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Effect of the Structure Parameters of a Low Swirler on Premixed Characteristics

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Abstract: Combustion with lean premixed and low swirl is an effective way of flame organization. It can improve the flame stability and reduce NO_x emission. In this kind of combustion, one of the most important issues is fuel/air premixed characteristics. How the structure parameters influence that issue is figured out through numerical simulation. The structure parameters concerned in the study are as follows. They are shape of blades, number of blades, location and shape of gas jet. The influences of them are analysed with comprehensive consideration of many aspects. With the same light shading rate and stagger angle, the axial swirler with curved blades has worse premixed uniformity and lower pressure loss than the one with straight blades. With the same structure of each blade, the decrease of the quantity of blades does influence the pressure loss, while the quantity of gas jets changes correspondingly. But it has little effect on premixed uniformity in a certain range. However, more blades make contribution to better premixed performance. When the total flow area is the same, the axial and circumferential positions of the fuel jets also greatly influence the premixing process. When the fuel jets are upstream the blades and locate at middle of the vanes, the premixing performance is the best. Meanwhile, the jet direction of the fuel jets is a very important influencing factor of the premixing process. When the fuel jet direction is oblique downward at an angle of 30° to the horizontal, the premixing effect is better than the horizontal outflow, which is better than the oblique upward structure.

Keywords: micro gas turbine, low swirler, premixed characteristics, numerical simulation

1. Introduction

How to reduce the emission of nitrogen oxide, or NO_x, has become a common problem in combustion chamber design [1]. The Zeldovich mechanism described the production route of thermodynamic NO_x which was the dominant type of NO_x in high temperature zone [2]. Lean premixed combustion technology has a great potential to reduce NO_x generation [3]. It is because that the use of lean premix technology could decrease the temperature of combustion zone, and finally reduce the generation of thermodynamic NO_x [4–6]. Therefore, lean premixed combustion is increasingly used in the design of low-emission combustion chambers for gas turbines.

When using lean premixed combustion technology, the uniformity of mixture of air and fuel is directly related to the NO_x emission. Lyons et al. [7] defined the inlet mixing inhomogeneity *S*. The influence of fuel and air mixing inhomogeneity on NO_x generation was analysed by theoretical calculations and related experimental studies. The trend of NO_x generation with inhomogeneity *S* was derived for different equivalence

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ratios. When the equivalence ratio of combustion is less than 0.7, NO_x emission rose with the increase of fuel/air nonuniformity. Barnes and Mellor [8] quantified the spatial mixing inhomogeneity in a lean premixed combustion chamber. The experimental results showed that the NO_x generation in the combustion chamber increased within the growth of mixing inhomogeneity. Xu et al. [9] and Feng et al. [10] investigated the effect of premixing uniformity on combustion characteristics and emission characteristics of dry low-NO_x combustion chambers and concluded that the key to dry low-NO_x combustion technology was to achieve uniform premixing of fuel/air under the premise of controlling the total fuel/air equivalent ratio. For diesel engine using partially premixed charge compression ignition (PPCCI) mode, K. Bhaskar et al. [11] investigated the effect of different premixed fuel ratio from 25% to 75% on the combustion performance and emission. It was found that in a more homogenous condition, the NO_x and smoke emissions were reduced remarkably.

Swirlers were important parts in combustion chambers of gas turbines, which could change the flow structures [12, 13], and alter the flame shape and influence the stability of system [14, 15]. Structures of swirler also played an important role in premixing performance [16]. Many structure parameters such as swirl rotation direction, swirl number, axial length of the swirler blades, blade angle, number of blades, swirler vanes number, radial swirler angle, and etc., could influence the premixing performance and NO_x emissions [17–20]. The structures of nozzles, such as their locations and diameters also had great influence on premixing performance [21]. In gas turbines, the fuel nozzles were usually located in the vane of swirler. So, the placement of fuel nozzles needed to be considered in the design of swirler.

In the presented work, the effects of different structural parameters on premixing uniformity were investigated for a low swirler. The parameters include shape of blades, number of blades, location and shape of gas jets.

