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PHYSICAL AND NUMERICAL MODELLING OF A NON-STATIONARY STEEL FLOW THROUGH A SUBENTRY SHROUD WITH AN INNER METERING NOZZLE

FIZIKALNO IN NUMERIČNO MODELIRANJE NESTACIONARNEGA TOKA JEKLA SKOZI POTOPLJEN IZLIVEK Z NOTRANJO ŠOBO

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The paper presents new knowledge about physical and numerical modelling of a non-stationary steel flow into a mould through a subentry shroud with an inner, pressed metering nozzle. The physical and numerical modelling was realized under the conditions of the Department of Metallurgy and Foundry at VSB-Technical University of Ostrava. A special type of the subentry shroud is used during continuous casting of steel in Třinecké železárny, a.s. During continuous casting of steel, two unfavourable phenomena were observed. In the first case, it was not possible to increase the casting speed, though the diameter of the metering nozzle was extended. In the second case, a fluctuation of the casting speed among individual casting strands was detected. These two problems did not allow an improvement of the performance of the casting machine. Therefore, the physical and numerical modelling was performed. Attention was focused on the verification of the effect of the inner diameter of the nozzle body and internal diameter of the metering nozzle on the resulting volume flow rates. Four diameters of the metering nozzle – (16; 17; 17.5; 18) mm – were tested. The physical modelling was done on a 1 : 1 model constructed from Plexiglas. The numerical modelling was realized in the ANSYS FLUENT software. On the basis of the results of the modelling study and in cooperation with the VESUVIUS company, a new type of the profile of the subentry shroud with a metering nozzle was designed. The first experimental results in the steel plant led to an increase in the productivity of the continuous-casting machine.

Keywords: steel, continuous-casting machine, subentry shroud, metering nozzle, physical and numerical modelling

Članek predstavlja novo znanje o fizikalnem in numeričnem modeliranju nestacionarnega toka jekla v kokilo skozi potopljen izlivek z notranjo šobo. Fizikalno in numerično modeliranje je bilo izvršeno v Oddelku za metalurgijo in livarstvo na VSB Tehniški univerzi, Ostrava. V Třinecké železárny, a. s., se uporabljajo posebne izvedbe potopljenih izlivkov med kontinuirnim ulivanjem jekla. Pri tem sta bila opažena dva neželena pojava. Pri prvem ni bilo mogoče povečati hitrosti litja, čeprav je bil povečan premer notranjega izlivka, pri drugem pa je bilo opaženo spreminjanje hitrosti litja med posameznimi žilami. Ta dva pojava nista omogočila izboljšanja zmogljivosti livne naprave. Zato je bilo izvršeno fizikalno in numerično modeliranje. Pozornost je bila usmerjena na preverjanje vpliva notranjega premera telesa izlivka in notranjega premera izlivne šobe na stopnje pretoka. Preizkušeni so bili štirje premeri (16; 17; 17,5 in 18) mm notranjega izlivka. Fizikalni model je bil izdelan na modelu 1 : 1, izdelanem iz pleksi stekla. Numerični model je bil izdelan s programsko opremo ANSYS FLUENT. Na osnovi rezultatov in s sodelovanjem podjetja VESUVIUS je bila konstruirana nova vrsta potopnega izlivka z notranjo izlivno šobo. Prvi preizkusi v jeklarni so omogočili povečanje produktivnosti naprave za kontinuirno ulivanje.

Ključne besede: jeklo, naprava za kontinuirno ulivanje, potopni izlivek, izlivna šoba, fizikalno in numerično modeliranje

1 INTRODUCTION

A special type of the subentry shroud with an inner, pressed metering nozzle is used during continuous casting of steel on the CCM No.2 in Třinecké železárny, a.s. (TŽ, a.s.). A metering nozzle serves here as a stabilizing element adjusting the volume flow rate of the steel. However, while using this type of the nozzle two adverse effects were observed:

1) It was not possible to increase the casting speed when increasing the diameter of the metering nozzle.
2) Fluctuations of the casting speed in individual casting streams were detected.

Both of these factors eliminated the possibility of increasing the performance of the entire casting machine.

Due to a long-term mutual cooperation, the TŽ, a. s., team contacted the research team at the Department of Metallurgy and Foundry at VSB-TU Ostrava, which has extensive experience in the optimization of metallurgical processes using modelling methods.[1–4] The sophisticated methodology of the experiments and a well-selected system of physical and numerical modelling results, transformed into the operational experience with verified use of the similarity theory, provide an opportunity to address the other fundamental technological problems.[5–7] Physical and numerical modelling was used to study the behaviour of a steel flow through an inner metering nozzle. Its goal was to assess the behaviour of the steel flow through the nozzle, analyse its causes and propose solutions in the form of a new geometry of the inner, pressed metering nozzle of the subentry shroud. The parameters such as the influences of the inner diameter of the body of the subentry shroud and the inner diameter of the metering nozzle on the resulting volume flow rates at a constant hydrostatic (ferrostatic) height above the subentry shroud (a constant steel height in the tundish) were tested. The efforts were aimed at finding the limiting factor that restricts the increase in the rate of the steel flow through the subentry shroud even when the diameter of the inner metering nozzle is increased.

