HiSST: International Conference on High-Speed Vehicle Science Technology

26–29 November 2018, Moscow, Russia

Large Eddy Simulation of Combustion in Full-scale Kerosene Fueled RBCC Engine

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Abstract

In this paper, Large Eddy Simulation (LES) of combustion adopting Partially Stirred Reactor (PaSR) combustion model is performed for a full-scale kerosene fueled RBCC engine. In order to investigate the applicability and accuracy of the seven different kerosene global reaction mechanisms in RBCC, the ignition delay time, distribution of temperature and species are investigated based on operating conditions of RBCC. A 10-Step global reaction (C11H21) is proved to be the reasonable reactions. The combustion characteristics of two RBCC configurations (different strut locations) operating at scramjet mode are investigated by using compressible LES solver, which is implemented in an Open source Field Operation and Manipulation (OpenFOAM). The code is validated against experimental wall pressure, the results are satisfactory. Then, the wall pressure distribution, heat release, area-average Mach number, combustion efficiency and flame structure of the two configurations are studied.

Keywords: *Large Eddy Simulation, RBCC, Kerosene, Supersonic combustion*

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Nomenclature

$\langle \overline{Ma} | A_{yz} \rangle$ –The average Mach number at different cross section
Ma – Mach number
P – Statics pressure
T – Temperature

1. Introduction

Many countries around the world are interested in the propulsion systems of aerospace and hypersonic vehicles. The rocket-based combined cycle (RBCC) engine takes advantage of synergies between conventional liquid rockets and air-breathing engines [1]. RBCC is one of the most promising propulsion systems for SSTO and TSTO, with satisfactory performance across the full range of ballistic trajectories. It is most likely to be used in the next generation of hypersonic RLVs and fast-response aerospace vehicles [2, 3].

There are still some problems to be solved before its large scale engineering applications, such as the mixing, combustion etc. Although experimental tests have been extensively conducted, little insight is provided for the transient internal flow due to that the difficulties in measuring the high-speed complex unsteady flow field restrict the available experimental data. Hence, CFD is of great method for a close examination of the flow physics in combustors [4].

Among the challenges, one of the key problems to be solved in the RBCC combustor is to realize efficient combustion to improve engine performance. Therefore, flame holders are required to maintain a stable flame so that the combustor can operate over wide range conditions [5]. Strut is usually used as an efficient fuel injector and flame holder in the supersonic combustor to obtain a stable flame [5].

In this study, the ignition delay time, distribution of temperature and species of the seven different kerosene global reaction mechanisms are calculated based on operating conditions of RBCC. The combustion characteristics of two RBCC configurations (different strut locations) operating at scramjet mode are investigated by using Large Eddy Simulation. The combustion efficient, area-average Ma and heat release are analysed.

2. Computational configuration and inflow conditions

In this paper, the simulated flight Mach number is 5.5. This number is associated with the scramjet mode. The air inflow is preheated by an alcohol-fueled vitiation heater at a mass flow rate of 4 kg/s. Table 1 shows the simulated air inflow conditions. A schematic of the model RBCC engine configuration used in the present study is shown in Fig. 1. The combustor with a constant width of 145 mm included an isolator and two combustor segments named First combustor (2 degree) and Second combustor (1.5 degree) respectively. H=60mm, W=145mm and L=1500mm. L1=120mm for Case-1 and L1=250mm for Case-2.

