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Numerical Study of Reactive Flow dynamics in a Hydrogen-fueled Direct-Connect Scramjet Combustor depending on Number of Injector

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Abstract

This study numerically investigated the reactive flow dynamics of a laboratory-scale gaseous hydrogen-fueled scramjet combustor depending on the number of injectors. The present study's primary goal is to investigate a flame structure and combustion dynamics by changing fueling schemes and to reveal the effect of injector schemes on combustion performance. A numerical simulation was performed using an improved delayed detached eddy turbulent model (IDDES) and Jachimowski's hydrogen-air reaction mechanism. The simulation utilized high-order accuracy-based numerical schemes to ensure high-resolution and fidelity results. Single and multi-injectors with five equivalence ratio cases in one set were considered for a quantitative comparison of the effect of injector schemes. Comprehensive numerical results found intricate coupled fluid-combustion dynamics and their transition depending on the fueling schemes and global equivalence ratio. A counter-rotating vortex pair (CRVP) of the multi-injector case was not maintained, resulting in decreased fuel/air mixing and combustion performance. Due to this phenomenon induced by an interaction between the jet-jet and jet-wall surface, it was revealed that the combustion efficiency is significantly reduced for the multi-injector compared to the single-injector under a similar global equivalence ratio. These findings indicated that the multi-injector scheme cannot guarantee increased mixing and combustion performance of a scramjet combustor without meticulously considering the interaction between the injector-to-injector and injector-to-wall surface.

Keywords: *Direct-Connect Scramjet Combustor, Number of Injector, Combustion Performance, High-resolution Numerical Simulation*

1. Introduction

A hypersonic vehicle typically utilizes a multi-injector configuration to increase the fuel-air mixing performance in an environment with short residence time in the combustor due to the high Mach number of incoming air. However, more studies are needed to investigate overall combustion characteristics and local flame structure when changing the number of injectors [1-6]. In this context, we attempted to find an effect of single- and multi-injector, e.g., fueling scheme, on the flame structure and combustion performance by conducting a comprehensive high-resolution numerical simulation.

In order to achieve this purpose, we performed an IDDES simulation with the high-order numerical scheme and sufficient grid resolution on a lab-scale direct-connect gaseous hydrogen-fueled scramjet combustor. A total of ten cases, combining two injector schemes and five injection pressure conditions, were employed to investigate the effect of a equivalence ratio (ER) with each fueling scheme.

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2. Methodology

2.1. Governing Equation and Numerical Approach

A density-based, compressible reactive in-house code called "PNURPL3DFR" was used in the present study. A chemical species, momentum, energy, and turbulent transport equation, in which a fluid and chemical reaction are fully coupled, were used as the governing equations. All equations were treated using the finite volume method (FVM) and based on a fully structure grid. A density was treated by the sum of the partial density of each radicals. The temperature was calculated using the total energy and temperature relationship with a Newton-Raphson iterative approach. The pressure was calculated using an ideal gas equation of state (EoS). Previous numerical studies have noted more detailed numerical framework information of the present framework [7-19].

Jachimowski detailed the H_2/air chemical reaction mechanism [20], which consists of 8 species and 19 reaction steps, was selected. Including nitrogen as an inert gas, so the total number of species is nine. Owing to sufficient grid level with a small volume (O(100 cm^3)), the present study selected the "quasi-laminar approach", instead of applying a turbulent-combustion model, such as a partially stirred reactor (PaSR) [21,22].

The present study used an improved delayed detached eddy simulation (IDDES), which avoided the grid-induced separation (GIS) problem in delayed detached simulation (DES) and controlled log-layer mismatch (LLM), a critical problem in delayed detached eddy simulation (DDES).

In order to achieve high-resolution result, spatial reconstruction was treated using the fifth-order optimized multi-dimensional limiting process (oMLP) method. Previous studies confirmed that the oMLP scheme performs better than the weighted essentially non-oscillatory (WENO) scheme [23]. Viscous flux was calculated using the fourth-order central difference method, and the AUSMPW+ scheme treated flux splitting. A second-order accurate, fully implicit optimized lower-upper symmetric gauss-seidel (LU-SGS) scheme with a maximum five-step Newton sub-iteration method was used as a time marching scheme.

