Numerical simulation on combustion and exhaust emission of staged combustor

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Abstract. Aiming at the goal of low pollution and high efficiency, combustion characteristics and exhaust emissions of radial staged combustor are studied using a numerical simulation method. The result shows that the combustion efficiency of staged combustor is all over 97%. The emission of pollutants, especially the CO and NO_x, is obviously reduced. The advantages of staged combustor cannot be fully exploited, when the airflow is evenly distributed in the double-head. Higher combustion efficiency and lower pollutant emission can be achieved with an appropriate flow distribution ratio.

1. Introduction

With the rapid development of China's aviation career, the emission of pollutants from the aero-engine is increasing, and its' pollution to the atmosphere is becoming more and more serious [1]. At the same time, public awareness of environmental protection and energy saving has been deepening [2]. The main development direction of civil aviation engine has become low pollution and high efficiency [3]. All of countries around the world have carried out extensive research on the low-pollution combustion technology of aero-engines, and developed different low-pollution combustion chambers.

From the 1970s, the United States developed many practical technologies [4, 5], such as the staged combustion, Lean premixed prevaporized (LPP), Variable geometry combustor (VGC), Rich-burn/quick-mix/lean-burn (RQL) [6, 7], et al. In the 1990s, General Electric (GE) Company developed a combustor of double-loop premixed swirler to make the pollution emission be 85% lower than the current standard [7, 8]. In addition, SNECMA in France developed double-head combustion chamber to make the emissions lower. Rolls-Royce in England developed a lean single-stage and axial staged combustion chamber, which can reduce emission of NO_X [1].

China has also conducted research on low-pollution combustion technology, and has made some progress in the low-pollution combustion chamber of gas turbine. Lin Yuzheng [8, 9] et al developed a low-pollution combustion chamber of staged/lean premixed prevaporized to achieve the combination of staged combustion and LPP, which can reduce NO_X emissions. Ma Wenjie [10] et al experimentally investigated the air axially-staged approach's influence on combustion and exhaust emissions.

The main research objectives of advanced aero-engine combustion chamber are reducing the exhaust emissions, especially the NO_X emissions in the future. Therefore, the development of cost-effective low-NO_X emission technologies is important. Based on the radial staged combustion chamber, a double-head staged combustor was designed, and the numerical simulation was carried out to study its combustion characteristics and exhaust emission.

2. The design of double-head staged combustion chamber

When aero-engine combustion chambers are in low-power or high-power operating conditions, emissions of pollutants are different. The staged combustion was proposed to reduce the emissions of pollutants. It divides the combustion chamber into two main combustion zones. As shown in figure 1, each of the main combustion zones has an inlet head, respectively, which is supplied fuel and air alone. Each inlet head is equipped with a swirler, which makes the fuel and air well mixed. Low emissions of pollutants are achieved by controlling the temperature of each main combustion zone.

The double-head staged combustion chamber is an annular combustor. Axial cross-sectional view is shown in figure 1. Flame tube is divided into two primary combustion zone, the length of the main combustion zone is 62mm in First-head, the length of the primary combustion zone is 72mm in Second-head, and total length of flame tube (including double-head) is 127mm. According to the flow distribution, two swirlers are arranged in the head of flame tube, primary holes and dilution holes are provided in the flame tube.

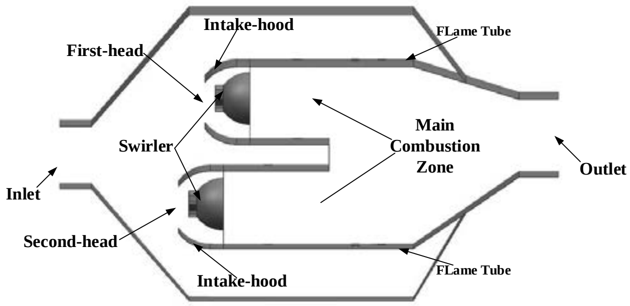


Figure 1. Axial cross-sectional view of the double-head staged combustion chamber.

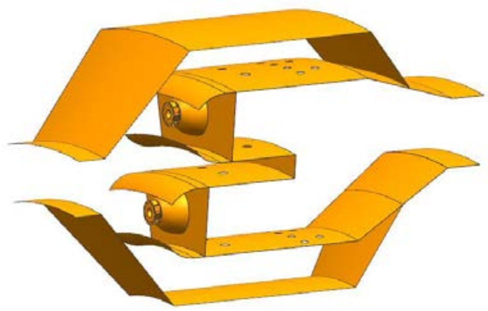


Figure 2. The computational domain.

