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Numerical Optimization of the Nozzle Air Inlet Structure in H₂-CH₄ Micromix Combustor

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Abstract: Achieving uniform fuel-air mixing is essential for reducing NO_x emissions from gas turbines fueled with H₂/CH₄ blends during the transition toward clean energy. As a core component of a gas turbine combustor, the design of the micromix nozzle directly determines the overall fuel-air mixing performance. In this work, the air inlet structure of a nozzle fueled with H₂/CH₄ blends was numerically investigated to improve its mixing performance. The effects of the number of air inlet holes and graded hole diameter were systematically evaluated, and the corresponding geometric parameters were optimized at a hydrogen blending ratio of 20%. The fuel flexibility of the optimized nozzle was then assessed under hydrogen blending ratios ranging from 0% to 100%. The results indicate that a multi-stage hole arrangement can induce multi-stage vortex structures, thereby increasing the contact area and mixing time between fuel and air. The introduction of a graded hole diameter essentially redistributes the air momentum, and a reasonable momentum allocation significantly improves the mixing performance of the nozzle. The optimized nozzle exhibits good fuel flexibility. Under hydrogen blending ratios of 0-60%, the mixing uniformity index UI can reach 0.98. The present work elucidates the influence of the nozzle air inlet structure on the internal turbulent mixing mechanism and provides a basis for optimizing micromix combustor design.

Keywords: Micromix combustion; H₂/CH₄ blends; Gas turbine; Mixing performance; CFD simulation

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1. Introduction

With the continuous implementation of carbon peaking and carbon neutrality targets, gas turbines are facing stricter requirements for carbon emission reduction [1]. Owing to its carbon-free nature, hydrogen has become an important route for the low-carbon upgrading of gas turbines [2]. However, the extremely high reactivity of hydrogen also substantially increases the risk of flashback in combustors [3]. Meanwhile, the high reaction rate can induce local hot spots, thereby enhancing the formation and emission of thermal NO_x [4-5]. To overcome these limitations, the micromix combustion concept was initially developed at Aachen University of Applied Sciences [6]. Subsequent investigations [7-12] demonstrated that micromix combustors offer strong potential for low- NO_x combustion and flashback suppression. Unlike conventional combustors, this concept uses a large number of micro-scale channels and injection elements to divide the reactants into small jets, thereby replacing the large-scale injection structures typically used in traditional combustor designs. The individual mixing channels significantly enhance the mixing intensity between air and fuel, and then sufficient mixing of the reactants can be achieved rapidly [13]. Numerous densely distributed small flames are generated in the combustor, replacing the large-scale diffusion flames in conventional combustors [14-15]. By decreasing the flame scale, upstream flame propagation can be suppressed, while the residence time of reactants in high-temperature regions is reduced, leading to lower NO_x formation [16-17].

Micromix combustion technology can be divided into diffusion-type [18] and premixed-type configurations. In diffusion-type micromix combustion, hydrogen is transversely injected into a high-speed air stream through micro-holes, producing a large number of small diffusion flames, and the combustion process depends on diffusion mixing. In contrast, premixed-type micromix combustion adopts enhanced mixing techniques such as transverse jets [19], swirl mixing [20], or co-flow jets [21-24] in the micromixing channels, so that fuel and air can be fully premixed inside the

micro-channels. This reduces local hot spots and significantly lowers NO_x emissions, showing greater potential for low-emission combustion. Therefore, this study investigates a premixed-type micromix nozzle and focuses on its cold-flow fuel-air mixing performance.

Fuel-air mixing characteristics are a major research focus in micromix combustion. Chen et al. [25,26] examined the influence of nozzle geometric parameters and inlet aerodynamic conditions on the mixing behavior. The results showed that decreasing the mixing-channel diameter can increase the mixing intensity, whereas increasing the premixing length can reduce the mixing efficiency. When the equivalence ratio is between 0.335 and 0.685, fuel and air can be uniformly premixed at the nozzle outlet. Liu et al. [27] enhanced nozzle mixing by introducing a twisted tape and analyzed the effects of swirl number, equivalence ratio, and Reynolds number on fuel-air mixing. Their results showed that the twisted-tape configuration improved mixing performance over a wide operating range, and an appropriate combination of parameters increased the uniformity index (UI) to 0.91. Mo et al. [28-29] embedded a divergent vortex generator (DVG) in a micro-channel and used the coupling between the induced air stream vortex (ASV) and hydrogen jet vortex (HJV) to significantly enhance the mainstream disturbance, achieving uniform mixing within an axial distance of 30 mm. Ren et al. [30] employed large eddy simulation (LES) to investigate mixing in micro-tubes with various geometries. Their results highlighted the important role of counter-rotating vortex pairs in enhancing mixing and showed that the jet angle and fuel-hole number significantly influence fuel distribution. Berger [31] increased the penetration depth by changing the aspect ratio of the air gate, which enhanced mixing intensity and reduced NO_x emissions without affecting pressure loss. Li et al. [32] examined how nozzle diameter and spacing affect combustion performance. Their results showed that a larger nozzle diameter of 6 mm combined with a smaller spacing ratio of 1.5 improved flame stability and reduced NO_x emissions. Lei et al. [33] optimized key internal geometric parameters, including the mixing distance and air-gate height. Their results

indicated that a longer mixing distance enhances fuel-air mixing and contributes to NO_x reduction, whereas reducing the air-gate height lowers the combustor temperature and further suppresses NO_x formation. Zuo et al. [34] numerically simulated the combustion characteristics of fuel micro-holes with different diameters, spacings, and hole shapes in a micromix combustor and found that both excessively large and excessively small hole diameters and spacings can intensify NO_x formation. Based on a cross-jet structure, Qu's group [35-36] designed a new nozzle in which fuel enters from micro-holes at the nozzle bottom and collides with air entering transversely from the side wall. They investigated the combustion characteristics under H_2O steam dilution and found that H_2O steam dilution can suppress NO_x formation.

Previous studies have shown that flow-field variations caused by structural optimization affect the mixing characteristics and consequently the NO_x emissions. However, existing configurations still have several limitations during optimization. On the one hand, mechanical disturbance devices such as vortex generators [28-29] or twisted tapes [27] are often inserted into nozzle channels, which increases both aerodynamic resistance and micro-channel complexity. On the other hand, insufficient fuel-air jet interaction in conventional micromix nozzles limits the contact area and mixing time, thereby weakening the mixing performance.

Therefore, a micromix nozzle with a multi-stage hole arrangement is proposed to improve mixing performance. A numerical simulation method was adopted with H_2/CH_4 blends as the fuel. Without introducing complex mechanical disturbance devices, the effects of the number of air holes and graded hole diameter on the mixing performance of the nozzle were systematically investigated. By constructing a multi-stage vortex mixing mechanism, the contact area and mixing time between fuel and air were increased, thereby enhancing the mixing performance of the nozzle. In addition, numerical simulations were performed under multiple operating conditions to examine the effect of hydrogen blending ratio on the mixing performance and to evaluate the fuel flexibility of the optimized nozzle, providing theoretical support for future studies

on micromix combustion.

