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RESEARCH PAPER

STUDY ON A TWO-PHASE LOW-TEMPERATURE MODEL OF THE FEATURES OF METAL TAPPING IN BASIC OXYGEN FURNACE

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ABSTRACT

Under standard conditions of basic oxygen furnace (BOF) melting, during the blowing, slag is formed in the amount of 10-20% by the weight of the metal bath that enters the steel ladle during the tapping of the metal. Slag has a significant negative impact on the steel ladle and is the main quality indicator of further out-of-furnace metal processing. Various methods are used to reduce the slag entering the steel ladle; for instance, destructible plugs are used. The paper shows the results of a study of the influence of the cut-off method of the slag by using destructible plugs on the quantitative indicators of the redistribution of slag and metal in the steel ladle during the metal tapping operation from the converter. The research has been carried out with low-temperature physical modelling. The laboratory setup simulates a real 160-ton industrial top-blown oxygen converter, and a steel ladle at a scale of 1:18 has been used to fulfill the study. Water was chosen as a liquid steel imitator, and machine oil was chosen for slag with parameters that ensure the similarity of physical parameters in the metal-slag system. The physical modelling of the tapping process of a two-phase converter bath in the case of a destructible plug in the tap hole compared to the tapping option without it showed a significant positive effect of the presence of the plug in the initial period from the moment the converter is tilted. The plug makes it possible to retain slag in the volume of the converter and some phase separation in the converter that reduces the amount of slag that enters the ladle at the initial tapping stage and prolongs the pool tapping period due to the initial separation period by 4-10%, increasing the amount of tapped metal by 5-11%. At the same time, the amount of slag in the ladle in the case of the presence of the plug was noted at the level of 5–10%.

Keywords: two-phase basic oxygen furnace process simulation, metal tapping in the steel ladle, slag cut-off plugs, tapping time, slag and metal separation

INTRODUCTION

In 2020, global steel production was around 1,9 billion tonnes [1, 2]. Among many metallurgical routes [3, 4], the integrated route is the most common for steel production. This route includes cokemaking, iron ore sintering [5], iron ore pelletizing, blast furnace (BF)-based ironmaking, and conversion to steel by the BOF. The idea of the BOF process is to oxidize excess impurities in a metal bath, predominantly made up of molten iron, using oxygen blowing [6, 7]. During this process, oxidized iron impurities pass into the gas phase and slag that collects on the melt surface, involving the metal phase and forming a slag-metal emulsion on the melt surface. Under standard BOF conditions, slag in 10-20% of the metal mass is produced [9]. Increased slag mass is caused by blast furnace slag entering the BOF converter during iron pouring, metal scrap contamination, excessive lime additions, and a significant reduction in the carbon content of the metal at the tapping, blowing to a low carbon content of less than 1 % and especially less than 0.05 %, which is ensured by blowing the BOF converter bath [8].
The slag's chemical and physical (viscosity, density, surface tension) properties are determined by the ratio of the concentrations of their basic and acidic oxides. The levels of the main physical characteristics of the slag and metal phases typical for the steelmaking process in BOF converters are shown in **Table 1**.

Table 1 Main physical characteristics of slag and metal melt in BOF [8]

Phase	Physical parameters		
	Viscosity, Pa·s	Density, kg/m^3	Surface tension, kJ/m^2
Slag	0.1-0.3	3200-4000	1000-1200
Metal	0.005	7100-7600	1200-2000

Furthermore, an important physicochemical indicator of the BOF converter slag is its oxidation level, i.e., the level of iron oxides. On average, BOF slag contains 10-15% iron oxides. With a carbon content of less than 0.05%, the amount of iron oxides in the slag rises to 30-40%. However, a high oxidation level can also occur when the concentration of carbon in the metal is high (20-30 % or more of iron oxides in the slag) [8] if the bath temperature is low and the slag is heterogeneous.
The slag from the BOF converter is released in a certain quantity into the steel ladle. According to authors [9, 10], slag

entering the steel ladle during the BOF converter tapping reaches 15-20%, namely at the beginning of the tapping and at the end of the tapping until the BOF converter returns to operating position. The slag has a significant negative impact on the steel ladle and main quality indicators of the further out of furnace metal treatment:

