models and cold physical (water-oil) models. The idea of monitoring slag flow using thermal imaging is of interest to Ł-IMN, which focuses on the study of non-ferrous metallurgical processes, and to Ł-GIT, which has been using thermal imaging to monitor metallurgical processes in the context of slag for many years. These activities include, among others, detecting slag during steel tapping from the furnace and estimating the concentration of iron oxides in slag based on its emissivity [5]. This article presents laboratory-level work testing and verifying the monitoring of metallurgical slag movement using thermal imaging markers.

The role of slag and the idea of monitoring its movement on the metal surface

The steelmaking process, in its most general sense, involves removing admixtures (for example: C, Si, Mn, P, S, and others.) which are undesirable for the steel grade being produced. The process of removing these admixtures takes place through oxidation or other chemical means, and binding the products of these chemical reactions (e.g., MnO, SiO₂, P₂O₅, CaS, MnS) in slag that is insoluble in the metal bath, or removing them in gaseous form to the surrounding atmosphere (CO, CO₂, SO₂). By absorbing the products of metallurgical reactions, slag changes its chemical composition during the process. However, the chemical composition of slag is not a simple consequence of the accumulation of steel smelting products and impurities introduced with the charge. The chemical composition, and therefore the properties of slag, are deliberately determined by the appropriate selection of additives known as slag-forming materials [6]. The composition of steelmaking slag depends on the process. During steelmaking in a furnace, slag can contain 30 to 50% CaO, 20–30% FeO (up to 35% in the BOF process), 5–10% SiO₂, 5–8% MgO, 1–5% Al₂O₃, and others. In a ladle furnace, the CaO content can be up to 60%, Al₂O₃ 10–30%, SiO₂ 3–10%, MgO 5–10%, and FeO + MnO below 2%. The slag temperature during the process typically ranges from 1580 (LF) to 1650°C (EAF, BOF), but under the arc in an EAF furnace, it can locally heat up to 3000°C. The viscosity of steelmaking slag, depending on the process and temperature, typically ranges from 0.8–5.0 Pa × s. The effectiveness of slag's interaction with the molten metal is strongly related to the dynamics of these two liquid phases. The natural phenomenon of convection currents in the ladle, as well as mixing induced by external forces (inert gas, electromagnetic), influence the dynamics of the refining processes. Regardless of the cause, the phenomenon of slag displacement on the molten metal surface significantly impacts the effectiveness of slag interaction with the refined steel, as well as with the refractory lining. Reducing the consumption of refractory materials is a crucial element in optimizing metallurgical technologies. Furthermore, knowing the slag flow rate under given conditions

allows us to deduce its viscosity and, consequently, its reactivity towards the molten steel and the refractory lining. In extreme cases, steelmaking processes reach temperatures of up to 1700°C, and 1650°C should be considered standard for BOF or EAF processes. Therefore, refractory lining protection is a crucial element of steelmaking technology, and the requirements for refractory materials in steelmaking processes are very high, which is a significant challenge.

The designed target composition of steel slag is a compromise between properties that promote lining protection and the potential for steel refining. For example, MgO in the slag slows lining erosion but increases viscosity and impairs refining properties, while Al₂O₃ in the slag lowers viscosity and enhances its steel refining properties but increases the rate of refractory lining erosion. Slag in non-ferrous metallurgy is typically a waste product that can be processed in other processes to recover the valuable metals bound within it. An example of this type of metal recovery from slag is the reduction of slags generated during copper production using the flash smelting process. The slag contains approximately 12% copper. In addition, this slag contains 11–13% FeO, 29–31% SiO₂, 13–15% CaO, and other elements. Its temperature during the process ranges from 1280–1320°C at the beginning of the process to 1390–1430°C at the end. The viscosity of the slag at the beginning of the process, i.e., at a temperature of approximately 1300°C, is 4.5–5.0 Pa × s, and its melting point is approximately 1000°C. The viscosity of the waste slag at the end of the process (after decopperization) at a temperature of 1410°C is 4.5–5.0 Pa × s, and its melting point is approximately 1100°C. Reduction of oxidized copper is carried out in an electric furnace, where heat is generated by the flow of electric current through the slag (resistor) – the Joule effect. Analysis of the speed at which the slag is stirred can allow us to determine the mechanisms that improve the rate at which reduced copper droplets fall to the bottom of the furnace. After recovering valuable metals from the slag, it can be used as road aggregate, as an additive to specialized cements, as a filler in depleted mines replacing natural sand, or in other applications in the cement, ceramics, and other industries. As indicated above, monitoring slag movement can help optimize individual technological stages in broadly defined metallurgical processes. The idea of monitoring slag movement on the surface of the liquid metal, described in this paper, involves placing markers on its surface, which are recorded in successive thermograms depicting the bath surface.

