Effects of Hydrogen Multijet and Flow Rate Assignment on the Combustion Flow Characteristics in a Jet-Stabilized Combustor

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ABSTRACT: In this study, a hydrogen fuel jet-stabilized combustor is proposed, the combustion flow characteristics are numerically investigated under the conditions of three equivalence ratios (1, 0.37, and 0.22), and the effects of hydrogen flow rate assignment on the combustion flow are also analyzed. The results show that it is easier for the multijet scheme to form a full and stable vortex structure pair in the recirculation zone under lean conditions than the single-jet scheme, and it has a uniform reaction rate to form larger combustion zones, which makes it easier to achieve flame stabilization. The combustion efficiency of two fuel jet schemes is less than 65% when the equivalence ratio is 1, and complete combustion can be achieved under lean conditions; however, the outlet temperature distribution factor (OTDF) is basically the same. For the multijet scheme with an equivalence ratio of 0.22, as the flow rate assigned to the central jet decreases, a stable and full vortex pair is formed in the recirculation zone, and a high-temperature region can be formed under each working condition, but its area decreases with the central jet flow rate. The combustion efficiency in the recirculation zone increases first and then decreases as the central jet flow decreases, and the OTDF decreases with it.

1. INTRODUCTION

The rapid development of aerospace power has increasingly higher requirements for engines. Wide lean blowout limit and low pollutant emissions are two key issues that need to be addressed in combustion devices, and the wide lean blowout limit is mainly reflected in combustion stabilization. Traditional aero engines or gas turbines often use a swirler as the flame stabilizer,1−3 which has a positive effect on the atomization and evaporation of liquid fuels, but with an inefficient fuel and air mixing as well as a narrow combustion stabilization range. Therefore, it is necessary to develop various efficient combustion and flame stabilization technological devices, such as trapped vortex combustor,4 advanced vortex combustor,5,6 and cavity-stabilized combustor for ramjet or scramjet,7,8 the principle of which involves the addition of blunt bodies or cavity structures in the combustors to form a low-speed recirculation zone for fuel and air mixing and combustion. The vortex-stabilized combustion technology has attracted more and more researchers because of its advantages in terms of combustion efficiency, wide lean burn-out limit, and pollutant emissions. However, the best combustion performance needs to be obtained by optimizing the structural size of the bluff body or cavity.9

In addition, the jet-stabilized technology is another easier way to form the recirculation zone by jet interactions. In a jet-stabilized combustor, the air jet holes are arranged on the wall surface, and two injections move against and hit each other in the center; then, a large part of fluid flow upstream and impacts with the fuel jet again, thereby effectively forming a recirculation zone for fuel and air mixing and reactions.10,11 Compared with the vortex-stabilized or cavity-stabilized combustor, the jet-stabilized combustor has the advantages of simple structure and wide range of fluid operation, and it has also attracted increasing attention. Bauer et al.12 first measured the local flow parameters such as fluid velocity, temperature, and species distributions in a jet-stabilized model combustor using liquid diesel and gaseous propane as fuels separately, and the results provide wide validation for numerical calculation models. After that, researchers carried out a lot of numerical simulations on the combustion and NOx emission characteristics of liquid fuel jet-stabilized combustor.13−17 However, with the deterioration of the environment and the continuous depletion of fossil fuels, modern engines require transition from traditional fossil fuels to clean and renewable...
fuels, and hydrogen utilization has gained more and more attention as an alternative fuel in various combustion systems. This is because hydrogen fuel combustion does not produce greenhouse gases but exhibits high reactivity and a high heat release. Most importantly, the small molecular weight of hydrogen results in large mass diffusion, so the flame propagation speed is several times that of natural gas; thus, it may cause the flame to flashback. To avoid flashback, increasing the jet velocity is a usual method, but a large velocity can easily cause flame blowout. Therefore, the benefits of hydrogen needs further and specific studies on combustion stabilization for advanced engine development, and hydrogen is often used by mixing with the hydrocarbon fuel to improve the ignition and flame stability performance in various combustors; some studies even focus on pure hydrogen fuel utilization.

In our previous work, the characteristics of pure hydrogen combustion and flow in a jet-stabilized combustor have also been numerically investigated. It is found that the equivalence ratio has a great impact on the vortex structure and the high-temperature distribution in the recirculation zone. Especially, at a large equivalence ratio, the recirculation zone cannot form a stable vortex structure to promote flame stabilization, and the large hydrogen jet velocity is the main reason for that. In this study, a hydrogen jet-stabilized combustor with the fuel multijet scheme is presented. The main objective of this study is to investigate the effects of the fuel multijet scheme and the fuel flow rate assignment on the combustion flow characteristics of the jet-stabilized combustor and compare the results with those from the scheme of the fuel single jet. The results will provide new insights into the design of the combustor with wide lean blowout limit and low emissions.

