

## Article

# Research on the Temperature Control and Protection Effects of Low-Temperature Nitrogen on the Water Jet Cutting Process of Alloy Steel

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## Abstract

During abrasive waterjet cutting of alloy steel in complex field environments, local heat sources can induce temperature rise and oxidation risk. To address this issue, this study proposes a low-temperature nitrogen jet (LTNJ) method for simultaneous local cooling and air displacement near the cutting zone. A three-dimensional fluid-solid coupled heat-transfer and species-transport numerical model was established to investigate the coupled cooling and gas-coverage behavior. The study was further supported by infrared thermal-imaging measurements, in which the measured maximum apparent surface temperature remained within 32.1–33.6 °C during cutting under LTNJ assistance. The simulation results show that a nitrogen-enriched low-oxygen coverage region can be formed above the local heat source; for example, when the local nitrogen volume fraction reaches 64.74%, the estimated oxygen volume fraction decreases to approximately 7.39%. The gas temperature above the heat source decreases by more than 240 °C under the simulated conditions, and the relative position between the nozzle and heat source is the dominant factor affecting local cooling and gas coverage. Considering cooling effect, nitrogen utilization, and field implementation feasibility, the recommended parameter combination within the simulated range is a 10 mm horizontal distance between nozzle axis and heat-source center, a 30 mm vertical distance from nozzle outlet to workpiece surface, an initial nitrogen temperature of −50 °C, and a nitrogen flow rate of 5 m<sup>3</sup>/h. These results provide a numerical and preliminary experimental basis for low-temperature nitrogen-assisted temperature control and low-oxygen protection during abrasive waterjet cutting in complex field environments.

**Keywords:** low-temperature nitrogen jet; abrasive waterjet cutting; local heat source control; species transport; numerical simulation; infrared temperature validation



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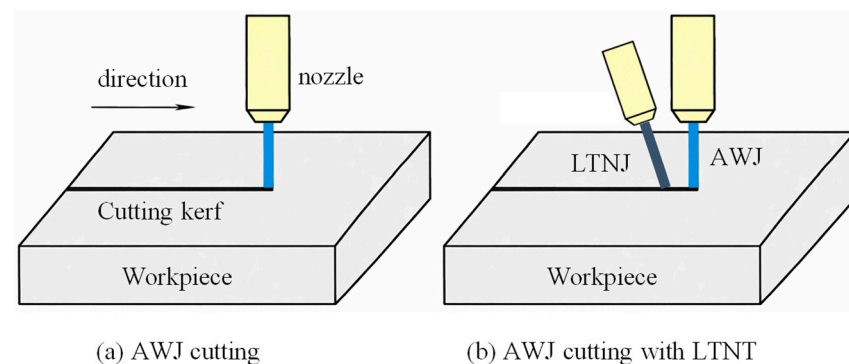
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## 1. Introduction

In emergency rescue, hazardous material removal, decommissioning of obsolete equipment, and component cutting in confined spaces, it is often necessary to cut metal components safely and efficiently in complex field environments. Such scenarios typically feature limited working space, complicated ambient conditions, high risks of flammability and explosion, and difficulties in equipment transportation and deployment, imposing higher demands on the mobility, safety, and environmental adaptability of cutting technologies [1,2]. Although traditional thermal cutting methods such as flame, plasma, and laser are widely used, they often face significant constraints in complex field environments: flame and plasma cutting have high heat input, which can easily cause thermal deformation of materials and potentially triggering secondary safety accidents such as fires and

explosions [3]; laser cutting requires stringent power conditions, equipment stability, and working environment, making it difficult to meet the requirements for rapid deployment and flexible operation under emergency conditions [4]. In contrast, high-pressure abrasive waterjet cutting offers advantages such as cold cutting, low reaction force, high mobility, and good environmental adaptability. It enables efficient cutting of metal materials under relatively low overall heat input, making it highly promising for metal dismantling, emergency disposal, and confined space operations in complex field environments [5,6].

Abrasive waterjet cutting uses a high-pressure water jet as a carrier to transport abrasive particles, forming a high-speed jet that removes material through continuous erosion. Figure 1 shows a schematic diagram of abrasive waterjet cutting. Although high-pressure abrasive waterjet cutting is generally considered a low-heat-input processing method, “cold cutting” does not imply a complete absence of thermal effects during the cutting process. In actual cutting, the continuous impact of the high-speed water jet and abrasive particles on the workpiece surface is accompanied by processes such as erosion, friction, plastic deformation, and particle fracture, generating local transient heat sources in the vicinity of the kerf [7]. For engineering metals such as alloy steel, this local heat accumulation can cause a rapid temperature rise near the cut, leading to issues such as the expansion of the heat-affected zone, increased surface oxidation, and degradation of local microstructure and mechanical properties [8]. Therefore, effectively suppressing local temperature rise and mitigating thermal damage risks in the cutting zone has become a pressing issue in the engineering application of high-pressure abrasive waterjet cutting.



**Figure 1.** Schematic diagram of AWJ cutting assisted with LTNT, (a) AWJ cutting; (b) AWJ cutting with LTNT.

To address the above issue, introducing a low-temperature nitrogen jet for simultaneous displacement and cooling in the cutting zone is an engineering-feasible heat-control approach. On one hand, the nitrogen jet can continuously dilute and displace ambient air around the cutting zone, forming a nitrogen-enriched low-oxygen coverage region above the local heat source and thereby reducing the probability of high-temperature oxidation reactions. On the other hand, the low-temperature high-speed jet enhances near-wall convective heat transfer on the workpiece surface, accelerates local heat removal, and inhibits hot-spot temperature rise and heat-affected-zone expansion [9]. Because the cutting heat source is locally concentrated, positionally migrating, and short-lived in complex field environments, low-temperature nitrogen-assisted heat control is a transient coupled heat and mass transfer process involving air displacement, inert-gas enrichment, near-wall heat-transfer enhancement, and internal conductive response of the solid.

Regarding the issues addressed in this paper, scholars both domestically and internationally have conducted relevant research from the aspects of thermal effects in abrasive jet cutting, gas impingement jet heat transfer, and local inert atmosphere protection. Hashish [10] systematically studied the abrasive jet cutting process of ductile metals

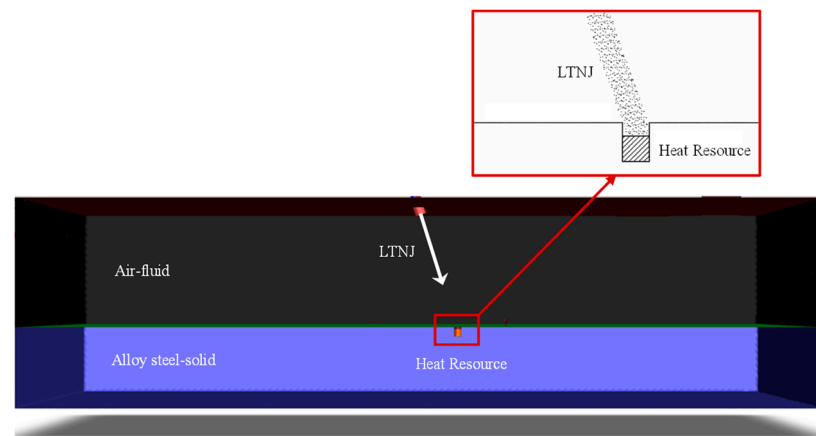
through experiments and theoretical modeling, demonstrating that cutting depth, kerf geometry, and surface quality are closely related to factors such as water pressure, abrasive flow rate, particle parameters, and traverse speed, laying a foundation for understanding energy input and material removal mechanisms in abrasive jet cutting. Spadło et al. [11] analyzed local temperature changes during abrasive waterjet cutting and their effects on material microstructure, showing that significant local thermal effects exist near the cutting zone. In terms of impingement jet heat transfer, Martin [12] systematically summarized the heat and mass transfer laws between impinging gas jets and solid surfaces, pointing out that nozzle geometry, nozzle-to-wall distance, and flow organization are key factors affecting local heat transfer performance, with the stagnation zone typically exhibiting high local heat transfer intensity. Jambunathan et al. [13] summarized the effects of jet distance, Reynolds number, and radial position on local heat transfer characteristics. Shin and Kim [14] further indicated that nitrogen jets possess strong local heat removal capability. Regarding local inert atmosphere protection, Zhang et al. [15] used a coaxial double-layer shielding nozzle to construct a local inert atmosphere and studied the effect of oxygen content in the local shielding zone on the forming quality of Ti6Al4V. The results showed that as local oxygen concentration decreased, surface oxidation and discoloration were significantly reduced, and forming quality improved. Bernauer et al. [16] pointed out that the stability of the local inert coverage layer is closely related to nozzle geometry, gas flow rate, and flow field organization. Park et al. [17] suggested that nitrogen can provide an inert environment while enhancing cooling, thereby reducing oxidation and deformation. Existing research has achieved certain results in the areas of cutting thermal effects, jet heat transfer, and inert protection, but studies on the coupling mechanism among simultaneous low-temperature nitrogen displacement, inert coverage formation, and local temperature response during high-pressure waterjet cutting of metals in complex field environments are still lacking. In particular, systematic research targeting the synergistic effects of nozzle arrangement, jet distances, nitrogen temperature, and flow rate in the context of this paper is needed.

