Exploring the Behavior of a Coherent Flow Field Produced by a Shrouding Laval Nozzle Structure

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For achieving a better stirring effect, the coherent jet technology has been widely adopted in the metallurgy field; a key feature of this technology is the use of a combustion flame to protect the main oxygen jet. In this paper, a shrouding nozzle with a Laval nozzle structure using preheating technology is introduced. The effect of the shrouding gas flow rate on the behavior of the main oxygen jet is investigated at room and high ambient temperatures. A computational fluid dynamics model has been built to investigate the flow field of the coherent jet in simulation studies. In addition, an experimental study has been carried out to verify the results of the numerical simulation. Based on the results, the new method improves the shrouding gas velocity and forms a low-density zone, which makes its velocity potential core length 178% and 174% longer than that generated by the traditional method at room and high ambient temperature, respectively. However, the shrouding jet forms a shock wave at the exit of the Laval nozzle, which results in removing kinetic energy from the main oxygen jet. As a result, the axial velocity of the coherent jet is smaller than that of the conventional jet, and the velocity variation increases as the flow rate increases.

KEY WORDS: coherent jet; supersonic; numerical simulation; preheating.

1. Introduction

Controlling the reaction rates, stirring effects, and temperature distributions of molten baths in steelmaking and refining processes remain important and challenging problems.1–3) The poor process control causes inconsistency in impurity element content and mechanical property for the metallurgical product, which worsens its mechanical property and working performance. For the BOF (basic oxygen furnace) and RH (Ruhrstahl-Heraeus) process, the oxygen has a great influence on the removal of impurity elements and inclusion distributions.

The oxygen lance has been used widely in the steelmaking field to deliver the oxygen into the molten bath. In comparison to the subsonic oxygen jet, the supersonic oxygen jet generated by a Laval nozzle can obtain greater penetration depth and a larger impact area.4–6) Therefore, the supersonic oxygen lance is an important component of the equipment. As a supersonic oxygen jet travels away from the Laval nozzle, its velocity dramatically reduces due to the entrainment effect of the ambient gas. To achieve metallurgical and operational benefits, the coherent jet technology is used widely in Electric Arc Furnaces (EAFs).7–10) When the shrouding gases (CH4 and O2) are injected into an EAF, a high temperature flame is formed by the combustion of the methane gas, which then wraps the main supersonic oxygen jet. This results in the suppression of the entrainment phenomenon, which occurs between the main oxygen jet and the ambient gas. Consequently, the coherent jet technology can significantly prolong the length of the velocity potential core and protect the kinetic energy of the main oxygen jet.

Many investigations have been carried out over the years that focus on the behavior of coherent jets using experimental and numerical studies, in order to optimize the parameters of coherent lances. Odenthal et al.11) have reported the Laval nozzle, which is designed by the characteristic-line method, can produce a longer potential core than that produced by the one-dimension isentropic flow theory at the same inlet pressure. Alam et al.12) have presented the effects of flow rates, temperatures, and the kind of shrouding gas on the behavior of the coherent jet flow field at different ambient temperatures. Wei et al.13) have analyzed the effect of the gas flow temperature on the flow field characteristics and penetration depth by numerical simulations; the parameters of the shrouding supersonic jet demonstrate advantages in stirring the liquid bath. Liu et al.14) introduce the development and application of two kinds of coherent lances in an industrial application process.

Some Chinese steelmaking companies cannot acquire CH4 easily, because there is no chemical plant nearby. Therefore, they deploy many conventional supersonic oxygen lances in
the EAF to improve the stirring effect of the molten bath. The hydromechanics theory has established that the higher velocity of the shrouding gas suppresses the deceleration of the oxygen jet.\(^15\) Hence, the shrouding nozzle is designed as a Laval nozzle structure fitted with a loop arrangement to increase the velocity of the shrouding gas, and the shrouding gas is preheated to further improve its velocity.

In this research, the Mach number and temperature of shrouding jet are first determined. Both a numerical simulation and an experiment are carried out to investigate the effects of the shrouding jet flow rate and the ambient temperature on the behavior of the coherent jet. The axial velocity and the total temperature of the main oxygen jet at the centerline are measured in the experimental studies; these results are used to verify the accuracy of the simulation results.