Table 1. Flight conditions

Ma_{flight}	Total Temperature (K)	Mass Flow Rate (kg/s)	$Ma_{isolator}$
5.5	1300	4	2.4

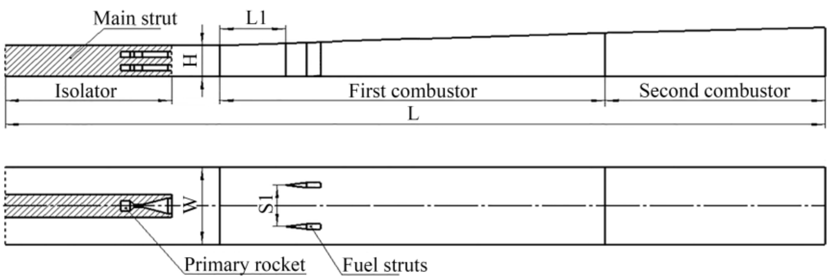

Fig 1. Schematic of the model engine configuration

3. Results and Validation

In rder to investigate the applicability and accuracy of the seven different kerosene global reaction mechanisms in RBCC, the ignition delay time, distribution of temperature and species are calculated based on operating conditions of RBCC, include 10-steps (C10H20) [6], 10-steps (C11H21) [7], 26-steps (C12H23) [8], 13-steps (C12H24) [9], 2-steps (C10H20) [10], 3-steps (C12H23) [11] and 12-steps (C10H22) [12].

Fig. 2 shows the ignition delay time of the seven global reactions. Fig. 3 shows the temperature and main species mole fraction under different equivalence ratios. The results show that the 10-Step global reaction (C11H21) is the reasonable reactions for simulating RBCC engine.

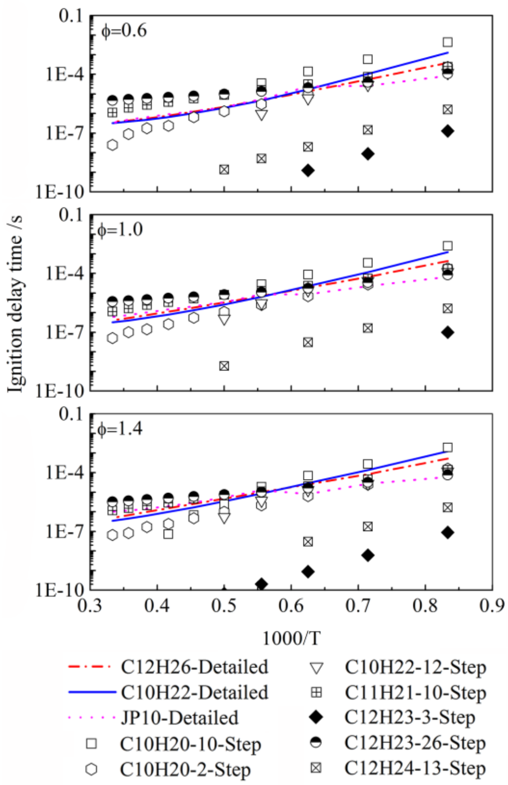

Fig 2. Ignition delay time

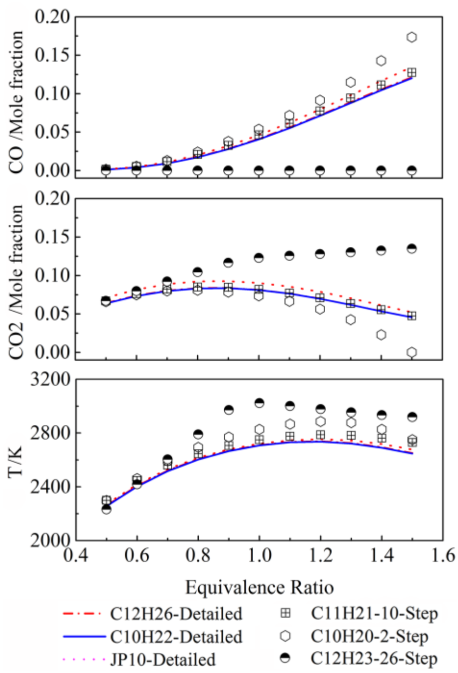

Fig 3. Temperature and main species mole fraction under different equivalence ratios

The solver is implemented in an Open Source Field Operation and Manipulation (OpenFOAM). The Partially Stirred Reactor (PaSR) combustion model and 10-Step global reaction (C11H21) is employed for the numerical analysis of full-scale RBCC engine, which has been experimentally tested in a direct connect supersonic combustion test platform assembled in Science and Technology on Combustion, Internal Flow and Thermal-structure Laboratory (Northwestern Polytechnical University, Xi'an, China). The grid contains 15 million structured cells. Results for the wall pressure distribution are validated using experimental data, as shown in Fig. 4. Fig. 5 shows the flame structures of simulation and experiment for case-1. The results show that the numerical simulation method can reasonably simulate the combustion process in RBCC engine.

