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Simulation and Optimization of Structural Parameters of Nozzle for Abrasive Water Jet Stubble Breaking

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Abstract: Aiming at the demand for removing maize stubble in sticky soil areas of Southwest China, this study conducts simulation and optimization on nozzle structural parameters to improve the impact capacity and energy concentration of abrasive water jet. With garnet particles of 0.2 mm in diameter and an abrasive inlet velocity of 15 m/s as basic working conditions, the single-factor simulation method is adopted to investigate the influences of outlet length, convergence angle and mixing chamber length on jet velocity, beam convergence and energy distribution. The results show that the optimal parameter combination is determined as the outlet length of 20 mm, convergence angle of 30° and mixing chamber length of 30 mm. Under this structural configuration, the impact velocity of the jet reaches 180 m/s at a standoff distance of 200 mm. The jet features good beam convergence and slow kinetic energy attenuation along the path, which can effectively enhance the crushing performance of maize stubble. The research findings can provide theoretical references for the design and engineering application of nozzles used in agricultural abrasive water jet stubble breaking.

Keywords: Abrasive water jet, Stubble breaking, Nozzle, Flow field simulation, Parameter optimization.

1. Introduction

Maize is one of the major food crops in China [1]. With large-scale cultivation, residual maize stubbles in fields combine with cohesive soil to form high-strength root-soil complexes. Traditional mechanical stubble removing machines suffer from high working resistance, frequent blockages and severe soil disturbance, which fail to meet the requirements of conservation tillage [2]. As a non-contact processing technology, abrasive water jet features strong impact force, low disturbance and wide adaptability, and has been gradually applied to the cutting of agricultural materials and field operations [3].

The nozzle acts as the core energy conversion component of the abrasive water jet system. Its structure directly affects jet velocity, flow field pattern and energy concentration, and further determines the stubble crushing performance [4]. Although numerous studies on water jet nozzles for industrial applications have been conducted at home and abroad [5], researches on special nozzles tailored for maize stubble removal in cohesive soil areas of Southwest China are still insufficient. Foreign scholars have applied water jet technology to field residue treatment and verified its application potential under no-tillage conditions [6, 7]. Relevant experiments on water jet cutting of maize straw have also been carried out domestically [8]. Nevertheless, most existing studies have not conducted refined structural design of nozzles according to actual agricultural working conditions. In view of the above problems, this paper adopts CFD numerical simulation method to optimize the nozzle outlet length, convergence angle and mixing chamber length via single-factor analysis. The optimized nozzle structure suitable for maize stubble removal is obtained, which provides technical support for the research and development of agricultural abrasive water jet stubble removing equipment [9].

2. Simulation Model and Parameter Settings

2.1. Selection of Numerical Models

The research object in this paper is gas-liquid-solid three-phase abrasive water jet. The standard turbulence model is adopted to simulate the high-speed turbulent flow inside the nozzle. It features excellent computational stability and is well suited for the simulation of jet flow [10]. The Volume of Fluid (VOF) model is used to track the two-phase interface between air and water, so as to accurately capture the entrainment and diffusion of the jet. The Discrete Phase Model (DPM) is combined to simulate the motion trajectories of garnet abrasive particles and realize the coupling calculation of solid and liquid phases. The combined application of the above three models can fully characterize the flow field characteristics of abrasive water jets, and this modeling method has been widely verified in multiphase flow simulations. A large number of domestic and foreign studies have adopted similar models for water jet flow field calculation, and the simulation accuracy can meet the requirements of engineering analysis [11].

2.2. Geometric Model and Mesh Generation

A three-dimensional model is established based on the conical nozzle commonly used in agricultural operations. The inlet diameter of the main nozzle is 20 mm, and the diameter of the abrasive inlet is 3 mm. A cuboid computational domain with dimensions of 800 mm × 800 mm is built for the external flow field of the nozzle. Structured meshes are adopted for division, and a mesh independence verification is conducted. The total number of meshes is finally set at approximately 300,000. This mesh configuration balances computational accuracy and simulation efficiency, which is a general solution for water jet flow field simulation [12].

2.3. Basic Simulation Parameters

All basic simulation parameters are determined according to field operating conditions and preliminary simulation results. Clean water is taken as the continuous phase, with a density of 998 kg/m3 and dynamic viscosity of 0.001003 Pa·s. The discrete phase selects 60-mesh garnet abrasive with a particle size of 0.2 mm, a material density of 3890 kg/m3 and a Mohs hardness of 7.5. This type of abrasive is environmentally friendly and causes no pollution to farmland soil, which is fully adaptable to field working environments.

