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Numerical Comparative Analysis of the Influence of Fuel Micro-Hole Geometry on the Combustion Characteristics of Hydrogen Micro-Mixing Combustor

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Abstract: Hydrogen micro-mixing combustion technology is to quickly mix air and hydrogen through many microchannels to form a micro-scale flame, which can shorten the residence time of nitrogen in the high temperature region, thus greatly reducing the formation of nitrogen oxides, and solving the problem that hydrogen is easy to backfire and thermoacoustic oscillation under traditional premixed combustion. Based on ANSYS Fluent software, Realizable k-epsilon model, scalable wall function (SWF) and laminar flame model (FGM) are selected in this paper. The combustion characteristics of different pore aperture, pore spacing and pore types of fuel micro-holes in micro-mixing combustion chamber are numerically simulated. Through the analysis of combustor outlet temperature, combustion uniformity and NOx emission, it is found that too large and too small aperture and hole spacing will aggravate the formation of NOx. The combustion temperature of the round hole is the lowest but the uniformity is the worst, and the influence of the elliptical hole and the square hole with equal area on the combustion is not significantly different. In this paper, the influence of the geometric structure of fuel micropores on combustion is studied. And it provides a reference for the design optimization of micro-mixing combustor.

1. Introduction

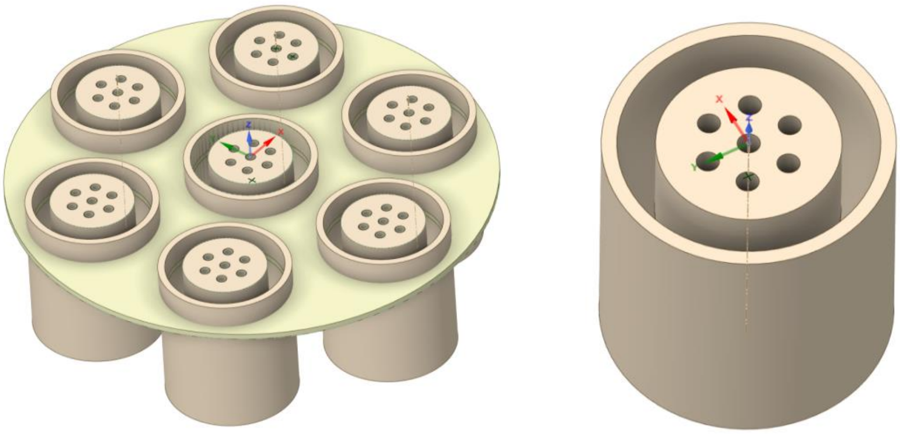
Gas turbine has the characteristics of high heat capacity, low carbon emission, fast start-up, flammable and environmentally friendly fuel. It is widely used in aviation, power generation, shipbuilding, petrochemical and other fields, and has great potential for technological and economic growth [1]. Among them, hydrogen fueled steam turbine power generation is considered to be one of the important flexible power sources in China 's carbon neutralization period and is expected to develop rapidly in the first 10 to 15 years before carbon neutralization [2]. However, due to the characteristics of low hydrogen density, slow diffusion, high combustion temperature and fast flame propagation speed, it is prone to tempering and has the risk of explosion and thermoacoustic oscillation. Therefore, hydrogen combustion cannot use the swirl premixed combustion chamber traditionally used to burn natural gas. Based on this, in recent years, some scholars have proposed micro-mixing diffusion combustion technology to achieve low NOx combustion of hydrogen in gas turbines [3].

The micro-mixing combustion technology is to inject hydrogen into the mainstream high-speed air of the head micropores through micropores for mixed combustion, quickly forming multiple micro-scale diffusion flames, making the reaction area small-scale, and shortening the residence time of nitrogen in the high temperature zone. At the same time, lean combustion and strong mixing are achieved in each diffusion flame, and the formation of nitrogen oxides can be greatly reduced by reducing the flame temperature [4-6].

Many scholars have also made contributions in the field of micro-mixing combustion. Ayed and Funke developed a micro-mixing diffusion combustion technology to reduce the nozzle size and array the nozzles, so that the fuel and air can be mixed quickly to achieve stable and low-pollution combustion under the hydrogen-rich fuel of the burner [7-8].

