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THE INTERACTION OF THE ARGON CURTAIN AT THE INTERFACE: METAL-SLAG IN A TUNDISH

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Due to the need to improve the quality of the produced steel, especially its metallurgical purity, attempts are made to use inert gas bubbling curtain in the tundish. The article presents the results of the research of metal-slag interaction carried out with the use of the trough-type two-strand tundish water model, made on a reducing scale – 1 : 2,5. The tundish model is built with two gas bubbling curtain. The aim of the research was to determine the optimal value of the flow rate of the blown gas, ensuring the safe course of the process taking into account the secondary contamination of liquid steel with atmospheric gases and endogenous inclusions originating from the slag.

Keywords: steel, tundish, gas bubbling curtain, liquid metal-slag, slag eye

INTRODUCTION

The hydrodynamic phenomena occurring in the tundish have a decisive influence on the quality of the continuous billets. This fact is the reason why researchers are widely interested in the problems of flow and mixing of liquid steel.

The most frequently conducted works concern the possibility of using various types of flow control devices (FCD) [1-2]. Depending on the design of tundish and the expected effects of their application, the following types of flow control devices are considered: dams, weirs, baffles [3-4] and turbulence inhibitors (TI) [2,5,6]. The use of dams, weirs and baffles is mainly aimed at directing the liquid steel flow stream in tundish in such a way as to force the formation of the assumed plug to turbulent flow ratios and to limit the size of the dead flow areas. Moreover, it aims to improve the refining capacity at the metal-slag interface and to equalize the time of reaching the liquid steel from the inlet point to the individual outlets. Other requirements apply to turbulence inhibitors (TI), which are installed in the inlet zone of the tundish. Their task is to dissipate the kinetic energy of the liquid steel stream hitting the impact plate. The TI design causes the liquid steel to flow at a reduced speed towards the liquid metal-slag interface. This promotes the effective absorption of non-metallic inclusions. The conducted research showed [2,7] that the application of TI gives better results than the dams, weirs and baffles set for the control of non-metallic inclusions (NMI) flotation.

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FCDs are an additional development of the tundish working space. While they are effective tools for regulating the flow of liquid steel and are frequently used, they are not without their drawbacks. The main problem is the risk of their washing out by the liquid steel stream and, consequently, its secondary contamination with endogenous NMI.

In order to obtain the above-described effects of regulating the flow of liquid steel through the tundish, with the simultaneous limitation of the occurring hazards, studies are carried out with the use of the gas bubbling curtain [8-11]. Although the implementation of this solution in industrial conditions is difficult, the results of the research cited in the literature [10,11] give very good prospects for its effectiveness.

The main problem in the case of the devices for continuous casting of steel that are already in operation is their technical adaptation to new working conditions. It is required to design and build a gas supply installation to ensure the safe course of the process. This is a major investment effort. Therefore, the application of such a solution must be preceded by extremely thorough scientific research. The purpose of these tests should be to precisely determine the changes in the flow and mixing of liquid steel in tundish due to the impact of the gas blown stream, and to identify technological parameters (method and place of gas injection, gas stream intensity). Of particular importance is the effect of stream of the flowing gas bubbles on the surface of the metal-slag separation interface. This area is responsible for the efficiency of liquid steel refining. An important issue in this area is the identification of the risks of excessive exposure of the steel mirror and the risk of the slag being drawn due to the incorrect intensity of the gas stream.

The article presents the results of model tests aimed at determining the minimum and maximum gas flow stream in the tested tundish as well as determining the conditions and manner of occurrence of danger of the secondary contamination of liquid steel with slag.

PHYSICAL MODELLING

A typical trough-type two-strand slab tundish was selected to carry out this study, for this purpose a perplex model was constructed in the scale 1 : 2,5 using the geometric dimensions shown in Figure 1. The model is built in accordance with the requirements of the theory of geometric, dynamic and kinematic similarity [12] and described in detail in [13].

