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TYPE OF SUBMERGED ENTRY NOZZLE vs. CONCENTRATION PROFILES IN THE INTERMIXED ZONE OF ROUND BLOOMS WITH A DIAMETER OF 525 mm

PRIMERJAVA VRSTE POTOPLJENE ŠOBE IN PROFILA KONCENTRACIJE V OBMOČJU MEŠANJA PRI OKROGLIH BLOKIH S PREMEROM 525 mm

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This work compares the experimental results of nickel-concentration measurements in the intermixed zone of the continuously cast round blooms with a diameter of 525 mm using two types of submerged entry nozzles (SEN) – a straight-through nozzle and the one with 5-ports. Based on the determination of the system and optical interface in a bloom, a detailed study of the concentration profiles on the bloom surface in a small-radius area, on the right-hand side, and then also on the cross sections of the blooms was carried out. The results were further analysed using the approximation models, and were used to verify the proposed model predicting the intermixed zones for the continuous-casting machines. The developed model was based on the results of the physical and numerical modelling.

Keywords: continuous casting machine, steel round bloom, submerged entry nozzle, SEN, intermixed zone, concentration profile

V tem delu so predstavljeni eksperimentalni rezultati merjenja koncentracije niklja v območju mešanja kontinuirno ulitih okroglih blokov s premerom 525 mm pri uporabi dveh vrst potopljenih šob (SEN) – gladke ravne šobe in šobe s 5 odprtinami. Opravljen je bil podrobnejši študij profila koncentracije na površini bloka na področje majhnega premera, na ravnem delu in tudi na prečnem prerezu bloka. Rezultati so bili analizirani z uporabo modelov približka in uporabljeni za napovedovanje območja mešanja pri napravah za kontinuirno ulivanje. Razviti model temelji na rezultatih fizikalnega in numeričnega modeliranja.

Ključne besede: naprava za kontinuirno ulivanje, okrogel jeklen blok, potopljena vstopna šoba, SEN, območje mešanja, profil koncentracije

1 INTRODUCTION

When casting two different steel grades in a sequence, the steels tend to get mixed in the tundish and, in certain cases, also in the liquid cores of the solidifying blanks. This leads to an emergence of chemistries that correspond neither to the first nor to the second cast-steel grade. As a result, the so-called intermixed zones occur in the continuously cast blanks, with their chemical composition being out of the tolerance specified for either of the cast-steel grades. The identification and minimisation of these intermixed zones are important in order to increase the productivity of continuous-casting machines (CCM).[1–4]

Currently, the **M**odel for predicting **I**ntermixed **Z**ones (MIZ) that systematically manages and identifies composite blooms resulting from the sequential casting of different steel grades with different chemical compositions is being put into operation under the conditions of a 5-strand-bloom CCM No.1 at Třinecké železárny a.s. (TŽ). A similar model has been fully operational since 2005 under the conditions of an 8-strand-billet CCM No.2.[5,6]

The model for the CCM No.1 was developed on the basis of the data received from the physical and numerical modelling,[6,7] which took into account all the relevant changes in the operating boundary conditions, such as the initial and final mass/weight of the steel in the tundish during the refilling, the intensity (the mass-flow rate) of the tundish refilling, the casting speed, the stopping of casting strands, etc.

The results of the model experiments were then processed using mathematical and statistical methods, with which the regression equations of linear parameters in intermixed zones were obtained,[8,9] and, in the next step, these were generalized for all the cast formats on the CCM No.1.

While adjusting the MIZ to the conditions of the CCM No.1, a possible penetration of a new steel grade into the molten core of a bloom, which can be expected, especially when utilizing the straight-through SENs with a highly dynamic effect of a molten steel stream, as well as in the case of larger formats of cast blooms, needed to be taken into account.[10]

In order to clarify the intensity of this penetration, several complex plant experiments providing the data about the concentration profiles on the surfaces and the cross-sections of the blooms present in the intermixed zones, were carried out.

