

Numerical Simulation of Mixing and Combustion Characteristics based on Air Turbine Rocket Engine Rocket Afterburner

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Abstract. The gas combustion efficiency of the afterburner of the Air Turbo Rocket (ATR) engine directly affects the performance of the engine. In order to study the reaction mechanism of mixing combustion of gas and air in the afterburner, the paper numerically simulates the turbulent mixing and combustion process of rich fuel gas and air, and analyzes the influence of air intake mode and intake parameters on engine performance. The results show that: The both sides air intake is better than the one sides air intake; The air incidence angle is 90°, the engine performance is ideal; The air intake position is selected between the length to diameter ratio of the afterburner from 1.0 to 1.5, and the combustion efficiency of the afterburner is higher.

Keywords: Numerical imulation; Afterburner; Chemical reaction; Air Turbo Rocket (ATR).

1. Introduction

The gas mixing flow and combustion in the afterburner is one of the key technologies in the research of ATR engines. It is necessary to carry out the research on the mixing and combustion process in the afterburner. Many studies have been done on the mixing combustion of the afterburner at home and abroad [1-3], and these studies have achieved a lot of results. In order to analyze the mixing combustion process of the afterburner more deeply and accurately, the paper uses the numerical simulation results as the basis, uses the suitable combustion efficiency evaluation method to evaluate the results of the numerical simulation, and selects the structure of the engine afterburner with good performance.

2. Calculation model

2.1 Physical model

In order to meshing, the real engine structure is reasonably simplified, the working principle of the afterburner of the ATR engine is similar to that of the solid ramjet engine. The paper refers to Simulation of Secondary Combustion for Zygomorphic Tangential Air-in Solid Rocket Ramjet by Liu Jie et al., Northwestern Polytechnical University [4], and obtains the preliminary construction of the afterburner of the ATR engine is shown in Fig. 1.



Fig. 1 Structure of afterburner

2.2 Mathematical model

2.2.1 Basic assumptions

The flow field in the afterburner of the ATR engine is very complex, including violent chemical reactions and complex turbulent flow. In order to simplify the analysis and calculation, the following assumptions are made for the flow field in the afterburner:

- (1) All gases in the afterburner are ideal gases, which conform to the ideal gas state equation;
- (2) The flow in the afterburner is a steady three-dimensional flow;
- (3) The flow process in the afterburner is adiabatic;
- (4) The diffusion coefficients of the components in the combustion simulation are the same.

2.2.2 Turbulence model

The fuel, oxides and products in the afterburner of the ATR engine studied in the paper are all in the gas phase, so the three-dimensional viscous compressible flow N-S equation including component transport and chemical reaction is used as the control equation of gas turbulent flow and combustion, and the finite volume method is used to discretize and solve the control equation. The form of N-S equation in Cartesian coordinate system is as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = \frac{\partial E_v}{\partial x} + \frac{\partial F_v}{\partial y} + \frac{\partial G_v}{\partial z} + S \quad (1)$$

The turbulence model used in the paper is the SST k- ω model. Compared with the standard k- ω model, the SST k- ω model adds a lateral dissipation derivative term, and at the same time, the turbulent shear stress transport is considered in the definition of turbulent viscosity. During the process, the turbulence constants used in the model are also different. These characteristics make the SST k- ω model more applicable[5].

2.2.3 Combustion model

The gas and air enter the afterburner from different inlets, and mixing combustion in the afterburner. The turbulent combustion process can be numerically simulated by the general finite rate method. In the paper, Finite-Rate/Eddy-Dissipation model is used as the gas phase combustion model. The chemical reaction equations and reaction parameters are shown in Table 1.

Table 1. Chemical reaction equation and reaction parameters

Number	Chemical reaction formula	Pre-Exponential Factor	Activation Energy(J/kg·mol)
1	$\text{CH}_4 + 2\text{O}_2 = \text{CO}_2 + 2\text{H}_2\text{O}$	2.119×10^{11}	2.027×10^8
2	$2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O}$	9.87×10^8	3.1×10^7
3	$2\text{CO} + \text{O}_2 = 2\text{CO}_2$	2.239×10^{12}	1.7×10^8

3. Boundary conditions

Table 2. The boundary conditions

Position	Boundary conditions	Parameters and processing methods
Gas inlet	Mass flow inlet	Mass flow rate 0.06kg/s, total temperature 987K
Air inlet	Mass flow inlet	Mass flow rate 0.15kg/s, total temperature 410K
Nozzle outlet	Pressure outlet	Standard atmospheric pressure 101325Pa
Wall of afterburner	Solid wall	Adiabatic, no slip

The boundary conditions used in the calculation in this paper mainly include mass flow inlet boundary, pressure outlet boundary and solid wall boundary. The turbine outlet gas parameters are used as the input parameters of the gas inlet of the afterburner, and the compressor outlet air parameters are used as the air inlet parameters of the afterburner. The boundary conditions are set as shown in the table 2 [6].