There are 18 double-head structures evenly distributed in the circumferential direction, so they are periodic symmetrical. Considering the computational resources and calculation precision, a 20-degree fan-shaped region is selected for computational domain. As shown in figure 2, a complete double-head structure, the primary holes and dilution holes, distributed on the downstream surface of flame tube, are in the computational domain.

3. Flow distribution schemes and boundary condition setting

This paper focuses on the impact of air staged proportion on combustion performance and pollutant emissions. Air staged is achieved by different inlet airflow distributions at the double-head sections. As shown in the table 1, two schemes were studied to show the differences in the overall combustion performance resulting from the different inlet airflow distributions at the heads. In the two schemes, the total inlet airflow is the same. The total inlet airflow is evenly divided into two equal portions in Scheme 1, which means the inlet airflow at First-head and Second-head respectively accounts for 50% of total inlet airflow. In the Scheme 2, the inlet airflow at First-head accounts for 45% of total inlet airflow, while the inlet airflow at Second-head accounts for 55%.

The different inlet airflow distributions are achieved by the different area of double-head sections. In order to ensure the same total flow, the total area of double-head sections is designed to be identical. According to different distribution ratio to build the corresponding model. The proportion of the area is exactly the same as the flow rate distribution at each head. The corresponding intake-hood is set outside the head to ensure that the airflow into the flame tube, and improve the static pressure near the head.

Table 1. Schemes of flow distribution.

Scheme	1	2
First-head (%)	50	45
Second-head (%)	50	55

According to the typical working condition of the aero-engine's main combustion chamber, the inlet airflow parameters are selected as follows: the temperature is 850K, inlet Mach number is 0.3, and gas-oil ratio is 0.03. The injector is located behind the swirler.

4. Numerical simulation methods

The numerical simulation is based on 3-dimensional incompressible Navier-Stokes equations. The standard k-epsilon model is a turbulence model, which was proposed by Launder and Spalding. It's a two-equation model and given by the empirical formula. It's used widely in engineering applications and is stable and relatively accurate in high Reynolds number flows. Therefore, using the standard k-epsilon model to calculate turbulent viscosity, selecting the standard wall function to solve the boundary layer flow. The second-order upwind discretization scheme was used in differential equation discrete, the standard SIMPLE algorithm was used in pressure-velocity coupling [11].

In this paper, aviation kerosene was chosen as the fuel. Aviation kerosene is mainly composed of different fractions of hydrocarbon compounds, the chemical formula can be written as $C_{12}H_{23}$. The combustion process is simulated by the non-premixed combustion model, the interaction between chemical reaction and turbulence is simulated by the probability density function (PDF) model. The discrete phase model (DPM) is used to simulate the discrete phase in the flow field. This method is suitable for simulating the problems which must consider turbulent flow and complex chemical reaction mechanism, so it can be well used to calculate the complex combustion in the main combustion chamber. Fuel atomization using Rosin-Rammler distribution, the Santer mean diameter (SMD) is 0.05mm.

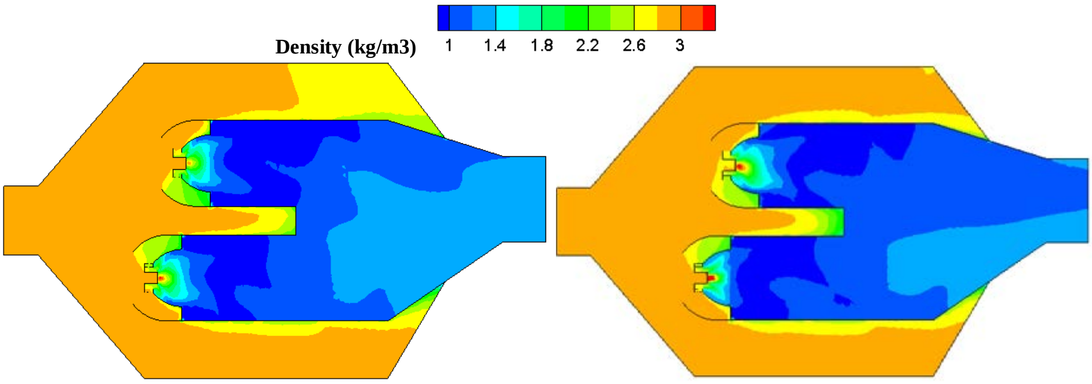
The calculate grids adopt unstructured grids. Compared 2.3 million to 3.7 million of grid number, the deviation of combustion efficiency is less than 0.3% in Scheme 1. That means the result of numerical simulation is independent of different grid densities and it is accurate. Therefore, we selected 2.3 million grid numbers to save computing resources and times in this paper.