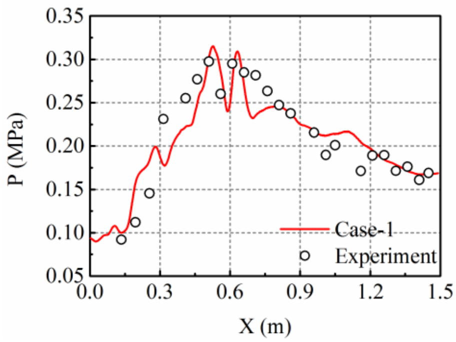

Fig 4. LES pressure validation against experimental data for Case-1

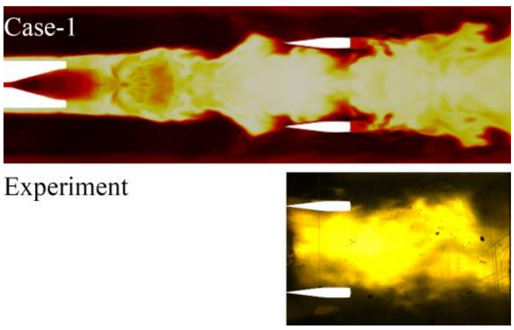

Fig 5. Flame structures of simulation and experiment for case-1

Fig. 6 shows the comparison between the pressure of the wall for Case-1 and Case-2. It can be seen that the pressure peak and the shock train are moved back by moving the fuel struts back. Fig. 7 shows the area-average Mach number calculated by follow formula (1). As can be seen that the combustion near the struts is subsonic combustion, and the Mach number at the struts is the lowest.

$$\langle \overline{Ma} | A_{yz} \rangle = \iint_A Madydz \,/ \iint_A dydz$$

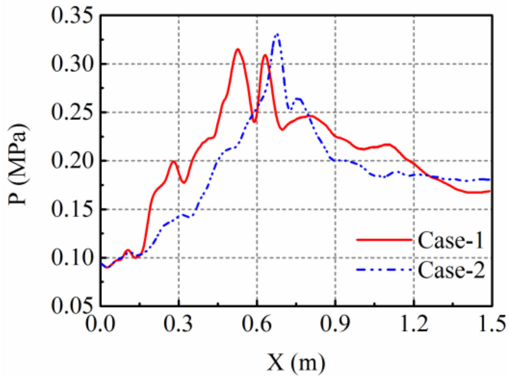

Fig 6. The results of wall pressure for Case-1 and Case-2

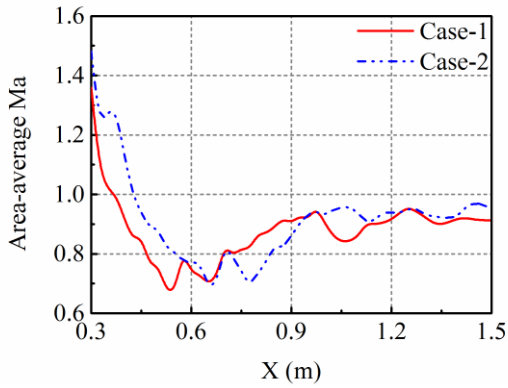

Fig 7. The area-average Ma at different cross section for Case-1 and Case-2

Fig. 8 shows the curves of heat release along the X direction at different cross section of Case 1 and Case 2. It can be seen that there are two exothermic peaks in both cases. At the same time, the second peak of Case 1 is relatively large, because the fuel strut of Case 1 is close to the rocket, which enables the rocket hot gas to improve kerosene combustion well. Fig. 9 shows combustion efficiency curves along the flow direction, as can be seen that both Cases can achieve full combustion within a very short distance (about 0.15m).

