POWER INCREASE OF SUPersonic JETS IN OXYGEN CONVERTER

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Numerical studies targeted to increasing power supersonic jets in oxygen converter during slag splashing process have been presented in this paper. The calculations are based on a special design of the gas-cooled lance, in which the structure was simplified, as compared with a water-cooled lance. Importantly, the sprayed slag with nitrogen and magnesium-containing (MgO) powder were used in the study. The maximum heating temperature in lance nitrogen was equal to 493 °C. The work was preceded by laboratory studies conducted for converter slag received in one of the European plants. The analysis of the computation results shows that the cooling of the lance with gas leads to the heat recuperation, which increases the temperature of the injected mixture, so that 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.

1 Introduction

Higher resistance of refractory lining of oxygen converters considerably limits the environmental effect of steel making technology by reducing dust emissions accompanied by the piling of waste refractory material after fixing furnace lining. For instance, in Mariupol, Ukraine there are two biggest metallurgical plants in that part of Europe, which evidently have a negative influence on the ecological situation there. Only in 2013 282,000 Mg gaseous pollutions were emitted to the atmosphere, which is about 0.6 Mg per citizen [1]. A considerable part of post-production waste consisted of slag from metallurgical technological processes and waste refractory lining. These are integral elements of the steel production process and cannot be eliminated. Over the last 100 years a few waste disposal sites were established in the vicinity of Mariupol where millions of slag and used refractory lining were discharged. The present environmentally-friendly policy obliges steel producers to stop degrading the environment and limit the amount of produced and deposited metallurgical waste. According to the present waste management trends, the closed circuit waste management models are recommended [2].

The slag splashing method applied after the liquid steel melting in an oxygen converter to generate a protective layer in the refractory lining of the converter is a radical way of saving resources and efficient way of limiting environmental emissions. With this technology the resistance of the refractory lining can be increased 5-10 times. The amount of generated waste can be reduced by
almost the same order. However the practical implementation of this technology in the steel works requires certain investments aided by simulations of the slag splashing process with informatic tools. The interaction of high power (~4 MW) jets with liquid slag has been preliminarily modeled by various authors [3,6]. Erosion of refractory lining is caused by chemical corrosion due to its contact with liquid metal bath and slag. Another impact is on the part of mechanical damage done while loading metal waste. The cracks and microcracks facilitate penetration of liquid metal bath into the pores, which additionally deteriorates the situation. A powdered MgO is added to increase the adhesiveness of slag to the refractory lining, and protect against the corrosive activity under the influence of FeO, which is the main component of slag. Of course, more complex forms of Ca$_2$SiO$_4$, CaSiO$_3$, FeSiO$_3$, Fe$_2$SiO$_4$, Ca$_2$Si$_2$O$_6$ and Ca$_4$Si$_2$O$_8$ may occur and the presence of MgO favors the formation of complex silicates: CaO·MgO·SiO$_2$ (monticellite), 2CaO·SiO$_2$ (dicalcium orthosilicate). After insufflating MgO to slag, its alkalinity increases and consequently the silicate structures are disrupted. Therefore, for increasing the efficiency of the slag splashing method, 10-13% MgO is introduced in the form of baked or melted or powdered materials; for blowing – powdered materials are used. This type of additive comes from refractory materials post-production or used refractory materials [7-9]. Only few scientific works point to the existence of important premises for the realization of research and experiments in this subject. The slag splashing technology can be improved by increasing the power of media jets flowing out of the lance and decreasing dissipative processes in dispersed jets directed on liquid slag. The efficiency of the slag splashing method can be significantly improved if the nitrogen + MgO powder mixture is preheated before being administered to the nozzles. In this solution the design of lance will be modified into a heat exchanger, where the heat carrier, i.e. N$_2$+MgO recuperates heat. In this way the heat which was previously lost through the converter’s gas outlets to the atmosphere as a thermal pollution, can be partly utilized. Mariupol with its catastrophic environmental conditions needs more than any other European city new technological solutions for its two biggest steel works in Ukraine. Liquidation of plants generating contaminations control of waste and industrial emission – these and many other environmental recommendations, are strictly regulated by the Kyoto protocol [7]. Meeting these guidelines is possible by working out ‘clean technologies’ and closed circuit waste management technologies. Among such activities are, among others, supersonic slag splashing with single or two-phase jets. It is conditioned by the lance nozzle size and may total up to 4 MW. The principle of this technology is that a 7 – 12 mm protective layer is introduced on the refractory lining of an oxygen converter so the melting process takes place in this layer. In this process the modified converter slag is given high-energy nitrogen jets or MgO enriched nitrogen through the lance. The total power of jets ejected from the nozzle to the converter (350 Mg) with the slag splashing method, totals to a few MW. If this energy is correctly used, the durability of the lining can be increased several times [5-6].

2 Mathematical model
The calculations were based on a mathematical model already presented in [3,5], where $o$ – isentropic flow deceleration; $l$ – nozzle exit, $g$ – converter's gas cavity, $x$ – control section of the jet, $n$ – normal physical conditions.