2. Numerical Method

2.1 Geometric Model

A micromix nozzle structure with a multi-stage hole arrangement was proposed in this study based on Refs. [35-36]. The geometric structure of the micromix combustor nozzle is shown in Fig. 1. The nozzle body is a cylindrical tube with an outer diameter D of 14 mm, a wall thickness d of 2 mm, and a total length Z of 100 mm. The fuel inlet is located at the bottom of the nozzle ($Z = 0$ mm section) and consists of four circular holes with a diameter D_f of 1 mm. The air inlets are arranged on the side wall of the nozzle, with four air inlets each having a diameter D_a of 4 mm. The distance between the air inlet and the bottom is $H = 20$ mm. The axial coordinate origin is defined at the fuel inlet ($Z = 0$ mm) for describing the mixing distance.

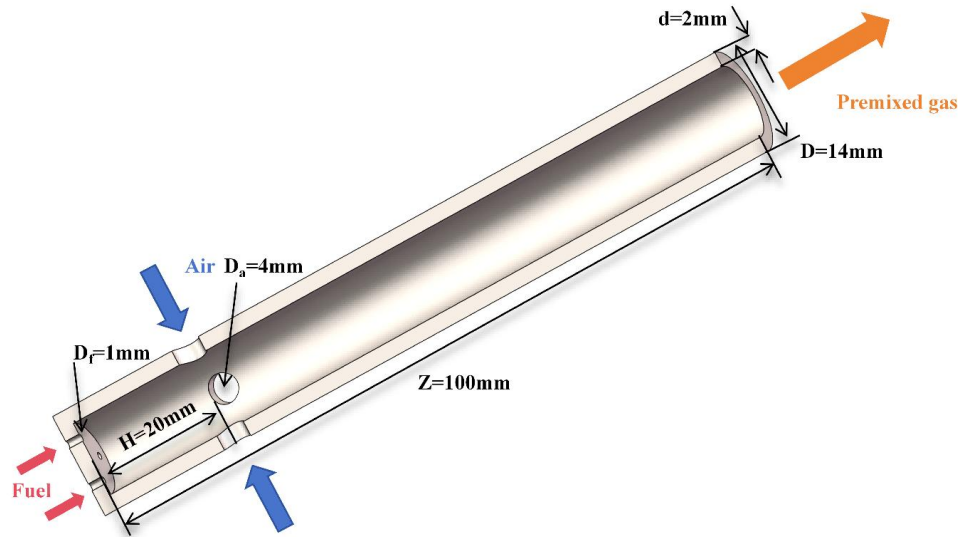


Fig. 1. Half-sectional schematic of the nozzle structure.

2.2 Governing equations

This study mainly focuses on the turbulent mixing characteristics inside the nozzle. To simplify the calculation and highlight the dominant fluid-dynamic mechanisms, the following assumptions are made for the fluid in the computational domain: (1) the mixing process is three-dimensional and steady; (2) the fluid medium is treated as a

continuous and incompressible Newtonian fluid; (3) the mixing process is isothermal at 300 K; and (4) the effect of gravity on fluid mixing is neglected. Based on the above assumptions, the flow and mixing processes inside the nozzle satisfy the continuity equation, momentum conservation equation, and species transport equation. The governing equations were formulated based on the Turbulent Flow, $k - \omega$ interface and the Transport of Concentrated Species interface in COMSOL Multiphysics 6.3, and were used to describe the turbulent flow and multicomponent gas convection-diffusion mixing process inside the nozzle [37]. The equations are expressed as follows:

Continuity equation:

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

Momentum conservation equation:

$$\rho u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij} \right] \quad (2)$$

where x_i and x_j are the spatial coordinate components; u_i and u_j are the corresponding time-averaged velocity components; ρ is the fluid density; p is the time-averaged static pressure; k is the turbulent kinetic energy; μ and μ_t are the molecular dynamic viscosity and turbulent dynamic viscosity, respectively; and δ_{ij} is the Kronecker delta.

Species transport equation:

$$\frac{\partial(\rho u_j \omega_s)}{\partial x_j} + \frac{\partial j_{s,j}}{\partial x_j} = 0 \quad (3)$$

where the subscript s denotes different chemical species; ω_s is the mass fraction of species s ; and $j_{s,j}$ is the diffusive mass flux of species s in the x_j direction.

The conventional standard $k - \varepsilon$ model strongly relies on wall functions when dealing with near-wall flows. Because the governing equations are difficult to integrate directly into the viscous sublayer, its prediction accuracy is limited for flows involving strong pressure gradients and large curvature. Therefore, the standard $k - \omega$ turbulence model [38], which has advantages in near-wall treatment, is adopted in this

study.

The transport equations for the mean turbulent kinetic energy and the mean dissipation-related variable in the standard $k - \omega$ turbulence model is written as follows:

$$\rho u_j \frac{\partial k}{\partial x_j} = P_k - \beta^* \rho k \omega + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (4)$$

$$\rho u_j \frac{\partial \omega}{\partial x_j} = \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] \quad (5)$$

The turbulent dynamic viscosity μ_t and production term P_k are defined as follows:

$$\mu_t = \rho \frac{k}{\omega}, \quad P_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (6)$$

where P_k is the turbulent kinetic energy production term caused by the mean velocity gradient, ω is the specific dissipation rate; and $\alpha, \beta, \beta^*, \sigma_k, \sigma_\omega$ are constants in the standard $k - \omega$ turbulence model.

2.3 Calculation scheme

COMSOL Multiphysics 6.3 was used to numerically simulate the gas flow and mixing process. The boundary conditions were set as follows: (1) the fuel and air inlets were specified as volume-flow-rate inlets with a temperature of 300 K; (2) the outlet was specified as a pressure outlet with a pressure of 1 atm; and (3) the inner wall of the nozzle was treated with a no-slip boundary condition. A tetrahedral mesh was used to discretize the computational domain of the micromix combustor nozzle, and local mesh refinement was applied near the small fuel and air inlets, as shown in Fig. 2.

To eliminate the influence of mesh number on the numerical results, a mesh-independence study was carried out. The baseline operating condition was used as the reference case, and four mesh models with different densities were generated by changing the mesh size while keeping the geometric structure and boundary conditions consistent. The total numbers of mesh elements were approximately 70,000, 150,000,

270,000, and 700,000. Considering that the momentum exchange is relatively strong in the central region of the nozzle, the axial velocity distribution along the nozzle centerline was selected as the verification index. The results are shown in Fig. 3. Comparison among the four meshes shows that when the mesh number exceeds 270,000, further refinement to 700,000 has only a minor effect on the centerline axial velocity distribution. Therefore, considering both accuracy and computational cost, the mesh with 270,000 elements was adopted in the subsequent simulations.

