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Research on Effect of Pollution Gas Components Based on Computational Simulation and Computational Fluid Dynamics Technology on Supersonic Combustion

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Based on computational simulation and computational fluid dynamics (CFD), this paper analyzes and compares the effects of incoming flow with clean air and air containing CO_2/H_2O pollution components on the performance of supersonic combustion of hydrogen fuel and ethylene fuel in the combustor through simulation and calculation. The research conclusion shows that the pressure change in the combustor obtained by the numerical simulation results and the theoretical calculation result are basically the same, indicating that both can distinguish the effect of pollution components on the performance of supersonic combustion. For hydrogen fuel, numerical simulation and calculation results show that the monomer and mixed pollution components have a strong inhibiting effect on the increase of pressure in the combustor, and the decline of pressure is nonlinear. Besides, the presence of pollutants can change the operating model in the combustor. For ethylene fuel, pollutants can lead to a decrease in the mass fraction of the chemical reaction product—H_2O. Both hydrogen fuel and ethylene fuel will lead to a decrease in the temperature in the combustor and a reduction in combustion efficiency.

1. Introduction

When conducting scramjet engine performance test, the current practice is to obtain high-enthalpy test gas by combustion heating. In the course of hypersonic speed ground propulsion through suction method, it is inevitable that there will be a small amount of H_2O, NO, C_xH_y and other pollution gas in suction air. The above pollution gas will have an adverse effect on the operation of the engine, resulting in a significant difference between the test result and the actual work result of the scramjet engine, which is of great practical significance to evaluate the effect of pollution gas on the performance of engine (Heynderickx et al, 2001; Oprins and Heynderickx, 2003; Nejma et al, 2008; Yin and Gang, 2006; Cecere et al, 2011; Tahsini and Mousavi, 2015; Bednas et al, 2010). CFD technology is an important method to study the working principle of scramjet engine. CFD's powerful numerical calculation ability can carry out key analysis work such as data preprocessing and flow field diagnosis of engine performance test. At present, CFD technology has been widely used in fluid dynamics, heat and mass transfer, multiphase flow system and other fields while there are few numerical analysis of ethylene two-dimensional combustion flow field by CFD technology (Han et al, 2004; Yu et al, 2011; Stefanidis et al, 2006; Stefanidis, And and Marin, 2006; Ladeinde, 2015; Kamel et al, 2013; Bricalli, Brown and Boyce, 2014; Candler et al, 2017).
Based on computational simulation and CFD, this paper analyzes and compares the effects of incoming flow with clean air and air containing CO_2/H_2O pollution components on the performance of supersonic combustion of hydrogen fuel and ethylene fuel in the combustor through simulation and calculation.

2. Calculation Model and Method

2.1 Calculation model

Figure 1 shows the model of the combustor of scramjet engine. Injector-1 and Injector-2 are the injection positions of hydrogen and ethylene respectively. The two-dimensional and three-dimensional numerical

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simulations of combustion flow field are carried out on the model to establish a structured grid that is conducted on localized encryption processing.

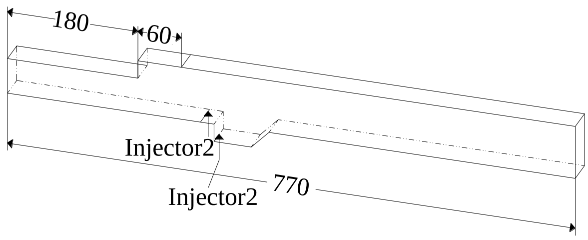


Figure 1: Structural diagram of combustor

2.2 Calculation method

The governing equations are compressible Reynolds equation and component equation. The viscous flux is calculated by Gauss theorem and the factor of variable specific heat of working medium is taken into account. The total incoming flow pressure of the combustor inlet, static pressure and total temperature value are set and the combustor outlet is set as the initial atmospheric pressure. Combustor walls are assumed to be adiabatic and slip-free.

Equivalent gas-oil ratio of hydrogen fuel and ethylene fuel is respectively Φ=0.42 and Φ=0.57. The effect of pollutants on the performance of combustor of scramjet engine is studied when pollutants become H_2O and CO_2.

Table 1 shows the parameters of incoming clean air and polluted air to the combustor.

