Numerical Simulation of Combustion and Emission Characteristics of a Hydrogen Jet-Trapped Vortex Combustor

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Abstract

A wide flame stability range and low pollutant emissions are two important aspects in the design of modern aero-engine combustors. Trapped vortex combustors have attracted extensive attention because of their excellent flame stability and low-emission characteristics, but insufficient heat and mass exchange between the mainstream and the cavity limits further performance improvement. Therefore, based on the trapped vortex combustor configuration, a jet flame stabilization method is introduced in this study, and a novel jet-stabilized trapped vortex combustor configuration is designed. The high mixing efficiency and sufficient heat and mass exchange characteristics of jet flame stabilization are used to overcome the shortcomings of conventional trapped vortex combustors. Numerical simulations are conducted to analyze the effects of different air jet angles on the flow, combustion, and emission characteristics in a hydrogen-fueled jet-stabilized trapped vortex combustor. The results show that under different air jet angles, a vortex-pair structure can form in the interaction region between the hydrogen fuel jet and the air jet, and complete combustion can be achieved at the specified equivalence ratio. When the air jet angle is 0°, the overall combustion efficiency and temperature distribution uniformity of the combustor are relatively better. As the air jet angle is further increased, the combustion efficiency and temperature distribution uniformity gradually decrease, while the overall nitrogen oxide emissions of the combustor first increase at an air jet angle of 10° and then gradually decrease.

Full Text

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Abstract: A wide flame-stability range and low pollutant emissions are two relatively important aspects in the design of modern aero-engine combustors. Trapped vortex combustors have attracted broad attention because of their excellent flame-stabilization and low-emission characteristics; however, the problem of insufficient heat and mass transfer between the mainstream and the cavity limits further performance improvement. To this end, on the basis of a trapped vortex combustor configuration, a jet-stabilized flame mode is introduced. In this study, a novel jet-trapped vortex combustor configuration is designed, using the high mixing efficiency and sufficient heat and mass transfer characteristics of jet-stabilized flames to compensate for the shortcomings of conventional trapped vortex combustors. A numerical simulation method is adopted to analyze the effects of different air jet angles on the flow, combustion, and emission characteristics inside a hydrogen-fueled jet-trapped vortex combustor. The results show that, under different air jet angles, vortex-pair structures can form in the interface region between the hydrogen fuel jet and the air jet, and complete combustion at a given equivalence ratio is achieved. When the air jet angle is 0°, the overall combustion efficiency and the uniformity of the temperature distribution in the combustor are relatively good. If the air jet angle is further increased, the combustion efficiency and temperature-distribution uniformity gradually decrease, and the overall nitrogen oxide emissions of the combustor first increase at an air jet angle of 10° and then gradually decrease.

Keywords: jet-trapped vortex combustor; jet angle; hydrogen combustion; NO_x emission; numerical simulation

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Numerical investigation on the combustion and emission characteristics in a hydrogen jet-trapped vortex combustor

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Abstract: The two critical aspects in the design of modern aero-engine combustors are the width of the flame stability limits and the reduction of pollutant emissions. Trapped vortex combustor (TVC) have attracted significant attention due to their excellent flame stabilization and low-emission characteristics; however, insufficient heat and mass transfer between the mainstream flow and the cavity region limits further performance improvement. To enhance performance, a novel jet-trapped vortex combustor combined with jet-stabilized method and the conventional TVC is proposed. Therefore, in this study, the numerical method is employed to investigate the effects of different air jet angles on the flow, combustion, and emission char-

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acteristics within a hydrogen jet-trapped vortex combustor. The results indicate that under various air jet angles, vortex pair structures are formed at the interface between hydrogen and air jets, enabling complete combustion at a given equivalence ratio. When the air-jet injection angle is set to 0°, the combustor exhibits the highest overall combustion efficiency and the most uniform temperature distribution. Incrementally increasing the injection angle progressively decreases both parameters. Notably, the total nitrogen-oxide emissions first rise, peaking at an injection angle of 10°, and then decline with further angular augmentation.

Key words: jet-trapped vortex combustor; jet angle; hydrogen combustion; NO_x emissions; numerical simulation

With the intensification of global climate change, higher requirements have been placed on the technological development of aero-engines and gas-turbine combustors. In combustor design, the trapped vortex combustor (TVC) has shown advantages in flame stabilization and pollutant emissions, but it also suffers from insufficient heat and mass exchange between the mainstream and the cavity. The jet-stabilized combustor (JSC), however, has a simple structure and offers advantages such as high air–fuel mixing efficiency and relatively sufficient heat and mass exchange. Therefore, a jet-trapped vortex combustor (JTVC), designed by combining the JSC and TVC, integrates the advantages of both combustors and is expected to enhance the mass and energy exchange efficiency inside the combustor while maintaining the stability of the vortex structure.