5. Analysis of numerical results

5.1. Combustion characteristics

Combustion characteristics of aero-engine combustion chamber is mainly represented by the combustion efficiency, higher combustion efficiency represents better combustion performance. In this paper, the combustion characteristics of staged combustion chamber will be studied from three aspects: density, velocity and temperature, which are all closely related to combustion efficiency.

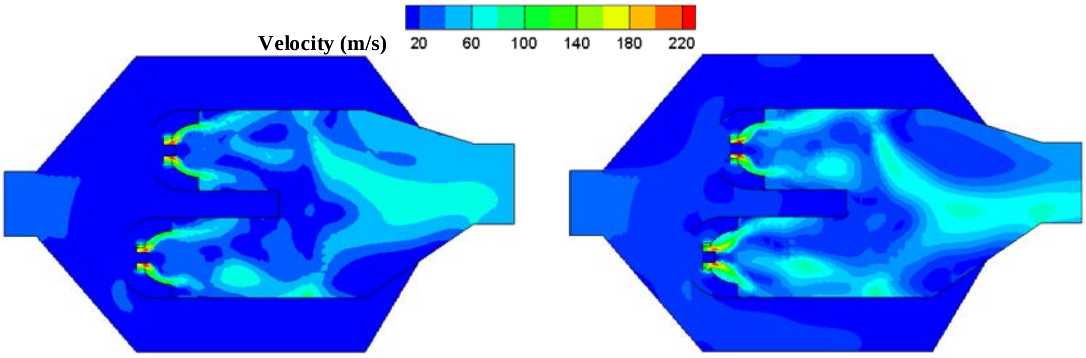
Figure 3 shows the density contour of the combustion chamber along the axial section. The gas is obviously compressed through the swirlers and the holes. The primary combustion zone is in a low-density state, because of the combustion. After the primary combustion zone, the gas gradually expands, and the density of gas is significantly increased near the outlet. Comparison with the schemes, the density changes dramatically at the swirler in Scheme 1, but it is more evenly distributed at the rear of the primary combustion zone.



Scheme 1 Scheme 2

Figure 3. The density contour of the combustion chamber along the axial section.

As shown in figure 4, the zone with the highest speed appears in swirlers, which can make the gas stays for longer periods of time to ensure the gas mixed well with the fuel and burns adequately. The velocity of the primary combustion zones is relatively small, but the changes are quite dramatic. When the air flow to the outlet, the speed is gradually increasing.



Scheme 1 Scheme 2

Figure 4. The velocity contour of the combustion chamber along the axial section.

Figure 5 shows the temperature contour of the combustion chamber along the axial section. The primary combustion zone of the Scheme 2 is wider. High-temperature zone concentrated in the main combustion zone, which means the combustion efficiency is pretty well. The combustion efficiency was calculated by the temperature rise method. The formula is:

$$\eta = \Delta T_r / \Delta T_{th} = (\overline{T}_{out-r} - \overline{T}_{in}) / (\overline{T}_{out-th} - \overline{T}_{in}) \quad (1)$$

Character *T* represents the temperature, the subscript of *out* represents the theoretical temperature rise, and the subscript of *r* represents the actual temperature rise.

As shown in table 2, the average velocity at the outlet of Scheme 2 is lower, which means that the air and fuel have more time to mix with each other and burn. It results an increase in the average temperature at the outlet, a decrease in density, and an increase in combustion efficiency. The combustion efficiency is 97.0% in Scheme 1 and 97.6% in Scheme 2. It means that the Scheme 2 has better combustion performance.