And the geometric parameters of hydrogen micropores are important parameters in the design of micro-mixing combustion chamber, which have a great influence on combustion. York found that the current thin and short channel design can reduce the tempering risk of gas at 1650 K [9]. Hao found that as the diameter of the micro-tube increases from 8 mm to 14 mm, the turbulence intensity at the outlet of the micro-tube decreases slightly. And the smaller the diameter of the micro-tube is, the higher the turbulence intensity at the outlet is, and the shorter the absolute flame length is [10]. Based on the principle of transverse jet, Lin explored the influence of radial unit spacing on NOx emissions. The results show that with the increase of unit spacing, the overall temperature level decreases, the amount of air involved in combustion in the mainstream increases, and the local equivalent ratio decreases, which can reduce NOx emissions [11]. In summary, the geometric structure of fuel micropores will affect the combustion characteristics. Therefore, in this paper, the numerical simulation of hydrogen combustion in a micro-mixing combustion chamber is carried out, and the influence of hole diameter, hole spacing and hole shape on the combustion and emission characteristics is analyzed. The purpose is to provide some reference for the design and use of micro-mixing combustion chamber.

2. Basic Model



(a) combustor (b) micro-mixing nozzle

Figure 1: The structure of combustor and micro-mixing nozzle

The burner structure used for analysis is shown in Fig.1a, which contains seven identical micro-mixing nozzles. The distance between the central nozzle and the six circumferentially uniformly distributed nozzles is 24 mm. The upper surface of the nozzle is the XY plane, and the axis of the burner is the Z axis. The structure of the nozzle is shown in Fig.1b. The mixing mode outside the tube is adopted. The air flows from bottom to top in the annular gap. After fully developed, it mixes and ignites with the high-speed hydrogen jet in the reflux section, theoretically avoiding tempering [7].

The nozzle diameter D_{seg} is 12 mm, and the middle seven fuel micro-holes emit hydrogen. The pore diameter is recorded as D_H . The distance between the middle micro-holes and the six circumferentially uniformly distributed micro-holes is equal, which is recorded as the hole spacing *S*, and the outer diameter of the air annular gap D_{exit} is 17 mm.

3. Numerical Simulation

3.1 Grid Independence Verification and Calculation Model Setting

Numerical simulation research is an important technical means in the field of combustion science, which can help researchers to explore the flow characteristics of the internal flow field [12-13]. In this section, ANSYS Fluent software is used for numerical simulation. Tetrahedral meshes are generated in Workbench Meshing, and then converted into polyhedral meshes in Fluent. In order to improve the calculation accuracy, local densification is carried out in the fuel micropore and recirculation zone, as shown in Fig.2. The grid independence verification is carried out before the formal calculation. Before the formal calculation, the grid independence verification is carried out. According to the experience, The Realizable k-epsilon model, the scalable wall function (SWF), the laminar flame model (FGM), the pressure-based solver and the Coupled algorithm are selected to solve the fluid control equations. The relaxation factor is set to 0.6, the residual term is set to 1×10^{-3}, and the energy residual is 1×10^{-6} [14]. When the monitoring value is stable for 500 steps, the calculation results are considered to be convergent.

As shown in Fig.3, four meshes of 1.84 million, 2.88 million, 4.06 million and 5.22 million grids are obtained. When the number of grids exceeds 2.88 million, the axial velocity of the burner no longer changes significantly with the increase of the grid. Therefore, 2.88 million grids are used for calculation in this paper.

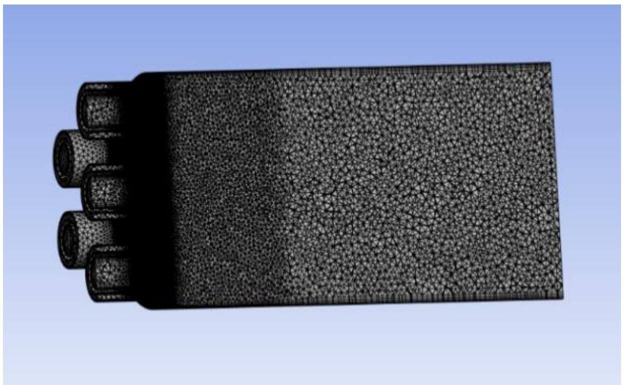


Figure 2: Grid of combustion chambe

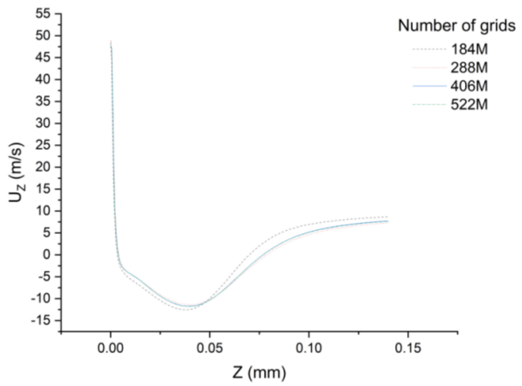


Figure 3: Grid independence verification

3.2 Model Analysis

The inlet of hydrogen and air is the inlet of mass flow rate, in which the hydrogen flow rate is 0.343 g/s and the initial temperature is 300 K; the air flow rate is 15.5 g/s, the initial temperature is 650 K, and the residual gas coefficient is 1.17. In these conditions, the flame is easier to ignite and remains relatively stable. The outer ring of the burner is a non-slip adiabatic wall, and the pressure outlet boundary conditions are selected. In addition, the given operating pressure is 0.1 MPa.