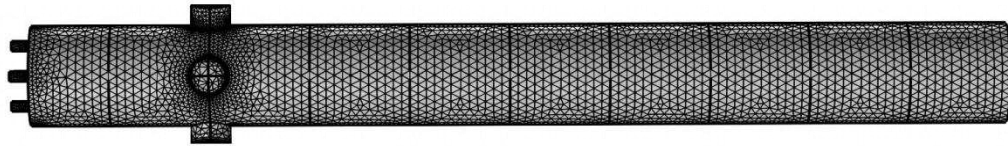


Fig. 2. Schematic of the computational mesh.

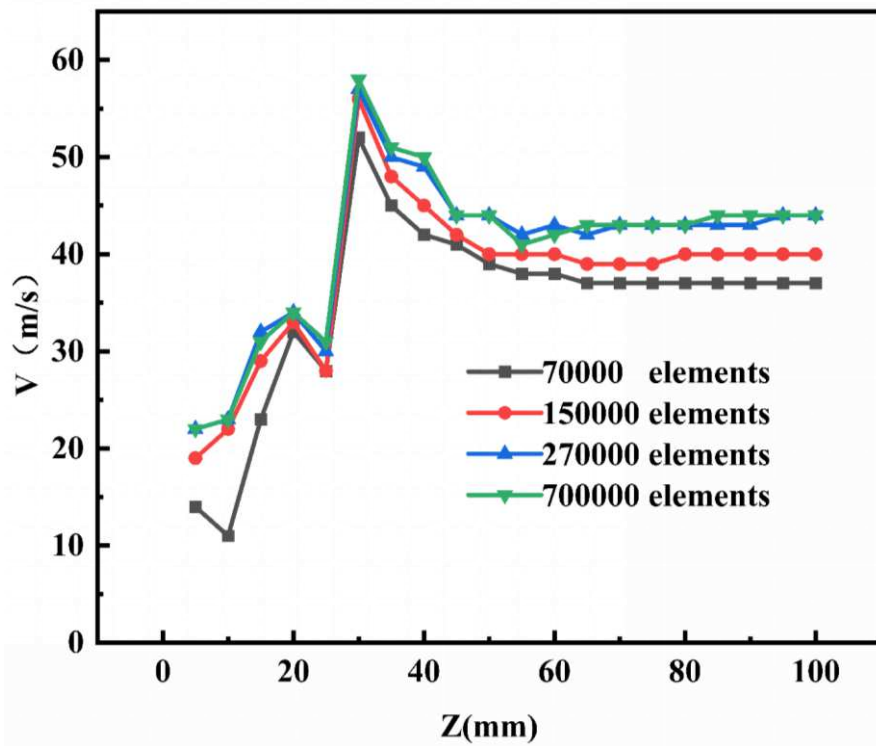


Fig. 3. Centerline axial velocity distribution.

2.4 Evaluation criterion for mixing performance

To quantitatively evaluate the fuel/air mixing performance inside the nozzle, the spatial mixing uniformity index UI [22] was introduced. This index is based on an integral method and evaluates the mixing effect by calculating the statistical deviation

between the local fuel concentration and the average concentration over a cross-section. It is defined as follows:

$$UI = 1 - \frac{\iint |f - \bar{f}| dA}{A\bar{f}} \quad (7)$$

where A is the reference cross-sectional area, dA is the differential area, and f and $\bar{f}$ are the local fuel mass fraction and the area-weighted average fuel mass fraction over the reference section, respectively. The value of UI ranges from 0 to 1. A value closer to 1 indicates a more uniform fuel-air distribution over the section and better overall mixing performance. In combustor design of gas turbine, the uniformity index at the outlet plane is generally required to be higher than 0.95 [39].

3. Results and Discussion

3.1 Effect of the number of air holes on mixing performance

To investigate the effect of the number of air inlet holes on mixing performance, the number of air holes was varied while the total air inlet area was kept constant (50 mm²). The mixing performances of 4-hole, 8-hole, and 12-hole schemes were compared. The three schemes correspond to single-layer, double-layer, and triple-layer arrangements, respectively, with four holes in each layer. The air-hole radii were 2.0, 1.4, and 1.2 mm, respectively. The air holes were symmetrically distributed above and below the $Z = 20$ mm section to reduce the influence of differences in the overall inlet position on the mixing performance. The axial spacing between adjacent air holes was 6 mm. Figure 4 presents the simulation results for the three air-hole-number schemes. During the calculations, the hydrogen blending ratio was 20%, the equivalence ratio was set to 0.6, the temperature was set to 300 K, the air inlet volume flow rate was 2.4×10^{-3} m³/s, and the fuel inlet volume flow rate was 1.787×10^{-4} m³/s.

Figure 4 shows the velocity distributions and streamlines for different numbers of air holes. A recirculation vortex can be observed between the lower air holes and the fuel holes. As shown in Fig. 5, the transverse air jet injected from the side-wall air inlet

(gray-white tube bundle) produces an aerodynamic blockage effect on the axial fuel jet (red-yellow region). The transverse air jet acts like a gas barrier, forcing the upward fuel jet to decelerate sharply and separate, thus forming a recirculation vortex below the air jet.

Although the single-layer arrangement (4 holes) can form a recirculation vortex at the bottom, the turbulent kinetic energy decays rapidly after the fluid passes through the air jet, and the streamlines tend to develop upward in a nearly parallel manner. As a result, the downstream mixing capacity is significantly weakened. In contrast, the multi-layer arrangements (8 holes and 12 holes) can form secondary recirculation vortices between adjacent layers of air jets. After preliminary mixing by the bottom recirculation vortex, the fluid continues to move upward and is further entrained and stretched by the interlayer secondary recirculation vortices. Compared with the coaxial-jet micromix combustor with a single layer of side-wall air inlets adopted by Liu et al. [22], the multi-layer air-hole jets increase the fuel-air contact area and the effective mixing time, thereby improving the overall mixing performance of the nozzle.

Figure 6 shows the variation of the cross-sectional mixing uniformity index UI with the axial position Z for different numbers of air holes. The UI of the single-layer 4-hole structure is lower than those of the other two schemes throughout the mixing process, indicating that a multi-layer hole arrangement can effectively improve the nozzle mixing performance. Further comparison between the 8-hole and 12-hole schemes shows that, in the early mixing stage ($Z = 30$ mm), the UI of the 12-hole scheme is higher than that of the 8-hole scheme, with an improvement of up to 7%. However, in the latter half of the mixing process ($Z \geq 40$ mm), the improvement of the 12-hole scheme over the 8-hole scheme is only about 2%, and the benefit becomes much smaller.