Table 1: Computing the state of inflow with clean air and polluted air

Gas oil ratio	Combustor inlet condition parameter			
	Inflow pollution level	Pressure/KPa	Temperature/K	Mach number
Hydrogen	Clean air	748	788	2.0
	7.5%H_2O	755	902	2.0
	7.5%CO_2	759	804	2.0
	17.5%H_2O	756	770	2.0
	7.5%H_2O+7.5%CO_2	791	793	2.0
Ethylene	Clean air	757	805	2.0
	7.5%H_2O	786	795	2.0
	7.5%H_2O+7.5%CO_2	769	787	2.0

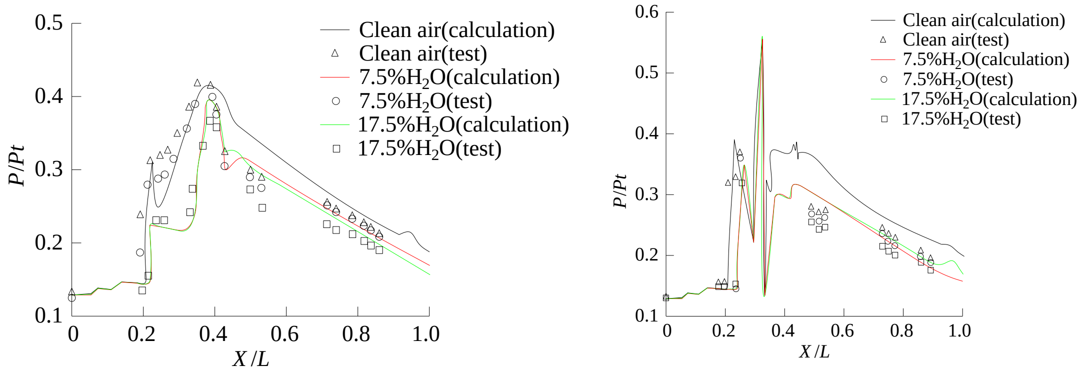
Equivalent gas-oil ratio of hydrogen fuel and ethylene fuel is respectively Φ=0.42 and Φ=0.57. The effect of pollutants on the performance of combustor of scramjet engine is studied when pollutants become H_2O and CO_2.

3. Test Results and Analysis

3.1 Analysis of combustor test results based on hydrogen fuel

Figure 2 shows the changes in the wall pressure of the combustor of scramjet engine under the influence of ordinary air and air polluted by H_2O when taking hydrogen as fuel. It can be seen from the figure that the calculated value of wall of the combustor is almost the same as the experimental value. The calculated value and the experimental value show that the change trend of the pressure in the combustor is the same under different pollution concentrations of H_20. Under the condition of clean air, the calculated and experimental values of the wall pressure are the maximum. With the increase in concentration of H_2O in the air, the calculated value and experimental value of the wall pressure decrease gradually, indicating that the presence of H_2O has an inhibiting effect on the pressure in the combustor. It can also be seen from the figure that the inhibiting effect of H_2O on the increase in pressure in the combustor is non-linear.

Figure 3 shows the changes in the wall pressure of the combustor of scramjet engine under the influence of ordinary air and air polluted by H_2O and CO_2. It can be seen from the figure that the wall pressure of the combustor is significantly smaller than that of clean air when the incoming flow is pollution gas containing H_2O and CO_2 as a whole. When the pollutant is CO_2, the wall pressure in the combustor is smaller than that of the pollution gas of H_2O and the average wall pressure decreases by about 10% and 21% respectively when both are 7.5% compared with that of clean air, indicating that CO_2 has a more severe effect on the performance of the combustor. When the pollutants are mixture of H_2O and CO_2, wall pressure further reduces compared to that of CO_2.



(a) Upper wall surface

(b) Inferior wall surface

Figure 2: Pressure distribution of hydrogen fuel in wall surface of the combustor with clean air and polluted air containing H_2O

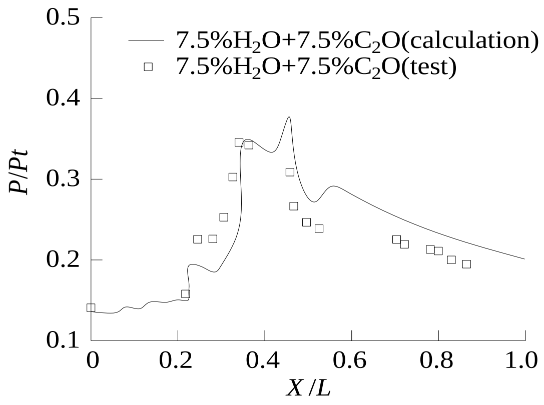


Figure 3: Pressure distribution of hydrogen fuel in wall surface of the combustor with clean air and polluted air containing H_2O and CO_2