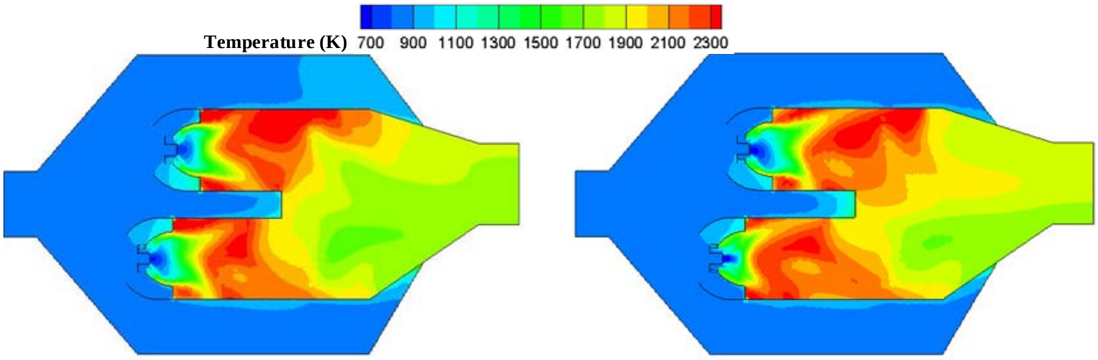


Figure 5. The temperature contour of the combustion chamber along the axial section.

Table 2. Airflow parameters at the outlet and combustion efficiency.

	Density (kg/m^3)	Velocity (m/s)	Temperature (K)	Combustion Efficiency (%)
Scheme 1	1.226	50.0	1791.3	97.0
Scheme 2	1.224	48.8	1796.7	97.6

5.2. Exhaust emissions

The main emissions of aero-engine are: H_2O, CO_2, CO, unburned hydrocarbons (UHC), black smoke and NO_x. Because the combustion efficiency of civil aero-engine combustor is very high, the UHC and black smoke is relatively few and easily oxidized than CO, CH_4 is chosen to represent the UHC in this paper.

Figure 6 shows the distribution of mole fraction of CO, figure 7 shows the distribution of mole fraction of CO_2. CO is a product of incomplete combustion, usually formed in the main combustion zone, and is oxidized to CO_2 in the middle area. As shown in figure 6, CO is mainly distributed in the region near the swirler, and the molar fraction of CO in the two heads is almost the same, because of the same flow distribution. There are less CO in the Second-head than in the First-head. The distribution area of CO_2 in Scheme 2 is larger than in Scheme 1, especially in the Second-head. The reason is that the Second-head of Scheme 2 can get more oxidant to participate in combustion reaction, CO can be quickly oxidized to CO_2 at high temperatures.

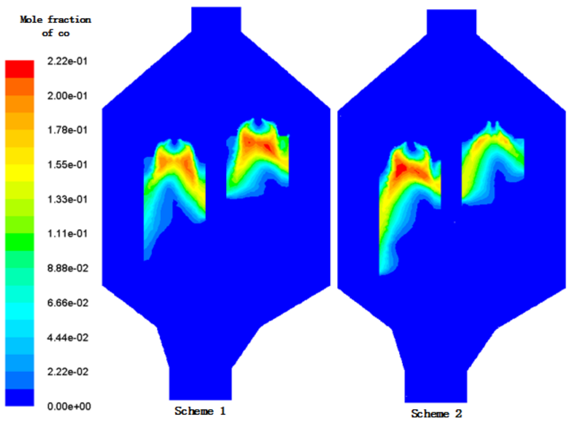


Figure 6. Mole fraction of CO.

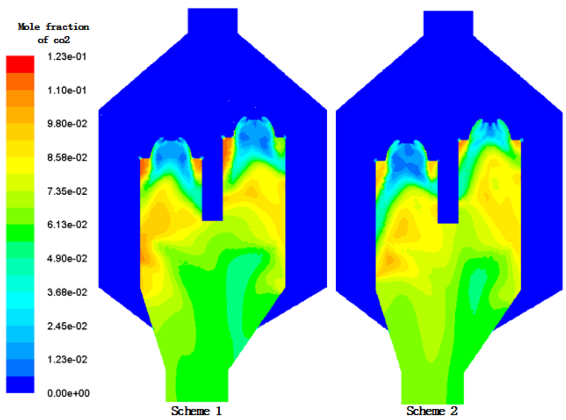


Figure 7. Mole fraction of CO_2.

Figure 8 shows the distribution of mole fraction of NO, figure 9 shows the distribution of mole fraction of N_2O. The molar fraction of NO in the Scheme 1 is obviously higher than in Scheme 2, especially around the swirler. The distribution of N_2O in the 2 Schemes is roughly the same, but the area is larger in the Scheme 2.

