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Citation for the original published paper (version of record):

Svensson, J., Memarpour, A., Brabie, V., Jönsson, P. (2016)

Studies of the decarburisation phenomena during preheating of submerged entry nozzles (SEN) in continuous casting processes.

Ironmaking & steelmaking

<http://dx.doi.org/10.1080/03019233.2016.1156900>

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N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-185229>

Studies of the decarburisation phenomena during preheating of submerged entry nozzles (SEN) in continuous casting processes

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Decarburisation of the submerged entry nozzles (SEN) during the preheating process was investigated based on plant trials and thermodynamic modelling at three different steel plants. During the trials the preheating processes were mapped, the temperature profiles were registered and post mortem studies of the SENs with scanning electron microscopy (SEM) were performed.

Typically, the glass/silicon powder will form a dense and protective layer inside the SEN when heated over 1100°C. However, this study found that the temperature distribution inside the SEN did not always reach this critical temperature. Thus, decarburisation of the SEN was found at all steel plants. The overall results illustrate that the control of the pre-heating process needs to be improved at all steel plants. It is suggested that future research should be focused on the development of new coating materials to prevent decarburisation of the RBM, which would decrease the chances of clogging during casting.

Key words: Continuous casting, Industrial plant trials, Preheating, Decarburisation, Submerged entry nozzle

List of symbols

ΔG – Gibbs free energy

T – Temperature

R – Universal gas constant

p – Partial pressure

a – Activity

1. Introduction

During continuous casting, the submerged entry nozzle (SEN) is used to achieve optimal flow conditions and to protect the molten steel from oxygen and nitrogen pick-up when transferring the molten steel from the tundish to the mould. This steel flow through the SEN can be disturbed by non-metallic inclusions which accumulate on the SEN's internal surface and lead to clogging of the SEN. This in turn can result in halted production, production losses, impaired quality and therefore increased costs [1-4].

During steelmaking the molten steel has a temperature of around 1600°C and if the SEN is at room temperature before being put in contact with the steel there is a high risk for thermal shock and resulting damage of the refractory base material (RBM). To minimize this phenomenon, the SEN is

preheated before a casting operation is initiated [1]. This preheating of the SEN can initiate a decarburisation of the RBM, which can influence the casting process. Specifically, the effect on the clogging tendency of the molten steel during casting due to decarburisation has been studied by previous researchers [4-7].

Overall, the time and heating rate during the preheating process are considered to be the most important preheating parameters. A short preheating time could cause a crack formation as a result of the thermal shock. Furthermore, a long preheating time in combination with high temperatures could lead to an increased carbon oxidation. Specifically, a maximum carbon oxidation and other physical changes occur at temperatures between 550°C and 950°C. Thus, it is necessary to move passed this temperature range quickly during the preheating process to prevent the graphite corrosion. When the temperature reaches 1200°C, the SEN is normally heated for 30 to 60 min to complete the preheating operation. Already stated [7], the temperature of the SEN should never be over 800°C after preheating. However, these high preheating temperatures enable an increase of the interaction between the refractory base material and the molten steel during casting [1]. Hence, it is of great importance to obtain knowledge about the SEN's behaviour during the preheating process. Previous studies have shown that all RBMs that contain graphite have a high probability to be decarburised during the preheating operation, which is due to an increased oxygen activity near the inner wall of the refractory [8-11]. Here, it should be noted that RBMs normally contains about 5 to 35 wt-% graphite. From a thermodynamically point of view, the decarburisation reactions are possible from temperatures as low as 550°C. Since the steelmaking temperatures are around 1600°C, the SENs have to be heated to temperatures where decarburisation definitely may occur [4-8].

Isothermal oxidations experiments using Al_2O_3 -C RBM by Sasai et al. [12], with both free- SiO_2 and containing SiO_2 RBM, revealed that carbon is oxidised by air and that it is only slightly affected by the presence of SiO_2 . Instead, it is the diffusion of O_2 gas and CO gas through the Al_2O_3 -C RBM that controls the oxidation process. In addition, Sunayama et al. [9] also found that diffusion of O_2 through the decarburised layer is the rate-determining step for the oxidation process of MgO -C RBMs during an isothermal heating of MgO -C RBMs in an Ar-O_2 atmosphere. Moreover, laboratory experiments with MgO -C RBMs which were heated isothermally showed that the decarburisation rate increased with an increased temperature in the temperature range of 800 to 1400°C. Thereafter, the decarburisation rate was approximately constant in the temperature range of 1400 to 1600°C [10]. Therefore, the time between the end of the preheating operation and the start of the casting should be kept to a minimum to increase the chances of a successful start of the casting operation.

