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Numerical study on effect of air throttling on combustion mode formation and transition in a dual-mode scramjet combustor

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ABSTRACT

Air throttling has a great effect on combustion mode formation and transition in a dual-mode scramjet combustor. An unsteady CFD method was used to investigate this effect in the present paper. The simulation was carried out under the inflow conditions of Mach number of 2.0, static temperature of 656.5 K and static pressure of 0.125 MPa respectively. The location of air throttling was 575 mm downstream the combustor entrance. Our results indicated that the combustion mode could change from supersonic combustion to subsonic combustion with throttling air injected into the combustor. Without air throttling, the combustion flame was extinguished near the down wall of the combustor, which was corresponding to the supersonic combustion mode. With air throttling, the flame was stabilized near the down wall of the combustor, which was corresponding to the subsonic combustion mode. The mode transition was mainly effected by two parameters: the mass flux of throttling air and the throttling off time. The more mass flux a higher wall pressure was, the transition was easy, but too small mass flux could not cause the mode transition and too large mass flux might cause unstart of the inlet. The shorter the air throttling off time the lower combustion heat release was, but an insufficient heat release could not maintain the existence of the shock train, combustion mode translation would not realized by air throttling.

1. Introduction

Dual-mode scramjet has a good thrust performance in the wide range of flight Mach number. When the flight Mach number was 3∼6, the combustion mode should be subsonic combustion, which was called ramjet. When the flight Mach number was larger than 6, the combustion mode should be supersonic combustion, which was called scramjet.

Mode transition in a hydrogen-fueled Scramjet Combustor was investigated at the Avery Propulsion Research Laboratory of the Johns Hopkins University Applied Physics Laboratory by Sullins et al. [1]. When increased the total temperature and kept the fuel/air equivalence ratio constant, the combustor transitioned from a dual mode ramjet with a pre-combustion shock system creating subsonic flow at the injection plane, to a scramjet with no pre-combustion shock system [1]. A H_2-fueled scramjet was tested under Mach 4 to Mach 8 fight conditions by Mitani et al. [2], rate processes governing combustion in scramjet engines were investigated using the gas sampling, and the wall pressure, and the heating rate data were also obtained. Their data suggested that switching from the reaction-controlled to the mixing-controlled combustion with increasing fuel rate in the Ma6 tests. Direct-connect experiments and numerical simulation investigations on combustion mode transition were studied by Xiao et al. [3]. A quantitative distinguishing criterion of combustion mode was constructed by using wall pressure ratio of isolator outlet and inlet. The combustor worked in scram-mode when the pressure ratio was lower than 1.5, while it was in ram-mode when the pressure ratio was larger than 1.5. The effect of equivalence ratio and fuel distribution on combustion performance of the dual-mode scramjet engine was investigated by Tian et al. [4]. When the combustion mode was subsonic combustion, the position of thermal throat was at the fixed location. The dual-mode operation of a scramjet combustor was studied experimentally by Kanda et al. [5] in a Mach 2.4 wind tunnel. Two subsonic combustion and a supersonic combustion modes were obtained. The down-stream combustion ramjet mode was attained, when fuel was injected in the divergent section. In the mode, air was decelerated in the divergent section with consequent subsonic combustion. The subsonic combustion gas was choked at the exit of the combustor with no wall throat. The downstream high pressure did not affect the airflow

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Nomenclature

Ma	Mach number
P	Wall pressure of combustor
t	Time after ignition starts
t0	Time when cold flow starts
t1	Time when air throttling starts
t2	Time when ignition and fuel starts
t3	Time when ignition was turned off
t4	Time when air throttling was turned off
x	Distance from combustor entrance
T	Mass averaged temperature
Isp	Specific impulse
F	Thrust
$\dot{m}$	Mass flux
$\vec{V}$	Velocity
$\vec{n}$	Unit normal vector
g	Acceleration of gravity
S	Area

Subscript

i	Inlet of isolator
e	Outlet of combustor
air	Inflow air
fuel	Fuel injected

condition in the isolator. Thrust was smaller, but the maximum pressure was lower in the downstream-combustion ramjet mode than those in the ordinary ramjet mode. The classification of combustion modes, as well as the method and mechanism of mode transition, were introduced in detail by Zhang et al. [6]. A series of research on combustion performance and combustion mode transitions were conducted by Chang et al. [7–14] using the hydrogen fueled [7–9] or kerosene fueled [10–14] scramjet combustor. The flame transition characteristics and dynamics characteristic at different combustion modes, the effect of combustion modes on the performance of scramjet engine, and the analysis of combustion mode and operating route for scramjet engine were studied.

