

Numerical simulation of the jet characteristics of a six-hole dual-Mach-number oxygen lance for a 120 t converter

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Abstract

To further address the practical issues of enhancing steelmaking efficiency, improving the slag melting rate, and reducing molten steel splashing in Chinese steel enterprises, this study proposed a six-hole dual-Mach-number oxygen lance (DMNOL) nozzle and investigated the effect of the dual-Mach-number design on the jet characteristics of the oxygen lance through numerical simulation. The results show that, compared with the original enterprise nozzle ($Ma = 2.0$), the coalescence distance of the DMNOL jet was significantly increased, effectively delaying jet velocity decay. The optimal dual-Mach-number nozzle was the one with $Ma = 2.0$ and 2.05 . Compared with the original enterprise nozzle, the optimal dual-Mach-number nozzle exhibited an 11.06% increase in the supersonic region length of the jet and a 36.22% extension in the jet coalescence distance. At the optimal steelmaking lance height of 1.2 m, the optimal nozzle achieved a 9.26% increase in the effective impact area and an approximately 3.23% decrease in impact depth, improving steelmaking efficiency while reducing molten steel splashing. At the optimal slag melting lance height of 1.8 m, the optimal nozzle achieved a 33.33% increase in the slag melting impact area and a 3.69% increase in impact depth, enhancing the slag melting rate while promoting bath stirring.

Keywords: Dual-Mach-number oxygen lance; impact area; impact depth; converter steelmaking; numerical simulation

1. Introduction

As a core process in modern steel production, converter steelmaking directly determines molten steel quality and production cost through its production efficiency, energy consumption, and endpoint control [1,2]. As a key piece of equipment in converter steelmaking, the oxygen lance has nozzle structural parameters that directly affect oxygen jet characteristics and smelting performance [3,4]. However, under high oxygen supply intensities, conventional oxygen lance designs often face challenges such as the difficulty in balancing impact depth with impact area, severe splashing, and low energy efficiency [5-8]. Nozzle structure innovation has therefore become one of the key factors restricting the high-quality development of converter steelmaking.

In recent years, to accommodate the development trend of green and efficient steelmaking, innovative structural design and process optimization of oxygen lances remain a research hotspot in the field of converter steelmaking. In terms of oxygen lance structure optimization, researchers have made progress in conventional oxygen lances [9], swirling oxygen lances [10], single-flow post-combustion oxygen lances [11], and dual-Mach-number oxygen lances (DMNOLs) [12]. Chen et al. [12] developed a six-hole staggered DMNOL and investigated, through numerical simulation, the effects of variable-pressure operation and oxygen lance structural parameters on jet flow morphology and the bath impact region. The results show that

under a high-pressure condition of 0.9 MPa, the supersonic length increases, and the bath impact depth and stirring kinetic energy are also significantly enhanced. Wang et al. [13] designed and optimized the structure of a conventional oxygen lance. The research results indicate that the gas velocity of the new oxygen lance with a central hole is significantly higher than that of the conventional oxygen lance. Zhang et al. [14] employed numerical simulation to verify the feasibility of a swirling oxygen lance in the slag splashing process. Liu, Zheng, and their colleagues [15,16] investigated the jet characteristics of a single-flow post-combustion oxygen lance and a conventional oxygen lance using numerical simulation. The results show that the post-combustion oxygen lance achieves higher molten steel velocity, a smaller dead zone area, and a larger impact area. Liu et al. [17] combined a swirling structure with post-combustion oxygen lance technology, enhancing jet momentum transfer and expanding the impact area by increasing the secondary nozzle radius. Jia et al. [18] designed a staggered dual-structure six-hole oxygen lance to improve the stirring ability of the jet on the molten bath. In terms of steelmaking process optimization, metallurgical researchers have conducted studies on oxygen lance height [19], oxygen flow rate [20], operating pressure [21], stagnation temperature [22-24], and mixed injection [25,26]. Wei et al. [26] investigated the effect of CO₂ mixing on the jet characteristics of a four-hole oxygen lance. The results show that the combustion flame is mainly distributed in the region between the multiple jets, and the high-temperature flame significantly influences the low-velocity regions of the jets. Yang et al. [27] found through numerical simulation that as the top-blown oxygen lance height decreases, the splashing density and splashing area ratio first increase and then decrease. Wang Xi et al. [28] discovered through physical experiments that the operating height of a swirling oxygen lance has a greater effect on cavity shape than the oxygen flow rate. Zhuang et al. [29] employed numerical simulation to reveal the effects of oxygen lance parameters on the temperature field, flow field, and scrap preheating temperature in a converter. The results indicate that oxygen lance position and nozzle angle significantly influence the temperature field and the average temperature of the scrap.

Despite the optimized designs of the novel central-hole oxygen lance and the staggered DMNOL mentioned in the above studies, the increase in the jet impact area of the central-hole oxygen lance is limited by its flow ratio and inclination angle, with the effective impact area being improved by only 7.6% at most [30,31]. Moreover, current research on the staggered DMNOL remains focused on the orifice flow ratio, inclination angle, and operating pressure, aiming to enhance the jet impact area by increasing the operating pressure and total flow rate [12,32]. However, the influence law of the dual-Mach-number nozzle on the jet characteristics and the optimal matching scheme of the dual-Mach-number have not yet been clarified under the premise of controlling the total flow rate and operating pressure. In this study, a six-hole staggered DMNOL nozzle was designed for a 120 t converter. Numerical simulation was employed to investigate the jet coalescence, velocity decay, impact area, and impact depth of the six-hole DMNOL, aiming to provide a theoretical reference for the practical application of the six-hole staggered DMNOL nozzle.