Laboratory trials by Memarpour et al [8] confirmed that samples containing Al_2O_3 -C, ZrO_2 -C and MgO -C RBM were decarburised during preheating in oxygen and carbon dioxide atmospheres at a ratio equal to a propane-gas combustion. This was done in two different industrial combustion systems, namely an oxy-fuel and an air-fuel system. Also, the results suggested that the preheating of a SEN should be carried out at higher temperatures and during shorter holding times instead of at lower temperatures and longer holding times.

Alkaline (Na_2O and K_2O) glass/silicon powder coatings are used for protection against a graphite oxidation of the SEN's internal wall during preheating, which leads to the formation of a dense and protective glaze [1, 5]. During preheating experiments, Memarpour et al. [1] found that a protective high viscous alumina rich glaze penetrated into the Al_2O_3 -C RBM. Besides that the alkalis in the glaze reacted with the graphite; the penetration resulted in an uneven surface where primary inclusions in the molten steel were found to agglomerate on the surface [1]. Post mortem studies by Memarpour et al. [5], found that when 2 mm of the internal SEN's wall was decarburised a 10 mm thicker build up of an accretion layer was created in comparison to a surface that had not been decarburised. This build up consisted of multi-layers, where the rare earth metal (REM) alloying elements had interacted with Al_2O_3 and SiO_2 from the RBM [5]. The difference in the build up thickness on the internal SEN wall due to the decarburisation is presented in **Figure 1** [5]. In addition, Poirier et al [6] observed three area

zones in the RBM to the hot face; a decarburised area, a first layer of deposited material and a final layer of the deposit. The decarburisation of the RBM resulted in changes in the density and the apparent porosity in the decarburised area, due to the graphite and oxide losses [2, 13]. Another study of the interface between an $\text{Al}_2\text{O}_3\text{-C}$ RBM and molten steel showed an increased carbon pick-up by the molten steel with increased carbon levels in the RBM. It was also found that an extensive penetration of the molten steel into the RBM and a larger penetration in the RBM had occurred in samples with lower carbon levels compared to samples with higher carbon contents [14]. The present study was carried out to map the preheating process at three different steel plants to study the decarburisation process of SENs. Thermodynamic modelling was used to study the condition during which decarburisation of a SEN takes place during the preheating operation. Also, post mortem studies of the SENs were done using scanning electron microscopy to study the ceramic interfaces after a completed preheating.

2. Experiments - Industrial Preheating Plant Trials

Preheating trials were performed at three different steel plants: SP1, SP2 and SP3. The trials were performed according to the respective steel plant's standard preheating process conditions and using each plant's respective standard equipment. During the preheating process, the temperature distribution inside the SENs was measured at all steel plants. Thermocouples were placed in channels in the RBM, inside at the interface of the RBM and the internal surface, to measure the flue gas in contact with the RBM. In addition, at steel plant SP1 and SP3 the CO , CO_2 and O_2 contents in the flue gas were measured. All evaluated SENs in this study consisted of the same three RBM zones: $\text{Al}_2\text{O}_3\text{-C}$, MgO-C and $\text{ZrO}_2\text{-C}$ (**Figure 2**). In **Table 1** and **Table 2** the chemical compositions of the SEN's $\text{Al}_2\text{O}_3\text{-C}$ RBM and the protective glass/silicon powder coatings are presented, respectively [5]. The setup for steel plants SP1 and SP3 included one SEN placed in the tundish and on steel plant SP2 the tundish was equipped for three strands with three SENs. The SENs were preheated with oxy-propane torches; which were placed at the SENs outlet. On steel plants SP1 and SP2, tundish lids with oxy-propane torches were also used. All measurements of the flue gas and temperature were from SENs heated physically in the tundish.