Based on this, this paper investigates the low-temperature nitrogen displacement and temperature-control mechanism during abrasive waterjet cutting of alloy steel in complex field environments. Different from previous work that mainly considered cryogenic cooling, nitrogen shielding, impinging-jet heat transfer, or abrasive waterjet cutting thermal effects separately, this study focuses on the coupled behavior among nitrogen-air species transport, local inert-gas enrichment, jet impingement cooling, and solid heat conduction near a localized cutting heat source. A three-dimensional numerical model is established using Fluent to simulate gas flow, species distribution, and temperature-field evolution in the cutting zone. Infrared thermal-imaging measurements are further introduced as preliminary validation of the temperature-control tendency. The objective is to clarify the influence of nozzle arrangement, jet distance, nitrogen temperature, and flow rate, and to provide a cautious parameter-selection basis for low-temperature nitrogen-assisted abrasive waterjet cutting under field conditions.

## 2. Model Establishment and Numerical Method

### 2.1. Geometric Model

Considering the structural complexity of the actual device and the fact that this paper focuses on the displacement and heat transfer behavior of the low-temperature nitrogen jet on the local high-temperature zone, the actual object is reasonably simplified while retaining the main geometric features and physical processes. A three-dimensional geometric model is established, as shown in Figure 2.



**Figure 2.** 3D geometric model.

The model mainly includes the steel plate solid domain, external gas domain, local heat source zone, surface cavity zone, and nozzle inlet. A fluid-solid coupling interface enables bidirectional heat transfer between the fluid domain and the solid domain. The steel plate represents the cut metal component, the local heat source zone simulates the high-temperature region formed during cutting, the cavity zone represents the local morphology after surface material removal, and the nozzle inlet is used to construct the inclined low-temperature nitrogen impingement jet. The main geometric parameters of the model are listed in Table 1.

**Table 1.** Geometric model parameters. In the revised model description, the nozzle axis is inclined toward the local heat-source region, and the nozzle-to-wall distance and horizontal offset listed in Table 1 are defined with respect to the nozzle outlet and the heat-source center. The gas domain boundaries represent an open ambient environment, while the local solid-domain simplifications are used to focus the calculation on the jet-heat-source interaction region.

| Parameter                                                      | Value  | Parameter                                                 | Value  |
|----------------------------------------------------------------|--------|-----------------------------------------------------------|--------|
| Steel plate length                                             | 200 mm | Heat source temperature                                   | 300 °C |
| Steel plate width                                              | 100 mm | Cavity diameter                                           | 2 mm   |
| Steel plate thickness                                          | 20 mm  | Cavity height                                             | 1 mm   |
| Heat source diameter                                           | 2 mm   | Heat source height                                        | 2 mm   |
| Horizontal distance between nozzle axis and heat source center | 10 mm  | Vertical distance from nozzle outlet to workpiece surface | 30 mm  |

## 2.2. Mathematical Model

To describe the flow, heat transfer, and gas displacement processes in the local high-temperature region under the action of a low-temperature nitrogen jet, a fluid-solid coupled mathematical model is established based on reasonable simplifications. The model simultaneously considers mass conservation, momentum conservation, energy conservation, and species diffusion processes. A turbulence model is used to close the complex impinging jet flow, enabling the unified solution of the temperature, velocity, and nitrogen concentration fields.

### (1) Governing equations

Due to the significant temperature difference between low-temperature nitrogen and ambient air, the fluid density exhibits spatial non-uniformity with temperature, forming a variable-density flow field. Meanwhile, after the high-speed jet impacts the wall, complex flow structures such as the stagnation zone, wall jet zone, and recirculation zone are

formed. The continuity equation characterizes the mass conservation relationship in the flow field [18,19], expressed as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

where  $\rho$ —fluid density (kg/m<sup>3</sup>);  $t$ —time (s);  $\vec{v}$ —velocity vector (m/s).

During the high-speed nitrogen jet impingement process, significant pressure gradients, velocity gradients, and shear effects exist in the flow field. Meanwhile, density variations caused by temperature differences induce buoyancy forces. Therefore, the momentum conservation equation is used to describe the flow characteristics, coupled with the continuity equation [20], expressed as follows:

$$\frac{\partial(\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \vec{\tau} + \rho \vec{g} + \vec{F} \quad (2)$$

where  $p$ —static pressure (Pa);  $\vec{\tau}$ —viscous stress tensor (Pa);  $\vec{g}$ —gravitational acceleration vector (m/s<sup>2</sup>);  $\vec{F}$ —other body forces.

In the low-temperature nitrogen jet cooling process, multiple energy transfer forms such as convection and conduction exist in the flow field, with significant temperature-driven effects [21]. Jet impingement also introduces some viscous dissipation effects. At the fluid-solid interface, energy transfer must satisfy the heat flux continuity condition [22]. Therefore, the energy conservation equation is used to describe the above process, expressed as follows:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot (k_{eff} \nabla T) + \nabla \cdot (\vec{\tau}_{eff} \cdot \vec{v}) + S_h \quad (3)$$

where  $E$ —total energy of the fluid (J/kg);  $k_{eff}$ —effective thermal conductivity (W/m·K);  $T$ —temperature (K);  $S_h$ —volumetric heat source term (W/m<sup>3</sup>), which is zero in this model.

## (2) Turbulence model

During the jet impingement process, the flow exhibits characteristics such as strong shear, curvature, and local separation, imposing high demands on the suitability of the turbulence model. Therefore, the Realizable k- $\epsilon$  turbulence model is selected to close the flow. This model has good accuracy in predicting jet expansion, impingement flow, and separated flow, while balancing computational efficiency [23,24]. Its transport equations are as follows:

### a. Turbulent kinetic energy (k) equation:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \epsilon \quad (4)$$

### b. Dissipation rate ( $\epsilon$ ) equation:

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} \quad (5)$$

where  $C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right]$ ;  $C_2 = 1.9$ .

This model improves the prediction capability for complex flow structures by modifying the turbulent viscosity formulation and introducing functions related to the flow field deformation rate.

## (3) Multi-component gas transport model

To accurately describe the displacement and diffusion process between nitrogen and air, a multi-component transport model is used to simulate the gas mixing behavior. This model captures the non-uniform distribution characteristics of species concentrations and updates the thermophysical properties of the gas mixture in real time based on local composition changes, thereby improving the reliability of the calculation result [25].