2. Structure Design and Experimental Measurement

The structure of a shrouding Laval nozzle is designed using the one-dimension isentropic flow theory. To research the effect of flow rate of shrouding gas on the behavior of main oxygen jet, there were five kinds of selected design flow rates of the shrouding gas, which were 60\% (1 500 Nm\(^3\)/h), 80\% (2 000 Nm\(^3\)/h), 100\% (2 500 Nm\(^3\)/h), 120\% (3 000 Nm\(^3\)/h) and 140\% (3 500 Nm\(^3\)/h) of the flow rate of the main oxygen jet, respectively. The preheating furnace was designed to have max preheating temperature of 1 123 K (850°C) at its gas exit, when the flow rate of the shrouding gas of 3 500 Nm\(^3\)/h. And considering the heat dissipation of the gas channel, the design inlet temperature of a shrouding nozzle was 1 073 K (800°C) to suppress the temperature fluctuation. Besides, the machining cost for the supersonic shrouding nozzle increased with increasing its Mach number. As a result, the 1.4 was selected as the design Mach number of the shrouding nozzle. Based on above parameters, the throat and exit area are calculated with the following equations\(^{15}\)

\[
q = 1.782C_D \frac{S_P}{T} \quad \text{(1)}
\]

\[
\frac{S_1}{S_2} = \frac{Ma}{\left(\frac{2}{\kappa + 1}\left(1 + \frac{\kappa - 1}{2} Ma^2\right)^{\frac{\kappa + 1}{2(\kappa - 1)}}\right)} \quad \text{(2)}
\]

where \(q\), \(P\) and \(T\) are the design flow rate, inlet pressure, and gas temperature of the shrouding jet, respectively. \(S_1\) and \(S_2\) are the throat and exit area of the Laval nozzle, respectively. \(C_D\) is the utilization coefficient of shrouding jet. \(\kappa\) and \(Ma\) are the specific heat ratio and Mach number of the flow gas, respectively.

In this research, the maximum design ambient temperature generated by the combustion furnace was 1 873 K (1 600°C). However, the supply ability of the CH\(_4\) for the combustion furnace was suppressed, because the CH\(_4\) was also used by heating furnace to increasing the inlet temperature of main oxygen. As a result, the temperature of 1 700 K was selected for a high ambient temperature in the combustion furnace. Figure 1 illustrates the structure of a shrouding nozzle; the detailed parameters are depicted in Table 1. When the \(R_d\), \(S_1\) and \(S_2\) have been determined, the \(A_1\), \(A_2\), \(B_1\) and \(B_2\) can be calculated as follows:

\[
R_d = \frac{A_1 + A_2}{2} = \frac{B_1 + B_2}{2} \quad \text{(3)}
\]

\[
S_1 = \pi \cdot (A_1^2 - A_2^2) \quad \text{(4)}
\]

\[
S_2 = \pi \cdot (B_1^2 - B_2^2) \quad \text{(5)}
\]

![Fig. 1. The shrouding nozzle. (Online version in color.)](image)