For hydrogen–air combustion, Meier et al. [1] investigated H_2/N_2/air jet diffusion flames with two different exit velocities and N_2 dilution levels, providing a comprehensive dataset that can be used as a test case for flame models. Bazdidi-Tehrani et al. [2], in numerical simulations of JSCs with two-phase diesel/air combustion reactions, found that compared with the eddy-dissipation model, the probability density function (PDF) model could predict the temperature distribution more accurately. Zeinivand et al. [3] found that the effect of jet-hole location on nitrogen-oxide concentration emissions from the combustor was far greater than that of the number of jet holes. Alemi et al. [4] found that at high jet Reynolds numbers, variation in the jet-injection direction had a relatively large effect on nitrogen-oxide emissions. Sun et al. [5-6] were the first to conduct numerical calculations using hydrogen fuel in a JSC. Their results showed that, as the equivalence ratio decreased, the dominant factor in the vortex structure changed from fuel jets to air jets, and the vortex structure also changed from a single vortex to a stable double-vortex structure. Pu Zhiwei et al. [7] found that, compared with a circular combustor, the NO emissions of a combustor with a gradually varying jet-stabilized cross section were reduced by 51.26%. Hasan et al. [8] found that, for the same combustor system arrangement, when the air ratio was 0.15, the exit-temperature uniformity increased by 48.49%. Sampat et al. [9] found that the percentage of H_2 in the blended fuel and the mixture equivalence ratio had significant effects on the flame stabilization position and mechanism.

Regarding TVCs, early experiments by Hsu et al. [10] found that TVCs exhibited excellent performance in lean blowout characteristics, combustion efficiency, and pollutant emissions. In recent years, Jiang et al. [11–12] proposed a mixed-flow trapped vortex combustor. Studies showed that this combustor had good ignition performance, with combustion efficiency above 96% under all operating conditions and nitrogen-oxide emission indices below 2.1. Sun et al. [13] carried out numerical research on TVCs using a reverse-diffusion combustion method. When the jet holes were arranged at the same position, a multi-jet scheme was more conducive than a coaxial-jet scheme to enhancing flame stability and fuel-air mixing performance inside the cavity. Kang Yudong et al. [14–16] conducted experimental studies on the influence of radial stabilizers on improving the performance of trapped vortex combustors. Xu Wei et al. [17] found that fuel injection from the top of the front cone could improve the overall combustion efficiency of the combustor. Zhang Qiufeng et al. [18] carried out experimental research on the performance of a swirling TVC with three swirler structural schemes. Zhai Yunchao et al. [19] found that, for airblast atomizing nozzles, the air pressure and oil pressure had relatively large effects on the receiving angle of the oil-mist cone. Liu Yingli et al. [20] found that the use of a new crescent-shaped cone could effectively improve combustion performance. Wang Jinshou et al. [21] found that when the opening ratio of the cooling holes in the cavity stabilizer was low, the recommended equivalence ratio of oil vapor inside the cavity was 1.2–1.5. Zhong Shilin et al. [22] studied the flow characteristics during combustion-mode transition in a cavity trapped-vortex hypergolic combustor. Guo et al. [23] proposed a novel swirling trapped vortex combustor and found that it exhibited high performance in total-pressure recovery, combustion stability, combustion efficiency, and exit-temperature distribution; by increasing the inlet reference velocity or reducing the temperature, the flame area could be reduced [24–25].

Although TVCs perform well in flame stabilization and low pollutant emissions, previous studies have identified insufficient heat and mass exchange between the mainstream in the combustor and the interior of the cavity. Therefore, Roquemore et al. [26], Agarwal et al. [27–28], and Merlin et al. [29] all added disturbance devices inside the combustor cavity. These studies showed that the design of disturbance devices could enhance heat and mass exchange, but would correspondingly make the combustor structure more complex.

To integrate the characteristics of both TVCs and JSCs, some researchers have carried out comprehensive studies related to the two. Ren Guanlong et al. [30] conducted cold-flow numerical simulations of JSCs with different configurations and found that jet combustors with cavity structures had better fuel–air mixing performance. Tian et al. [31], based on a cylindrical JSC, proposed three new JSC schemes with cavities, vertical bluff-body rings, and vertical bluff-body columns, respectively,

Studies have found that, compared with the original combustor, the NO emissions of combustors with a cavity and a vertical bluff-body ring configuration are reduced to varying degrees. These findings indicate that designing a cavity structure in a JSC helps improve the mixing effect between fuel and air and reduce NO emissions. Regarding the current state of research on JTVCs, Hou et al.

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investigated the influence of different air-jet-hole positions on the combustion flow and emission performance inside the combustor. The results showed that the closer the air-jet holes were to the fuel nozzle, the more beneficial they were for promoting the mixing of hydrogen and air. This not only significantly reduced NO emissions in the downstream region of the cavity, but also improved the uniformity of the temperature distribution at the combustor outlet. In summary, even if the air-jet holes are far from the fuel nozzle, as long as they are arranged on the downstream wall of the cavity, NO emissions can still be suppressed to a certain extent. It can be seen that TVCs and JSCs have each been sufficiently studied and developed. However, current research on JTVCs is still at an early stage, and understanding of combustion flow, pollutant emissions, and flame stabilization mechanisms remains insufficient; therefore, further research is needed.

With the substantial improvement of computer performance and computational accuracy, computational fluid dynamics (CFD) methods have been widely applied

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. Based on the commercial CFD software Fluent, this study conducts numerical simulation research on the hydrogen combustion flow and NO_x emission characteristics of a JTVC under the influence of the air-jet angle, providing a reference for JTVC design.

1 Numerical Computational Model and Methods

1.1 Governing Equations

The flow governing equations for incompressible steady flow include the continuity equation, momentum equation, and energy equation

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, which are listed below in sequence.

Continuity equation

$$\nabla \cdot (\rho v) = 0 \qquad (1)$$

Momentum equation

$$\nabla \cdot (\rho v v) = -\nabla p + \nabla \cdot (\tau_{ij}) \qquad (2)$$

where ρ is the fluid density; v is the velocity component; p is the static pressure; and τ_{ij} is the stress tensor.