The model considers two components, nitrogen and air. For each component  $i$ , the conservation equation for its mass fraction  $Y_i$  is:

$$\frac{\partial(\rho Y_i)}{\partial t} + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i \quad (6)$$

where  $\vec{J}_i$  is the diffusion flux of component  $i$  ( $\text{kg}/\text{m}^2 \cdot \text{s}$ ), typically described by Fick's Law:

$$\vec{J}_i = -\rho D_{i,m} \nabla Y_i \quad (7)$$

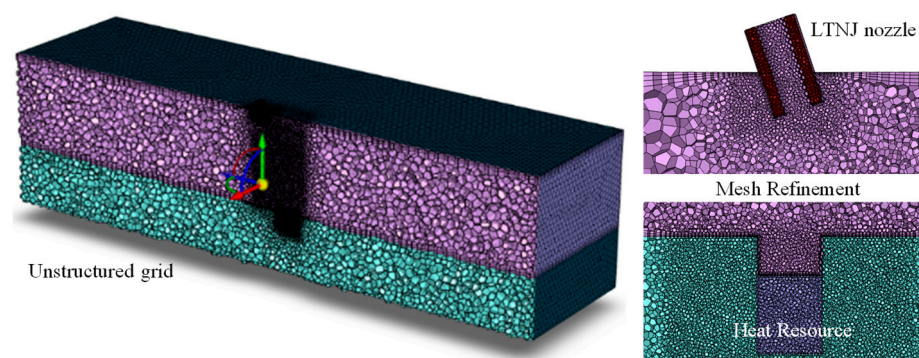
where  $D_{i,m}$  is the mass diffusion coefficient of component  $i$  in the mixture ( $\text{m}^2/\text{s}$ ). For the nitrogen-air binary system, the Fuller-Schettler-Giddings empirical formula can be used to calculate the diffusion coefficient:

$$D_{AB} = \frac{1.0 \times 10^{-7} T^{1.75} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}}}{P \left[ (\sum v)_A^{1/3} + (\sum v)_B^{1/3} \right]^2} \quad (8)$$

where  $T$ —temperature (K);  $P$ —pressure (atm);  $M_A, M_B$ —molecular weights of components;  $\sum v$ —diffusion volume of the component.

### 2.3. Mesh Generation and Solver Settings

After establishing the geometric and mathematical models, the computational domain was discretized and the corresponding solution settings were specified. A predominantly hexahedral mesh with local refinement was adopted in the nozzle outlet region, impingement region, gas–solid interface, cavity zone, and heat-source neighborhood to resolve velocity, temperature, and species-concentration gradients, as shown in Figure 3. The minimum local mesh size was 0.05 mm. To address mesh sensitivity, three mesh levels were compared using the average steel temperature within 3 mm of the heat source and the nitrogen volume fraction above the heat source as monitoring quantities. The results of the grid independence test are shown in Table 2. The medium mesh level is sufficient to meet the requirements of the present numerical simulation; therefore, the final mesh count is set to 932,654.



**Figure 3.** Structured mesh and local refinement near the nozzle, cavity, heat source, and gas–solid interface.

**Table 2.** Mesh sensitivity analysis table.

| Mesh Level | Cell Number | Average Steel Temperature Near Heat Source | Nitrogen Volume Fraction Above Heat Source |
|------------|-------------|--------------------------------------------|--------------------------------------------|
| Coarse     | 325,838     | 205.6 °C                                   | 0.58                                       |
| Medium     | 653,682     | 187.2 °C                                   | 0.66                                       |
| Fine/final | 932,645     | 186.7 °C                                   | 0.67                                       |

Regarding material properties, the ideal gas law is used for gas density, and the specific heat capacity is set as a temperature-dependent function. For steel, the density is 8030 kg/m<sup>3</sup>, and both thermal conductivity and specific heat capacity are considered temperature-dependent to reflect thermophysical property variations during heat transfer.

The initial conditions were set as follows: the initial flow velocity was 0 m/s, the pressure was 101,325 Pa, the initial temperature was 20 °C except in the prescribed local heat-source zone, and the initial gas in the computational domain was air. The nitrogen inlet was set as a mass-flow inlet corresponding to the specified volume flow rate under the inlet temperature and pressure; pure nitrogen was assigned at the inlet. The mass flow rate was calculated from the volume flow rate according to  $m_t = \rho_{N_2}Q$ , where  $\rho_{N_2}$  is the nitrogen density at the inlet state and  $Q$  is the volume flow rate. The outlet was set as a pressure outlet at ambient pressure, and the far-field gas boundaries were treated as open ambient boundaries. The heat-source surface was prescribed as a 300 °C constant-temperature wall with the geometric size listed in Table 1. The remaining distant solid boundaries were simplified as thermally insulated boundaries to focus on the local cooling response; the influence of exposed-edge heat loss under open-air field conditions is discussed as a model limitation. The CFD solution used a pressure-based solver with energy, turbulence, and species-transport equations enabled. The pressure-velocity coupling scheme, discretization schemes, residual convergence criteria, and monitored residual values should be reported explicitly from the final Fluent setup in the revised numerical-method table.

The heat-source treatment is an idealized local thermal boundary representing the concentrated thermal effect generated by abrasive impact, friction, local plastic deformation, and particle fracture during cutting. This constant-temperature boundary allows the influence of LTNJ cooling and air displacement to be isolated under controlled numerical conditions. A moving heat-source model will be required in future work to reproduce continuous cutting more completely.

### 3. Results Analysis

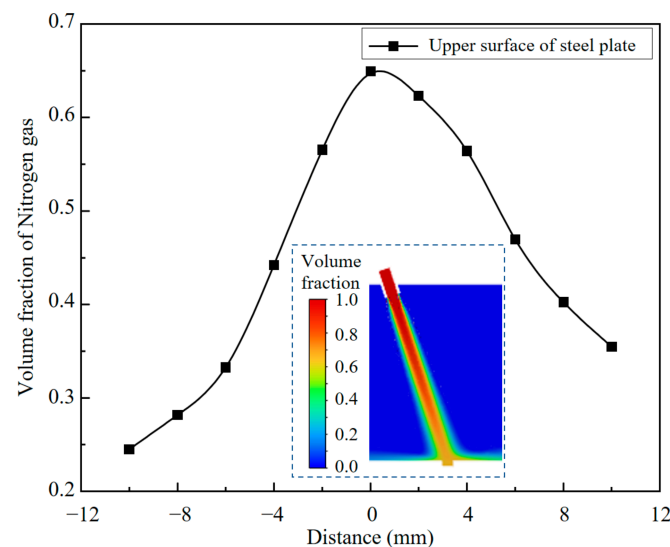
#### 3.1. Characteristics of Low-Temperature Nitrogen Displacement of Air

##### (1) Distribution of low-temperature nitrogen volume fraction

To quantitatively characterize the displacement capability and spatial distribution characteristics of the low-temperature nitrogen jet on air, the nitrogen volume fraction is selected as a key evaluation parameter. This parameter intuitively reflects the extent of nitrogen diffusion, coverage, and enrichment in the computational domain, which is important for revealing the gas transport and mixing patterns under the action of the jet. Based on numerical simulation results, the spatial distribution of nitrogen volume fraction and its variation along the wall are analyzed. The relevant results are shown in Figure 4.

It can be seen from the figures that the nitrogen jet forms a clearly defined high-concentration jet plume structure in the air domain. The nitrogen volume fraction is high in the main jet axis region, gradually decreasing along the jet direction, exhibiting a slender conical distribution with good continuity and directionality. In the region near the steel plate surface, the jet directly acts on the area above the heat source, forming a local high-

concentration nitrogen accumulation zone. In this zone, the nitrogen volume fraction is high, and the air volume fraction is significantly reduced, showing a coverage-like distribution. As the distance from the heat source center increases, the nitrogen volume fraction gradually decreases, reflecting a clear spatial gradient characteristic.



**Figure 4.** Distribution of the volume fraction of low-temperature nitrogen at different distances from the heat source and the corresponding spatial contour map.

The nitrogen volume fraction reaches a peak value of 64.74% directly above the heat source and decays bilaterally from this center. The distribution along the steel plate surface is asymmetric: the decay is faster on the left side, reaching 44.25% at 4 mm from the heat source and 28.17% at 8 mm; the decay is relatively slower on the right side, reaching 56.45% at 4 mm and still 40.27% at 8 mm. The overall distribution exhibits a “steep left, gentle right” pattern, indicating that nitrogen has a stronger expansion and coverage capability on the right side.