- thick slag layer on the surface of the metal causes a hard crust that prevents additional reheating operations in the ladle;
- complicates the process of introducing additional materials to refine the melt;
- high level of iron oxides in the slag leads to a higher total oxygen content in the steel;
- unstable oxides in the slag react with aluminum and other additives, leading to increased deoxidant loss, thus requiring increased aluminum consumption. And, in turn, leads to the formation of aluminum oxide inclusions (Al_2O_3) that can deposit on the walls of the slide gate channel and cause it to tighten;
- phosphorus in the slag gets into the steel during the out of furnace treatment and impairs its properties;
- iron oxides in the slag react with refractory materials, causing erosion and destruction.

In addition, when metal is tapped, a certain amount of liquid metal remains in the converter with slag since the slag prevents the whole tapping in the form of metal drops in the slag-metal emulsion. Thus, in terms of improving the technological performance of molten metal production, it is required to control the process of slag entering the ladle [11, 12].

Various methods are used to reduce the amount of slag entering the steel ladle: the use of a destructible plug placed in the tap hole to cut off the primary slag flows [13, 14], control of slag entry at the end of metal tapping can be achieved, for example, by closing the taphole from the inside after the meltdown with a stopper ball, which is covered with a refractory layer of the magnesite powder mixture and placed on the metal-slag boundary [15, 16] or by using an aluminosilicate refractory dart stopper with forced insertion on the rod [14-16]. It is also possible to use a slide gate [15, 17, 18] or the use a pneumatic stopper that ensures that when slag comes in, the steel outlet is closed mechanically or by a gas flow to the outlet [15, 19]. For even more accurate slag cutting, special technical devices detect slag, e.g., electromagnetic [14] or infrared sensors [14, 20, 21].

The paper aims to study the impact of the primary slag cut-off method by using destructible tapping plugs on the quantitative indicators of slag and metal redistribution in the steel ladle during the BOF metal tapping operation.

MATERIAL AND METHODS

The research was carried out by means of low-temperature physical modelling. A specially designed laboratory apparatus was used (Figure 1), based on a model of an actual top-blown 160-t industrial BOF converter on a scale of 1:18. The model is made of transparent polycarbonate. To study the behavior of the slag phase for two-phase blowing, water was chosen as the model liquids simulating steel, and machine oil Lukoil SAE 5W20 was chosen for slag with the physical parameters given in Table 2. To reach the ratio of the viscosities of the modelling fluids to the conditions of similarity to the real process, the experiments were carried out at a temperature of 40 °C.

Modelling followed dimensionless similarity criteria to meet the experimental conditions for the actual technological process. Based on a literature review, the Reynolds and Froude criteria were considered for cold simulations using water and machine oil as model fluids [23-29].