Energy equation

$$\nabla \cdot [v(\rho E + P)] = \nabla k_{\text{eff}} \nabla T - \sum_i h_i J_i + (\bar{\tau}_{\text{eff}} \cdot v) + S_E \qquad (3)$$

where E is the total energy,

$$E = h - \frac{p}{\rho} + \frac{|v|^2}{2};$$

h is the sensible enthalpy; J_i is the diffusion flux of species i; and S_E is the heat source term of the chemical reaction. J_i and S_E are described as

$$J_i = -\left(\rho D_{i,m} + \frac{\mu_t}{S_{C_t}}\right) \nabla Y_i \qquad (4)$$

$$S_E = -\sum_i \frac{h_i^0}{M_i} \mathfrak{R}_i \qquad (5)$$

where μ_t is the turbulent viscosity; $D_{i,m}$ is the mass diffusion coefficient of species i in the mixture; S_{C_t} is the turbulent Schmidt number; Y_i is the mass fraction of species i; h_i^0 is the enthalpy of species i; M_i is the molecular weight of species i; and $\mathfrak{R}_i$ is the volumetric production rate of species i.

1.2 Turbulence Model

The Realizable k-ε model is an improved form based on the standard k-ε model. In simulation experiments of JSC combustion, Yang et al.

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found that the prediction results of the Realizable k-ε model were superior to those of the standard k-ε model. Therefore, this study adopts the Realizable k-ε model

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as the turbulence model for steady-state simulation. The model is described as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]}{\partial x_j} + G_k - \rho\varepsilon \qquad (6)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_j)}{\partial x_j} = \frac{\partial\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]}{\partial x_j} + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} \qquad (7)$$

where k is the turbulent kinetic energy; ε is the dissipation rate; G_k is the turbulent kinetic energy generated by the mean velocity; C_2 is an empirical constant; σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively; and C_1 is defined as

$$C_1 = \max\left(0.43, \frac{\eta}{\eta + 5}\right) \qquad (8)$$

where

$$\eta = S\frac{k}{\varepsilon}; \qquad S = \sqrt{2S_{ij}S_{ij}}; \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right).$$

1.3 Combustion Model

In this study, a non-premixed probability density function (PDF) combustion model was used to solve the entire combustion process

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. The assumed PDF model simulates the interaction between combustion and turbulence. The PDF is a function used to describe dependent and independent variables in a turbulent combustion system. All quantities in turbulence can be regarded as random variables. The basis of the non-premixed modeling method is that, under certain simplifying assumptions, the instantaneous thermochemical state of the fluid is related to a conserved scalar called the mixture fraction. The mixture fraction f is a conserved scalar used to describe the instantaneous thermochemical state of the fluid, and its expression is

$$f = \frac{Y_i - Y_{i,\mathrm{ox}}}{Y_{i,\mathrm{fuel}} - Y_{i,\mathrm{ox}}} \qquad (9)$$

where Y_i is the mass fraction of species i. The subscripts ox and fuel respectively denote the mass fractions at the oxidizer inlet and fuel inlet. The mean mixture fraction in the turbulent flow is expressed as

$$\frac{\Delta(\rho\bar{f})}{\Delta t} + \frac{\Delta(\rho u_i \bar{f})}{\Delta x_i} = \frac{\Delta\left(\frac{\mu_t}{\sigma_t}\frac{\partial \bar{f}}{\partial x_i}\right)}{\Delta x_j} \qquad (10)$$

Its mixture-fraction variance is denoted by $\overline{f'^2}$, and the equation is

$$\frac{\partial(\rho\overline{f'^2})}{\partial t} + \frac{\partial(\rho u_j \overline{f'^2})}{\partial x_j} = \frac{\partial\left(\frac{\mu_t}{\sigma_t}\frac{\partial \overline{f'^2}}{\partial x_j}\right)}{\partial x_j} + C_g \mu_t \left(\frac{\partial \bar{f}}{\partial x_i}\right) - C_d \rho \frac{\varepsilon}{k}\overline{f'^2} \qquad (11)$$

where k is the turbulent kinetic energy; $\sigma_t = 0.85$; $C_g = 2.86$; $C_d = 2.0$;

$$f' = f - \bar{f}.$$

For the assumed PDF model, $p(f)$ can be calculated from the above mean mixture fraction and mixture-fraction variance. The mean reaction rate is obtained from the mean values of temperature and species concentration. Here $p(f)$ is

$$p(f) = \frac{f^{\alpha-1}(1-f)^{\beta-1}}{\int f^{\alpha-1}(1-f)^{\beta-1}\mathrm{d}f} \qquad (12)$$

$$\alpha = \bar{f}\left[\frac{\bar{f}(1-\bar{f})}{f'^2} - 1\right] \qquad (13)$$

$$\beta = (1-\bar{f})\left[\frac{\bar{f}(1-\bar{f})}{f'^2} - 1\right] \qquad (14)$$

Equation (15) is used to determine the mean values of species mass fraction, density, and temperature.

$$\bar{\varphi}_i = \int_0^1 \varphi_i(f, \bar{H})\, p(f)\, \mathrm{d}f \qquad (15)$$

In a non-adiabatic system, to determine $\bar{\varphi}_i$, the transport equation for the mean enthalpy must be solved, namely

$$\frac{\partial}{\partial t}(\rho \bar{H}) + \nabla \cdot (\rho v \bar{H}) = \nabla \cdot \left(\frac{k_t}{c_p} \nabla \bar{H} \right) + S_h \qquad (16)$$

