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INFLUENCE OF HYDRODYNAMIC AND TEMPERATURE CONDITIONS ON THE EFFICIENCY OF THE SLAG SPLASHING METHOD

Key words: slag splashing method, lance, refractory lining, nozzles, nitrogen flow.

Abstract: The paper is devoted to an important problem encountered in the exploitation of an oxygen converter, i.e. wearing out of refractory lining. One of the most efficient methods of limiting the erosion of the lining is the use of the slag splashing method. Authors presented the results of a computer simulation of the process with the use of numerical calculations. The results were used for determining conditions for this process in two design variants of the lance for injecting the N_2 +MgO mixture. Attention was also paid to the hydrodynamic parameters and temperature. The cooling of the lance with gas leads to the heat recuperation, which increases the temperature of the injected mixture, so the kinetic energy of the outflowing jet in the converter increases about 3.5 times, and the slag is splashed higher than in the case of a conventional water-cooled lance. Heating of the carrier, i.e. nitrogen, is recommended to increase the splashing effect, which is connected with the melting of slag and the modifiers.

Wpływ parametrów hydrodynamicznych i temperatury na efektywność metody slag splashing

Słowa kluczowe: rozprysk żużla, lanca, wyłożenie ogniotrwale, dysze, strumień azotu.

Streszczenie: Artykuł poświęcony jest istotnemu problemowi w procesie eksploatacji konwertora tlenowego, jakim jest zużywanie się wyłożenia ogniotrwałego. Jedną ze skutecznych metod ograniczenia zjawiska erozji wymurówki jest stosowanie metody rozpryskiwania żużla wraz z modyfikatorami na wymurówkę pieca – slag splashing. Autorzy przedstawili wyniki symulacji komputerowej procesu z zastosowaniem obliczeń numerycznych. Wyniki pozwoliły określić warunki prowadzenia procesu przy dwóch wariantach konstrukcyjnych lancy do wdmuchiwania mieszanki N_2 +MgO. Pod uwagę brano również parametry hydrodynamiczne procesu oraz temperaturę. Zastosowanie chłodzenia lancy za pomocą gazu prowadzi do odzysku ciepła, co zwiększa temperaturę wdmuchiwanej mieszanki, a w związku z tym energia kinetyczna wypływającego strumienia mieszanki w objętości konwertera rośnie około 3,5 razy, w konsekwencji powoduje to rozpryskiwanie żużla na większą wysokość w porównaniu z konwencjonalną lancą z chłodzeniem wodnym. Stwierdzono również, że podgrzewania czynnika nośnego, jakim jest azot jest wskazane w celu polepszenia efektu rozbryzgiwania, co jest związane z roztapianiem żużla wraz z modyfikatorami.

Introduction

The increasing requirements and strict legal regulations on the environment and also the exploitation of metallurgic systems, in that oxygen converters and melting technology caused that steel producers have been looking for design solutions and undertake remediation actions aimed at recycling procedures to lower the cost of generated by steel mills [1–3]. The utilization of waste and re-use of materials are some of the most efficient methods of elongating the life of an oxygen converter. One of such methods is maintaining the refractory lining with converter slag, which is a waste product. Refractory lining in a converter is wearing away in the process of melting the metallic charge and oxygen injection. The degree of the degradation of the lining depends on the Si, Mn, and C content in the liquid bath, the temperature of the process, and the chemical composition of slag, mainly the presence of FeO and MgO [2, 4].

The regeneration and maintenance of the oxygen converter's lining lying in slag treatment or refractory gunning has been known and broadly described in literature [4–5]. Presently, slag splashing is one of the most efficient methods of lowering the cost of steel production by increasing the durability of the refractory lining and the utilization of a waste product, i.e. converter slag [2, 5–6]. This method has been successfully used in worldwide metallurgy for over 30 years. The respective analyses reveal that this method increases the resistance of refractory lining to the operation of agents used in relation to the high-temperature impact of liquid phases on the refractory lining. The slag splashing technology allows increasing the resistance of the refractory lining even 5–7 times [7–8]. The efficiency of the slag splashing method depends on a number of factors, i.e. hydrodynamic conditions of slag splashing, appropriate ductility of the nozzles, and the physicochemical properties of slag: viscosity and surface tension, which depend on the presence of modifiers in the slag, which increase the adhesiveness of slag to the lining.