Movement of slag on the metal surface and the continuity of its layer

Slag, as a diverse phase compound, is characterized, among other things, by variable viscosity. This is an important parameter determining the exchange of elements or chemical compounds between steel and slag. Low-melting slags generally have lower viscosity (0.8–1.5 Pa × s) and, being more fluid, are much more desirable in most technological operations. This results from the greater dynamics of the chemical compound exchange reaction between metal and slag. In the case of high viscosity slags (3–5 Pa × s), the lower layer, located near the liquid metal, participates in the steel refining processes, while the upper layer is largely excluded, which negatively affects the overall effectiveness of the slag's interaction with the smelted steel. A similar situation also occurs with steel, which may be excluded from the slag refining processes due to its great depth (up to several meters). This is prevented to some extent by convection currents that occur as a result of the steel contacting the cooler walls of the ladle. However, these currents are usually insufficient, and forced stirring is used to homogenize the metal bath. In most cases, the steel is purged from the bottom with an inert gas. The need for multi-aspect optimization (homogenization efficiency, temperature drop, surface exposure) of the inert gas purging process has led to numerous studies in this field [4,5,7]. Slag flow processes are discussed in many theoretical and practical works. The phenomena occurring on the ladle surface are analyzed using numerical simulations and physical models. When steel is blown with an inert gas in a LF (ladle furnace), the metal surface is exposed as a result of the intensification of the slag and steel flow processes (Figure 1). This is an undesirable phenomenon that negatively impacts steel quality. Controlling and modeling this phenomenon can help select blowing parameters to minimize undesirable surface exposure and erosion of the refractory lining. Analysis of slag flow processes on the ladle surface during blowing using the proposed method should provide information essential for modeling this phenomenon and subsequently validating the developed models. This is important because numerous interactions occur in the metal-slag-gas system, making it difficult to predict and model phenomena occurring particularly near the gas escape to the bath surface (above the gas-permeable fitting – Figure 1).

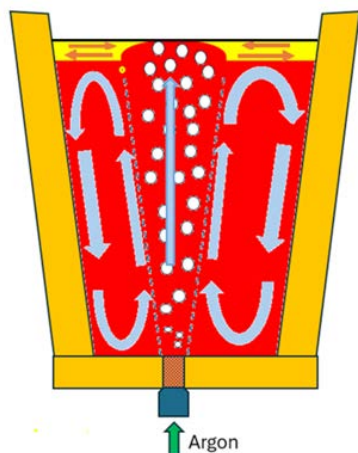


Figure 1. Directions of steel and slag flows in LF as a result of mixing steel with inert gas

Thermographic measurements of slag and liquid steel

Thermographic measurements of metallurgical slag have been used in metallurgy for many years. One of the most important applications is the use of thermal imaging in “slag detection” systems [8–13]. According to the technology, steel tapping from the furnace (EAF or BOF) should be completed so that as little furnace slag as possible gets into the secondary metallurgy process. Using the difference in emissivity coefficient between liquid slag (0.75–0.85) and liquid steel (approx. 0.4) at a temperature of approximately 1600°C, the steel and slag in the thermogram differ significantly in temperature (Figure 2). It is possible to use typical cameras operating in the ranges of 3–5 μm and 7.5–13 μm , but research by Optris IR Sensing [13] shows that the wavelength of 7.9 μm ensures minimal interference from dust and smoke, as these particles have no absorption band at this wavelength. Furthermore, research in this area conducted at Ł-GIT has shown that thermal imaging can be used as a “steel detection” system during slag pouring in BOF converters. Slag pouring from the steel-filled BOF occurs during slag-replacement during high-phosphorus hot metal (liquid pig iron) processing. This technology is not used in Poland, therefore, only a few emergency tests have been performed, but its feasibility has been demonstrated.