2 PREPARATION AND IMPLEMENTATION OF THE EXPERIMENT

To determine longitudinal and lateral chemical concentration profiles in the round blooms of the intermixed zone, the experimental methods, whose principles lie in mild alloying of two consecutive cast heats with nickel and chromium using the "cross method" and in the subsequent determination of the content of these elements on the surface of the blooms, and, in particular, on the cross sections of these blooms, were used.

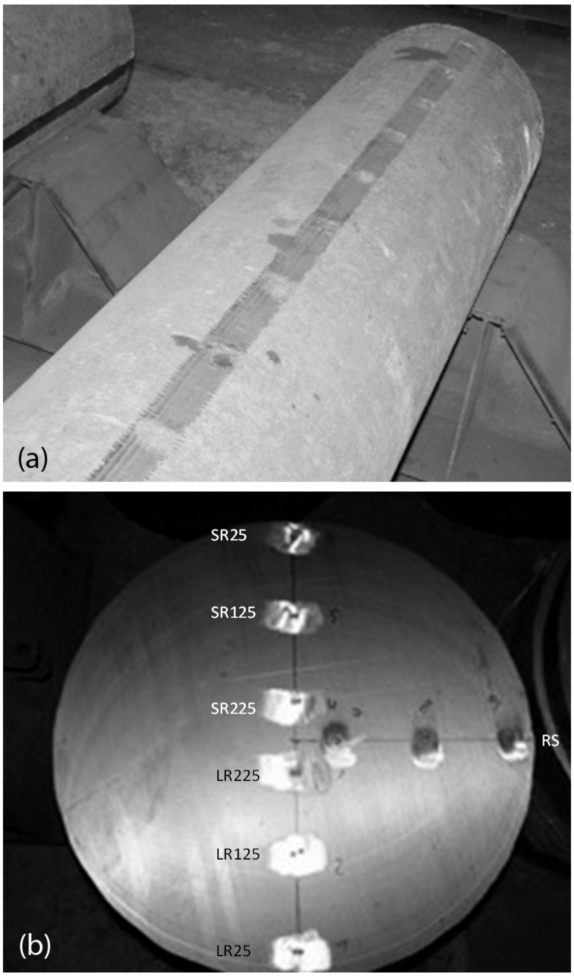

Figure 1: Separated blooms with a 525-mm diameter after spectrographic analyses: a) on the surfaces and b) on cross sections
Slika 1: Blok s premerom 525 mm po spektrografski analizi na: a) površini in b) prerezu

During the first test using the straight-through SENs the heats were purposely alloyed to achieve the goal of w(Ni) = 0.26 % and w(Cr) = 0.26 %, and during the second test the 5-port SENs (complemented with the bottom fifth optimized port) were used to achieve w(Ni) = 0.27 % and w(Cr) = 0.28 %.

Both tests maintained the same weight of steel in the tundish at the initiation of its refilling (24 t) and very close intensities of the mass flow into the tundish (5.8 t/min and 6.3 t/min). The second test was carried out on a casting strand (CS) No.5 with an active electromagnetic stirrer of the M-EMS type.

To evaluate the chemical composition itself, the round blooms with a 525-mm diameter were separated from the intermixed zone of the monitored casting strands, i.e., CS No.1 and CS No.5 (first test), CS No.4, and CS No.5 (second test). After the cooling, the blooms were transported into the roughing room, in which, during the first stage, the grinding of the solid longitudinal surfaces on a small radius (SR) and on the right-hand side (RS) of the bloom took place to carry out spectrometric analyses across the entire length of all the evaluated blooms (**Figure 1a**).

After evaluating the results a cutting plan was prepared and the blooms were cut with a band saw into approximately 40-cm-long pieces (logs), and detailed analyses were carried out on the resulting cross sections in the direction from the small radius (SR) through the centre to the large radius (LR), as well as from the right-hand side towards the centre of the bloom, and in a total of 9 locations of the cross section (**Figure 1b**).