The boundary conditions also include the types and mass fractions of the primary gas chemical components. The main components and mass fractions of the primary gas are calculated by the CEA as shown in the table 3.

Table 3. The main components and mass fraction of primary gas

Element	CH ₄	CO	CO ₂	H ₂	H ₂ O
Mass fraction	0.04237	0.65013	0.13598	0.06494	0.10656

4. Evaluation method

Engine performance evaluation indicators include specific impulse, thrust, combustion efficiency and other parameters. In the paper, component combustion completion rate is mainly used to represent engine combustion efficiency. The calculation formula for secondary combustion efficiency of gas phase components at any section is as follows [7, 8]:

$$\eta_{i,g} = 1 - \frac{\int_A \rho u Y_{i,g} dA}{\dot{m}_{i,g}} \quad (2)$$

In the formula: $\eta_{i,g}$, $Y_{i,g}$, $\dot{m}_{i,g}$ respectively represent the combustion efficiency, mass fraction and total inlet flow of the i -th combustible gas in the fuel gas.

5. Calculation results and analysis

5.1 Analysis of the results of one side intake and both sides intake

In the paper, the basic structure of the afterburner combustion chamber is divided into two types: Air enters the afterburner from one side and from both sides. Through the numerical simulation of these two afterburner structures, the temperature distribution in the afterburner is obtained as shown in Fig. 2 and Fig. 3.

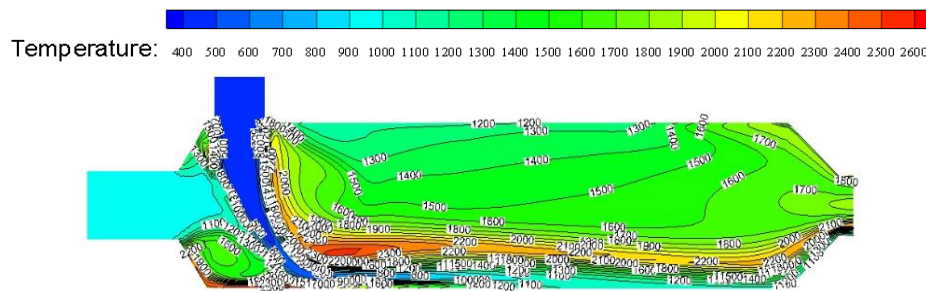


Fig. 2 Air enters the afterburner from one side

Fig. 2 is the temperature distribution diagram of the air intake on one side. It can be seen from the diagram that the temperature field distribution is complicated. The maximum temperature in the afterburner can reach 2600K, and an initial high temperature zone is formed at the head of the afterburner; The temperature of the upper half of the wall in the middle area of the afterburner is lower than the temperature of the second half. This is because in the middle of the afterburner, most of the air is located on the lower wall, and the air and gas are not mixed enough, and after the afterburner in the half, the mixing of gas and air is relatively complete.

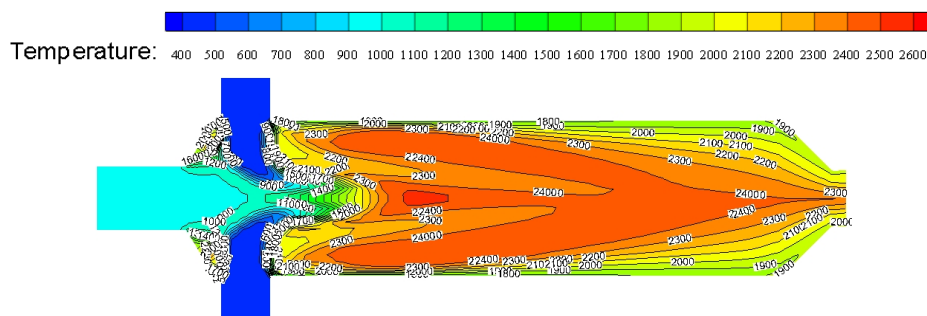


Fig. 3 Air enters the afterburner from both sides

Fig 3 is the temperature distribution diagram of the air intake on both sides. It can be seen from the figure that a small combustion area is formed at the head of the afterburner, and as the length of the afterburner increases, the high temperature area gradually diffuses to the outside; The high temperature area Mainly distributed inside the afterburner and the temperature near the wall is low. When the air is intake on one side, the local wall temperature of the afterburner is too high. Therefore, the intake on both sides is conducive to the thermal protection of the afterburner.