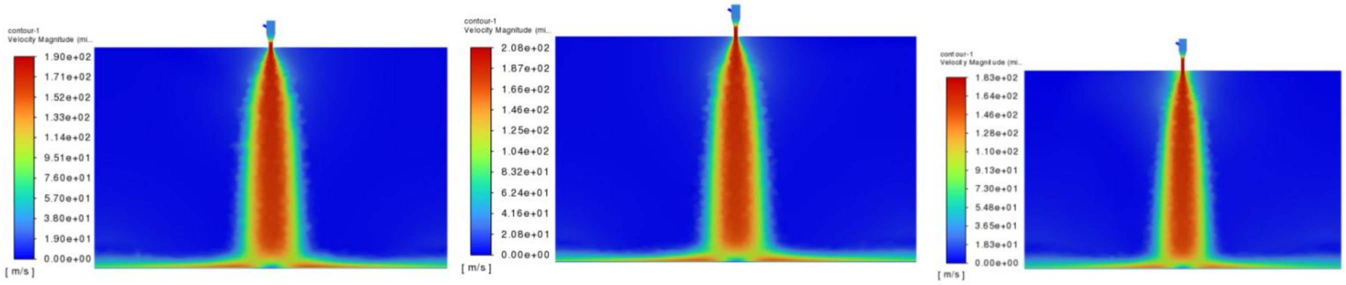
Both the water inlet and abrasive inlet are set as velocity inlets. The water flow velocity is 40 m/s, the abrasive inlet velocity is 15 m/s, and the corresponding abrasive mass flow rate is 7.3 g/s. The flow field outlet is defined as a pressure boundary with a gauge pressure of 0 Pa, and all wall surfaces adopt the no-slip boundary condition. The second-order upwind scheme is selected for discretization, and the convergence residual is set to 10−3. All parameter settings refer to relevant literature on abrasive water jet simulation [13].

3. Single-factor Simulation Optimization of Nozzle Structure

The jet axial velocity, radial velocity at the standoff distance of 200 mm and jet convergence are taken as evaluation indicators. Single-factor simulation analyses are carried out on the nozzle outlet length, convergence angle and mixing chamber length in sequence. Only one variable is changed in each group while all other parameters remain constant.

3.1. Optimization of Outlet Length

Simulations are conducted with outlet lengths set to 10 mm, 20 mm and 30 mm respectively, and the corresponding flow field characteristics are compared.



(a) 10mm (b) 20mm (c) 30mm

Figure 1. Velocity cloud diagrams of internal and external flow fields for nozzles with three outlet lengths

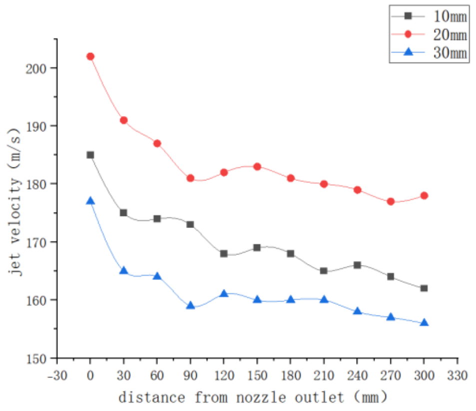


Figure 2. Jet velocity distribution along the central axis of nozzles with three outlet lengths