In order to explore the influence of the geometric structure of the fuel micro-hole of the micro-mixing nozzle on the hydrogen combustor, the three factors of the hole diameter, the hole spacing S and the hole type are analyzed. As shown in table 1, it can be divided into three groups of Models: Model 1, 2, 3 (only change the pore size of circular micropores); Model 1, 4, 5 (only change the hole spacing); Models 1,6,7 (only change the pore type and ensure that the micropore area remains unchanged). The influence of fuel micropore geometry on combustion is based on the comparison of combustion results among the Models in each group.

Table 1: Combustion chamber Model

Model	Hole shape	Hole diameterD_H/mm	Hole spacing S/mm
1	circular	1.5	3
2	circular	1	3
3	circular	2	3
4	circular	1.5	2
5	circular	1.5	4
6	elliptical	—	3
7	square	—	3

4. Numerical Results and Analysis

4.1 Effect of Hole Diameter on Combustion

4.1.1 Velocity Distribution

The influence of the pore size of the fuel micro-hole on the flow field of the combustion chamber is shown in Fig.4. From top to bottom, the three flow field Models are Model 2 (hole diameter 1mm), Model 1 (hole diameter 1.5mm) and Model 3 (hole diameter 2mm).

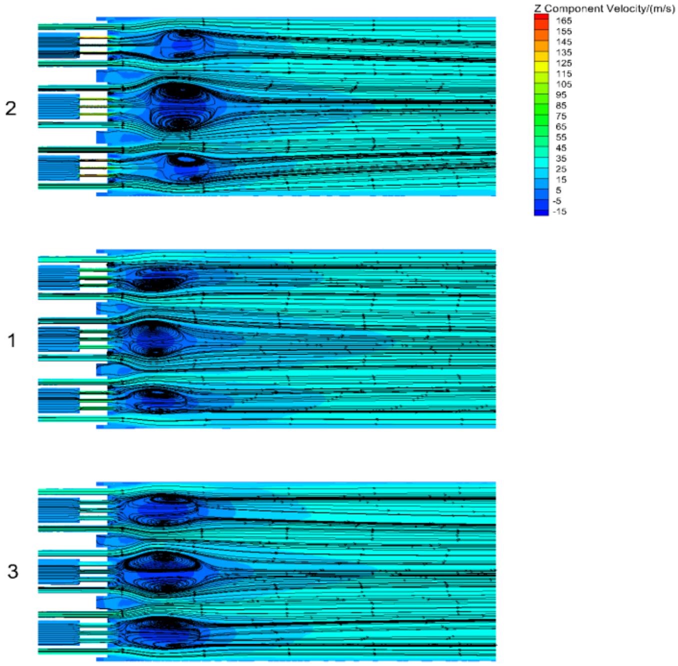


Figure 4: The velocity distribution and streamline of the central section with different hole diameter

Due to the high-speed jet of air and hydrogen from the annular gap and small holes into the sudden expansion space, according to Bernoulli's theorem, the pressure will increase sharply and the speed will decrease rapidly, thus forming a central recirculation zone and an external recirculation zone. The recirculation zone also increases the residence time of the high temperature gas, which is conducive to the full reaction [15]. The flow field can be divided into three regions: rapid mixing, reflux and stable development and the following temperature analysis is to analyze the reference section in the stable development zone of the flow field [16].

It can be seen from Fig.4 that as the aperture increases, the flow field gradually moves forward. This is because the smaller the aperture is, the higher the fuel velocity is, and a larger jet distance is required to decelerate to form a recirculation zone. The size of the recirculation zone decreases first and then increases with the increase of the pore size, and the recirculation zone of Model 1 is the smallest, which suggests that its efficiency is the lowest and the combustion uniformity is the worst in this working condition.