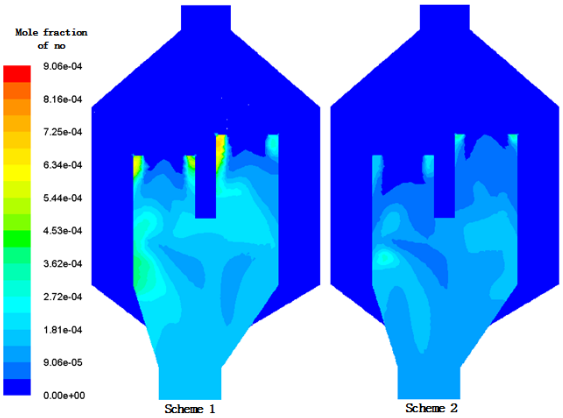


Figure 8. Mole fraction of NO.

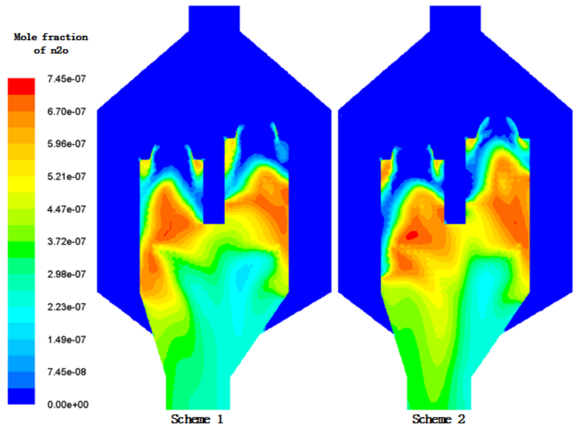


Figure 9. Mole fraction of N_2O.

Figure 10 shows the emission of pollutants at the outlet of the staged combustion chamber. Compared with Scheme 1, the mass fraction of NO at the outlet in Scheme 2 is lower, but the mass fraction of N_2O is a little higher. In terms of the NO_x, the total emissions of Scheme 2 is less, because the mass fraction of N_2O is only one thousandth of NO. And the mass fraction of unburned hydrocarbons is less the 10^{-9}, so it can be ignored. The emission of CO_2 is roughly the same, the CO of Scheme 2 is less.

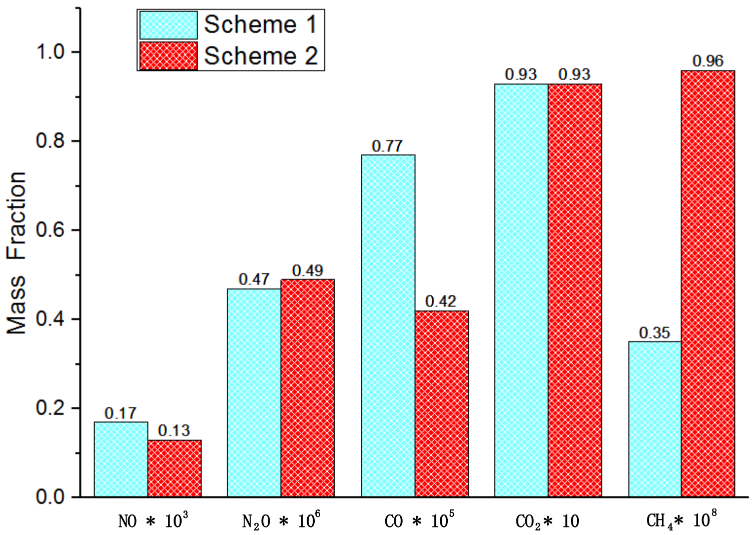


Figure 10. The emission of pollutants at the outlet of the staged combustion chamber.

In general, staged combustion chambers with different flow distributions have less emissions and higher combustion efficiency. There is an optimum flow distribution ratio that will optimize the combustor's combustion performance and pollutant emissions. The most appropriate flow distributions scheme also needs further study in the future work.

6. Conclusion

The paper studied on combustion and exhaust emission of staged combustor in 3 different flow distribution schemes using the numerical simulation method, and obtained some conclusions as following:

- Staged combustion is a new combustion technology with high efficiency and low pollution. The combustion efficiencies of staged combustor are all above 97% under the conditions setting in this paper, and the pollutant emission conforms to the latest civil aviation engine emission standard.
- When the airflow is evenly distributed in the double-head, the advantages of staged combustor cannot be fully exploited.
- By controlling the airflow distribution ratio in the double-head, it was possible to improve the uniformity of the distribution of temperature, density and velocity in the flame tube, and improve the combustion efficiency.
- By selecting an appropriate airflow distribution ratio, it was possible to significantly reduce the emission of pollutants, especially the CO and NO_x.

Acknowledgments

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