2. Model Establishment

2.1 Governing Equations

Numerical calculations of the oxygen jet were performed using ANSYS Fluent software. To establish model equations accurately describing the jet motion, oxygen was assumed to be

an ideal gas, the flow was modeled as three-dimensional, steady-state, compressible, and non-isothermal, and the nozzle inner wall was considered smooth and frictionless. The mathematical model comprised the mass equation, momentum equation, and energy equation, expressed as Equations (1) to (5).

The mass balance equation is expressed as follows:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad (1)$$

In the expression, ρ represents the fluid density, kg/m³; u_i denotes the velocity in the i -direction, m/s.

The momentum equation is expressed as follows:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial(\tau_{ij} - \rho \overline{u_i u_j})}{\partial x_j} \quad (2)$$

$$-\rho \overline{u_i u_j} = \mu_t \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k} \right) \delta_{ij} \quad (3)$$

In the expression, u_j and u_k represent the velocities in the j and k directions, m/s; p denotes static pressure, Pa; τ_{ij} represents viscous stress due to molecular viscosity, N/m²; μ_t denotes turbulent viscosity, Pa·s; k denotes turbulent kinetic energy, m²/s²; δ_{ij} denotes the Kronecker delta function (if $i=j$, then $\delta_{ij}=1$; if $i \neq j$, then $\delta_{ij}=0$).

The energy equation is expressed as follows:

$$\tau_{ij} = \mu_{\text{eff}} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2\partial u_k}{3\partial x_k} \delta_{ij} \right) \quad (4)$$

$$\frac{\partial(\rho u_j C_p T)}{\partial x_j} = u_j \frac{\partial p}{\partial x_j} + \tau_{ij} \frac{\partial u_i}{\partial x_j} + \lambda_{\text{eff}} \frac{\partial^2 T}{\partial x_j^2} \quad (5)$$

In the expression, μ_{eff} represents the effective viscosity, Pa·s; μ denotes the laminar viscosity, Pa·s, where $\mu_{\text{eff}} = \mu + \mu_t$; C_p is the specific heat capacity, J/(kg·K); T is the fluid temperature, K; λ_{eff} is the effective thermal conductivity, W/(m·K).

2.2 Turbulence model

This study employs the standard k - ε turbulence model, whose expressions are listed below (Equations (6)–(8)).

$$\frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\alpha_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (6)$$

$$\frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\alpha_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (7)$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (8)$$

In the expression, k and ε are two fundamental unknowns: k represents turbulent kinetic energy,

m^2/s^2 ; ε represents the turbulent dissipation rate, m^2/s^3 . G_k denotes the turbulent kinetic energy production term induced by the mean velocity gradient, $\text{kg}/(\text{m}\cdot\text{s}^3)$. G_b denotes the turbulent kinetic energy production term induced by buoyancy, $\text{kg}/(\text{m}\cdot\text{s}^3)$. Y_M represents the dissipation rate due to compressible turbulent wave expansion, $\text{kg}/(\text{m}\cdot\text{s}^3)$. $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, and C_μ are empirical constants, set to 1.44, 1.92, 1.00, and 0.09, respectively. α_k is the Prandtl number for turbulent kinetic energy k , set to 1.00; α_ε is the Prandtl number for dissipation rate ε , set to 1.30. S_k and S_ε are custom source terms, both set to 0.

2.3 Geometric Model and Boundary Conditions

In this study, a six-hole nozzle of a 120 t converter oxygen lance was taken as the research object. The total designed flow rate of the oxygen lance was $Q = 28000 \text{ Nm}^3/\text{h}$, and the flow rate per hole was $q = 4667 \text{ Nm}^3/\text{h}$. A comparative study was conducted between the designed dual-Mach-number nozzle and the original nozzle used in the enterprise. The original nozzle scheme from the enterprise (designated as S1) was a single-Mach-number design, whereas the newly designed dual-Mach-number nozzle schemes (designated as S2, S3, S4, and S5) had two Mach numbers, with orifices of different design Mach numbers arranged alternately. A total of five research schemes were established in this study. The design Mach number combinations for the schemes are listed in Table 1, the orifice dimensions corresponding to different design Mach numbers are listed in Table 2, and the orifice arrangements of the enterprise's original nozzle and the newly designed dual-Mach-number nozzles are shown in Fig. 1.

Table 1. Design Mach Number Combinations for the DMNOL Schemes

Scheme	S1	S2	S3	S4	S5
Ma ₁	2.00	2.00	2.00	2.00	2.00
Ma ₂	2.00	1.95	2.05	2.10	1.90

*Note: S1 refers to the enterprise's original nozzle design; S2–S5 refer to the newly designed six-hole dual-Mach-number nozzle designs presented in this paper.

Table 2. Throat and Outlet Diameters of Nozzles for Different Design Mach Numbers

Exit Mach number	1.90	1.95	2.00	2.05	2.10
Throat Diameter / (mm)	41.6	40.0	38.5	37.0	35.6
Outlet Diameter / (mm)	51.8	50.9	50.0	49.0	48.2

*Note: Each design Mach number corresponds to one nozzle group. A DMNOL uses two design Mach numbers and therefore has two sets of nozzle dimensions.