2.2. Governing Equation and Numerical Approach

The experimental rig of the Pusan National University Direct-Connect Scramjet Combustor (PNU-DCSC), which is a gaseous hydrogen-fueled direct-connect scramjet combustor, is depicted in Fig 1. The PNU-DCSC consists of a rocket-type vitiation air heater (VAH), shape transition nozzle [24,25], and scramjet combustor. Isolator has square cross-sectional area with a 20 mm x 20 mm. The scramjet combustor has a design point with a Mach number of 2.0 and a static temperature of 1,000 K at the isolator entrance and the nozzle exit. More detailed information on PNU-DCSC and preliminary experiments is noted in our previous study [26,27].

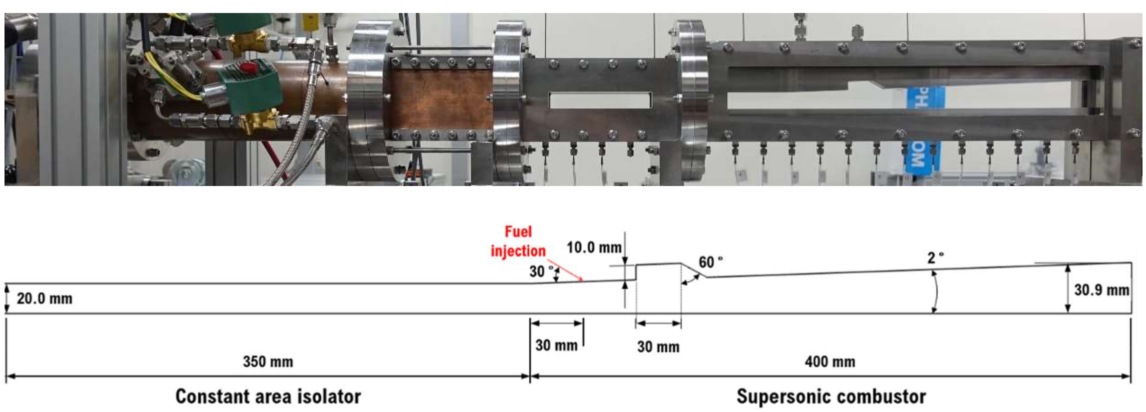

Fig. 1 (top) Experimental test rig of the PNU-DCSC, (bottom) configuration of computation domain and its specific size.

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A previous study performed a grid refinement test using 7.0, 16.0, 34.0, and 62.0 million grids as coarse, medium, fine, and superfine grid levels. The computational domain is divided into 1,034 blocks, and each block is treated by intel Xeon Gold 6154 CPUs for MPI parallel calculation. Because the coarse and medium grids do not have sufficient grid resolution (~ 0.48, 0.33 mm) to capture the reaction-zone thickness (~ 4 mm), a converged solution was only achieved from the fine and super fine grids. These two converged numerical solutions are in good agreement with our experimental results.

The present study considered a two-injector configuration, as depicted in Fig 1. The total exit area between the two injector schemes is slightly different. Therefore, the global equivalence ratio is also not precisely the same. However, due to the similarity in the overall range of the global equivalence ratios, combustion characteristics can be compared by fueling schemes using comprehensive numerical data. The present study considered a total of ten working fluid conditions. Uni-incoming air conditioners are considered. Two fueling schemes have a total of five injection pressures (global equivalence ratio, ER). More detailed information on working fluid is noted in Table 1.

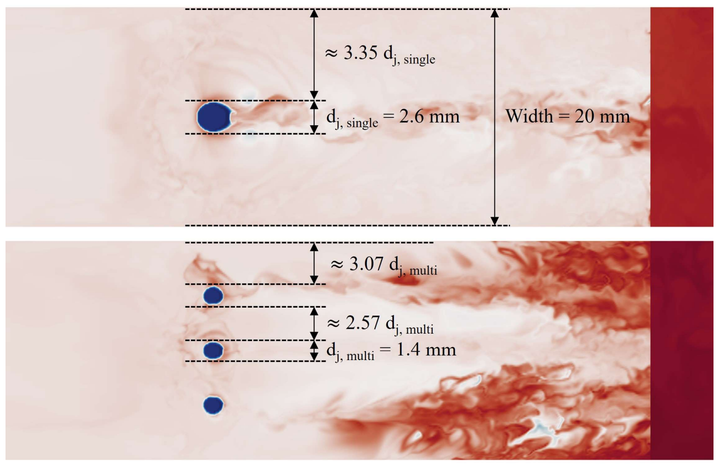

Fig. 2 Injector configuration of each fueling schemes. (top) single-injector case, (bottom) multi-injector case.

