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MODEL TESTING OF THE BATH FLOW THROUGH THE TUNDISH OF THE CONTINUOUS CASTING MACHINE

MODELOWE BADANIE PRZEPŁYWU KĄPIELI PRZEZ KADŹ POŚREDNIĄ URZĄDZENIA COS

The tundish of the continuous casting machine is considered an important metallurgical unit improving cleanness of cast steel. Findings of laboratory tests are presented in the paper. The objective of the tests was to learn about possibilities of modification of the most important parameters of the bath flow through the tundish. A "cold" model of tundish used for the tests was made to 1 : 8 scale. The flow quality was assessed on the basis of three criteria, value of which was calculated for each of the tested flow variants. The tests proved it was possible to achieve a significant improvement of flow parameters. However one should emphasize the incorrect design can lead also to a considerable worsening of tundish performance. The "cold" model of tundish used for the tests met the similarity criterion based on the Froud number value.

Kadź pośrednia urządzenia do ciągłego odlewania stali COS uważana jest za ważny agregat metalurgiczny poprawiający czystość odlewanej stali. W pracy zaprezentowane zostały wyniki badań laboratoryjnych, których celem było poznanie możliwości modyfikacji najważniejszych parametrów przepływu kąpieli przez kadź. Zastosowany do badań „zimny" model kadzi pośredniej wykonano w skali 1 : 8. Jakość przepływu oceniana była w oparciu o trzy kryteria, których wartość wyliczono dla każdego z badanych wariantów przepływu. Badania wykazały, że możliwa jest do osiągnięcia istotna poprawa parametrów przepływu. Należy jednak podkreślić, że nieprawidłowa konstrukcja może prowadzić również do znacznego pogorszenia pracy kadzi. Zastosowany do badań „zimny" model kadzi spełniał kryterium podobieństwa oparte o wartość liczby Frouda.

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1. Introduction

Continuous casting of steel is a process that determines the production flow of each steelmaking shop. At present a broad range of steel grades is cast continuously. This involves increase in quality requirements of cast strands. First of all, the requirements concern steel cleanness, mainly the amount and distribution of oxide non-metallic inclusions. Hence, apart from the properly set bath temperature, the oxygen content plays a key role in the continuous casting process. Therefore a steel production process line should ensure protection of metal against the air contact. Shortcomings in this area can cause serious production problems manifesting in nozzle clogging or in the extreme case in metal leaks under the mould. Economic results of such events badly affect the steelmaking shop performance. Oxygen content in the bath should be controlled first of all in secondary metallurgy processes. In this case vacuum methods are the most effective. The RH method is at present the most widely used one. Regardless of the applied secondary metallurgy method the tundish is the final control unit of the total oxygen level in the metal bath. Correct performance of this function by the tundish requires optimisation of its design. Directions of these modifications should be determined on the basis of tests performed on a physical model of the tundish. The method based on model testing is widely used for evaluation of flows in ferrous metallurgy.

2. The role of the tundish in the process of continuous casting of steel

The basic function of the tundish in the continuous casting machine consists in reduction of ferrostatic pressure of metal and division of the bath into the required number of cast strands. Its presence enables also sequential casting allowing replacement of ladles without breaking of the process. All the above mentioned elements are taken into account at optimisation of its design. Total operational volume of the tundish and its height are the main parameters.

As the operational experience was being gained, attention was paid to the tundish as a metallurgical reactor where the final correction of the bath chemical composition consisting in assimilation of non-metallic inclusions could be performed. At the same time it was found that the incorrect tundish operation could result in material worsening of cast steel parameters and in the extreme case in the necessity to break the continuous casting process. An analysis of numerous papers on the problem of the continuous casting machine tundish [1 ÷ 4] allows to conclude that both physical phenomena i.e. the metal flow through the tundish and chemical reactions at the metal- slag interface should be fully controlled. Only under these conditions it is possible to cast slabs or blooms of required quality.