In this study, a three-dimensional model of the six-hole oxygen lance nozzle was drawn using the modeling software SolidWorks, as shown in Fig. 1. Based on the symmetry of the oxygen lance nozzle, the computational domain model of the oxygen lance jet was simplified to a one-third physical model to improve computational efficiency, as shown in Fig. 2(a). This model consisted of two Laval nozzles with different exit Mach numbers and a one-third cylinder with a radius of 1 m and a height of 2 m. Mesh generation was performed using ANSYS ICEM software, with a structured mesh type and local refinement applied. According to previous studies by the research group [12,33], a mesh quality above 0.75 and a mesh count of approximately 1.6 million per single nozzle met the accuracy requirements for the calculation, at which point mesh independence was achieved.

In this study, simulation calculations were performed using the software Fluent 19.0. An implicit formulation based on a density-based solver was adopted for the calculations. The

discretization schemes for turbulent kinetic energy and turbulent dissipation rate were set to the second-order upwind scheme. The boundary conditions were set as pressure inlet and pressure outlet. Pressure inlet 1 and pressure inlet 2 represented the oxygen pressures at the inlets of the high-Mach-number and low-Mach-number nozzles, respectively, while the pressure outlet was set as the ambient pressure at the nozzle outlet. The specific boundary condition settings are listed in Table 3. The symmetry plane was defined as the periodic boundary condition, and the wall was set as the no-slip wall, as shown in Fig. 2(b).

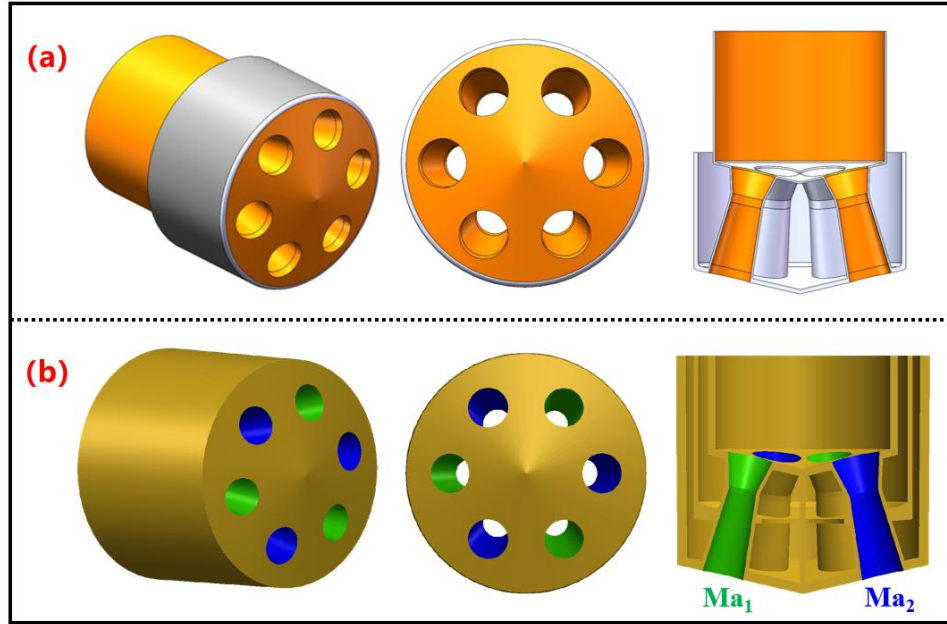


Figure 1. Three-dimensional models of a six-hole oxygen lance nozzle: (a) the enterprise's original six-hole nozzle design, (b) the newly designed six-hole dual-Mach-number nozzle

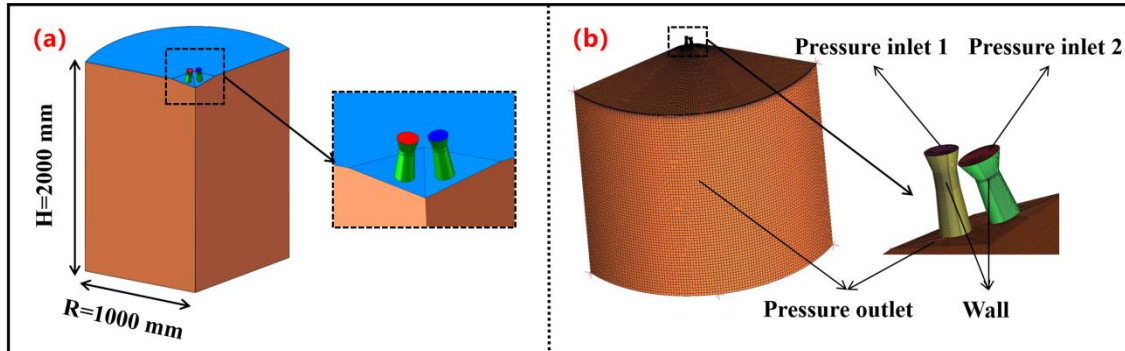


Figure 2. (a) Computational domain of the oxygen lance nozzle, (b) Mesh generation and boundary conditions

Table 3. Boundary conditions

Name of boundary	Type of boundary condition	values
Different nozzles	Exit Mach number	1.90/1.95/2.00/2.05/2.10
Pressure inlet	Inlet oxygen pressure (MPa)	0.70/0.75/0.81/0.88/0.95
	Inlet oxygen temperature (K)	300
Pressure outlet	Ambient pressure (MPa)	0.104
	Ambient temperature (K)	300

2.4 Model Validation

To validate the effectiveness of the simulation model and the mathematical model, experimental verification was carried out using a cold-state jet test system, as shown in Fig. 3. The test system consisted of an air compressor, a nozzle test device, a data acquisition device, and a data analysis system. The air compressor was capable of compressing air to 1.0 MPa and storing the high-pressure gas in a surge tank. The nozzle was installed on the nozzle test device, and the outlet pressure was regulated by a valve. A probe mounted on the data acquisition device was used to collect data on the velocity and pressure of the supersonic jet, which were then output through the data analysis system.