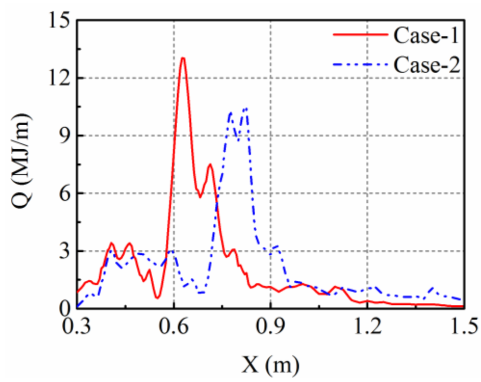

Fig 8. The heat release at different cross section for Case-1 and Case-2

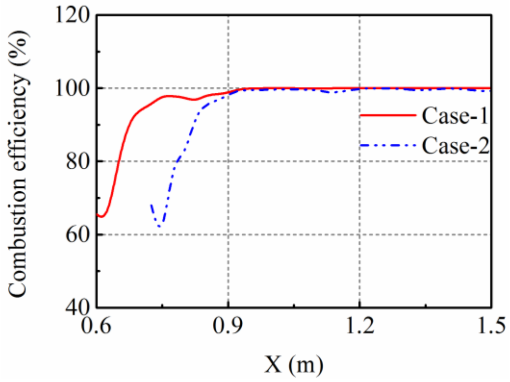

Fig 9. The combustion efficient for Case-1 and Case-2

Fig. 10 shows the OH distribution of Case-1 and Case-2. It can be seen that the heat release of RBCC engine mainly focuses near the struts, because the velocities at the struts are low, and the shock wave can promote the mixing and combustion.

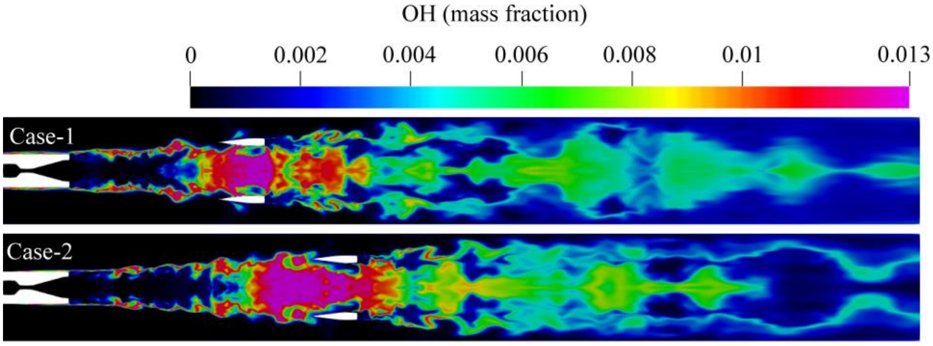

Fig 10. The OH distribution of Case-1 and Case-2

4. Conclusion

Seven different global reaction mechanisms of kerosene are calculated and compared, and it is found that the 10-Step global reaction (C11H21) is the reasonable reactions for simulating RBCC engine. Two RBCC engines with different configurations (different strut locations) are investigated in combination with large eddy simulation and the 10-Step global reaction (C11H21) mechanism. The results show that the numerical simulation method can simulate the combustion process reasonably and accurately. By analysing the pressure curve of the wall and the area-average Mach number that the pressure at the fuel struts is the highest and the Mach number is the lowest. There are two peaks of heat release along the direction of the flow direction. The first is the heat release of the rocket hot gas, and the second is the intense combustion of kerosene at the end of the fuel struts. The curves of combustion efficiency are shown that kerosene achieve full combustion within a very short distance (about 0.15m).

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