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Problem solving with modeling support: evaluation with a numerical fluid dynamic model of the different configurations of the slag-cutting deflector for oxygen jet lance tips in the BOF

D. Ressegotti, A. Dell'Uomo, A. Cristallini, M. De Santis, E. Cassone, D. Esposito

In the primary steel production, hot metal produced in the blast furnace (BF) is fed via a ladle to the Basic Oxygen Furnace (BOF), where it is converted to liquid steel. During the metallurgical operations, slag can form and solidify on the refractory walls during tapping. These oxide deposits must be periodically removed, to ensure the regularity of BOF operations over time. Cleaning operations slow the process, as they require dedicated plant operations. For this reason, a collaboration between RINA-CSM and ADI was set up to find a solution to shorten the BOF "cleaning times", by managing the injected o8xygen flow.

The investigated solution (slag-cutting baffle) is based on two countermeasures: an operational one, jet "upstream" flow management, and one "downstream", thanks to an appropriately designed baffle, adaptable to the heads of the oxygen lances, to properly guide the jet. To comply with the required effects without impacting on internal lining safety, the oxygen jet blown must meet certain requirements. First, it must be oriented and concentrated within a "blade" shape, for a "compact" stream. Furthermore, the jet in the BOF must be fast enough to provide for slag melting, but without local velocity "hot spots", harmful to internal lining integrity. Therefore, different configurations were designed for the deflecting system (walls, slits), based on the geometric characteristics of the oxygen lances tips.

The study presented hereinafter shows the approach to the problem, the configurations designed, the evaluation criteria of the expected performance, and the results of the computational fluid dynamics (CFD) simulations carried out to verify jet performance. This study made it possible to identify critical issues in the initial configurations, and then to fix them, with solutions considered reliable and industrially applied.

KEYWORDS: STEEL; CONVERTER; CFD; MODELLING; NOZZLES; LANCES; METALLURGY;

FOREWORD

In primary route steel production, hot metal produced in the blast furnace is charged into the Basic Oxygen Furnace (BOF), where it is refined into liquid steel. During BOF operation, slag is formed and progressively solidifies on the refractory lining in the BOF upper cone section, leading to the well-known skulling formation. These deposits, typically rich in iron oxides, must be periodically removed to ensure safe and efficient furnace operation. Conventional de-skulling practices are mainly mechanical and require dedicated procedures and extended furnace downtime, which can last several hours and significantly affect plant productivity [1-3].

Davide Ressegotti
RINA Consulting, Centro Sviluppo Materiali S.p.A, Dalmine, Italy

Alessandro Dell'Uomo,
Alessandro Cristallini, Michele De Santis
RINA Consulting, Centro Sviluppo Materiali S.p.A, Rome, Italy

Egidio Cassone, Domenico Esposito
Acciaierie d'Italia S.p.A. in A.S., Italy

Skulling formation and adhesion are influenced by local thermal conditions, slag composition and process parameters. For this reason, increasing attention has been devoted to operational strategies aimed at mitigating slag build-up without negatively impacting the efficiency of converter operations. Among these, to remove skull by means of oxygen blowing directed onto the affected refractory walls zone represents a practical solution. Indeed, as oxygen blowing directly affects both thermal conditions and local flow dynamics near the refractory walls. So, the lance jet management is a key factor to ensure the success of this countermeasure. In this context, the post-combustion technique has gained increasing interest also for skull mitigation. However, drawbacks like increased refractory wear or reduced lance lifetime are also reported [4, 5]. In order to reduce idle times to restore the furnace and in order to avoid huge plant modifications, a different approach, i.e. an oxygen deflector, is here presented.

Therefore, the present study applies CFD simulations to evaluate different configurations of the oxygen jet deflector, assessing their impact on jet homogeneity, velocity distribution and wall impingement characteristics. The numerical results are used to identify critical design features and to support geometry optimization, with validation provided through comparison with industrial observations. This integrated numerical-industrial approach aims to bridge the gap between modeling and practical applications, offering a reliable methodology for the design of oxygen jet management solutions for BOF de-skulling operations.