1.4 NO_x formation model

The pollutants produced by fuel combustion are mainly NO and NO_2. During combustion, the principal sources of NO are thermal NO, prompt NO, and fuel NO. The overall equivalence ratio of the hydrogen-fuel reaction is approximately 0.34, and the fuel (hydrogen) contains no nitrogen. Therefore, prompt NO and fuel NO can be neglected [31]. The main chemical reaction pathways of thermal NO are as follows:

$$\mathrm{N_2 + O \leftrightarrow NO + N} \qquad (a)$$

$$\mathrm{O_2 + N \leftrightarrow NO + O} \qquad (b)$$

$$\mathrm{N + OH \leftrightarrow NO + H} \qquad (c)$$

The reaction rate of thermal NO is expressed as

$$\frac{\mathrm{d}_{[\mathrm{NO_{thermal}}]}}{\mathrm{d}t} = 2k_{1[\mathrm{O}][\mathrm{N_2}]} \cdot \left(\frac{1 - \dfrac{k_{-1}k_{-2[\mathrm{NO}]^2}}{k_{1[\mathrm{N_2}]}k_{2[\mathrm{O_2}]}}}{1 + \dfrac{k_{-1[\mathrm{NO}]}}{k_{2[\mathrm{O_2}]} + k_{3[\mathrm{OH}]}}} \right) \qquad (17)$$

where k_1, k_2, and k_3 are the forward rate constants of reactions (a), (b), and (c), respectively; k_{-1} and k_{-2} are the reverse reaction rates of reactions (a) and (b), respectively; [O] and [OH] are determined using the partial-equilibrium assumption [4]. The nitrogen oxide emission model has been validated in Ref. [31].

2 Computational mesh and model validation

2.1 Combustor geometric dimensions

The model of the jet trapped-vortex stable-flame combustor is shown in Fig. 1. The length, width, and height of the combustor are 320, 60, and 80 mm, respectively; the cavity length and height are 64 and 20 mm, respectively; and the outlet position height is 40 mm. A circular fuel jet hole with a diameter of 3 mm is located at the center of the left-side head face of the combustor. The origin O of the Cartesian coordinate system is the center of the fuel inlet, and the fuel injection direction is perpendicular to and points toward the outlet. Air jet holes with a diameter of 8 mm are symmetrically arranged on the upper and lower walls of the cavity, at distances of 32 and 30 mm from the left-side head face and the side wall, respectively. Therefore, taking the air jet direction injected vertically downward from the upper wall as an example, the air jet angle θ is defined as the included angle between the actual jet direction and the negative direction of the Y axis; that is, an increase in θ means that the downward-injected jet direction rotates counterclockwise in the XOY plane.

Fig. 1 Geometric configuration of combustor

2.2 Boundary conditions and operating conditions

The finite volume method is used to solve the transport equations, and the SIMPLE algorithm is used to solve the pressure–velocity coupling. The flow terms are discretized using a second-order upwind difference scheme, and the diffusion terms use a second-order central difference scheme. The convergence criterion for all equations is 10^{-6}. The inlets of air and hydrogen gas are

are all mass-flow inlets, with mass flow rates of 0.005 and 5×10^{-5} kg/s, respectively, and the overall equivalence ratio is 0.34. The inlet temperature is set to 300 K. The pressure outlet is set as a pressure-outlet boundary with a pressure of 101 325 Pa. In addition, the near-wall region of the combustor adopts a no-slip wall boundary condition and is treated using standard wall functions. A total of five operating conditions are set with different air-jet angles. Operating conditions 1–5 correspond to air-jet angles of 0°, 10°, 20°, 30°, and 40°, respectively.

2.3 Grid-Independence Verification

The combustor model is meshed using a structured hexahedral mesh, with mesh counts of 0.55 million, 1.12 million, and 2.08 million, respectively. Figure 2 shows a schematic of the structured mesh of the combustor. Figure 3 shows the radial temperature distribution on the combustor center section $Z = 0$ mm at the axial position $X = 23$ mm. As can be seen from Fig. 3, for the mesh count of 0.55 million, the temperature curve near the radial position of 0 mm differs relatively greatly from those of the other two mesh sets, whereas the differences between the calculation results for the 1.12-million and 2.08-million

Fig. 2 Combustor with a structured mesh

Figure 1: Fig. 2 Combustor with a structured mesh

Fig. 3 Radial temperature distribution of the central section of the combustor (Z=0 mm) at the axial X=23 mm

Figure 2: Fig. 3 Radial temperature distribution of the central section of the combustor (Z=0 mm) at the axial X=23 mm

meshes are small. Therefore, to save computational time, the 1.12-million-cell model is selected for the numerical simulations.