Thermal imaging finds applications in continuous casting, a key process in the metallurgical industry, particularly in the production of steel, aluminium, and copper. In this process, molten metal is continuously

poured into a water-cooled mold. This produces a continuous ingot, which is then further processed. In continuous casting, fluctuating molten metal temperatures and incorrect flux (kind of slag) amounts can lead to breakthroughs, damaging equipment, halting production, and risking worker safety. By monitoring flux surface temperature in real time, the infrared camera enables automated flux feeder control, ensuring stable casting conditions and preventing critical temperature deviations [14].

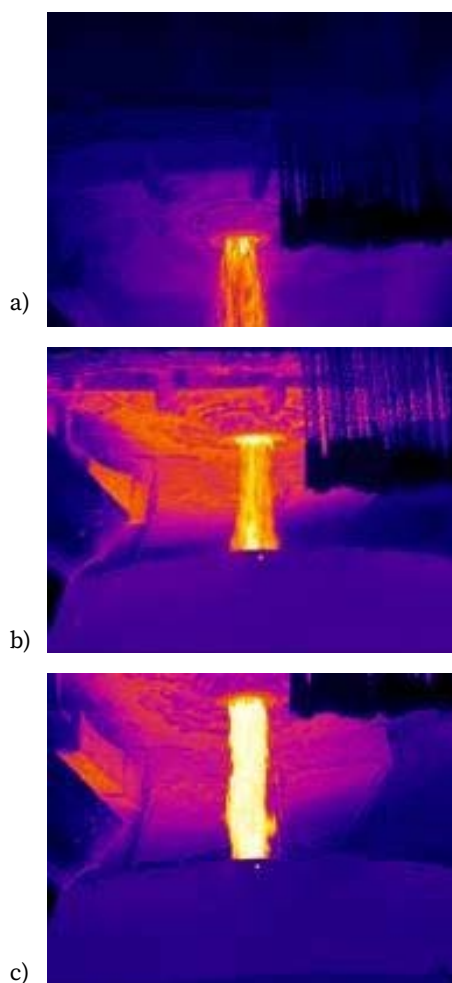


Figure 2. Slag detection using thermal imaging in Basic Oxygen Furnace (BOF): a) steel tapping; b) steel tapping with visible slag appearance – the BOF begins to move up; c) slag tapping – further move up of the BOF to minimize the amount of slag entering the ladle [Ł-GIT’s own material]

Thermovision measurements were also used in research on the estimation of FeO content in BOF slag performed jointly by Lodz Technical University and Ł-GIT. Under the research, the methodology and computer software were developed to allow the determination of radiation parameters, which, together with emissivity, characterise steelmaking slag. The values of

these parameters were determined by static treatment of steel and slag stream images using the multispectral measuring system with two infrared radiation thermal cameras (medium- and long-wave) and the RGB device to record images in the visible light band. For classification and approximation of measuring data the artificial neural networks are used where the initial value corresponds to ferric oxide content in steel slag that occurs during steel tapping from metallurgical furnace to ladle [15–17]. The FeO content in the slag is important for further process planning. Thermal imaging measurements in metallurgy are difficult and can be subject to errors resulting from radiation from the hot surroundings and the atmosphere permeability. The total infrared radiation power reaching the camera in a given spectral range from the object, the background, and the atmosphere is expressed by the equation (1) [18,19]:

$$P_t = \varepsilon \cdot \tau_a \cdot P(T) + (1 - \tau_a) \cdot P(T_a) + (1 - \varepsilon) \cdot \tau_a \cdot P(T_e) \quad (1)$$

where:

P_t – total power reaching the camera;

$P(T)$ – the radiation power of a black body at temperature T ;

$P(T_a)$ – the radiation power of the atmosphere at temperature T_a ;

$P(T_e)$ – the radiation power of the environment at temperature T_e ;

τ_a – atmospheric permeability coefficient between the object and the camera;

ε – emissivity of the object.