According to the similarity criteria, the medium simulating liquid steel was water [1,2,4,5,10,13]. This is mainly due to the fact that water at a temperature of 20 /°C has a kinematic viscosity similar to that of liquid steel at 1 600 /°C. Argon-gas, although having different properties, was simulated with air. This enables the use of appropriate similarity criteria in the design of the experiment and makes air commonly used in water modeling of metallurgical processes [4,10]. Similarly, in order to simulate the slag layer, various fluids are used, including modified silicone or paraffinic oils, benzene and paraffin [14,15]. Paraffin oil was used in the research. Table 1 shows the properties of the fluids used in the model tests.

Taking into account the two-phase fluid flow (water-air) in the model, the complexity of the tested process and the difficulties in meeting all the similarity criteria at the same time, the modified Froude criterion (Fr_N) was adopted as the dominant criterion for the determination of dynamic similarity, represented by the formula:

$$\mathrm{Fr_N} = \rho_g \cdot V^2 / \rho_l \cdot g \cdot L \tag{1}$$

where: ρ_g - gas density; ρ_l - liquid density; g - acceleration due to gravity; L - liquid height in the model; V - gas injection velocity.

Froude criterion is supplemented with Weber›s criterion number (We) in order to take into account surface phenomena. The mathematical form of the Weber criterion is expressed by the formula:

$$\mathrm{We} = (V^2 \cdot L \cdot \rho) / \sigma \tag{2}$$

where: σ - interfacial tension.

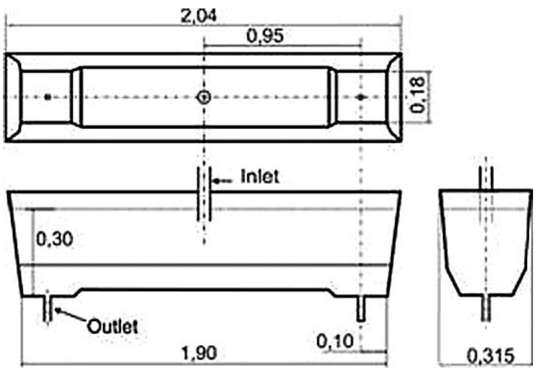

Figure 1 The geometric dimensions / m of the tundish model

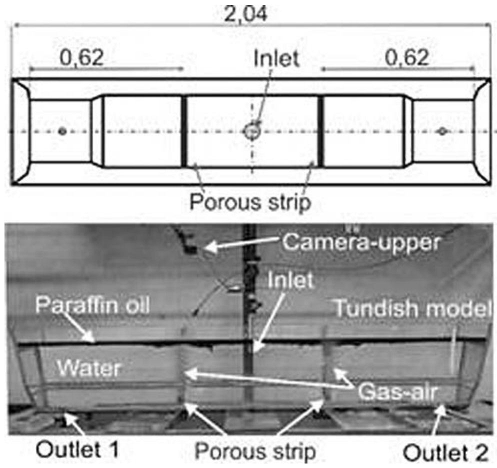

Figure 2 Location of the gas bubbling curtain in the tundish model

Ideally, the ratio of the We number in the model and for real conditions should be one. Using the combination of equations (1) and (2), the Weber number ratio index can be calculated in both conditions of the conducted research.

To model the gas bubbling curtain, a 0,9 / cm diameter and 17 / cm long gas-permeable strip was placed in the position indicated in Figure 2.

The control and measurement equipment installed in the model enables smooth regulation and recording of the gas (air) flow rate.

The conducted research was of a visualization nature. The course of the experiment was recorded with the use of video cameras located in three planes - central, side and top. Such an arrangement of cameras allowed for uninterrupted observation of the studied phenomenon.

The research was divided into two stages. In the first stage, the behaviour of the slag layer represented by the paraffine oil was observed, and in particular the size of the slag eye formed as a result of outflowing gas bubbles. The tests were carried out for 2 variants of the slag layer thickness and 4 variants of gas flow rates. The volumetric velocity of the model liquid flow through the tundish model was kept constant. Table 2 shows the cases studied in this work.