2. GEOMETRY AND NUMERICAL METHODS

2.1. Geometric Model. Based on the jet-stabilized model combustor described in the literature, this study describes a jet-stabilized combustor with the hydrogen multijet scheme, as shown in Figure 1. The combustor has a three-dimensional cylindrical configuration with a length of 400 mm and a diameter of 80 mm. Four air jet holes with 8 mm diameter are situated 60 mm downstream from the combustor head, and the angle between each other is 90°. There are two schemes for the hydrogen jet layout, and for the single-jet scheme, the hydrogen jet hole with 3 mm diameter is situated at the center of the head plate. For the multijet scheme, there are five jet holes with the same diameter of 3 mm. Among them, one jet hole is arranged in the center similar to the arrangement in the single-jet scheme, and the others are arranged at the periphery with a 30 mm distance from the center hole, and one jet hole corresponds to one air jet hole, both of which are in the same central section.

2.2. Numerical Model and Boundary Conditions. 2.2.1. Numerical Methods. 2.2.1.1. Governing Equations. The governing equations for incompressible steady flow, including the continuity equation, momentum equation, energy equation, and species equations are shown below.

Continuity equation: \[ \nabla \cdot \vec{v} = 0 \] (1)

Momentum equation: \[ \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot \tau + \vec{f} \] (2)

where \( \rho \) is the fluid density, \( \vec{v} \) is the velocity component, \( p \) is the static pressure, and \( \tau \) is the stress tensor.

Energy equation: \[ \nabla \cdot (\rho \vec{v} E) = -\nabla \cdot \vec{q} + \nabla \cdot \vec{Q} + \epsilon \] (3)

where \( E \) is the total energy, \( \vec{q} \) is the heat source term of the chemical reaction, \( \epsilon \) is the rate of production of the turbulence kinetic energy.

Species equation: \[ \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J} + \dot{R}_i \] (6)

where \( \dot{R}_i \) is the net rate of production of species \( i \) by the chemical reaction.

2.2.1.2. Turbulence Model. Realizable \( k - \varepsilon \) model is a modified style based on the standard \( k - \varepsilon \) model, which introduced the items about rotation and curvature, and can be used in this study. The model descriptions are as follows.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho \vec{v} k) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} + G_k - \rho \varepsilon
\] (7)

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \vec{v} \varepsilon) = \frac{\partial}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + \rho C_{\varepsilon} \frac{\dot{Q}_t}{k} - \rho C_{\varepsilon} \frac{\varepsilon^2}{k + \sqrt{\varepsilon}}
\] (8)

where \( k \) is the turbulence kinetic energy, \( \varepsilon \) is the rate of dissipation, \( G_k \) is the generation of the turbulence kinetic energy due to the mean velocity, \( C_{\varepsilon} \) is a constant, \( \sigma_k \) and \( \sigma_\varepsilon \) are...
the turbulent Prandtl numbers for $k$ and $\epsilon$, and $C_i$ is defined as follows:

$$C_i = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right]$$

(9)

where $\eta = S^2 \epsilon / \nu$, $S = 2\sqrt{\nu \rho_b \epsilon / \rho}$, $\eta_i = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$.

2.2.1.3. Combustion Model. The mechanism of the H$_2$/Air one-step global reaction is used in this study.

$$2H_2 + O_2 \rightarrow 2H_2O$$

(R1)

The finite rate/eddy-dissipation (FR/ED) model$^{17}$ is adopted to model the turbulence-chemistry reaction. The FR/ED model considers comprehensively the dynamics and turbulence factors.

The molar rate of the creation/destruction of species $i$ in reaction $r$ is concluded using the following equation:

$$\hat{R}_{i,r} = \Gamma(w_i^r - v_i^r) \left( k_{ri} \prod_{j=1}^{N} [C_{ij}]_{i}^{(r_j)} {\eta}_i^{r_j} \right)$$

(10)

where $\Gamma$ is the net effect of third bodies on the reaction rate, $w_i^r$ and $v_i^r$ are the stoichiometric coefficients for product and reactant species, $C_{ij}$ is the molar concentration of species $j$ in reaction $r$, $\eta_i^r$ and $\eta_j^r$ are the rate exponents for reactant and product species $j$ in reaction $r$.

For the eddy-dissipation model, the net rate of the production of species $i$ in reaction $r$ can be determined by two equations below, and $R_{i,r}$ is determined by the smaller.

$$R_{i,r} = v_i^r M_{w,i} A_B \rho^E \min_k \left( Y_k \frac{Y_k}{w_k M_{w,k}} \right)$$

(11)

$$R_{i,r} = v_i^r M_{w,i} A_B \rho^E \sum_j Y_j \frac{w_j / M_{w,j}}{v_j}$$

(12)

where $Y_k$ is the mass fraction of a particular reactant, $Y_j$ is the mass fraction of any product species, $M_{w,i}$ is the molecular weight of species $i$, $A$ and $B$ are the empirical constants, $A = 4.0$, $B = 0.5$.