2 ANALYSIS OF THE PROBLEM

Fluctuations of the casting speed during the casting of steel on the CCM No. 2, equipped with the shrouds with inner metering nozzles, are perfectly evident from **Figures 1** and **2**. **Figure 1** shows the behaviour of the casting speed on individual casting strands (CS) during a sequence of heats cast using the subentry shrouds equipped with inner metering nozzles. See **Figure 2** for an example of the behaviour of the casting speed at a constant steel weight in the tundish. The following was determined:

- When using the subentry shrouds equipped with metering nozzles, the variability of the casting speed is much greater than when regulating it with the stopper rods only.
- The casting speed (or the steel flow through the nozzle) is slightly dependent on the weight of the steel in the tundish (or on the steel height in the tundish) – **Figure 1**.
- Despite the nearly constant weight of the steel in the tundish, the casting speed increased in some cases – **Figure 2**.

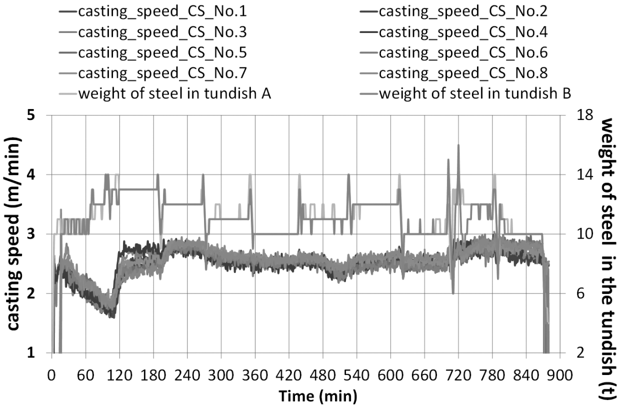


Figure 1: Example of the behaviour of the casting speed on individual casting strands during a sequence of heats cast using subentry nozzles equipped with metering nozzles

Slika 1: Primer vedenja hitrosti ulivanja na posamezni livni žili med sekvenčnim ulivanjem talin z uporabo potopljenega izlivka, opremljenega z notranjo izlivno šobo

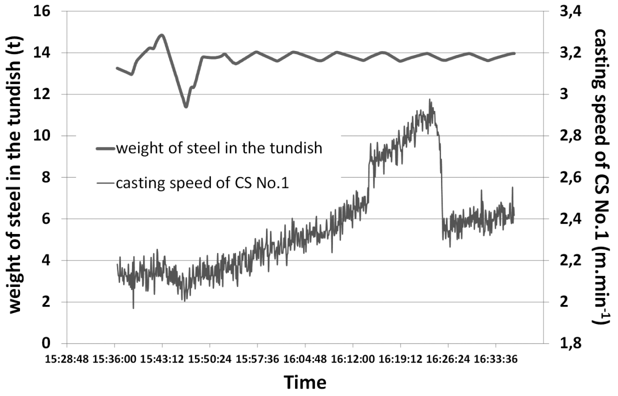


Figure 2: Example of the behaviour of the casting speed on casting strand No.1 at a constant weight of the steel in the tundish

Slika 2: Primer vedenja hitrosti litja na livni napravi št. 1 pri konstantni masi jekla v vmesni ponovci

- Fluctuations in the volume flow rate indicate the presence of a non-stationary flow in the nozzle.
- An inability to further increase the casting speed while increasing the metering-nozzle diameter shows the existence of an undetermined limiting factor affecting the flow, which limits the volume flow of the steel through the subentry shroud.

On the basis of the calculation of the volume flow rate for the casting speed of 2.5 m min^{-1} and the cast dimensions of 150 mm × 150 mm, it was found that:

- The rate of the volume flow of the liquid steel through the nozzle with the inner diameter of 20 mm is approximately 60 L min^{-1}.
- The calculated Re criterion reaches approximately 89,000.
- The value noted above is specified for circular cross-sections far beyond the critical value of the transition from the laminar to the turbulent flow. In other words, we can expect that, within the nozzle, the steel flow is of a strong turbulent character, which, of course, bears the risk of large-scale non-stationarities of the steel flow, especially if the diameter of the nozzle is, at some spot/location, made even narrower (in the area of the inner, pressed metering nozzle).
- It is likely that the hydraulic resistance of the subentry shroud below the metering nozzle was so high that an increase in the metering-nozzle diameter could no longer allow a further increase in the steel flow rate (the casting speed).

To confirm these partial, theoretical conclusions, the researchers decided to assess the nature of the steel flow using physical and numerical modelling.