PROBLEM AND APPROACH

In primary steel production, steel conversion occurs in the Basic Oxygen Furnace (BOF). During the metallurgical operations, slag forms and solidifies on the upper cone inner refractory walls, requiring periodic material removal and in turn affecting productivity.

To eliminate slag deposits on the converter, the technical solution identified at ADI steelworks, considering the existing plant layout, was to install a deflector, hooked with tie rods, and placed downstream with respect to the lance tip, to deflect the O_2 jet onto the walls. The idea called for a suitable deflection system design to manage the flow from the lance, promoting slag melting and removal through oxygen-assisted action, while maintaining a homogeneous flow distribution and preserving lining safety.

The next step consisted of checking the reliability of different deflectors' geometry and positions to identify the most efficient configuration for the purpose. The activity was developed within a collaboration between RINA-CSM and Acciaierie d'Italia and was based on CFD (Computational Fluid Dynamics) simulations by RINA-CSM, with vast expertise in the matter (e.g., [1]). In particular, the CFD approach relies on the description of the behavior of supersonic oxygen jets in BOF steelmaking. This issue has been extensively investigated in the literature, with particular emphasis on jet coherence, penetration depth and momentum transfer as a function of lance height, nozzle geometry and operating pressure [6, 7]. Nowadays, CFD represents a consolidated tool for analyzing oxygen jet behavior, enabling detailed characterization of velocity fields, jet interactions and impingement patterns. CFD-based approaches have proven effective in supporting lance design and operational optimization, reducing the need for costly trial-and-error plant testing [8-10].

However, most existing studies focus on upstream jet generation and lance tip geometry, while comparatively limited attention has been paid to downstream flow manipulation solutions. Only a few contributions address auxiliary or geometric devices designed to modify jet direction or energy distribution after its formation, and these are generally not conceived for de-skulling purposes [11, 12]. In particular, systematic CFD-based evaluations of dedicated jet-deflecting systems aimed at achieving effective slag removal while avoiding localized velocity hot spots that could compromise refractory lining integrity remain scarcely documented in open literature.

The CFD code used for this study is ANSYS Fluent (version 2023-R2) to solve conservation of mass, momentum and energy equations. Turbulence is described via SST-kω with compressibility effects and curvature correction. Energy equation is activated, and an ideal gas is used to model the compressibility of the O_2 gas. A flow rate of 200 Nm^3/min was imposed, (as "mass flow inlet") under oper-

ating conditions of 1600°C surrounding temperature. The domain represented is long 2,5 m and meshed with about 2,5 million of cells (prismatic layer on the lance walls and polyhedral core mesh).
Under the mentioned conditions, the different layout options were the only options for the different cases simulated.

A schematic of the system lance-deflector is shown in figure 1. The plate below the lance is drilled centrally to reduce the mechanical load on the plate for stability. The proposed deflector is mechanically connected to the oxygen lance head and incorporates slit based outlets and guiding walls. Its purpose is to transform the primary jet into a thin, blade like flow capable of:

- distributing the jet over a nearly 360° pattern;
- maintaining adequate kinetic energy for slag removal;
- avoiding localized high velocity zones that risk damaging the refractory lining.