The operation of slag splashing on the refractory lining takes place after casting the steel and slag, but a certain amount is left in the furnace. For increasing the adhesiveness of slag to the refractory materials, an additional quantity of MgO of maximum 12% is introduced along with other additives playing the role of slag modifiers. The addition of MgO increases the viscosity and adhesiveness of slag to the converter's walls, and it also limits the negative impact of FeO, i.e. corrosion. The slag is splashed with the use of a lance. The liquid slag is splashed under the influence of an injected mixture of nitrogen and MgO under a pressure of 1.25 MPa [5, 7]. As a result of splashing, the slag adheres to the worn out lining forming a protective coating 10 mm thick [9].

A schematic of an oxygen converter with slag splashing technology is presented in Figure 1.

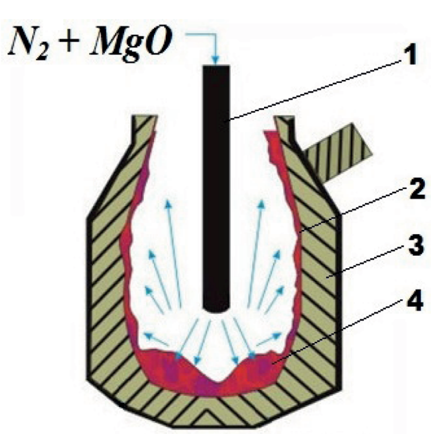

Fig. 1. Schematic of slag splashing in oxygen converter with slag splashing method: 1) lance; 2) slag layer; 3) refractory lining; 4) slag

An example of a lance for injecting the N_2 +MgO mixture is presented in Figure 2 [10].

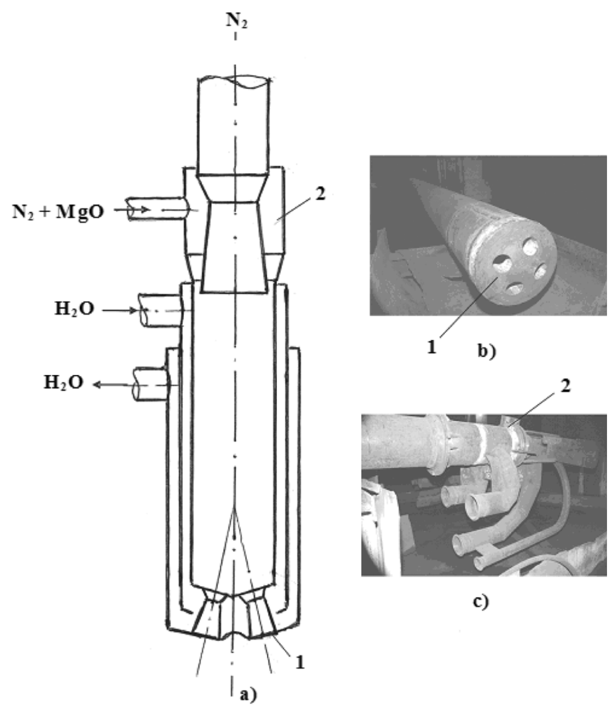

Fig. 2. Water-cooled lance for injecting N_2+MgO mixture [10]: a) schematic of lance; b) nozzle mounting; c) photo of water-cooled lance, 1- de Laval nozzles (4 items), 2 – conduit supplying N_2+MgO mixture

The result of using the slag splashing method is permanent, and hydrodynamic conditions and surface (capillary) phenomena determine the parameters. However, a number of problems related to the technological and design parameters should be solved to provide maximum efficiency of the process:

– The design and type of lance: water-cooled or gas-cooled lance (Fig. 2);
– The construction of the lance – location and number of nozzles;
– The difference of pressure on the nozzle outlet and in the converter volume;
– The assumed mass of air and slag, as well as the jet of injected mixture;
– The increased adhesion of slag to the refractory lining;
– Obtaining a definite viscosity of slag before the splashing and at the moment of splashing to limit the effect of slag flowing down the refractory lining;
– The percentage of MgO added to the slag; and,
– The idle time of oxygen converter.