2.2.1.4. Radiation Model. The discrete ordinate method (DOM) is used in this study to calculate the radiative term in the form of the radiative transfer equation in the energy equation. The nongray gas properties are considered by the weighted-sum-of-gray-gases (WSGG) model. The DOM is widely adopted with the WSGG model to calculate the turbulence radiation.$^{14-16}$

2.2.2. Discretization Procedure and Boundary Conditions. In this numerical study, the finite volume method (FVM) is adopted to solve the equations of flow transport, and the SIMPLE algorithm is used to solve the pressure–velocity coupling in the CFD software Fluent. The second-order central difference scheme and the second-order upwind difference scheme are used respectively for the diffusion terms and the convective terms. The convergence criterion is set as $10^{-6}$ for all the equations.

The boundary condition of the air and hydrogen jets is the mass flow inlet with a temperature of 300 K and that of the combustor outlet is the pressure outlet boundary with one atmosphere. To describe the near-wall treatment of the combustor, the no-slip wall boundary with the standard wall function is adopted, and the heat flux model is used to consider the wall heat transfer. Table 1 shows the operating conditions for air and hydrogen inlets; there is a change in the air mass flow rate but the mass flow rate for hydrogen is constant to obtain different equivalence ratios, and the single-jet scheme just contains case 1, case 2, and case 3. For the multijet scheme, the assignments of the hydrogen fuel flow rate are all in the condition of $\Phi = 0.22$, and the details are shown in Table 1.

2.3. Grid Independence Test. Figure 2 depicts the computational domain with structured hexahedral meshes, where a refined mesh is employed at the air inlet, fuel injection, and combustion reaction region of the combustor. Three mesh sizes are employed in the grid independence test, and the total hexahedral cell numbers are 0.67 million, 0.99 million, and 2.17 million, respectively. Figure 3 shows the effects of three mesh sizes on the radial temperature profiles at $x = 0.098$ m of the central section. It is found that the comparison results of the three grids have small differences on the whole. Near the central axis, the temperatures of the coarse grid (0.67 million cells) are significantly lower than the other two, while that of the medium grid (0.99 million cells) coincides with that of the fine grid (2.17 million cells). Therefore, the medium grid with 986102 cells was chosen in this study to save the computing time.

Table 1. Operating Conditions

| style    | case | mass flow rate of H$_2$ (g/s) | mass flow rate of H$_2$ annular multijet (kg/s) | mass flow rate of air jet (kg/s) | equivalence ratio ($\Phi$) |
|----------|------|------------------------------|-----------------------------------------------|---------------------------------|---------------------------|
| single jet | 1   | $5 \times 10^{-5}$          | $1.1 \times 10^{-5}$                          | $1$                             | $1$                       |
|          | 2   | $5 \times 10^{-5}$          | $3 \times 10^{-5}$                          | $0.37$                           |
|          | 3   | $5 \times 10^{-5}$          | $5 \times 10^{-5}$                          | $0.22$                           |
| multijet | 4   | $1 \times 10^{-5}$          | $4 \times 10^{-5}$                          | $1.1 \times 10^{-3}$           | $1$                       |
|          | 5   | $1 \times 10^{-5}$          | $4 \times 10^{-5}$                          | $3 \times 10^{-5}$             | $0.37$                     |
|          | 6   | $4 \times 10^{-5}$          | $1 \times 10^{-5}$                          | $5 \times 10^{-5}$             | $0.22$                     |
|          | 7   | $3 \times 10^{-5}$          | $2 \times 10^{-5}$                          | $5 \times 10^{-5}$             | $0.22$                     |
|          | 8   | $2 \times 10^{-5}$          | $3 \times 10^{-5}$                          | $5 \times 10^{-5}$             | $0.22$                     |
|          | 9   | $1 \times 10^{-5}$          | $4 \times 10^{-5}$                          | $5 \times 10^{-5}$             | $0.22$                     |
|          | 10  | $0.0$                        | $5 \times 10^{-5}$                          | $5 \times 10^{-5}$             | $0.22$                     |

Figure 2. Structured grid of the combustor.

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3. RESULTS AND DISCUSSION

3.1. Model Validation. The validation of the hydrogen/air combustion flow models is carried out by comparing the numerical results with the experimental database M2 of TNF Data Archives-DLR, with a composition of 75% hydrogen and 25% nitrogen in mole fraction. Figure 4 shows the comparisons of temperature and species profiles at the axial location of x = 0.04 m. As shown in Figure 4a,b, regardless of whether the numerical results of temperature or species (H₂, H₂O, or N₂) are in agreement with the experimental results, the relative errors are all less than 15% except the point of r = 10 mm, which shows that the numerical models used in this study are acceptable to simulate the H₂/Air combustion flow.

