Numerical Study of Low-frequency Supersonic Combustion Instability in a Hydrogen-fueled Scramjet Engine

Seung-Min Jeong, Hyung-Seok Han, Eun-Sung Lee and Jeong-Yeol Choi*
Department of Aerospace Engineering, Pusan National University
Busan, Republic of Korea, 46241

1 Introduction

During the last decade, scramjet engine has been advanced to the level of real-world application but also identified some issues for further development. In the early, because of short residence time, it was been accepted that combustion oscillation or acoustic waves could not propagate upstream of supersonic combustor. Contrary to this belief, a series of studies reported that combustion instability occurs, and studies on supersonic combustion instability of scramjet were accelerated[1-2]. These experimental studies have given keen insight into low-frequency combustion instability and its local phenomena[3-5], but also have sort of limited in identifying the behavior of mechanisms and reactive flow fields from a macro perspective of view. In addition, several large scale three-dimensional simulations performed by various research groups also remain in the acquisition of several “ms(millisecond)” levels of results due to practical difficulties. The key factor of combustion instability on scramjet engine is low frequency behavior, and in order to understand the behavior of the low frequency instability which has the order of 100 Hz range, it is necessary to obtain data for a quite long physical time. In this context, we performed a two dimensional high resolution numerical simulation of the DCSC(Direct Connect Supersonic Combustor) to identify combustion instability mechanisms through numerical analysis.

2 Methodology and Computational model

The DCSC, which is a computational model of numerical experiment, is a scramjet combustor with a combustion experiment scheduled at Pusan Natl. Univ., consist of VAH(Vitiation Air Heater) and CRST[6] (Circular-to-Rectangular Shape Transition) nozzles and supersonic combustor.

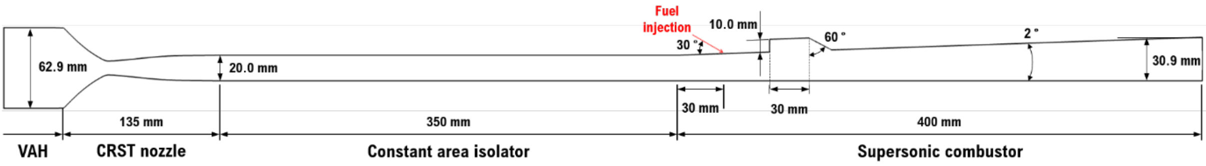

Figure 1: Configuration of computational domain except for the exit wake region.

Correspondence to: aerochoi@pusan.ac.kr

For a two-dimensional numerical experiment, the VAH downstream and the CRST nozzle were converted into the area ratio of a square duct having a width of 2 mm. This DCSC is designed that the main flow can form a supersonic flow with Mach number 2.0 and 1,000K in the isolator. Fuel, gaseous hydrogen, is injected through choked condition. Working fluid conditions are noted in Table.1. Inflow stream, VAH downstream, consist of N_2, O_2, H_2O in a ratio of 60.5:21.1:18.4, respectively.

In the two-dimensional coordinate system, continuity, momentum, energy, and chemical species conservation equations in which the flow and chemical reaction are fully coupled, were used as the governing equations. SST-DDES which classify as a hybrid RANS/LES model was applied. For the chemistry, the UCSD(UC San Diego) hydrogen/air reaction mechanism was selected. The spatial discretization was treated by 5th order oMLP scheme. The viscous and convective fluxes were discretized using the ASUMDV flux-splitting method and 4th order central difference. Each iteration step employed the 2nd order fully implicit method with the 4-stage sub-iteration. The time interval between each iteration is approximately 1.5^{-8} seconds. Each case took about five months of wall clock time. The grid convergence test of the 2D grid system was evaluated in a total of 16 grids level. Based on the grid convergence test, approximately 570,000 grid-level was selected. The DCSC is currently performing combustion tests to verify design points. Therefore, code validation was evaluated using the experiment of a supersonic coaxial jet problem performing by Evans et al.[7]. The result showed that distribution of the O_2 mass fraction and pitot pressure is good agreement with the measurement value.

Table 1: Initial and working fluid condition.