1. Selected source data for calculations

1) Temperature of gas and powder mixture
   $t_o = 30 – 600°C$
2) Temperature of nitrogen flowing from lance
   $t_1 = 900 – 1600°C$
3) Temperature of gases in converter
   $t_g = 300 – 1500°C$
4) Pressure of gases in converter
   $p_g = 0.1$ MPa
5) Heat capacity of nitrogen
   $c_{p1} = 1.25$ kJ/kg·K
6) Nitrogen consumption by one nozzle
   $V = 96$ m^3/min
7) Nozzle diameter at critical place
   $d_{kr} = 30$ mm
8) Nozzle diameter at outlet
   $d_{wy} = 40$ mm
9) Pressure before nozzle
   $p_1 = 1.8$ MPa

2. Mathematical model

The mathematical model used in the calculations was presented in previous works [4]. The following parameters were used in the model:

Indices of the parameters: *o* – isentropic flow deceleration; *1* – at the nozzle exit, *g* – converter's gas cavity, *x* – in the control section of the jet, *n* – under normal physical conditions.

Added mass was calculated as [4]

$$g = mg/m_1 \tag{1}$$

where

$m_1=\rho_1 w_1 F_1$ – the flow rate through the nozzle [kg/s];
m_g – the mass flow of the acquired gas jet from the cavity of the converter [kg/s];
ρ_1, w, F_1 – density [kg/m^3], speed [m/s] and area of exit section the nozzle [m^2].

Methods of calculating *g* nonisobaric supersonic jet includes a joint solution 8 of equations. More details on this method are presented in [4].

This value is defined as

$$g = \frac{2\bar{r}_{\max}\bar{x}}{D\sigma} C\left(1-C^2\right)^{1/2}\left(I_{1R}-I_{2R}\right) \tag{2}$$

where

C – the number of Crocco = $C = \sqrt{1-\left(1+\frac{k-1}{2}M_i^2\right)^{-1}}$

where

M_i – the number Mach at the boundary of the jet and the surrounding gas,
k – ratio of specific heats.

Coefficient *D* establishes a link between the Mach number M_1 at the nozzle exit and the degree of pressure ratio *n* flowing supersonic jet $D = \left(\frac{k-1}{2}\right)^{1/2} M_1 n^{\frac{k+1}{2k}}$.

Relative to the maximum radius of the first "barrel" nonisobaric jet with shock waves $\bar{r}_{\max}$ was calculated in [5].

In the formula (2), $\bar{x} = x/r_1$ – the distance from the nozzle to the calibre to control section along the axis of the jet;

r_1 – the radius of the nozzle in exit section. The numerical values of the integrals I_{1R} and I_{2R} defined as in [5].

Neglecting speed w_g of ejected gases, for this section, the law of the conservation of energy is in the following form:

$$m_1 c_{p1} T_O + m_g c_{p_g} T_g = \left(m_1+m_g\right) c_{px} T_x + \left(m_1+m_g\right) w_x^2 / 2000 \tag{3}$$

where

T_0 – thermodynamic temperature [K];
c_{p_g} – heat capacity of nitrogen [kJ/kg·K];
w_x – averaged speed in an arbitrary section *x* [m/s].

And, in equation (3) T_x:

$$T_x = c_{p_1} T_1 + \frac{\alpha_1 m_1 w_1^2}{2} + g\, c_{p_g} T_g - \alpha_x \left(1+g\right)\frac{w_x^2}{2} \tag{4}$$

where

α_1 – the ratio of the kinematic energy of the flow;
α_x – the ratio of the kinematic energy of the flow at a distance *x*.

$$w_x = \left[w_1 + \frac{p_g\left(n-1\right)}{\rho_1 w_1}\right]\frac{1}{\left(1+g\right)\beta} \tag{5}$$

where

β – flow turbulence coefficient (about 1.03).

It is assumed that the specific heat c_{pg} depends on temperatures T_g and T_o. In view of the apparent mass *g*, the average heat capacity of gas jet is

$$c_{px} = \sum c_i g_i = c_{p_1} g + c_{p_g} g_g \tag{6}$$

$$c_{p_g} = c_{p_{N_2}} = \frac{k}{k-1} R_{N_2} \tag{7}$$

Under the power $N_{X,}$ we can understand the kinetic energy of the jet, which is determined by the following formula:

$$N_x = V_n \rho_n \left(1 + g\right) w_x^2 / 2000 \qquad (8)$$

Power N_x can be expressed through the assumed mass adopts g and the degree of pressure ratio n. Therefore, knowing the diameter of the nozzle in critical d_{kr} and the exit section d_1 determined by gas-dynamic function flow $q(\lambda_1) = d^2_{kr} / d^2_1$, and in table by $q(\lambda_1)$ found gas-dynamic pressure function $\pi(\lambda_1) = p_1 / p_{op}$, the design pressure before the nozzle (when $p_1 = p_g$) is $p_{op} = p_g / \pi (\lambda_1)$. As the actual pressure p_o' upstream of the nozzle is known, and the non-isobaric degree will equal to $n = p_1 / p_g$.