4.1.2 Temperature Distribution

The cross section of Z = 100mm (axial distance is 100mm) is selected to analyze the temperature characteristics. Because the cross section is in the stable section of the flow field, the flame is relatively stable. As shown in Fig.5, from top to bottom, the Models of the three temperature cloud images are Model 2 (hole diameter 1mm), Model 1 (hole diameter 1.5mm) and Model 3 (hole diameter 2mm).

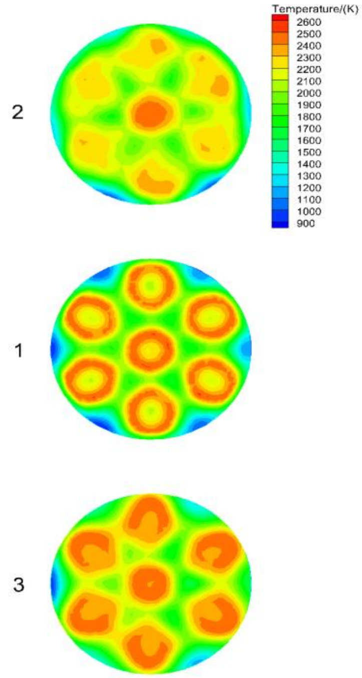


Figure 5: Temperature distribution in the stable section with different hole diameter

It can be seen from Fig.5 that due to the violent combustion of hydrogen, the central recirculation zone has a higher combustion temperature. The temperature of the external recirculation zone mainly comes from the heat conduction of the central reaction zone because it almost does not react. It can be seen that the flame of Model 2 is relatively unstable, which is due to the smallest aperture, the deepest jet depth, and the backward movement of the recirculation zone. In addition, the velocity and the turbulence intensity is so large, that the flow field and the flame is relatively unstable. For the uniformity of the flame, it can be seen that Model 3 is the most uniform, followed by Model 2, and Model 1 is the worst. As for Model 2, due to the large turbulence intensity, the combustion is sufficient and the temperature is relatively uniform. As for Model 3, due to the large recirculation zone, the gas residence time is longer and the combustion is more sufficient.

4.1.3 Comparison of NOx Emissions

There are three sources of NO in the combustion chamber: thermal NO, that is, NO formed by the reaction of nitrogen and oxygen in the air due to high temperature ; instantaneous NO, that is, NO produced by HC-based effect when the fuel does not contain nitrogen; fuel-type NO, that is, the fuel contains organic nitrogen, NO produced by combustion [17]. Therefore, under this condition, the NO in the combustion chamber is only thermal NO.

The generation of thermal NO is mainly affected by combustion temperature (represented by combustion chamber outlet temperature T4), combustion uniformity (represented by outlet temperature field distribution coefficient OTDF) and residence time [18-19]. The higher the combustion temperature, the worse the uniformity and the longer the residence time, the more NO is generated [20]. Fig.6 shows the combustion temperature T4, combustion uniformity OTDF and NOx emissions of three different aperture Models.

It can be seen from Fig.6 that the combustion temperature T4 of model 3 is the highest, model 2 is the second, and model 1 is the lowest. The combustion uniformity of Model 3 is the most uniform, followed by Model 2's, and the combustion of Model 1 is the most uneven, which is consistent with the conclusions obtained from Fig.4 and Fig.5.As for the NOx formation of each Model, it can be clearly found that the NOx emission of Model 1 is the lowest, followed by model 2, and the NOx emission of Model 3 is the highest, which is consistent with the change trend of combustion temperature and opposite to the change trend of combustion uniformity. This is because: 1) The combustion temperature T4 of Model 1 is the lowest, and the influence of combustion temperature on NOx generation is far greater than that of combustion uniformity, that is, OTDF, so that NOx generation is the lowest; 2) The combustion temperature T4 of Model 3 is the highest, and due to the large recirculation zone and long gas residence time of Model 3, the NOx production is the most.

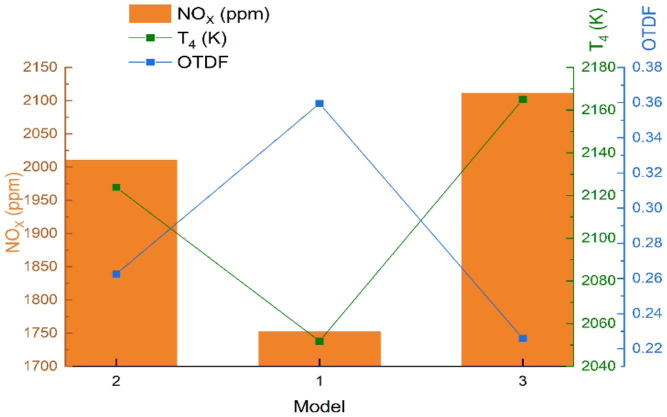


Figure 6: NOx emission and temperature characteristics of combustor with different hole diameter

In summary, under this condition, the effect of combustion temperature on NOx formation is much greater than that of combustion uniformity. The pore size of fuel has a great influence on combustion, and too small pore size will lead to combustion instability. Too large or too small pore size will significantly aggravate the formation of NOx.