<table>
<thead>
<tr>
<th>Type of boundary</th>
<th>Type of boundary condition</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow inlet (Main oxygen inlet)</td>
<td>Flow rate</td>
<td>2 500 Nm(^3)/h</td>
</tr>
<tr>
<td></td>
<td>Mach number</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Mass fractions</td>
<td>(O_2 = 100%)</td>
</tr>
<tr>
<td></td>
<td>Oxygen temperature</td>
<td>298 K</td>
</tr>
<tr>
<td>Mass flow inlet (Shrouding gas inlet)</td>
<td>Flow rate</td>
<td>1 500 Nm(^3)/h, 2 000 Nm(^3)/h, 2 500 Nm(^3)/h, 3 000 Nm(^3)/h, 3 500 Nm(^3)/h</td>
</tr>
<tr>
<td></td>
<td>Mach number</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>(A_1/A_2)</td>
<td>40.67/34.43 mm, 41.70/33.40 mm, 42.74/32.36 mm, 43.78/31.32 mm and 44.82/30.28 mm</td>
</tr>
<tr>
<td></td>
<td>(B_1/B_2)</td>
<td>41.02/34.08 mm, 42.18/32.92 mm, 43.34/31.76 mm, 44.50/30.60 mm and 45.65/29.45 mm</td>
</tr>
<tr>
<td></td>
<td>Mass fractions</td>
<td>(O_2 = 23%, N_2 = 77%)</td>
</tr>
<tr>
<td></td>
<td>Gas temperature</td>
<td>1 073 K</td>
</tr>
<tr>
<td></td>
<td>Static pressure</td>
<td>101 325 Pa</td>
</tr>
<tr>
<td>Pressure outlet (Outlet of model)</td>
<td>Mass fractions</td>
<td>(O_2 = 23%, N_2 = 77%)</td>
</tr>
<tr>
<td></td>
<td>Ambient temperature</td>
<td>298 K, 1 700 K</td>
</tr>
</tbody>
</table>
The Mach number of main oxygen is 2.0, with diameters for the throat and exit of 13.0 mm and 16.9 mm, respectively. The heating furnace and heat exchange furnace are used to preheat the shrouding gas, and then the high temperature gas is delivered using a metal hose covered with an insulation layer. A brief overview of the experiment is presented here; detailed information about the experimental system is available elsewhere.\(^{10-18}\)

For measuring the axial velocity and total temperature, the Pitot tube and thermocouple have been fixed at specific locations with an axial direction during the measurement process. The Pitot tube has been designed with a water-cooling structure. In measurements, the coherent lance was fixed with the metal bracket. The axis of the Laval nozzle was tilted 0° relative to the horizontal plane, so that the central point of the nozzle exited and the Pitot tube (thermocouple) appeared to be collinear. And the Pitot tube has been designed with a water-cooling structure. For measuring the axial velocity of the main oxygen jet, the Pitot tube and pressure sensor were positioned on the bedstand in advance to measure the dynamic and static pressure produced by the oxygen jet. Then the Pitot tube would be replaced by a thermocouple to collect the temperature data. In this experiment, the measuring time for both Pitot tube and thermocouple was 30 s after their data fluctuation becoming stable, and then their average data have been calculated to analyze the flow field.

The experimental equipment is illustrated in Fig. 2. Equations (6) and (7) have been adopted to compute the axial velocity by measuring dynamic and static pressure of the jet.\(^4\)

\[
V = \sqrt{\frac{2\gamma RT}{\gamma-1} \left( \frac{P_d}{P_s} \right)^{(\gamma-1)/\gamma} - 1}, \quad \text{Ma} > 0.3 \quad (6)
\]

\[
V = \frac{2(P_d - P_s)}{\rho}, \quad \text{Ma} < 0.3 \quad (7)
\]

where \(P_d\) and \(P_s\) are the dynamic and static pressures of the supersonic jet, respectively, and \(\gamma\) and \(R\) are the ratio of the oxygen heat capacity and the ideal gas state constant, with the value 1.4 and 8.314, respectively.

In this research, a Pitot tube (JIS B8330) was used to measure the pressure of the main oxygen jet, due to the preview research.\(^4\) To insure the accuracy of the experimental data, the maximum value of the main oxygen jet could be first measured by a pressure sensor with a large range, then a measuring range of the pressure sensor, which was 1.5–2 times of this maximum value oxygen jet, should be selected. Besides, there were two kinds of thermocouples could be used for measuring the temperature of the coherent jet. The K (B) type thermocouple was used, when the jet temperature was range from 273 K (1 273 K) to 1 473 K (2 073 K).\(^{20}\)

The measuring errors of K and B type thermocouple are \(\pm 0.004\left|\frac{T_m}{T_i}\right|\) and \(\pm 0.0025\left|\frac{T_m}{T_i}\right|\), respectively, and the \(\left|\frac{T_m}{T_i}\right|\) was the absolute value of measurement of jet temperature. Because of the experimental condition, the K type thermocouple was selected to use in this research to measure the temperature of main oxygen jet in the ambient temperature being 300 K.