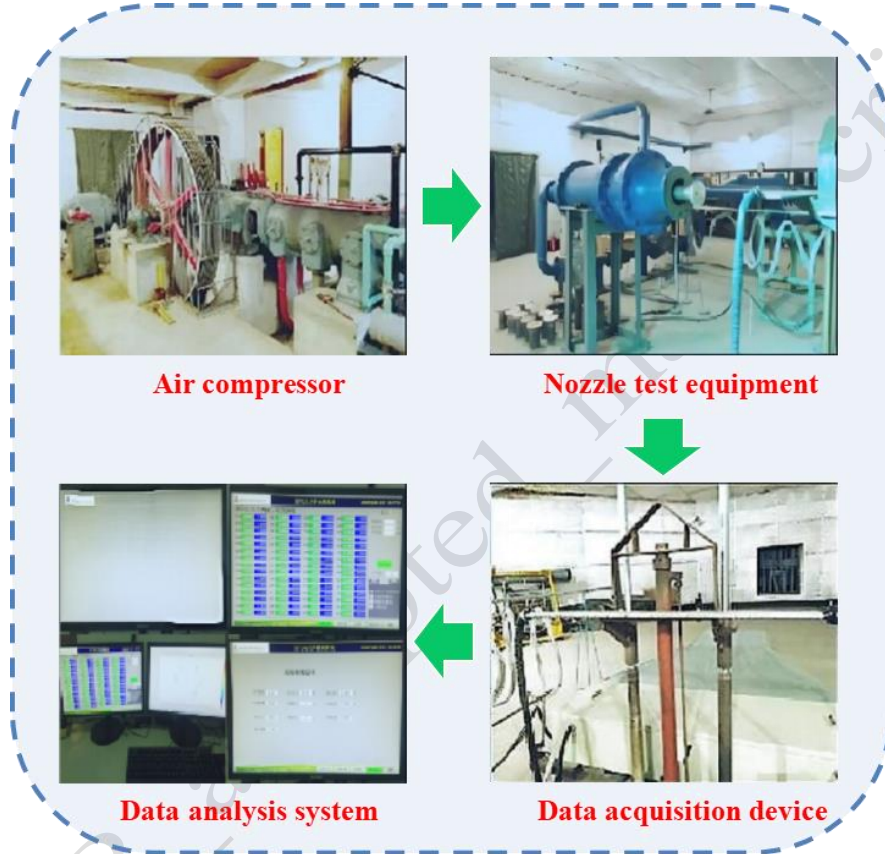


Figure 3. Cold jet test system[34]

In the experiment, the airflow rate was set to $28000 \text{ Nm}^3/\text{h}$, the gas pressure was set to 0.81 MPa, and the ambient temperature was maintained at 300 K. The axial velocity distributions of the jet obtained from the experiment and simulation for lance scheme S1 were compared, as shown in Fig. 4. The results indicate that the minimum and maximum errors between the simulated and experimental results are 1.03 m/s and 16.85 m/s, accounting for 0.39% and 6.34% of the mean jet velocity, respectively. The simulation results are in good agreement with the experimental results, which validates the accuracy of the numerical model.

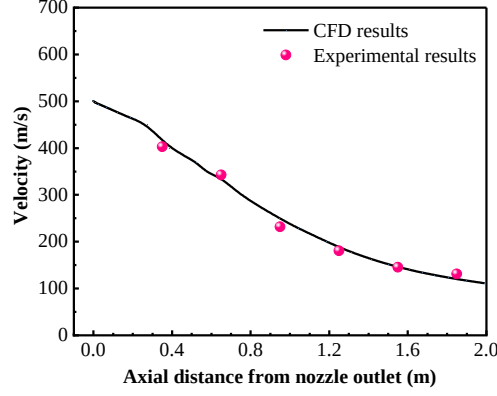


Figure 4. Comparison of simulation results with experimental results for the axial distribution of jet velocity

3. Results and discussion

3.1 Impact area of the oxygen jet

The impact area formed after the supersonic oxygen jet contacts the molten steel directly affects the efficiency and quality of converter steelmaking. Therefore, in this study, the analysis was conducted from two aspects: the effective impact area of the jet (the cross-sectional area where the jet dynamic pressure is ≥ 4000 Pa) and the slag-formation impact area (the cross-sectional area where the jet dynamic pressure is ≥ 1700 Pa). It should be noted that the jet dynamic pressure criteria corresponding to these two types of impact areas are derived from our previous work [34] and the findings of other researchers [22,35], rather than being arbitrarily chosen. Figure 5 illustrates the influence of different dual-Mach-number nozzles on the effective impact area of the oxygen jet. As shown in Fig. 5(a), with the axial distance increase, the effective impact areas of the different dual-Mach-number oxygen jets all exhibit a trend of first increasing and then decreasing, and reach their maximum values at an axial distance of 1.2 m. Therefore, the optimal steelmaking lance height for the different dual-Mach-number jets was 1.2 m. The maximum effective impact areas of the different dual-Mach-number oxygen jets are further compared. As shown in Fig. 5(b), in terms of the maximum effective impact area, all the dual-Mach-number nozzle schemes exhibit larger values than the original nozzle scheme S1 used in the enterprise. When the Mach number configuration was S3, the maximum effective impact area of the jet reaches its maximum value of 0.118 m^2 . Compared with the oxygen jet of scheme S1, the maximum effective impact area of scheme S3 is increased by 9.26%.