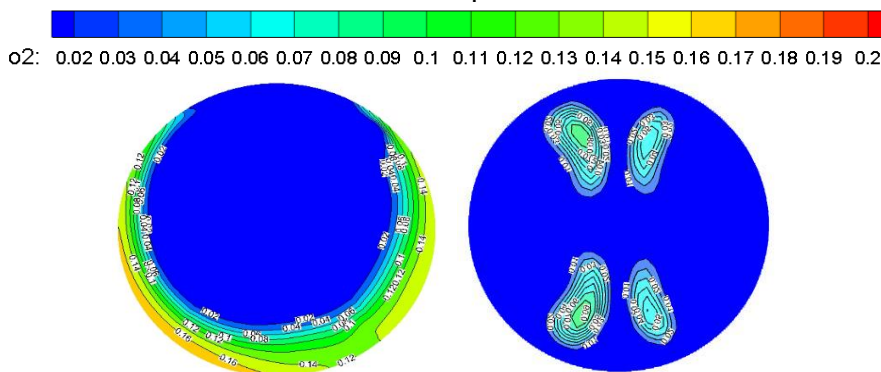


Fig. 4 Distribution diagram of oxygen content in the exit section of the afterburner

Fig. 4 shows the distribution of oxygen content at the outlet section of the afterburner. It can be seen from the figure that when the air is intake on one side, the oxygen content near the upper wall of the outlet section of the afterburner is almost 0, while the oxygen content near the lower wall is high, up to 0.16; When the air enters the air on both sides, the oxygen content in most areas of the outlet section of the afterburner is very low, almost 0. Only the oxygen content in some areas is slightly higher, and the highest is only 0.07. Compared with the one side air inlet mode, the average oxygen content at the outlet section of the afterburner is much lower.

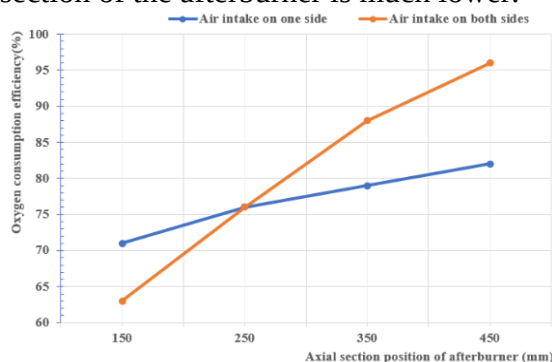


Fig. 5 Oxygen consumption efficiency curves of different cross sections

Fig 5 is a graph of the average value of oxygen consumption efficiency of the cross section of the afterburner at different axial positions. As the axial position of the afterburner moves toward the

outlet, the oxygen consumption efficiency of the two air intake methods gradually increases. However, as the axial position increases, the oxygen consumption efficiency of the intake air on both sides increases faster than that of the one side intake. It can be seen that when the air is intake on both sides, the combustion in the afterburner is relatively sufficient and the gas combustion efficiency is higher.

5.2 Air inlet Angle influence analysis

Air enters from the side of the afterburner, and its incidence angle affects mixing combustion in the afterburner. Under the condition of a certain air flow, the greater the angle of incidence, the stronger the ability of the air to penetrate the gas flow in the afterburner, and the residence time in the afterburner is longer. The following is verified and analyzed by numerical simulation.