3. Numerical Simulation

3.1. Governing Equations

During the numerical simulation process, the Reynolds-Averaged Navier-Stokes (RANS) method has been used to calculate the flow field of the supersonic jet with a steady-state model.\(^{21}\) The governing equations are as follows:

Continuity equation:

\[
\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad \text{..................................(8)}
\]

Momentum equation:

\[
\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho \mu \frac{\partial u_i}{\partial x_j} \right) + S_i \quad \text{..................................(9)}
\]

Energy equation:

\[
\frac{\partial}{\partial x_i}(\rho u_i T) = -\frac{\partial}{\partial x_j} \left( \frac{\mu + \frac{\mu_t}{\sigma}}{P} \frac{\partial T}{\partial x_j} \right) + S_h \quad \text{..................................(10)}
\]

where \(\rho\) and \(\mu\) are the gas density and molecular viscosity, respectively. The average velocity components in the \(i_{th}\) and \(j_{th}\) directions are \(u_i\) and \(u_j\), respectively. The fluctuating velocity components in the \(i_{th}\) and \(j_{th}\) directions are \(u_i'\) and \(u_j'\), respectively. The volumetric heat source and turbulent Prandtl number are \(S_h\) and \(P_r\). The thermal conductivity and temperature are \(T\) and \(\lambda\), respectively. Based on the Boussinesq approximation, the \(\rho u_i' u_j'\) represents the Reynolds stress to evaluate the turbulent effect, as shown in Eq. (11).

\[
\rho u_i' u_j' = -\mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{2}{3} \left( \rho k + \mu \frac{\partial u_i}{\partial x_i} \right) \delta_{ij} \quad \text{..................................(11)}
\]

where \(\mu\) and \(k\) are the turbulent viscosity of the fluid and the turbulent kinetic energy, respectively. \(\delta_{ij}\) is the Kronecker delta (\(\delta_{ii} = 1\) if \(i = j\), and \(\delta_{ij} = 0\) if \(i \neq j\)).\(^{22}\)

The realizable \(k-c\) turbulence model is adopted and combined with the explicit solver to obtain the simulation results, because the wave shock has a significant effect on the behavior of supersonic jet.\(^{23}\) The turbulence kinetic energy \((k)\) and its dissipation rate \((\varepsilon)\) are obtained from the following transport equations:

\[
\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] - G_k + G_h - \rho c - Y_{ed} + S_k \quad \text{..................................(12)}
\]

\[
\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] - C_1 \frac{\varepsilon}{k} G_k + C_2 \frac{\varepsilon}{k} Y_{ed} + \frac{\varepsilon \varepsilon}{k} \rho \frac{\partial u_i}{\partial x_i} \quad \text{..................................(13)}
\]
where \( C_{c1}, C_{c1}, \sigma_c \) and \( \sigma_c \) are the constants for the k-\( \varepsilon \) model, and their values are 1.44, 1.90, 1.0 and 1.2, respectively. \( S_k \) and \( S_\varepsilon \) are user-defined source terms. \( G_k \) and \( G_b \) present the generation of turbulence kinetic energy formed by the mean velocity gradient and buoyancy. \( Y_M \) is the fluctuating dilatation in the compressible turbulence process, which is computed as follows:

\[
Y_M = 2 \rho \varepsilon M_c^2 = 2 \rho \varepsilon \frac{k}{\gamma R T} \quad \text{............(14)}
\]

In this research, the gas phase has been defined as an ideal-gas in the simulation, because of the significant temperature and velocity gradient. Therefore, the gas density is computed as follows:

\[
\rho = \frac{P M}{n R T} \quad \text{...............(15)}
\]

where \( M \) and \( n \) are the mass and mole number of the gas, respectively. \( R \) is the ideal gas state constant, with the value 8.314.

### 3.2. Simulation Details

Based on the structure of the coherent lance, a 3D geometrical model has been developed to research the behaviors of the coherent jet flow field. The main computational domain includes the coherent lance and the coherent jet flowing zone, with the exit diameter of the main oxygen Laval nozzle defined as 1De. The supersonic jet flow zone ranged from the tip of the Laval nozzle to 85 De downstream in an axial direction and 12.5 De in a radial direction. The boundary conditions of the simulation model are illustrated in Fig. 3. The boundary condition types and values of the model are summarized in Table 1. The initial conditions are defined such that no oxygen or shrouding gas is introduced; only air is present. The mass flow inlet boundary conditions are used to generate the oxygen jet and the shrouding gas parameters. The thermo-physical properties of the gases are presented in Table 2.