3 PHYSICAL MODELLING

Physical modelling was performed with a nozzle constructed from Plexiglas on the geometric scale of 1 : 1 (**Figure 3a**). The following diameters of the metering nozzles were tested: (16; 17; 17.5 and 18) mm, having the outlets (the internal diameters of the nozzles below the metering nozzles) of 20 mm and 24 mm, hereafter referred to as nozzle A and nozzle B. The submersion of a nozzle below the surface of the steel in the mould was in all the cases identical – 120 mm. This value corresponds to the central part of the bottom zirconium protection.

Given that when applying the geometric scale of 1 : 1, both identity criteria, Re and Fr, are maintained, we can assume there is a significant agreement between the phenomena occurring in the flow in the actual nozzle and in its model in terms of the character of the flow, swirl and stationarity (stability). It is evident that the thermal processes that may affect the steel flow cannot be detected with this type of modelling. In particular, it is the influence of the temperature on the steel viscosity, erosion and corrosion of the material of a nozzle (that is contingent upon the flow rate of steel and its temperature) and the associated change in the internal profile of the nozzle, which may be essential for the stability of the flow and its fluctuations.

4 NUMERICAL MODELLING

Physical modelling was also complemented with numerical modelling of the steel-flow behaviour in the original nozzle with the metering nozzles having the diameters of (17; 17.5 and 18) mm and with an outlet of only 20 mm in diameter. Numerical modelling of the steel flow through a subentry shroud with inner metering nozzles was performed using the simulation package ANSYS WORKBENCH, providing a 3D modeller called DesignModeler, a generator of a computational mesh and the CFD software FLUENT. The nozzle geometry was modelled on the 1 : 1 scale. The 3D CAD geometry of the nozzle, including a detailed view of the area of the metering nozzle is shown in **Figure 3b**.

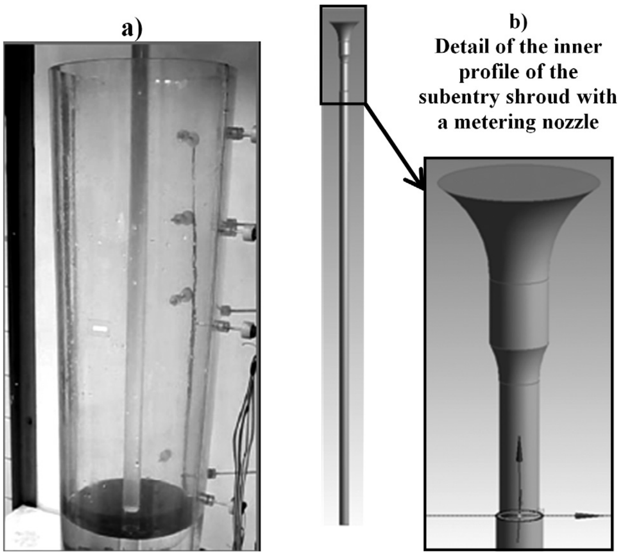


Figure 3: a) Physical model, b) 3D CAD model of the metering nozzle of the subentry shroud

Slika 3: a) Fizikalni model, b) 3D CAD model notranje izlivne šobe potopljenega izlivka

The volume mesh was automatically generated for the nozzle. The entrance into the nozzle was defined as the PRESSURE INLET and the exit from the nozzle was defined as the PRESSURE OUTLET. These boundary conditions allow a definition of the input parameters when the input speed is not known exactly, but the pressure indicated by the height of the steel in the tundish is known. The total pressure defined the pressure-input condition, which is the sum of the hydrostatic and dynamic pressure.[8]

The hydrostatic pressure is defined by the product of the steel height in the tundish with the steel density and gravitational acceleration. The dynamic pressure is defined as the square of the flow speed multiplied by the density of steel and one-half.[8]

The pressure outlet was defined in a similar way to the inlet pressure. However, only the hydrostatic/ferrostatic output pressure, the turbulence intensity and the hydraulic diameter need to be specified. The pressure outlet was the same for all simulated variants.

The steel flow was simulated to be incompressible and turbulent with the turbulence-model k-ε standard having a standard wall function. The gravity of 9.81 m s^{-2} was considered in the z axis. In the simulation, the operating conditions and material properties listed in **Table 1** were defined.

Table 1: Operating conditions and material properties of the steel at the temperature of 1843 K

Tabela 1: Delovne razmere in materialne lastnosti jekla pri temperaturi 1843 K

Condition	Value	Unit
Operating pressure	101325	Pa
Operating temperature	1843	K
Operating density	7030	kg m^{-3}
Heat capacity	750	J kg^{-1} K^{-1}
Heat conductivity	41	W m^{-1} K^{-1}
Viscosity	0.006995	Pa s

The study focused on the effect of the inner geometry of the nozzle on the rate of the flow through the nozzle. Attention was also focused on the character of the velocity and pressure field inside the nozzle. The results were also complemented with the distribution of the shear stress on the walls of the nozzle, allowing a prediction of the risk of erosion of the nozzle material.