Figure 4 shows the temperature curve of walls of the combustor in different flow components. As can be seen from the figure, the overall temperature and temperature increase of the incoming flow components are clean air, 7.5% CO_2, H_2O, 17.5% mixed gas of CO_2 and H_2O, and 7.5% mixed gas in descending order. It shows that the presence of CO_2 and H_2O has an inhibiting effect on temperature rise and combustion efficiency in the combustor. At the same time, CO2 and H2O can absorb more heat than clean air under the same heat release because the specific heat capacity of CO_2 and H_2O is higher. As can be seen from the figure, the combustion efficiency of 7.5% CO_2, H_2O, 17.5% mixed gas of CO_2 and H_2O, and 7.5% mixed gas in the combustor decreases by 6.5%, 9.9%, 12.1% and 13.1% compare with that of clean air.

Figure 5 shows the curves of the mass-weighted Mach numbers of walls of the combustor under different incoming flow components. It can be seen from the figure that the Mach number in the combustor with the clean air is the smallest and the sub-factor combustion state appears in the output end. It also proves that the combustion efficiency is highest in the clean air. In the presence of pollutants, the Mach number is 7.5% H_2O, CO_2, 17.5% H_2O and 17.5% mixed gas in ascending order, when the combustor in the supersonic combustion state.

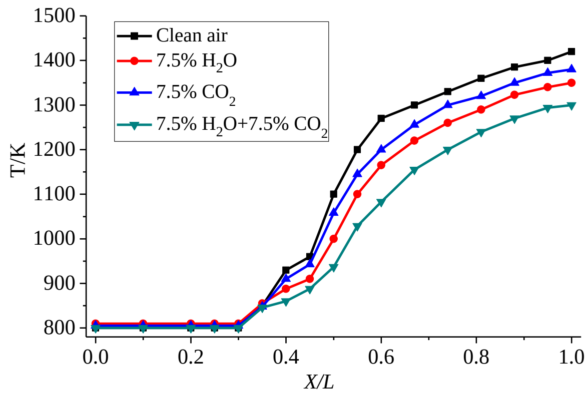


Figure 4: The temperature correlation curve of wall surface of the combustor along flow direction

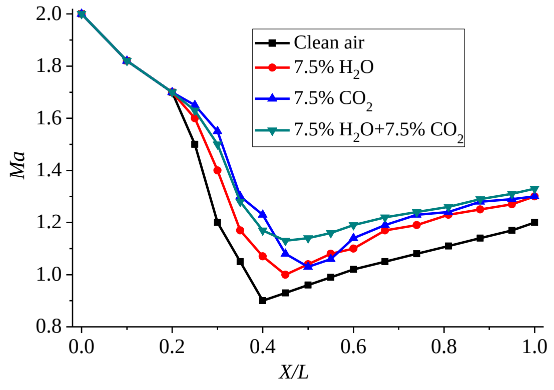


Figure 5: The Mach number correlation curve of wall surface of the combustor along flow direction

3.2 Analysis of combustor test results based on ethylene fuel

Figure 6 shows the changes in the wall pressure of the combustor of scramjet engine under the influence of ordinary air and air polluted by H_2O when taking hydrogen as a fuel. It can be seen from the figure that the pressure changes on the upper wall and the lower wall of the combustor are the same, and the pressure of the wall of the combustor is clean air, 7.5% H_2O and 7.5% mixed gas in descending order. Compared with the clean air, the pressure of the latter two decreases by 6.32% and 8.03% respectively, indicating that the presence of ethylene as fuel also has an inhibiting effect on the pressure in the combustor.