Table 1. Inflow and fuel injection

		Isolator inlet ▼			Fuel Injectio ▼		
Mach number		2.0			Sonic condition		
Static temperature		1,200 K			291.15 K		
Static pressure		1.65 bar	3.3 bar	4.8 bar	6.3 bar	7.8 bar	9.3 bar
ER, single-injector		-	≈0.24	≈0.35	≈0.46	≈0.57	≈0.68
ER, multi-injector			≈0.21	≈0.29	≈0.39	≈0.48	≈0.58
Mole fraction	N2	0.5952			-		
	O2	0.2227			-		
	H2O	0.1821			-		
	H2	-			1.0		

3. Numerical Results

In the multi-injector case, interactions between the recirculation flows of the central and side jet CRVP (Counter-rotating Vortex pair) occur. Each sidewall impedes the outer edges of the side jet's CRVP

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recirculation zone, resulting in an overall attenuation of the vortex strength in the side recirculation zone. This process leads to the collapse of the CRVP structure and a reduction in jet momentum, a crucial factor influencing fuel penetration. Due to these jet-jet and jet-wall interactions, fuel/air mixing performance dramatically decreases compared to the single-injector case. In Fig. 3, the OH mass fraction results indicate that combustion is held only on the thin-plat-shaped fuel/air contact surface. This trend occurs throughout the axial length of the combustor and maintains these characteristics at the combustor exit. Owing to the decrease in fuel/air mixing, a significantly shorter flame length is derived under the multi-injector case than a single injector.

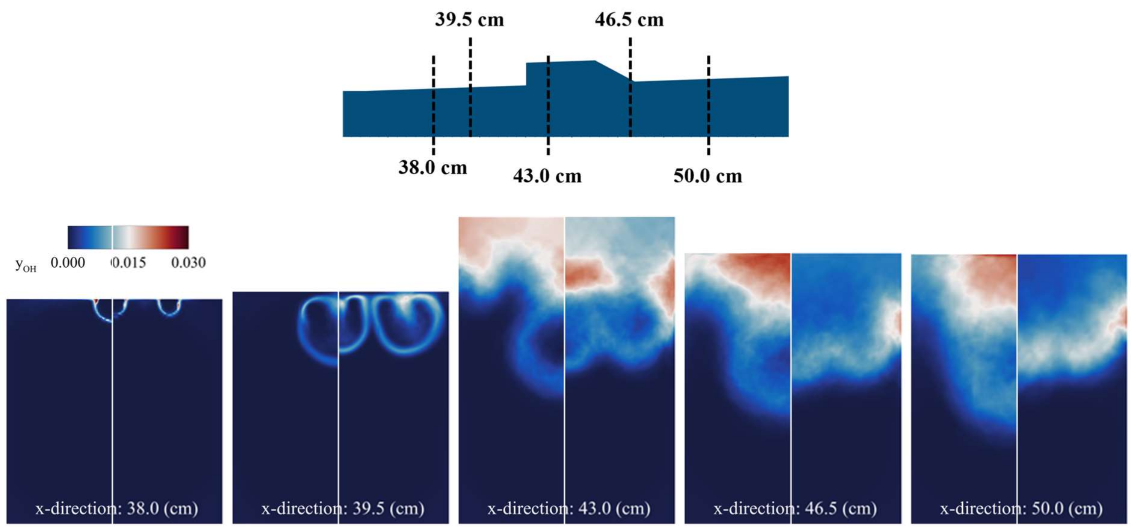

Fig. 3 Time-averaged results of temperature, OH mass fraction at each Y-Z plane; $P_{injt.}$ = 9.3 bar with (left side box) single-injector and (right side box) multi-injector