图 2 燃烧室的结构化网格

Fig. 2 Combustor with a structured mesh

图 3 燃烧室中心截面（$Z = 0$ mm）在轴向位置 $X = 23$ mm 处的径向温度分布

Fig. 3 Radial temperature distribution of the central section of the combustor ($Z = 0$ mm) at the axial $X = 23$ mm

2.4 Model Validation

The numerical results are compared with the experimental data of Meier et al. [1] to validate the hydrogen/air combustion and flow models. In the experiment of Meier et al. [1], the combustor consisted of a straight stainless-steel tube (central fuel nozzle inner diameter 4 mm, total inner diameter 144 mm, total length 350 mm). The fuel composition was 75%H_2+25%N_2, $Re = 9\,800$, and the fuel outlet velocity was 94 m/s. The fuel nozzle was surrounded by coflowing dry air with an outlet velocity of 0.4 m/s. Figure 4 compares the simulated and experimental distributions of H_2, O_2 components and flame temperature at $X = 80$ and 240 mm. As can be seen from Fig. 4, large temperature differences exist within 12.5 mm $< r <$ 16 mm at $X = 80$ mm and within 0 mm $< r <$ 30 mm at $X = 240$ mm; the maximum and minimum relative errors are approximately 21.7% and 7.5%, respectively. Large differences in the mole fraction of H_2 occur within 0 mm $< r <$ 13 mm at $X = 80$ mm and within 0 mm $< r <$ 12 mm at $X = 240$ mm; the maximum and minimum relative errors are approximately 36.4% and 5.3%, respectively. Large differences in the mole fraction of O_2 occur within 10 mm $< r <$ 26 mm at $X = 80$ mm and within 0 mm $< r <$ 20 mm at $X = 240$ mm; the maximum and minimum relative errors are 23.6% and 0.7%, respectively. The relatively large errors may be caused by simplification of the geometric model. The numerical results in the remaining regions are basically consistent with the experimental data, and the overall relative errors are all less than 12%. This indicates that the model has relatively high accuracy in simulating the flow and combustion processes inside the combustor and is suitable for numerical investigation of the combustion flow in a hydrogen-fueled jet trapped-vortex combustor.

3 Results and Discussion

3.1 Velocity Field and Vortex Structure

Figure 5 presents the streamline distributions and velocity distributions on the combustor center section $Z = 0$ mm and on the section at $X = 32$ mm under the different operating conditions. It can be seen that, under the combined action of the air jet and the hydrogen jet, a low-velocity recirculation zone is formed in the combustor cavity, and a vortex structure appears. The streamlines and velocity distributions for all operating conditions are mostly symmetrically distributed along the jet-flow direction. In operating condition 1, the air-jet angle θ is 0°. A pair of vortices forms in the upstream region of the air jet, with the vortex centers located at $X = 18$ mm, $r = \pm 10$ mm, while no vortex structure forms in the downstream part of the cavity. On the section at $X = 32$ mm, two pairs of vortices can be observed. As the air-jet angle θ increases, the impingement effect of the air jet in operating condition 2 weakens, but the impact on the region to the right of the jet increases, and the length of the high-speed jet at the hydrogen nozzle end increases. The size of the pair of vortex structures upstream of the cavity decreases, and the vortex centers move downstream to

$X = 20$ mm, $r = \pm 10$ mm. At the $X = 32$ mm section, the size of the counter-rotating vortex is reduced compared with the condition at $\theta = 0^\circ$. This is because the direction of the air jet shifts downstream along the cavity; the upstream low-velocity recirculation region becomes larger, and the impact of the jet on the downstream region is enhanced.

(a) Components at $X = 80$ mm

(b) Radial temperature at $X = 80$ mm

(c) Components at $X = 240$ mm

(d) Radial temperature at $X = 240$ mm

Fig. 4 Distribution of radial temperature and components (H_2 and O_2) at two axial positions of $X = 80$ mm and $X = 240$ mm

When the air jet angle θ is increased to 20° in operating condition 3, the size of the upstream counter-rotating vortex structure is further reduced, and the vortex center moves downstream to $X = 28$ mm, $r = \pm 10$ mm. At $X = 32$ mm, the vortex structure is reduced compared with operating condition 2, and the vortex center moves toward both sides. As the air jet angle θ increases to 30°, in operating condition 4 the size of the upstream vortex structure continues to decrease, and the vortex center moves to $X = 36$ mm, $r = \pm 8$ mm; a small counter-rotating vortex structure appears downstream. At the $X = 32$ mm section, the vortex structure continues to decrease, and the vortex center moves close to the upper and lower walls. When the air jet angle θ is further increased to 40°, in operating condition 5 the size of the vortex pair in the cavity is further reduced, and the vortex center moves to $X = 45$ mm, $r = \pm 6$ mm.

The downstream counter-rotating vortex of the air jet moves downstream to $X = 85$ mm, $r = \pm 15$ mm. At the $X = 32$ mm section, the center of the vortex structure approaches the center of the section.

Vortex strength can be characterized by vorticity. The vorticity distribution in the combustor is calculated using the Q criterion[^32]. The formula for calculating the Q criterion is as follows:

$$Q = -\frac{1}{2}\left(e_{ij}e_{ji} + \Omega_{ij}\Omega_{ji}\right) = \frac{1}{2}\left(\Omega_{ij}\Omega_{ji} - e_{ij}e_{ji}\right)$$

$$= \frac{1}{2}\left(|\Omega|^2 - |E|^2\right) \qquad (18)$$

where Ω is the rotation tensor, and e is the strain-rate tensor.

A low-vorticity region indicates that the vortex strength in that region is relatively low, even to the point that no distinct vortex structure is present. The vorticity distributions in all operating conditions show obvious differences, and the high-vorticity regions are all distributed on both sides of the air jet and the hydrogen jet. This is because the air jet has a relatively large momentum of impingement, causing the high-vorticity regions to be distributed on both sides of the air jet. The high-vorticity regions on both sides of the air jet are far larger than those on both sides of the hydrogen jet.