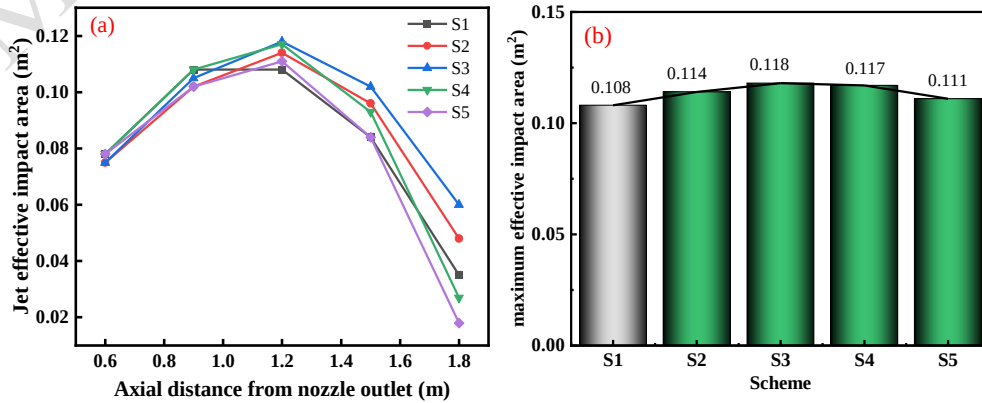


Figure 5. DMNOL jet: (a) effective impact area at different axial distances and (b) maximum maximum effective impact area

Figure 6 illustrates the variation in the slag-formation impact area of the oxygen jet for different dual-Mach-number nozzles. As shown in Fig. 6(a), with the axial distance increase, the slag-formation impact areas of schemes S1 to S4 all gradually increase, reaching their maximum values at an axial distance of 1.8 m. In contrast, the slag-formation impact area of scheme S5 reaches its peak at an axial distance of 1.2 m. The maximum slag-formation impact areas of the different schemes were statistically analyzed and compared. As shown in Fig. 6(b), in terms of the maximum slag-formation impact area, only schemes S2 and S3 exhibit larger values than the original nozzle scheme S1 used in the enterprise. At an axial distance of 1.8 m, scheme S3 achieves the maximum slag-formation impact area of 0.24 m^2 , representing a 33.33% increase in the slag-formation impact area of the jet compared with scheme S1. Since the maximum slag-formation impact areas of schemes S4 and S5 are smaller than that of the original nozzle scheme S1 and do not show advantages in slag formation, schemes S4 and S5 are not further analyzed in the subsequent discussion.

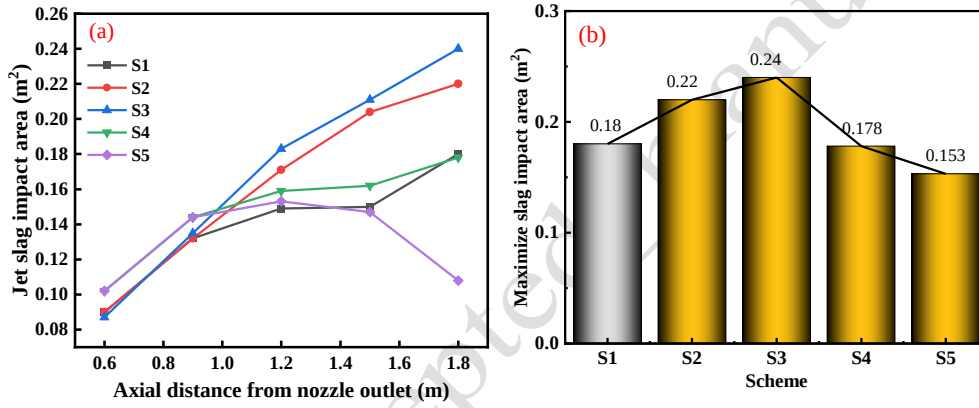


Figure 6. DMNOL Jet: (a) slag impact area at different axial distances and (b) maximum slag impact area

3.2 Motion Characteristics of Oxygen Jets

In this study, the iso-velocity line of 40 m/s is defined as the jet boundary, and the iso-velocity line of 490 m/s is defined as the boundary of the high-velocity region of the jet. Accordingly, the jet width is defined as the radial width of the jet boundary at an axial distance of 2.0 m from the nozzle outlet, i.e., the radial distance between the two 40 m/s iso-velocity lines. Figure 7 shows the velocity fields of the oxygen jets for different dual-Mach-number nozzles. At an axial distance of 2.0 m, the jet widths of schemes S1, S2, and S3 are 0.961, 0.892, and 0.907 m, respectively, and the lengths of the high-velocity region of the jet are 0.633, 0.691, 0.693, 0.715, and 0.694 m, respectively. Compared with scheme S1, the jet widths of S2 and S3 are reduced by 7.18% and 5.62%, respectively, while the lengths of the high-velocity region of the jet for S2 and S3 are increased by an average of 9.32% and 11.30%, respectively. The results indicate that the dual-Mach-number design of the oxygen lance nozzle reduces the entrainment along the jet and enhances its independence, thereby resulting in a longer high-velocity region and a narrower jet width.