The added mass was calculated with formula [3]

$$ g = m_g / m_i, $$

where:

$m_i$ = $\rho_i \cdot w_i \cdot F_i$ – mass consumption by each of 5 nozzles [kg/s];
$m_g$ – mass consumption to be obtained by supersonic jet after leaving the nozzle [kg/s];
$\rho_i, w, F_i$ – density [kg/m$^3$], speed [m/s] and area of exit section in the nozzle [m$^2$].
Authors [5] describe in detail the method of calculating the supersonic jet making use of 12 mathematical equations. In [5] parameter \( g \) was described with

\[
g = \frac{2\bar{r}_{\text{max}} x}{D_{x}} C_{i} \left( 1 - C_{i}^{2} \right)^{1/2} \left( I_{1R} - I_{2R} \right)
\]

(2)

where:

\( C_{i} \) – the number of Crocco = \( C_{i} = \sqrt{1 - \left( 1 + \frac{k-1}{2} M_{i}^{2} \right)^{-1}} \)

\( \sigma \) – similarity parameter characterizing level of jet turbulence.

\( \Sigma = 12 + 2.58 M_{i} \),

and:

\( M_{i} \) – Mach number,

\( k \) – parameter characterizing thermal capacities.

\( D \) – coefficient, on the basis of which the dependence between \( M_{i} \) and \( n \) can be established

\( \bar{r}_{\text{max}} \) – radius of the first bubble in supersonic jet [3,5].

In equation (2) and in the calculation results \( x = l / r_{i} \) – length of jet for which calculations were performed to entry nozzle diameter ratio;

The \( I_{1R} \) and \( I_{2R} \) values calculated for the conditions of cool jet \( (t_{o} = 30^\circ C) \) and hot gas \( (t_{g} = 1500^\circ C) \) are presented in [5].

If speed of ejected gases \( w_{g} \) is neglected, the energy conservation law can have the form:

\[
m_{1} c_{p_{1}} T_{0} + m_{g} c_{p_{g}} T_{g} = (m_{1} + m_{g}) c_{p_{x}} T_{x} + (m_{1} + m_{g}) w_{x}^{2} / 2 \times 10^{3},
\]

(3)

where:

\( T_{0} \) – thermodynamic temperature [K]; \( c_{p} \) – isobaric thermal capacity [J/K]; \( w \) – averaged flow rate [m/s].

Hence, temperature along distance \( x \):

\[
T_{x} = c_{p_{1}} T_{1} + \frac{a_{1} m_{1} w_{1}^{2}}{2} + g c_{p_{x}} T_{g} - a_{x} (1 + g) \frac{w_{x}^{2}}{2}
\]

(4)

where:

\( d_{j} \) – the diameter of the nozzle the exit section [mm].

\[
w_{X} = \frac{\dot{E}}{\dot{Q} v_{j}} + \frac{p_{g} (n - 1) \dot{m}}{r_{i} w_{i}} \frac{1}{1 + \frac{1}{1 + g} b}
\]

(5)

Thermal capacity \( c_{pg} \) will depend on temperatures \( T_{g} \) and \( T_{o} \).

\[
c_{p_{x}} = \int c_{1} g_{1} = c_{p_{g}} + c_{p_{g}} g_{g}
\]

(6)

\[
c_{p_{x}} = c_{p_{g_{2}}} = \frac{k}{k-1} R_{N_{j}}
\]

(7)
\( N_X \) – kinematic energy of supersonic jet, which can be calculated with:

\[
N_X = V_n r_n (1 + g) w_n^2 / 2 \times 10^3
\]  

(8)

3 Results and discussions

Authors of this paper modeled the process of jetting a medium to the liquid slag. This issue was investigated on the basis of a system of differential and algebraic equations of motion and heat exchange in a gas-powder flow, in a definite cross-section (at a given distance) and analysis of impact of the effect of carrier gas heating on the power of the gas/powder jet flowing into liquid slag of the oxygen converter.

The most interesting results of numerical calculations were obtained for variable MgO powder content \( \mu \). Computer simulation (figure 1) showed that the powder additive significantly affects the efficiency of the slag splashing process. For instance, for the jet length \( x = 20 \), \( \mu = 0.2 \), the gas temperature in the converter was 455°C, and power of supersonic jet 359 kW. With the increase of \( \mu \) to 1, gas temperature in the converter and jet power increase to 555°C and 445 kW, respectively.

![Figure 1](image)

**Figure 1.** The influence of different concentration refractory powder on the temperature (––) and power supersonic jet (—) at various distances from nozzle \( x \).  

The plot in figure 2 shows that, with the increase MgO powder content \( \mu \), the added mass insignificantly increases, whereas relative power, i.e. ratio of jet power at a distance \( x \) to jet power on the nozzle inlet \( (N_\text{n}/N_\text{x}) \) considerably lowers. At a distance \( x = 20 \), for MgO powder content \( \mu = 0.2 \), the added mass amounted to 0.18 and relative power to 0.61. At the same distance, with increasing \( \mu = 1 \), the added mass increases to 0.2, whereas relative power decreases to 0.36.
Dependence added mass (—) in cavity oxygen converter and different concentration refractory powder (––) on relative power at distance $x$.

4 Conclusions

1. Heating of nitrogen in the lance prior to introducing it to the supersonic nozzles and increasing gas temperature in the converter lead to a significant increase of power of supersonic jet when splashing slag in the oxygen converter. For increasing 2-3 times the jet power from the lance and increasing the efficiency of the slag splashing process, the lance has to be gas-cooled, with the possible heating of nitrogen or its mixture with MgO to at least 400°C.

2. Adhesion of the slag layer for the refractory lining significantly improves when a strictly defined chemical composition of slag is provided, as it guarantees obtaining given viscosity and formation of low- and high-melting phases. This can be achieved when the participation of MgO in the splashed slag is on a level of 10-13% [7].

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