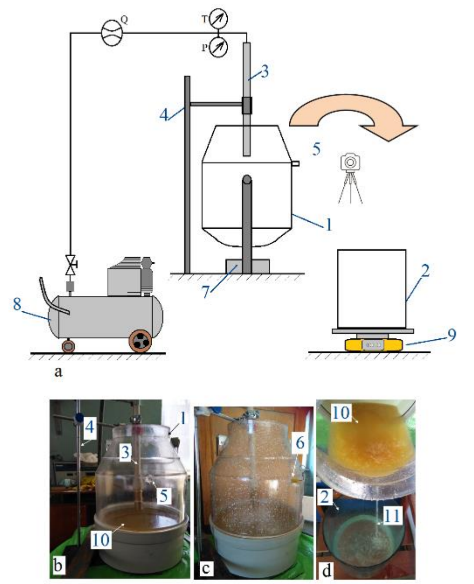

Fig. 1 Scheme of the experimental setup: a – main scheme of the experimental setup; 1 - transparent BOF converter model, 2 – transparent steel ladle, 3 – oxygen lance, 4 – lance positioning unit at a required height, 5 – tap hole, 6 - plug, 7- a unit for turning the BOF converter to a specified angle to the vertical axis, 8 – compressor, 9 – weighing device, 10 – "metal-slag" phase, 11 – tapping "metal"; (b) image of the start of blowing; (c) image of the finish of blowing; (d) image of tapping "metal"

Table 2 Main physical characteristics of fluids simulating metallic and slag phase under experimental conditions [19, 20]

Fluid	Physical characteristics		
	Viscosity, Pa·s	Density, kg/m^3	Surface tension, kJ/m^2
Machine oil	0.042	834.7	33.3
Water	0.00065	992.2	79.65

The object of the study was the period of metal tapping from the BOF vessel. For that reason, the vessel simulating a BOF converter was first filled with water to a height of 111 mm, providing a similar size to the metal bath of an industrial BOF converter, and then oil was poured in. The amount of machine oil was varied between 5-25 % by weight of the amount of water (in 5 % by weight step). The blowing nozzle, fitted with a Laval nozzle tip, was then positioned at a height corresponding to the working position of the blowing (40 calibers). Then the air was blown through with a compressor at controlled pressure and temperature for 3 minutes to ensure that conditions were similar at the time of metal tapping, namely the presence of a foamy complex "slag-metal" emulsion on the surface.

After blowing, the lance was removed, and the liquid was tapped through the transparent steel tap hole of a fixed diameter by tilting the BOF converter horizontally. The tap hole

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diameter corresponded to the outlet diameter of the simulated industrial BOF converter, considering the scaling, and was 8 mm. The tapping process was videotaped. The tapping was carried out until mineral oil (slag) appeared in the water jet, after which the tapping process was stopped, and the BOF converter was lifted back to its original position. Two similar tapping processes were carried out to simulate the action of a destructible plug: without and with a tightly fitting solid cylinder inserted in the tap hole - plug, which was removed after 10 seconds. This is the time corresponding to the lifetime of the plug to be destroyed in contact with the liquid metal undercurrent industrial conditions [30]. The bath was tapped into a clear glass container of known weight, graduated in advance by the volume of liquids poured. After tapping, the tank was weighed, and the amount of slag received was assessed by visually assessing the amount of tapped metal-water and slag-oil by marking. The emulsion left in the converter was poured into a separate container, weighed, and then visually evaluated for separation into metal-water and slag-oil. Each test run with a different amount of slag-oil, both without and with the insert, was repeated three times to assess the reproducibility of the experimental results.

RESULTS AND DISCUSSION

The visual behavior of the fluids at the BOF converter trapping was observed in the two variants of test runs. A layer of oil-water emulsion (similar to the slag-metal emulsion in a BOF converter) was formed on the bath's surface due to blowing. Each phase showed its physical characteristics differently at tapping, clearly visible due to the transparent tap hole. Thus, the movement of the emulsion along the tap hole in the absence of water was accompanied by its complete filling with a viscous, smooth (laminar) outflow in an even jet of a characteristic yellow color. The movement of water (transparent in nature) along the tap hole, on the contrary, was characterized by the formation of turbulent eddies in the tap hole. However, under the experimental conditions, turbulence occurred only in the tap hole itself without the formation of vortices in the volume of the converter, regardless of the amount of slag on the surface and the liquid level at the tapping, which is due to the relatively small diameter of the tapping tap hole to the bath.

The tapping process can be divided into three periods. It starts with the period of the initial entry of slag into the tap hole. The main one is the period of tapping metal-water only, and the final period, the period of reappearance of slag-oil in the jet, marking the end of the tapping and the requirement for a sharp rise in the model. The images of the periods are shown in **Figure 2**.