3.2. Effects of the Equivalence Ratio. 3.2.1. Turbulence Flow Characteristics. The stable vortex structure is the key for jet-stabilized combustion, and the vortex structure can be displayed through the velocity vector distribution. The velocity vector distributions of the combustor central section (z = 0 mm) with the equivalence ratio is 1, 0.37, and 0.22, as shown in Figure 5. It can be seen that the symmetrical vortex structure can be formed under all conditions, so only the upper vortex structure is analyzed in the following. At Φ = 1, a small-scale vortex structure is formed near the junction of the hydrogen jet and the air lateral jet in the scheme of the hydrogen central single jet. That is because the hydrogen jet momentum is much larger than the air jet momentum in this case, the hydrogen jet streamlines directly through the impinge point of the air jets, which makes it impossible for the air jets to hit each other, so it is difficult to form an effective backflow for the air jets. Compared with the hydrogen single-jet scheme, two vortexes are formed in the hydrogen multijet scheme, among which the primary vortex on the right is larger in size, and the secondary vortex on the left is squeezed near the hydrogen central jet. The primary vortex is mainly formed by the backflow caused by air jets, and the peripheral hydrogen jet merges with the air backflow, which can effectively enhance the vortex strength. The secondary vortex structure is mainly caused by the hydrogen central jet encountering the air backflow, and in this case, the impinge point location is x = 21 mm, which shows that the hydrogen central jet momentum is significantly reduced compared to the hydrogen single-jet scheme, so the secondary vortex is formed.

At Φ = 0.37, two vortex structures appear in the hydrogen central single-jet scheme, and there exists an impinge point in the recirculation zone of x < 0.6 m. It is mainly because, in this case, the increased air mass flow rate leads to an increase in the air jet momentum, so the air jets can impact each other and form an effective backflow. The backflow formed impacts with the hydrogen jet again to form the primary vortex structure. The secondary vortex structure is caused by another part of hydrogen being blocked by the air backflow. Although the primary vortex size is smaller than that of the secondary vortex, its momentum is significantly greater, indicating that sufficient air has started to enter the recirculation zone. For the multijet scheme, the vortex structure has evolved from double vortex to single vortex, and the position of the primary vortex center does not change in the radial direction but changes from x = 52 mm to x = 42 mm in the axial direction, and the impinge point is greatly decreased from x = 45 mm to x = 6 mm. Because the hydrogen central jet momentum has been shared by other holes at this time, the backflow formed by the air jets plays a dominant role and extremely squeezes the hydrogen central jet. At the same time, the momentum of the annular jets continues to merge into the vortex structure, making the vortex structure more stable.

In the case of Φ = 0.22, the vortex pair continues to appear in the single central jet scheme, but the scale of the primary vortex exceeds that of the secondary vortex. This is because the air mass flow rate is further increased at this time, so the amount of backflow formed by the air jets is correspondingly increased, thereby squeezing the secondary vortex, indicating

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Figure 3. Grid independence test.

Figure 4. Model validation results: (a) temperature profiles and (b) species profiles.
that the air backflow at this time starts to play a leading role in the process of vortex formation. At this time, in the multijet scheme, the air backflow completely dominates, and the hydrogen central jet cannot form a vortex. The hydrogen central jet is forced to flow radially and merge into the vortex structure. Similarly, the annular hydrogen jets are merged together into the vortex structure, thereby strengthening the vortex structure in many ways. In contrast, the primary vortex center position is basically the same, but the impinge point is changed from $x = 30$ mm for the single-jet scheme to $x = 3$ mm for the multijet scheme.

It can be seen that because the multijet scheme disperses the momentum of the central jet, no matter how the equivalence ratio changes, the backflow formed by air jets can play a dominant role, which can form a large-scale stable vortex. On the other hand, the annular hydrogen jet directly enters the vortex structure, thereby further enhancing the vortex stability.

In general, compared with the single central jet scheme, the vortex structure of the multijet scheme varies much less with the equivalence ratio and is more inclined to form a single vortex structure, which is beneficial to the vortex stability.

Figure 6 shows the axial velocity distribution of the $z = 0$ mm section. As shown, when the equivalence ratio is 1, the axial velocity of the hydrogen single central jet scheme decreases in the axial direction from 80 m/s at $x = 5$ mm to 20 m/s at $x = 55$ mm, but the velocity is still positive, indicating that the hydrogen jet momentum plays a dominant role, and the air jets cannot directly impact because of the effect of the hydrogen jet. In the case of the hydrogen multijet scheme, because hydrogen is evenly distributed to the five jet holes, the axial velocity of hydrogen jets is substantially the same as 18 m/s at $x = 25$ mm. In the axial direction, the axial velocity of the central jet decreases and changes to a negative value at $x = 25$ mm. This is because the backflow formed by the air jets...
impacts the hydrogen jet again, and an impact point is formed around at $x = 25$ mm, thus forcing the central hydrogen jet to form a small-scale vortex pair, as shown in Figure 5.

When the equivalence ratio is 0.37, the increase of the air jet flow rate causes the axial velocity to decay more rapidly in the axial direction for the hydrogen single-jet scheme, and the velocity decreases to 0 m/s at $x = 45$ mm, which also corresponds to the impinge point of the hydrogen jet and air jet shown in Figure 5, thus forming the phenomenon that the secondary vortex is larger than the primary vortex, as shown in Figure 5. In the scheme of the hydrogen multijet, the axial velocity of the central jet at $x = 5$ mm is lower than that of the annular jets, but the value is slightly greater than 0 m/s, indicating that the air backflow has an influence on it. After that, the axial velocity is negative along the axial, which shows that the air backflow already plays a dominant role. It is worth noting that at $x = 35$ mm, the axial velocity distributions of the single-jet and multijet schemes are consistent, which indicates that the air backflow has completely dominated under large air momentum.