From the above references, we found the combustion mode was transformed always by changing the inflow condition or fuel injected condition. The technology of air throttling used for ignition and flame stabilization has already been studied by many researchers [15–18], but few published papers investigated the combustion mode transition being controlled by air throttling, which was our main purpose of the present paper. The mechanism of air throttling was introduced as follows: When the flow was established, the throttling air was injected into the combustor, and then a series of oblique shock waves was generated in the combustor due to the increased back pressure caused by the throttling air. The interactions of the shock waves and boundary layer would cause the wall boundary layers to spate, which would enhance the fuel/air mixing. And the pressure and temperature became larger, the velocity became lower. After the air throttling was turned off, stable combustion was achieved in the combustor.

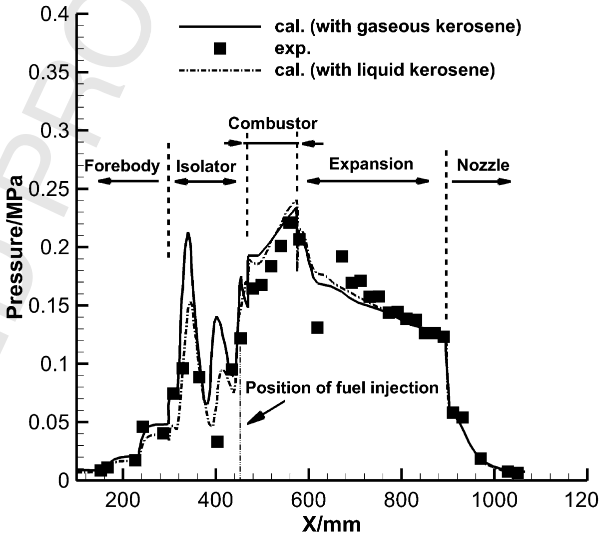

Fig. 1. Comparison of wall pressure between gaseous kerosene, liquid kerosene and experimental results [22].

2. Numerical simulation methods

2.1. Numerical methods

In this study, the in-house CFD code AHL3D was used for computation. The physical and chemical models of the code had already been validated in references [19,20].

For our present simulation, a fully coupled form of species conservation equations and Reynolds averaged Navier–Stokes equations were used as a governing equation set for a chemically reacting supersonic viscous flow. Cell-averaged finite volume techniques were used to discrete the governing equations. *LU-SGS* method was used for solving linearized equations. Third order *MUSCL* interpolation method and *AUSMPW+* scheme were used for inviscid fluxes construction, central difference method was used for viscous fluxes. Kok's modified k–ω TNT two-equation turbulence mode [21] was used for turbulence simulations. The dual-time stepping method was used for unsteady numerical simulation and the time step was 1×10^{-7} s. The kerosene reaction mechanism developed by Le et al. [19], involving 12 elementary reaction steps and 10 reaction species, was used. A structured grid with total number of 250,000 grid points was used in this simulation. The effects of multi-phase had already been considered in our previous work [22], our results indicated that the wall pressure was almost same except for a small difference in combustor, as shown in Fig. 1. Considering the calculating costs, the present calculation did not consider the kerosene atomization process, the variables at the injection are set to be sonic boundary condition with gaseous kerosene injection.

We use two-dimensional numerical simulation to investigate the effect of air throttling on combustion mode formation and transition. However three-dimensional effect cannot be ignored for several reasons [18], such as the corner flow effect, the boundary layer of the side wall and fuel injected methods. Two-dimensional simulation still has great advantages considering the computation efficiency, because the three-dimensional unsteady numerical simulation will cost much time, the three-dimensional grid points of the scramjet combustor in this paper are nearly 21,000,000. Taking 720 CPUs for instance, for three-dimensional grid, only 0.3 ms can be simulated per day, but each case should be calculated 20.0 ms at least, it needs 67 days, which is too long for different case parameter study. The computational efficiency of two-dimensional simulation gives more chances for us to investigate many cases. The two dimensional simulation is still useful for the qualitative understanding of the effect of air throttling on combustion mode formation and transition.

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