3 RESULTS OF THE CHEMICAL COMPOSITION ON THE SURFACES AND CROSS-SECTIONS OF THE BLOOMS

Using the CCM No.1 operating database, detailed time data related to the cast lengths of the blooms, the casting speed, the change in the weight of the steel, both in the tundish and in the casting ladle, were obtained. These data were used to identify the precise locations on the blooms, which correspond to the initiation time of the steel flow from the new casting ladle into the tundish. The length parameters in the appropriate charts are subsequently related to the point, or the location, that corresponds to this change. Negative length values may indicate that a bloom had been cast (pulled from the mould) before the initiation of the steel flow from the new ladle.

Given that the change in the chromium content has mirrored the change in the nickel content, the other parts of the paper only present the results and an evaluation of the changes in the nickel content.

As shown in **Figures 2** and **3**, some gradual changes in the content of nickel were detected on the surfaces and cross-sections of the blooms (and, similarly, converse changes in the content of chromium were also observed),

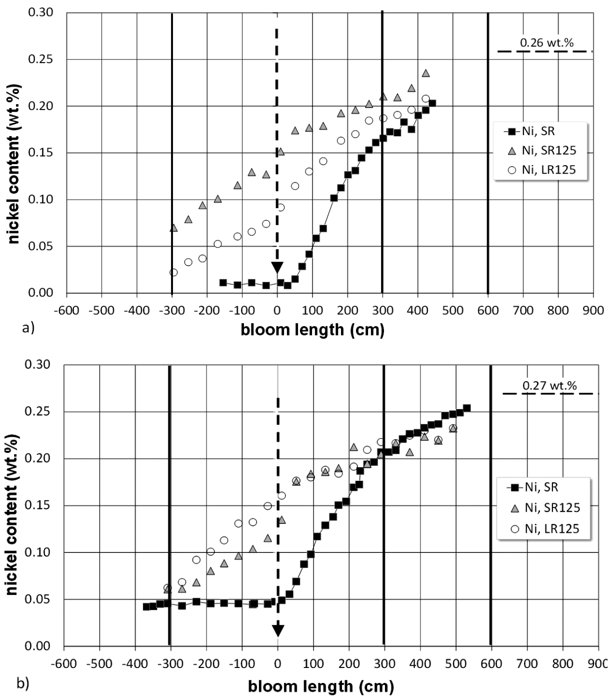

Figure 2: Graphic illustrations of the variations in the content of nickel on the surface and cross sections of CS No.5 blooms at a distance of 125 mm from the surface of round blanks in the casts using: a) a straight-through SEN and b) a five-port SEN

Slika 2: Grafični prikaz spreminjanja vsebnosti niklja na površini in na prerezu CS No. 5 blokov na razdalji 125 mm od površine ulitka z uporabo: a) ravne šobe SEN in b) šobe s petimi odprtinami