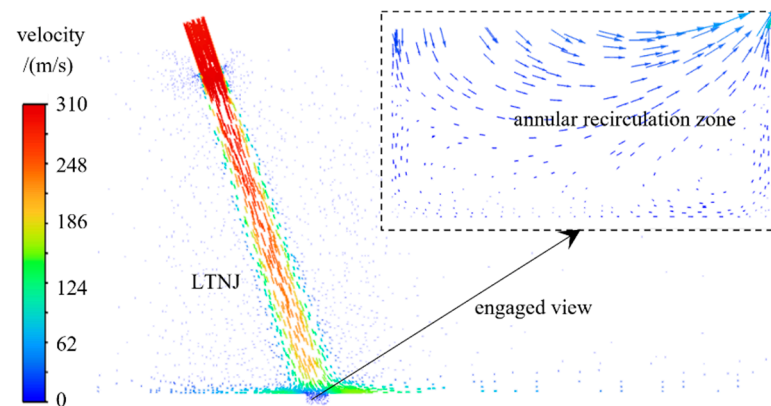
To avoid interpreting nitrogen volume fraction as direct proof of complete oxygen isolation, the oxygen content near the heat-source region was estimated from the residual air fraction. Assuming dry air contains approximately 20.95% oxygen by volume, the local oxygen volume fraction can be estimated as  $X_{O_2} = 0.2095 \times (1 - X_{N_2})$ . Therefore, when the nitrogen volume fraction above the heat source reaches 64.74%, the estimated oxygen volume fraction is approximately 7.39%. The protective region is therefore described as a nitrogen-enriched low-oxygen coverage region rather than a completely oxygen-isolated zone.

## (2) Velocity distribution of low-temperature nitrogen

To analyze the flow evolution and momentum distribution characteristics of the low-temperature nitrogen jet, the velocity vector is used to characterize the flow field structure. The velocity field intuitively reflects the jet development process, energy attenuation law, and flow pattern after interaction with the wall, serving as an important basis for identifying the stagnation and recirculation zones. The velocity distribution characteristics of the flow field are shown in Figure 5.

It can be seen from the figure that the velocity is highest near the nozzle outlet, and the airflow develops in a concentrated manner along the jet direction, forming a stable main jet zone. As the jet proceeds downstream, the velocity gradually decreases, showing a clear attenuation trend. In the region where the jet contacts the steel plate surface, the streamlines bend significantly, forming local flow separation and recirculation structures. In the magnified region, it can be seen that near the impingement point, the gas splits to

both sides, and the velocity vectors transition from concentrated to dispersed, forming a local annular recirculation zone above the heat source. Within the recirculation zone, the vector directions are interlaced, and the velocity is low, indicating strong flow disturbance and weak flow field stability.

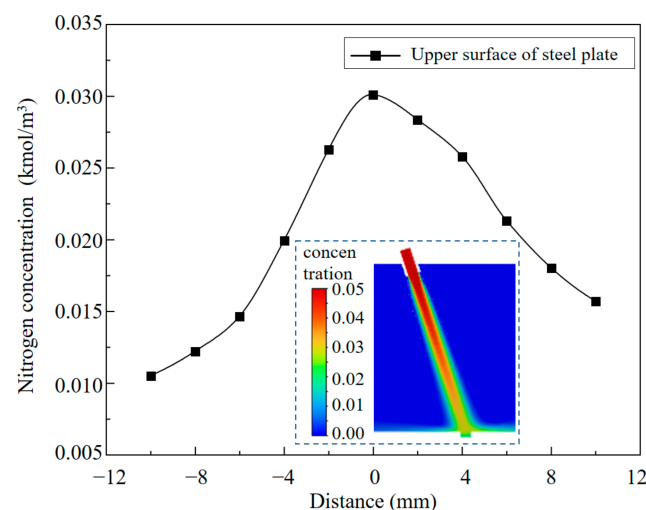


**Figure 5.** Velocity-vector distribution of the low-temperature nitrogen jet.

Above and around the impingement point, some vectors extend upward and to the right, indicating secondary flow after jet impingement, with gas exhibiting a circular circulation motion in the low-velocity zone. In the overall flow field, the main jet zone has high velocity and concentrated direction, while the secondary flow zone has low velocity and dispersed direction, showing distinct zoning characteristics.

### (3) Concentration distribution of low-temperature nitrogen

To further characterize the transport and diffusion behavior of low-temperature nitrogen in the flow field, the nitrogen concentration is selected as a characterization parameter, and its spatial distribution and wall variation patterns are analyzed. Nitrogen concentration reflects the gas mixing and diffusion process at the molecular scale, helping to reveal the actual effectiveness of the jet in displacing air. The relevant results are shown in Figure 6.



**Figure 6.** Low-temperature nitrogen volume-fraction distribution on the upper surface of the steel plate and in the gas domain.

It can be seen from the figures that nitrogen exhibits a typical jet diffusion pattern in the flow field. The high-concentration region is concentrated near the nozzle outlet and extends downstream along the jet direction, forming a slender high-concentration

mainstream zone that gradually attenuates downstream. There is a clear concentration gradient at the periphery of the mainstream zone, indicating continuous mixing between nitrogen and the surrounding gas; far from the jet region, the concentration distribution becomes relatively uniform, and diffusion effects weaken. The overall distribution is consistent with the volume fraction results, indicating good correspondence in spatial characteristics between the two.

Centered on the heat source, the nitrogen concentration reaches a maximum value of  $0.030 \text{ kmol/m}^3$  at the zero point and decreases bilaterally along the upper surface of the steel plate, exhibiting an asymmetric “steep left, gentle right” characteristic. The left side decays faster, dropping to  $0.020 \text{ kmol/m}^3$  and  $0.012 \text{ kmol/m}^3$  at 4 mm and 8 mm from the heat source, respectively; the right side decays more gently, with corresponding values of  $0.026 \text{ kmol/m}^3$  and  $0.018 \text{ kmol/m}^3$ , indicating stronger diffusion and coverage capability on the right side.

In summary, the low-temperature nitrogen jet has a strong air displacement capability, can form a relatively stable high-nitrogen coverage zone above the heat source, and exhibits a “steep left, gentle right” asymmetric decay pattern along the steel plate surface. The coupling effect of the main jet, wall spreading, and local recirculation jointly determines the diffusion and coverage range of nitrogen.

### 3.2. Preliminary Infrared-Temperature Validation

To provide experimental support for the simulated temperature-control tendency, infrared thermal-imaging measurements were conducted during low-temperature nitrogen-assisted abrasive waterjet cutting. As shown in Table 3, the measured maximum apparent surface temperature was  $28.6^\circ\text{C}$  before cutting and remained within  $32.1\text{--}33.6^\circ\text{C}$  during cutting, with a value of  $33.0^\circ\text{C}$  at cutting completion. Although the infrared measurement point and the numerical monitoring point are not strictly identical because of differences in emissivity, field of view, boundary simplification, and heat-source idealization, the measurement confirms that the assisted process suppresses substantial surface heat accumulation during cutting.

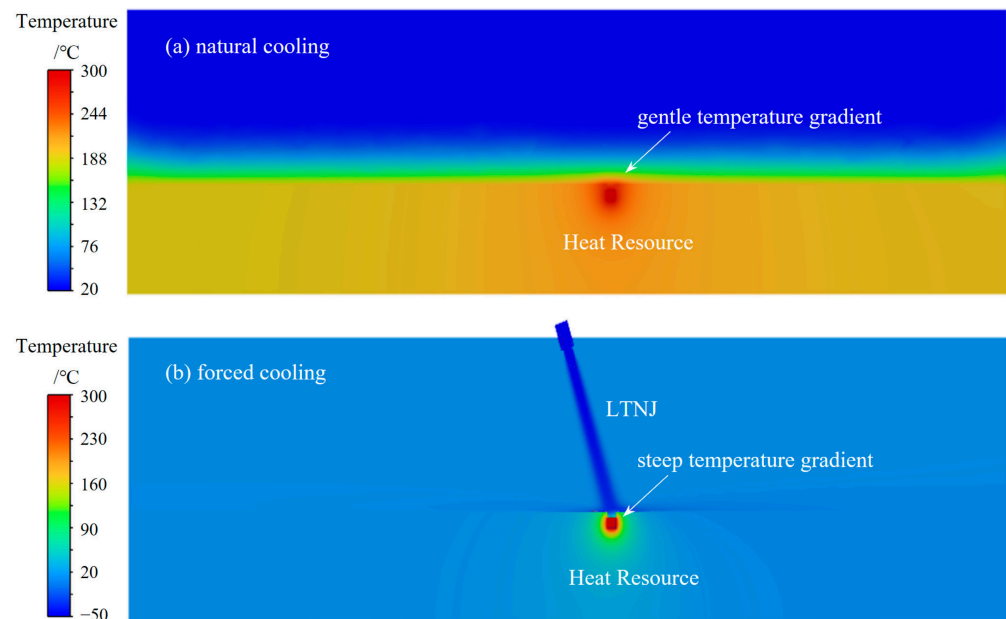
**Table 3.** Temperature measurement results with infrared thermal-imaging system.