Materials and methods

The first tests of slag movement monitoring based on recording changes in the position of floating markers on the slag surface were conducted at the Ł-IMN laboratory in an electric arc furnace. This is a two-electrode furnace with a capacity of approximately 70 kg of iron and a basic (magnesia) lining, in which typical steel slag was formed from typical slag-forming materials (CaO, sand (SiO₂), dolomite, bauxite, iron ore).

FLIR SC 660 thermal imaging camera, specially adapted by the manufacturer to capture objects at temperatures up to 2000°C, was used for the measurements. Spectral range 7.5–13 mm, uncooled microbolometer – 640 × 480 pixels. Field of view (FOV) = 80° × 63°. The camera recorded the image from a distance of approximately 5 meters at an angle of 55°. For ceramic materials, the change in emissivity coefficient at an angle of 55° is not significant, and the viewing angle was the same for the slag and the markers. The purpose of the measurements was not to measure temperature, but to observe the apparent temperature difference, as in the case of slag detection.

In the first attempt, markers made of briquetted carbonized PKS (Palm Kernel Shells) were used, as

they provided very good contrast. The markers had dimensions of approximately 20 × 40 mm. However, their durability proved to be a drawback, especially in open-batch conditions.

Preliminary studies of various refractory ceramic materials were conducted in terms of reflectance as a function of wavelength using a hyperspectral VNIR camera operating in the 400 to 1000 nanometre range. The following materials were included in the research: electro-corundum, raw vermiculite, graphite, magnesite, bio carbon, waste corundum, dolomite, fly ash, quicklime, chalk, perlite, anthracite, magnesium carbonate, micro silica, sodium carbonate.

Results and discussion

The first laboratory tests, conducted through the charge port of a relatively small furnace, were limited to monitoring a section of the bath surface and should therefore be considered a preliminary verification of the method. It should be noted that the slag flow was not forced by an inert gas, and therefore its movement was not very intense. The collected evidence indicates that the method itself allows for the determination of slag flow within a given area of the ladle surface. Figures 3a to 3e show successive thermograms depicting the slag surface in an electric arc furnace, showing the movement of the marker marked with a blue ellipse in Figure 3a. In Figure 3e, the new position is marked with a red ellipse, while the previous position is consistently marked with a blue ellipse. A significantly smaller shift of the second visible marker in the opposite direction is also noticeable. The irregular shapes of the charge slag can serve as reference points for observing movement. From the perspective of the effectiveness of tracking slag movement, the method has proven its usefulness. However, a relatively rapid decline in marker visibility is easily observed in subsequent thermograms. Due to combustion, they become increasingly less visible until they disappear completely. The recording times between individual thermograms are provided in Table 1.

Table 1. Recording time of individual thermograms

Thermogram	Recording time	Elapsed time, s
3a	9:30:58	0
3b	9:31:04	6
3c	9:31:14	16
3d	9:31:29	31
3e	9:31:40	42