Figure 7 shows the normalized fuel mass fraction distributions at different axial sections ($Z = 10\sim 100$ mm) for the double-layer 8-hole structure. At the initial stage ($Z = 10$ mm), four symmetric high-concentration regions appear on the section, and the

concentration gradient is large, indicating that the fuel has just been injected from the inlet and has not yet been sufficiently mixed. At $Z = 20$ mm, the fuel is entrained by the bottom recirculation vortex, and the high-concentration regions are clearly dispersed. At $Z = 30$ mm, the effect of the interlayer secondary recirculation vortex is essentially completed. The macroscopic mixing dominated by vortices has been achieved, the normalized fuel mass fraction decreases to approximately 0.15, and the corresponding UI increases to 0.64 (Fig. 6). In the $Z = 40\sim 50$ mm range, the macroscopic concentration gradient over the section is further weakened, the normalized fuel mass fraction decreases to approximately 0.1, and the UI exceeds 0.93. To clearly identify the downstream species distribution, a higher-resolution color scale on the order of 10^{-2} is used for the $Z = 60\sim 100$ mm range. As the fluid moves downstream, the large-scale vortex system dissipates, and the mixing mechanism transitions to molecular diffusion. The growth rate of UI becomes slower. From $Z = 60$ mm to the outlet section, UI increases by only about 3% and finally reaches approximately 0.98, while the normalized fuel mass fraction at the outlet section decreases to about 0.05.

Although the 12-hole structure exhibits the best mixing performance, its improvement over the 8-hole structure is marginal, with an enhancement of only approximately 2%. In addition, when the total inlet area is kept constant, increasing the number of holes reduces the diameter of each hole, which increases manufacturing difficulty and cost. Considering both mixing performance and practical manufacturability, the double-layer 8-hole structure is selected as the baseline configuration for the subsequent study.

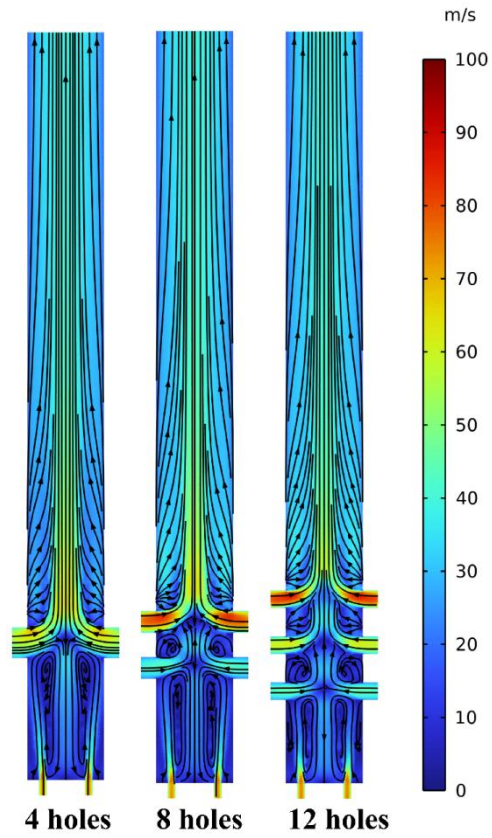


Fig. 4. Velocity contours on the axial center section for different numbers of air holes.

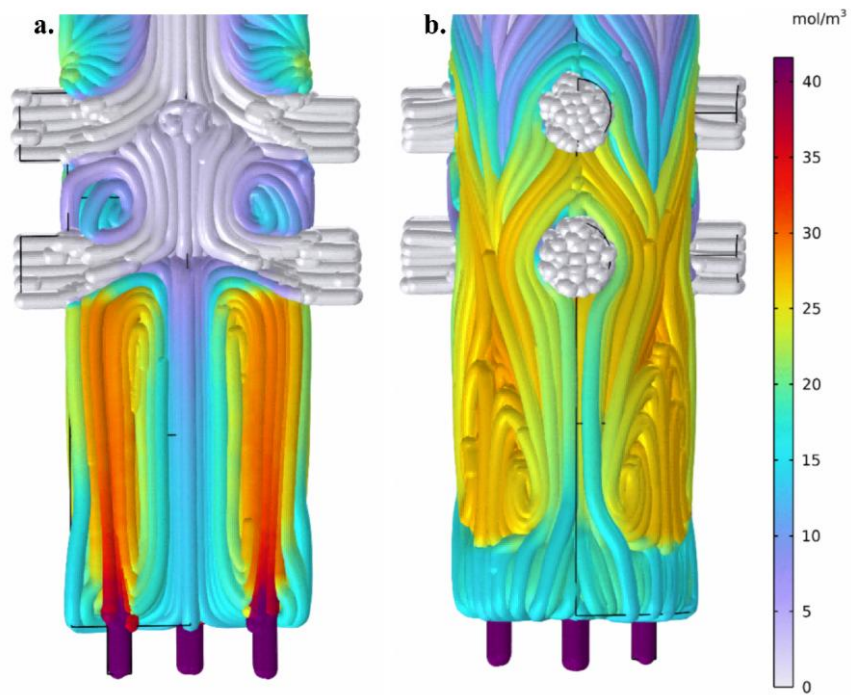


Fig. 5. Streamlines and fuel concentration distribution: (a) sectional view; (b) side view.

