Experimental Investigation on the Ignition Characteristics of Scramjet Combustor Using a Micro Pulse Detonation Engine

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1 Introduction

Scramjet engine is considered a core technology for air-breathing hypersonic vehicles, and active research is underway. Beginning with the Hypersonic Research Engine(HRE) program from the early 1960s, the National Aero-Space Plane(NASP) program and Hyper-X are research related to hypersonic vehicles. In addition, the flight test of X-51 Waverider, Long-Term Advance Propulsion Concepts and Technologies(LAPCAT) in Europe, the HyShot flight project in the USA-Australia, and the Hypersonic International Flight Research Experimentation(HIFiRE) have been conducted. These hypersonic researches have been developed through databases of previous experiences and accompanying ground and flight tests. Therefore, a supersonic combustion ground test facility that simulates the flow conditions (high-pressure, high-enthalpy, Mach number) of the target flight conditions and can secure enough time to stable hypersonic flow and combustion phenomena is required. In general, types of ground facility for supersonic combustion are classified as shown in Table.1. The supersonic combustion facility used in this study is constructed by direct-connecting a small rocket combustor type vitiation air heater(VAH) and a scramjet combustor.

Table 1: Types of Supersonic ground test facilities.

Operation type	Continuous	Blowdown			Shock Tube
Characteristic	Pure air	Vitiation	Dissociation	Particulates	Shock driven
Heat generation	Compressor	Combustion	Electric heat	Heat accumulation	Pressure / Temperature rise by shock compression
Operation time	Continuous	Order of sec			Order of 10 ms
Cost	Very high	Low			Low

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Stable ignition and combustion reactions of scramjet combustors must be performed to achieve reliable performance, but the fuel residence time of scramjet combustors is very short, order of 1-2 ms, which is significantly challenging. Therefore, it is necessary to improve mixing efficiency, stable combustion and flame-holding performance through active or passive excitation and rapid ignition methods. Numerous cavity-related experiments and analysis studies have already been performed, and many studies using active excitation such as pulse jet injection or plasma intensified mixing have also been conducted [1,2].

In this study, after briefly dealing with the VAH performance verification test results using the wedge, the ignition and combustion characteristics of scramjet combustors using the μPDE ignitor according to the equivalence ratio and the number of cavity flame holder were experimentally investigated and compared.

2 Experimental Apparatus

Pusan National University Direct-Connect Scramjet Combustor(PNU-DCSC) constructed and utilized in this study consists of a gas supply system, VAH, isolator, and scramjet combustor as shown in Fig.1. The target design point is an altitude of 20-25 km and a flight Mach number of 4.0-5.0. High enthalpy and high pressure vitiated air with a Mach number of 2.0, a total pressure of 1.731 MPa, and a total temperature of 1,000 K was supplied through the VAH exit to simulate the target design point. In addition, the Circular to Rectangular Shape Transition(CRST) nozzle was applied for easy design, visualization, and measurement of experiment while satisfying Mach number 2.0 [3]. The dimensions of the isolator and the scramjet combustor with single and tandem cavity, respectively, are shown in Fig.2. The dimension of the applied cavity is the same: bottom length 30mm, depth 10 mm, ramp angle 30°. The rear cavity of the tandem case is located 142 mm from the front cavity. The scramjet fuel was injected as gaseous hydrogen through injectors with an inclination of 30°. For VAH ignition, Combustion Wave Ignitor(CWI) was installed on the wall as shown in Fig.3(left) and operates. Fuel of GH_2 and oxidizer of GO_2 were injected with a total mass flow rate of 1.02 g/s and an equivalence ratio of 1.04 and ignited via a spark plug. μPDE was installed vertically on the floor at the mid-point of the cavity. The inner diameter and length of chamber channel are 3.86 mm and 155 mm, respectively. To show the ignition effect by the detonation wave, the total mass flow rate should be less than 2% of the