The mean residence time of a metal elementary volume in the tundish is a parameter that can approximately estimate the bath flow through the tundish. Assuming absolute lack of mixing of the bath i.e. occurrence of the so called plug flow, the residence time of a bath elementary volume can be calculated on the basis of process parameters according to the formula:

$$t_R = \frac{V_{kp}}{\dot{V}}, \tag{1}$$

where: t_R — residence time of an elementary volume in the tundish [min],
V_{kp} — bath volume in the tundish [m^3],
$\dot{V}$ — volume flow rate of the bath through the tundish, [m^3/min].

In turn the volume flow rate $\dot{V}$ is calculated from the formula:

$$\dot{V} = n_p * V * F, \tag{2}$$

where: n_p — number of cast strands,
V — velocity of strand drawing, [m/min],
F — single strand cross-section area, [m^2]

The time t_R calculated according to the formula (1) is theoretically the longest possible mean residence time of a metal elementary volume in the tundish. In practice it is much shorter. This is caused by the nature of the actual bath flow through the tundish where so called "dead" zones form reducing the effective volume of the tundish. In consequence it results in occurrence of a flow which can be defined as the tunnel flow. Heaving left the ladle nozzle, the metal bath immediately passes to the zone of outlets above the moulds. This phenomenon causes that the effective residence time in the tundish slag influence zone is much shorter than it follows from the formula (1).

The reason to strive for maximization of the time t_R is the phenomenon of non-metallic inclusion assimilation occurring in the tundish, mainly of Al_2O_3 type oxide inclusions. Formation of conditions which enable inclusions to reach the metal — slag zone and formation of slag capable to assimilate them is a prerequisite of the correct course of inclusion assimilation. Theoretical calculations of time of surfacing of inclusions from the bath lead to a conclusion that it is much longer than the feasible time t_R. Therefore it should be assumed beforehand that inclusions must be partially transported by convection. This objective can be achieved by directing the bath stream to the metal — slag interface with appropriately shaped dams installed in the tundish. The advantage of the dams consists not only in improved inclusion assimilation but also in reduction of the volume of the "dead" zones in the tundish.

In practice it is difficult to achieve this objective due to the system kinetics. The movement of the bath in the interface zone must not result in disturbances like the phenomenon of entrainment of slag into metal or breaking the slag layer covering the bath.

The carried out considerations lead also to a conclusion that the slag quality plays a key role in the assimilation process. The parameters of fundamental importance are: chemical composition of the slag, its viscosity and surface tension of the metal and assimilated inclusions.

3. Physical model of the tundish of the continuous casting machine. Similarity criteria of the actual reactor and its physical model

Physical models of actual reactors build to-the-scale have been widely used for research in metallurgy. It concerns mostly research on mixing of steel in the ladle, in the RH-degassing vessel and examination of the bath flow through the tundish of the continuous casting machine [5-7]. Water is used in all these models. This is substantiated by a similar value of kinematical viscosity of water at 20°C of 1 cs and kinematical viscosity of metal bath at the temperature of 1600°C of 0,9 cs. The kinematical viscosity is the ratio of viscosity to density of the liquid.

There are many possible similarity criteria however it is assumed that in examination of the bath flow and mixing processes the Froud number similarity plays the most important role apart from the geometrical similarity. The Froud number is defined as the ratio of the inertia force F_b to the gravitation force F_g.

$$Fr = \frac{F_b}{F_g} = \frac{V^2}{gL}, \tag{3}$$

where: V — rate, [m/s],
g — gravitational acceleration, [m/s^2],
L — characteristic linear dimension, [m].