5 DISCUSSION OF RESULTS

5.1 Effect of the metering-nozzle diameter and nozzle-outlet diameter on volume flow rates

The effect of the diameter of the metering nozzle and the diameter of the nozzle outlet on the achieved maximum volume flow rates at a constant hydrostatic (ferro-

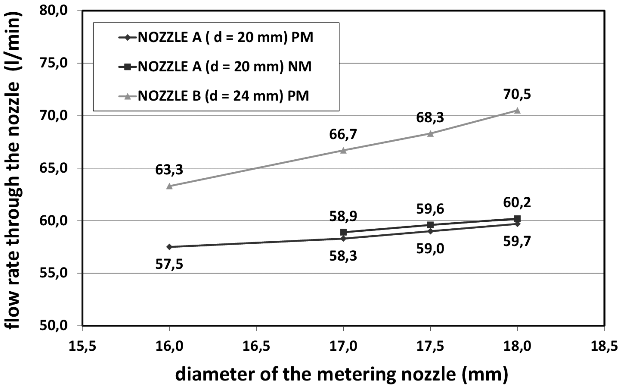


Figure 4: Effect of the metering-nozzle diameter and nozzle-outlet diameter on the volume flow through the subentry shroud for a 120 mm submersion in the mould

Slika 4: Vpliv premera notranje izlivne šobe in izstopni premer izlivka na volumenski tok skozi potopljen izlivek pri potopitvi 120 mm v kokilo

static) height above the nozzle (the constant steel height in the tundish) obtained with physical (PM) and numerical modelling (NM) is shown in **Figure 4**.

The main findings that can be defined from the graph above are as follows:

- An increase in the metering-nozzle diameter results in the increases in the volume flow rates for both types of nozzle, A and B (with the outlet diameters of 20 mm and 24 mm).
- The nozzle with the outlet diameter of 20 mm shows an increase in the volume flow rate of only 1.4 L min^{-1} (or 1.3 L min^{-1} according to the results of the numerical simulation) when switching from the metering-nozzle diameter 17 mm to 18 mm. This increase corresponds to a very small increase in the casting speed, i.e., 0.06 m min^{-1}.
- The nozzle with an outlet diameter of 24 mm shows a more noticeable increase in the volume flow rate, i.e., 3.8 L min^{-1}, representing an increase in the casting speed by 0.16 m min^{-1}.
- A very good agreement of the results of the physical and numerical modelling for the nozzle outlet of 20 mm is evident.

To sum up the results stated above, we can conclude that when we use the nozzle with a 20-mm outlet diameter, the flow rate can be increased only very slightly by simply increasing the diameter of the metering nozzle. This is due to a great hydraulic resistance of the nozzle located below the metering nozzle, which prevents a bigger increase in the volume flow rate. An increase in the flow rate can only be achieved by increasing the input ferrostatic pressure (the height of the steel in the tundish), but only to a very limited extent. A more significant increase in the volume flow rate and, thus, the casting speed can be expected after increasing the diameter of the nozzle below the metering nozzle from 20 mm to 24 mm, when the diameter of the metering nozzle has already started to perform the actual role of the flow-rate restrictor.

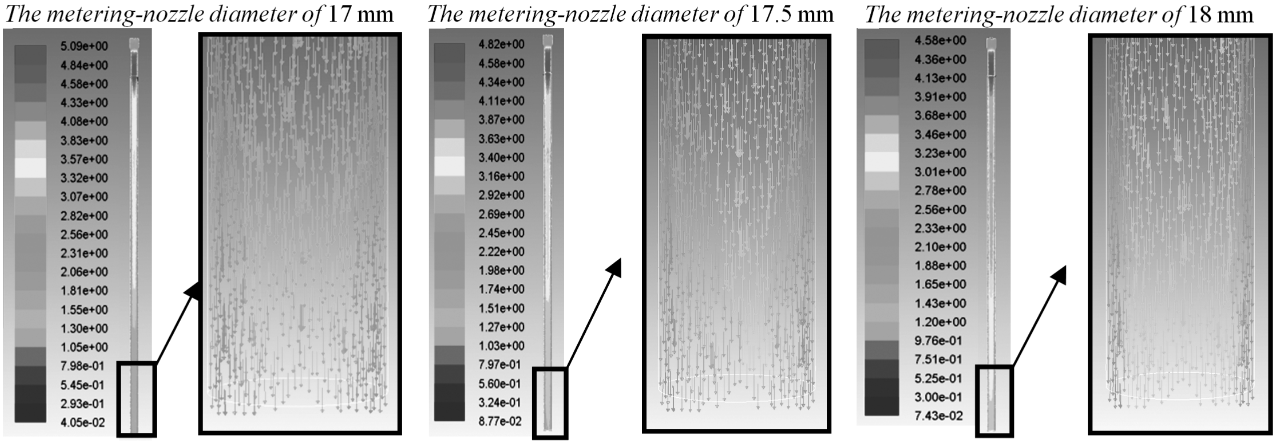
5.2 Fluctuation of the rate of the volume flow through the subentry shroud/nozzle

The fluctuation of the flow rate (and, in practice, of the casting speed) is an interesting phenomenon that may be associated with the changes in ferrostatic conditions, especially with a change in the flow character in the nozzle itself.