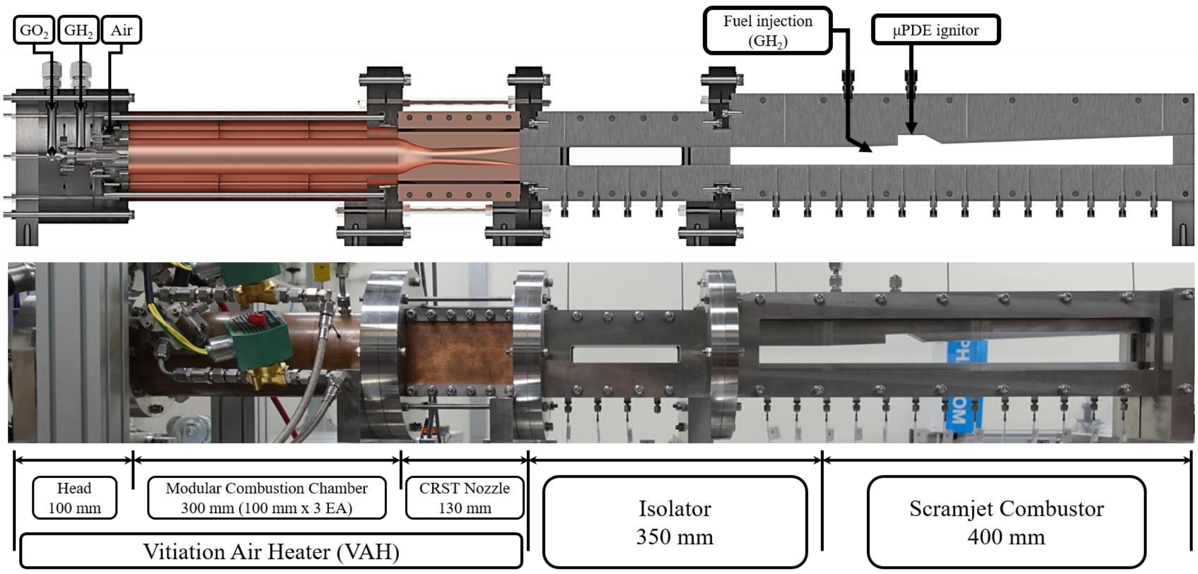

Figure 1: PNU-DCSC. Upper: CAD model. Lower: Experimental model.

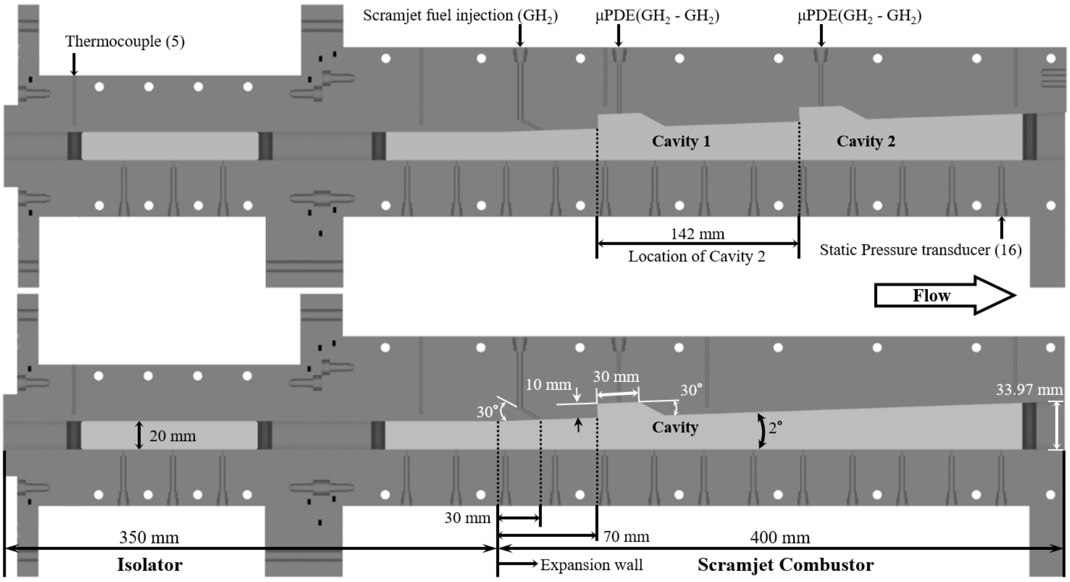

Figure 2: Dimensions of Isolator and Scramjet Combustor with Cavity and location of μPDE. Upper: Tandem cavity. Lower: Single cavity.