| Time (s) | Process State     | Measured Maximum Apparent Surface Temperature ( $^\circ\text{C}$ ) |
|----------|-------------------|--------------------------------------------------------------------|
| 10       | Before cutting    | 28.6                                                               |
| 30       | Cutting           | 32.1                                                               |
| 40       | Cutting           | 32.3                                                               |
| 50       | Cutting           | 32.6                                                               |
| 60       | Cutting           | 33.4                                                               |
| 80       | Cutting           | 32.9                                                               |
| 90       | Cutting           | 33.6                                                               |
| 100      | Cutting           | 33.3                                                               |
| 110      | Cutting completed | 33.0                                                               |

#### (1) Temperature field distribution around the heat source

To analyze the heat transfer behavior around the heat source under different medium conditions, the temperature field distribution characteristics must first be examined. Figure 7 shows the temperature distribution contours around the heat source under ambient air and low-temperature nitrogen jet conditions, respectively, to compare the differences

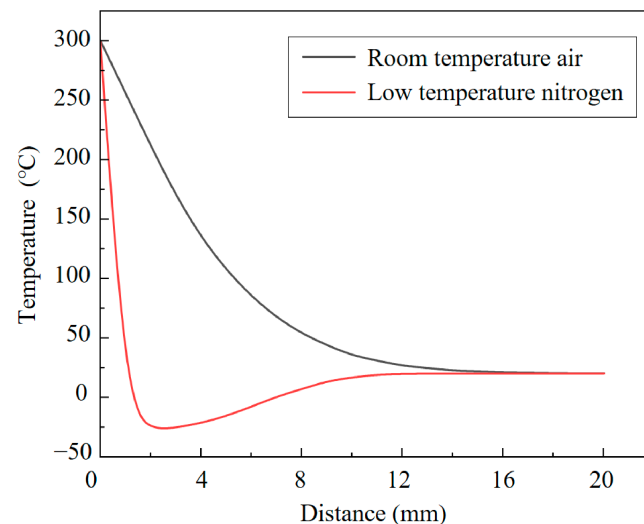
in temperature field morphology, high-temperature zone range, and temperature gradient variations between the two environments.



**Figure 7.** Temperature contours under ambient-air conditions and under low-temperature nitrogen jet assistance, (a) natural cooling; (b) forced cooling.

The results show that under ambient air, the temperature field around the heat source exhibits a relatively symmetric distribution overall. The high-temperature region extends radially from the heat source. The isothermal surfaces are approximately spherical, with a relatively gentle temperature gradient. There is an obvious high-temperature accumulation phenomenon directly above the heat source, and the high-temperature zone is relatively large. In contrast, under the low-temperature nitrogen jet, the temperature field around the heat source exhibits a significant asymmetric characteristic. A distinct low-temperature zone forms in the jet impingement region. The isotherms are densely distributed in the upstream region, indicating an increased temperature gradient. In the downstream region, the temperature extends along the wall direction, and the high-temperature zone is noticeably contracted. The isothermal surfaces transition from approximately spherical to asymmetric ellipsoidal, indicating that the low-temperature nitrogen jet has a significant cooling and compressing effect on the temperature field around the heat source.

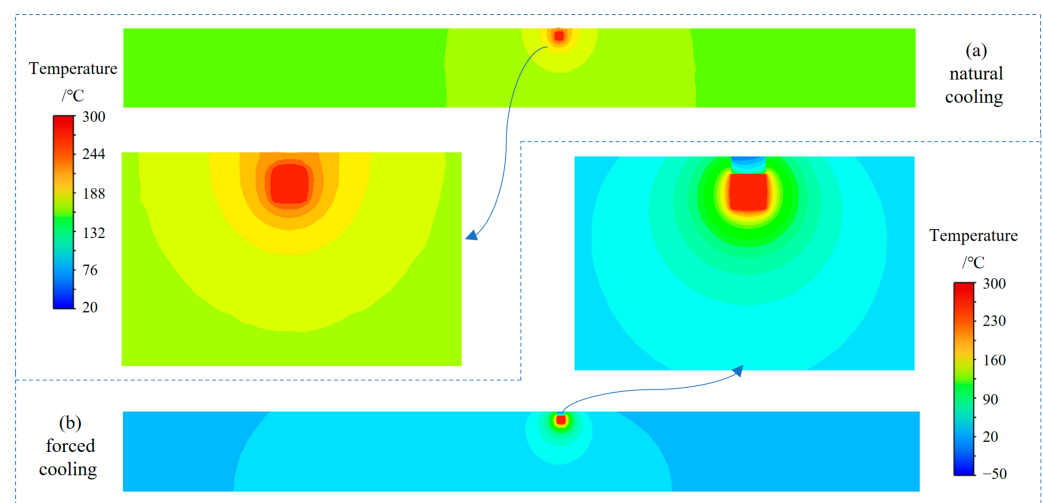
Figure 8 shows the temperature variation at different heights from the heat source under the two environments. In the range of 0–10 mm above the heat source, the temperature variation characteristics differ significantly between the two environments. In the near-field region 0–2 mm from the heat source surface, the gas temperature under the low-temperature nitrogen jet is significantly lower than that under the ambient air condition, with the largest temperature difference. As the vertical distance increases to 2–12 mm, the temperature difference between the two environments persists but gradually decreases. When the height reaches 12 mm, the gas temperatures under both conditions gradually approach the ambient temperature of 20 °C, indicating that the influence of the heat source essentially disappears. Throughout the measurement range, the temperature under the low-temperature nitrogen jet condition is always lower than that under the ambient air condition, and the two temperature curves gradually converge with increasing height, essentially coinciding at 16 mm.



**Figure 8.** Temperature variation at different heights from the heat source.

## (2) Temperature field distribution inside the steel plate

To further analyze the heat transfer behavior inside the steel plate under different medium conditions, it is necessary to examine the temperature field distribution characteristics. Figure 9 shows the temperature contours on the cross-section along the thickness direction of the steel plate under ambient air and low-temperature nitrogen jet conditions, respectively, to compare the distribution patterns and thermal influence ranges of the temperature field inside the steel plate in the two environments.

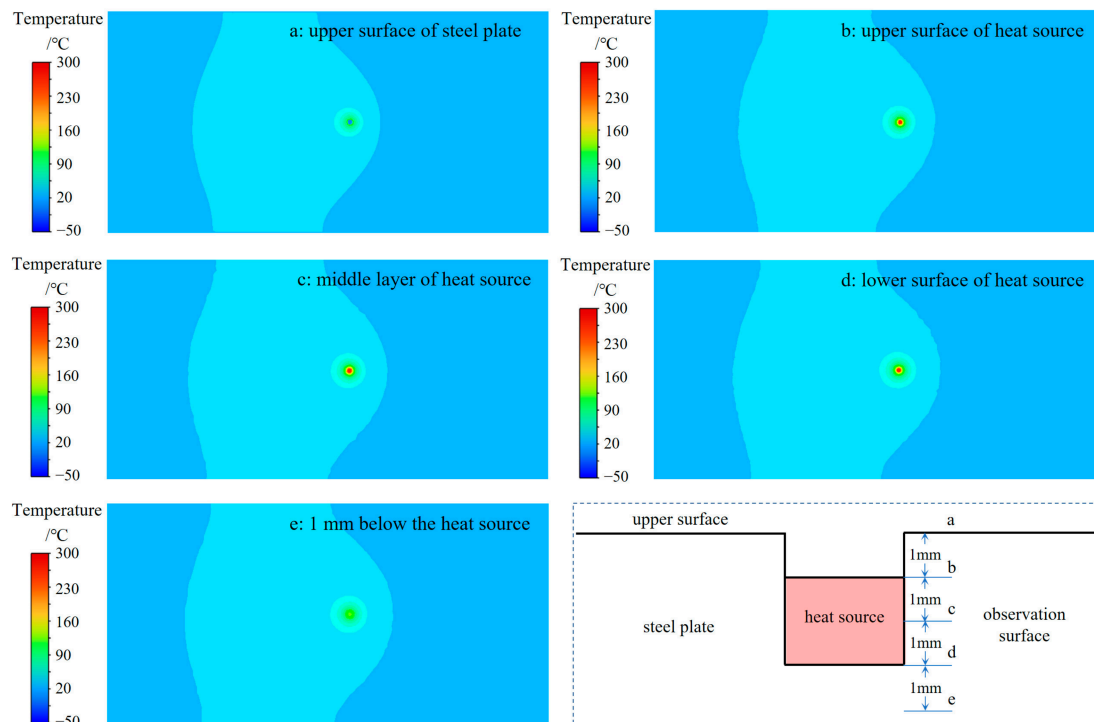


**Figure 9.** Temperature contours on the steel-plate thickness section under ambient-air and low-temperature nitrogen jet conditions, (a) natural cooling; (b) forced cooling.

