이중 모드 스트램제트 엔진의 시동 천이 과정

최정열*† · 노진현** · 변종렬*** · 임진식***

Starting Transients in Dual-Mode Scramjet Engine

Jeong-Yeol Choi*† · Jin-Hyun Noh** · Jong-Ryul Byun*** · Jin-Shik Lim***

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. Following the fuel injection, air-throttling is applied at the expansion part of the combustor to provide mass addition to block the flow to subsonic speed. The ignition occurs several ms later when the fuel and air are mixed sufficiently. 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. Present simulation shows the detailed processes in the dual-mode scramjet combustor for better understanding of the operation regimes and characteristics.

초 록

에틸렌 연료의 이중모드 스크램제트 연소기에서 연소와 충격파 열 발생의 과도 과정을 고해상도 기법을 이용하여 수치적으로 연구하였다. 연료 분사 이후 질량 공급에 의한 아음속 유동 감속을 위하여 연소기 확장부에 조절용 공기를 공급한다. 공기와 연료가 충분히 혼합된 수 ms 이후 점화가 이루어지며, 압력 상승은 격리부에 흡입구 노즐까지 전진하는 충격파 열을 형성한다. 이후 후방 공기 공급을 중단하면 배출 과정이 진행되면서 후방 공기 공급 이전 상태로 서서히 복원된다. 본 연구의 결과는 이중모드 스크램제트 연소기에서 작동 영역과 특징의 이해를 돕는 상세 과정을 보여주었다.

Key Words: Dual Mode Scramjet(이중 모드 스크램제트), Supersonic Combustion(초음속 연소), Ethylene Fuel(에틸렌 연료), Shock-Combustion Interaction(충격파-연소 상호 작용)

1. Introduction

Air-breathing hypersonic propulsion based on supersonic combustion has been studied for

---

* 부산대학교 항공우주공학과
** 삼성테크윈(주)
*** 국방과학연구소 1기술연구본부 5부
† 교신저자, E-mail: aerochoi@pusan.ac.kr

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.[1] 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, 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.

To improve the ignition and combustion characteristics of hydrocarbon scramjet engines, several flow choking devices were employed at the end of the combustor. Among them, the air throttling technique making a temporary throat aerodynamically by injecting air at the end of the combustor.[2] Thus, the combustion enhancement by the air throttling is worth of investigation by numerical means for further optimization of the hydrocarbon scramjet engine system.

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 with finer resolution to investigate the detailed flow structures during the transient process.[3]

2. Numerical Modeling Approaches

2.1 Physical Models and Numerical 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 reacting species are O, O2, H, H2, OH, H2O, CO, CO2, C2H4. Nitrogen is regarded as inert gas since it has little effects on chemical kinetics and heat of reaction. For the ethylene reaction mechanism modified version of Singh and Jachimowski's quasiglobal chemistry mechanism, involving 10 elementary reaction steps and 8 reaction species is used.[4] 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.[5]

2.2 Direct-Connect Supersonic Combustor Configuration

The combustor length of AFRL direct-connect supersonic combustor is 178.9 cm consisting of a facility nozzle, an isolator, a combustor, and an exhaust nozzle. The isolator height is 3.81 cm. The simulated flight Mach number covers the range of 3.5-6, and the dynamic pressure varies from 24 to 96 kPa. Fuel injectors are mounted on the top and bottom walls of the combustor at x=106 and 111 cm, respectively. In the present two-dimensional numerical simulations, circular injectors are replaced by slit configurations while maintaining the equivalent injection area. The specific geometry is determined by the fuel mass flow rate. The cavity flame holder starts from 116 cm. The depth is 1.7 cm, and the upper and lower lengths are 5 and 10 cm, respectively. The combustor wall diverges 2.6 degree upward, while the bottom wall remains flat.

2.3 Computational Conditions

Numerical simulations were carried out under the flight condition of Mach 5 and dynamic pressure of 24 kPa. The mass flow rate of the inlet air is 0.757 kg/s, the static temperature is 1,050 K and the static pressure is 3.744 atm. The Mach number, static temperature and static pressure at the exit of the facility nozzle are 2.22, 560 K and 0.328 atm, respectively. No-lip adiabatic conditions are applied along the walls. Gaseous ethylene is injected into the combustor after the air flow is stabilized. The ethylene mass flow rate is 0.052 kg/s, corresponding to the equivalence ratio of 1.0. The ethylene fuel is injected under the Mach number 1.66, static temperature 273 K and static pressure 1.920 atm. Air throttle is mounted at the top of the combustor wall at x=136 cm which injects 0.151 kg/s air vertically downward at 1 ms after the fuel injection. All the flow conditions are summarized in Table 2

The computation domain is covered by 2,415x151 grid for main combustor and 300x121grid for cavity region. The grid convergence study has been reported in the previous work [3], but twice 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. Summary of Results

After the stabilization of supersonic non-reacting flow in the combustor, Fuel injection is started. 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 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 meeting presentation.