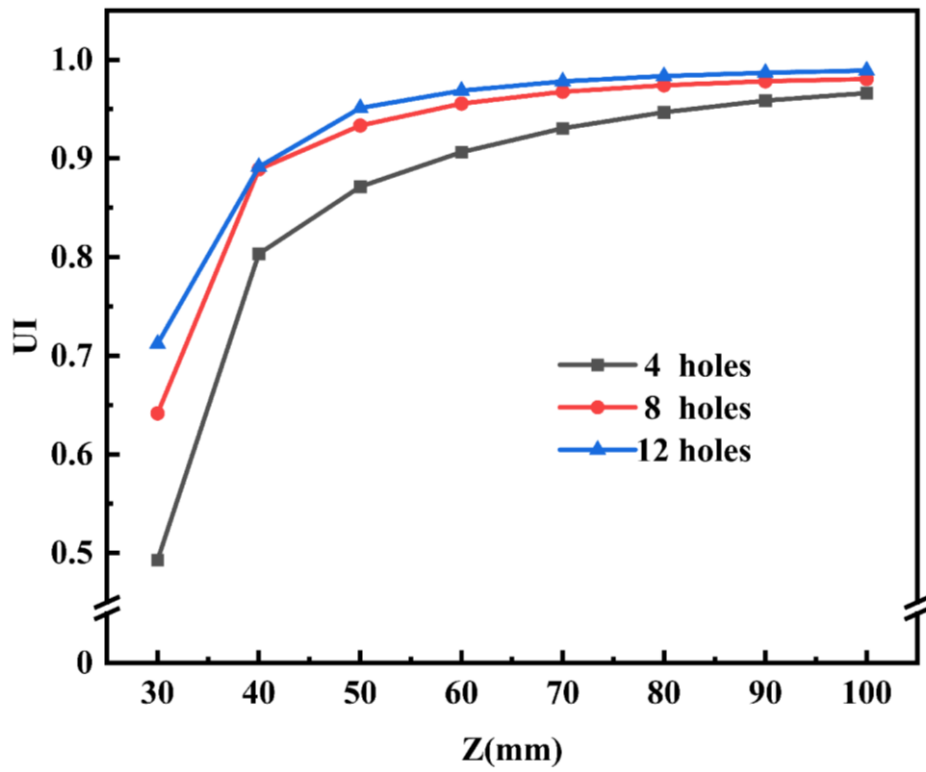


Fig. 6. Mixing performance for different numbers of air holes.

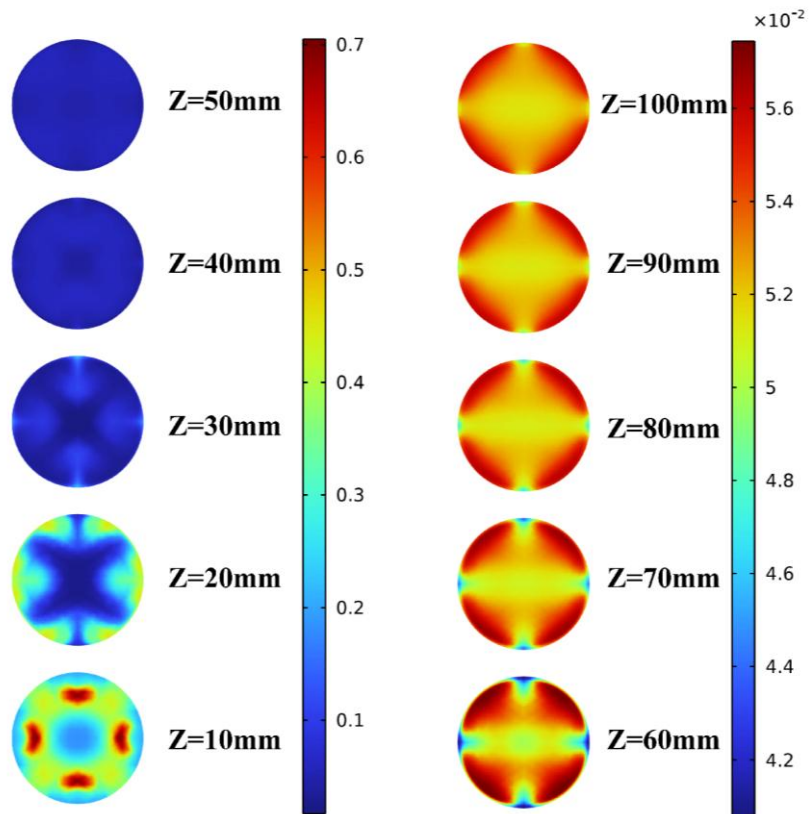


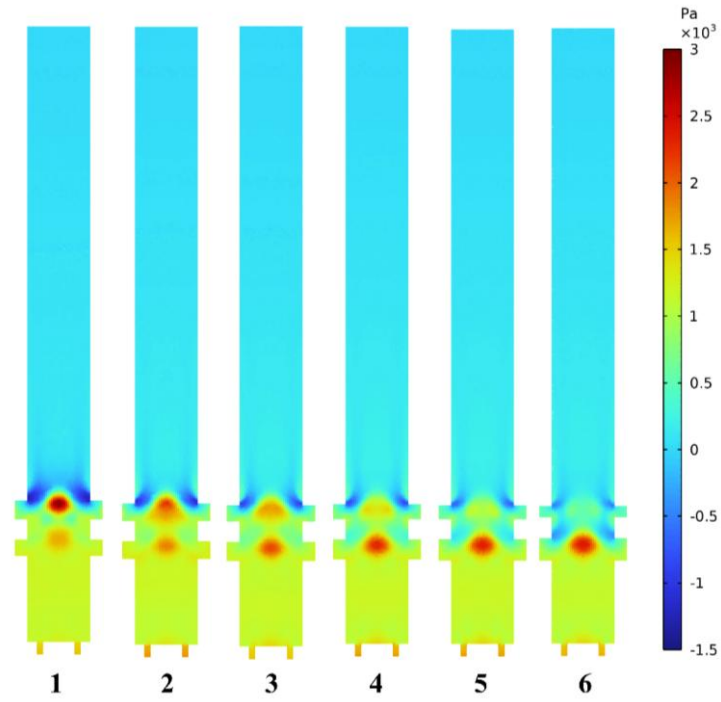
Fig. 7. Normalized fuel mass fraction distributions on cross-sections at different axial positions of the double-layer nozzle.

3.2 Effect of graded air-hole diameter on mixing performance

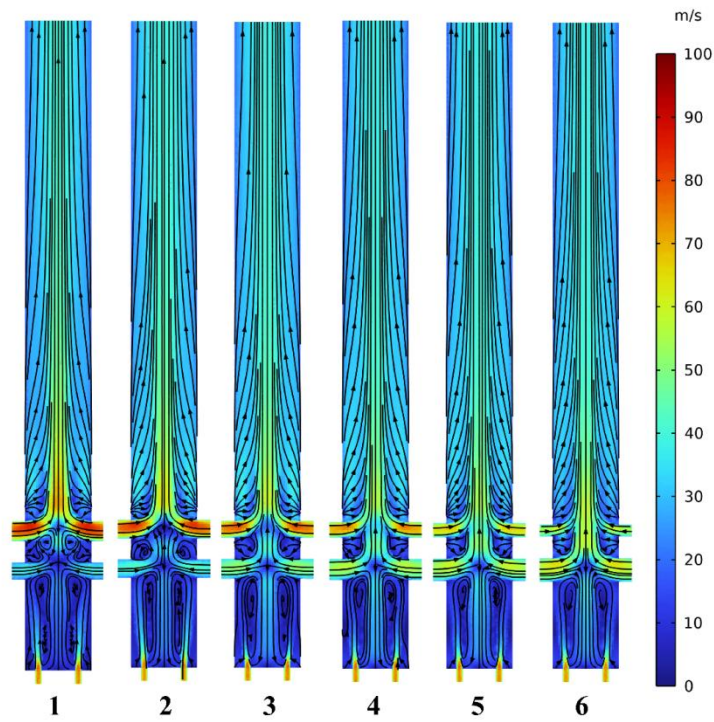
The upper and lower air jets exhibit different velocity and momentum distributions despite having identical hole diameters and inlet conditions. This is mainly related to the pressure distribution inside the nozzle. After the transverse air jet blocks the axial fuel jet, a relatively high-pressure region is formed near the lower air holes, which increases the inlet resistance of the lower layer and weakens its jet momentum. Based on this phenomenon, a graded hole-diameter design is introduced in this section while the total air-hole area and total air volume flow rate are kept approximately constant. The air-jet momentum is redistributed by adjusting the radii of the upper and lower air holes. Figure 8 shows the cross-sectional static pressure distributions for six graded hole-diameter configurations. The lower/upper hole radii of the six cases are 1.3/1.5, 1.4/1.4, 1.5/1.3, 1.6/1.2, 1.7/1.1, and 1.8/0.9 mm, respectively.