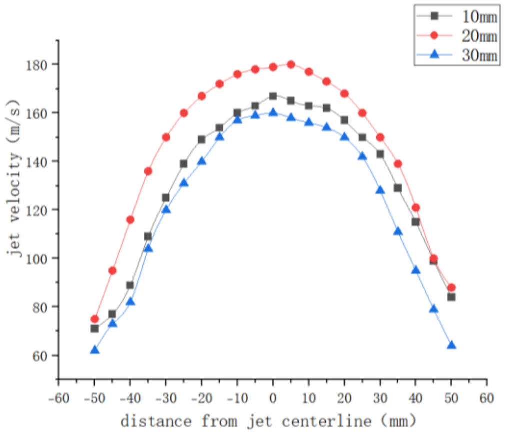
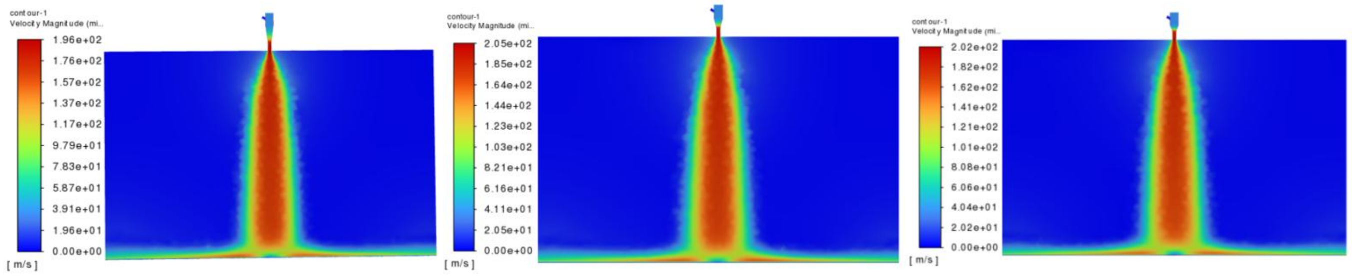


Figure 3. Radial velocity distribution at 200 mm from the outlet of nozzles with three outlet lengths

Simulations are performed on nozzles with outlet lengths of 10 mm, 20 mm and 30 mm. For the 10 mm outlet, the internal flow passage of the nozzle is short. Although the initial jet velocity is relatively high, the jet spreads rapidly after exiting the nozzle with poor convergence performance. The peak jet velocity at the standoff distance of 200 mm is only 165 m/s, and most of the kinetic energy is dissipated due to air disturbance. For the nozzle with a 30 mm outlet, the longer flow passage increases the frictional resistance of fluid flow, leading to a decrease in the overall jet velocity. The peak velocity drops to 160 m/s at the standoff distance of 200 m/s, which fails to provide sufficient impact kinetic energy for stubble breaking. When the outlet length is set to 20 mm, a good balance is achieved between flow resistance and jet convergence. The jet presents a small diffusion range and a gentle velocity attenuation along the axial direction. At the standoff distance of 200 mm, the peak jet velocity reaches 180 m/s, accompanied by a larger high-speed core region. Based on the comprehensive analysis of flow field performance, the optimal outlet length of the nozzle is determined to be 20 mm.

3.2. Optimization of Convergence Angle

With the outlet length fixed at 20 mm, simulations are carried out at convergence angles of 15°, 30° and 45°.



(a) 15° (b) 30° (c) 45°

Figure 4. Velocity cloud diagrams of internal and external flow fields for nozzles with three convergence angles

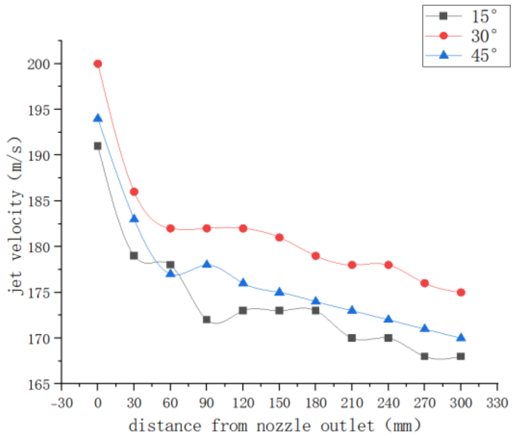


Figure 5. Jet velocity distribution along the central axis of nozzles with three convergence angles

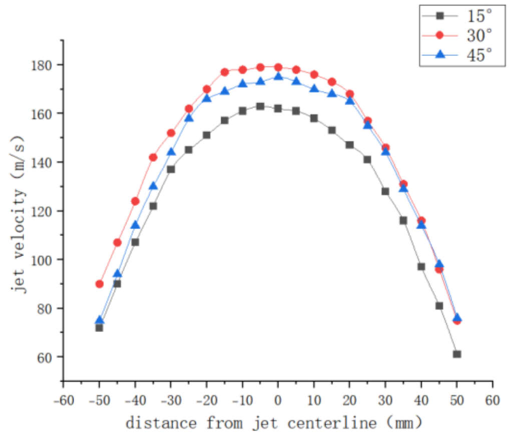
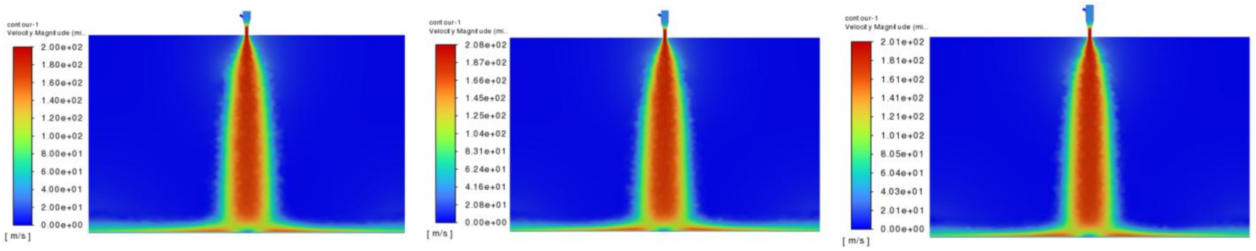