References

1. 노진현, 최정열, 변종렬, 길현용, 윤현걸, 임진식, "DARPA의 극초음속 항공기 및 TBCC 엔진 프로그램," 한국추진공학회지, 제 14권 1호, 2010년 2월, pp.65~78.
2. Donbar, J., Powell, O., Gruber, M., Jackson, T., Eklund, D. and Mathur, T., “Post-test Analysis of Flush-Wall Fuel Injection Experiments in a Scramjet Combustor,” AIAA Paper 2001-3197.
3. Noh, J.-H., Choi, J.-Y., Byun, J.-R., Gil,

H.-Y. and Lim, J.-S., “Numerical Study of the Auto-Ignition by Aero-throttling in an Ethylene Fueled Scramjet Engine,” AIAA 2010-7036, 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Jul. 25-28, 2010, Nashville, TN.

4. Singh, D.J. and Jachimowski, C.J., "Quasigolbal Reaction Model for Ethylene Combustion", AIAA Journal, Vol. 32, No. 1, pp.213-216.

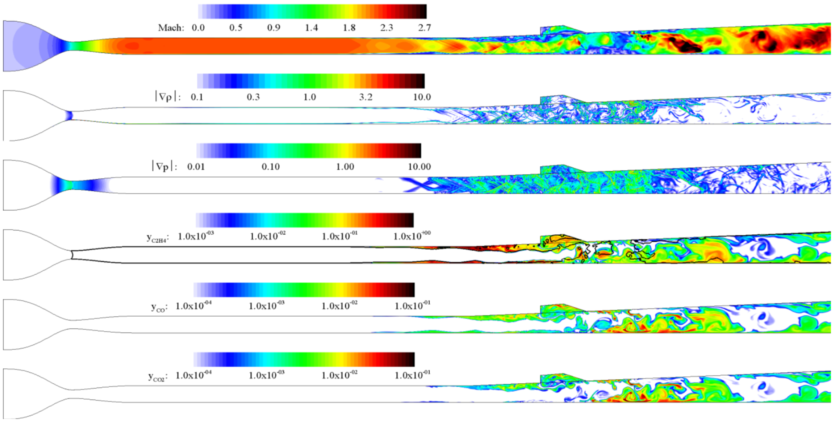

Fig. 1 Early phase of air-throttling (3.0 ms)

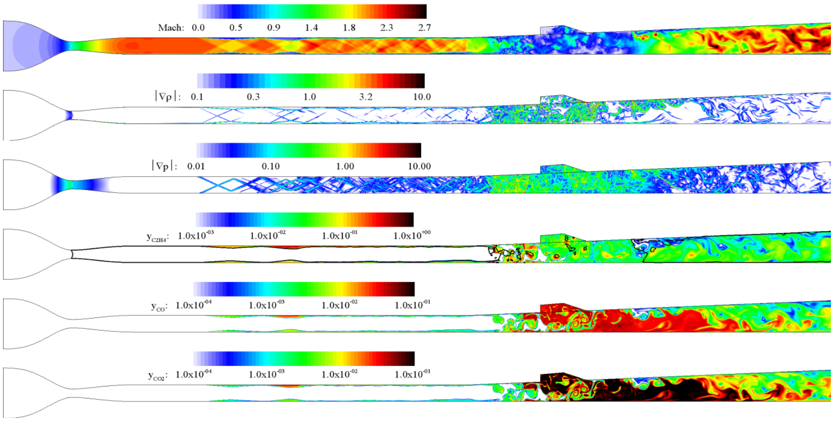

Fig. 2 Auto ignition phase (4.5 ms)

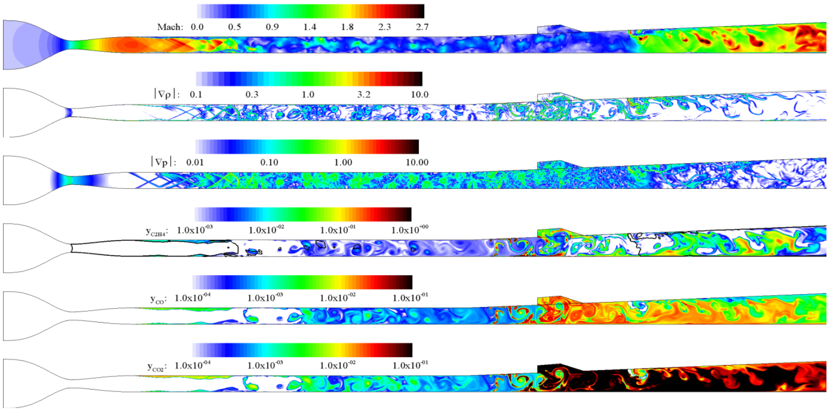

Fig. 3 End of air-throttling (7.5 ms)