2. Numerical Methods

In this study, the structure of the axial-flow swirler (Fig. 1) is redesigned based on a micro gas turbine combustor which has been industrialized. The micro gas turbine combustor adopts regenerative cycle, the air temperature at the inlet is 862.5 K, and the pressure is about 0.454 MPa.

The optimization objective of the study is the premixing uniformity of fuel and air at the outlet of the main combustion stage swirler. In order to save computational resources while ensuring the accuracy of the study, a separate simulation study of the structure of the main combustion stage swirler was carried out. The structures retained in the numerical simulation are shown in Fig. 2. The outer wall surface of the main combustion stage swirler, the part of the main fuel inlet pipe in the gas chamber, the middle gas chamber, the main fuel nozzle, and the main combustion stage swirler blades are the structures retained. The fuel enters from the main fuel tube, passes through the fuel nozzle, enters the main combustion stage swirler, mixes with the air and enters the combustion chamber.

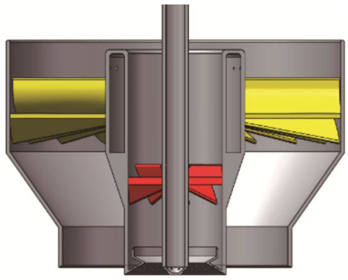

Fig. 1 Two-stage axial swirler structure

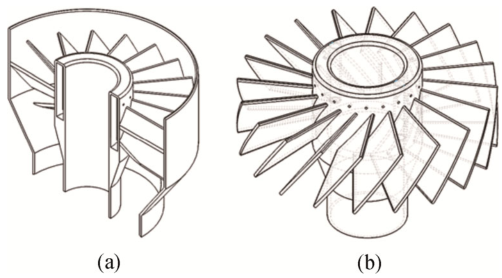

Fig. 2 Schematic diagram of the structure of the main combustion stage swirler

The computational domain of the numerical simulation was expanded by about 400 mm forward and backward, respectively, as shown in Fig. 3.

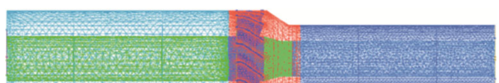

Fig. 3 Calculation domain and mesh division of the main combustion stage swirler for numerical simulation

The simulations were performed using the commercial software ANASY Fluent, and a steady-state solution based on a pressure solver was used. Among them, the realizable *k-ε* model was chosen for the turbulence model, and the DO radiation model was used to calculate the effect of radiation on the airflow temperature and wall temperature with coupled algorithm. The simulation of the flow process is carried out. The mass flow rate of the air inlet is 0.820 kg/s for the main combustion air flow rate and the temperature is 862.5 K. The mass flow rate of the fuel inlet is 0.2475 kg/s and the temperature is 295 K.

3. Results and Discussion

3.1 Blade structure

The structure of the blades of the main combustion stage swirler has a great influence on the flow rate and direction of the air passing through the blades, thus affecting the premixing uniformity. This subsection will compare the structure of two different blades, straight and curved. The blade outlet installation angle is kept constant.

If the blade height of the two blades is guaranteed to be constant, the straight blade structure is simpler, resulting in an excessively long blade length. This greatly increases the pressure loss in the main combustion stage swirler and makes the air flow distribution incorrect. So in the two structures of the same number of blades and shading (blade in the axial vertical surface of the projection area of the proportion of the total circulation area) is similar to the case to compare the two blade structure on the impact of premix uniformity.

As shown in Fig. 4, the two blade structures have little effect on the fuel-air mixing uniformity, and their distribution uniformity of fuel volume fraction is 0.719 and 0.810, respectively.

In comparison, the premixing uniformity of straight blades is better. This is due to the fact that the circumferential velocity at the end of the blades of the swirler with straight blades is 34.1 m/s, which is much higher than that with curved blades. And the distribution of the circumferential velocity is more uniform, which is conducive to the mixing of gas and air. However, at the same time, the pressure loss of the swirler with straight blades is about 25% higher than that of curved blades, which will make the air flow distribution deviate and also increase the pressure loss of the whole combustion chamber.