Figures 8 and 9 show the axial-section pressure and velocity fields under different graded hole-diameter configurations. As the lower hole diameter increases and the upper hole diameter decreases, more air momentum is allocated to the lower jet. The high-momentum lower air jet strengthens the turbulent entrainment capability of the bottom recirculation vortex, and fuel enrichment near the nozzle bottom is alleviated. Figure 10 compares the UI values for the six cases. As the lower hole diameter increases, the overall mixing performance improves, and the fifth case provides a maximum UI increase of about 15% compared with the equal-diameter second case. However, when the lower hole diameter is further increased in the sixth case, the upper air hole becomes too small and the momentum of the upper air jet becomes insufficient, weakening the interlayer mixing performance. Therefore, the overall UI of the sixth case is slightly lower than that of the fifth case. To further demonstrate the effect of graded hole-diameter optimization, the fuel concentration distributions of the equal-diameter baseline case (Case 2) and the optimal graded hole-diameter case (Case 5) are compared. As shown in Fig. 11, the high-concentration region near the nozzle bottom is significantly reduced in Case 5, and the fuel distribution becomes more uniform,

282 indicating that the graded hole-diameter design effectively improves bottom mixing in
 283 the nozzle.



284
 285 **Fig. 8. Static pressure distributions on the central section for different graded hole**
 286 **diameters.**



287
 288 **Fig. 9. Axial-section velocity streamlines for different graded hole diameters.**

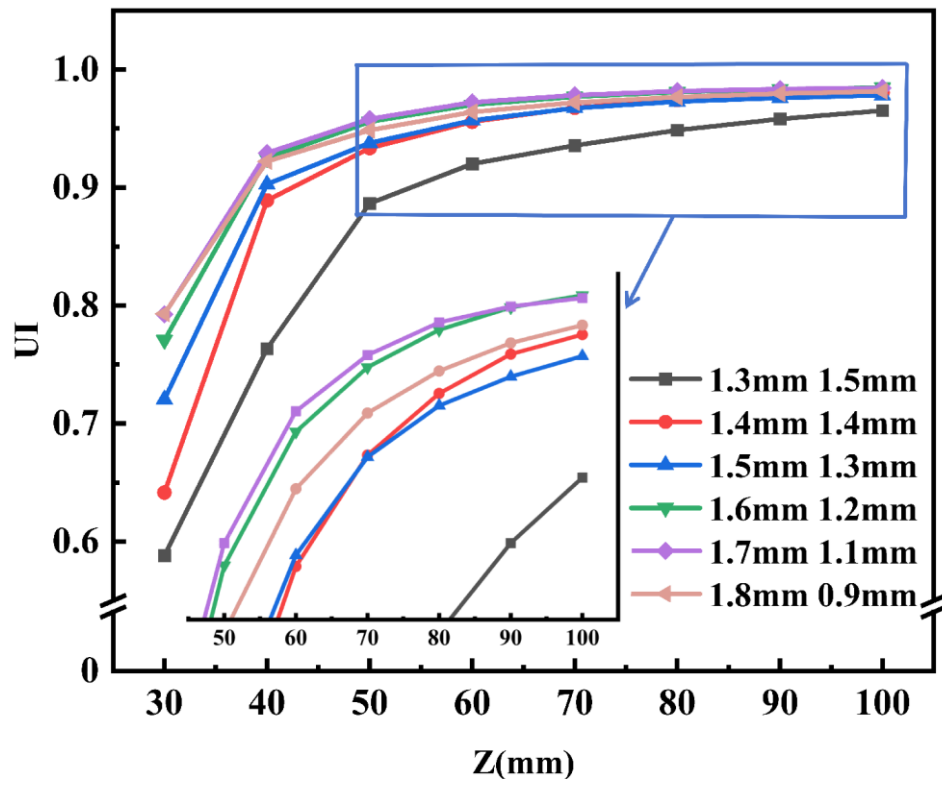


Fig. 10. Mixing performance for different graded air-hole diameters.

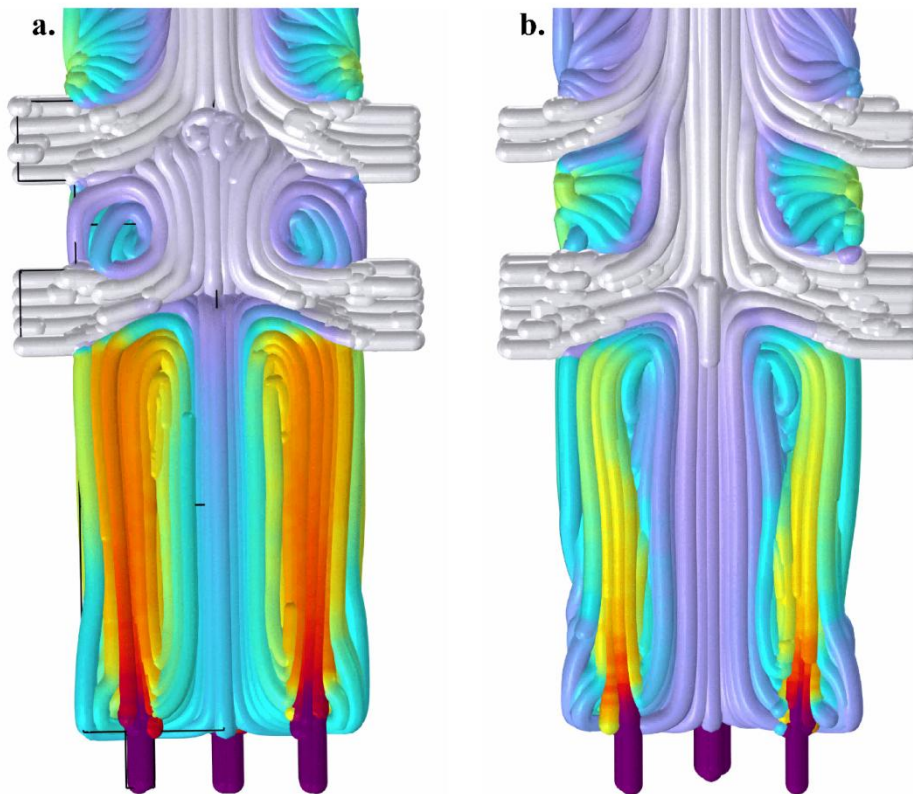


Fig. 11. Fuel concentration distributions: (a) Case 2; (b) Case 5.