In the absence of a plug when the model is tilted towards the ladle, regardless of the amount of "slag" - emulsion on the surface in the first period, the first portions that merge into the ladle were portions of the emulsion - "slag," visually containing little water, which was clearly distinguishable due to the yellow color of the emulsion. This is because the surface tension of the emulsion is much lower than the surface tension of water, and the viscosity, on the contrary, is higher respectively. When in contact with the model surface, it did not allow portions of the metal-water to move actively. **Figure 2 (a)** shows a typical image of the moments of the start of tapping for conditions of different slag-oil content on the surface. The images were taken in the same period from the moment the bath was tapped, regardless of the option (without the insert or with insert) of 5 seconds. With an increase in the amount of slag-oil on the surface in the initial period, the nature of the tapped liquid jet changes in the initial period, completely turning into an emulsion jet to 20-25% slag-oil. In the case of using the plug, which was removed after 10 seconds from the beginning of its contact with liquid metal, certain portions of the emulsion in the jet were also observed after its removal. However, its amount was visually much less. **Figure 3 (b)** shows the moments when the bath is tapped only after opening the insert. In this case, the ingress of oil-slag portions is associated with some "vacuum" effect created by the moment of removing the insert, provoking the tightening of the emulsion portions deep into the tap hole (the image shows portions of the emulsion in the tap hole, staining it yellow in places). In addition, the dragging of the emulsion was also reflected in the behavior of the jet itself, the absence of turbulent eddies until the emulsion stopped flowing into the jet.

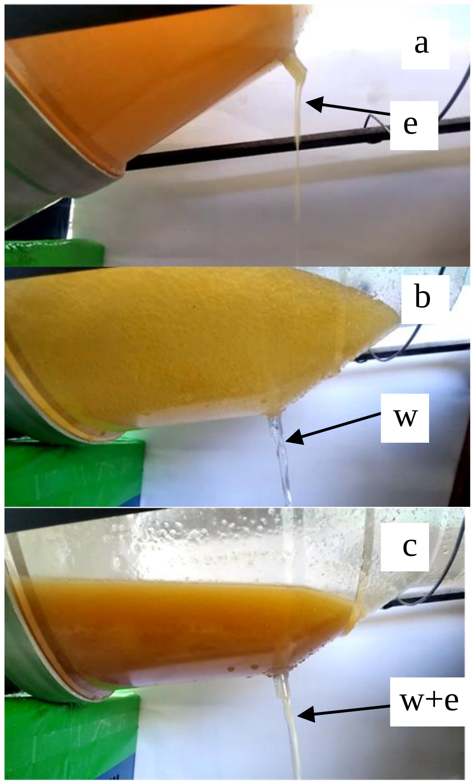

Fig. 2 Images of bath tapping periods (a) start with emulsion movement; (e), (b) main one with water-metal tapping (w); (c) the final period with the appearance of an emulsion in a jet of water (e+w)

The influence of the plug placed in the tap hole was also shown to reduce the initial period (**Figure 4**) by 14-28% relative to the tapping option without the plug. At the same time, it was noted that with an increase in the amount of slag-oil on the bath's surface, for both options for the tapping, the initial period was reduced. This is because the emulsion density is lower than the density of water. With its significant presence relative to the water layer, the emulsion rose faster under the action of Archimedes' forces.