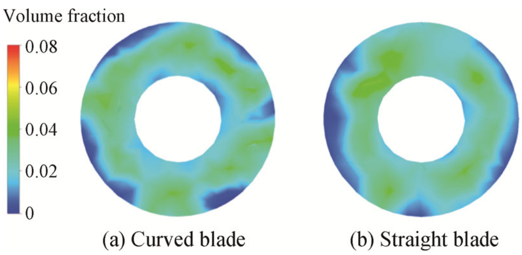

Fig. 4 Fuel volume fraction distribution at the outlet of swirler with different blade structures

3.2 Number of blades

Reducing the number of cyclone blades can reduce the cost of processing and the difficulty of assembly. The number of blades is involved in the calculation of the structure. It is found that the appropriate number of blades is between 16 and 20, so the impact of the two swirlers with 16 and 20 leaves on the premixing uniformity is compared. Main size parameters of two swirlers are shown in Table 1.

To ensure the constant position of the main fuel jets, the swirler with 16 blades also is designed with 16 main fuel jets, located in the middle of two blades and above the top of the blade. To ensure the same jet velocity of the fuel, the diameter of the jets is increased accordingly.

As shown in Fig. 5, the fuel is distributed close to the inner wall at the exit of the swirler with 20 blades, while it is the opposite for the swirler with 16 blades.

This is due to the larger fuel jet depth of the 16-blade swirler, as shown in Fig. 6. Also the circumferential velocity at the outlet is 29.6 m/s and 25.7 m/s for the 16-blade and 20-blade swirler, respectively. The more compact 16-blade swirler has a greater circumferential

Table 1 Main size parameters of swirler with different number of blades

Parameters	Swirler with 20 blades	Swirler with 16 blades
Inner diameter/mm	74	74
Outer diameter/mm	174	162
Blade thickness/mm	2	2
Circulation area/cm^2	52.9	52.6

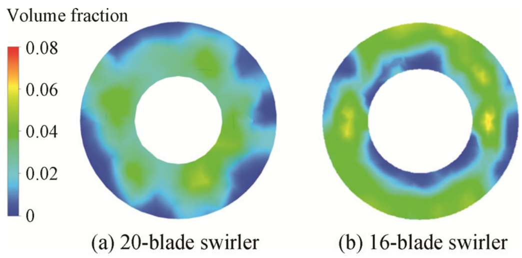

Fig. 5 Fuel volume fraction distribution at the outlet of swirler with different number of blades

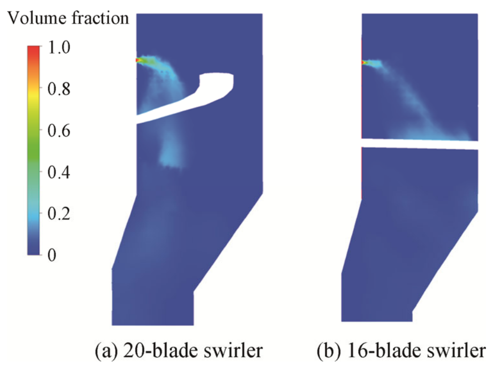

Fig. 6 Fuel volume fraction distribution at the main fuel jets of swirler with different number of blades

velocity for the premixed gas. The above two reasons make the distribution become the state shown in Fig. 5.

The distribution uniformity of fuel volume fraction for them is 0.719 and 0.730, respectively. The difference between them is small. So when the number of blades is reduced within a suitable range and the swirler structure is changed accordingly with the number and aperture diameter of the main fuel jets, the effect on the fuel-air premixing uniformity is small.

At the exit of the swirler, when the gas is too close to the outer wall surface, it tends to cause the high temperature combustion area to be close to the inner wall surface of the flame tube, resulting in wall over-temperature. So although the difference between the premixing uniformity of the two is not large, 20-blade swirler is chosen finally.

3.3 Circumferential position of fuel jets

When the position structure of the main fuel jets is changed, the air flow rate and direction at the jet position are different, which will affect the jet depth of the fuel, and also lead to different length and structure of the premixing area. All these factors will affect the mixing uniformity of the fuel and air at the exit of the swirler.