4.2 Effect of Hole Spacing on Combustion

4.2.1 Velocity Distribution

The influence of fuel micro-hole spacing on the flow field of the combustion chamber is shown in Fig.7.

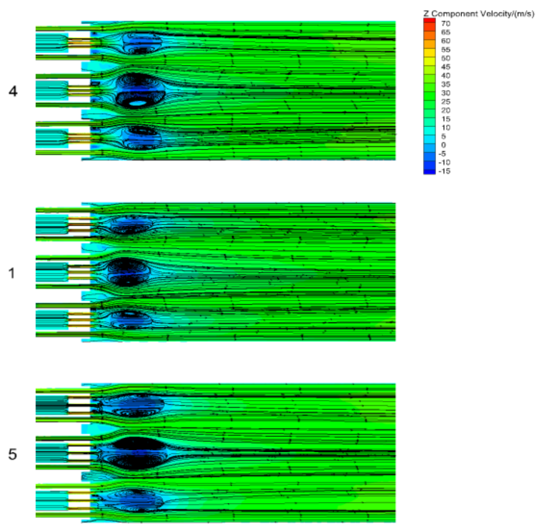


Figure 7: The velocity distribution and streamline of the central section with different hole spacing

From top to bottom, the three flow field Models are Model 4 (hole spacing 2mm), Model 1 (hole spacing 3mm), and Model 5 (hole spacing 4mm). It can be seen from Fig.7 that as the hole spacing increases, the recirculation zone gradually moves forward. This is because with the increase of hole spacing, it is difficult for adjacent jets to aggregate to form large-size jets, and the momentum is small. Therefore, the recirculation zone moves forward [4]. At the same time, due to the interaction of small recirculation zones formed by adjacent jets, a larger overall recirculation zone is formed. It can be seen that with the increase of hole spacing, the recirculation zone is gradually increasing.

4.2.2 Temperature Distribution

As shown in Fig.8, to ensure the relative stability of the flame, the cross section of the stable section of the flow field is taken to analyze the temperature distribution. From top to bottom, the Models of the three temperature cloud images are Model 4 (hole spacing 2mm), Model 1 (hole spacing 3mm) and Model 5 (hole spacing 4mm).

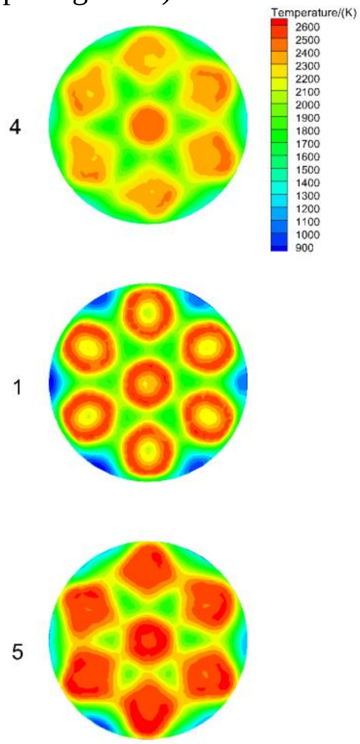


Figure 8: Temperature distribution in the stable section with different hole spacing

It can be seen that the flames of all Models are relatively stable, which proves that it is feasible to improve the performance of the combustion chamber by adjusting the spacing of the micropores from Fig.8.As for the uniformity of the flame, it can be seen that Model 4 has the most uniform combustion, followed by Model 5, and Model 1 has the most uneven combustion. This is because the hole spacing of Model 4 is the smallest, and the small jet is easier to gather into a large jet whose momentum and the turbulence intensity is large. These factors make the Model 4 heat exchange fully, the combustion is more sufficient and the temperature is relatively uniform. And it is because the recirculation zone is large and the gas residence time is long, the combustion of Model 5 is more sufficient.

4.2.3 Comparison of NOx Emissions

Fig.9 shows the combustion temperature T4, combustion uniformity OTDF and NOx emissions of three different hole spacing Models.