A change in ferrostatic conditions may be related to a change in the steel weight in the tundish, i.e., with a change in the height of the steel in the tundish. As the flow rate is not only a function of the height of the steel in the tundish, but, more accurately, a function of the distance between the height of steel in the tundish and the height of steel in the mould, it is also necessary to take into account the change in the elevation position of the tundish, which is sometimes made to allow an even wear of the outer surface of the nozzle. A shift in the steel-level distances by 10 cm will change the volume flow rate of the model by 1.33 L min^{-1} and, in the operating conditions, it will change the casting speed by 0.055 m min^{-1}.

However, a far more significant factor is the character of the steel flow rate in the nozzle. **Figure 5** shows the flow character displayed with the velocity vectors in the cross-section of a nozzle. **Figure 5** shows that an increase in the metering-nozzle diameter (17 mm → 17.5 mm → 18 mm) leads to a slight decrease in the maximum velocity in the area of the metering nozzle, while the area of the medium speed of 3.2 m s^{-1} slightly increases below the metering nozzle and in the nozzle-outlet area. On the other hand, the walls of the nozzle show a slowdown of the casting strand due to the presence of the so-called laminar sublayer[9], which is a typical phenomenon in a highly turbulent flow of a liquid in the pipelines. The velocity of the steel flow is, thus, not the same in the entire section of the nozzle, as shown in the detailed views of the distribution of the velocity vectors at the nozzle outlets.

The velocity distribution also determines the distribution of the pressure of the flowing steel in a nozzle. As confirmed with the detailed views of the pressure profiles at the metering nozzles (**Figure 6**) an enlarged diameter of a metering nozzle results in a reduction of the pressure (or, as noted above, of the maximum speed). On the other hand, below the metering nozzles, as shown by the details in **Figure 6**, the bigger the metering-nozzle diameter, resulting in a slight increase in the volume flow rate, the bigger is the area with the maximum pressure field near the nozzle outlet. However, if one looks closely, an increase in the area with the maximum pressure field is very subtle, which could be related, as stated above, to a large hydraulic resistance, which also prevents a higher increase in the volume flow rate.

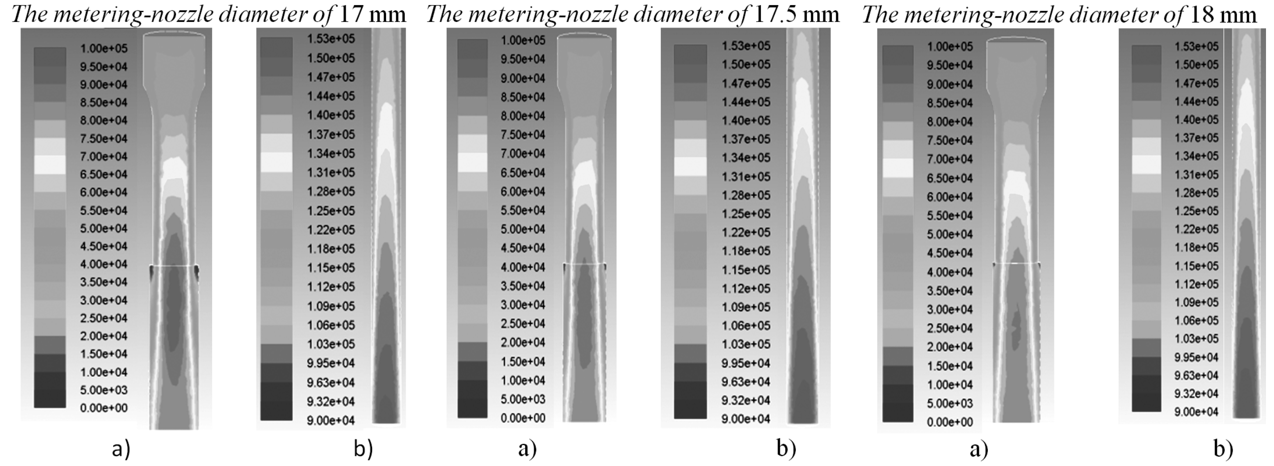

The metering-nozzle diameter of 17 mm

The metering-nozzle diameter of 17.5 mm

The metering-nozzle diameter of 18 mm

Figure 5: Steel-flow characteristics in the nozzles displayed with the velocity vectors (m s^{-1}) in the cross-sections of the nozzles with detailed views at the nozzle outlets for individual nozzles with the metering-nozzle diameters

Slika 5: Značilnosti toka jekla v šobi, prikazane z vektorji hitrosti (m s^{-1}) na prerezu šobe z detajlnim pogledom pri izstopu iz šobe za posamezne šobe s premeri notranjih šob