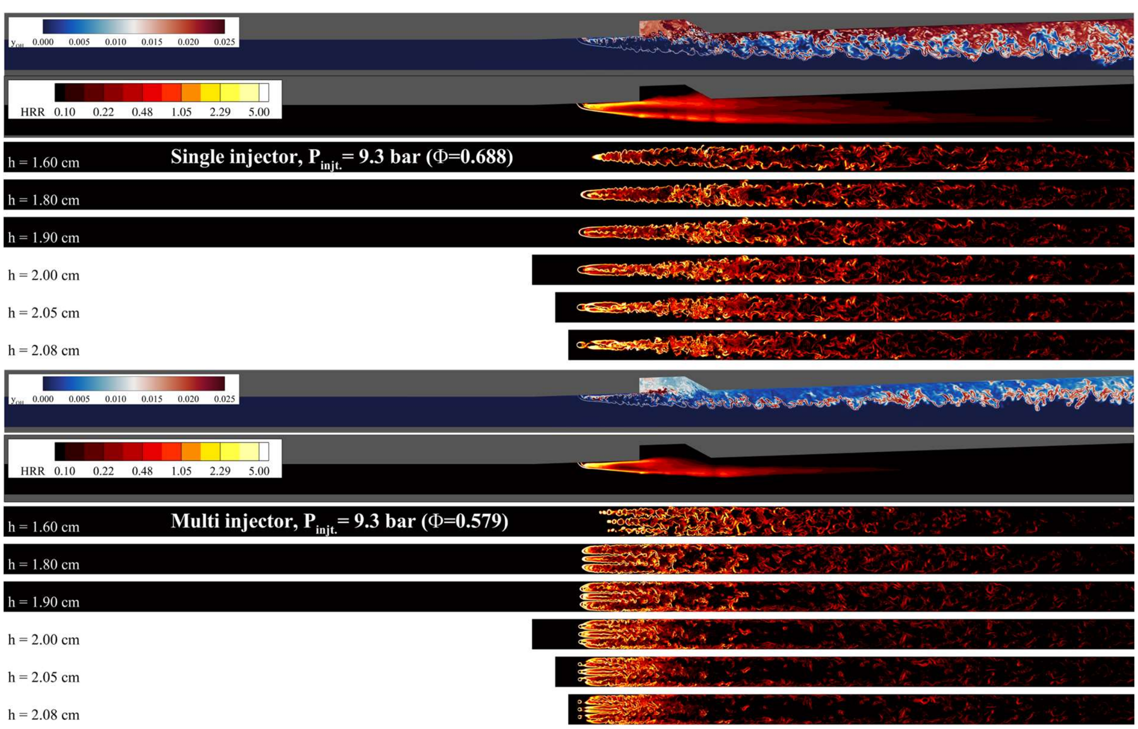

Fig. 4 Instantaneous results of OH mass fraction and HRR at the X-Z center plane and each X-Y plane; $P_{injt.}$= 9.3 bar with (top) single-injector, (bottom) multi-injector

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The combustion efficiency of single- and multi-injectors is depicted in Fig. 5. At the single injector results, the combustion efficiency showed a steep decrease up to the equivalence ratio of 0.35. However, it gradually decreases when the equivalence ratio condition is more than 0.40. In contrast, in the multi-injector cases, the combustion efficiency decreases rapidly as the equivalence ratio increases. If the equivalence ratio is 0.40 or higher, a multi-injector's combustion efficiency is less than a single injector. The characteristics between single- and multi-injector cases suggest that the multi-injector scheme did not always guarantee an increase in combustion efficiency. Moreover, it also suggests that the injector configuration, such as the distance of the injector to the injector and the injector-wall surface, is also crucial in combustion performance.

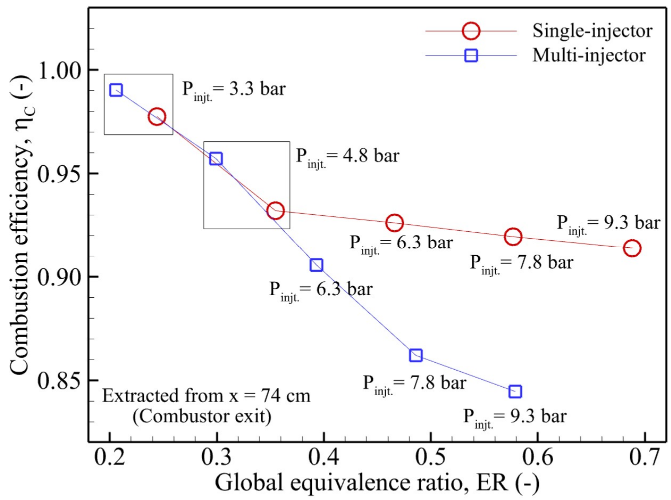

Fig. 5 The combustion efficiency at the combustor exit under the entire cases

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