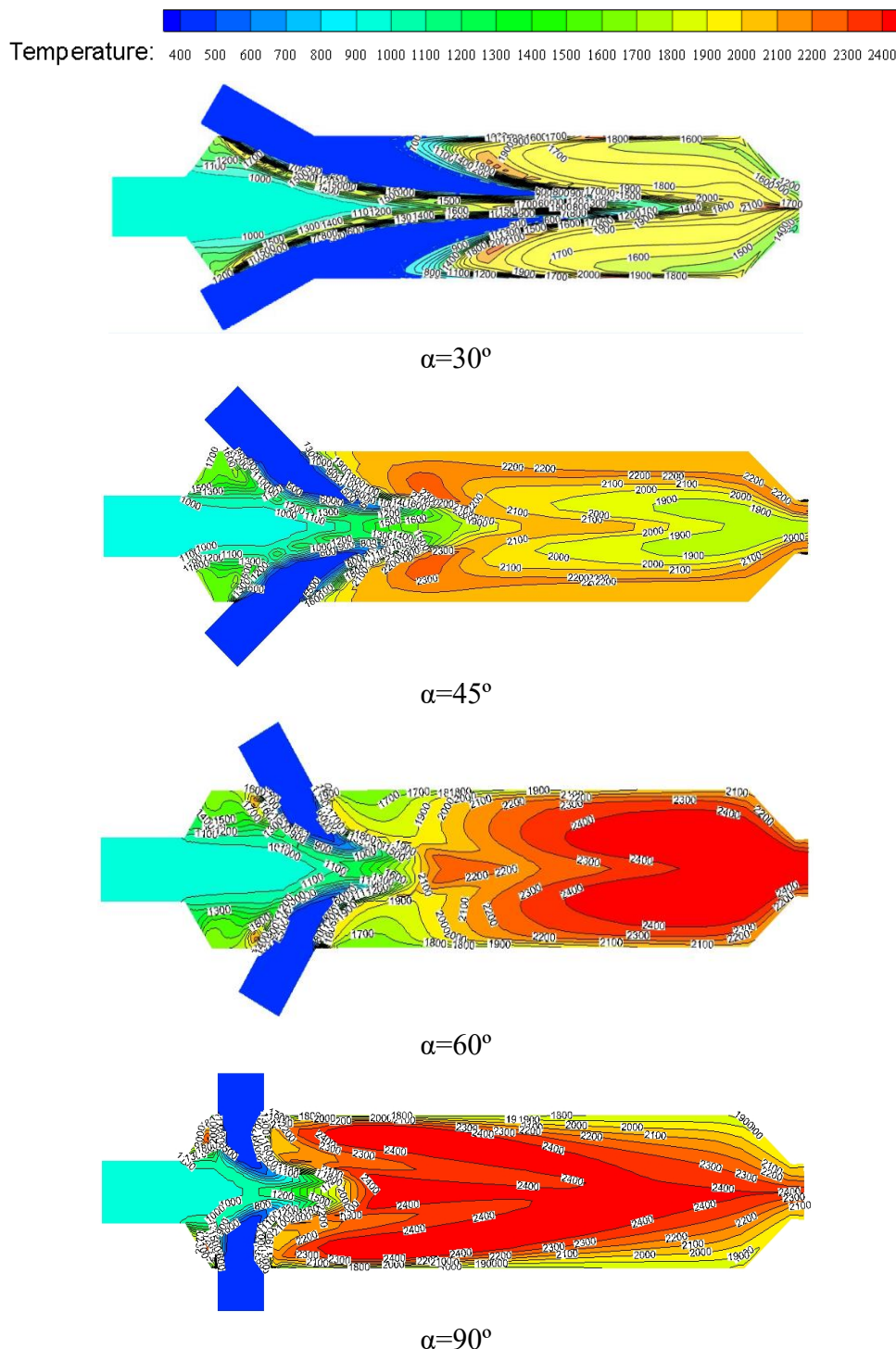


Fig. 6 Temperature distribution of afterburner at different intake angles

The influence of air intake angle on the combustion performance of the afterburner is shown in Figure 3. There are four working conditions set in the figure, and the intake angle is 90° , 60° , 45° and 30° respectively. When the incident angle is 90° and 60° , a high temperature zone is formed near the air inlet and the tail of the afterburner. The temperature of most of the surface of the afterburner is greater than 1900K, and the highest temperature reaches 2400K; The incident angle is 60° and 45° , the temperature in most areas is lower than 1900K.