The specific heat of \( O_2 \) and \( N_2 \) in Table 2 are expressed by polynomial equations as follows:

\[
C_p = A_1 + A_2 T + A_3 T^2 + A_4 T^3 + A_5 T^4 + A_6 T^5 \quad \text{...........(16)}
\]

where \( A_1, A_2, A_3, A_4, A_5 \) and \( A_6 \) are the constants for the polynomial. For the temperature of oxygen gas is range

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**Fig. 3.** (a) The numerical simulation model with boundary conditions. (b) The mesh model of the computational domain. (Online version in color.)

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**Table 2.** Thermo-physical properties of gases.

<table>
<thead>
<tr>
<th></th>
<th>Density/(kg·m(^{-3}))</th>
<th>( O_2 ) Ideal gas</th>
<th>( N_2 ) Ideal gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p )/(J·kg(^{-1})·K(^{-1}))</td>
<td>Piecewise-Polynomial</td>
<td>Piecewise-Polynomial</td>
<td></td>
</tr>
<tr>
<td>Molecular Weight/ (kg·kmol(^{-1}))</td>
<td>31.999</td>
<td>28.013</td>
<td></td>
</tr>
<tr>
<td>Standard State Enthalpy/ (J·kmol(^{-1}))</td>
<td>0.01634</td>
<td>1 429.881</td>
<td></td>
</tr>
<tr>
<td>Standard State Entropy/ (J·kmol(^{-1})·K(^{-1}))</td>
<td>2.051×10(^5)</td>
<td>1.915×10(^5)</td>
<td></td>
</tr>
</tbody>
</table>
from 250 K to 1 000 K, their values are $8.348 \times 10^2$, $2.930 \times 10^1$, $-1.496 \times 10^{-2}$, $-3.414 \times 10^{-7}$ and $-2.278 \times 10^{-10}$, respectively. For the temperature of oxygen gas is range from 1 000 K to 2 000 K, their values are $9.608 \times 10^2$, $1.594 \times 10^1$, $-3.271 \times 10^{-5}$, $4.613 \times 10^{-9}$ and $-2.953 \times 10^{-13}$, respectively. For the temperature of nitrogen gas is range from 250 K to 1 000 K, their values are $9.790 \times 10^2$, $4.180 \times 10^1$, $-1.176 \times 10^{-2}$, $1.674 \times 10^{-6}$ and $-7.256 \times 10^{-10}$, respectively. For the temperature of nitrogen gas is range from 1 000 K to 2 000 K, their values are $8.686 \times 10^2$, $4.416 \times 10^1$, $-1.687 \times 10^{-4}$, $2.997 \times 10^{-8}$ and $-2.004 \times 10^{-12}$, respectively.

The pressure-velocity coupling with pressure based solution method has been adopted. To convert the differential equations that govern the fluid flow, a set of algebraic equations have been used; the standard spatial discretization method has been used for pressure. Meanwhile, other variables including the energy, turbulent kinetic energy, and dissipation rate are calculated by the QUICK (Quadratic Upstream Interpolation for Convective Kinematics) scheme. The standard wall function with a non-slip condition has been established in this model.23) The solution convergence of the numerical model has been obtained by two methods: (a) The residual energy is less than $10^{-7}$, and other variables are less than $10^{-5}$; and (b) The variations of the downstream outlet average temperature and velocity are allowed to be within 1.0 K and 1.0 m/s, respectively, at the outlet of the computational domain.

The mesh model of the computational domain is shown in Fig. 3(b). The structured grid has been adopted to build the model, with the grid number being 152 million. The local mesh refinement approach has been used at the exit of the main oxygen and the shrouding Laval nozzle, because of the velocity gradient of the supersonic jet.

4. Results and Discussions

4.1. Velocity Profile

As presented in Fig. 4, a low-density zone formed by the high-velocity shrouding gas suppresses the entrainment effect between the oxygen jet and the ambient gas, thus prolonging the length of the potential velocity core. Based on the previous research,15) the main oxygen velocity is 492 m/s, when its Mach number and static temperature are 2.0 and 297 K. The shrouding gas velocity is 781 m/s, when its Mach number and static temperature are 1.4 and 1 073 K. Although the design Mach number of the shrouding flow is lower than that of the main oxygen jet, a high preheating temperature makes the velocity of the shrouding flow greater than that of main oxygen jet.