The results show that under ambient air, the temperature field inside the steel plate exhibits a typical diffusion characteristic. The high-temperature region expands uniformly around the heat source and in the thickness direction. The isothermal surfaces are approximately hemispherical, with relatively regular isotherm distribution: dense near the center and gradually sparse outward. In contrast, under the low-temperature nitrogen jet, the temperature field inside the steel plate exhibits obvious asymmetry. The isothermal surfaces transition from regular hemispherical to asymmetric ellipsoidal. The heat-affected zone is significantly contracted, and its expansion in the jet impingement direction is suppressed. In the thickness-direction cross-section, the high-temperature region shifts downstream

relative to the jet direction. The isotherms are denser on the impingement side and sparser on the leeward side, indicating that the low-temperature nitrogen jet significantly enhances local cooling and alters the heat diffusion path inside the steel plate.

To further analyze the distribution characteristics of the temperature field inside the steel plate along the thickness direction, five characteristic horizontal cross-sections are selected along the thickness direction for observation, as shown in Figure 10: a (upper surface of steel plate), b (upper surface of heat source), c (middle layer of heat source), d (lower surface of heat source), and e (1 mm below the heat source). The corresponding temperature contours are also shown in Figure 10.



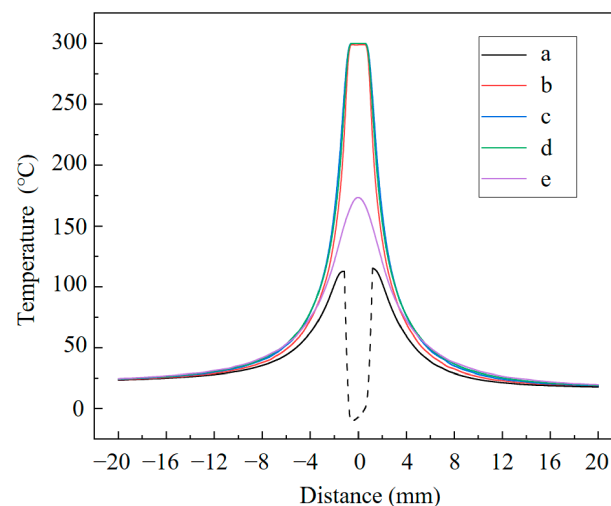
**Figure 10.** Temperature contours of representative cross-sections and schematic of the steel-plate cross-section positions, (a) upper surface of steel plate; (b) upper surface of heat source; (c) middle layer of heat source; (d) lower surface of heat source; (e) 1 mm below the heat source.

From the temperature contours of each cross-section, it can be seen that the overall temperature distribution inside the steel plate exhibits a clear directional characteristic. In the jet impingement direction, the temperature on the right side of the steel plate is significantly lower than that on the left side, with the asymmetry being most pronounced in cross-section a. As the observation position moves from cross-section a to cross-section e, this asymmetry weakens but always persists. The isotherms on each cross-section expand outward from the heat source. On cross-section a, the isotherms are distinctly asymmetric ellipses. As depth increases, the isotherms gradually transition to approximately circular shapes.

At a horizontal distance of 1 mm from the heat source, the temperatures on the five cross-sections are different: cross-section a: 106.78 °C, cross-section b: 261.88 °C, cross-section c: 294.95 °C, cross-section d: 286.56 °C, cross-section e: 156.36 °C. It is evident that the temperature distribution along the thickness direction exhibits clear layering characteristics. Cross-section c has the highest temperature, followed by cross-sections b and d, while cross-sections a and e have relatively lower temperatures, indicating that a concentrated high-temperature core forms in the middle region of the heat source. Meanwhile, the

temperature on cross-section e is significantly higher than that on cross-section a, indicating a significant temperature gradient along the steel plate thickness direction.

Figure 11 shows the temperature distribution patterns of the various cross-sections of the steel plate, where the dashed segment represents the nitrogen temperature variation within the cavity zone of the steel plate. It can be seen that within the range of 0–10 mm from the heat source, the temperatures on the five characteristic cross-sections (a, b, c, d, e) all drop rapidly, with the most drastic drop occurring in the range of 0–5 mm. In the range of 10–15 mm, the temperature drop becomes gradual, and the temperature differences between different cross-sections gradually diminish. When the horizontal distance reaches 16 mm, the temperatures on all cross-sections stabilize at approximately 20 °C, essentially consistent with the ambient temperature. From the comparison of different cross-sections, at the same horizontal distance, cross-section c always maintains the highest temperature, followed by cross-sections b and d, while cross-sections a and e are relatively lower. This order remains consistent throughout the measurement range, but the temperature differences between cross-sections gradually weaken with increasing horizontal distance.



**Figure 11.** Temperature distribution pattern of different sections of the steel plate, dashed line denotes the kerf, not a solid boundary.

In summary, the low-temperature nitrogen jet can significantly reduce the temperature around the heat source, compress the high-temperature region, and enhance the local temperature gradient, transforming the temperature field from a relatively symmetric distribution to an asymmetric distribution with a clear directionality. Simultaneously, the heat diffusion path inside the steel plate is altered under the action of the nitrogen jet, and the heat-affected zone is significantly contracted, effectively reducing heat accumulation and the thermal influence range.

## 4. Discussion

### 4.1. Mechanisms of Displacement and Cooling

#### (1) Mechanism and process analysis of air displacement by nitrogen jet

The displacement of air by a low-temperature nitrogen jet is essentially the result of the coupling of momentum transfer, species diffusion, and temperature difference effects. After being ejected at high speed from the nozzle at an incline, the nitrogen first relies on the jet momentum to force the displacement of the ambient air in the impingement region, forming an initial nitrogen-occupied zone near the heat source. Simultaneously, a significant velocity gradient exists between the jet boundary and the surrounding air,

which readily induces shear mixing and local vortex structures, thereby facilitating mass exchange between nitrogen and air.

As the jet continues, a nitrogen-dominated coverage region gradually forms around the heat source. This process mainly includes two stages: impact displacement and coverage stabilization. The former is characterized by the rapid expulsion of the air layer near the steel plate surface by the high-speed nitrogen, and the latter is characterized by the formation of a relatively stable low-temperature protective layer near the heat source under the combined action of jet inertia, buoyancy effects, and near-wall flow. The formation and stability of the protective layer are influenced by factors such as jet parameters, nozzle arrangement, and environmental conditions.

Comparing conditions with and without nitrogen jet, without nitrogen protection, the heat source is directly exposed to the ambient air, and the surrounding gas is primarily controlled by natural convection, with heat continuously diffusing outward and the heat-affected zone continuously expanding. Under nitrogen jet conditions, the air near the heat source is effectively displaced, the local oxygen concentration is significantly reduced, and the low-temperature nitrogen enhances the convective heat transfer capability near the heat source, thereby achieving coverage protection and rapid heat removal from the heat source region.

## (2) Mechanism and process analysis of local heat source energy transfer

The energy transfer process of the local heat source mainly includes heat conduction inside the steel plate and convective heat transfer at the gas–solid interface, representing an energy migration process involving multiple heat transfer modes. Inside the steel plate, heat is transferred from the heat source to the surrounding region primarily through conduction. Due to the small size of the heat source and concentrated energy input, a large local temperature gradient forms near the heat source, driving heat transfer outward both along the thickness direction and the in-plane direction of the steel plate. This process is controlled by the thermal properties of the material, such as thermal conductivity and specific heat capacity, and determines the distribution range and reduction characteristics of the temperature field inside the steel plate.