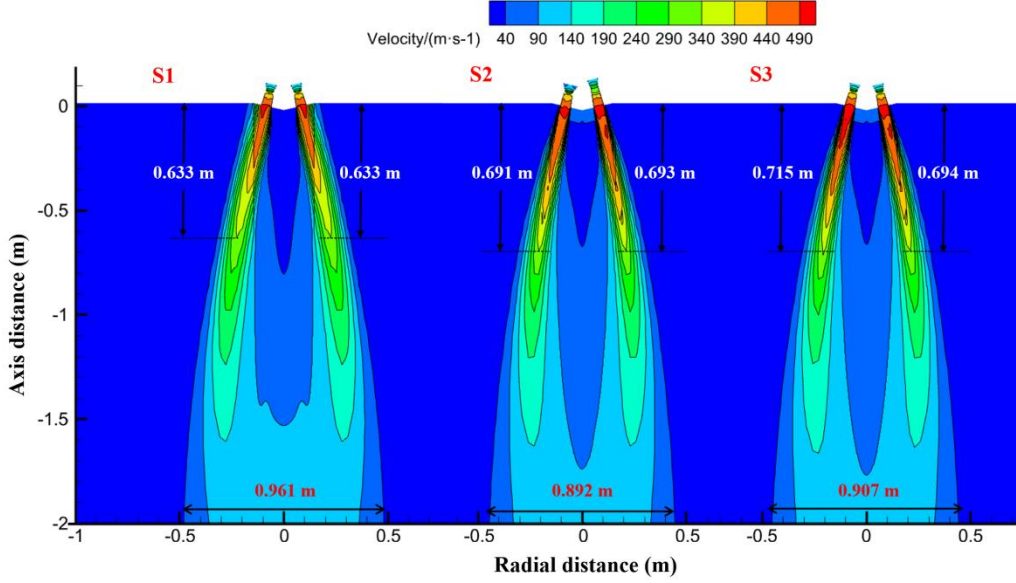


Figure 7. Velocity fields of oxygen lances at different dual mach numbers

To further reveal the influence of the dual-Mach-number on the motion of the oxygen lance jet, Fig. 8 compares the motion trajectories and coalescence distances of the jet centers for different DMNOLs. As shown in Fig. 8(a), the jet generated by the original nozzle used in the enterprise exhibited a larger radial distance, but the jets of scheme S1 had already coalesced at an axial distance of 0.98 m, while the coalescence distances of schemes S2 and S3 were significantly larger than that of scheme S1. In this study, the average coalescence distance of the DMNOL jet was defined as the arithmetic mean of the coalescence distances of the jets with different Mach numbers. As shown in Fig. 8(b), the average coalescence distances of schemes S2 and S3 were 1.260 m and 1.335 m, respectively. Compared with scheme S1, the coalescence distances of schemes S2 and S3 were increased by 28.57% and 36.22%, respectively, indicating that the DMNOL jet exhibits greater rigidity.

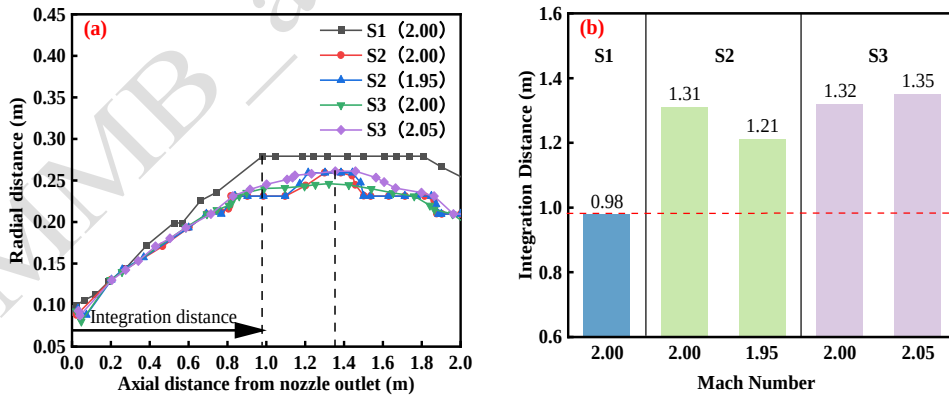


Figure 8. Oxygen jet characteristics of nozzles with different dual-Mach-numbers: (a) Central motion trajectory of the oxygen jet; (b) Integration distance

3.3 Velocity Decay Characteristics of Oxygen Jets

The decay behavior of oxygen jet velocity is one of the important indicators of jet characteristics. Since the ambient temperature in this study was room temperature (300 K), the speed of sound at room temperature, 340 m/s, was used to define the supersonic region of the jet. In this study, the average supersonic region length of the DMNOL jet was defined as the

arithmetic mean of the supersonic region lengths of the jets with different Mach numbers.

Figure 9 shows the velocity distribution of the oxygen jet for different dual-Mach-number nozzles. As shown in Fig. 9(a), after the oxygen lance jet exits the nozzle, the jet velocity of scheme S1 decays more rapidly, and its supersonic region length was the shortest. At an axial distance of 1.8 m, the velocity of the DMNOL jet remains slightly higher than that of the original nozzle scheme S1 used in the enterprise. As shown in Fig. 9(b), the average supersonic region lengths of schemes S2 and S3 are 0.692 m and 0.703 m, respectively. Compared with scheme S1, the average supersonic region lengths of schemes S2 and S3 are increased by 9.32% and 11.06%, respectively. The results indicate that, due to the asymmetric flow field of its jet, the DMNOL effectively delays the overall jet velocity decay.