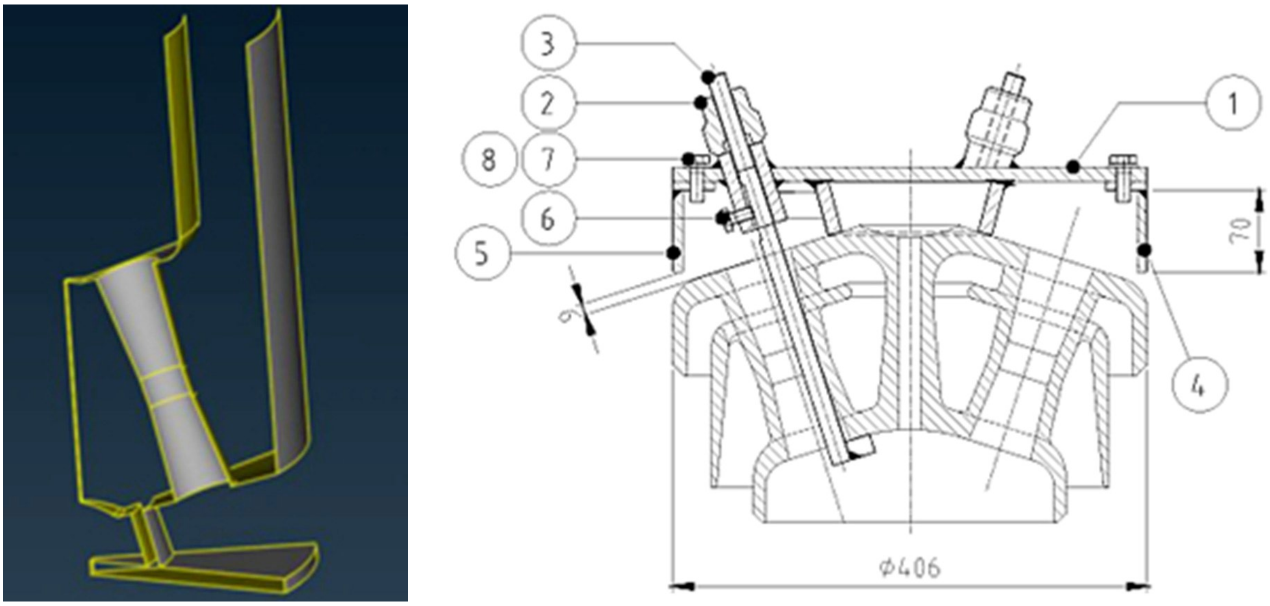


Fig.1 - Schematic of the lance deflector system (left) and geometry of the lance tip (right).

The purposes of the new configurations were, on the one hand, to make uniform the jet over 360° in the lance-walls space, on the other hand to let the distributed flow have kinetic energy enough to perform the desired removal action.

RESULTS

CFD simulations indicate that the reference geometry produces a compact and strongly directional jet, with limited lateral dispersion. Modified configurations yielded varying degrees of jet widening, upward deviation, and interaction with leakage streams.
An example of a velocity field from the lance is shown in figure 2, for a reference configuration (top-left) and several modified ones (top-right and bottom row). The results of the fluid velocity analyses are com-prehensively shown in figure 3, showing the configurations tested and the related flow field on a plane at 2500 mm from the center of the head.
Some configurations exhibited strong interference between the primary jet and leakage flows exiting secondary slits. These interactions resulted in non-uniform circumferential velocity distributions and undesired vertical deviations. The velocity field is not perfectly uniform, since the jets can have mutual interactions, thus the velocity can locally increase and decrease, see figure 4, showing the nozzle position in correspondence with velocity peaks on the 2500 mm-distance plane.

Part of the design was aimed at reducing such inhomogeneity. In other cases, the jet is deflected upwards. In short:

- from configuration 0 (reference), highly sectorial flow and poor uniformity results;
- for configuration 1-2, improved circumferential distribution but still local peaks;
- for configuration 3, strong upward deviation because of main-secondary flow interaction;
- for configuration 4-5, with geometry adjustments, improved flow uniformity result show non uniformities;
- for configuration 5, the best overall uniformity and acceptable peak velocities are achieved.

Overall, a comparison between nozzle positions and velocity peaks indicates that non uniformities can often be traced to geometric asymmetries or unintended leakage paths.