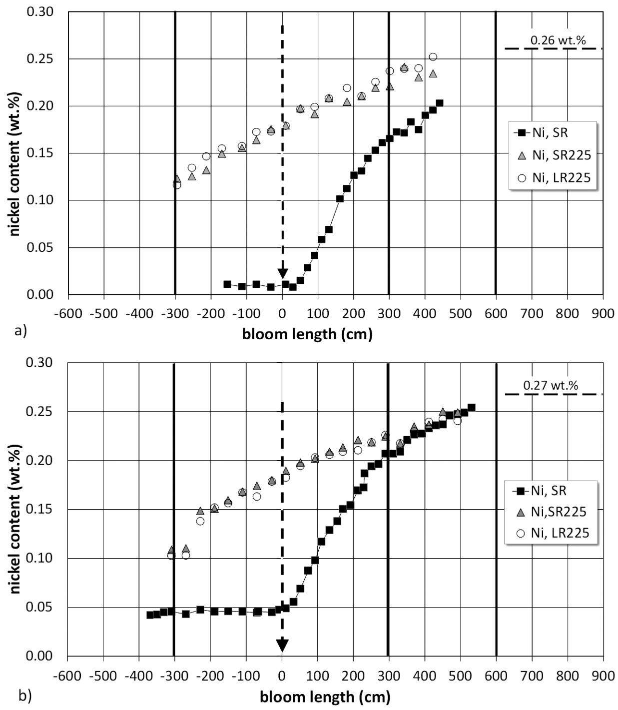

Figure 3: Graphic illustrations of the variations in the content of nickel on the surface and cross sections of CS No.5 blooms at a distance of 225 mm from the surface of the round blooms in the heats using: a) a straight-through SEN and b) a five-port SEN

Slika 3: Grafični prikaz spreminjanja vsebnosti niklja na površini in na prerezu CS No. 5 blokov na razdalji 225 mm od površine ulitka z uporabo: a) ravne šobe SEN in b) šobe s petimi odprtinami

which correspond to the composition of the subsequently cast heats.

In terms of individual cross-sections, relatively high differences in chemical compositions caused by the reciprocal stirring of the bloom's molten core with the new steel coming through the submerged entry nozzles are found.

The evidence observed after complete chemical analyses (2 locations on the surface and 9 locations on cross sections) can then be summarized as follows:

The results of the surface analyses on a small radius and on the right-hand side of a given strand are practically identical; the concentration changes on the surface are balanced along the bloom perimeter.

At a distance of 25 mm below the surface of the blooms, some minor differences between the changes in the contents of Cr and Ni are apparent after the surface analyses. The chemical composition is already affected by the composition of the subsequent heat. In this case the changes in the composition in the area of a small radius are similar to the ones on the side of a large radius.

The chemical composition of an inside part of the bloom at the distance of 125 mm below its surface is already completely different from the composition of the surface (**Figure 2**). The penetration of "new" steel from the subsequent heat to the bloom core is significantly apparent here, creating a characteristic concentration gradient across the cross section of the bloom. It is obvious that the changes in the chemical composition inside the bloom at the distance of 125 mm from the surface "are foreruning" the surface analyses by at least 2 m, and in some cases by more than 3 m.

The chemical composition of the blooms at the depth of 225 mm below the surface also exhibits significant differences compared to the bloom surface (**Figure 3**). The charts can also help us estimate, with a certain degree of accuracy, the penetration of the liquid molten metal, and thus also the reciprocal stirring for a distance exceeding 3 m to 3.5 m from the outlet of a five-port SEN (more than 4.5 m for a straight-through SEN).

It can also be inferred from the charts that the chemical composition of the subsequent heat in the cast blooms can be located at the distance of approximately 6–8 m from the location corresponding to the steel-flow initiation from the new casting ladle with the nominal casting speed of 0.32 m/min that equals 1125–1500 s (approximately 19–25 min).

A mutual comparison of the concentration-change courses also led to important findings, according to which the effect of a 5-port SEN on the concentration-change behaviour in the cross sections of the bloom was, in comparison with a straight-through SEN, less significant. In the case of the straight-through SEN, the radius of the casting strand penetration into the molten steel core of the bloom can then be expected to be found at a distance of more than 4–5 m and, in the case of the 5-port SEN, at a distance of 3–4 m.

In the case of the straight-through SEN, the changes in the chemical composition were first shown on the side of a small radius, whereas in the case of the 5-port nozzle, they were shown on the side of a large radius, but considerably less significantly than with the straight-through SEN. The above-described behaviour seems to be associated with the nature of the steel outflow from both types of nozzles – in the case of the straight-through nozzle, reverse recirculation in the subsurface layers takes place more intensely on the side of the small radius due to the interaction of the outlet casting stream as well as the curvature of the mould (or the bloom's wall). On the other hand, in the case of the 5-port nozzle, there is a more dominant effect of the orientation of the side ports with regard to the bloom's wall (i.e., settling of the bloom), and also an effect of the uneven sedimentation of the side ports, etc. can be assumed.