In the case of $\Phi = 0.37$, the increase in air momentum makes the axial velocity of the hydrogen single-jet scheme negative at $x = 35$ mm, and the velocity of the multijet scheme is negative at $x = 15$ mm. Otherwise, the axial velocity distribution curves of the single-jet and multijet schemes basically coincide at $x = 35$ mm, $x = 45$ mm, and $x = 55$ mm, indicating that the air backflow in these regions plays the dominant role. Because $V_{r = 0} = 22$ m/s at $x = 25$ mm and $V_{r = 0} = -18$ m/s at $x = 35$ mm, the impinge point of the central jet and air backflow should be somewhere between them, as shown in Figure 5, and the point is $x = 30$ mm.

Combining the streamline and axial velocity distributions of the $z = 0$ mm section, it can be known that the vortex formation mainly depends on the momentum of the hydrogen central jet and air jet. The mutual influence of the hydrogen and air jets forms an impact intersection in the position with $V_{r = 0} = 0$ m/s, where the boundary point of vortex pairs with

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**Figure 6.** Axial velocity profiles of the $z = 0$ mm section with different equivalence ratios. (a) $\Phi = 1.0$, (b) $\Phi = 0.37$, and (c) $\Phi = 0.22$. 

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different scales is present. Compared with the single central jet scheme, the momentum of the multijet scheme is dispersed so that the air backflow plays a dominant role; thus, a relatively stable vortex structure can be formed.

### 3.2.2. Temperature Distribution.

The temperature contours of the central section \(z = 0 \text{ mm}\) in the schemes of the single jet and multijet are shown in Figure 7. In the case of \(\Phi = 1\), the high-temperature distribution area of the hydrogen single-jet scheme is relatively wide, mainly concentrated in the near-wall area downstream of the air jet holes, but the high-temperature area distribution of the multijet scheme is opposite to that of the single-jet scheme, and the high temperature is concentrated in the downstream central zone. In addition, in the range of \(x < 60 \text{ mm}\), the temperature distribution is relatively uniform but with a low value in the scheme of the hydrogen single jet, and there is a significant high-temperature area in the center zone with the multijet scheme, which provides sufficient conditions for flame stability.

When the equivalence ratio is 0.37, the high-temperature region of the single-jet scheme is sharply smaller, which is mainly distributed in the near-wall triangle region downstream of the air jet holes. In the case of the multijet scheme, the high-temperature region downstream of the air jet holes is also reduced in a relatively large area, and its distribution is consistent with that of the single-jet scheme, all concentrated in the near-wall triangle. However, in the range of \(x < 60 \text{ mm}\), there is a greater change in temperature than when the equivalence ratio is 1 mainly because a full high-temperature area at \(\Phi = 1\) is divided into two upper and lower regions. In the case of \(\Phi = 0.22\), the high-temperature region downstream of the single-jet scheme is degraded, and a large-area high-temperature region is formed upstream. In the scheme of the hydrogen multijet, although the downstream high-temperature region is more degraded than that of \(\Phi = 0.37\), the upstream high temperature region does not change much and only has a small difference in position.

From the abovementioned analysis, it can be seen that as far as the head region \((x < 0.6 \text{ m})\) of the combustor is concerned, the equivalence ratio has a great influence on the temperature distribution of the hydrogen single-jet scheme, but it has a relatively weak effect on the temperature distribution of the hydrogen multijet scheme. It can form a certain high-temperature area in the head area regardless of the equivalence ratio in the scheme of the multijet, and the annular hydrogen jets make it difficult for the high-temperature area to form near the wall. At the same time, combined with the vortex structure shown in Figure 5, it can be found that when a stable vortex structure is formed in the combustor head region, the distribution of high-temperature regions at the corresponding locations will also be relatively stable, as shown in the cases of \(\Phi = 0.37\) and \(\Phi = 0.22\). It is shown that the hydrogen multijet scheme can overcome the vortex structure, and the high-
temperature region distribution changes dramatically with the equivalence ratio, which is beneficial to the flame stabilization when the equivalence ratio is changed.

To further analyze the temperature distribution characteristics, the temperature distribution factor (TDF) is introduced as a parameter for judging the quality of the temperature distribution, and its definition is as follows:

$$\text{DF} = \frac{T_{\text{max}} - T_{\text{average}}}{T_{\text{average}} - T_{\text{air}}}$$

where $T_{\text{max}}$ and $T_{\text{average}}$ are expressed as the maximum temperature and the average temperature on the section, respectively, and $T_{\text{air}}$ is expressed as the intake air temperature. Figure 8 shows the axial TDF comparisons. It can be seen that the TDF value of the multijet scheme is larger than that of the single-jet scheme, but the difference between the outlet TDF (OTDF) of the combustor ($x = 0.4$ m) is the smallest.