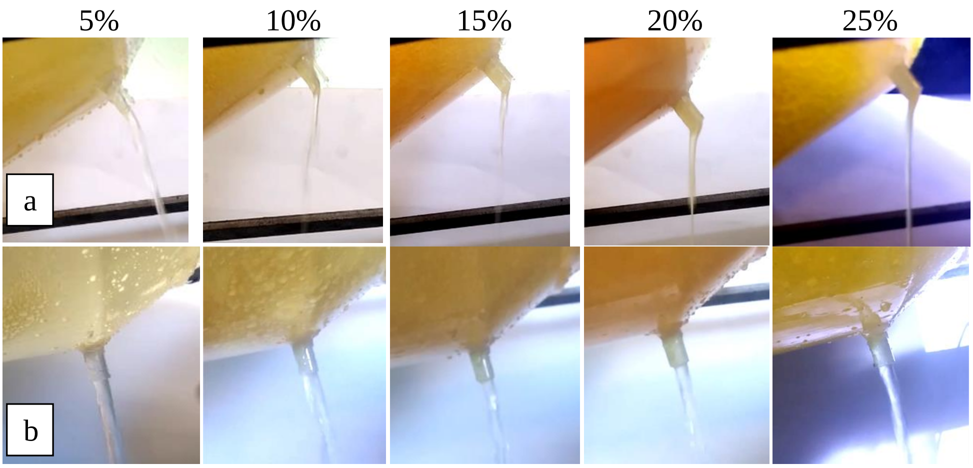

Fig. 3 Images of the initial period of bath tapping with different amounts of oil-slag on the surface (5-25% of the mass of metal-water) in the case of tapping the bath without the plug (a) and with the plug (b)

The main bath tapping period did not differ depending on the initial tapping start option. It was characterized by active metal-water tapping with the formation of a turbulent, swirling transparent jet (Figure 2b). Additionally, the amount of slag-oil emulsion on the surface did not affect the nature of the outflow into the main bath tapping process. However, the amount of slag-oil on the surface had a significant effect on the total duration of the bath tapping until the reappearance of the emulsion in the jet, reducing the possible release time with an increase in the amount of slag-oil from 5 to 25% by 8–10% (**Figure 5**). At the same time, the influence of the presence of an insert in the initial period had a positive effect on the duration of the bath tapping (an increase in the course by an average of 4-10% was noted compared to the tapping option without the plug, **Figure 5**).

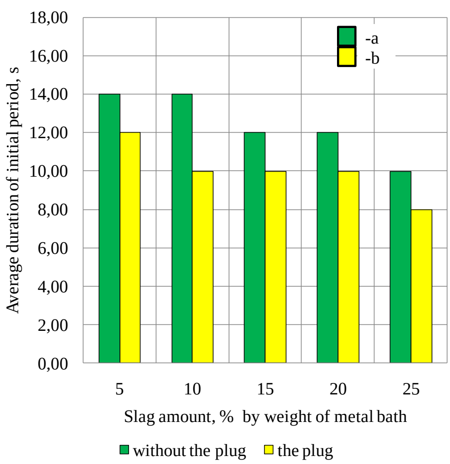

Fig. 4 Influence of the variant of bath tapping on the duration of the initial period for (a) tapping without the plug; and (b) with the plug for different amounts of slag-oil on the bath surface.

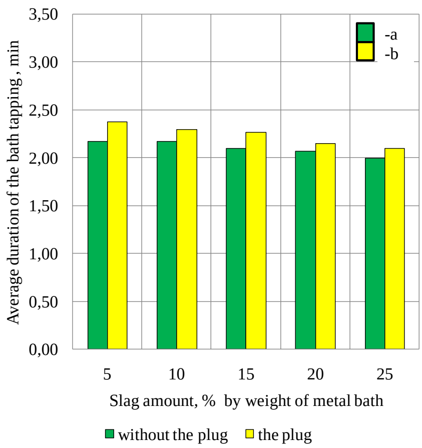

Fig. 5 Influence of the metal-water tapping option and the amount of slag-oil on the surface of the bath tapping time for (a) tapping without the plug; and (b) with the plug at different amounts of slag-oil on the bath surface.

Evaluation of the total amount of tapped water also confirms the positive effect of the plug on the tapping process, regardless of the initial level of slag-oil on the surface (**Figure 6**). In the presence of the plug in the initial period, the amount of tapped metal-water increases by 5-11% compared to the option without the plug.