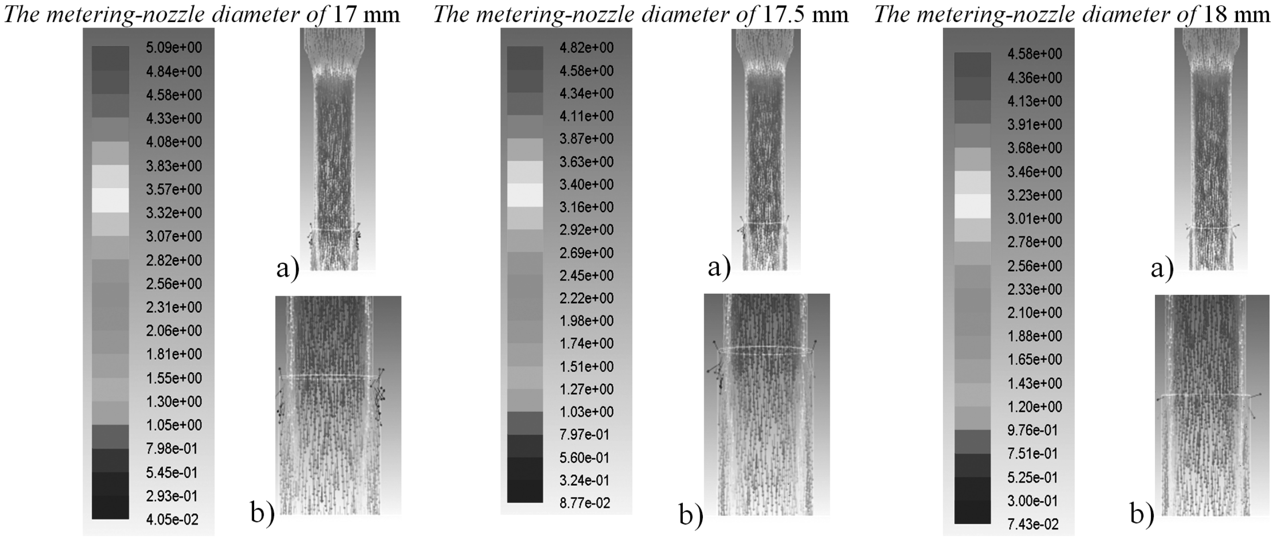

The metering-nozzle diameter of 17 mm

The metering-nozzle diameter of 17.5 mm

The metering-nozzle diameter of 18 mm

Figure 6: Detailed views of the pressure profiles (Pa): a) in the metering nozzles and b) in the areas of the nozzle outlets

Slika 6: Podroben prikaz profilov tlaka (Pa): a) v notranji izlivni šobi in b) na področju izstopa iz šobe

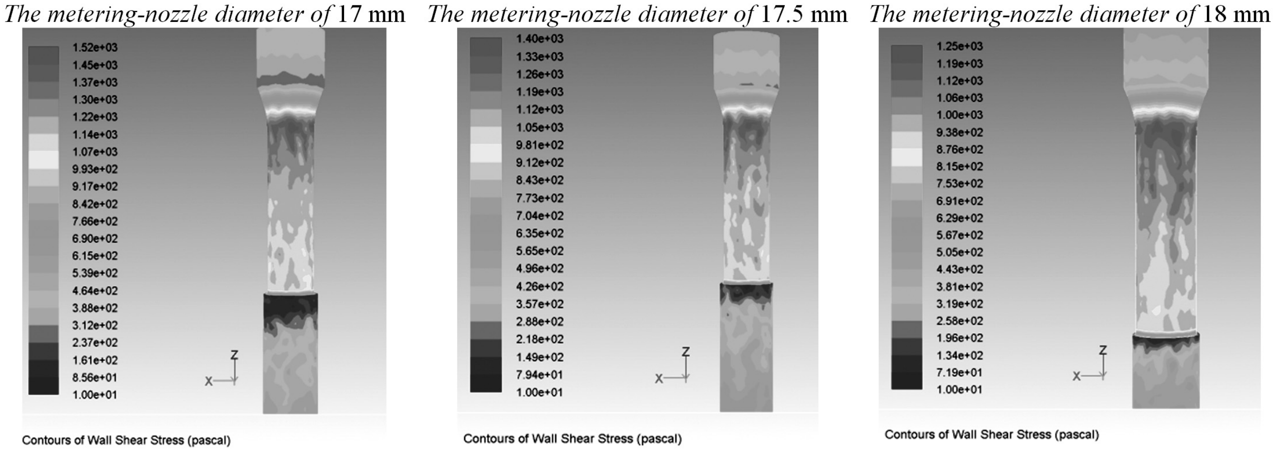

The metering-nozzle diameter of 17 mm

The metering-nozzle diameter of 17.5 mm

The metering-nozzle diameter of 18 mm

Figure 7: a) Character of the steel flows in the nozzles shown with the velocity vectors (m s^{-1}) at the cross-sections of the nozzles – in the metering nozzles and b) details just below the metering nozzles

Slika 7: a) Vedenje toka jekla v šobi, prikazano z vektorji hitrosti (m s^{-1}) na prerezu šobe – notranje šobe in b) detajl tik pod izlivno šobo