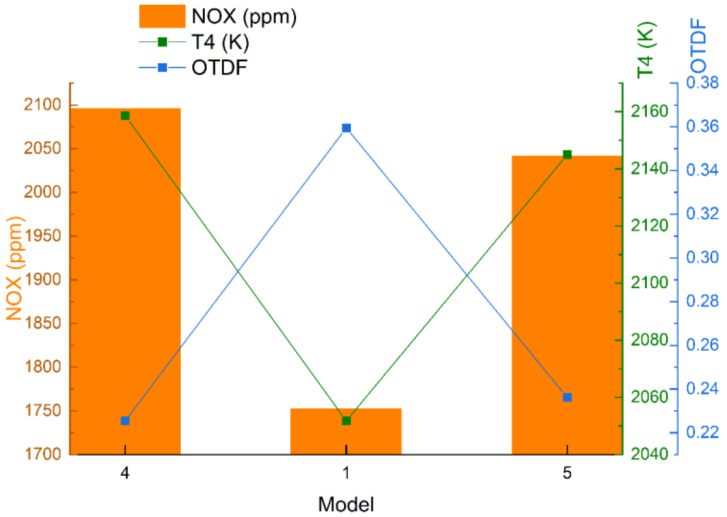


Figure 9: NOx emission and temperature characteristics of combustor with different hole spacing

From Fig. 9 it can be seen that the combustion temperature T4 of Model 4 is the highest, Model 5's is the second, and Model 1's is the lowest. The combustion of Model 4 is the most uniform, followed by Model 5, and the combustion of Model 1 is the most uneven, which is consistent with the conclusion of the cloud analysis in Fig.8.

As for the NOx formation of each Model, it can be seen that the NOx emission of Model 1 is the lowest, followed by Model 5's, and the NOx emission of Model 4 is the highest, which is consistent with the trend of combustion temperature and opposite to the trend of combustion uniformity. This is because: 1) The combustion temperature T4 of Model 1 is the lowest, and the influence of combustion temperature on NOx generation is far greater than that of combustion uniformity, that is, OTDF, so that NOx generation is the lowest; 2) Although the combustion of Model 4 is the most uniform, its combustion temperature T4 is the highest, which leads to the largest amount of NOx production; 3) The combustion temperature of Model 5 is slightly lower than that of Model 4 and due to its larger recirculation zone, the flame residence time is longer, so the NOx production is in the middle position, which is very close to the production of Model 4.

In summary, under this condition, the effect of combustion temperature on NOx formation is much greater than that of combustion uniformity. The spacing of fuel micropores has a great influence on combustion, and it is feasible to improve the performance of combustion chamber by adjusting the spacing of micropores. Too large or too small hole spacing will significantly increase the formation of NOx.

4.3 Effect of Hole Shape on Combustion

4.3.1 Velocity Distribution

The influence of fuel micropore shape on the flow field of combustion chamber is shown in Fig.10. From top to bottom, the three flow field diagram Models are Model 1 (circular hole), Model 6 (elliptical hole) and Model 7 (square hole) in turn. Fig.10 shows that the recirculation zone of Model 1 is relatively front and small; the location, size and shape of the recirculation zone of Model 6 and Model 7 are basically the same, indicating that the combustion results of the two Models may be very close.

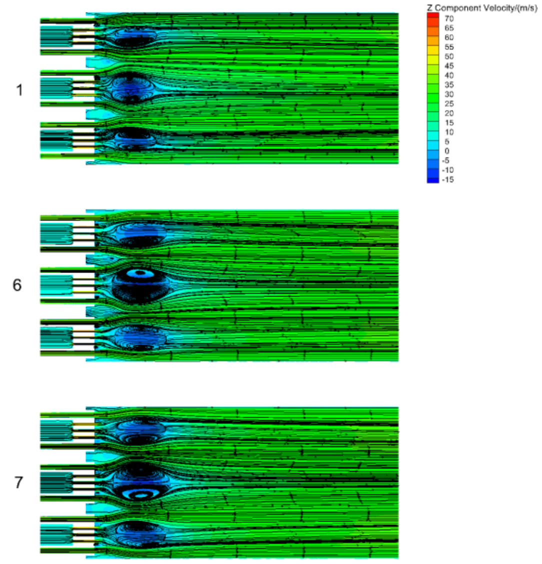


Figure 10: The velocity distribution and streamline of the central section with different hole shape

4.3.2 Temperature Distribution

As shown in Fig.11, to ensure the relative stability of the flame, the cross section of the stable section of the flow field is taken to analyze the temperature distribution. From top to bottom, the Models of the three temperature cloud images are Model 1 (circular hole), Model 6 (elliptical hole) and Model 7 (square hole). It can be seen that the flames of all Models are relatively stable and symmetrical, which proves that it is feasible to improve the performance of the combustion chamber by adjusting the micro-hole shape. As for the uniformity of the flame, it can be seen that the uniformity of the flame of Model 6 and Model 7 is basically the same from Fig.11, and the uniformity of the flame of Model 1 is the worst, which is consistent with the conclusion of the streamline diagram analysis of Fig.9.