At the same time, the most indicative visually is the moment of assessing the amount of slag-oil on the surface of the ladle after tapping. **Figure 7** compares images of ladles after tapping the bath with an initial slag-oil content on the surface in the converter of 20% when tapping without the plug and with it. In the case of tapping the bath without the plug (**Figure 7a**), the water's surface in the ladle is covered with a yellow emulsion of a certain thickness (about 2–3 mm), which can be seen in the frontal image. Only individual emulsion spots are visible when using the plug on the water's surface in the ladle after the tapping (the thickness is almost impossible to estimate).

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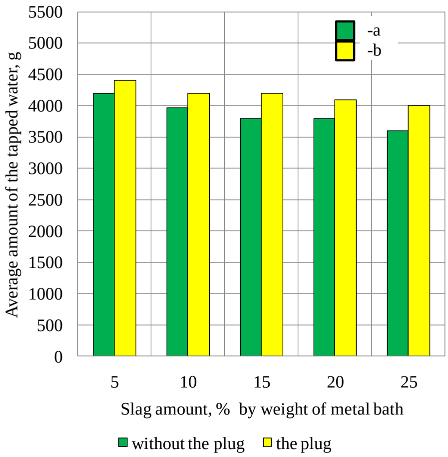

Fig. 6 The average amount of tapped water-metal according to the experimental options for (a) tapping without the plug; and (b) with the plug at different amounts of slag-oil on the bath surface.

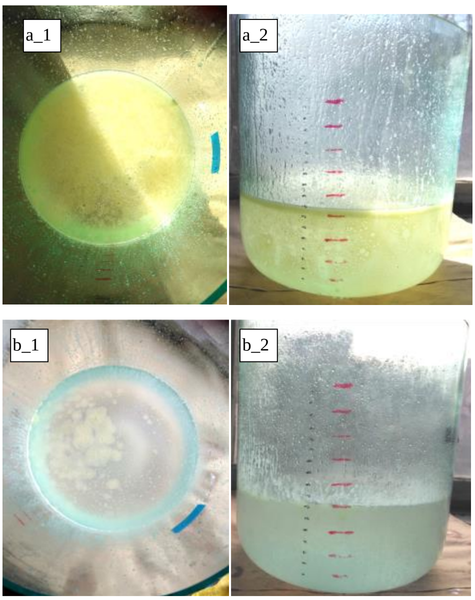

Fig. 7 Images of the ladle after tapping the bath in the case of a 20% slag layer on the surface of the bath in the converter before tapping, when tapping (a) without using the plug; and (b) using the plug (1b is a top view, 2b is a front view).

It was established that the amount of slag-oil that has entered the ladle under the conditions of bath tapping without the plug is on average 10-30%, depending on the initial slag-oil content in the converter, which agrees with the papers of other authors [23-29]. At the same time, when using the plug, the amount of slag-oil in the ladle is 5–10%, which should significantly improve the quality of the produced metal-water and its further processing in the ladle. The experimental results correlate well with the industrial test run using a primary slag cut-off plug in 60-t converters [30]. Additionally, indirectly, the amount of slag entering the steel ladle correlates with the absorption of the deoxidizer elements.

CONCLUSIONS

The physical modelling of the BOF tapping process in the case of using a destructible tapping plug in the tap hole versus an option without it has been carried out. The results show that the plug improved the efficiency of the BOF tapping process. Thus, a significant positive effect of the presence of the plug in the initial period from the moment the converter is tilted was established. This made it possible to retain slag-oil in the volume of the converter and some separation of the phases in the converter. It also made it possible to reduce the "slag" that fell into the ladle at the initial stage of tapping and prolonged the period of bath tapping due to the initial period of phase separation by 4-10%. At the same time, the amount of tapped "metal" in the ladle has increased by 5-11%. The amount of "slag" in the ladle in the case of the plug used was at the level of 5–10%.

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