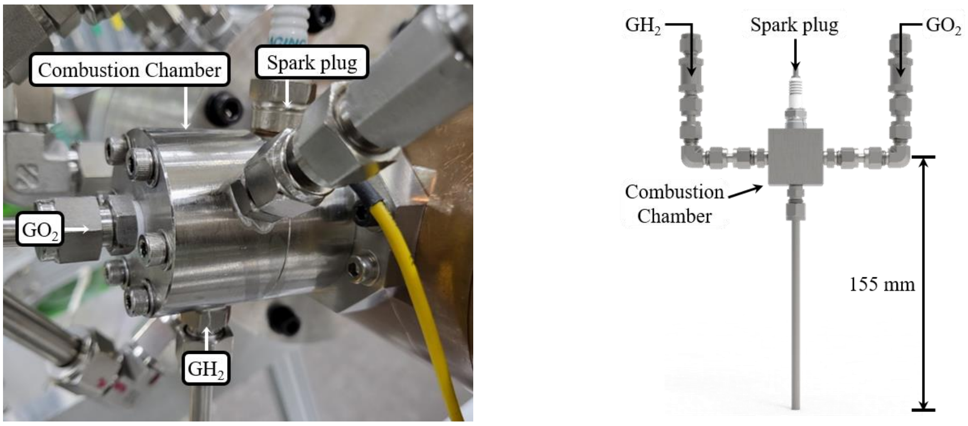

Figure 3: CWI for VAH ignition and μPDE for scramjet combustor ignition. Left: Installation of CWI. Right: Dimension of μPDE.

total mass flow rate of PNU-DCSC. μPDE is operated by injecting fuel and oxidizer for 0.075 s at a total mass flow rate of 1.80 g/s and an equivalence ratio of 1.01 ± 0.013. The μPDE model referred to the research of Han et al [4].

The high pressure gas supply system utilized an electronic dome regulator(ProportionAir Inc., GX series) to precisely control the downstream supply of GH_2, GO_2 and air. By controlling GN_2 using a spring regulator(Swagelok, KPR series), downstream pressure setting for purge, pneumatic valve(Swagelok Inc., AT series), and dome regulator control were performed. A differential pressure type mass flow meter(Enbac Inc., FM153B, < 0.2% FS accuracy) was applied to each supply line. A pressure transmitter(WIKA Inc., S-20 series, < 0.5% error) was used for measurement of plenum pressure. Tests were performed using NI LabVIEW and CompactRIO modules as a remote control and monitoring system. The system can control the valve sequence, save acquired data. Also, it is possible to synchronize the measurement point by triggering a multi-channel pressure scanner(Scanivalve Inc., DSA3217, 16 ports) and a high-speed camera(Phantom Inc., v2512).

3 Experimental Results

Preliminary tests were conducted to verify the VAH exit flow conditions using the wedge made of tungsten and inclined at θ = 20°, as shown in Fig.4(Left). The result of Mach number 2.04 ± 0.04 was derived through the θ-β-M relation between the β measured through Schlieren snapshot and the specific heat ratio calculated using NASA CEA [5-6]. Fig.4(Right) shows the propagation of the detonation wave through a single μPDE test.

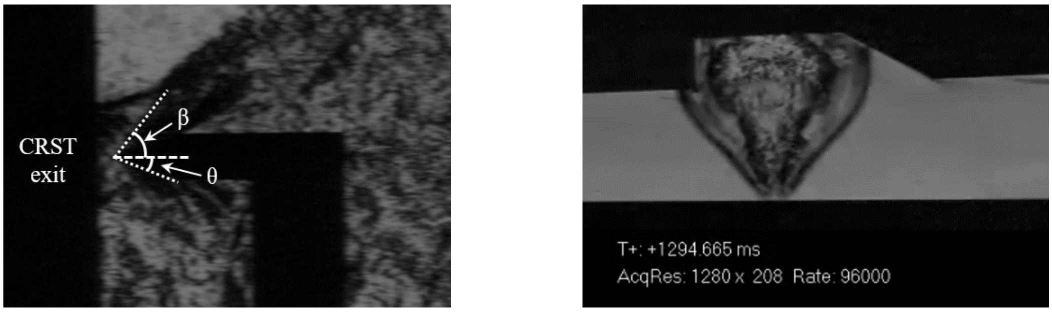

Figure 4: Schlieren snapshots of preliminary tests. Left: Schlieren snapshot with VAH chamber pressure 1.685 ± 0.072 MPa. Right: Schlieren snapshot of μPDE.