Figure 6. Radial velocity distribution at 200 mm from the outlet of nozzles with three convergence angles

In this simulation, the flow field characteristics of nozzles with convergence angles of 15°, 30° and 45° are analyzed in sequence. When the convergence angle is 15°, the flow passage contracts gently. As a result, the water and abrasives cannot be fully accelerated, producing a jet with low overall velocity and a narrow effective impact range. When the convergence rises to 45°, the flow passage shrinks drastically, causing local flow separation inside the nozzle and substantial energy loss. The jet velocity decays rapidly after leaving the nozzle. At the convergence angle of 30°, the flow passage has an optimal contraction ratio. Both fluid and abrasive particles are fully accelerated, and no obvious vortex structure forms inside the nozzle. At the standoff distance of 200 mm, this scheme delivers the highest peak jet velocity among the three groups. The width of the region where the velocity exceeds 160 m/s is optimal, and the overall energy distribution is uniform and stable. According to the comprehensive analysis of simulation results, the optimal convergence angle of the nozzle is determined to be 30°.

3.3. Optimization of Mixing Chamber Length

The outlet length is fixed at 20 mm and the convergence angle at 30 mm. Simulations are conducted with mixing chamber lengths of 20 mm, 30 mm and 40 mm. The mixing chamber serves as the core area for the mixing and momentum exchange between water and abrasives.



(a) 20mm (b) 30mm (c) 40mm

Figure 7. Velocity cloud diagrams of internal and external flow fields for nozzles with three mixing chamber lengths

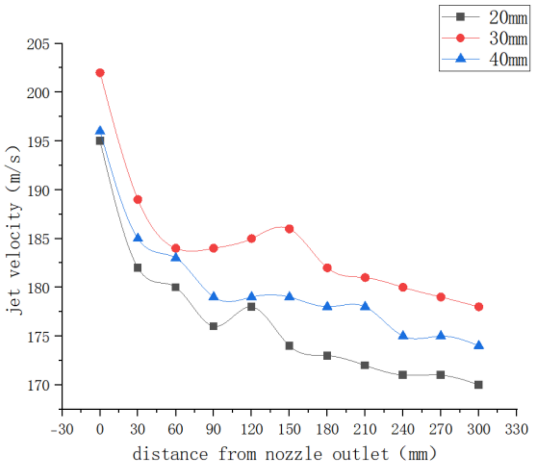


Figure 8. Jet velocity distribution along the central axis of nozzles with three mixing chamber lengths

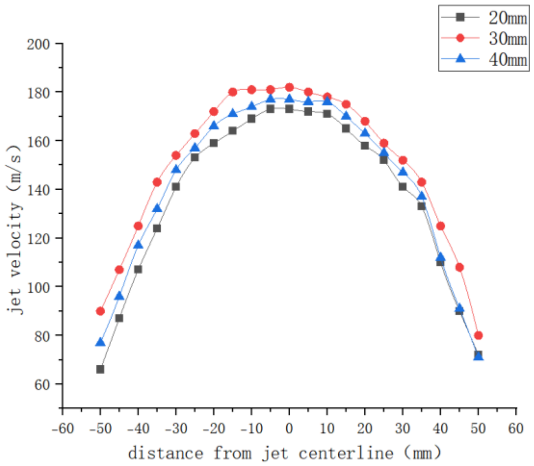


Figure 9. Radial velocity distribution at 200 mm from the outlet of nozzles with three mixing chamber lengths

Comparative simulations are carried out for mixing chamber lengths of 20 mm, 30 mm and 40 mm. When the mixing chamber length is 20 mm, the travel distance for water and abrasives to mix is insufficient. The abrasives fail to achieve full acceleration, resulting in a jet with low overall kinetic energy. When the length is increased to 40 mm, the excessively long flow passage intensifies wall friction and causes additional energy loss, which leads to a remarkable drop in the core jet velocity. By contrast, the mixing chamber of 30 mm strikes a balance between two-phase mixing performance and flow resistance. It enables sufficient momentum exchange between water and abrasives while avoiding excessive frictional loss. The jet presents excellent axial penetration capacity and the slowest kinetic energy attenuation along the flow path. Based on the simulation results, the optimal length of the mixing chamber is determined as 30 mm.

