

# 에틸렌을 연료로 하는 Direct-Connect 스크램제트 엔진 연소기의 2차원 수치 해석

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## Two-Dimensional Numerical Study of Starting Process of a Ethylene Fueled Direct-Connect Scramjet Engine Combustor

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### ABSTRACT

The numerical simulations of hydrocarbon fueled scramjet engine have been studied less than them of hydrogen fueled scramjet engine. Ethylene is selected in hydrocarbon because of its good thermochemical properties and a direct-connect scramjet combustor at the American Air Force Research laboratory is taken to a two-dimensional simulation model. Ignition time delay of ethylene was monitored and air throttling was imposed to generate ignition inside the model scramjet.

### 초 록

수소를 연료로 하는 스크램제트 엔진의 수치해석에 비해 탄화수소를 연료로 하는 스크램제트 엔진의 수치해석이 적은 편이었다. 본 논문에서는 탄화수소 계열의 연료 중에 에틸렌을 연료로 하였고, 미공군 연구소에 있는 Direct-connect 스크램제트 연소기를 모델로 2차원 수치해석을 수행한다. 에틸렌의 점화 지연 특성을 볼 수 있었고, 모델 스크램제트 내에 연소를 발생시키기 위해 Air throttling을 하였다.

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

### 1. Introduction

Scramjet engine has been studied and developed for over 50 years and the development result is very promising

,especially in the USA. X-51A SED-WaveRider is about to test flight and HTV project is ongoing for a scramjet cruise vehicle.[1, 2] A hydrogen fueled scramjet engine was already flight tested by X-41A and the USA is developing hydrocarbon fueled scramjet engine. Hydrocarbon fuel has several advantage, it is far less dangerous than hydrogen and it is cheap and can be easily

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produced. Ethylene is one of the most representative hydrocarbon and it is used during the starting process of X-51A because of its significant thermochemical properties, such as low ignition point and less ignition delay among the hydrocarbon. Hydrogen fueled scramjet combustor has studied a lot ,while Ethylene fueled scramjet combustor hasn't studied much. For those reasons ethylene is considered to scramjet fuel in the study and two-dimensional numerical simulation of starting process is studied in the paper.

## 2. Configuration and Calculation Conditions

A direct-connect scramjet combustor at the American Air Force Research laboratory (AFRL) is used as a model scramjet in the study and it is depicted in Fig. 1. This is 178.9 cm long and consists of a nozzle, an isolator, a combustor and a cavity. The height of the isolator is 3.81 cm. The inlet nozzle is assembled before an isolator to simulate Mach 5 flight conditions and an proper isolator is demanded to stabilize combustion and flame. Four slit injectors are used on the top and bottom of the combustor at  $x=106$  cm, 111 cm and they inject ethylene 15 degrees inclined to the vertical line. The entrance height of the combustor is the same with the isolator but the upper wall of the combustor diverges 2.6 degree upward, while the bottom wall is designed flat. After the flow field inside the model scramjet is stabilized, 0.052 kg/s ethylene is injected and the mass flow rate of inlet air is 0.757 kg/s therefore, the equivalence ratio is 1.01. Air throttling is mounted top of the combustor at  $x=136$  cm and injects air 0.151 kg/s vertically. At the entrance of the nozzle the Mach number is 0,

the temperature is 1,050 K and the pressure is 3.744 atm, respectively. As a result, the Mach number is 2.18, the temperature is 566 K and the pressure is 0.331 atm at the center of the inlet of the isolator. Fuel injection condition and air throttling conditions are written in Table 1.

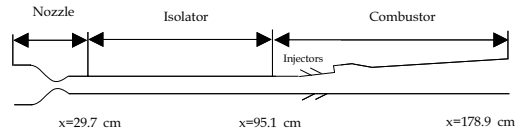


Fig .1. AFRL model scramjet combustor

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

## 3. Governing Equation

The species conservation equation, two-dimensional Reynolds averaged Navier-Stokes equation and turbulent transport equations are utilized to investigate the chemically reaction supersonic viscous flow inside the model scramjet combustor. Those equations are expressed in the conservative vector form in the equation (1).

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} = \frac{\partial \mathbf{E}_v}{\partial x} + \frac{\partial \mathbf{F}_v}{\partial y} + \mathbf{W} \quad (1)$$

$$\mathbf{Q} = [\rho_k \quad \rho u \quad \rho v \quad \rho e \quad \rho k \quad \rho \omega]^T$$

$$\mathbf{W} = [\omega_k \quad 0 \quad 0 \quad 0 \quad S_1 \quad S_2]^T$$

The subscript k denotes reaction species ( $O, O_2, H, H_2, OH, H_2O, HO_2, H_2O_2$ ) from 1 to N. Nitrogen is regarded to an inert gas since it

doesn't affect much in the reaction mechanism. The vector  $Q$  is the conservative variable vector and the vector  $W$  is the source term vector. Convective flux vector  $E$  and  $F$  are discretized by the Roe's flux difference splitting(FDS) method and viscous flux vector  $F_v$  and  $G_v$  are discretized by a central difference method. The fifth order MUSCL and WENO scheme are adopted for high order spatial accuracy and the Chatkravathy-Osher limiter is also used for the total variable diminishing (TVD) properties. The Menter's shear stress transport (SST) model with SST DES extension derived from the k-w two equation model is used for the turbulence modeling.[3] and the second order implicit time integration is used for sub-iterations. For the ethylene reaction mechanism Singh and Jachimowski's reduced chemistry involving 10 elementary reaction steps and 8 reaction species is employed.[4] For the boundary conditions the non-slip adiabatic conditions are imposed on the top and bottom walls including a cavity, and combustor exit conditions are extrapolated.