Figure 5 illustrates the axial velocity profile of main oxygen jet at different shrouding flow rates and ambient temperatures. In this paper, the ambient temperatures of 300 K and 1 700 K are shorted as room and high ambient temperatures, respectively. To distinguish the axial velocity profile generated by various shrouding flow rates, the simulation data are represented by solid and dotted lines, respectively. The measurement data for the experimental test are shown as various symbols (□, ○, △, ▽, ◇). The symbol □, ○, △, ▽, ◇ represent the measurement data for the conventional lance and the coherent lance with 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h, respectively. Based on the results, the variation of axial velocity measured by the experimental study and the numerical simulation is 4.6
The main oxygen jet using a shrouding gas is classified as a coherent jet, whilst the main oxygen jet without a shrouding gas is classified as a conventional jet. The velocity potential core length of the coherent jet at room ambient temperature, using 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h shrouding flow rates results in the lengths of 17, 18, 19, 21, and 23 De, respectively. The velocity potential core length of the coherent jet at high ambient temperature using 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h shrouding flow rates results in lengths of 23, 26, 28, 30, and 32 De, respectively. In comparison, the velocity potential core length of the conventional jet at room and high ambient temperatures are 11 De and 16 De, respectively. As a result, the shroud shrouding flow rate relative to the conventional jet, and the potential core length increases as the shrouding flow rate and ambient temperature increase.

Moreover, the potential core length of the coherent jet at high ambient temperature with 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h shrouding flow rates result in lengths that are 1.35, 1.44, 1.47, 1.43, and 1.39 times larger than that of the coherent jet under room ambient temperature, respectively. As the ambient temperature increases, the increasing rate of the potential core length first increases, and then declines as the shrouding flow rate increases. When the shrouding flow rate reaches the design rate, the increasing rate of the potential core length is the highest value.

Figure 5 illustrates that a velocity variation exists between the coherent and the conventional jet in the region of the velocity potential core. At the room ambient temperature, the velocity fluctuation caused by the shock wave in the range 0 to 5 De using 0, 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h shrouding flow rates are 12.3, 24.8, 36.1, 45.7, 53.1, and 56.6 m/s, respectively. Meanwhile, their velocity fluctuations in the range 0 to 5 De are similar to those at the high ambient temperature. With a larger shrouding jet flow rate, more kinetic energy is removed from the main oxygen jet as it passes though the shock wave, resulting in the reduction of the axial velocity of the coherent jet and the formation of a velocity variation. Therefore, although the high-velocity shrouding gas prolongs the potential velocity length of the coherent jet, it reduces the average axial velocity of the main oxygen jet in the potential velocity zone.

### 4.2. Total Temperature Profile

Figure 6 depicts the total temperature distribution of the main oxygen jet at the centerline at room and high temperatures with various shrouding flow rates. When the high-velocity gas flow is brought to rest, the kinetic energy is converted to thermal energy. As a result, the gas is compressed and experiences an adiabatic increase in temperature. Therefore, the total temperature represents the total energy of the supersonic jet, including thermal energy and kinetic energy, and the total temperature of gas flow is calculated as follows:

$$T_{\text{total}} = T_{\text{static}} \times \left(1 + \frac{1}{2} \frac{V}{\sqrt{\gamma R T_{\text{ambient}}}}\right)$$

where $T_{\text{total}}$ and $T_{\text{static}}$ are total temperature and static temperature, respectively.

In this research, the total temperature of the oxygen jet is only measured at room ambient temperature, since the thermocouple may be damaged during the heating process for the furnace. Furthermore, the heat absorption rate is defined as the ratio of the per flow rate of the main oxygen maximum total temperature to the per flow rate of the shrouding gas’ initial temperature.