3.3 Effect of hydrogen blending ratio on mixing performance

Based on the optimized structure, this section further investigates the effect of hydrogen blending ratio on mixing performance. Six fuel compositions are considered, with the hydrogen volume fraction varying from 0% to 100%. The fuel heating value is kept constant, and the equivalence ratio is maintained at 0.6. Because hydrogen has a relatively low volumetric heating value, a higher hydrogen blending ratio requires a larger fuel volume flow rate to maintain the same heat input. With a fixed fuel-hole diameter, the fuel jet velocity therefore increases. The simulation results show that when the hydrogen volume fraction increases from 0% to 100%, the average velocity at the fuel inlet increases from 50.7 m/s to 169.1 m/s, corresponding to a 3.3-fold increase.

Figure 12 shows the mixing performance under different hydrogen blending ratios. When the blending ratio is in the range of 0-60%, the mixing performance is good and the differences among the cases are small. When the blending ratio is further increased to 100%, the UI curve decreases significantly, and the mixing performance at the outlet decreases by about 10%. Figure 13 further presents the effect of hydrogen blending ratio on mixing performance. The UI curves are close to each other in the range of 0-60%, whereas UI gradually decreases in the range of 60-100%, especially near the early mixing stage at $Z = 30$ mm. This result indicates that a single nozzle structure cannot adapt to the full variation range of hydrogen blending ratio from 0% to 100%. The current optimized structure can maintain good mixing performance in the range of 0-60% hydrogen blending ratio.

Figure 14 shows the sectional velocity streamlines for hydrogen blending ratios of 60-100%. As the hydrogen blending ratio increases, the fuel volume flow rate and jet velocity increase, and the fuel-jet momentum increases accordingly. When the hydrogen blending ratio is 100%, the fuel-jet momentum is too large and penetrates the transverse air jet, which significantly weakens the aerodynamic blockage effect of the transverse air jet. As a result, a stable recirculation vortex is difficult to form at the

nozzle bottom. The original vortex mixing mechanism fails, and the bottom flow field tends to become parallel and stratified. At the same time, the excessively high fuel velocity shortens the effective mixing time. The local maximum velocity reaches approximately 212 m/s, leading to a significant reduction in mixing performance. Zhang et al. [40] found that increasing the hydrogen blending ratio improved the mixing performance in a rotary-cut nozzle, whereas the present study shows a decrease in mixing performance when the hydrogen blending ratio exceeds 60%. The main reason is that the enhanced mixing mechanisms are different. In swirl mixing, increasing fuel velocity strengthens the swirl disturbance, whereas the nozzle in the present study relies on transverse air jets to induce recirculation vortices. Excessive fuel momentum therefore affects the formation of the recirculation vortex.

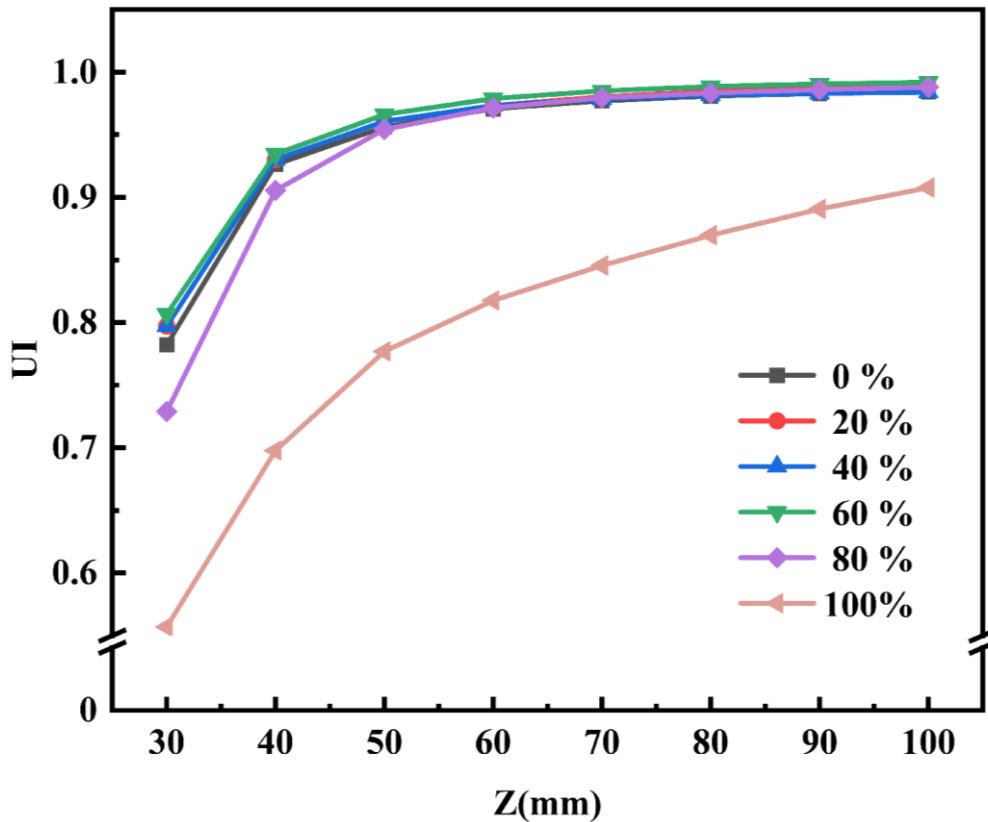


Fig. 12. Mixing performance under different hydrogen blending ratios.