At SP2, the preheating process was first mapped for SEN B1 (strand 1) and then for SEN B3 (strand 3). Also, on SP3 two preheating trials were performed. Due to problems with the analysing equipment, the flue gas was measured only during the first trial and the temperature was measured only during the second trial. In addition, the CO , CO_2 and O_2 contents were measured in the flue gas inside the SENs during the preheating operation. On SP1, the flue gas was measured using a M&C Analysentechnik instrument of type PMA 25, which was equipped with a paramagnetic detector. Moreover, the CO and CO_2 concentrations were measured with a Maihak analyser of type MULTOR 610, which was equipped with a Non-Dispersive Infra Red detector. At SP3, a Testo 300M equipment was used to measure the gas concentrations. Specifically, the accuracy of the CO_2 -value was ± 0.2 vol-% and that of the CO -value was ± 20 ppm.

The temperature was measured inside the SEN (**Figure 3**); in channels 1-5 using thermocouples of type S, and in channel 6 using a thermocouple of type K. The thermocouples were manufactured by Pentronic AB. Type S has a 10% Pt/Rh wire protected by high purity Al_2O_3 ceramic and was equipped with a standard contact that can measure up to 1600°C . The sheathing material for type K was Inconel 600, and was of conduit model that can measure up to 1200°C . The thermocouples were connected to Pico USB TC-08 Temperature Logger, which logged the temperature every second.

To mount thermocouples 1-5, channels were drilled in the SEN. From the SEN's bottom to thermocouple 1 the distance was 190 mm, and between the thermocouples the distance was 80 mm. At steel plant SP2, the distance between thermocouple 4 and 5 was 100 mm. Also, a channel for thermocouple 6 was drilled 3 cm down the top of the seat. At the position of channel 5 an additional

channel was drilled to enable the flue gas analysis. In **Figure 3** a schematic diagram for steel plant SP1 is presented, including the placements of thermocouples and the gas intake.

During each trial, an evaluation of the effect of the preheating process on the SENs was done by observing the RBM and the internal coating by SEM analyses after the completion of each trial. Also, the decarburisation was evaluated from both a macroscopic and a microscopic perspective and samples were collected from both unused and preheated SENs. In addition, the samples were analysed using an Ultra 55 Field Emission Gun Scanning Electron Microscope, FEG-SEM (a Carl Zeiss instrument equipped with an Inca Penta FETX3Oxford Instrument), equipped with an energy dispersive X-ray spectrometry (EDS).

3. Results & Discussion

3.1. The Influence of Preheating Parameters on Decarburisation

The aim of the present study was to evaluate the current SENs preheating processes during industrial conditions at three different steel plants: SP1, SP2 and SP3. All evaluated SENs contained three ceramic zones: $\text{Al}_2\text{O}_3\text{-C}$, $\text{ZrO}_2\text{-C}$ and MgO-C . In addition, the SENs came from two different manufactures. However, since the SENs consisted of the same type of RBM, the same heating conditions were recommended by both SENs manufactures. It should be noted that the preheating process setup was different for the three steel plants, including different numbers of strands and placements of torches. Thus, the trials were performed to provide an understanding of how different process parameters affect the preheating process and the decarburisation of the SEN by the influence of a tundish lid and number of strands on the temperature profiles.

The temperature profiles of the preheating processes from all three steel plants for all 6 channels are presented in **Figures 4-7**. In general, it can be seen that the temperature in channels 4 and 5 were the lowest among all measurement positions. This was true despite that, steel plants SP1 and SP2 use torches in the tundish lid. Here, the thermocouples were positioned approximately 240-320 mm from the torches at the SEN outlet and furthest away from the torches, which explains the lower temperatures at these specific positions.

At the steel plants that use a tundish lid with torches (**Figures 4-6**) it can be seen that the temperatures in channel 6 have different heating rates compared to the rest of the channels in the SEN. In general, the heating process is higher in channel six in comparison to the other measurement positions. Furthermore, in channel 6 the seat is initially heated to a higher temperature in comparison to the other measurement positions. Since the clogging in the seat is the flow limiting factor in the SEN, it is of most importance to have a controlled preheating process [15]. Even though torches in the tundish lid were used, the lower temperature in channel 6, compared to the highest measured temperature, indicates that the temperature contributions from the torches in the tundish lid to the SEN were lower than from the torches at the SEN outlet. This explains why channel 6 reached a higher temperature faster compared to the rest of the measurement positions in the SEN. Specifically; this was due to that the seat was heated from torches placed both in the tundish lid and in the SEN.