Figure 6 shows the vorticity distribution on the combustor center section $Z = 0$ mm and the high-vorticity iso-surfaces colored according to velocity magnitude. In operating condition 1, on the combustor center section, four relatively large high-vorticity regions exist on both sides of the air jet; in addition, two high-vorticity regions also exist below the cavity step in the combustor. However, the iso-surfaces inside the cavity show that the overall high-vorticity distribution is relatively small. When the air jet angle θ increases to 10° in operating condition 2, on the combustor center section, the areas of the two high-vorticity regions on the left side of the air jet decrease, while the overall high-vorticity distribution range expands. This is because, as the air jet angle increases, the jet impingement weakens, but the impact on the region to the right of the jet is enhanced, thereby increasing the area of the high-vorticity region on that side. With a further increase in the air jet angle θ, the high-vorticity regions in operating conditions 3, 4, and 5 gradually move downstream; however, the area of the high-vorticity region on the left side of the air jet gradually decreases, while the area of the high-vorticity region on the right side gradually increases. This is because the direction of the air jet shifts downstream along the cavity, causing the impact of the upstream cold air on the jet to weaken, while the impact on the downstream region is enhanced.

Fig. 5 Streamline distribution and velocity profile of the center section of the combustor ($Z = 0$ mm) central section and axial section ($X = 32$ mm)

Fig. 5 Streamline distribution and velocity profile of the center section of the combustor ($Z = 0$ mm) central section and axial section ($X = 32$ mm)

Figure 3: Fig. 5 Streamline distribution and velocity profile of the center section of the combustor ($Z = 0$ mm) central section and axial section ($X = 32$ mm)

Fig. 6 Distribution of vorticity at the center section of the combustor ($Z = 0$ mm) and the velocity coloring iso-surface $Q = 0.6$ million

Figure 4: Fig. 6 Distribution of vorticity at the center section of the combustor ($Z = 0$ mm) and the velocity coloring iso-surface $Q = 0.6$ million

(a) Center section of the combustor ($Z = 0$ mm) (b) Iso-surface (Q is 600,000)

Fig. 6 Distribution of vorticity at the center section of the combustor ($Z = 0$ mm) and the velocity coloring iso-surface $Q = 0.6$ million

3.2 Temperature Distribution

Figure 7 shows the temperature distribution at the combustor center section $Z = 0$ mm and at the section $X = 32$ mm. Under operating condition 1, the high-temperature region in the combustor is mainly concentrated on the left and right sides of the air jet inside the combustor cavity, especially at the upper and lower positions near the wall. In operating condition 2, when the air-jet angle θ is increased to 10°, the area of high-temperature distribution on the left side of the air jet in the combustor cavity increases, while the temperature on the right side of the air jet in the cavity decreases significantly; the high-temperature distribution area at the $X = 32$ mm section also increases relative to that under operating condition 1. This is because the air-jet angle shifts downstream into the cavity, strengthening the impingement of cold air on the regions on both sides of the jet, which reduces the impingement on the space on the left side, while increasing the impingement on the space on the right side. As a result, the impingement of cold air on the right-side region of the air jet is enhanced, leading to a marked change in the temperature inside the combustor cavity.

As the air-jet angle θ is further increased, for operating conditions 3, 4, and 5, the area of high-temperature distribution on the left side of the air jet in the combustor cavity gradually increases, but the high-temperature value also gradually decreases. Although the high-temperature area on the right side of the air jet in the cavity gradually decreases, the high-temperature value gradually increases. This is because, after the air-jet angle shifts downstream, the influence of the jet cold air impingement on the temperature on its left side gradually weakens, causing the high-temperature distribution area in that region to expand, while the temperatures in the upper and lower regions on the right side of the air jet gradually rise. At the $X = 32$ mm section, the area of high-temperature distribution also gradually increases, but the high-temperature value decreases

Fig. 7 Temperature distribution of combustor center section ($Z = 0$ mm) and axial section ($X = 32$ mm) under different air jet angle schemes

Figure 5: Fig. 7 Temperature distribution of combustor center section ($Z = 0$ mm) and axial section ($X = 32$ mm) under different air jet angle schemes

significantly.

Fig. 7 Temperature distribution of combustor center section ($Z = 0$ mm) and axial section ($X = 32$ mm) under different air jet angle schemes

To further analyze the temperature distribution characteristics inside the combustor, the concept of the temperature distribution factor (TDF) [5] is introduced. The expression for the temperature distribution factor is

$$T_{\mathrm{TDF}} = \frac{T_{\mathrm{max}} - T_{\mathrm{ave}}}{T_{\mathrm{ave}} - T_{\mathrm{in}}} \qquad (19)$$

where T_{max} is the maximum temperature of the section; T_{ave} is the average temperature; and T_{in} is the temperature at the air inlet. The outlet temperature distribution factor (OTDF) characterizes the temperature distribution characteristics at the outlet position, and its calculation method is consistent with Eq. (19). The larger the temperature distribution factor, the poorer the uniformity of the temperature distribution at that position.

The temperature distribution factor of the combustor axial section is shown in Fig. 8. It can be seen that the temperature distribution factor varies sharply in the region near the air jet; at positions closer to the jet, the temperature distribution uniformity is poorer. When the condition changes from operating condition 1 to operating condition 2, the maximum value of the temperature distribution factor decreases, and the value on the left side also decreases, while the value on the right side ⋯

decreased gradually in the region where X was 32–80 mm, and then remained basically stable. This is because the air-jet direction shifted toward the downstream side of the cavity, so the impact of the jet cold air on the upstream side decreased, while the impact on the downstream side increased. When the air-jet angle θ was gradually increased to 40°, the position of the maximum temperature distribution factor shifted downstream; the values in the region where X was 0–25 mm decreased, whereas those from $X = 60$ mm to the outlet increased. In the region where X was 25–60 mm, changes in the air-jet angle under different operating conditions led to relatively large fluctuations in the temperature distribution factor. The shift of the air-jet angle toward the downstream side of the cavity weakened the cold-air impact upstream and strengthened the impact downstream, thereby improving the uniformity of the upstream temperature distribution but worsening the uniformity of the downstream temperature distribution.

