Numerical Simulation and Analysis of Combustion Characteristics of Natural Gas in Slotted Swirler Combustor

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Abstract. In order to study the effect of inlet air distribution in swirling combustion chamber, we present a new type of slotted swirler which suits to main combustion chamber. Numerical simulation are employed for the research on the combustion performance in three swirl burners with different structures (normal swirler, 4 slits swirler, 8 slits swirler), analyze the flow field characteristics and temperature field characteristics in slotted swirler chamber. The slotted swirler combustor has certain superiority in terms of combustion performance. The results showed that the slotted swirler combustor has some advantages in lower flow resistance, better combustion stability and higher combustion efficiency.

Introduction

Combustion process consists of a series of complicated process such as flow, heat transfer, mass transfer and chemical reaction, only when the fuel burn fully in the combustion chamber, the higher the chemical energy transfer into kinetic energy, thus it is great significant to improve the work efficiency of burner for improving the working performance. As one of the key parts of the combustion chamber, the swirler has attracted the attention of domestic and foreign scholars, and the intensified combustion is a very effective method. Zhuxu Ren of Huazhong University of Science and Technology put forward a new type of with hole swirler and applied to the aero-engine combustion chamber. It has some advantages but there is no in-depth study on the influence of the number of slits on combustion, this paper is in the existing basis of the cyclone, with 4 slits and 8 slits axial vane swirlers are designed, Three tapes swirlers (with 4 slits and 8 slits and none) are simulated by CFD simulation software, and obtained theses combustion chambers’ flow field and temperature field characteristics.

Qun Zhang, Dongbo Yan[1], from Northwestern Polytechnic University, response to the two-stage axial vortex combustor flow field and combustion performance of the theoretical and numerical research, concluded that the vortex strength increases with the expansion Angle of the downstream sleeve of the cyclone, but the airflow "detached" from sleeve when at critical Angle, they also established a set of expansion to estimate the sleeve exit airflow Angle. Wenming Rui[2] et al. analyzed the pure oxygen combustion characteristics of combustor with different swirl intensity by changing the blade Angle of the cyclone, and the results showed that the combustion effect of the cyclone was the best.

Huazhong University of Science and Technology of Zhu Xuren[3] analyzed the flame characteristics and combustion efficiency of the new type hydrocyclone by measuring the outlet temperature and pollutant emissions from the new combustion chamber, and proved by experiment. The slits in the combustion chamber is very important for stabilizing the flame and improving the flame characteristics.

Chen Li and Xiangsheng Li[4] from Xi'an Jiaotong University changed the inlet air pressure, temperature, axial velocity respectively to simulate the combustion characteristic under different air inlet conditions, it is concluded that low vortex combustor flow field structure has little influence on
inlet air conditions and it can maintain the stability of the front flame at wider air inlet conditions, so as to improve the stability of the burner work.

Mathematical Model

Design of Burner and Cyclone

The structure of swirl combustion chamber is shown in the figure below. The design power of the burner is $P=4.2\text{MW}$, and the gas type is natural gas. Using one step combustion reaction, combustion chamber diameter $D=1.6\text{m}$, length $L=4.5\text{m}$. The axial blade cyclone in the head configuration of the combustion chamber is shown in the figure2. With 12 leaves, the blade thickness is 1 mm, cyclone blade outlet Angle of 45°, inner diameter $D = 0.5\text{ m}$, diameter $D = 0.8\text{ m}$, slits are distributed evenly around the central nozzle, and the air will flow directly into the combustion chamber through the slits. The number of slits in cyclone are 0, 4 and 8 in this paper.

![Figure 1. Schematic diagram of swirl burner.](image1)

![Figure 2. 3D schematic diagram of cyclone.](image2)

Physical Model and Grid Division

In this paper, SolidWorks2014 is used to establish a three-dimensional model of burner as shown in the Fig.3. Considered the complex swirler structure, so the burner's head is divided by the unstructured mesh of tetrahedron, and the combustion chamber adopts hexahedral mesh. The mesh of the inlet section of the chamber is encrypted, and the number of meshes without slits is 2.22 million.

![Figure 3. Grid division of combustion chamber.](image3)

![Figure 4. None, 4 slits and 8 slits cyclone grid division.](image4)

Boundary Conditions

The discrete phase model is used to calculate the gas flow, and the combustion model chooses the non-premixed model, which adopts the SIMPLE algorithm pressure and the velocity coupling, and the first-order winding-wind discrete format.
Air inlet and gas inlet adopt speed entrance, air rate of 10 m/s and gas velocity of 20 m/s, pressure export for combustion conditions, in order to facilitate the internal combustion of combustion chamber, so the wall in accordance with the standard wall function processing, thermal insulation and not consider the influence of the gas molecular diffusion and internal heat conduction.