The temperature differences at steel plant SP1 was $\sim 460^\circ\text{C}$ and at steel plant SP2 (strand 1 and 3) were $\sim 500^\circ\text{C}$ and $\sim 480^\circ\text{C}$, respectively. At SP3 no lid was used during the preheating. Thus, a clear temperature difference of $\sim 550^\circ\text{C}$ was detected between the measurements in the seat at channel 6 compared to the rest of the measurement positions in the SEN. The temperature in the SEN's seat at SP3 was $\sim 550^\circ\text{C}$ lower during the whole time and it was almost constant during the whole heating operation, **Figure 7**. The temperature difference in channel 1 to 5 was $\sim 200^\circ\text{C}$. Based on the results from all the steel plants, it can be seen that the use of torches in the tundish lid helped to maintain a more even temperature distribution in the SEN. This is due to that the use of a tundish lid with torches at SP3 would decrease the temperature gap between the seat and the rest of the SEN.

According to earlier experimental research results [7, 8] the SEN should be heated to a high temperature in a fast manner without exceeding 800°C to decrease the tendencies for decarburisation during the preheating operation. For all steel plants, it was observed that higher temperatures were achieved faster in the lower part of the SENs compared to the upper part of the SENs. Also, the results showed that a large variation of the temperature distribution as well as the heating rate existed at all steel plants during the preheating process. More specifically, the SENs were heated for 40 to 75 min and using a rapid heating rate at all steel plants. Especially at steel plant SP3 the heating rate was excessive. This can also be explained by that the torches are only placed at the SEN's outlet. Thus, if a tundish lid were implemented the contribution from the existing torches could be lowered. However, the most important factor is to have a controlled preheating process. Already, when the SEN has been heated to 550°C it is possible for the decarburisation process to start. After the SEN has been heated above 1100°C, the glass/silicon powder coating forms a dense and protective glaze layer. Therefore, it is essential to use a high heating rate until the glaze is formed [8].

The thermodynamics of oxidation reactions were considered to determine which reaction is dominant during the non-isothermal and isothermal heating of RBM containing carbon. The partial pressures for O₂, CO and CO₂ were measured during the preheating trials; collected at 1 min, 9 min and 20 min, respectively after the preheating started, **Table 3**. Based on the measurement of the flue gas, calculations were made to determine if a direct oxidation (decarburisation) was possible during the preheating operation. This was done, according to reactions (1)-(3) and with the assumption that the activity of carbon equal to unity. Since the major constituents of Al₂O₃-C SEN are Al₂O₃ and C the direct oxidation of graphite reactions that could take place during the preheating process are as follows [8-11,16]:

The standard free energy equations refer to reactants and products in their standard states, i.e. the condensed phases in their pure form at the temperature of concern and for a total pressure of 0.1013 MPa as well as for pure gases of a 0.1013 MPa pressure at the specific temperature of concern [16]. According to the thermodynamic calculations (**Table 3**) reaction (2) was found to control the reaction rate. At steel plant SP3, reaction (2) is controlling the reaction during the preheating. Also, the process is rapid and high temperatures that become constant are attained after just minutes. Meanwhile, at steel plant SP1 reaction (1) is first controlling the heating rate. As the temperatures are becoming stabilised, reaction (2) controls the reaction rate. Since a high concentration of CO forms a reducing atmosphere, the CO₂ concentration can be considered as the only oxidising agent. This is due to that the O₂ and CO gases control the oxidation rates through the RBM.

An increase in the oxygen activity in the SEN during the preheating process increases the clogging tendency when the clogging sensitive steel grades are casted [8]. Also, the clogging tendency has been found to increase when the RBM contains components such as SiO₂, Na₂O and K₂O and when an indirect oxidation of graphite takes place according to any of the following reactions in the RBM [1, 5, 17]:

Overall, it is most important that a protective dense layer is formed during heating, before the molten steel comes in contact with the SEN [17]. For all SENs heated at all three steel plants, the inner temperature did not reach 1100°C in all channels. Therefore, the glass/silicon powder could not form a dense protective layer on the whole internal surface before the casting started. For some of the evaluated SENs the protective layer could not form until after up to 30 minutes of heating or even after longer heating times. During this time, a temperature of 550°C had been reached. Thus decarburisation had been possible in the RBM. Also, since a protective glaze had not been formed the decarburisation of the SEN could continue.