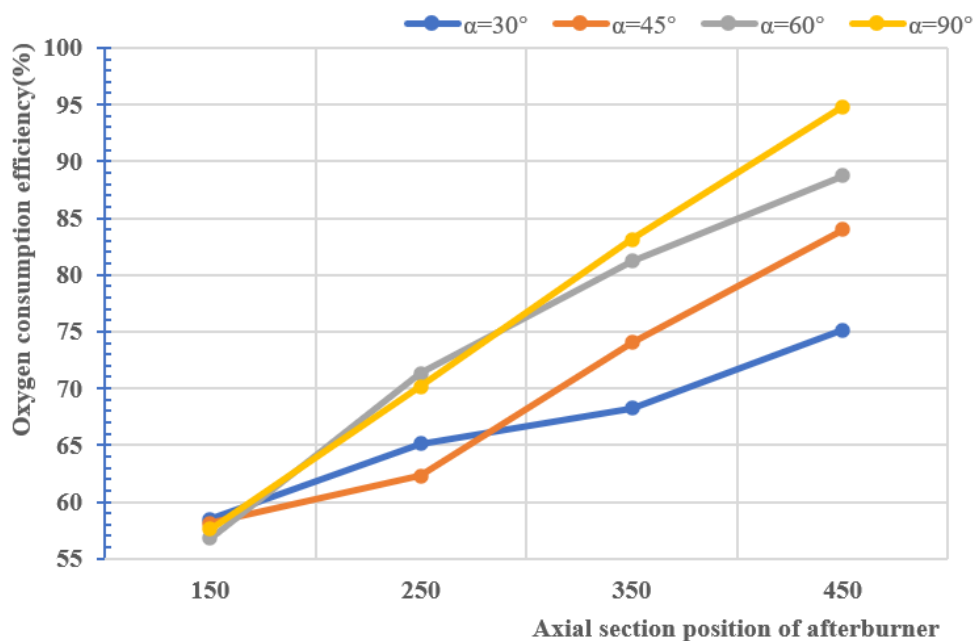


Fig. 7 Oxygen consumption efficiency at different air incident angles

Fig. 7 is the distribution curve of oxygen consumption efficiency at different air incidence angles. It can be seen from the figure that when the distance to the air inlet is close, the oxygen consumption at different air incidence angles is not much different, and they are all below 60%. As the axial position of the afterburner moves toward the outlet, the oxygen consumption efficiency increases. When the incident angle is 90° , the outlet of the afterburner reaches 94.83%; When the incident angle is 60° , the oxygen consumption efficiency at the outlet of the afterburner reaches about 89%; At 45° and 30° , the oxygen consumption efficiency is 84.01% and 75.12%, respectively. Therefore the air incidence angle has a greater impact on the combustion efficiency of the engine, when the incidence angle is 90° , the engine performance is ideal.

5.3 Analysis of the influence of air intake position

The effect of air intake position on the combustion performance of the afterburner is shown in the fig 8. The paper sets four working conditions, namely $L/D=1.0$, 1.3, 1.5, 1.8, where L is the distance between the air intake and the head of the afterburner, and D is the diameter of the afterburner. It can be seen from the figure that when $L/D=1.0$, 1.3, 1.5, the temperature of most areas inside the afterburner is higher than 1900K, and the temperature at the rear of the afterburner is higher than 2100K; When $L/D=1.8$, there is only a local high temperature zone at the air inlet, and the temperature in other areas is lower than 1800K, and most of the head of the afterburner is not used, it is filled with primary gas, and there is no mixing combustion.