4 MATHEMATICAL AND STATISTICAL PROCESSING OF THE MEASUREMENT RESULTS

Given the fact that the performed operational experiments using a straight-through and a 5-port SEN were primarily intended to determine the concentration profiles in the blooms and to assess the extent of the intermixed zone, or the degree of the reciprocal-stirring process in the molten core of the bloom with a diameter of 525 mm, the results achieved were intended to be processed using an appropriate approximation model.

In the period following the start of filling the tundish, using a new steel grade, with a different composition, a response to the changes in the concentrations of the chemical elements at the outputs of the tundish is characterized with a certain dependence, which corresponds to the so-called transition curve (its characteristics), and which is a graphical representation of the so-called transition function.

In the calculations, the length (no time) parameters of the blooms were considered, which were related to the location of the so-called "optical" interface, i.e., the location that corresponds to the start of filling the tundish with the steel from another ladle with a different chemical composition.

The results of the concentration measurements were first standardized to the dimensionless concentration cn, taking into account the values of the average (specified) element content.

For an approximation of these concentration processes, a proportional system of the first order with a time delay and an amplification unit was selected. Its transition characteristics (as a response to a unit step of the change in the mass content of the alloying elements) with respect to the length parameters (the shape of the model is the same as for the time parameters; the length parameters can be derived from the time parameters using a simple linear transformation $L_x = v\ x\ T_x$, where v is the casting speed) are as follows:

$$c_{\mathrm{an}}(l)=\begin{Bmatrix} 0 & \text{pro } l \le L_{\mathrm{d}} \\ 1-\exp\left(-\dfrac{l-L_{\mathrm{d}}}{L_{\mathrm{l}}}\right) & \text{pro } l > L_{\mathrm{d}} \end{Bmatrix}\ (–) \qquad (1)$$

where the symbols represent the following:

c_{an} – approximated standardized concentration of the element in the steel $\in \langle 0,1)$ (–)

l – bloom length (m)

L_{d} – (transport) length delay (m)

L_{l} – system length constant (m)

Figures 4 and **5** show graphic illustrations of the results of this approximation for the surface analyses obtained at the distance of 125 mm from the bloom surface.

In the next step, an appropriate simple (with the lowest number of parameters and from a set of basic functions) non-linear approximate-regression function of the dependence of calculated L_{d} on h (distance from the surface of a round bloom) was searched. The appropriate function seems to be an exponential function with an (absolute) shift of values (which often represents a solution to common equations, and, in the proximity,