Table 1 **Physical quantities — laboratory research and industry**

Parameter	Unit /	Value
Water density	kg/m^3	998,2
Water kinematic viscosity	m^2/s	$1{,}00 \cdot 10^{-6}$
Liquid steel density	kg/m^3	7 010
Liquid steel kinematic viscosity	m^2/s	$0{,}913 \cdot 10^{-6}$
Argon density	kg/m^3	1,622
Air density	kg/m^3	1,258
Slag density	kg/m^3	2 539
Slag viscosity	kg/m·s	0,2664
Oil density	kg/m^3	847
Oil viscosity	kg/m·s	0,046
Surface tension model	N/m	0,04
Surface tension industry	N/m	1,6

Table 2 **Cases studied in this work**

Case	Volumetric flow water (inlet)		Gas (air) flow rate (gas bubbling curtain)	Slag layer thickness
	/ m^3/s	/ l/min	/ l/min	/ mm
A1	$3{,}23 \cdot 10^{-4}$	19,4	0,5	10
A2			1,0	
A3			1,5	
A4			2,0	
B1			0,5	15
B2			1,0	
B3			1,5	
B4			2,5	

The second stage of the research consisted in the observation of the metal-slag interface in order to identify the phenomena of the slag being drawn into the liquid steel as a result of interaction with the outgoing gas bubbles. The purpose of these tests was to determine the limit value of the blown gas flow rate at which this type of hazard occurs.

RESULTS AND DISCUSSION

Figure 3 shows selected visualization results (cases A1, A2, A3, A4) recorded in three planes.

During the visualization of the process of gas bubble impact on the surface of the oil layer representing the liquid phase of the slag, accumulation of bubbles under its surface was observed at low gas flow rates, not exceeding 0,5 / l/min. The bubble energy is then too low for the slag layer to burst. The bubbles merge into larger