#### 4. Code Validation

Three grids systems are adopted to validate two-dimensional CFD code and define the most effective and accurate grid model. The grids numbers are written in table 2.

Table 2. Grids numbers

Grid level	x-direction	y-direction	Cavity	Total
1	603	101	75	68,478
2	1205	101	150	136,855
3	2415	101	300	274,215

Figure 2 shows the comparison of experimental data with numerical data. The

experimental data and numerical data demonstrate good agreement in the inlet of the isolator but after  $x=80$  cm numerical results under-estimate pressure because boundary layer doesn't developed enough in two-dimensional simulation therefore airflow is over expended and pressure is more decreased.

Grid level 1, 2, 3 showed similar results but grid level 1 can't detect shock train inside the isolator and grid level 3 consumes much computation resource therefore grid level 2 is selected for two-dimensional simulation.

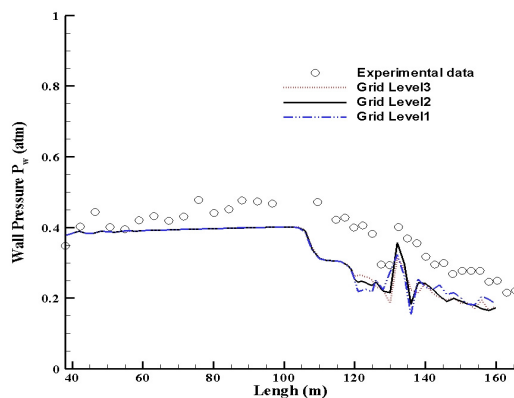


Fig. 2. Comparison of experimental data and numerical data along with grid levels

#### 5. Calculation results

##### 4.1 Ignition Time Delay

After stabilizing flow field inside the combustor ethylene is injected at 25 ms and air throttling is introduced after 1 ms. To detect the effect of air throttling temperature history of upper wall at  $x=126$  cm is drawn in Fig. 3. The pressure and temperature starts to increase after air throttling and the temperature reaches 900 K which is the auto ignition point at 27.5 ms but combustion doesn't occur because of ignition time delay. The temperature rises 1000 K to 2300 K during the time of 29 ms to 30 ms, that is combustion happens.

#### 4.2 Temperature and Pressure

Figure 4 compares the temperature, pressure and Mach number inside the combustor from  $x=100$  cm to 145 cm with air throttling to without air throttling. Even though the temperature of without air throttling is over 900 K, ignition doesn't happen because of ignition time delay. After air throttling temperature and pressure increase by aerodynamic choking.

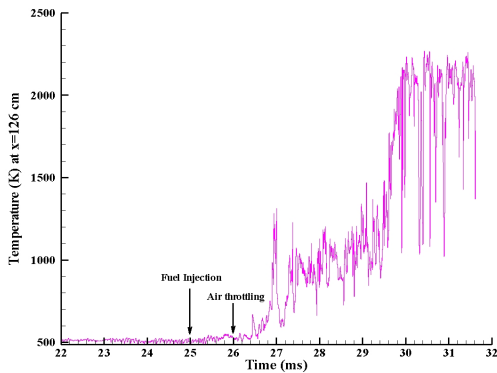


Fig. 3. Temperature history of upper wall at  $x=126$  cm

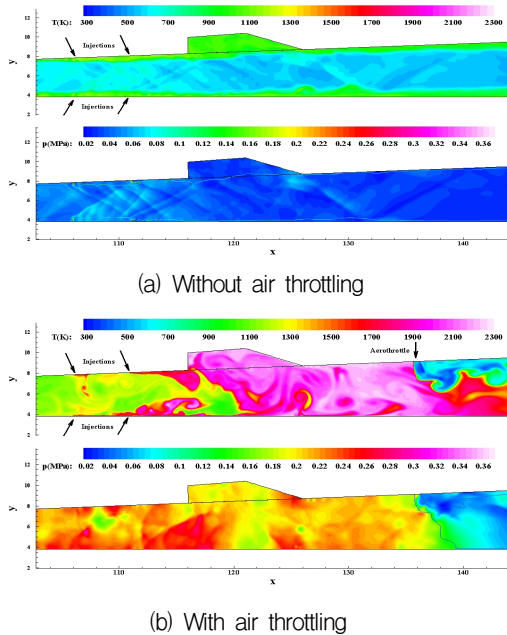


Fig. 4. Instantaneous figure of temperature and pressure

Figure 4. (b) represents fierce combustion, as a result temperature reaches over 2300 K. The high mole fraction of intermediate radical CO and products  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  are detected in the calculation with air throttling.

#### 5. Conclusion

Ethylene has comparatively low auto ignition temperature in hydrocarbon but combustion doesn't show up without air throttling because of ignition time delay. The air throttling is introduced and it produces aerodynamic choking, consequently combustion take place inside the model combustor.

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