For $\Phi = 0.37$ and $\Phi = 0.22$, in the range of $x > 0.06$ m, the TDF distributions of the single jet and multijet are equivalent, especially in the range of $x > 0.3$ m, and the TDF distribution curves of the two almost coincide. However, in the range of $x < 0.06$ m, the TDF value of the multijet scheme is much larger than that of the single-jet scheme. It can be seen that the arrangement of the hydrogen jet holes has a great impact on the quality of the temperature distribution at the combustor head, but it has little effect on the quality of the temperature distribution at the combustor outlet. The reason is that the temperature distribution of the single-jet scheme in the $x < 0.06$ m range is relatively uniform at $\Phi = 1$ and $\Phi = 0.37$. In the case of $\Phi = 0.22$, the high temperature is mainly distributed in the range of $x < 0.06$ m, and the high-temperature area is relatively large, so the temperature distribution is relatively uniform. For the multijet scheme, no matter what the equivalence ratio is, a high-temperature region can be formed in the range of $x < 0.06$ m, but the proportion of the high-temperature region is relatively small. Thus, obviously, the temperature distribution uniformity is much worse, resulting in a larger TDF value of the multijet scheme.

It can be seen that although the uniformity of the temperature distribution of the multijet scheme is lower than that of the single-jet scheme, it can form a high-temperature region in the combustor head regardless of the equivalence ratio, which is more conducive to the flame stabilization.

### 3.2.3. Reaction Characteristics

The abovementioned temperature distribution difference mainly depends on the zone where the combustion reaction occurs and the reaction rate. The reaction rate contours (cutoff the value below 0.05 kg · mol/m$^3$ · s) under different working conditions are shown in Figure 9. In the case of $\Phi = 1$, the high reaction rate zone of the single-jet scheme is mainly concentrated in the range of $0.04 < x < 0.09$ m, but that of the multijet scheme is enlarged to the range of $0.03 < x < 0.12$ m. The reaction heat release in the high reaction rate area will transfer to the surrounding area, which will increase the surrounding temperature, thereby forming a high-temperature region. Therefore, a large high reaction rate area will form a large high temperature area; hence, in the range of $x < 0.06$ m, a high-temperature zone with a certain area can be formed in the multijet scheme.

In the case of $\Phi = 0.37$, the high reaction rate area of the single-jet scheme is concentrated at $0.03 < x < 0.08$ m, compared with the case of $\Phi = 1$, the reaction zone expands upstream, and the reaction rate distribution is more uniform,
resulting in an increase in the high-temperature area at the combustor head. For the multijet scheme, the reaction zone is expanded upstream to the central jet outlet position, but in the range of \(x > 0.06\) m, there is a large reduction in the reaction region compared to the case of \(\Phi = 1\), thus resulting in a large decrease of the high-temperature distribution in this region. Comparing the single-jet scheme and the multijet scheme in the region of \(x > 0.06\) m at the same time, it is found that the reaction regions of the two are equally distributed, which shows that the temperature distribution of the two regions are also basically the same (Figure 7). In the zone of \(x < 0.06\) m, although the reaction region of the multijet is larger than that of the single-jet scheme, the reaction rate value is small; thus, the high-temperature region formed by heat release is smaller than that of the single-jet scheme, resulting in a larger TDF. In the case of \(\Phi = 0.22\), the reaction zone of the single-jet scheme is mainly distributed in the zone of 0.01 m < \(x < 0.04\) m, while that of the multi-jet scheme is in the range of \(x < 0.06\) m. In comparison, although the reaction zone of the single-jet scheme is smaller, its reaction rate value is the largest, so the area of the high-temperature region formed by heat release is larger than that of the multijet scheme in this range.

In general, the position of the high reaction rate does not coincide with the high-temperature position, and the above thermal diffusion may be only a part of the factors. The key reason is that the reaction rate only represents the intensity of the reaction between the fuel and the oxidant (or the mixing degree of the fuel and the oxidant) and not the total heat release of the combustion reaction. Therefore, in the high reaction rate region, it is not necessarily the region with the largest heat release, that is, the high-temperature region does not coincide with the high reaction rate region. To explore the causes of the formation of the high temperature region, in addition to analyzing the reaction rate, it is also necessary to analyze the content of fuel and air in the flow field as well as the equivalence ratio, which is also the point to be further studied in the future.