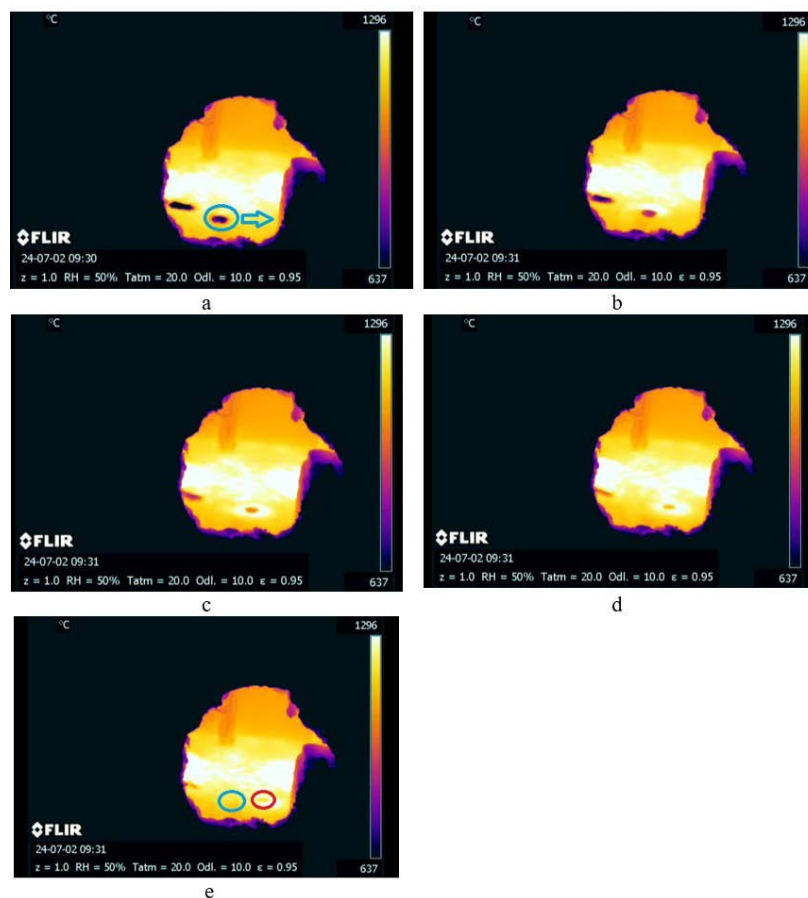


Figure 3. Thermograms of the slag surface with floating markers recorded at time intervals of 6 to 15 seconds (provided in Table 1)

Total distance travelled by the observed marker was approximately 45 mm. It should be noted that under industrial conditions, when stirring the bath with argon, marker movement will be significantly faster and provide significantly richer research data. 70 kg of iron has a volume of approximately 9 liters, and it is impossible to recreate industrial-scale conditions in this situation. Industrial ladles range in volume from 10 m³ to 45 m³. The research presented in this publication was conducted in conjunction with other research projects and aimed to determine whether it would be worthwhile to seek funding to continue them and to initiate discussions with industry about the possibility of conducting research tests at a steel mill. It should be noted that laboratory-scale ladle furnaces do not exist. This process cannot be arbitrarily scaled down. During industrial tests, it will be possible to determine whether the markers are not covered with slag and are sufficiently durable. Experience gathered during the initial measurement sessions indicates that the practical implementation of the thermal imaging slag flow monitoring concept requires meeting criteria for both

the markers and the infrared measurement method itself, as well as the interpretation of the results.

Marker criteria: To fulfil their role, markers must possess several characteristics:

- Have a specific density lower than the slag to remain on the slag surface.
- Have a high melting/sublimation/destruction temperature to function as long as possible without changing their shape or dimensions while on the slag surface.
- Have an emissivity coefficient significantly different from the slag (at the measurement temperature) so that they clearly stand out from the slag in thermograms - this condition can also be met indirectly by coating the marker with a substance with the desired emissivity coefficient. In this case, the substance does not need to have a lower specific gravity than the slag.

Measurement criteria: The very difficult measurement conditions resulting from the liquid steel temperature of 1600°C must be taken into account. Strong thermal radiation from the ladle surface precludes

placing a camera above the ladle. The image must be recorded at an angle, with the camera positioned outside the ladle outline, as in Figure 4.

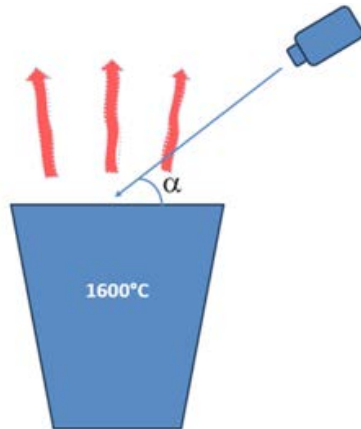


Figure 4. Camera positioning relative to the ladle during marker recording on the slag surface; the measurement is performed at an angle α , depending on local technical and logistical conditions

Regarding the interpretation of measurement results: Analysis of the path travelled by individual markers must take into account the measurement angle according to the formula (2) and formula (3), and presented in Figure 5.

$$l_R = l_y / \cos \alpha \quad (2)$$

$$l_R = [l_x^2 + (l_y / \cos \alpha)^2]^{1/2} \quad (3)$$

where:

l_R – real distance;

l_y – distance visible on the thermogram (apparent distance);

α – the angle of observation.