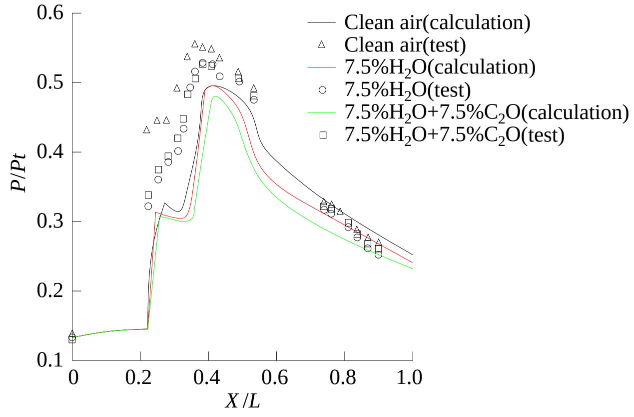


Figure 6: Pressure distribution of ethylene fuel in wall surface of the combustor with clean air and polluted air containing H_2O and CO_2

Combustion of ethylene will generate H_2O. The mass fraction of H_2O reflects the speed of chemical reaction in the combustor. Figure 7 shows the mass fraction curve of H_2O of sections of the combustor in different incoming flow components. It can be seen from the figure that H_2O generated by the mixed pollutants is the smallest for the larger molar mass and specific heat capacity of CO_2. A smaller increase in the temperature in the combustor results in a decrease in combustion efficiency and pressure so that ethylene can't be completely cracked, resulting in that the mass of generated H_2O is small and the reaction can't be fully carried out.

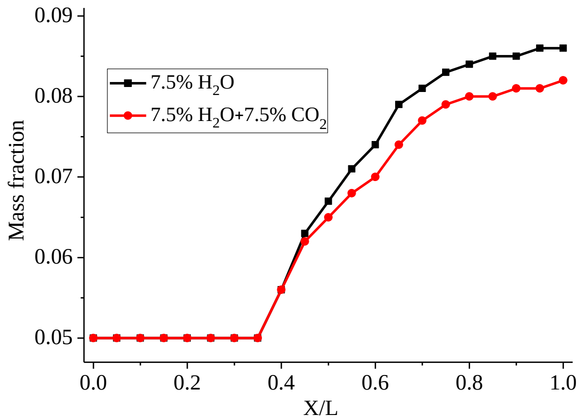


Figure 7: The H_2O mass fraction curve of wall surface of the combustor along flow direction

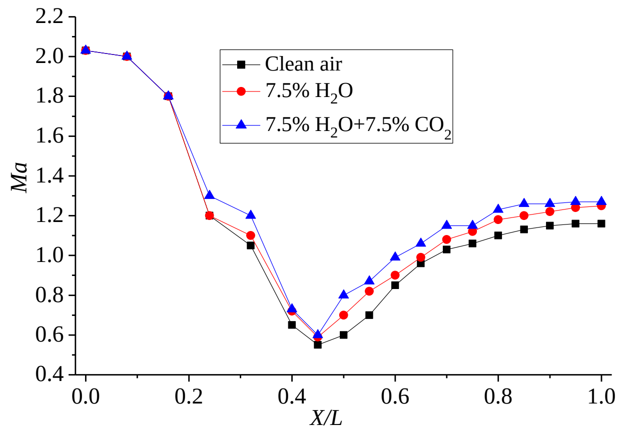


Figure 8: The Mach number correlation curve of hydrogen fuel in wall surface of the combustor along flow direction

Figure 8 shows the curve of the mass-weighted Mach number of walls of the combustor under three different incoming flows. The Mach numbers are mixed gas, pollution of gas 7.5% H_20 and clean air in descending order. Affected by the heat released by the combustion, the Mach number at the outlet section decreases to the sonic velocity and the subsonic state appears in the combustor.

4. Conclusions

Based on the computational simulation and CFD, this paper analyzes and compares the effects of incoming flow with clean air and air containing CO_2/H_2O pollution components on the performance of supersonic combustion of hydrogen fuel and ethylene fuel in the combustor through simulation and calculation. The conclusions are as follows:

(1) The change trend of the pressure in the combustor obtained by the numerical simulation and the theoretical calculation is basically the same, which shows that both can distinguish the effect of the pollution components on the performance of supersonic combustion.

(2) For hydrogen fuel, numerical simulation and calculation results show that the monomer and mixed pollution components have a strong inhibiting effect on the increase of pressure in the combustor, and the decline of pressure is nonlinear. Besides, the presence of pollutants can change the operating model in the combustor.
(3) Both hydrogen fuel and ethylene fuel will lead to a decrease in the temperature in the combustor and a reduction in combustion efficiency. For ethylene fuel, pollutants can lead to a decrease in the mass fraction of the chemical reaction product— H_2O.

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