3. Results of calculations

The results of computer simulations are presented in Figures 3–5. The analysis of Figure 3 reveals that heating of nitrogen prior to disposing it in the nozzle of the lance causes a considerable increase in average speed w_x. For instance, heating of nitrogen before the nozzle t_0 from 25°C to 600°C, a tan increment $\overline{x}$ to 30, allows for increasing the jet flow rate w_x from 180 *m/s* to 380 *m/s*. The calculations showed that the transformation of a lance into an efficient heat exchanger allows increasing the power of the jet N_x even 4–5 times, when introducing the mixture to the liquid slag.

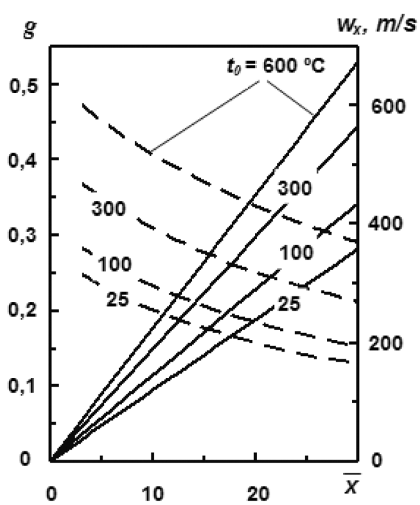

Fig. 3. The influence of heating temperature of nitrogen t_0 and length of nozzle x on assumed jet mass g (—) averaged speed in an arbitrary section x w_x (---)

The preheating of nitrogen in the lance results in introducing a smaller density jet ρ_g to the converter, and the assumed mass participation of g in the cross-section $\overline{x}$ = 30 increases from 0.13 (t_0 = 25°C) to 0.28 (t_0 = 600°C).

The influence of relative temperature Θ can be determined with the following dependence:

$$\Theta = t_g / t_0 \qquad (9)$$

where
t_g – the temperature in converter's gas cavity [°C];
t_0 – the temperature in isentropic flow deceleration [°C].

This parameter has an influence on the assumed mass g and relative velocity w_x/w_1.

The analysis of Figure 4 reveals that g increases over distance x for each Θ. For instance, if Θ = 4, then the assumed mass g increases from 0 (cross-section of nozzle) to 0.29 for $\overline{x}$ = 30, and the relative velocity w_x/w_1 decreases from 0.7 to 0.56. For x = 30, the increase of Θ from 1 to 7 leads to the decreasing of g from 0.69 to 0.19, and the relative velocity w_x/w_1 decreases from 0.6 to 0.45. This is caused by the fact that, with the drop of Θ, e.g., from 7 to 1, the gas temperature in the converter t_g considerably lowers. Jetting nitrogen into the converter, where the gaseous atmosphere has a lower density than the density of nitrogen supplied by the lance, results in a drop of jet velocity w_x, while the velocity of the output w_1 remains stable.

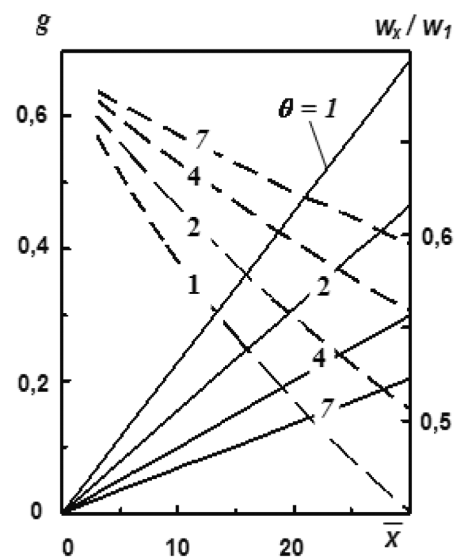

Fig. 4. The influence of relative temperature Θ on assumed mass g (—) and relative velocity w_x/w_1 (---) at distance x

The most interesting results of numerical calculations were obtained for variable power N_x at a different distance from the nozzle cross-section $\overline{x}$. For instance, when the converter is being cooled (Fig. 5), the jet power N_x decreases over distance x for each gas temperature t_g in the converter. This is caused by the fact that, further from the nozzle cross-section, there is more the gaseous atmosphere near the converter lowers velocity w_x, and jet power N_x. For instance, if t_g = 900°C, then N_x decreases from 520 kW (for x = 0, nozzle cross-section), to 375 kW (for $x = 30$). Another example, at a distance $x = 30$ the temperature drop t_g in a converter from 1500°C to 300°C leads to a decrease of power N_X from 417 kW to 305 kW. Modelling of the gas jet and the results of computer calculations revealed that flow rate and temperature of gas at the nozzle outlet increase with the increase of gas temperature in the converter.