As shown in the Fig. 6(a), the maximum total temperatures of the main oxygen jet at room ambient temperature with 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h shrouding flow rates are 438.1, 456.6, 474.6, 492.8, and 512.2 K, respectively. Therefore, the heat absorption rates of the coherent jet at the room ambient temperature with 1 500, 2 000, 2 500, 3 000, and 3 500 Nm$^3$/h shrouding flow rates are 0.73, 0.57, 0.47, 0.41, and 0.37, respectively. Hence, the heat absorption rate of the coherent jet reduces as the shrouding flow rate increases; the cause of this phenomenon is discussed in the last paragraph of this section.

As represented in Fig. 6(b), both the conventional and coherent jets show an uptrend as the supersonic jet develops at the high ambient temperature. If the computation domain is big enough, the oxygen jet keeps absorbing the thermal energy until its static temperature becomes equal to the ambient temperature.

![Fig. 6. Total temperature profiles of the main oxygen jet at centerline. (a) The ambient temperature of 300 K. (b) The ambient temperature of 1 700 K. (Online version in color.)](image-url)
ambient temperature. Therefore, the maximum temperature of the main oxygen jet is totally dependent on the ambient temperature, and the shrouding gas flow has no effect on it; the heat absorption rate at high ambient temperature is not discussed further in this paper.

**Figure 7** presents the total temperature distribution of the coherent jet on a longitudinal section at room ambient temperature. The high-temperature shrouding flow wraps the main oxygen jet, which suppresses the entrainment effect between the oxygen jet and the ambient gas. As the shrouding flow rate increases, the area of the green zone for the coherent jet enlarges. When the shrouding total temperature reaches 400 K, the radial position of the shrouding jet with 1,500, 2,000, 2,500, 3,000, and 3,500 Nm$^3$/h flow rates are 2.2, 2.4, 2.6, 2.9, and 3.1 De, respectively. As mentioned, both the main oxygen jet and the ambient gas absorb the heat energy from the high-temperature shrouding due to the temperature gradient. The exterior surface area of the shrouding gas grows, as the shrouding flow rate increases. This increases the entrainment phenomenon that occurs between the coherent jet and the ambient atmosphere, resulting in the loss of more thermal energy and a reduction in the heat absorption rate of the coherent jet.

**Figure 8** presents the total temperature distribution of the coherent jet on a longitudinal section at high ambient temperature. As the ambient temperature is higher than that of shrouding gas, the shrouding gas first absorbs the thermal energy from the ambient gas, and then transmits the thermal energy to the main oxygen jet. That is a different thermal energy transfer method, comparing with that at the room ambient temperature. When the shrouding total temperature reaches 1,200 K, the radial position of the shrouding jet with 1,500, 2,000, 2,500, 3,000, and 3,500 Nm$^3$/h flow rates are 2.0, 1.9, 1.8, 1.7, and 1.6 De, respectively. It seems total temperature of the shrouding flow shows a downtrend, as its flow rate increases, although the exterior surface area of the shrouding gas increases. As a result, the increasing rate of total temperature of main oxygen jet would reduce further, as shown in the Fig. 6(b).

### 4.3. Turbulence Kinetic Energy Profile

The turbulence kinetic energy (TKE) represents the average kinetic energy per unit mass that is caused by eddies in the turbulent flow. Hence, the TKE is a measure of the root-mean-square velocity fluctuation. Figures 9 and 10 present the TKE profiles of the conventional and coherent jets.

The results show the maximum TKE of both the coherent and conventional jets have a tendency to decrease as the axial location increases. Comparing to the coherent jet, the axial location of the maximum TKE value for the conventional jet is closer to the centerline of the main oxygen jet. Hence, the velocity fluctuation of the conventional jet in that region is greater than that of the coherent jet, since it is entrained by the ambient gas faster in a radial direction.

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**Fig. 7.** Total temperature distributions of the coherent jet on longitudinal section under room ambient temperature. (a) 1,500 Nm$^3$/h shrouding rate. (b) 2,500 Nm$^3$/h shrouding rate. (c) 3,500 Nm$^3$/h shrouding rate. (Online version in color.)

**Fig. 8.** Total temperature distributions of the coherent jet on longitudinal section under high ambient temperature. (a) 1,500 Nm$^3$/h shrouding rate. (b) 2,500 Nm$^3$/h shrouding rate. (c) 3,500 Nm$^3$/h shrouding rate. (Online version in color.)
resulting in a rapid reduction in velocity.