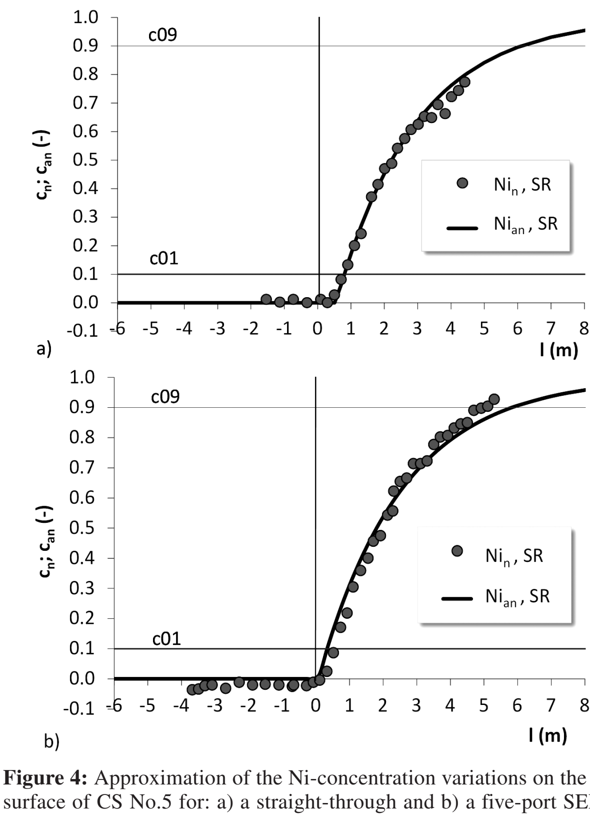

Figure 4: Approximation of the Ni-concentration variations on the SR surface of CS No.5 for: a) a straight-through and b) a five-port SEN

Slika 4: Približek spreminjanja koncentracije Ni na SR površini CS No.5 za: a) ravno šobo in b) šobo s petimi odprtinami

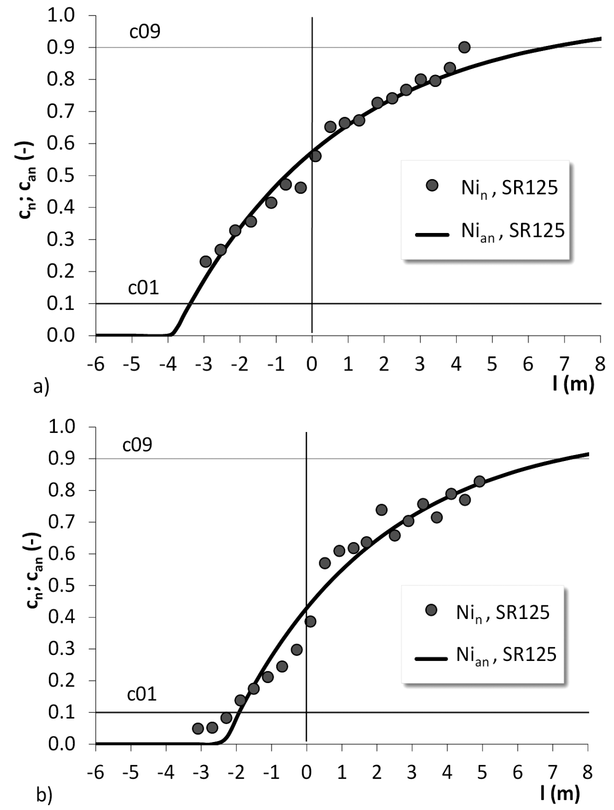

Figure 5: Approximation of the Ni-concentration variations on the cross sections of the CS No.5 blooms at a distance of 125 mm from the SR surface for: a) a straight-through and b) a five-port SEN

Slika 5: Približek spreminjanja koncentracije Ni na prerezu CS No. 5 bloka na razdalji 125 mm od površine SR za: a) ravno šobo in b) šobo s petimi odprtinami

even to partial differential equations) in the following form:

$$L_{da}(h) = a + b \cdot \exp(c \cdot h) \quad (2)$$

This function helps us estimate the penetration of the "new" steel into the bloom's core (the centre, or the longitudinal axis) filled with the "old" steel. The results for both, the straight-through and the 5-port nozzles are listed in **Tables 1, 2** and **3**, where the symbols represent the following:

h – distance from the surface of a round bloom

L_{da} – approximation of L_d using the nonlinear regression dependence of L_d on h

$l(0.1)$ – length of the beginning of the intermixed zone for the lower boundary of the concentration $c_{n,min}$ = 0.1

$l(0.9)$ – length of the end of the intermixed zone for the upper boundary of the concentration $c_{n,max}$ = 0.9

$l_S(0.1,0.9)$ – length of the intermixed zone between the lower and upper boundaries of the standard concentration c_m = {0.1, 0.9}

From the tables shown above it is apparent that the relatively smallest depth of penetration of the new steel into the body of a bloom was achieved in the case of CS No.4 utilizing a 5-port nozzle, and it was approximately 3.9 m.