Fig. 8

Figure 6: Fig. 8

Under all operating conditions, the temperature distribution factor from $X =$ 100 mm to the outlet gradually and gently approached 0 from values less than 0.24; the temperature distribution factor at the outlet was always less than 0.034. This indicates that near the outlet, the temperature distribution uniformity was relatively good under all operating conditions.

Figure 8 Temperature distribution factor of the axial section of the combustor and outlet temperature distribution factor

Fig. 8 Temperature distribution factor of axial section of combustor and outlet temperature distribution factor

3.3 Combustion Efficiency and Combustion Intensity

Combustion efficiency is one of the important factors reflecting the combustion characteristics of a combustor. The calculation formula for combustion efficiency [5] is as follows:

$$\eta_c = 1 - \frac{\int Y_{H_2} \rho u \mathrm{d}A}{\dot{m}_{\mathrm{fuel}}} \qquad (20)$$

where Y_{H_2} is the mass fraction of hydrogen fuel; ρ is the fuel density; A is the area of the transverse section; u is the magnitude of the fluid velocity; and $\dot{m}_{\mathrm{fuel}}$ is the mass flow rate of hydrogen fuel at the inlet.

The combustion efficiency of axial (X-direction) sections of the combustor is shown in Fig. 9. Complete combustion at the given equivalence ratio was achieved under all operating conditions. As the air-jet angle increased, the overall combustion efficiency in the combustor cavity first increased, then decreased slightly, and then increased again, approaching 1; meanwhile, the axial space required for complete reaction between hydrogen and air gradually increased. When the air-jet angle θ increased from 0° to 10°, the overall combustion efficiency from $X = 0$ mm to $X = 45$ mm in the cavity decreased, and under both operating conditions the complete reaction of fuel and air was achieved at $X = 45$ mm. In operating condition 1, the combustion efficiency in the range from $X = 2$ mm to $X = 10$ mm rose rapidly from 0.15 to 0.98; then, in the range from $X = 10$ mm to $X = 35$ mm, it further increased from 0.96 to 0.99, and remained stable without further change from $X = 35$ mm to the outlet. In operating condition 2, from $X = 2$ mm to $X = 15$ mm, the combustion efficiency increased from 0.10 to 0.95; from $X = 15$ mm to $X = 45$ mm, the combustion efficiency first decreased from 0.95 to 0.82 and then rose again to 0.99; and from $X = 45$ mm to the outlet, it remained stable. When the air-jet

Fig. 9

Figure 7: Fig. 9

angle θ continued to increase from 20° to 40°, the axial space required for complete reaction between hydrogen and air further increased, reaching complete combustion at $X = 60$, 70, and 80 mm, respectively. In operating condition 3, when X was in the range of 2–15 mm, the combustion efficiency decreased from 0.12 to 0.07; when X was in the range of 15–25 mm, the combustion efficiency increased from 0.07 to 0.85; when X was 25–60 mm, the combustion efficiency first decreased from 0.85 to 0.77 and then rose again to 0.99; and it remained stable from $X = 60$ mm to the outlet. In operating condition 4, when X was in the range of 2–25 mm, the combustion efficiency decreased from 0.13 to 0.08; when X was in the range of 25–35 mm, the combustion efficiency increased from 0.08 to 0.88; when X was in the range of 35–70 mm, the combustion efficiency first decreased from 0.88 to 0.74 and then rose again to 0.99; and it remained stable from $X = 70$ mm to the outlet. In operating condition 5, when X was in the range of 2–35 mm, the combustion efficiency increased from 0.13 to 0.14; when X was in the range of 35–45 mm, the combustion efficiency increased from 0.14 to 0.99; when X was in the range of 45–80 mm, the combustion efficiency first decreased from 0.99 to 0.88 and then rose again to 0.99; and it remained stable from $X = 80$ mm to the outlet.

Figure 9 Combustion efficiency of the axial section of the combustor under schemes with different air-jet angles

Fig. 9 Combustion efficiency of axial section of combustor under different air jet angle schemes

Combined with the velocity pathline plot in Fig. 5, it can be seen that when the air-jet angle θ increased from 0° to 40°, the recirculation space on the left side of the air jet further enlarged, but its vortex structure became smaller, and the vortex center gradually moved downstream in the combustor. The air-jet direction shifted toward the downstream direction of the combustor, and the air-jet velocity also gradually increased; therefore, the impact of the air jet on the left recirculation space became smaller and smaller, while its impact on the right-side region ···

gradually increases, thereby making the axial distance required for complete combustion in the head region of the combustor cavity gradually longer.