The axial position and number of main fuel nozzles remain unchanged. The circumferential position is changed from being located directly above the top of the blades to being located in the middle of the top of the two blades, which is shown in Fig. 7.

Since the main structure is not changed, the velocity at the exit of both cyclones is the same, as shown in Fig. 8.

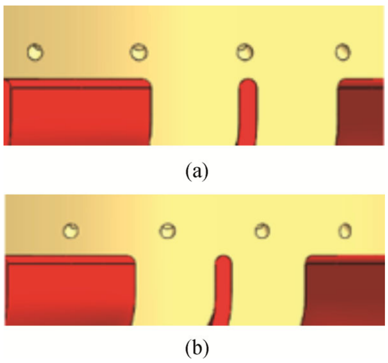

Fig. 7 Diagram of circumferential position change of jets

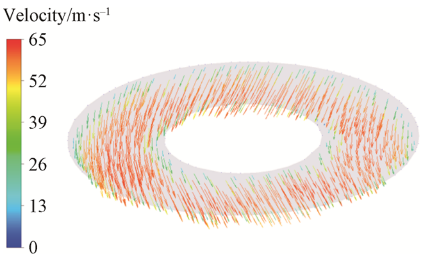

Fig. 8 Velocity vector diagram of outlet of swirler

The mixture of fuel and air forms a stable cyclonic flow at the outlet, with the highest flow velocity around 61 m/s and a uniform velocity distribution. The high speed zone is mainly concentrated in the centre area of the circulation area, and the velocity close to the wall is lower.

The fuel volume fraction distribution at the outlet of the swirler is shown in Fig. 9. The distribution uniformity of fuel volume fraction is 0.615 and 0.719, respectively. It is found that better premixing effect can be obtained when the position of the fuel jet is between the two blades.

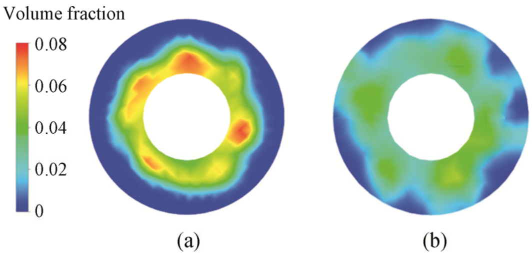

Fig. 9 Fuel volume fraction distribution at the outlet of swirler with different circumferential position of fuel jet

Thus the circumferential position of the main fuel jets was determined. In the subsequent simulations, the nozzles are located in the middle of the two adjacent leaf tops. Also the number of nozzles is the same as the number of blades.

3.4 Axial position of fuel jets

In studying the axial position of the main fuel jets, the relative circumferential position of the jets was kept constant, i.e., the position of the jets was located midway between the two adjacent blades. The jets are gradually moved from above the top of the leaf to below the root of the leaf, as shown in Fig. 10. The jets in Fig. 10(a) are located above the top of the blade; the nozzle in Fig. 10(b) are located at the end of the straight section of the blade inlet; the jets in Fig. 10(c) are located at the middle of the straight section of the blade outlet, and the jets in Fig. 10(d) are located at the position below the blade root.

The main fuel flow rate is small compared to the air flow rate, so it has less effect on the overall flow. Thus the velocity distribution at the exit of the outer cyclone is basically as shown in Fig. 8. However, the air flow velocity and direction at the main fuel jet position changes, which will affect the mixing of the air and fuel.

From the fuel volume distribution at the swirler outlet shown in Fig. 11, it is found that the premixing uniformity of (a) structure is not much different from that of (b) structure. And the uniformity of its volume fraction distribution is 0.719 and 0.724, respectively. This is due to the fact that in these two arrangements, the air has not been changed by the blades. And the flow velocity is only slightly increased by 6% because the blades crowd the circulation space. Also, the remaining length of the premixing section is to let fuel and air mix fully. So it makes the premixing uniformity of (a) and (b) structures vary little.