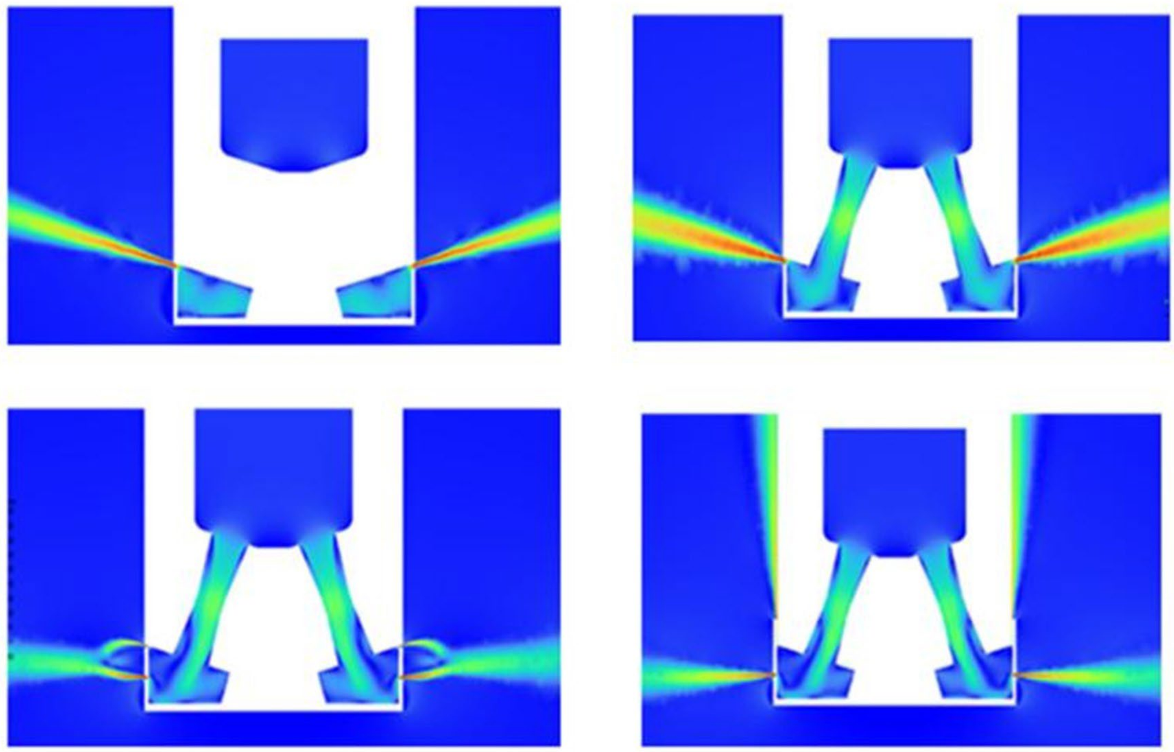


Fig.2 - Velocity field from the lance for a reference configuration (top) and a modified one (bottom).

The simulations highlight that even small leakage flows can substantially distort the final jet pattern. Man-aging these interactions through careful control of slit geometry, wall inclination, and deflector thickness is essential to achieving a homogeneous circumferential field.

The improvements observed in configuration 5 demonstrate that downstream jet manipulation can be effectively engineered without compromising jet coherence or refractory safety. This supports the value of CFD guided design for BOF oxygen lance accessories.

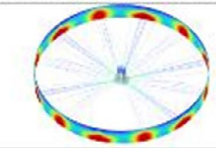
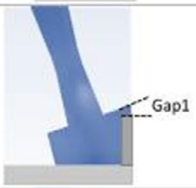
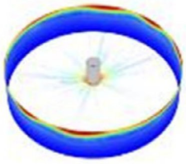
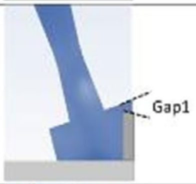
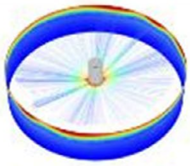
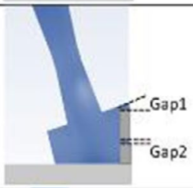
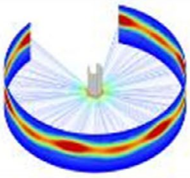
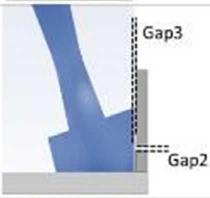
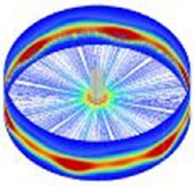
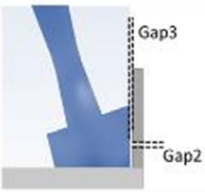
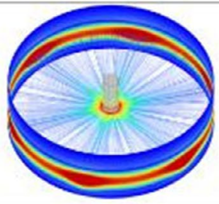
		Description	0 3 6 9 12 15 18 21 24 27 30 ***Velocity* Contour [m/s] @ plane at 2500mm distance**
Config. 0		**No walls**	
Config. 1		**Gap1**: 6mm	
Config. 2		**Gap1**: 6mm **Divergent-vertical wall**	
Config. 3		**Gap1**: 6mm **Gap2**: 6mm	
Config. 4		**Gap2**: 6mm **Gap3**:1.5mm	
Config. 5		**Gap2**: 4mm **Gap3**:1.5mm	