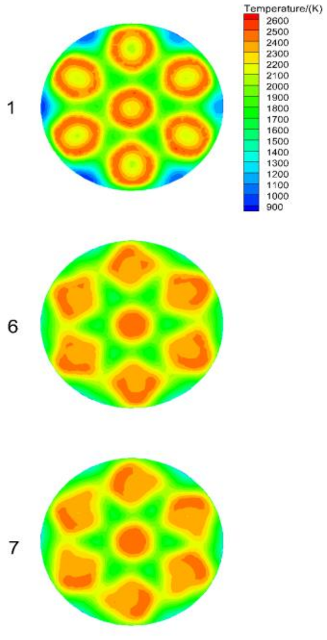


Figure 11: Temperature distribution in the stable section with different hole shape

4.3.3 Comparison of NOx Emissions

Fig.12 shows the combustion temperature T4, combustion uniformity OTDF and NOx emissions of three Models with different hole shape. As for Model 1, its combustion temperature is the lowest and the combustion is the most uneven. The combustion temperature and combustion uniformity of Model 6 and Model 7 are basically the same, which is consistent with the conclusion of cloud analysis in Fig.9.

As for the NOx formation of each Model, it can be clearly seen that the NOx emission of Model 1 is the lowest; the NOx emissions of Model 6 and Model 7 are basically the same from Fig.12. And the trend is consistent with the combustion temperature, but the trend is opposite to the combustion uniformity. This is because: 1) the combustion temperature T4 of Model 1 is the lowest, and the influence of combustion temperature on NOx generation is far greater than the influence of combustion uniformity, that is, OTDF, so that NOx generation is the lowest; 2) Although the combustion of Model 6 and Model 7 is more uniform, the combustion temperature T4 is higher, resulting in more NOx production.

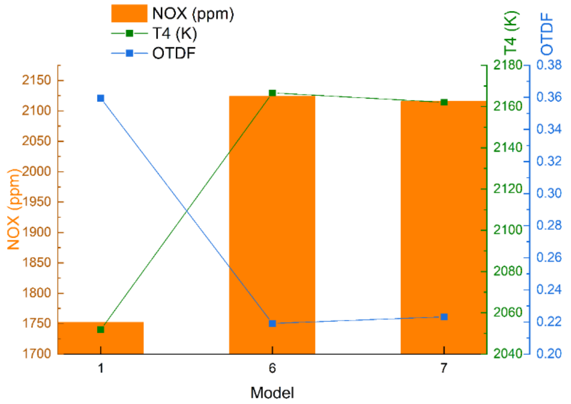


Figure 12: NOx emission and temperature characteristics of combustor with different hole shape

In summary, under this condition, the effect of combustion temperature on NOx formation is much greater than that of combustion uniformity. The pore shape has a great influence on the combustion, and it is feasible to improve the performance of the combustion chamber by adjusting the pore shape. The combustion temperature of the circular hole is the lowest but the uniformity is the worst, and the influence of the elliptical hole and the square hole with equal area on the combustion is not significantly different.

5. Conclusion

In this paper, the velocity distribution, temperature distribution and NOx emission of the combustion chamber flow field are analyzed under the working condition (hydrogen flow rate 0.343g/s, inlet temperature 300K; the air flow rate is 15.5 g/s, the inlet temperature is 650 K, and the residual gas coefficient is 1.17). It is found that changing diameter, spacing and shape of the fuel micro-mixing hole in the micro-mixing combustion chamber will affect the hydrogen combustion. The conclusions can be obtained as follows:

1) The influence of combustion temperature on the formation of NOx is much greater than that of combustion uniformity.

2) The hole diameter of fuel micropores has a great influence on combustion, too small pore size will lead to combustion instability. And too large or too small pore size will significantly aggravate the formation of NOx.

3) The hole spacing has a great influence on the combustion, and it is feasible to improve the performance of the combustion chamber by adjusting the micro-hole spacing. Too large or too small hole spacing will significantly increase the formation of NOx.

4) The hole shape has a great influence on the combustion, and it is feasible to improve the performance of the combustion chamber by adjusting the micro-hole. The combustion temperature of the circular hole is the lowest but the uniformity is the worst, and the influence of the elliptical hole and the square hole with equal area on the combustion is not significantly different.