	VAH downstream	Supersonic combustor	Fuel injection				
			$\Phi \approx 0.30$	$\Phi \approx 0.35$	$\Phi \approx 0.40$	$\Phi \approx 0.45$	$\Phi \approx 0.50$
Mach number	0.01	0.0	1.0 (choked)				
Temperature	1675.0 K	300 K	293.15 K				
Pressure	17.25 bar	1.0 bar	5.0 bar	5.9 bar	6.7 bar	7.6 bar	8.4 bar

3 Results

The fuel is injected from 8.0 ms when the supersonic flow field was fully stabilized after the VAH started. Up to 100 ms of the numerical results were obtained at all equivalence ratio conditions.

The pressure distribution on the lower wall at whole time range is depicted in Fig. 2. In this paper, it will be focused on the global equivalence ratio of 0.45. The maximum combustion pressure is anchored to the region of cavity ramp angle, which is captured by maintaining the cavity shear-layer combustion mode. However, the pressure gradient indicating the repeated behavior of propagation-dissipation-repropagation into the isolator induces strong fluctuation to the region where the maximum combustion pressure is induced. Especially, when the dissipation of adverse pressure gradient inside the isolator, the region of maximum combustion pressure is moved to the fuel injection region where the much upstream of the combustor. This behavior, which is not captured under a low equivalence ratio of 0.30, appears repeatedly over the entire time range. This fluctuation gradually intensifies and changes combustion mode from cavity shear-layer combustion mode to jet-wake combustion mode at 73 ms. After the combustion mode changes, the region of maximum combustion pressure anchored is changed from the cavity to directly after the fuel injection. In addition, the pressure propagation into the isolator is captured the same, but the cycle of this behavior is shortened considerably.

Although there is such a difference, most conditions except equivalence ratio of 0.30, are presented that the behavior of the pressure propagating to the isolator and the flow field inside the combustor interact with each other. This behavior of pressure propagating is so-called upstream-traveling shock wave. The results of the x-t diagram in Fig.2, which achieved as numerical analysis over a long physical time show that the upstream-traveling shock wave induces combustion instability in the combustor, and also presents the possibility that it can lead to unstart depending on the design and operating conditions.

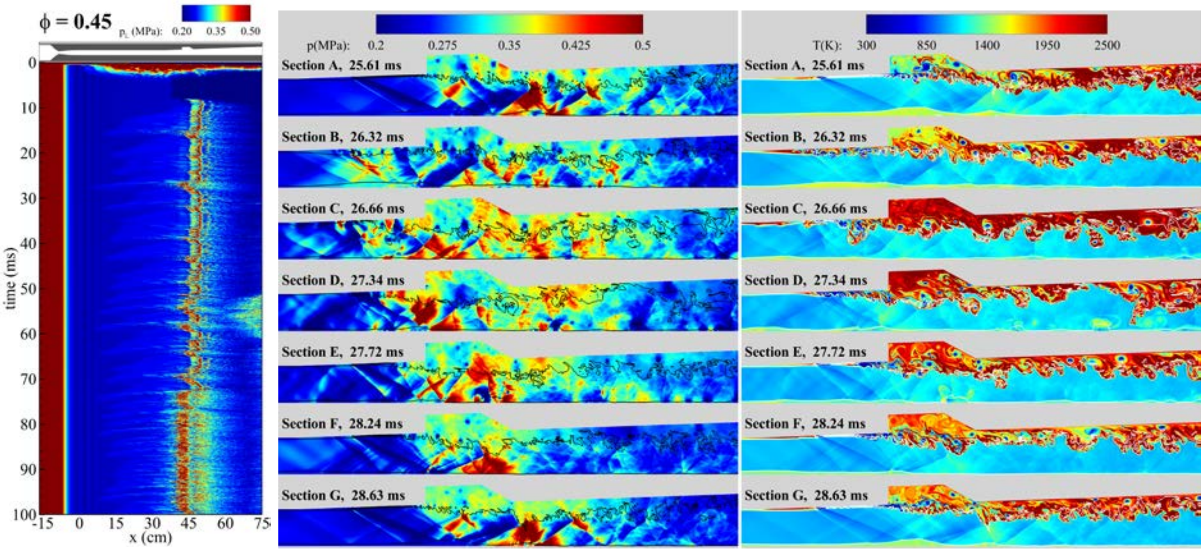

Figure 2: (left)x-t diagram for the pressure distribution on a lower wall; (right)instantaneous result for the pressure field and temperature distribution listed chronologically; 25.61 ms ~ 28.63 ms

The right side contour of Fig. 2 shows the instantaneous results for the pressure field and temperature distribution chronologically which consist of one cycle of combustion instability. To determine whether the combustor choked or not, the Mach line is marked as the black and white iso-line in the figure. All data was divided into sections A to G depending on the events occurring.