Hence the similarity based on the Froud number criterion assumes the form:

$$\left(\frac{V^2}{gL}\right)_M = \left(\frac{V^2}{gL}\right)_R . \tag{4}$$

Meaning of the indices; M — model; R — actual reactor

By a simple transformation the formula is obtained:

$$V_M^2 = \left(\frac{L_M}{L_R}\right) * V_R^2. \tag{5}$$

As the ratio $\left({}^{L_M}/_{L_R}\right)$ is the scale of the model, the flow rate of the bath in the model should be:

$$V_M = \sqrt{\lambda} * V_R, \tag{6}$$

where: λ — scale of the model.

It is explicit from the equation (6) that the more similar is the model size to the actual reactor size, the more similar are flow rates in the reactor and in the model. Sometimes it is more convenient to control examination of the flow stream of a bath volume expressed in m^3/s. In this case a simple transformation of the equation (6) leads to the equation

$$\dot{V}_M = \lambda^{2,5} * \dot{V}_R, \tag{7}$$

where $\dot{V}_M$ — volume stream of the bath in the model, [m^3/s],

$\dot{V}_R$ — volume stream of the bath in the actual reactor, [m^3/s].

The Reynolds, Weber, Grashof, Prandtl, Mach and Archimedes numbers should be named amongst other criterion numbers, which are used for modelling of flows. In the proposed method of carrying out experiments it is however not possible to meet all similarity criteria following these numbers. Therefore the similarity based on the criterion determined by the Froud number will be taken into account in further considerations.

4. Criteria for optimisation of internal design of the tundish

The objective of the performed tests was to improve operational parameters of the tundish by introducing a system of dams into it. The following three criteria are the measures of each tested variant:

1) maximum value of a signal recorded in the mould,
2) percentage share of the plug flow,
3) percentage share of the dead zone,

The first criterion regarding the maximum value of the measured signal characterizes the process of bath mixing. The higher is this value, the better are flow parameters. To facilitate evaluation of various experimental variants according to the above criterion, the maximum signal was normalized as described by the equation:

$$A_i^{\max} = \frac{\gamma_i^{\max}}{\gamma_{bp}^{\max}}, \tag{8}$$

where:

$\gamma_i^{\max}$ — actual maximum value of specific conductivity recorded for the i-th variant of dam arrangement, [mS/cm],

$\gamma_{bp}^{\max}$ — maximum value of conductivity recorded for the tundish without dams, [mS/cm],

$A_i^{\max}$ — nondimensional maximum value of the signal recorded in the mould,

The second criterion of assessment of the bath flow through the tundish is defined by the equation:

$$PF = \frac{t_{delay}}{t_R} * 100\% \tag{9}$$

where: PF — plug flow share , [%],

t_{delay} — time elapsing from the moment the marker is introduced to the moment of recording its presence in the mould, [s],

t_R — theoretical residence time of the marker in the tundish calculated according to the equation (1), [s].

As for the first criterion the plug flow share value should be as high as possible.

The last one of the presented criteria allows to assess the tundish with regard to the occurrence of the so called “dead“ zone that is a zone of weak flow in the tundish. The “dead“ zone share is defined as the percentage of the marker residing in the tundish after time $2t_R$.

$$S_m = \frac{V_{kp} * c_{2t_R}}{m_{KOH}} * 100\%, \tag{10}$$

where: S_m — “dead“ zone share, [%],

c_{2t_R} — marker concentration after time $2t_R$, [kg/m^3]

m_{KOH} — initial mass of the marker introduced, [kg],

V_{kp} — tundish volume, [m^3].

Obviously the percentage share of the “dead” zone should be as low as possible.