In general, it is feasible to adjust the combustion characteristics by changing the geometry of the fuel micropores in the micro-mixing combustor. In the future, automatic control can be used to adjust the micro-hole structure in real time according to different needs to further improve the performance of the combustion chamber.

References

[1] Jiang H., Ren J., Li X., et al. Status and development trend of the heavy-duty gas tur- bine[J]. Proceedings of the CSEE, 2014, 34(29): 5096-5102.

[2] Qin F., Qin Y., Shan T. The current status and development prospects of hydrogen-fueled gas turbine technology in the context of carbon neutralization[J]. Guangdong Electric Power, 2021, 34(10): 10-17.

[3] Shi R., Hu H. B., Du J., et al. Study on combustion characteristics of hydrogen fuel micro-mixed burner[J]. Thermal power engineering, 2024, 39 (01): 127-136.

[4] Mo D., Lin Y. Z., Han X., et al. Research status and future prospects of hydrogen micro-mixing combustion technology [J]. Journal of Aeronautics, 2024, 45(07): 36-62.

[5] Mo D., Liu Y. X., Lin Y. Z., et al. Development of hydrogen micro-mixing diffusion combustion technology[J]. Aeronautical power, 2024, (02): 37-40.

[6] Qiu P. H., Lu C., Zhang L. Y., et al. Research progress of hydrogen fuel micro-mixed combustion technology[J]. Thermal power engineering, 2023, 38 (05): 14-23.

[7] Ayed A. H., Kusterer K., Funke H. H. W., et al. Experimental and numerical investigations of the dry-low-NOx hydrogen micromix combustion chamber of an industrial gas turbine[J]. Propulsion and Power Research, 2015, 4(3): 123-131.

[8] Funke H. H. W., Beckmann N., Abanteriba S. An overview on dry low NOx micromix combustor development for hydrogen-rich gas turbine applications[J]. International Journal of Hydrogen Energy, 2019, 44(13): 6978-6990.

[9] York W D, Ziminsky W S, Yilmaz E. Development and testing of a low NOx hydrogen combustion system for heavy-duty gas turbines[J]. Journal of Engineering for Gas Turbines and Power, 2013, 135(2): 022001.

[10] Hao Y, Lei F., Zhang Z. Study on the effect of nozzle structure on methane micro-mixed combustion characteristics[J]. Thermal power generation, 2023, 52(01): 26-35.

[11] Mo D., Lin Y. Z., Ma H., et al. Study on hydrogen micro-mixing diffusion combustion organization based on bluff-body turbulence[J]. Journal of Aeronautics, 2024, 45(08): 94-108.

[12] Jing D. L., Wang K., Chen X. The progress on numerical simulation of combustion chamber[J]. Aerospace Power, 2018(1): 44-47.

[13] Suo J. Q., Feng X. Z., Liang H. X., et al. Numerical simulation for research and development of aero engine combustor [J]. Aerospace Power, 2021(2): 61-65.

[14] Geng S. J., Pan H. j., Yang H., etc. Numerical simulation of natural gas hydrogen-blended combustion and emission characteristics of gas turbine[J]. Journal of Xi 'an Jiaotong University, 2022, 56(12): 1-11.

[15] Zhang C., Lin Y. Z., Xu H. S., et al. Development status and level of civil aviation engine low emission combustion chamber technology[J]. Aeronautical Journal, 2014, 35(02): 332-350.

[16] Peng Z., Zhang Z., Lei F. Numerical study on combustion-air mixing characteristics of hydrogen micro-mixing burner[J]. Journal of Power Engineering, 2023, 43(11): 1391-1398.

[17] Xu B. C., Wu Z., Zhao Z. J., et al. Study on combustion and NOx emission characteristics of an F-class gas turbine[J]. China Science and Technology Paper, 2024, 19(03): 382-389.

[18] Li X. F., Xiao J. F., Wang W., et al. Effects of combustion chamber pressure changes on NOx emissions in heavy-duty gas turbines [J]. Thermal power generation, 2017, 46(09): 53-58 + 64.

[19] Zhao H., Lou G. F, Liu S. P. Effect of hydrogen addition on combustion and emission characteristics of natural gas combustor [J]. Science and Technology and Engineering, 2024, 24 (01): 223-229.

[20] Xiao J. F., Li X. F., Hu M. Q., et al. Correlation Analysis of Influencing Factors of Gas Turbine Pollutant Emissions[J]. Thermal Power Generation, 2018, 47(10): 37-43.