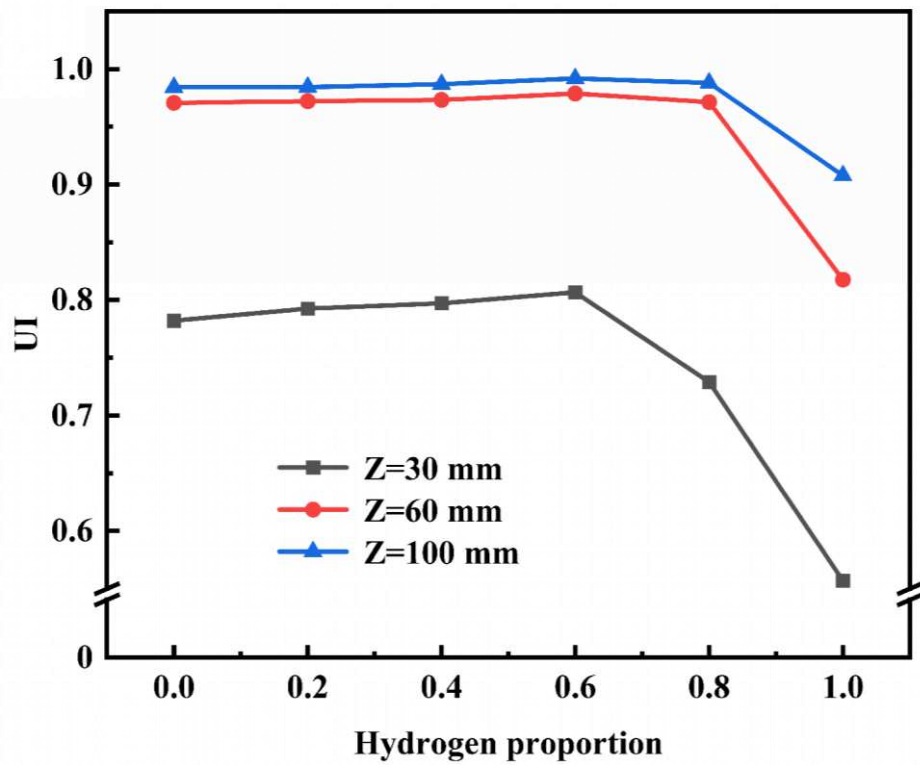


Fig. 13. Effect of hydrogen fraction on the variation of mixing performance.

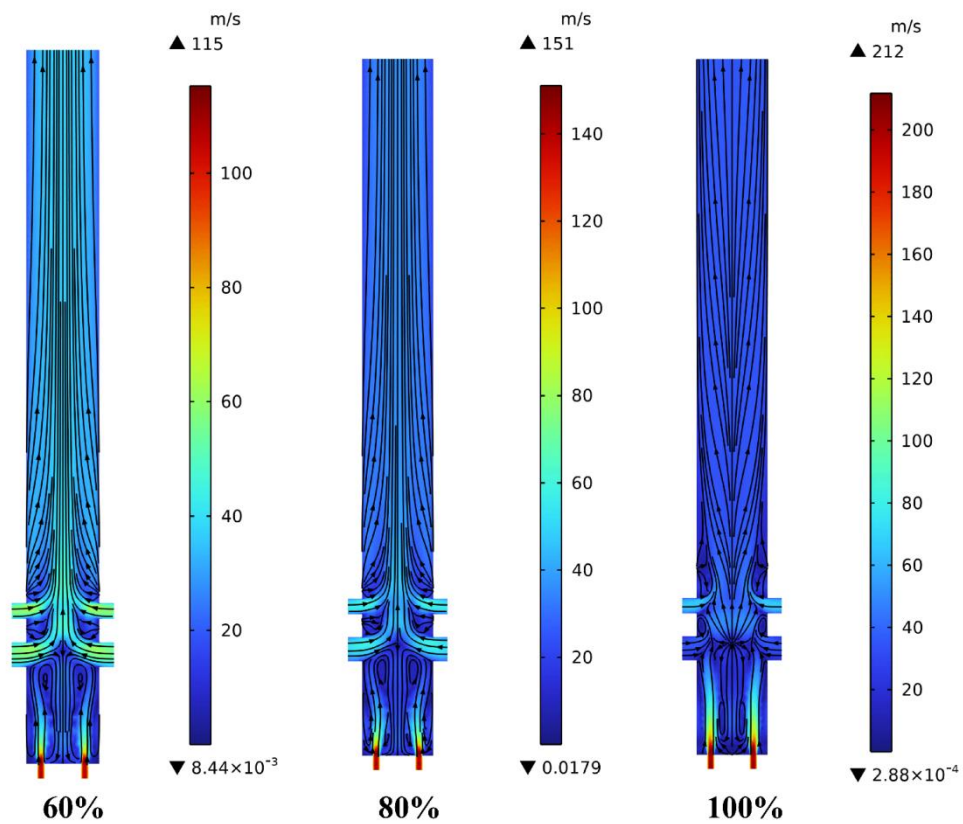


Fig. 14. Sectional velocity streamlines for hydrogen blending ratios of 60-100%.

3.4 Effect of nozzle length on mixing performance

The results discussed above show that the optimized air inlet structure (double-layer 8-hole arrangement and graded hole radii of 1.7 and 1.1 mm) exhibits excellent mixing performance, with the outlet UI reaching 0.98. The UI curve increases rapidly at the early stage, and the UI reaches 0.97 at an axial height of $Z = 60$ mm. In the downstream region from $Z = 60$ mm to the outlet, the UI increases slowly and improves by only 1%. Therefore, in the design and manufacturing of an engineering prototype, the total nozzle length can be reduced from 100 mm to approximately 60 mm. This scheme reduces the outlet UI from about 0.98 to about 0.97 but decreases the channel length by approximately 40%, which is beneficial for improving combustor space utilization and reducing manufacturing cost.

Compared with the original 4-hole nozzle, the optimized structure increases UI by about 30% in the early mixing-development stage ($Z = 30$ mm) and by about 8% at $Z = 60$ mm. Liu et al. [27] increased the uniformity index to 0.91 by inserting a twisted tape into the nozzle. In contrast, the present study optimizes the air inlet structure without introducing internal mechanical disturbance components, which reduces manufacturing complexity. Moreover, a UI of approximately 0.93 is achieved at a comparable nozzle length position ($Z = 40$ mm), indicating good potential for engineering application.

4. Conclusions

To address the fuel/air mixing problem in a micromix combustor, this study used numerical simulations to systematically optimize the air inlet structural parameters of the nozzle. Compared with the single-layer 4-hole structure, the double-layer 8-hole structure can form a bottom recirculation vortex and interlayer secondary recirculation vortices, increasing the fuel/air contact area and mixing time and thereby significantly improving the mixing performance. Changing the graded diameter of the air holes affects the flow field and thus the mixing performance of the nozzle. Proper selection

of the parameters (lower/upper air-hole radii of 1.7/1.1 mm) can significantly improve the nozzle mixing performance, with the outlet UI reaching 0.985. The optimized nozzle maintains can be applied within the hydrogen blending ratio range of 0-60%, and the outlet UI can reach above 0.97. Fuel and air already can be rapidly and uniformly mixed in the front section of the nozzle, and the UI reaches 0.97 at $Z = 60$ mm. The total nozzle length reduced to 60 mm can lowering manufacturing cost and can allow more compact combustor structure.

Author contributions

All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest

The authors state no conflict of interest.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

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