**Mathematical Model and Solution Method**

Using the Reynolds average N-S equation as the control equations, the three-dimensional fluid dynamics in cylindrical coordinates can be seen in the following formula:

\[
\frac{1}{r} \left[ \frac{\partial}{\partial x} \left( \rho_k \phi \right) + \frac{\partial}{\partial r} \left( \rho_k \phi \right) + \frac{\partial}{\partial \theta} \left( \rho_k \phi \right) \right] = \frac{\partial}{\partial x} \left( \Gamma_{eff} \phi \frac{\partial \phi}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( \Gamma_{eff} \phi \frac{\partial \phi}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( \Gamma_{eff} \phi \frac{\partial \phi}{\partial \theta} \right) + S_{\phi}
\]

(1)

The turbulence model adopts the standard k-epsilon equation, energy equation and continuity equation. Chose premixed combustion model as combustion model, the premixed combustion model used to solve the solutions for one or two conserved scalar transport equation (mixed), then predict the concentration of each component which derived from the mixture fraction distribution, this method is mainly used for simulating turbulent diffusion flame. The combustion chamber wall was under thermal insulation wall conditions.

The radiation model uses P1 radiation model which needs a small amount of calculate. The equation of P1 radiation model is shown as follows:

\[
q_r = \frac{1}{\varepsilon (\alpha + \sigma_t) - c_{\sigma_t}} \nabla G
\]

(2)

The combustion characteristics of gas and air are analyzed with Finite Rate Model. The combustion model adopts a one-step reaction mechanism, and assumes that the fuel is completely burned into CO2 and H2O, and the equation is as follows:

\[
\text{CH}_4+2\text{O}_2 \rightarrow \text{CO}_2+2\text{H}_2\text{O}
\]

(3)

**Simulation Results and Analysis**

**Analysis of Flow Field in Flame Tube**

As shown in Fig.5, z = 0 plane, gas flows through slits at different Numbers. The simulation results shows that the radial distribution of axial velocity of which away from the exit of nozzle. It can be seen that the speed of these three kinds swirl burner are presented symmetric distribution about the burner center axis, the speed of mixture gas which with slits are higher than ordinary one. Near the nozzle exit (X=0.95m), the mixture gas speed increases rapidly due to the influence of high speed gas.

With the increase number of slits, the air speed through 4 slits swirler is faster than 8 slits swirler and none slits swirler. The center temperature of 4 slits swirler burner is highest, Air which flow through the slits has a certain constraint on the flow of the central gas and makes gas velocity more concentrated, as well as the axial velocity increases. Compared with four figures in Fig.5, it can be found that, with the increase of axial distance, the axial velocity of the central part is rapidly attenuated, and the peak difference between none slit swirler and slits swirler is also reduced. At the full development stage, the rotational flow effect of the near wall is weakened, and the axial velocity tends to be the same.

**Temperature Field Analysis**

Fig.6 is a cloud diagram of the longitudinal section temperature distribution of the swirl combustion chamber of 0, 4 and 8. At the outlet of the cyclone, the high temperature segment of the combustion chamber moves back about 0.2m in slits swirlers. It makes the temperature of outlet and wall surface of
lower than that of the normal swirl burner, which prevents the swirler and nozzle from being burnt out. The 8 slits swirl combustion chamber length of center flame increased by 0.3m compared with that of the non-slit combustion chamber.

As a whole, the flame is more concentrated in the middle of the reflux area, and the temperature on the wall is smaller. It means that air in slits swirl burner mainly concentrated in backflow zone of gas combustion chamber which is the most beneficial for burning, guarantees the stability of the flame of the combustion chamber, which can not only make the fuel burning more fully, also increase the intensity of heat of the combustion chamber at the same time. The average outlet temperature of the slits swirler combustion chamber is 998K, and the average outlet temperature of common burner is 920K.

Figure 5. Radial distribution of axial velocity when X=0.92m, 1.34m, 1.76m, and 2.18m.

Figure 6. Temperature distribution of the swirl combustion chamber, n=0, 4 and 8.
Conclusion

In this paper, by using the numerical simulation method, the performance of the cyclone with none slit, 4 slits and 8 slits was studied. The collector without dc Kong Xuan bore, with 4 dc and 8 dc performance of hydrocyclone were studied, analysis the cyclone with and without slits and slits number on flow field, temperature field of the combustion chamber, comparing with experiment done by Xuren Zhu who is from Hua Zhong University of Science and Technology, the following conclusions can be drawn from the research results:

(1) After adding the slits structure in swirler design, it reduces the air turbulence intensity at the back of cyclone, and flow resistance is reduced, thus it increases the length of recirculation region in combustion chamber, which makes air and gas mix more fully and beneficial for enhancing combustion.

(2) The axial velocity along the radial direction in three kinds of swirlers were presented symmetric distribution about the center axis. However, the velocity of the mixed gas at the center of in 4 slits swirl burner is higher than that of the none slit swirl burner.

(3) The with slits burner makes the flame length longer and increases the average temperature of the flue gas in the combustion chamber. The central axis outlet temperature of the combustion chamber in slits swirl is 300K higher than that in none-slit swirl combustion chamber. This shows that the combustion of gas in the slits swirl burner is more complete, releasing more heat and improving the efficiency of the burner. Moreover, the temperature of the near wall surface in slits swirler is lower, which is beneficial to the cooling of the wall of combustion chamber.

References