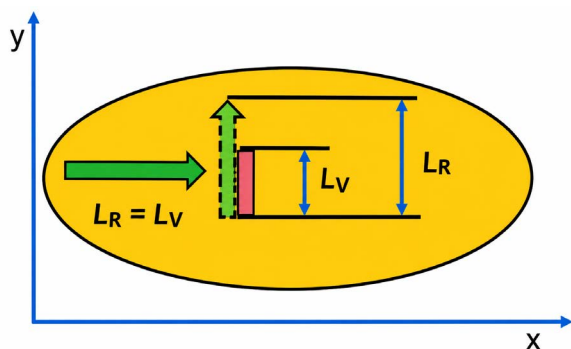


Figure 5. Real and apparent way of the marker depending on the direction of movement. The green arrow indicates the measured distance consistent with the actual value, the red arrow indicates the distance distorted by perspective, and the light green arrow indicates the calculated actual distance

Analysis of the movement of individual markers using image analysis software, essential for validating numerical models of steel and slag mixing and flow, must take this into account. Calculations determining the path travelled by a marker should take into account the perspective from which the image is recorded. Because this will be an observation from an angle, the paths of markers moving towards and away from the camera will be shortened the most (equation 1), while the actual path will be recorded for markers moving horizontally – Figure 5. Indirect shortening will occur for markers moving obliquely. The x component will be real, and the y component will be shortened identically to the vertically moving markers (general equation 3).

Conclusions

The method for monitoring the movement of metallurgical slag on the surface of liquid metal was verified in the laboratory as a result of joint work conducted by Łukasiewicz-IMN and Łukasiewicz-GIT. It was found that placing appropriate markers on the slag surface, whose positions are recorded on subsequent thermograms at known time intervals, allows for the determination of the speed and direction of slag movement in different areas of the surface. Practical implementation of the slag flow monitoring concept requires meeting criteria for both the markers and the infrared measurement method itself, as well as the interpretation of the results.

Transitioning from the laboratory phase to real-world industrial conditions requires further work, primarily involving the selection of materials used for the markers and the use of more advanced tools for identifying individual markers (shape, size, emissivity). Limited access to industrial ladles, which precludes the placement of a camera above the ladle, will require consideration of the effect of the viewing angle of the ladle surface on the distortion of measurements from this perspective.

Ethics statement

This study did not involve human participants, animals, or identifiable personal data; therefore, approval by a bioethical committee was not required.

Data availability

The data underlying the results are available from the corresponding author upon reasonable request

Use of AI tools

The authors declared that during the process of creating the publication they used AI tools (Google translate) for linguistic correction.