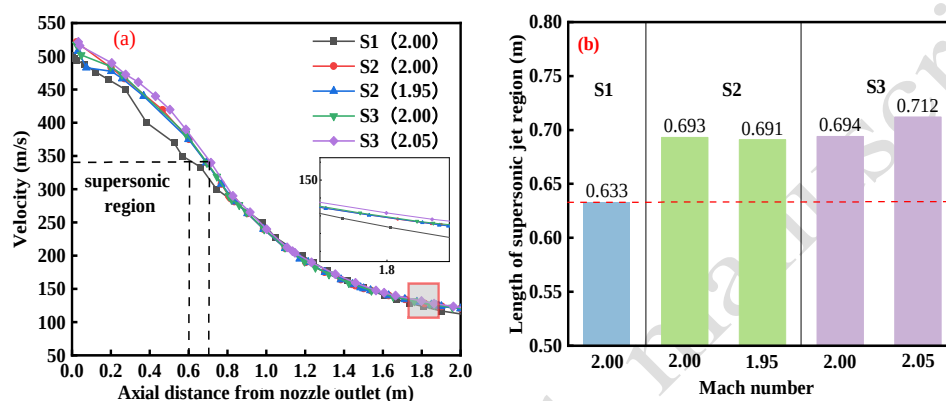


Figure 9. Velocity distribution and core length of oxygen jets from nozzles with different dual-Mach-numbers (a) Velocity distribution; (b) Length of supersonic region

3.4 Impact depth of the oxygen jet

As shown above, the axial distance of 1.2 m was the optimal steelmaking lance height, at which the maximum effective impact area was achieved and molten steel splashing should be prevented. The axial distance of 1.8 m was the optimal slag-formation lance height, at which the maximum slag-formation impact area was achieved and molten bath stirring should be enhanced. As shown in Fig. 10, at the steelmaking lance height of 1.2 m, the oxygen jet dynamic pressure exhibits a consistent distribution trend along the radial direction, first increasing and then decreasing, with a peak value present. The peak dynamic pressure of scheme S1 was larger than those of schemes S2 and S3, indicating that scheme S1 was prone to splashing. At the slag-formation lance height of 1.8 m, the oxygen jet dynamic pressure of scheme S1 exhibits a multi-peak distribution along the radial direction, while schemes S2 and S3 maintained a smooth single-peak morphology. The peak dynamic pressure of scheme S3 exceeds that of scheme S1 by 13.6%, suggesting that schemes S2 and S3 can generate a greater impact depth, thereby promoting bath stirring. The results indicate that the dual-Mach-number configuration of the oxygen lance can effectively delay jet coalescence and suppress turbulent kinetic energy dissipation, enabling the jet to reduce molten steel splashing at low lance heights and enhance bath stirring at high lance heights.

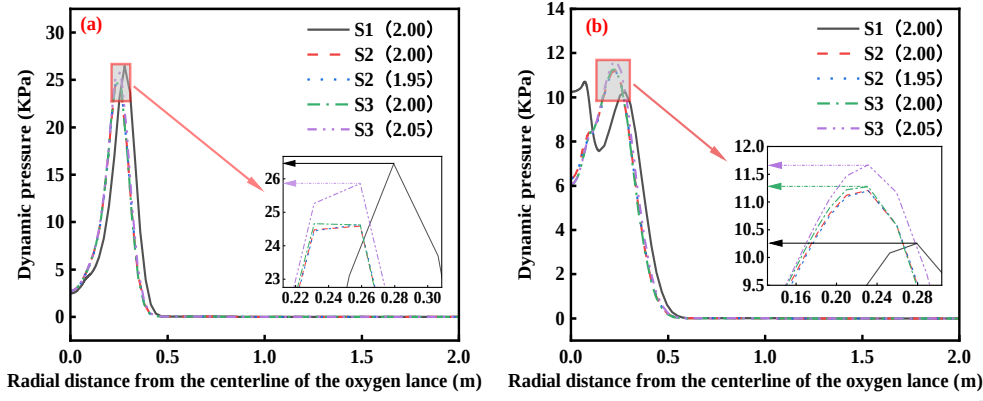


Figure 10. Radial dynamic pressure distribution of a DMNOL jet at lance heights of (a) 1.2 m and (b) 1.8 m

To more accurately evaluate the impact depth of the jet on the molten bath, the impact depth of the jet on the molten bath (slag layer and molten steel) was calculated using Equation (9) [36,37]:

$$H_p = H_{slag} + H_{steel} = H_{slag} + \frac{P_d - P_{slag}}{\rho_{steel} g} \quad (9)$$

In the equation, H_p is the theoretical penetration depth of the molten pool, m; H_{slag} is the thickness of the slag layer, taken as 0.058 m; H_{steel} is the impact depth of the molten steel layer, m; P_d is the maximum dynamic pressure at the oxygen jet cross-section, Pa; P_{slag} denotes the static pressure at the bottom of the slag layer, taken as 1700 Pa; ρ_{steel} is the density of molten steel, taken as 7000 kg/m³; g is the gravitational acceleration, taken as 9.81 m/s².

Figure 11 shows the impact depth of the DMNOL jet at the steelmaking lance heights of 1.2 m and 1.8 m. As shown in Fig. 11(a), at the steelmaking lance height of 1.2 m, the impact depth of scheme S1 was 0.527 m, while the impact depths of schemes S2 and S3 ranged from 0.500 m to 0.519 m. The average impact depth of scheme S3 was 0.51 m, representing a 3.23% decrease compared with scheme S1. This result indicates that during the high-intensity impact stage at a low lance height, the dual-Mach-number structure, through its asymmetric jet configuration, enabled asynchronous jet coalescence, thereby reducing excessive penetration into the molten bath, which was beneficial for suppressing molten steel splashing and reducing metal loss. As shown in Fig. 11(b), at the slag-formation lance height of 1.8 m, the impact depth of scheme S1 was 0.298 m, while the impact depths of schemes S2 and S3 ranged from 0.305 m to 0.312 m. The average impact depth of scheme S3 was 0.309 m, representing a 3.69% increase compared with scheme S1. This reverse trend suggests that the DMNOL jet, due to its delayed kinetic energy decay, possessed higher effective momentum under high lance height conditions, thereby achieving effective stirring of the molten bath.