5. Test stand

The test stand for simulating bath flow in the continuous casting machine is presented in Fig. 1. A tundish model made to the 1:8 scale compared to an actual tundish constitutes its main element. Like an actual tundish the model was fitted with stopper rods. Both in the ladle and in the tundish model scale submerged entry nozzles were installed. To control the bath flow intensity, rotameters were installed under each of the two moulds. The marker method was applied to examine the bath flow through

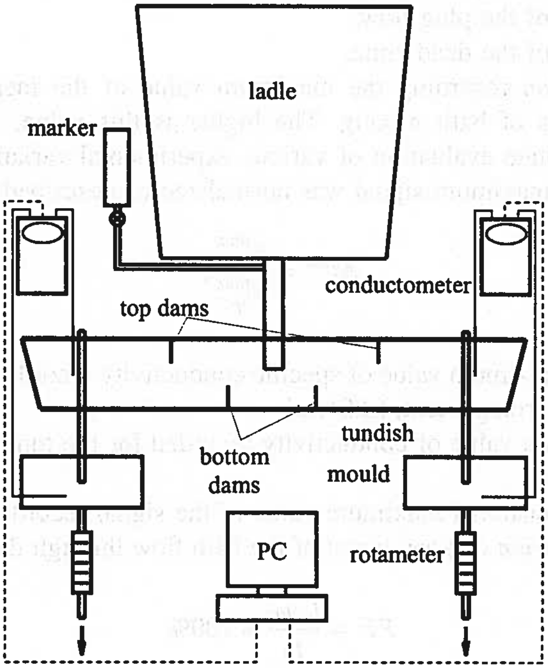

Fig. 1. The diagram of the laboratory stand for model tesing of the bath flow through the tundish of the continuous casting machine

the tundish. The ladle nozzle was fitted with a feeder, which enabled to add a set volume (10 ml) of 5% KOH solution into the tundish. The added KOH disturbs the specific conductivity of the bath in the tundish. Changes in conductivity are recorded independently in each mould. Specific conductivity is measured by conductometers with digital output so that measurement readings are recorded automatically. Each experiment produces an RTD (residence time distribution) curve which constitutes the basis for assessing the current conditions of the bath flow through the tundish.

16 variants of dam arrangement in the tundish were tested within the project. The parameters changed in individual variants are the height of dams and their location. The diagram of example of dam location along with geometrical parameters definition is presented in Fig. 2.

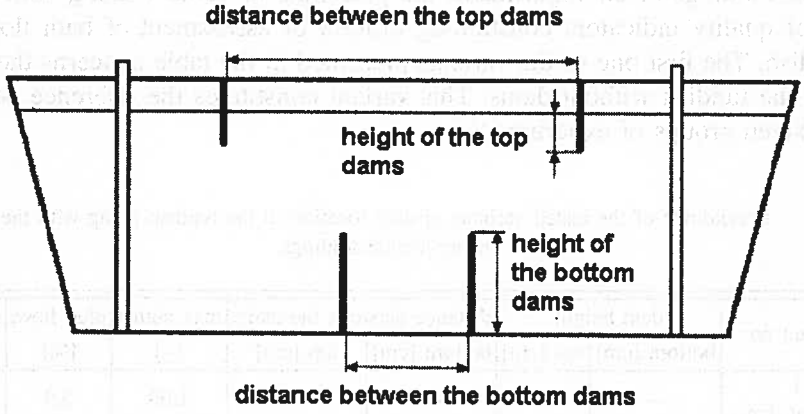

Fig. 2. The diagram of assumed designations of dam arrangement in the tundish

6. Findings and analysis of the test

The problem of standardization of experimental results plays an important role at processing of findings. Standardization can help to eliminate the influence of errors generated by fluctuations of the amount of the marker added or the initial level of specific conductivity of the bath used. Each actual RTD curve should be standardized according to the following equations:

$$\gamma_i^s = \frac{1}{F_{rz}} * \left(\gamma_i^{rz} - \gamma_0^{rz}\right) \tag{11}$$

$$F_{rz} = \sum_{i=0}^{n} (\gamma_i^{rz} - \gamma_0^{rz}) * \Delta t, \tag{12}$$

where: γ_i^{rz} — actual value of conductivity in time t_i [mS/cm],
γ_0^{rz} — initial value of conductivity for $t = 0$ [mS/cm],
γ_i^s — standardized signal value, [-],
Δt — time interval between subsequent readings of conductivity, [s],
n — number of recorded readings equal to 1000, [-]
F_{rz} — area under the RTD curve.