Figure 10 shows the average reaction rate of different sections along the axial direction. As shown, under different equivalence ratios, all the average reaction rate curves of the hydrogen single-jet scheme have a peak value, but the axial position corresponding to the peak changes upstream as the equivalence ratio decreases (\(x = 0.07\) m for \(\Phi = 1\), \(x = 0.05\) m for \(\Phi = 0.37\), and \(x = 0.03\) m for \(\Phi = 0.22\)). The peak size increases as the equivalence ratio decreases, indicating that the reaction zone and intensity in the single-jet scheme are greatly affected by the equivalence ratio. In the multijet scheme, the average reaction rate distribution shows a trend consistent with that of the single-jet scheme, that is, it first increases and then decreases in the axial direction, but the peak value is much smaller than that of the single-jet scheme with \(\Phi = 1\). However, for the cases of \(\Phi = 0.37\) and \(\Phi = 0.22\), the average reaction rate shows an overall trend of decrease along the axial direction, but the maximum value is about 0.1 regardless of the equivalence ratio. The average reaction rate distribution trend shows that the multijet scheme will increase the reaction zone area and make the reaction rate relatively uniformly distributed. The position and the size of the reaction zones are affected by the equivalence ratio, which is smaller than that of the single-jet scheme, and it is beneficial to the flame stability at different equivalence ratios.

Combustion efficiency is another main parameter that represents combustion characteristics, and its calculation formula is as follows.

\[
\eta_c = 1 - \frac{\int Y_{H_2} \rho u dA}{m_{\text{fuel}}} \tag{14}
\]

where \(Y_{H_2}\) is the mass fraction of the hydrogen fuel, and \(m_{\text{fuel}}\) is the inlet mass flow rate of hydrogen.
Figure 11 shows the combustion efficiency distribution along the axial direction. It can be seen that the combustion efficiency of the single-jet scheme or the multijet scheme is lower than 65% in the case of $\Phi = 1$. In the ranges of $x < 0.03 \text{ m}$ and $0.3 \text{ m} < x < 0.4 \text{ m}$, the combustion efficiency of the multijet scheme is slightly higher than that of the single-jet scheme, but the situation is just the opposite in the range of $0.06 \text{ m} < x < 0.12 \text{ m}$. This is because the combustion efficiency mainly depends on the reaction rate. At $\Phi = 1$, the high reaction rate of the single-jet scheme is mainly concentrated in the range of $0.04 \text{ m} < x < 0.09 \text{ m}$ (shown in Figure 10), so it consumes more hydrogen than the multijet scheme, which makes the combustion efficiency in this region relatively higher. The reason why both the schemes do not achieve complete combustion is that the fuel and air have no good mixing in $x < 0.06 \text{ m}$ range, so a large part of fuel will be blown out of the combustor in the time to burn.

In the case of $\Phi = 0.37$, both the single-jet scheme and the multijet scheme can achieve complete combustion in the range of $x < 0.1 \text{ m}$, but the combustion efficiency of the multijet scheme is still higher than that of the single-jet scheme in the $x < 0.04 \text{ m}$ range. As can be seen from Figures 9 and 10, the reaction zone of the multijet scheme has been completely moved at the combustor head, so the combustion efficiency is higher than that of the single-jet scheme. On the other hand, in the range of $0.03 \text{ m} < x < 0.05 \text{ m}$, the combustion efficiency curve of the single-jet scheme becomes steeper, indicating that the reaction rate in this region is higher than that of the multijet scheme. At $\Phi = 0.22$, the corresponding points of the single-jet scheme and the multijet scheme complete combustion are $x = 0.06 \text{ m}$ and $x = 0.07 \text{ m}$, respectively.
The combustion efficiency of the multijet scheme in the range of $x \leq 0.03$ m gradually increased to 100% in the axial direction, while that of the single-jet scheme was 0 in this region, and then, it suddenly increased to almost complete combustion. This is because the high reaction rate region of the single-jet scheme is mainly concentrated in the range of $0.03 \, m < x < 0.04 \, m$ under this condition, and the value is much higher than the multijet scheme. In addition, the equivalence ratio is the smallest at this time, and the combustion reaction is almost complete in this region, so the combustion efficiency curve shows a sudden increase.

3.3. Effect of Hydrogen Flow Rate Assignment. The equivalence ratio was set to 0.22, the air mass flow rate is $5 \times 10^{-3}$kg/s, and the total mass flow rate of hydrogen fuel is $5 \times 10^{-3}$kg/s. By assigning different hydrogen mass flow rates to the central jet and the annular multijet, as shown in Table 1, the flow and temperature fields would be changed. Figure 12 shows the velocity vector distributions in the central section ($z = 0 \, mm$). As shown, the hydrogen mass flow rates of the annular multijet in Case 3 and Case 6 are 0 and $1 \times 10^{-5}$kg/s, respectively, which are much smaller than the central jet mass flow rate; thus, the central jet plays a dominant role in Case 3 and Case 6, and double vortex is formed. The primary vortex in Case 6 is larger than that in Case 3. This is because in Case 6, the flow rate of the annular multijet is larger than that in Case 3, and the fluid directly flows into the primary vortex.