The distribution of hydroxyl (OH) can effectively characterize the reaction intensity in the combustor; a higher mass fraction usually indicates greater combustion intensity in that region. Figure 10 presents the distribution of hydroxyl mass fraction on the combustor center cross-section at four different axial positions. It can be seen from Fig. 10 that, under operating condition 1, the hydroxyl mass fraction at the four axial positions is relatively low in the radially central region, whereas it increases with increasing radial distance. This

Fig. 10 Distribution of hydroxyl mass fractions at four axial cross-sectional positions under different air jet angle schemes

Figure 8: Fig. 10 Distribution of hydroxyl mass fractions at four axial cross-sectional positions under different air jet angle schemes

indicates that, under this condition, the combustion intensity near the upper and lower walls inside the cavity is relatively high, while that in the radially central region is relatively low. At $X = 62$ and 42 mm, the hydroxyl mass fraction is markedly lower than that at $X = 2$ and 22 mm, indicating that combustion under this condition is mainly concentrated in the upstream region of the cavity air jet hole.

Under operating condition 2, the hydroxyl mass fraction at $X = 2$ and 22 mm decreases significantly compared with operating condition 1, while at $X = 42$ and 62 mm it is almost 0. Combined with the temperature distribution in Fig. 7, it can be inferred that the combustion under this condition is mainly concentrated in the upstream region of the cavity air jet hole. Under operating condition 3, the hydroxyl mass fractions at $X = 2$, 42, and 62 mm are all lower than those under operating condition 2; combustion is likewise concentrated in the upstream region of the cavity air jet hole, but the combustion intensity is relatively lower. Under operating condition 4, the hydroxyl mass fraction at $X = 42$ and 62 mm is much higher than that at $X = 2$ and 22 mm, indicating that combustion under this condition is mainly concentrated in the right-side region of the cavity air jet in the combustor cavity. The hydroxyl mass-fraction distribution under operating condition 5 is relatively similar to that under operating condition 4, but its hydroxyl mass fraction is slightly lower than that of operating condition 4. Combining this with the temperature distribution in Fig. 7, from operating condition 1 to operating condition 5, the main combustion region gradually develops from the left-side region of the cavity air jet in the combustor toward the right-side region, and under operating conditions 2 and 3 the hydroxyl mass fraction decreases significantly compared with the other conditions.

(a) $X = 2$ mm

(b) $X = 22$ mm

(c) $X = 42$ mm

(d) $X = 62$ mm

Fig. 10 Distribution of hydroxyl mass fractions at four axial cross-sectional positions under different air jet angle schemes

Fig. 11 Distribution of average NO concentration in axial section of combustor under different air jet angle schemes

Figure 9: Fig. 11 Distribution of average NO concentration in axial section of combustor under different air jet angle schemes

3.4 Nitrogen oxide emissions

Figure 11 shows the distribution of the average nitrogen oxide emissions over axial cross-sections under different operating conditions. It can be observed that, from operating condition 1 to operating condition 2, as the air jet angle increases from 0° to 10°, the overall nitrogen oxide emissions of the combustor increase significantly. When the air jet angle θ is further increased to 20° in operating condition 3, compared with operating condition 2, the nitrogen oxide emissions inside the combustor cavity decrease significantly, whereas the reduction in nitrogen oxide emissions in the downstream region of the cavity is relatively small. As the air jet angle θ increases from 20° to 40°, the overall nitrogen oxide emissions in the combustor decrease markedly. This is mainly because, from operating condition 3 to operating condition 5, the high-temperature temperature values inside the cavity decrease significantly. (When the temperature is higher than 1 773 K, for every increase of 373 K, the formation rate of thermal nitrogen oxides increases by 6 to 7 times; whereas when the temperature is lower than 1 773 K, the formation amount of thermal NO is very limited [36].) This factor leads to a significant reduction in the overall nitrogen oxide formation in the combustor. From operating condition 1 to operating condition 2, the overall nitrogen oxide emissions of the combustor increase, with an increase amplitude of 24%; from operating condition 2 to operating condition 5, the overall nitrogen oxide emissions of the combustor decrease,

reduction amplitudes are 18%, 19%, and 40%, respectively.

Fig. 11 Distribution of average NO concentration in axial section of combustor under different air jet angle schemes

4 Conclusion

This study numerically simulated and analyzed the influence of the air-jet angle θ on the flow, combustion, and nitrogen oxide emissions of a hydrogen jet trapped vortex combustor (JTVC). The following conclusions were obtained.

1) The air-jet angle θ is an important factor affecting combustor performance. At all angles, a vortex structure forms upstream of the air jet, and as θ increases, the vortex size decreases and the vortex center moves downstream. When θ increases from 20° to 30°, a new vortex structure appears downstream of the cavity, and its center moves further downward as θ increases. In addition, high-vorticity vortices are mainly distributed on both sides of the air jet and migrate downstream of the cavity as the angle increases.

2) The combustion reaction zone is mainly concentrated within the combustor cavity structure. As θ increases, the area of the high-temperature region inside the cavity gradually expands; however, the high-temperature temperature value on the left side of the cavity air jet also gradually decreases, and the uniformity of the downstream temperature distribution gradually decreases. Under all operating conditions, the outlet temperature distribution factor is less than 0.034, indicating that the outlet temperature distribution is relatively uniform and that complete combustion is achieved at the specified equivalence ratio. When $\theta = 0^\circ$, the overall combustion efficiency of the combustor is relatively high; however, as θ increases, the axial distance required for complete combustion also increases accordingly.

3) In operating condition 5, when $\theta = 40^\circ$, because the temperature value of the high-temperature region in the cavity is relatively small, the overall thermal NOx emission of the combustor is relatively low. Compared with $\theta = 30^\circ$, its reduction amplitude is approximately 40%. In addition, from operating condition 1 to operating condition 5, as θ increases from 0° to 40°, the overall nitrogen oxide emissions of the combustor first increase and then decrease.

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