The metering-nozzle diameter of 17 mm *The metering-nozzle diameter of* 17.5 mm *The metering-nozzle diameter of* 18 mm

Figure 8: Distribution of the shear-stress profile (a risk of erosion) on the walls of the outlets for individual diameters of the metering nozzles
Slika 8: Razporeditev strižnih napetosti (rizik erozije) na stenah pri izhodu za posamezni premer notranjega izlivka

As explained above, the flow fluctuations may be caused by a high Re number of the steel flow in the nozzle. A particularly critical point can be considered to be the narrowing in the metering nozzle. See **Figure 7a** for a detailed view of the behaviour of the flow in the metering nozzle and see **Figure 7b** for the way of the velocity distribution just below the metering nozzle, where the nozzle is expanded to a diameter 20 mm. By observing the velocity vectors, a velocity profile can be noted, from which it is obvious that the strand is being strongly held back on the metering-nozzle walls. In the area of the burst expansion just below the metering nozzle, a "weak spot" is visible, where the velocity is minimum, and where the minimum contact of the nozzle walls with the flowing steel can be expected. An intense steel strand begins to flow around the wall approximately 3 cm below the metering-nozzle extension. This area may be, thus, prone to a greater erosion of the internal profile of the nozzle.

It is understandable that during the casting a profile may change (due to erosion, corrosion, fouling, etc.), which greatly and adversely affects the flow character and, thus, the stationarity of the flow fluctuations and the emergence of steel-flow fluctuations. A more significant impact of the metering-nozzle wear will more likely apply to a smaller diameter of the metering nozzle, as evidenced with the distribution of the shear stress on the nozzle walls in **Figure 8**. The size of the shear stress signals a danger of erosion. The most significant risk of erosion is at the inlet to the metering nozzle. In the area of the burst expansion below the metering nozzle, a "weak spot", as mentioned above, with a length of approximately 2 cm can be seen as well as the impact of the strand on the walls of the nozzle and, thus, there is a potential danger of a further significant erosion at a distance of approximately 3 cm below the metering nozzle. The shear-stress results confirmed the earlier finding that an increase in the diameter of the metering nozzle influences the length of the "weak spot", which is reduced at the extension below the metering nozzle.

When designing the metering nozzles, the principles resulting from the design of the nozzles must be followed. In general, in the recommended design the angle of the leading edges at the narrowing should be less than 10° and, in the critical cases, it should be 5°. In other words, at the connection of the metering nozzle to the body of the nozzle there should be no sharp transition; neither should there be one at the end of the metering nozzle (the drainage edge).

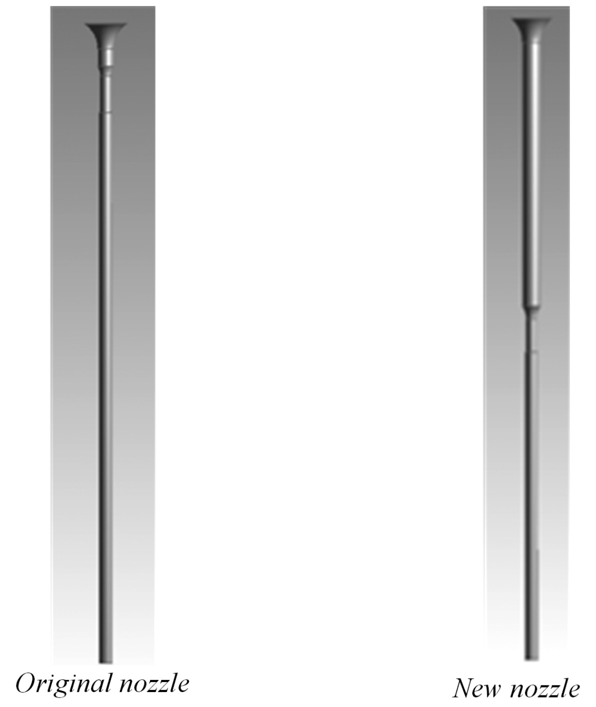
These conclusions were also confirmed experimentally on the physical model. It was also found that in the case of a sharp transition at a metering nozzle, it was not possible to provide a stable flow rate; the fluctuations amounted to 10 % of the volume flow rate values.

6 DESIGN OF A NEW NOZZLE PROFILE

Based on the above results, a design of a new structure (the inner profile) of the subentry nozzle was created in cooperation with the engineers at TŽ, a. s., and the staff of the VESUVIUS company, which should provide a greater volume flow of the steel (and, thus, higher casting speeds) and also eliminate the pulsation.

In the new construction design of the nozzle (the C nozzle) the lower end of the metering nozzle was moved 510 mm away from the nozzle outlet and the inner diameter of the nozzle above the metering nozzle was enlarged to 30 mm. The inner diameter of the nozzle below the metering nozzle remained the same (20/22 mm), as well as the metering-nozzle profile with a 17.5 mm diameter. A comparison of the original and modified geometry is shown in **Figure 9**.

