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이중모드 스크램제트 엔진에서 연소와 충격파의 상호작용

최정열* · 노진현** · 변종렬**

Combustion/Shock Interactions in a Dual-Mode Scramjet Engine

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ABSTRACT

A high-resolution numerical study is carried out to investigate the transient process of the combustion and the shock-train developments in an ethylene-fueled direct-connect dual-mode scramjet combustor. Air-throttling is then applied at the expansion part of the combustor to provide mass addition to block the flow to subsonic speed, hence to enhance the fuel-air mixing and ignition. Present simulation shows the detailed results for the better understanding of transient processes of the operation regimes in the dual-mode scramjet combustor.

초　록

에틸렌을 연료로하는 직결식 이중모드 스크램제트 연소기에서 연소와 충격파-열 발생 천이 과정에 대한 고해상도 수치 연구를 수행하였다. 연소기의 확산 부에는 질량 유량 공급으로 유효 면적을 줄이고 유속을 아음속으로 낮추어 연료-공기 혼합과 점화를 촉진하기 위하여 air-throttling을 적용하였다. 본 결과는 이중모드 스크램제트 연소기에서 작동 영역의 천이 과정을 잘 이해할 수 있는 상세한 보여주었다.

Key Words: Scramjet(스크램제트), Ethylene(에틸렌), Ignition time delay(점화 지연), CFD(전산유체공학)

1. Introduction

Air-breathing hypersonic propulsion based on supersonic combustion has been studied for more than 50 years, and has proved its potential through the hydrogen-fueled Hyshot and X-43A and hydrocarbon-fueled X-51A and HyFly flight test programs. The use of hydrocarbon fuels makes the scramjet engine much more efficient because of its higher volumetric energy density. Hydrogen, on the other hand, has higher energy per unit mass,

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higher propulsion performance, higher heat cooling capacity, and high flame speed and superior ignition characteristics. Hydrogen engines are considered as a viable propulsion system for space access, whereas hydrocarbon engines mainly used for atmospheric flight.

In the present study the transient process of flow establishment and combustion process is studied for an ethylene-fueled direct-connect dual mode scramjet combustor with air-throttling. This work is an extension of previous work [1] with finer resolution to investigate the detailed flow structures during the transient process.

2. Configuration and Calculation Conditions

Figure 1 shows the direct-connect supersonic flow test facility of consideration.[2] It measured a length of 178.9 cm and consists of a facility nozzle, an isolator, a combustor, and an exhaust nozzle. All the flow conditions are summarized in Table. 1, and more details are found in the previous work.[1]

The computation domain is covered by 2,415×151 grid for main combustor and 300×121grid for cavity region. The grid convergence study has been reported in the previous work [6], but twice the finer resolution in flow direction and 1.5 time finer resolution in transverse direction was used to capture the finer details of the flow structures.

3. Modeling Approaches

The flowfield is assumed to be two-dimensional for computational efficiency offering very fine resolution over the entire system and long operation time to investigate the overall characteristics. The computational code has been used for a supersonic combustor study previously and extended to fifth order accurate scheme using DES model extended from Menter's SST model and detailed chemistry for combustion. A modified version of Singh and Jachimowski's quasiglobal reaction mechanism is used for ethylene-air combustion involving 10 elementary reaction steps and 8 reaction species. It could predict better the equilibrium condition than the global chemistry model by including the intermediate species. Validity of the mechanism is addressed in the previous work [1]. The code has been parallelized by OpenMP for the optimum performance in multi-core SMP machines.

Table 1 Calculation conditons

	Static temperature	Static Pressure	Mach number
Nozzle	1050 K	3.744 atm	0.0
Isolator	560 K	0.328 atm	2.18
Fuel	520 K	0.261 atm	1.66
Air throttling	273 K	1.92 atm	1.0

4. Results and Discussions

The transient simulation begins with the supersonic air flow development by applying the low pressure condition at the right exit. Supersonic extrapolation boundary condition is applied after supersonic flow is established. The sequence of the flow establishment process is plotted in Fig. 2 and 3. Fuel injection time is set to 0.0 ms. Thus, the plots at t=0.0 ms shows the stabilized non-reacting flow field just before the fuel injection. Due to the flow oscillation by the presence of the cavity the flow is not at complete steady state. At 1.5 ms after the fuel injection at both the lower and upper injector fuel is layered along the combustor surface wall. Differently from the case of hydrogen injection studies in the previous work, the fuel neither mixes with air, nor ignites, though there is fluctuation at the surface of the fuel layer. It is consistence with the lower resolution case studies before.

Air-throttling is applied hereafter. 1.5 ms after the air-throttling (3.0 ms after the fuel injection) it is shown the temperature and pressure rise within the combustor. It is considered the blockage of flow by the air-throttling enhances the fuel-air mixing and increase the flow residence time by reducing the flow speed. However, the auto-ignition is not fully established yet, but takes little more time. Plots at t=4.5 ms shows the the auto ignition of the mixture. While the pressure builds up within 1 ms after fuel injection in case of hydrogen injection, the delay is about 3 ms after the air-throttling for ethylene fuel. The pressure build up by the combustion leads to the shock train formation in the isolator section that advances to the exit of the intake nozzle. Then, the air-throttling is deactivated and the exhaust process begins and the situation before the air-throttling is restored. Further details on each instances will be discussed in the following section.