As depicted in Figs. 9(a) and 10(a), TKE peaks are observed for the coherent jet, and the value of TKE peak increases as the radial location increases. The results also show only one TKE peak exists, as the X/De increases. As mentioned, the shock wave is formed by the shrouding jet in the range from 0 to 5 De, which generates an entrainment phenomenon effect between the main oxygen jet and the shrouding gas. As a result, a substantial velocity fluctuation and the TKE peak for the coherent jet forms in that region; the peak values increase even further if the shrouding flow rate increases. In addition, the entrainment phenomenon occurring between the main oxygen jet and the shrouding jet is smaller than that between the shrouding jet and the surrounding atmosphere, because the value of the TKE peak near the centerline is smaller. Moreover, the value of the TKE peak reduces at both room and high ambient temperatures, as the coherent jet develops, which represents a reduction in the intensity of the entrainment phenomenon effect between the shrouding jet and the surrounding atmosphere.

The average of the maximum TKE values for the coherent jet at the room ambient temperature with the X being 3, 8, and 12 De are $1.42 \times 10^4$, $0.87 \times 10^4$, and $0.73 \times 10^4$ m$^2$/s$^2$, respectively. The average of the maximum TKE values of the coherent jet at the high ambient temperature with the X being 3, 8, and 12 De, are $1.43 \times 10^4$, $1.08 \times 10^4$, and $0.94 \times 10^4$ m$^2$/s$^2$, respectively. Therefore, the high ambient temperature increases the maximum TKE. Moreover, the decline rate of the average maximum TKE value for the coherent jet in the range from 3 De to 12 De at room and high ambient temperature is 49.3% and 34.3%, respectively. Hence, the high ambient temperature suppresses the velocity fluctuation’s rate of decline and the TKE value.

5. Conclusion

In this paper, the behavior of a coherent jet with a shrouding Laval nozzle structure and preheating technology is investigated at different shrouding flow rates and ambient temperatures. A simulation and an experimental study are
conducted; the results of axial velocity and total temperature are in good agreement with each other in a case that the ambient temperature is room temperature. The main conclusions from the investigations are summarized as follows:

1) The shrouding Laval nozzle structure and the preheating technology can obviously increase the length of velocity potential core for the main oxygen jet by generating a low-density region. As the ambient temperature increases, the increasing rate of the potential core length first increases, and then reduces with an improving the shrouding flow rate. When the shrouding flow rate reaches the design rate, the increasing rate of the potential core length is the highest.

2) However, the shrouding jet forms a shock wave at the exit of the Laval nozzle, resulting in the removal of kinetic energy from the main oxygen jet after it passes through. As a result, the axial velocity of the coherent jet is smaller than that of the conventional jet; the velocity variation increases as the flow rate improves.

3) The exterior area surface of the shrouding gas improves as the shrouding flow rate increases, which improves the entrainment phenomenon that occurs between the coherent jet and the ambient atmosphere, resulting in the loss of more thermal energy. Therefore, the heat absorption rate of the coherent jet at room ambient temperature reduces as the shrouding flow rate increases.

4) The shock wave generates an entrainment phenomenon effect between the main oxygen jet and the shrouding gas, resulting in substantial velocity fluctuation and the peak value of the turbulence kinetic energy for the coherent jet. Based on the results, the entrainment phenomenon between the main oxygen jet and the shrouding jet is smaller than that between the shrouding jet and the surrounding atmosphere. In addition, the turbulence kinetic energy improves as the shrouding flow rate and the ambient temperature increases. However, the higher ambient temperature suppresses the decline rate of the velocity fluctuation for the coherent jet.

The results of this study provide a foundation for additional, future studies on the behavior of the flow field of the main oxygen jet with a shrouding Laval structure and preheating technology. The kinetic energy loss caused by the shock wave remains an important problem for improving the performance of the main oxygen jet in industrial applications. Moreover, the oxidative damage from the high preheating temperature to the shrouding nozzle should be taken into the consideration, which increases the manufacturing cost of the new coherent lance. The future research would focus on the design of the shrouding Laval structure for a coherent lance to retain the velocity of the main oxygen jet.

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