Samples from all preheated SENs with respective non preheated SEN, as a reference, were evaluated by using SEM. In **Figures 8-9** the RBM can be seen before and after preheating, for SENs from SP1, SP2 and SP3 respectively. In **Table 4**, the chemical analysis for points A-E and the RBM in SEM image (b) shown in **Figure 8** are presented. The high SiO₂ content in the RBM indicates a penetration of the glaze and the penetration could be detected at the maximum distance of 337 µm from the surface. From the SEM images in **Figures 9** it can be seen that the bulk mass of C has decreased and that porosity has increased in the bulk after the preheating operation. In **Table 5**, the chemical analyses for the SEM image (b) shown in **Figure 9** are presented. According to **Tables 4 and 5**, the silica content in the glaze decreased during the preheating process. This indicates that silica was reduced by carbon, according to reaction (5). Thereby, the glaze lost its protection against an oxygen diffusion through the SEN. Also, the samples from the preheating trials at SP3 showed no indication of a penetration of the formed glaze into the RBM. This was the steel plant with the highest preheating temperature as well as a heating rate of over 1100°C/min, during the first minutes of preheating in channels 1-5. During this stage, silica was reduced according to reaction (5). The existing coating material penetrated into the RBM in the examined SENs in the trials at two of the steel plants; SP1 and SP2. In addition, the gas composition and thermodynamic calculations in **Table 3** confirm that a decarburisation had occurred during the preheating process.

The graphite content in the Al₂O₃-C SEN contributes to a high slag corrosion resistance, a high thermal shock endurance, a large wettability reduction and a diminished thermal expansion [7, 14]. Such contributions could be changed when graphite is oxidised during the preheating process, due to a direct or an indirect carbon oxygen reaction. During the steel casting, the SEN can be treated as an open system, under a nearly constant pressure. Therefore, reduction reactions will proceed as long as the reaction products are removed from the reaction site.

The results from the industrial preheating trials have led to a better understanding of the change of the SEN properties during the preheating processes as well as to recommendation on how to improve the process. More specifically, the results show that it is important to obtain a glaze on the inner surface of a SEN in order to prevent the surface from being oxidised by of carbon. Due to this reason, future research should be directed towards developing a new coating method for SENs.

3.2. Oxidation protection of graphite during preheating of SEN and casting

Developments of new advanced stainless steel qualities require the use of very active alloying elements such as Ce and La, which worsen the conditions of continuous casting by causing clogging of the SEN. There is a strong link between the clogging phenomenon, composition and structure of SEN and cast steel composition due to oxidation of graphite present in the SEN. Under these conditions the protection against a graphite oxidation has become one of the most important challenges for developing new SEN designs. The development of new carbon fibre-reinforced ceramic matrix composite has led to the identification of the requirements of an effective oxidation protection system. Here, the most promising coatings are those composed by several ceramic layers, which are designed to protect the SEN against erosion, spalling and corrosion [18]. Furthermore, coatings that possesses a self-healing capability by the formation of a glassy phase when being exposed to oxygen [18].

According to the above presented experimental results, it is necessary to prevent an oxidation of the SENs refractory materials during the preheating process to improve the performance length of the SEN during continuous casting of special steel. Generally, the SENs refractories are coated with a glaze which reduces the oxygen permeation and prevents the graphite from oxidation. In the new generation of the commercial SEN coatings a powder layer is applied inside the SEN. This layer contains a mixture of glass and silicon powder.

The laboratory experiments conducted by Memarpour et al [1] revealed a penetration of the formed glaze into the SENs refractory base materials between alumina and silica particles. The study showed the vital effect of the glass/silicon powder coating on the clogging mechanisms. It was suggested that the use of a low or alkali free glaze such as a borosilicate glass could prevent the clogging phenomenon. Also, this study confirmed the importance of the SENs surface irregularities formed during the preheating process.