Bibliography

- [1] Bulko B, Kijac J, Borovsky T. The influence of chemical composition of steel on steel desulphurization. *Archives of Metallurgy and Materials*. 2011;56(3):605–609. <https://doi.org/10.2478/v10172-011-0065-1>.
- [2] Zhai J, Huang J, Zhao Y, Wang H, Wang Q, Li G. Influence of slag composition on desulfurization and cleanliness of silicon steel. *Journal of Materials Research and Technology*. 2025;38:5527–5538. <https://doi.org/10.1016/j.jmrt.2025.09.019>.
- [3] Criado M., Bernal SA, Garcia-Trinanes P, Provis JL. Influence of slag composition on the stability of steel in alkali-activated cementitious materials. *Journals of Materials Science*. 2017;53:5016–5035. <https://doi.org/10.1007/s10853-017-1919-3>.
- [4] Chakraborty S, Sahai Y. Effect of slag cover on heat loss and liquid steel flow in ladles before and during teeming to a continuous casting tundish. *Metallurgical Transactions B*. 1992;23:135–151. <https://doi.org/10.1007/BF02651849>.
- [5] Więcek B, Pacholski K, Olbrycht R, Strąkowski R, Kałuża M, Borecki M, Wittchen W. Termografia i spektrometria w podczerwieni: zastosowania przemysłowe. Warszawa: Wydawnictwo Naukowe PWN; 2017.
- [6] Turgodan ET. *Fundamentals of Steelmaking*. London: The Institute of Materials; 1996.
- [7] Borecki M, Mazur A, Wittchen W, Zdonek B. Wykorzystanie metody termowizyjnej do monitorowania wyłożenia ogniotrwałego kadzi stalowniczych. XI Konferencja Termografia i Termometria w Podczerwieni, Ustroń Jaszowiec, 22–24 września 2015, s. 197–207.
- [8] Zahorski F, Specht V. Schlackenerkennung auf Infrarothbasis mit einem Schlackendetektions-System. *Stahl u. Eisen*. 1999;119(11):61–63.
- [9] Goldstein DA, Sharan A, Stofanek JA. Infrared imaging for BOF slag detection. *Iron and Steelmaker*. 2000;27(7):31–38.
- [10] Rau H, Ropenack I. Application of thermographic slag detection. *MPT International*. 2002;1:52–55.
- [11] Wittchen W, Niesler M, Borecki M, Zdonek B. Application of thermovision method in analyzing metallurgical processes. 9th International Conference on Quantitative InfraRed Thermography, July 2-5, 2008, Krakow – Poland. 2008. p. 101–104. http://dx.doi.org/10.21611/qirt.2008.02_14_14.
- [12] Patra P, Sarkar A, Tiwari A. Infrared-based slag monitoring and detection system based on computer vision for basic oxygen furnace. *Ironmaking & Steelmaking: Processes, Products and Applications*. 2019;46(7):692–697. <https://doi.org/10.1080/03019233.2018.1460909>.
- [13] IR cameras & pyrometers for metal industry, ensuring precision in metal processing. [cited 2026 Aug 18]. Available from: <https://optris.com/us/application/metal/slag-detection-using-thermography/>.
- [14] Automating the flux feeder during the continuous casting process with IR. [cited 2026 Aug 18]. Available from: <https://optris.com/us/application/metal/continuous-casting-processes-flux-feeder/>.
- [15] Więcek M, Strąkowski R, Wiecek B, Olbrycht R, Świątczak T, Wittchen W, Borecki M. Estimation of steel slag parameters using thermal imaging and neural networks classification. 10th International Conference on Quantitative InfraRed Thermography, July 27–30 2010, Quebec (Canada). <https://doi.org/10.21611/qirt.2010.146>.
- [16] Więcek B, Pacholski K, Świątczak T, Wittchen W, Borecki M. Multispectral system for measuring the radiation parameters of steel slag during the discharge of steelworks furnace. 11th International Conference on Quantitative InfraRed Thermography, 11–14 June 2012, Naples Italy. 2012. <https://doi.org/10.21611/qirt.2012.297>.
- [17] Shatarah ISM, Imiela A, Surmacki J, Olbrycht R, Wittchen W, Borecki M, Abramczyk H, Więcek B. FeO content estimation in steel slag using Raman spectroscopy in NIR range. 14th Quantitative InfraRed Thermography Conference, 25–29 June 2018, Berlin, Germany. 2018. p. 109–114. <https://doi.org/10.21611/qirt.2018.p31>.
- [18] Madura H, Piątkowski T, Kastek M, Kołodziejczyk M. Metoda radiacyjnego pomiaru temperatury z kompensacją wpływu promieniowania słonecznego. *Biuletyn WAT*. 2009;58(2):157–173. <https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BWA9-0028-0010>.
- [19] Więcek B, Świątczak T, Olbrycht R, Wittchen W, Borecki M. Badania emisyjności żużla stalowniczego w zakresie podczerwieni MWIR i LWIR. *Pomiary Automatyka Kontrola*. 2009;55(11):914–918. <https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BSW4-0072-0012>.