It was found that in CS No.5, with the M-EMS turned on, there was a certain increase in the depth of the "new" steel penetration into the core (centre) of the "old" bloom by up to approximately 1.4 m (by approximately 36 % compared with CS No.4). However, it cannot be unequivocally stated that this is the effect of the electromagnetic stirring of the M-EMS type. The roll can, for example, have a clogging of the lower (fifth) output port of the SEN, and an associated lower-dynamic effect of the out-flowing steel stream, etc.

The largest value of the penetration depth of the new steel was detected when using the straight-through SEN. In the central part of the bloom this value was 5.6 m.

Table 1: Parameters of the new-steel penetration into the bloom's molten core with a diameter of 525 mm for CS No.5 using a straight-through SEN

Tabela 1: Parametri prodiranja novega jekla v staljeno skorjo bloka s premerom 525 mm pri CS No. 5 z uporabo ravne šobe SEN

Name	SR	SR25	SR125	SR225	Centre
h/(mm)	0	25	125	225	262.5
L_d/(m)	0.546	–0.516	–3.860	–5.238	–
L_1/(m)	2.413	2.395	4.528	4.452	–
L_{da}/(m)	0.614	–0.626	–3.786	–5.270	**–5.594**
$l(0.1)$/(m)	0.800	–0.264	–3.383	–4.768	–
$l(0.9)$/(m)	6.102	4.998	6.565	5.013	–
$l_S(0.1,0.9)$/(m)	5.302	5.262	9.948	9.782	–

Table 2: Parameters of the new-steel penetration into the bloom's molten core with a diameter of 525 mm for CS No.4 using a five port SEN

Tabela 2: Parametri prodiranja novega jekla v staljeno skorjo bloka s premerom 525 mm pri CS No. 4 z uporabo šobe SEN s petimi odprtinami

Name	SR	SR25	SR125	SR225	Centre
h/(mm)	0	25	125	225	262.5
L_d/(m)	–0.213	–0.301	–2.979	–3.548	–
L_1/(m)	1.822	2.588	4.798	4.242	–
L_{da}/(m)	0.048	–0.718	–2.704	–3.666	**–3.881**
$l(0.1)$/(m)	–0.021	–0.028	–2.474	–3.101	–
$l(0.9)$/(m)	3.984	5.660	8.069	6.219	–
$l_S(0.1,0.9)$/(m)	4.004	5.687	10.543	9.320	

Table 3: Parameters of the new-steel penetration into the bloom's molten core with a diameter of 525 mm for CS No.5 using a five port SEN and an electromagnetic stirrer (M-EMS)

Tabela 3: Parametri prodiranja novega jekla v staljeno skorjo bloka s premerom 525 mm pri CS No. 5 pri uporabi šobe s petimi odprtinami SEN in elektromagnetnim mešalom (M-EMS)

Name	SR	SR25	SR125	SR225	Centre
h/(mm)	0	25	125	225	262.5
L_d/(m)	0.069	–0.402	–2.371	–4.618	–
L_1/(m)	2.501	3.411	4.227	4.704	–
L_{da}/(m)	0.129	–0.405	–2.504	–4.541	**–5.290**
$l(0.1)$/(m)	0.333	–0.042	–1.925	–4.122	–
$l(0.9)$/(m)	5.828	7.453	7.362	6.215	–
$l_S(0.1,0.9)$/(m)	5.495	7.495	9.287	10.337	–