Fig.3 - Overview of the configurations identified for the CFD simulations and velocity field along the reference wall.

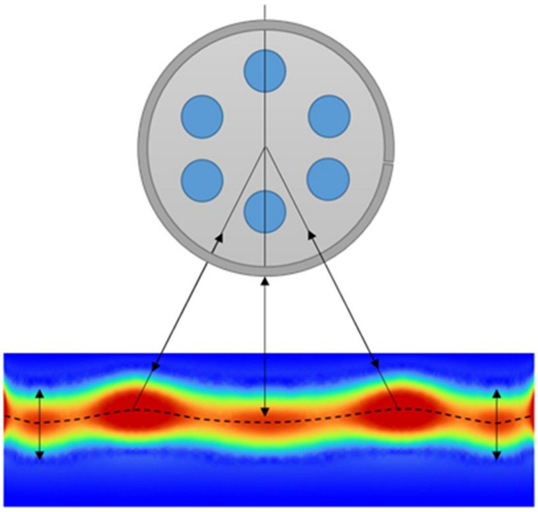


Fig.4 - Nozzle position correspondence with velocity peaks on the 2500 mm-distance plane.

Configuration 5 was tested successfully on-field, with:

- proper jet redirection toward slag impact regions;
- stable flow behaviour without lining over erosion;
- reduced cleaning time (qualitative);
- consistent performance across multiple heats.

To the scope, a comparison between the predicted flow-field and its effects during the industrial test is shown in figure 5 and an impressive matching can be noticed, showing the reliability of the solution pro-posed.

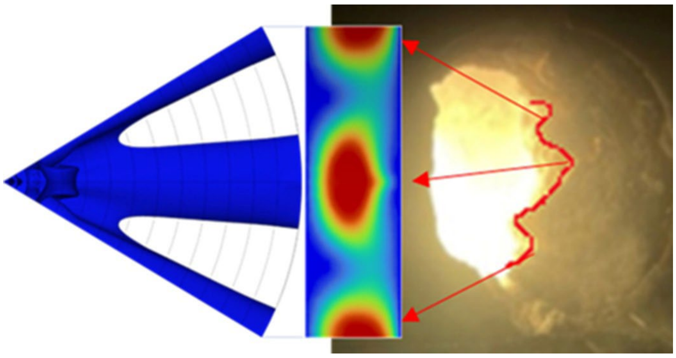


Fig.5 - Comparison between predicted flow field from CFD and image from industrial testing.

CONCLUSIONS

A collaboration between RINA-CSM and Acciaierie d'Italia S.p.A. in A.S. allowed this project to achieve a successful problem-solving action based on a strong synergy between operational insights and modelling tools. In particular, a downstream deflector system was designed to improve BOF slag removal by redistributing the oxygen jet over the converter walls. The CFD simulations identified key flow interactions affecting jet uniformity and guided the geometry optimisation, and the final configuration achieved near-uniform circumferential distribution the BOF wall without harmful velocity peaks.

Plant validation confirmed the reliability and operational benefits of the optimized deflector.

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