In order to improve the surface protection potential to diminish the graphite oxidation, Yttria Stabilized Zirconia (YSZ) plasma spray –PVD coated Al_2O_3 -C RBM was tested in laboratory scales. The experimental results showed that the coating material were resistance to carbon oxidation in combustion flue gas and air atmosphere [19]. Since the SENs RBM at all the steel plants have been decarburised during the preheating a new coating material for coating of the hot surface of the commercial SENs as an alternative to the traditional glass/silicon powder coating is recommended. Either a new coating material of the SEN internal surface or individually coating of the graphite particles in the RBM needs to be further evaluated.

4. Conclusions

The preheating processes at three different steel plants were mapped and the decarburisation behaviour in SENs during the preheating process was evaluated based on both thermodynamic modelling and post-mortem studies of SENs after a completed casting operation. Based on the results from the present study, the main conclusions can be summarised as follows:

- Decarburisation of refractory based SENs during the preheating process is thermodynamically possible at the investigated steel plants operational conditions.
- An increasing porosity was observed in the inner part of SENs after a completed preheating operation.
- It is necessary to maintain a proper preheating schedule, namely to control the preheating temperature and the preheating rate, to minimize the decarburisation during the preheating operation.
- The SENs have to be heated to temperatures around 1100°C to enable that a dense and protective glaze can be formed.
- The mapping of the preheating process at the three different steel plants revealed that the temperature profiles and preheating rates inside the SEN were uneven at all three plants.
- The experimental results suggest a need to develop a new coating material, which will protect the inner surface of the SEN against decarburisation.

Acknowledgment

The authors would like to express their gratitude to the committees TO23 and TO24 at Jernkontoret as well as VINNOVA and Dalarna University for their financial support to this study. The industrial

contributions from Outokumpu Stainless AB, Sandvik Materials Technology AB, SSAB EMEA AB Luleå are also greatly acknowledged.

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Figure Captions:

Figure 1. A transverse section of a clogged nozzle, including the different decarburised layers; the section is taken from level AA' in the SEN [5].

Figure 2. A longitudinal section of a commercial SEN; consisting of three different RBM zones.

Figure 3. The placement of the oxy-propane torches and thermocouples in the SEN during the trials; totally 6 thermocouples were placed in each SEN at 80 mm distance from each other. The torches were placed at the SENs outlet and in the tundish lid.

Figure 4. The temperature profile as a function of time during the preheating process for channel 6 at steel plant 1 (SP1).

Figure 5. The temperature profile as a function of time during the preheating process for channel 6 at steel plant 1 (SP1).

Figure 6 The temperature profile as a function of time during the preheating process for channel 6 for strand B3 at steel plant 2 (SP2).

Figure 7. The temperature profile as a function of time during the preheating process for channel 6 at steel plant 3 (SP3).

Figure 8. SEM images of the SEN's RBM from SP1: (a) RBM before preheating; (b) RBM after preheating at channel 1 [5].

Figure 9. SEM image of the SEN's RBM from SP3: (a) RBM before preheating: the glass/silicon powder coating is 304.6 μm in thickness; (b) RBM after preheating at channel 4. The longitudinal section shows the internal area of the SEN.

Table Captions:

Table 1. The chemical composition of the refractory based materials [5]

Table 2. The composition of the glass/silicon powder coating [5]

Table 3. Measurements of the gas compositions during the preheating trials at the two different steel plants

Table 4. Chemical analysis of the RBM from SP1 after preheating

Table 5. Chemical analysis of the RBM from SP3 after preheating

Figure 1. A transverse section of a clogged nozzle, including the different decarburised layers; the section is taken from level AA' in the SEN [5].

Figure 2. A longitudinal section of a commercial SEN; consisting of three different RBM zones.

Figure 3. The placement of the oxy-propane torches and thermocouples in the SEN during the trials; totally 6 thermocouples were placed in each SEN at 80 mm distance from each other. The torches were placed at the SENs outlet and in the tundish lid.

Figure 4. The temperature profile as a function of time during the preheating process for channel 6 at steel plant 1 (SP1).

Figure 5. The temperature profile as a function of time during the preheating process for channel 6 for strand B1 at steel plant 2 (SP2).

Figure 6. The temperature profile as a function of time during the preheating process for channel 6 for strand B3 at steel plant SP2.