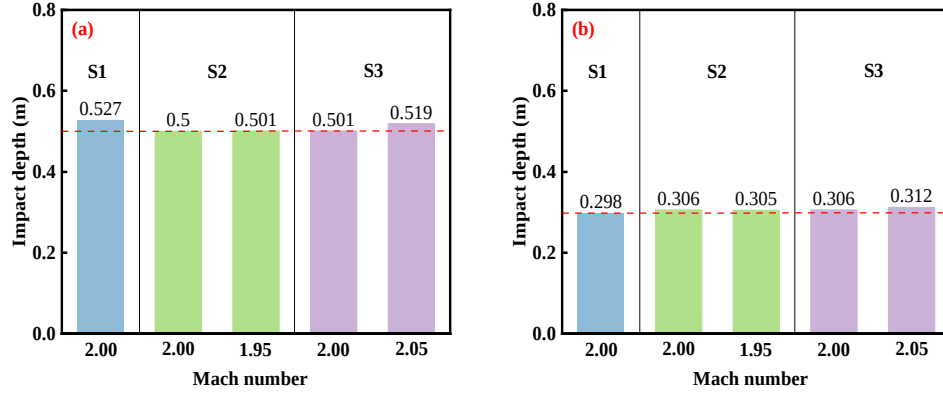


Figure 11. Impact depth of a DMNOL jet at lance heights of (a) 1.2 m and (b) 1.8 m

4. Conclusions

In this study, a novel six-hole DMNOL nozzle was designed. Through numerical simulation, the jet characteristics of the DMNOL nozzle were compared and analyzed with those of the original nozzle used in the enterprise. The main findings are as follows:

In terms of jet impact area, the dual-Mach-number nozzle schemes S2 and S3 both performed significantly better than the original nozzle scheme S1 used in the enterprise. The optimal steelmaking lance height for the dual-Mach-number nozzle was 1.2 m, and the optimal slag-formation lance height was 1.8 m. The optimal dual-Mach-number nozzle scheme was S3. Compared with scheme S1, scheme S3 increased the effective impact area by 9.26% and increased the slag-formation impact area by 33.33%.

In terms of jet motion and velocity decay, compared with scheme S1, the jet width of scheme S2 decreased by 7.18%, while that of scheme S3 decreased by 5.62%. The coalescence distances of schemes S2 and S3 increased by 28.57% and 36.22%, respectively, and their average supersonic region lengths increased by 9.32% and 11.06%, respectively. These results demonstrate the great potential of the DMNOL in maintaining jet independence and delaying jet coalescence and velocity decay.

In terms of jet impact depth, compared with scheme S1, schemes S2 and S3 exhibited lower peak dynamic pressure at the steelmaking lance height (1.2 m), with the impact depth of scheme S3 decreased by 3.23%, effectively reducing molten steel splashing. At the slag-formation lance height (1.8 m), schemes S2 and S3 exhibited higher peak dynamic pressure, with the impact depth of scheme S3 increased by 3.69%, effectively promoting molten bath stirring.

Scheme S3 is identified as the optimal one in this study and is recommended for further practical application. The lance height should be set to 1.8 m during the slag melting stage and to 1.2 m during the steelmaking stage.

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Authors contributions

Author 1 (Jiandu Yuan) was responsible for model construction, numerical simulation, data analysis, and drafting the initial manuscript. Author 2 (Wenjuan Liu) contributed to research design, manuscript revision, and experimental operations. Author 3 (Lianghua Feng) provided theoretical support for the research. Author 4 (Kun Liu) edited and reviewed the manuscript to

ensure it met peer review requirements. Author 5 (Shaoxuan Deng) provided experimental equipment and was responsible for experimental data collection.

Data availability

Data supporting the findings of this study are available upon request from the corresponding author.

Conflict of interest

On behalf of all authors, the corresponding author declares that there are no conflicts of interest.

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Figure 1. Three-dimensional models of a six-hole oxygen lance nozzle: (a) the enterprise's original six-hole nozzle design, (b) the newly designed six-hole dual-Mach-number nozzle

Figure 2. (a) Computational domain of the oxygen lance nozzle, (b) Mesh generation and boundary conditions

Figure 3. Cold jet test system

Figure 4. Comparison of simulation results with experimental results for the axial distribution of jet velocity

Figure 5. DMNOL jet: (a) effective impact area at different axial distances and (b) maximum effective impact area

Figure 6. DMNOL Jet: (a) slag impact area at different axial distances and (b) maximum slag impact area

Figure 7. Velocity fields of oxygen lances at different dual mach numbers

Figure 8. Oxygen jet characteristics of nozzles with different dual-Mach-numbers: (a) Central motion trajectory of the oxygen jet; (b) Integration distance

Figure 9. Velocity distribution and core length of oxygen jets from nozzles with different dual-Mach-numbers (a) Velocity distribution; (b) Length of supersonic region

Figure 10. Radial dynamic pressure distribution of a DMNOL jet at lance heights of (a) 1.2 m and (b) 1.8 m

Figure 11. Impact depth of a DMNOL jet at lance heights of (a) 1.2 m and (b) 1.8 m

Table 1. *Design Mach Number Combinations for the DMNOL Schemes*

Table 2. *Throat and Outlet Diameters of Nozzles for Different Design Mach Numbers*

Table 3. Boundary conditions

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