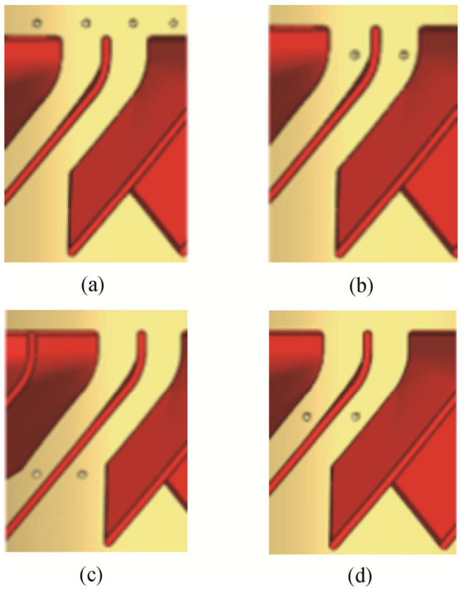

Fig. 10 Diagram of axial position change of jets

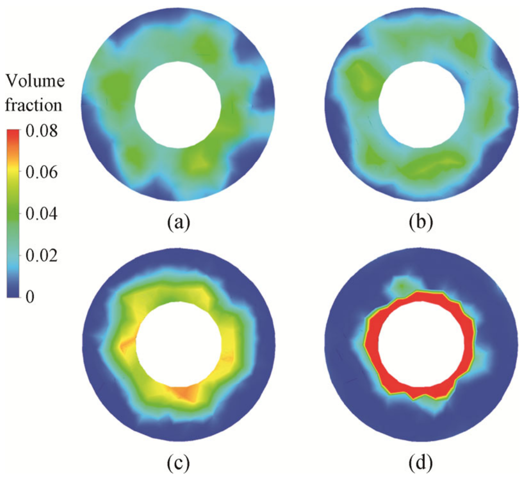

Fig. 11 Fuel volume fraction distribution at the outlet of swirler with different axial position of fuel jet

While for the (c) structure, the air has been changed the spin direction by blades. Due to the centrifugal force, the air flow velocity is higher at the exit of the main fuel jets. The fuel jet depth is reduced and the premixing section is shorter, both of which are not conducive to the adequate mixing of fuel and air. So the premixing uniformity decreases. The distribution uniformity of fuel volume fraction at the swirler outlet under (d) structure is only 0.280, which is mainly caused by the short premixing distance of air and fuel under this structure.

The axial position of the main fuel jets was finally determined to be above the top of the blade considering processing and operational inspection convenience.

3.5 Jet direction

The direction of the main fuel jet affects the relative angle of the gas and air flow directions. It mainly affects the depth of the jet and thus the uniformity of premixing. A schematic diagram of the three structures studied in this section is shown in Fig. 12.

The fuel jet direction in structure (a) is horizontal outflow at an angle of 90° to the air flow direction; the fuel jet direction in structure (b) is 30° oblique upward to the horizontal angle and 120° to the air flow direction; the fuel jet direction in structure (c) is 30° oblique downward to the horizontal angle and 60° to the air flow direction. Comparing the premixing effect of these three different structures, as shown in Fig. 13, the distribution uniformity of their fuel mass volume fraction was calculated as 0.719, 0.659 and 0.796, respectively. Which

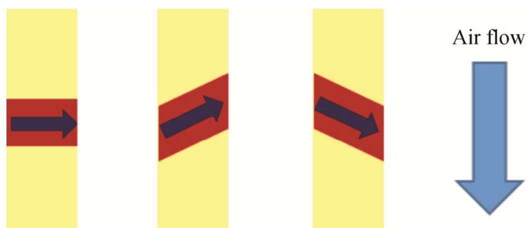

Fig. 12 Diagram of the main fuel jets with different jet directions

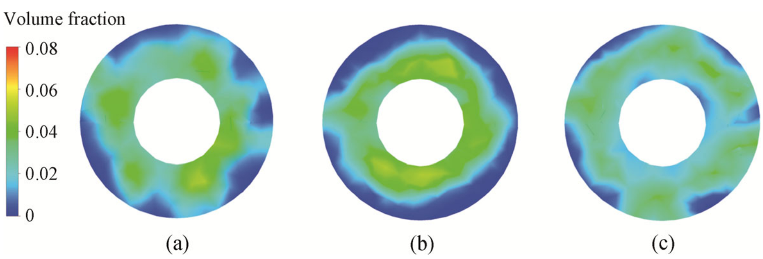

Fig. 13 Fuel volume fraction distribution at the outlet of swirler with different fuel jet directions