In Case 7, the annular multijet flow rate increased to $2 \times 10^{-5}$kg/s, while the central jet flow rate decreased to $3 \times 10^{-5}$kg/s. It can be seen that the vortex structure has changed greatly compared to Case 3, and the secondary vortex scale is much smaller than the primary vortex scale. This is because the central jet flow rate is reduced, and there is no much resistance to the air backflow. In addition, the annular multijet directly flows into the right vortex, which exacerbates the flow intensity. In Case 8, the primary vortex squeezed the secondary vortex even more, and in the following conditions Case 9 and Case 10, vortex formed by air backflow has become completely dominant. It can be seen that as the hydrogen mass flow rate assigned to the annular multijet increases, the vortex structure at the combustor head gradually develops from double vortex to single vortex. At the same time, the flow rate assignment of hydrogen has almost no effect on the primary vortex center position, and the vortex intensity is greatly enhanced because of the addition of the annular multijet momentum; thus, it is more conducive to flame stabilization.

In Case 6 shown in Figure 13, because of the large central jet flow rate, the high-temperature region is mainly distributed in the range of $0.015 \, m < x < 0.06 \, m$, while in Case 7, the high-temperature area in Case 6 is elongated and narrowed, and a high-temperature zone is formed between the central jet hole and the annular jet hole. After that, as the flow rate of the central jet decreases, the high-temperature region between the two holes decreases. The high-temperature region in Case 10 has a temperature distribution similar to that of Case 6, but the area is reduced by comparison. In the range of $x > 0.06 \, m$, the high-temperature zone is mainly formed near the angle between the air jet and the wall. The area of the high-temperature zone in Case 6 is the largest, but with the
adjustment of the hydrogen flow rate, the location and the area of the high-temperature regions are not significantly different.

On the whole, the flow rate assignment has little effect on the high-temperature region location, and only affects its area; especially, the flow assignment can promote the stable vortex pair formation in the range of \( x < 0.06 \) m (Case 8–Case 10).

Figure 14 shows the TDF distribution along the axis in different conditions. As shown, in the range of \( x < 0.06 \) m, the TDF increases gradually as the central jet flow rate decreases. This is because the high-temperature area will decrease as the central jet flow rate decreases. Because the mass flow rate assigned to the annular multijet is the smallest in Case 6, the central jet still plays the dominant role at this time, which causes its vortex structure to be an unstable vortex pair. As a result, the reaction zone is moved backward as a whole, and the fuel and air cannot achieve good mixing and combustion in the range of \( x < 0.06 \) m. Therefore, Case 6 shows that the combustion efficiency in this region is lower, and the complete combustion point is completely behind others.

4. CONCLUSIONS

In this study, the effects of the hydrogen single-jet scheme and multijet scheme on the combustion flow characteristics of the jet-stabilized combustor are compared and analyzed using numerical calculation methods. The influence of hydrogen mass flow rate assignment on combustion flow under multijet conditions is also studied. The following conclusions are obtained.

With different equivalence ratios, two vortex pairs are formed in the range of \( x < 0.06 \) m under the single-jet scheme, and the equivalence ratio exhibits a greater effect on the vortex size and position distribution. However, the equivalence ratio has a small effect on the vortex structure of the multijet scheme in the range of \( x < 0.06 \) m, and the stable and substantial vortex structures are formed here. The combustion reaction region of the multijet scheme is larger than that of the single-jet scheme, and the reaction rate distribution is relatively uniform; hence, it is easier to form a certain high-temperature zone in the range of \( x < 0.06 \) m. Otherwise, the location and size of the reaction rate zones in the multijet scheme are less affected by the equivalence ratio compared with the single-jet scheme; thus, the multijet scheme is more conducive to flame stabilization with different equivalence ratios.

The combustion efficiency of the multijet and single-jet schemes are both lower than 65%, but that of the multijet scheme is slightly improved in the case of \( \Phi = 1 \). Under lean conditions, both the jet schemes can achieve complete combustion, and the OTDF of the two is equivalent at different equivalence ratios. For the multijet scheme, with the decrease in the central jet flow rate, the vortex structure in the range of \( x < 0.06 \) m changes from double pairs to a stable and full vortex pair. Moreover, a certain high-temperature area can be formed in this region with different flow rate assignment, but the high-temperature area will decrease as the central jet flow rate decreases. At the same time, as the flow rate assigned to the central jet decreases, the combustion efficiency in the region increases first and then decreases, while the OTDF follows the law by which it decreases as the central jet flow rate decreases.

be seen that complete combustion can be achieved under these conditions, the combustion efficiency in each working condition gradually increases in the axial direction, and there is no sudden increase in the combustion efficiency, as shown in Figure 11. The corresponding point for complete combustion in Case 6 is \( x = 0.1 \) m, and the corresponding point in other operating conditions is \( x = 0.07 \) m. In the range of \( x < 0.06 \) m, Case 6 exhibits the lowest combustion efficiency, and the rest of the operating conditions basically show that the combustion efficiency decreases as the central jet flow rate decreases.

Figure 15 shows the combustion efficiency distribution in the axial direction under different operating conditions. It can

![Figure 14. TDF comparisons in the multijet scheme with different flow rate assignment.](image1)

![Figure 15. Combustion efficiency in the multijet scheme with different flow rate assignment.](image2)

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Notes
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