4. Comprehensive Analysis of Flow Field for the Optimized Structure

Full-domain flow field simulation is performed on the optimized nozzle with an outlet length of 20 mm, a convergence angle of 30° and a mixing chamber length of 30 mm to analyze the overall flow field characteristics.

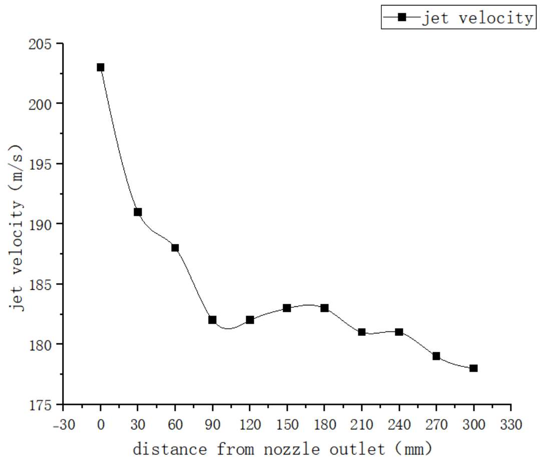


Figure 10. Curve of jet velocity distribution along the central axis at the outlet

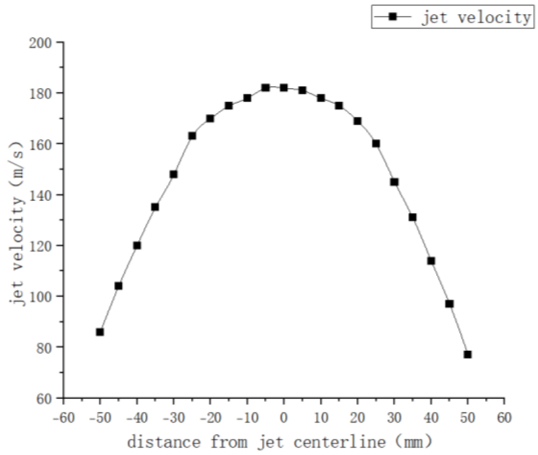


Figure 11. Curve of radial velocity distribution at 200 mm from the nozzle outlet

A comprehensive analysis of the flow field of the optimized nozzle shows that the fluid and abrasives can be fully accelerated in the mixing chamber and convergence section. The entire flow field maintains a good axisymmetric state, with no obvious vortex or flow separation inside, and the energy loss is effectively controlled. In terms of the variation of axial velocity, the peak velocity at the nozzle outlet is approximately 200 m/s. A stable velocity platform is formed within the range of 90 mm to 120 mm. At the conventional standoff distance of 200 mm, the jet velocity remains steady at 180 m/s, which is sufficient to provide the impact kinetic energy required for maize stubble crushing. Regarding the radial velocity distribution at the standoff distance of 200 mm, the jet presents a typical bell-shaped profile. The kinetic energy is mainly concentrated within the range of ±20 mm on both sides of the central axis, indicating a high level of energy concentration. This distribution characteristic ensures effective stubble crushing and meanwhile reduces disturbance to the surrounding soil, which complies with the operation requirements of farmland conservation tillage.

5. Conclusion

The VOF+DPM coupled simulation model established via Fluent can accurately simulate the internal and external flow fields of abrasive water jet nozzles, and it is applicable to the structural optimization of nozzles for stubble breaking. The test results reveal that outlet length, convergence angle and mixing chamber length all exert influences on jet velocity and convergence performance, and there exists an optimal combination of these three parameters. The optimal structural parameters are determined as an outlet length of 20 mm, a convergence angle of 30° and a mixing chamber length of 20 mm. Operating at the standoff distance of 200 mm, the nozzle achieves an impact velocity of 180 m/s. With excellent jet convergence and high kinetic energy utilization efficiency, it can greatly improve the stubble crushing efficiency. The research results can provide references for the design and engineering application of abrasive water jet nozzles for stubble breaking.

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