At the gas–solid interface, significant convective heat transfer occurs between the low-temperature nitrogen and the high-temperature steel plate. After the nitrogen jet impinges on the steel plate surface, a thin thermal boundary layer forms in the stagnation zone, significantly increasing the local heat transfer intensity. As the near-wall jet expands along the steel plate surface, the boundary layer thickness gradually increases, and the heat transfer intensity correspondingly decreases, but it remains significantly stronger than under natural convection conditions. The heat transfer characteristics on different regions of the steel plate surface also exhibit a certain asymmetry. The upstream region, directly subjected to jet impingement, experiences stronger local heat transfer. The downstream region is primarily affected by the wall jet, with relatively lower heat transfer intensity but a wider range of influence.

### 4.2. Parameter Influence Analysis

To make the parameter effects easier to compare, the paper summarizes the main indicators of each representative case, including steel temperature, nitrogen volume fraction, and estimated oxygen concentration. The oxygen concentration is calculated from the residual air fraction as described above. The statistical results of the parameter effects are shown in Table 4.

To reveal the influence mechanisms of different process parameters on the heat transfer and coverage characteristics of the low-temperature nitrogen jet, this paper focuses on analyzing the temperature field and nitrogen distribution patterns under variations in

parameters such as the horizontal distance between the nozzle and the heat source, the vertical distance from the nozzle to the workpiece surface, the initial nitrogen temperature, and the nitrogen flow rate. On this basis, a comprehensive optimization of the process parameters is carried out. By comparatively analyzing the influence patterns of each parameter, the key factors significantly affecting the cooling effect and inerting performance are identified, providing a basis for the optimal design of low-temperature nitrogen jet process parameters.

**Table 4.** Statistical results of the parameter effects.

| Case                        | Steel Temperature Indicator | N <sub>2</sub> Volume Fraction | Estimated O <sub>2</sub> Volume Fraction |
|-----------------------------|-----------------------------|--------------------------------|------------------------------------------|
| Baseline LTNJ               | 101.9 °C within 3 mm region | 0.6474                         | 7.39%                                    |
| Horizontal distance 30 mm   | 109.7 °C within 3 mm region | 0.48                           | 10.89%                                   |
| Vertical distance 90 mm     | 115.5 °C within 3 mm region | 0.17                           | 17.39%                                   |
| Nitrogen temperature −60 °C | 99.1 °C within 3 mm region  | 0.66                           | 7.12%                                    |
| Higher flow-rate case       | 88.6 °C within 3 mm region  | 0.68                           | 6.70%                                    |

The present parameter study is a first-stage sensitivity analysis in which one parameter is varied at a time. Interactions among the parameters may still be important. For example, a larger nozzle-to-wall distance can weaken jet momentum before impingement, and this effect may partly be compensated by increasing flow rate; similarly, decreasing nitrogen temperature increases the thermal driving force but may also affect gas density, jet momentum, and utilization efficiency. Therefore, the recommended parameter combination should be interpreted as an optimized set within the simulated parameter range rather than a universal optimum for all workpiece sizes and field environments.

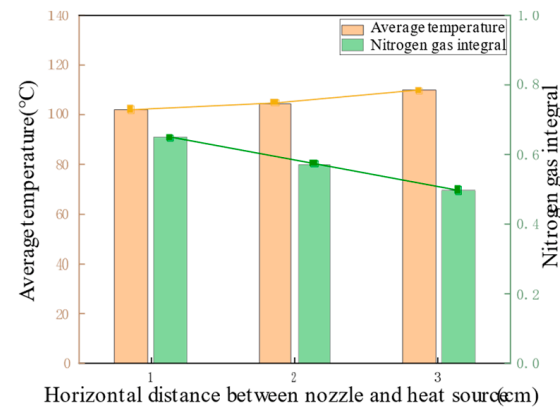
(1) Horizontal distance between nozzle and heat source

By varying the horizontal distance between the nozzle and the heat source, the variation patterns of the average temperature of the steel plate and the low-temperature nitrogen volume fraction at different horizontal distances are obtained, as shown in Figure 12. The results show that as the horizontal distance between the nozzle and the heat source increases, the average temperature of the steel plate tends to rise, while the low-temperature nitrogen volume fraction gradually decreases, showing an obvious inverse correlation. When the horizontal distance increases from 1 cm to 3 cm, the average temperature of the steel plate within 3 mm of the heat source increases from 101.9 °C to 109.7 °C, and the corresponding low-temperature nitrogen volume fraction decreases from 0.67 to 0.48. The results indicate that as the horizontal distance increases, the jet expansion range widens, and the dispersion and dilution of low-temperature nitrogen in the space are enhanced, leading to a decrease in nitrogen concentration near the heat source and a weakening of local cooling capability. Simultaneously, the inclined nozzle causes the jet action region to shift to the right, resulting in more pronounced cooling on the right side and insufficient cooling on the left side, further contributing to an increase in the overall average temperature.

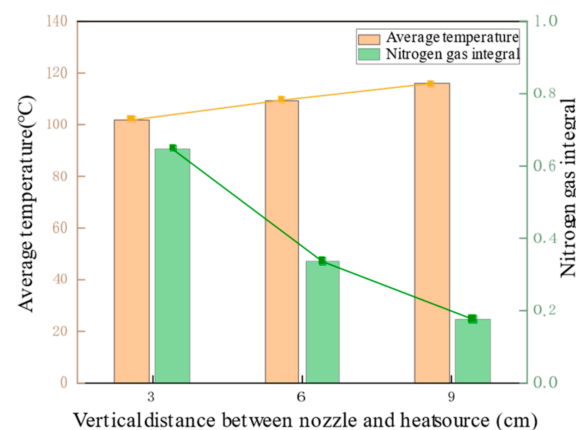
(2) Vertical distance between nozzle and heat source

By varying the vertical distance between the nozzle and the workpiece surface, the variation patterns of the average temperature of the steel plate and the low-temperature nitrogen volume fraction at different vertical distances are obtained, as shown in Figure 13. The results show that as the vertical distance between the nozzle and the workpiece surface increases, the average temperature of the steel plate within 3 mm of the heat source gradually increases, while the nitrogen volume fraction above the heat source continuously decreases, showing an obvious inverse trend. When the vertical distance increases from

3 cm to 6 cm and 9 cm, the average temperature of the steel plate increases from 101.9 °C to 109.3 °C and 115.5 °C, respectively, and the corresponding nitrogen volume fractions decrease from 0.65 to 0.33 and 0.17. The results indicate that as the vertical distance increases, the diffusion and attenuation of the jet before reaching the heat source region are enhanced, leading to a weakening of the nitrogen coverage capability above the heat source, thereby reducing the cooling effect on the steel plate and increasing the steel plate surface temperature.



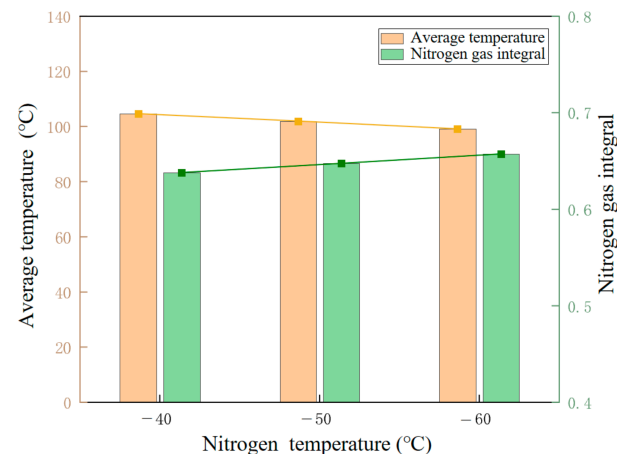
**Figure 12.** Variation in average steel temperature and low-temperature nitrogen volume fraction at different horizontal distances.



**Figure 13.** Variation in average steel temperature and low-temperature nitrogen volume fraction at different vertical distances.