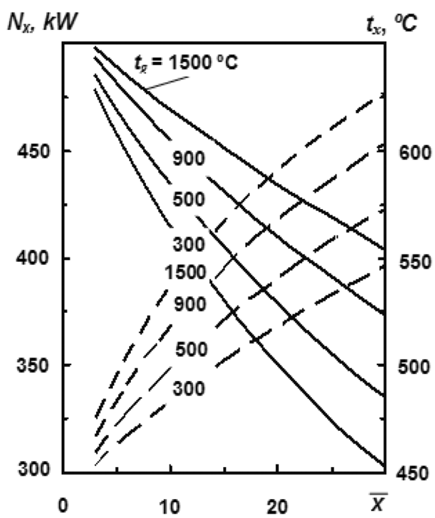

Fig. 5. Dependence of power N_x (—) and temperature t_x (---) of jet on converter gas temperature t_g at various distances from nozzle x

4. Adequacy of model

For the sake of verifying the correctness of the performed numerical calculations, a verification method was used. If we assume $x = 0$ (cross-section of the nozzle), the assumed mass participation $g = 0$ for each t_0 (Fig. 3) and each Θ (Fig. 4) is correct. If $x = 0$ (cross section of nozzle), then $N_x = N_1$ and is maximum, and it obviously does not depend on the volume of converter. The verification of model calculations with experimental results from a steel converter can be hard to realize. Therefore, computer simulation methods are associated with the results of laser measurements of refractory lining wearing.

The major shortcoming of the presented model and numerical calculations lies in the fact that they do not account for the influence of physicochemical properties of slag, i.e. chemical composition, basicity, viscosity, and surface tension. Another equally important factor to be considered is the drop of temperature of slag in the converter, and the resulting higher share of solid phase in slag, and consequently, the change of the physicochemical parameters of slag. This signifies that the drop of temperature results in higher viscosity, which will lead to the lower adhesiveness of slag and MgO mixture to the refractory lining in certain temperature conditions [5].

The calculation of the impact of chemical composition and temperature on the viscosity of converter slag used in the slag splashing method was already presented by authors in their previous publications [5, 12]. For the sake of increasing the efficiency of slag operation and adhesion to the refractory lining, the MgO participation in slag should be increased from original 6–7% to about 12–14%. The authors determined the temperature needed for obtaining the required slag parameters [5, 11–12] on the basis of calculations in mathematical models and commercial calculation program FACTSage employing the viscosity module for determining the viscosity of arbitrary oxide compounds. It was observed that a stable temperature of the process should be provided to obtain the slag in a liquid form. Model calculations revealed that slag in a liquid form can be obtained for the applied typical systems in the slag splashing method when the temperature is maintained at a level of 1400–1500°C.

Conclusions

1. Increasing the efficiency of slag operation and adhesion to the refractory lining requires a higher participation of MgO in slag from the original 6–7% to 12–14%.
2. Numerical modelling of the gas jet revealed that, with a growth of gas temperature in the converter, the flow rate and temperature of gas at the nozzle outlet also increase.
3. The increase of temperature and the relating growth of pressure after the nozzle outlet over the distance x lead to the reduction of the assumed mass of the surrounding gas and an increase of the flow rate.
4. Prior to injecting to the nozzle, the nitrogen should be heated. If the lance acts like a heat exchanger, then the impulse of the jet increases about 1.5–2 times and the power increases 2–3 times, causing the gas and MgO mixture to melt the slag upon entering it.
5. The applied water-cooled lance leads to the recuperation of heat, because the temperature of nitrogen + MgO mixture increases, and the kinetic energy of the outflowing mixture in the converter increases about 3.5 times as compared with water-cooled option. As a consequence, this leads to the splashing of slag at a bigger height as compared to the previous case.
6. A definite temperature of the process should be maintained to provide slag in a liquid form. Model calculations revealed that the temperature in which slag has a liquid form should be maintained on a level of 1400–1500°C.
7. All analyses performed in this work were aimed at solving these and other problems and can be implemented in industrial practice.

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