The standardization method on the basis of equations 11, 12 causes that in any case the area under the RTD curve is equal to 1. It is very important for assessment of tundish performance in the case of application of the first one of the formerly defined criteria.

Each of the 17 tested variants was measured twice and the obtained results were averaged. Findings of all experiments are presented in Table 1 along with calculated values of quality indicators constituting criteria of assessment of bath flow through the tundish. The first one of the variants presented in the table concerns the bath flow through the tundish without dams. This variant constitutes the reference point for all other sixteen groups of experiments.

TABLE

Breakdown of the tested variants of dam location in the tundish along with the experimental findings

Variant no	dam height		distance between the dams		max signal	plug flow,	dead zone,
	bottom [cm]	top [cm]	bottom [cm]	top [cm]	[−]	[%]	[%]
1 without dams	—	—	—	—	1.00	5.9	6.4
2	3	—	12	—	1.20	12.2	6.7
3	3	—	24	—	0.95	10.0	8.9
4	3	—	38	—	0.96	11.1	8.9
5	3	2	12	24	1.33	11.5	5.1
6	3	2	12	38	1.04	10.7	8.4
7	3	2	24	38	1.02	10.4	8.1
8	3	2	38	24	0.91	12.6	11.2
9	3	2	38	12	0.93	10.0	9.4
10	6	—	12	—	1.18	14.4	6.8
11	6	—	24	—	0.98	11.9	7.0
12	6	—	38	—	0.94	14.1	8.0
13	6	2	12	24	1.71	13.3	3.0
14	6	2	12	38	1.11	14.1	7.3
15	6	2	24	38	0.99	9.3	7.5
16	6	2	38	24	0.92	13.7	8.2
17	6	2	38	12	0.93	13.7	7,9

Taking into account the maximum of the measured signal one can find that the use of dams has a high impact on this parameter. It is characteristic that there are methods of dam arrangement which increase the maximum value (variant 2, 5 and 13). However most of the tested variants did not cause an improvement of the value of the achieved maximum, which in some cases was even reduced.

In the case of the second criterion regarding the percentage share of the plug flow, in all variants with dams an improvement was obtained in relation to the case without dams. The obtained result is in most variants more than twice as good.

The third criterion assessing the share of the "dead" zone yielded interesting results. It turns out, that an incorrect arrangement of dams can significantly worsen the tundish performance. It concerns mainly the variants 8 and 9.

By analysing together all criteria of assessment of the tested tundish one can say that the best results were obtained for the variant 13. The plug flow share increased in this case by more than twice, the maximum signal increased by 71% and the dead zone volume decreased by more than twice. It should be however pointed out that in the case of tundish design modification, life of all tundish elements is as important as improvement of steel flow parameters. Construction of dams, which very considerably disturb the flow, brings about an increase in risk of exogenous inclusion generation. In a case like this advantages caused by improvement of conditions of inclusion assimilation by slag are completely offset. Therefore any tundish design modifications should be a trade-off between optimisation of the steel flow and life of the tundish refractory lining.

7. Conclusions

The role of the tundish in a modern steel continuous casting machine is the reason to look for the best possible solutions of its design. Experiments carried out in the tundish model made to the 1 : 8 scale showed that there is much room for improvement of the metal flow, which should be similar to the plug flow in nature. Testing of numerous variants of arrangement of bottom and top dams allows to assess the scope of variability of the most important flow parameters, which constitute criteria for its assessment.

In the case of the tested tundish, in the variant considered the best one out of all tested solutions, all analysed indicators were improved as compare to the variant of the tundish without dams. The value of maximum signal increased by 71%, the plug flow share increased by 2.25 times reaching 13,3%, and the dead zone share decreased by more than twice.

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