Prior to manufacturing an operational variant and mounting the nozzle for the first test, a verification of the impact of the diameters of the metering nozzles on the volume flow rates, as well as the occurrence of non-stationarity of the flow were carried out using



Original nozzle *New nozzle*

Figure 9: Comparison of the inner profiles of the original and new nozzles

Slika 9: Primerjava notranjega profila originalnega izlivka in novega izlivka

physical and numerical modelling. Physical modelling was performed using the same methodology with the nozzles on a geometric scale of 1 : 1, and with the interchangeable metering nozzles of the diameters of (16, 17, 17.5 and 18) mm. Numerical modelling was performed for the geometry of the new nozzle on the scale of 1 : 1 with only the metering nozzle of the 17.5 mm diameter. The exact same input and output parameters of the calculation were used in the simulations, including the final step of the calculation. **Figure 10** shows the effect of the diameter of the metering nozzle on the volume flow rates. To enable a comparison, the previously discussed dependences on the metering nozzle in the inlet part of a nozzle are also shown.

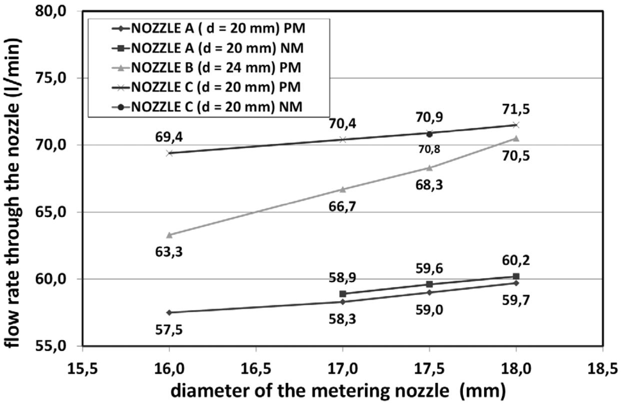


Figure 10: Effect of the metering-nozzle diameter on the rates of the volume flows through subentry nozzles A, B, C at a 120 mm submersion

Slika 10: Vpliv premera izlivka na hitrosti pretoka volumna skozi potopljeno šobo A, B, C pri potopitvi 120 mm

As evident from **Figure 10**, there was an increase in the flow rate for all the tested diameters of the metering nozzles at nozzle C during both physical and numerical modelling in comparison with nozzles A and B. It can be noted that the curve behaviour for nozzle C is shifted in relation to the curve of nozzle A by approximately 11 L min^{-1}, which is an increase by 18 % to 20 %. For the casting speed of 2.5 m min^{-1} this would mean an increase to 2.9 m min^{-1} or 3 m min^{-1}.

Similarly to nozzle A, a relatively low dependence of the volume flow rate on the diameter of the metering nozzle was registered in nozzle C. The cause may be the same: a poorly proportioned diameter of the nozzle below the metering nozzle. Increasing the diameter to approximately 25 mm would result in a greater incline of nozzle C and, thus, to a further increase in the flow through a subentry nozzle. These nozzles are significantly more sensitive to potential erosion in the metering nozzle.

Operational tests of the new subentry nozzle of type C resulted in an increase in the casting speed of the first casting sequence from 2.4 m min^{-1} to 2.8 m min^{-1}, representing an increase by 17 %. The situation was similar with the second and third test sequences of the heats.

7 CONCLUSIONS

The current type of the subentry shroud equipped with metering nozzles used in the continuous casting of steel on the CCM No. 2 in Třinecké železárny, a.s., did not allow a performance improvement of the casting machine even if the diameter of the metering nozzle was increased. For this reason, physical and numerical modelling was conducted, the goal of which was to assess and justify the behaviour of the steel flow and suggest a possible solution. On the basis of theoretical calculations and performed physical and numerical modelling, the following was found:

An inability to increase the casting speeds by further increasing the diameters of the metering nozzles in the subentry nozzles is due to a too small diameter of the nozzle-A outlet (20/22 mm) and, in particular, due to its length (approximately 1000 mm). Both parameters increase the hydraulic resistance and limit a further increase in the volume flow rate of the steel.

Fluctuations in the volume flow rate (and, thus, the casting speed) may be related to the turbulent nature of the flow; a metering nozzle and its implementation can have a significant impact; for this reason it should not have sharp leading and output edges – it is recommended that an angle is up to 5° and, at the maximum, up to 10°.

On the basis of the knowledge obtained with the physical and numerical modelling, a new type of nozzle, known as type-C nozzle, has been proposed. Here a shift of the lower end of the metering nozzle to a distance of 510 mm from the nozzle outlet, and an enlargement of the inner diameter of the nozzle above the metering nozzle to 30 mm were carried out.

Operational testing of the subentry nozzle led, during the first sequence, to an increase in the casting speed from 2.4 m min^{-1} to 2.8 m min^{-1}, an increase by 17 %, and similar results were achieved during the second and third test sequences of the heats.

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