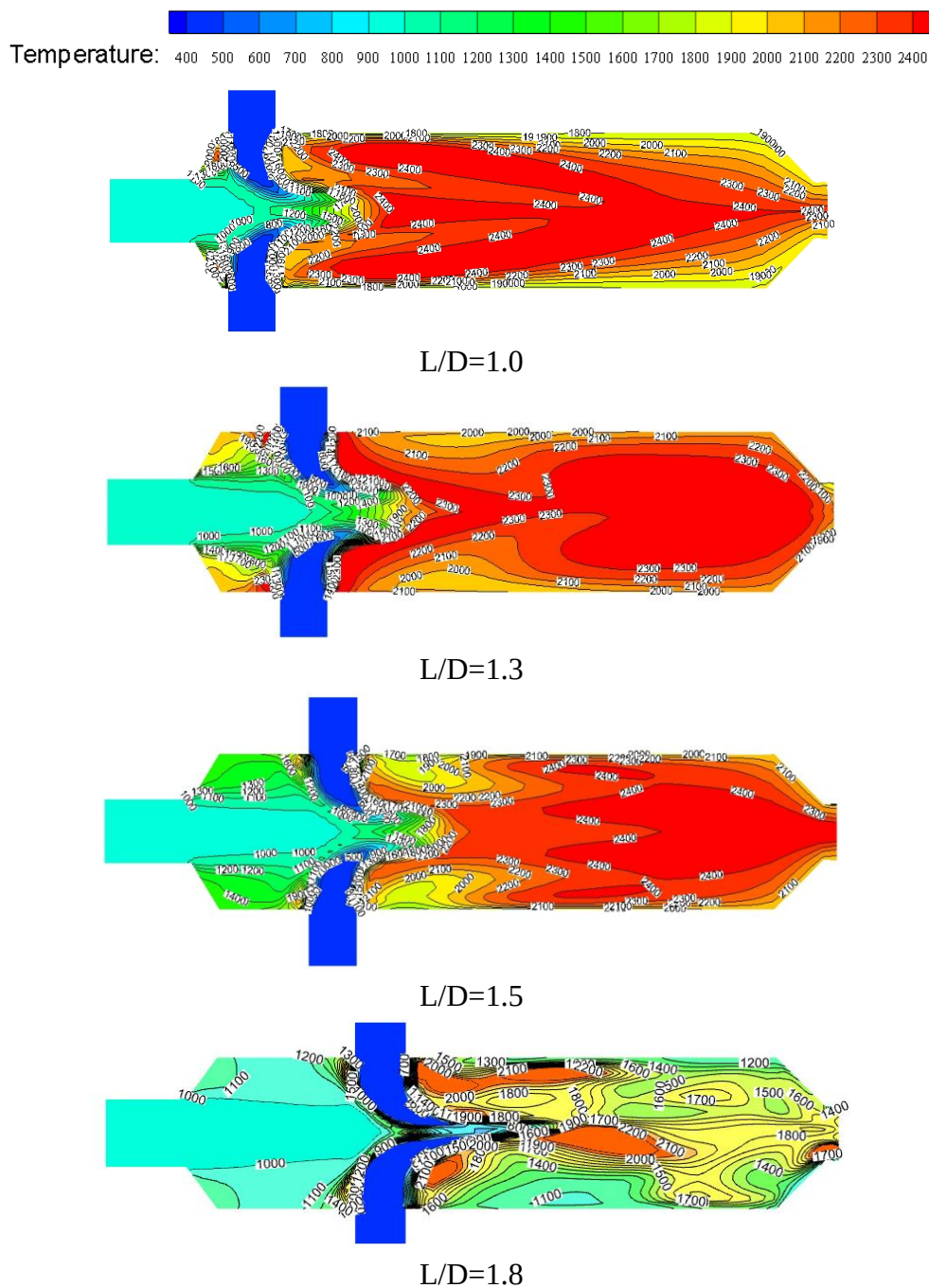


Fig. 8 Temperature distribution of afterburner at different intake positions

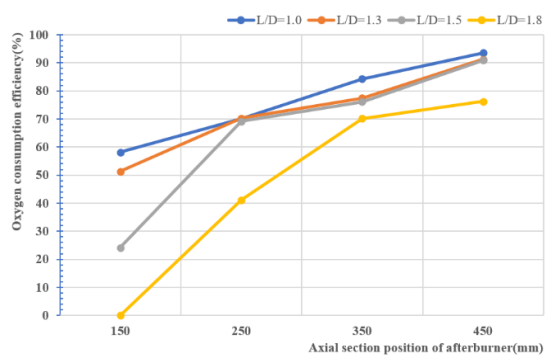


Fig. 9 Oxygen consumption efficiency of different cross sections at different intake positions

Fig 9 shows the axial oxygen consumption efficiency diagram of the afterburner at different intake positions. It can be seen from the figure that when the air intake position is $L/D=1.0$, 1.3 and 1.5 , the average temperature of the outlet section of the afterburner is about 2200K , and the oxygen consumption efficiency is also above 90% , when $L/D=1.8$, the average temperature of the outlet section is only about 1800K , and the oxygen consumption efficiency is only 76.25% . This is because the air intake position is too close to the outlet of the afterburner, and the residence time of gas and air in the afterburner is too short, and they are ejected from the nozzle before they are completely mixed, resulting in insufficient combustion and low temperature. Therefore, when the air intake position is selected as $L/D=1.0\sim 1.5$, the combustion efficiency is higher, and the engine efficiency is higher.

6. Conclusion

The research results show that the air intake is on both sides, the air incidence angle is greater than 60° , and the ratio of the distance between the air inlet and the head of the afterburner to the diameter is $L/D=1.0\sim 1.5$, the temperature distribution is ideal and the engine performance is higher.

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