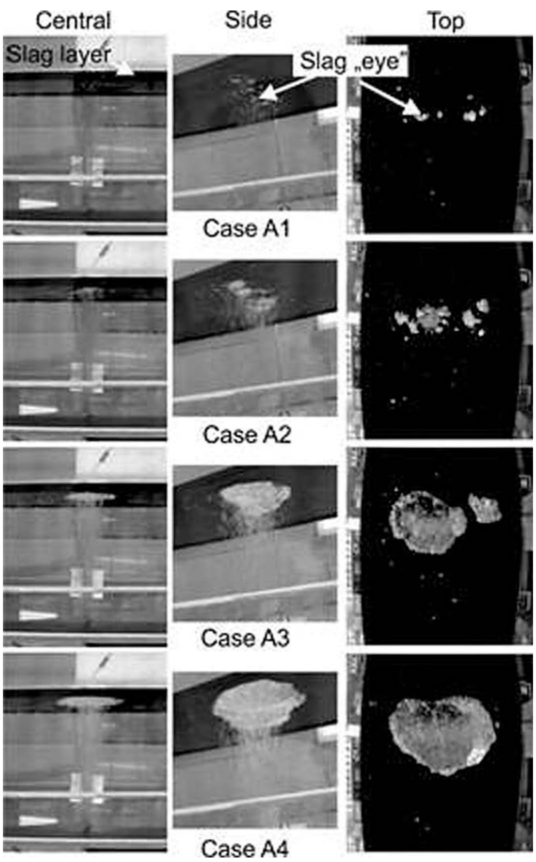

Figure 3 Visualization of gas injection into the tundish model

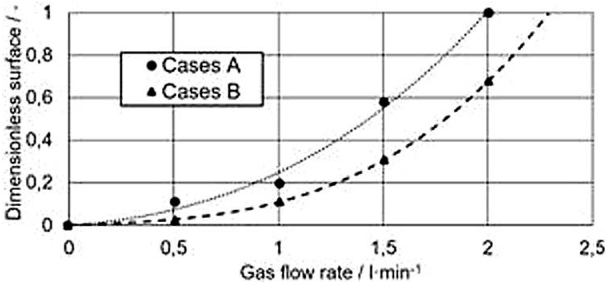

Figure 4 Slag eye area as a function of gas flow rate

complexes and travel to its surface one by one. The rupture of the slag surface was observed at the gas flow rate above 0,8 / l/min in variant A and 1,3 / l/min in variant B of the experiment. In the further phase of the experiment, the slag eye grows with the increase in gas flow. At the same time, a slight increase in the surface ripples of the model liquid was observed. Taking into account the purpose of the research consisting in determining the limit values of the growth of the slag eye due to interaction with the gas curtain, the tests were completed for the gas stream value of 2 / l/min.

The film material obtained as a result of the research was developed in such a way that the dimensionless surface of the exposed mirror of the model liquid was determined as a result of the gas curtain interaction for individual variants of the experiment. This procedure made it possible to objectify the test results and to assume that at a gas flow rate of zero the surface of the slag eye is 0, while for the gas flow rate of 2 / l/min in variant A it is 1. In this way, the relationship between the growth of the slag eye and the gas flow rate was determined. This relationship is shown graphically in Figure 4.

The determined curves (Figure 4) describe polynomial equations of the third degree of the type: $y = ax^3+bx^2+cx$.

Assuming that in the dimensionless scale for assessing the size of the slag eye area, the breakage of the slag continuity occurs at the value of 0,2, the gas flow rate values determined on the basis of the graph, at which this phenomenon occurs, coincide with the observations made during the visualization.

The second stage of the research focused on the phenomena occurring at the interface between liquid steel and slag. Representative visualization results are shown in Figure 5.

The analysis of the obtained research material made it possible to state that there was no risk of dragging the slag to the liquid steel at the value of the blown gas stream not exceeding 2 / l/min. Above this value, the situation changes. Slag dragging due to Kelvin-Helmholtz instability, increased meniscus fluctuation and excessive exposure of the mirror as a result of the dynamic impact of the stream of escaping gas bubbles were observed. These phenomena clearly indicate the possibility of secondary contamination of steel as a result of the interaction of slag with it.

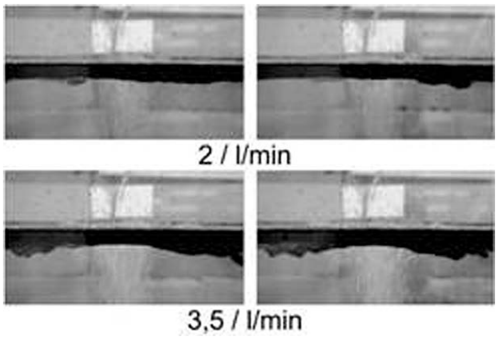

Figure 5 Visualization of the phase interface area for two values of the blown gas stream

CONCLUSIONS

Based on the model research and analysis of the results, the following conclusions can be drawn:

- The size of the eye slag area depends on the gas flow rate, and this relationship is polynomial of the third degree.
- The growth of the surface of the slag eye is also dependent on the thickness of the slag layer on the steel mirror surface.
- The critical value of the gas flow rate, at which the slag continuity is broken, in the model tests is 0,8 / l/min.
- The maximum value of the gas flow rate, to which the risk of slag dragging was not observed during the experiments, is 2,5 / l/min.
- In this range of gas flow, no excessive undulations of the surface of the model liquid were observed.
- In this range of gas flow rate, no excessive undulations of the surface of the model liquid were observed.

Taking into account the above conclusions, further studies on the efficiency of NMI removal from the liquid steel flowing through tundish under the influence of the gas bubbling curtain should be carried out in the gas flow rate from 0,8 / l/min to 2,5 / l/min.

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Note: The responsible for English language is Paulina Pieprzyca.