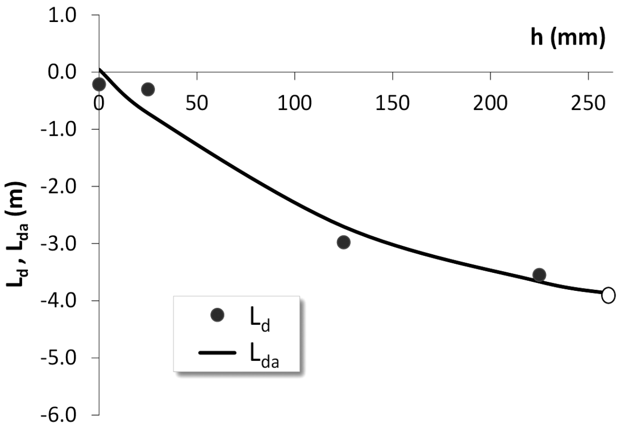

Figure 6: Approximative dependence of L_d on *h* for CS No.4, small radius, 5-port SEN

Slika 6: Približek odvisnosti L_d od *h* pri CS No.4, majhen premer, šoba s petimi odprtinami SEN

The measurements performed earlier on the blooms with a diameter of 410 mm using 5-port nozzles showed that the depth of the penetration of the strand into the bloom's core was approximately 1.7 m, which is more than twice the lower value of the blooms with a diameter of 525 mm.[11]

It has also been determined that there is a more balanced composition of the steel in the rated zone of the CS No.5 bloom than in the case of CS No.4, which resulted in a certain "linearization" of the dependent courses of the length parameters (see **Figure 7** for the parameters such as L_d) in the intermixed zone following the bloom's cross section (which were significantly nonlinear in CS No.4 – see **Figure 6**).

In addition to linearization, it is also possible to monitor a decrease in the dispersion, the length values of the end of the intermixed zone (*l*(0.9)) and the total length of the intermixed zone (*l*(0.1,0.9)) while considering the entire cross section.

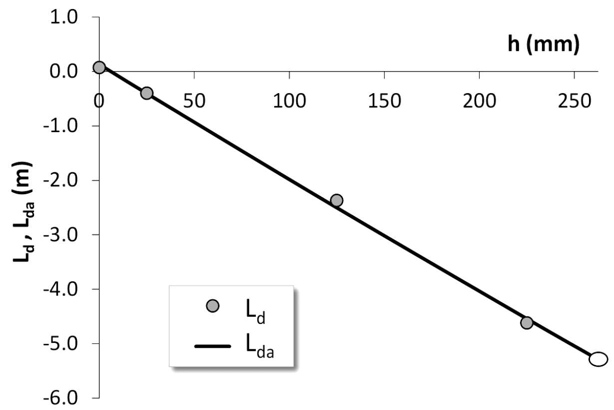

Figure 7: Approximative dependence of L_d on *h* for CS No.5 (with M-EMS), 5-port SEN, small radius

Slika 7: Približek odvisnosti L_d od *h* pri CS No.5 (z M-EMS), majhen premer, šoba s petimi odprtinami SEN

It can be concluded that the position of the intermixed-zone end in CS No.4 (without M-EMS) ranged from approximately 4 to 8 m (the variation range of approximately 4 m), while in CS No.5 (with M-EMS) it was approximately 6 m to 7.5 m (the variation range only approximately 1.5 m). Therefore, there is a shortening of the end of the intermixed zone of approximately 0.5 m.

Similarly, the total length of the intermixed zone ranged in CS No.4 from approximately 4 to 11 m (the variation range of approximately 7 m), while in CS No.5 (with M-EMS) it was approximately 6 m to 10 m (the variation range of only approximately 4 m). In this case the shortening of the intermixed zone reaches approximately 1 m.

5 CONCLUSION

The complex plant experiments focused on determining the concentration profiles in both the longitudinal and cross-section directions of the mixed blooms with a diameter of 525 mm allowed us to determine the depth of the penetration of new steel into the molten core of such blooms for two basic types of the used submerged entry nozzles: the straight-through SEN and the combined 5-port SEN.

The depth of the penetration of new steel into the bloom core depends not only on the type of SEN, or on the electromagnetic stirring, but also and quite distinctively on the cast profile.

The largest value of the penetration depth of new steel was detected when using the straight-through SEN. In the central part of the bloom and based on the analyses, this value was 5.6 m.

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