### (3) Initial nitrogen temperature

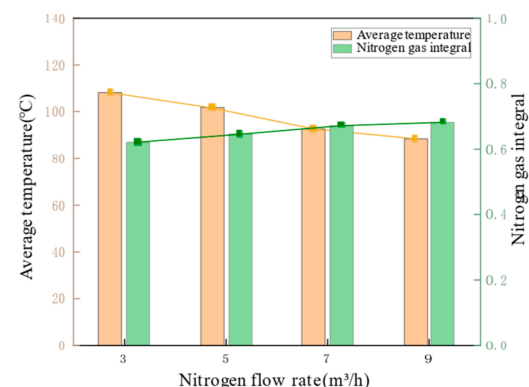
By varying the initial nitrogen temperature, the variation patterns of the average temperature of the steel plate and the low-temperature nitrogen volume fraction at different nitrogen temperatures are obtained, as shown in Figure 14. The results show that as the nitrogen temperature decreases from −40 °C to −60 °C, the average temperature of the steel plate within 3 mm of the heat source gradually decreases, while the low-temperature nitrogen volume fraction above the heat source slightly increases, showing an inverse trend. The average temperature of the steel plate decreases from 104.6 °C to 99.1 °C, and the corresponding low-temperature nitrogen volume fraction increases from 0.64 to 0.66. The results indicate that lowering the initial nitrogen temperature is beneficial for enhancing the cooling effect in the heat source region and also slightly improves the coverage capability of low-temperature nitrogen above the heat source.



**Figure 14.** Variation in average steel temperature and low-temperature nitrogen volume fraction under different inlet nitrogen temperatures.

#### (4) Nitrogen flow rate

By varying the nitrogen flow rate, the variation patterns of the average temperature of the steel plate and the low-temperature nitrogen volume fraction at different nitrogen flow rates are obtained, as shown in Figure 15. The results show that as the nitrogen flow rate increases, the average temperature of the steel plate within 3 mm of the heat source significantly decreases, while the low-temperature nitrogen volume fraction above the heat source gradually increases, showing an inverse trend. The average temperature of the steel plate decreases from 108.5 °C to 88.6 °C, and the corresponding low-temperature nitrogen volume fraction increases from 0.62 to 0.68. The results indicate that increasing the nitrogen flow rate can enhance the jet kinetic energy and nitrogen coverage capability, promoting the diffusion and spreading of low-temperature nitrogen near the heat source, thereby improving the cooling effect and reducing the steel plate surface temperature.



**Figure 15.** Variation in average steel temperature and low-temperature nitrogen volume fraction under different nitrogen flow rates.

#### 4.3. Comprehensive Optimization Strategy for Parameters

To obtain a process scheme that balances temperature control effectiveness, nitrogen coverage stability, and engineering feasibility, a systematic optimization of nozzle spatial arrangement and low-temperature nitrogen process parameters is carried out based on the comprehensive evaluation criteria of minimizing the average temperature within 3 mm of the heat source, maintaining the nitrogen volume fraction above the heat source stably above 60%, and keeping gas consumption and refrigeration load within engineering acceptable ranges. Parameter optimization focuses not only on local cooling capability

but also on nitrogen utilization efficiency and applicability under continuous field operation conditions, to achieve a reasonable balance between cooling performance and engineering cost.

The simulation results show that the relative position between the nozzle and the heat source significantly affects the temperature field and nitrogen coverage characteristics in the vicinity of the heat source. Reducing the horizontal distance between the nozzle and the heat source and the vertical distance from the nozzle to the workpiece surface is beneficial for enhancing the jet action intensity and improving the nitrogen coverage capability above the heat source. Simultaneously, lowering the initial nitrogen temperature and increasing the nitrogen flow rate can further enhance local convective heat transfer and improve the cooling effect in the heat source region. If the sole objective were to minimize temperature, parameter selection would tend towards lower nitrogen temperatures and higher flow rates; however, considering system capacity, continuous gas supply capability, and low-temperature nitrogen utilization efficiency, extreme parameter combinations are not the most engineering-feasible.

Based on comprehensive multi-parameter simulation results, the optimal process parameters are determined as: horizontal distance between nozzle and heat source of 10 mm, vertical distance from nozzle to workpiece surface of 30 mm, initial nitrogen temperature of  $-50\text{ }^{\circ}\text{C}$ , and nitrogen flow rate of  $5\text{ m}^3/\text{h}$ . Under this parameter combination, the jet can accurately act on the region above the heat source and form a relatively stable nitrogen coverage layer on the workpiece surface. Meanwhile, the moderate jet distance helps balance jet expansion range and momentum retention, avoiding coverage instability due to jet attenuation or excessive impingement. The initial nitrogen temperature of  $-50\text{ }^{\circ}\text{C}$  provides a strong heat transfer driving force, and the flow rate of  $5\text{ m}^3/\text{h}$  ensures local cooling capability while maintaining high nitrogen utilization efficiency.

Under this configuration, the nitrogen coverage layer above the heat source remains stable, the temperature in the vicinity of the heat source is effectively controlled, the temperature field distribution is relatively uniform, and the high-temperature concentration phenomenon is significantly alleviated. Local heat transfer transitions from being dominated solely by conduction to a synergistic effect of conduction and convection. The overall temperature gradient is reduced, and the effective range of cooling coverage is further expanded, thereby effectively suppressing air entrainment and reducing oxidation risk. This parameter combination achieves a good balance among local cooling capability, nitrogen coverage effectiveness, gas consumption, and engineering feasibility, and can be recommended as the process parameter set for subsequent experimental research and engineering applications.

For complex field applications, the recommended parameter set should be adapted according to workpiece thickness, local ventilation, available nozzle-installation space, and cutting-path accessibility. Practical improvement schemes include an adjustable nozzle bracket to maintain the nozzle-to-heat-source distance, real-time infrared-temperature monitoring, staged nitrogen-flow control, partial local shielding to reduce ambient-air entrainment, and recalibration of the flow rate and nozzle angle for different plate thicknesses or moving heat-source trajectories.

## 5. Conclusions

The main conclusions have been revised to avoid overstatement. The study now emphasizes that the low-temperature nitrogen jet improved local cooling and reduced air presence near the heat source under the simulated and preliminary infrared-measured conditions, while direct oxygen-concentration measurement and moving heat-source validation remain necessary in future work.

- (1) Based on the characteristics of the local heat source near the high-pressure abrasive waterjet cutting zone of alloy steel, a three-dimensional fluid-solid coupled heat transfer numerical model is established. This model can effectively characterize the flow behaviors such as the main jet, near-wall spreading, and local recirculation under inclined nozzle arrangement, providing an analytical tool for revealing the mechanisms of nitrogen displacement and temperature control.
- (2) Under the simulated conditions, the low-temperature nitrogen jet can establish a nitrogen-enriched low-oxygen coverage region near the heat source. Under the baseline design parameters, the low-temperature nitrogen forms a relatively stable inert coverage layer above the heat source. The peak nitrogen volume fraction above the heat source reaches 64.74%, exhibiting an asymmetric “steep left, gentle right” decay pattern along the steel plate surface.
- (3) The low-temperature nitrogen jet effectively suppresses local heat accumulation and reduces the thermal influence range. Compared with the ambient air condition, the low-temperature nitrogen jet significantly reconstructs the local temperature field. The gas temperature 2 mm directly above the heat source drops from above 212 °C to below −28 °C, a temperature drop exceeding 240 °C. Simultaneously, the high-temperature zone inside the steel plate is significantly contracted, and the thermal influence range is mainly limited to the approximately 16 mm region around the heat source.
- (4) The relative position of the nozzle significantly affects the cooling effect. Increasing both the horizontal offset and the vertical distance weakens the high-concentration nitrogen coverage above the heat source and the local cooling capability. Lowering the nitrogen temperature enhances convective heat transfer, while increasing the nitrogen flow rate improves the impact displacement capability; however, both must be balanced against flow field stability and energy consumption.
- (5) Considering the temperature reduction in the heat-source region, the nitrogen volume fraction above the heat source, estimated oxygen concentration, gas consumption, and field implementation feasibility, the recommended parameter combination within the simulated range is: horizontal distance between nozzle and heat source of 10 mm, vertical distance from nozzle to workpiece surface of 30 mm, initial nitrogen temperature of −50 °C, and nitrogen flow rate of 5 m<sup>3</sup>/h. This parameter combination ensures stable nitrogen coverage above the heat source and good local temperature control while keeping gas consumption and refrigeration load within reasonable ranges, demonstrating strong engineering applicability and providing a basis for field layout and parameter setting of low-temperature nitrogen-assisted processes.

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