Figure 7. The temperature profile as a function of time during the preheating process for channel 6 at steel plant SP3.

a)

b)

Figure 8. SEM images of the SEN's RBM from SP1: (a) RBM before preheating; (b) RBM after preheating at channel 1 [5].

a)

b)

Figure 9. SEM image of the SEN's RBM from SP3: (a) RBM before preheating: the glass/silicon powder coating is 304.6 μm in thickness; (b) RBM after preheating at channel 4. The longitudinal section shows the internal area of the SEN.

Table 1. The chemical composition of the refractory based materials [5]

Chemical composition	Weight percent
Al_2O_3	55.1
SiO_2	10.2
TiO_2	0.8
CaO	0.2
MgO	0.3
Na_2O	0.9
K_2O	0.1
$ZrO_2 + HfO_2$	0.6
Fe_2O_3	0.2

<i>C</i>	<i>31.6</i>
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Table 2. The composition of the glass/silicon powder coating [5]

<i>Chemical composition</i>	<i>Weight percent</i>
<i>Al₂O₃</i>	<i>20.07</i>
<i>SiO₂</i>	<i>55.25</i>
<i>CaO</i>	<i>0.99</i>
<i>Na₂O</i>	<i>19.04</i>
<i>K₂O</i>	<i>4.64</i>

Table 3. Measurements of the gas compositions during the preheating trials at the two different steel plants

<i>Steel plant</i>	SP1			SP3	
<i>Measurement</i>	<i>1 min</i>	<i>9 min</i>	<i>20 min</i>	<i>1 min</i>	<i>9 min</i>
<i>O₂ [Pa]</i>	<i>40530.0</i>	<i>202.7</i>	<i>202.7</i>	<i>622982.3</i>	<i>1119736.6</i>
<i>CO [Pa]</i>	<i>101.3</i>	<i>26243.2</i>	<i>27053.8</i>	<i>76.3</i>	<i>84.0</i>
<i>CO₂ [Pa]</i>	<i>101.3</i>	<i>6484.8</i>	<i>6788.8</i>	<i>124.7</i>	<i>140.8</i>
<i>T_{flue gas} [K]</i>	<i>413</i>	<i>713</i>	<i>1000</i>	<i>1383</i>	<i>1598</i>
<i>ΔG₁ [J]</i>	<i>-415020</i>	<i>-374154</i>	<i>-365744</i>	<i>-493188</i>	<i>-514770</i>
<i>ΔG₂ [J]</i>	<i>-340092</i>	<i>-327565</i>	<i>-368988</i>	<i>-652094</i>	<i>-723986</i>
<i>ΔG₃ [J]</i>	<i>74928</i>	<i>46589</i>	<i>-3244</i>	<i>-158907</i>	<i>-209216</i>

Table 4. Chemical analysis of the RBM from SP1 after preheating

<i>Point</i>	<i>SiO₂ (wt-%)</i>	<i>Al₂O₃ (wt-%)</i>
<i>A</i>	<i>85</i>	<i>15</i>
<i>B</i>	<i>85</i>	<i>15</i>
<i>C</i>	<i>70</i>	<i>30</i>
<i>D</i>	<i>65</i>	<i>35</i>
<i>E</i>	<i>47</i>	<i>53</i>
<i>RBM</i>	<i>10</i>	<i>55</i>

Table 5. Chemical analysis of the RBM from SP3 after preheating

<i>Element</i>	<i>A wt-%</i>	<i>A Atomic-%</i>	<i>B wt-%</i>	<i>B Atomic-%</i>
<i>Na K</i>	<i>1.53</i>	<i>1.41</i>	<i>0.88</i>	<i>1.16</i>
<i>Al K</i>	<i>48.68</i>	<i>38.02</i>	<i>53.65</i>	<i>20.33</i>
<i>Si K</i>	<i>2.64</i>	<i>1.98</i>	<i>4.07</i>	<i>4.39</i>
<i>K K</i>	<i>0.26</i>	<i>0.14</i>	<i>0.17</i>	<i>0.14</i>
<i>Zr L</i>			<i>0.02</i>	<i>0.01</i>
<i>O</i>	<i>43.56</i>	<i>57.38</i>	<i>38.25</i>	<i>72.41</i>