In section A, a primary upstream-traveling shockwave consisting of a structure of multiple-oblique shock, accompanied by a weak pressure gradient is very slowly propagated to the isolator. Due to effect of formation of lambda shocks on fuel stream, disturbances begin to occur in the fuel injection region in section B. Because of increased backpressure behind of oblique shock formed by fuel injection, a secondary upstream-traveling shockwave is generated and propagated to the isolator. Secondary shock push-up the primary upstream-traveling shockwave which was no longer moving, into the isolator upstream. In section C to D, it can be found that the primary upstream-traveling shockwave is re-propagated. To the rapid stretch of shock structure as depicted in Section C and D, downstream of upstream-traveling shockwave begin to dissipation. The upstream-traveling shockwave in the isolator continues to dissipate and collapse over the D-E section. In the process, the separation bubbles on the wall formed by the shock structure in the isolator are blown off. The detached separation bubbles develop to a locally low-Mach number and high-pressure region. Local flow field disturbance causes strong combustion instability. This dissipation continues until when most of the shock structures collapse except for the leading of the upstream-traveling shock wave. Only after reaching section F, the dissipation of the shockwave in the isolator is ended. At the same time, the stabilization of the combustion mode is also taken. The pressure distribution of the stabilized flow field is consistent with presented in section A. But simultaneously, a primary upstream-traveling shock wave is formed, which, again, slowly propagates to the isolator.

These series of behaviors constitute one-cycle of low-frequency supersonic combustion instability on this DCSC. When the equivalence ratio increasing, except that the upstream-traveling shockwave changes to a single shockwave accompanied with a strong pressure gradient, most of tendency exhibits similar behavior.

In Fig.3, the probe 5, 6 is placed at downstream of the isolator, and the other probes are located near the fuel injector. When the upstream-traveling shockwave was propagated into the isolator, and induced instability, the maximum pressure peak of probe 7 become increasing about approximately 1.5 times higher than reference pressure level. When this highly unstable flow passes through the fuel injection region and reaches probe 9, the pressure level increases considerably, resulting in a pressure peak of up to 4.0 times than P_{ref}. This pressure peaks of Fig.3 which appears identically in al probes have a time interval of about 2.0 ms to 5.0 ms, between each peak.

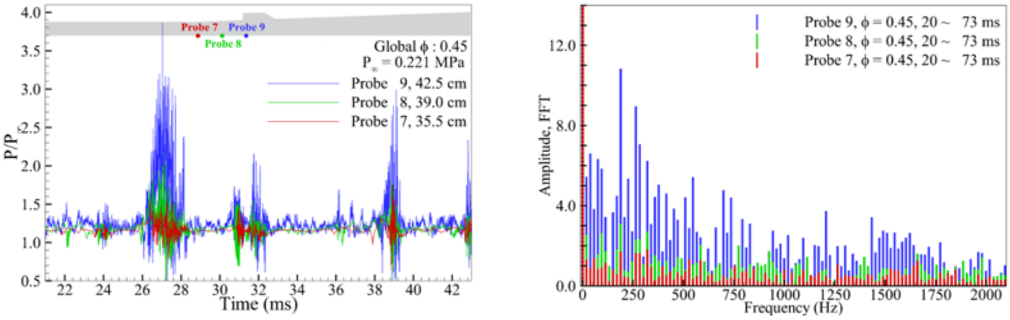

Figure 3: (left)The Pressure history of probe point located the isolator downstream and fuel injector region on the lower wall; (right) FFT analysis of pressure history measured at probe 7~9.

The supersonic combustor, which has inherently unsteady combustion characteristics, naturally exhibits high-frequency oscillations of several kHz. The left contour of Fig. 2 illustrating FFT analysis in a low-frequency range, excluding the results of the high-frequency shows the peak frequencies at 200 Hz, 500 Hz, 750 Hz, and 1250 Hz. Under low equivalence ratio conditions, such as 0.30~0.35, peak frequencies in these low-frequency ranges were not detected at all. This indicates that the upstream-traveling shockwave which behaves with a cycle of a few ms, causing a high-pressure peak is identified as the main factor in the generation of low-frequency supersonic combustion instability. And also it can be confirmed that this upstream-traveling shockwave is an important factor for combustion stabilization on the supersonic combustor.

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