5. Conclustion

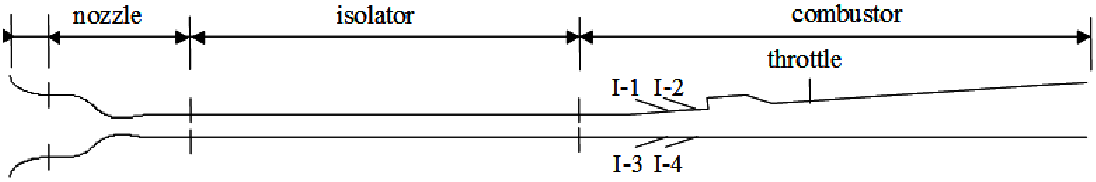

Fig. 1 Schematics of the direct-connect scramjet combustor

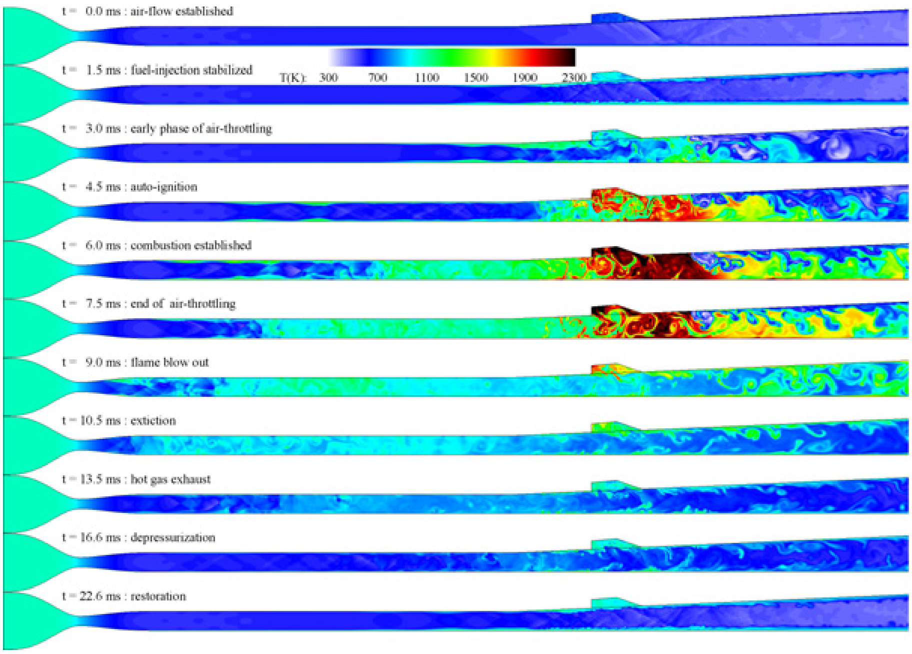

Fig. 2 Transients of temperature distributions

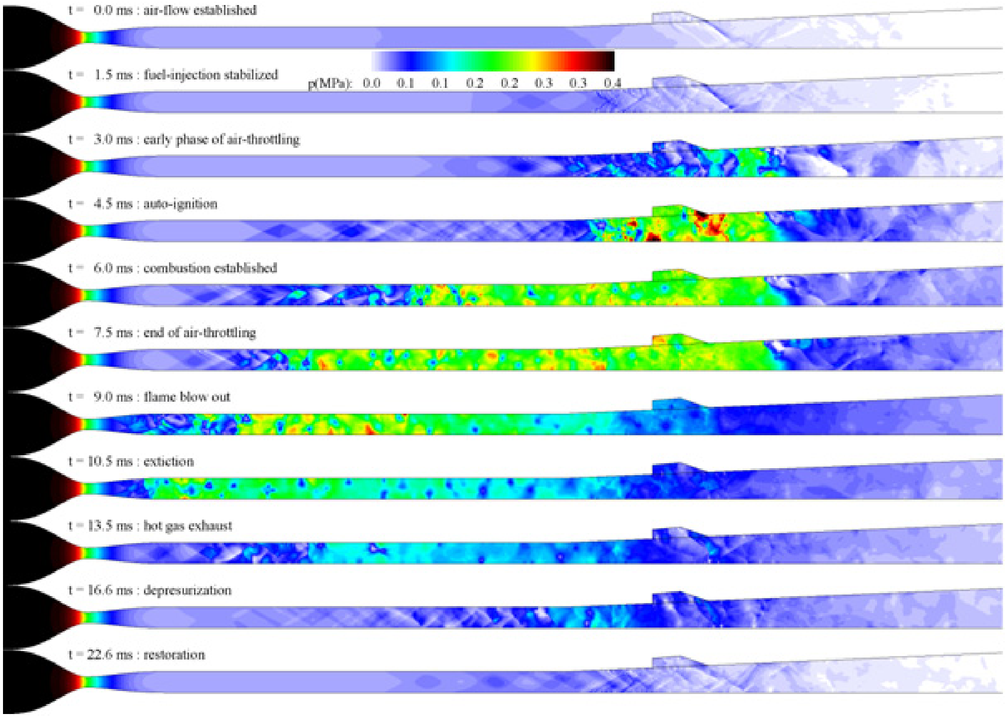

Fig 3. Transients of pressure distributions

Numerical studies on the transient process of ethylene fuel injection into a direct-connect dual mode scramjet combustor is carried out with application of air-throttling. Due to the slower kinetics of ethylene reactions about 3 ms of delay was required before the combustion establishment of ethylene, which is quite a long time in comparison with the flow characteristic time of the scramjet combustor. The air-throttling is confirmed to be effective means of the ethylene ignition and combustion establishment. The cavity is played a role of flame holder for broad range of flow speed from subsonic to supersonic. It is necessary to have further studies on the flame stabilization conditions including the amount of fuel injection and air throttling. Two-dimensional studies has shown to be effective to understand the various combustion flow features and operational characteristics in the dual mode scramjet combustor regardless of the modeling limitations.

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