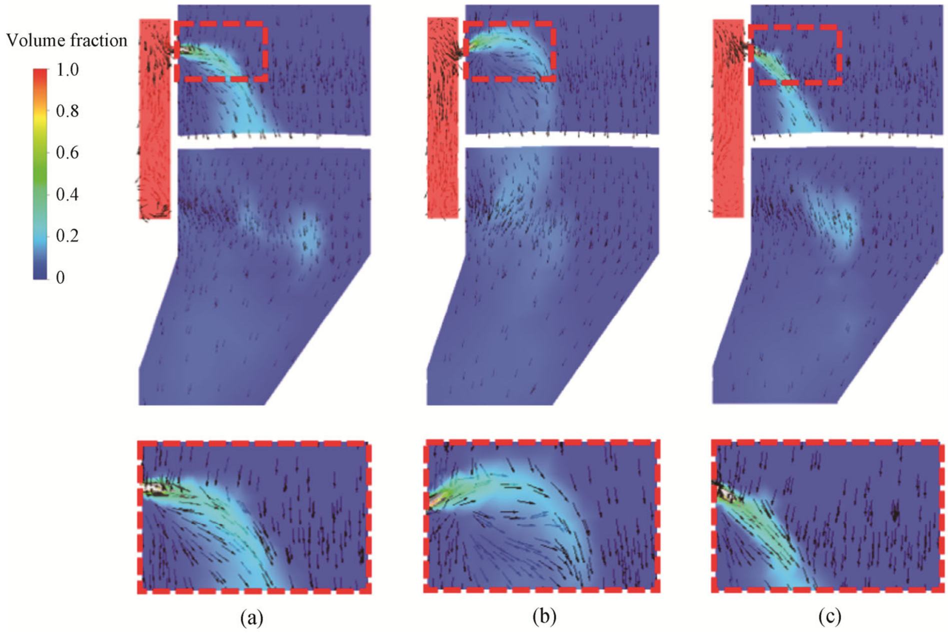

Fig. 14 Fuel volume fraction distribution at the main fuel jets of swirler with different fuel jet directions and diagram of velocity vector

shows that the smaller the angle between the jet direction and the air flow direction, the better the uniformity of premixing under the premise of constant position of the main fuel nozzle.

The reason for this result is shown in Fig. 14. The smaller the angle between the jet direction of fuel and air flow direction, the less radial velocity component of gas is reduced by mixing. The deeper the jet depth, the better it is for the fuel to mix with the air fully, so the premixing uniformity is better.

In summary, the position and structure of the main jets were finally determined. The direction of the gas jets is 30° downward from the horizontal, with good premixing uniformity.

4. Conclusions

The cyclone is a very important structure in the combustion chamber, which has a very important role in the flow distribution and flow field organization in the combustion chamber.

(1) The position of the main fuel jest has a strong influence on the premixing uniformity. The premixing uniformity is better when the jets are located between two adjacent blades and at the top of the vanes. When the jet hole position is lowered to the bottom of the blade root, the premixing uniformity decreases sharply because the length of the premixing section is reduced. The distribution uniformity at the swirler outlet decreases from 0.796 to 0.280.

(2) The fuel jet direction will affect the jet depth and thus the premixing uniformity. When the fuel jet angle is 30° down from horizontal, the jet depth is larger and the premixing uniformity is better.

(3) The number of blades and the structure of the blades have a relatively small effect on the premixing uniformity. When the number of blades is reduced and the structure is adjusted accordingly, the fuel distribution uniformity is slightly reduced by about 0.02. The use of straight blades improves the premixing uniformity slightly, but it brings higher pressure loss and affects the air flow distribution at the same time.

Acknowledgements

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