In the case of scramjet combustor with a single cavity, the wall pressure is distributed differently depending on the fuel injection and equivalence ratio(Φ), as show in Fig.5(Left). In the case of an Φ 0.04, the pressure rises rapidly after the leading edge of the cavity, but at the Φ 0.12 and 0.22, the pressure rises significantly even before the leading edge of the cavity. Even, in the case of an Φ 0.22, the pressure of the isolator rises significantly. After the cavity, the wall pressure decreased as it got closer to the combustor exit in all cases, and a flame was formed at the combustor exit as shown in Fig.6.

In the case of the tandem cavity, the test was conducted with different Φ and the location of μPDE. At Φ of 0.04, when ignited in cavity 1, a shear layer flame was formed along the leading edge of cavity 1. However, when ignited in cavity 2, the flame can't propagate to cavity 1, and the pressure rose only on the rear wall of cavity 2 as shown in Fig.5(Right). At Φ of 0.12, ignited in cavity 1, a flame is formed as in an Φ of 0.04. When ignited in cavity 2, the flam propagates to cavity 1 immediately after forming the shear layer flame in cavity 2, and the flame is held in cavity 1. At a relatively high Φ of 0.22, the flame propagated to the fuel injector exit regardless of the position of the ignitor, and developed as a jet wake flame.

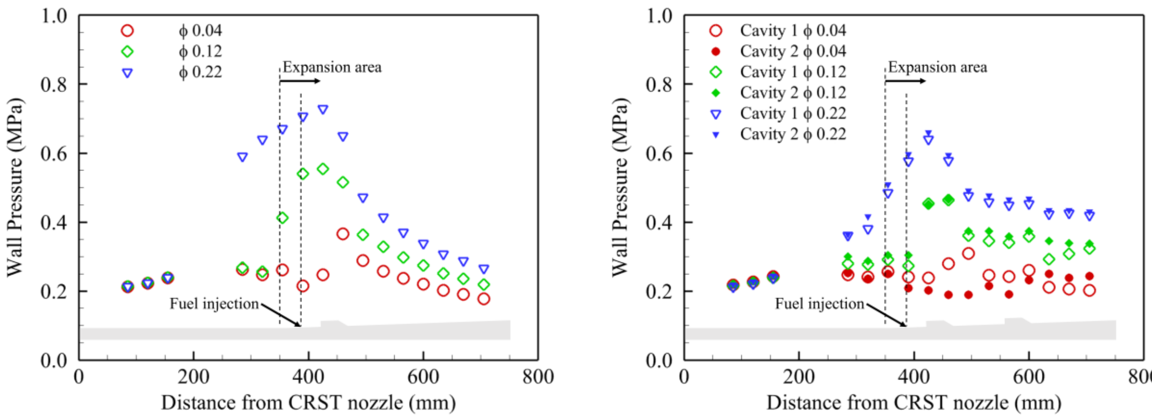

Figure 5: Bottom wall pressure distribution. Left: Case of single cavity(Φ: 0.04, 0.12, 0.22). Right: Case of tandem cavity(Φ: 0.04, 0.12, 0.22 / Position of μPDE ignitor: Cavity 1, Cavity 2).

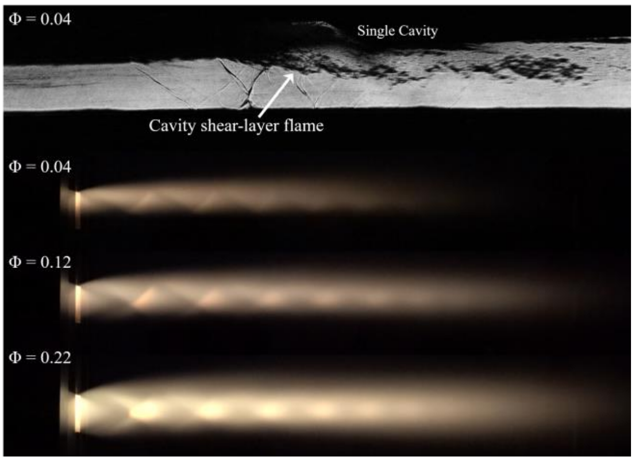

Figure 6: Schlieren and digital camera(Sony Inc., cyber-shot, 60fps) snapshots of the single cavity cases.

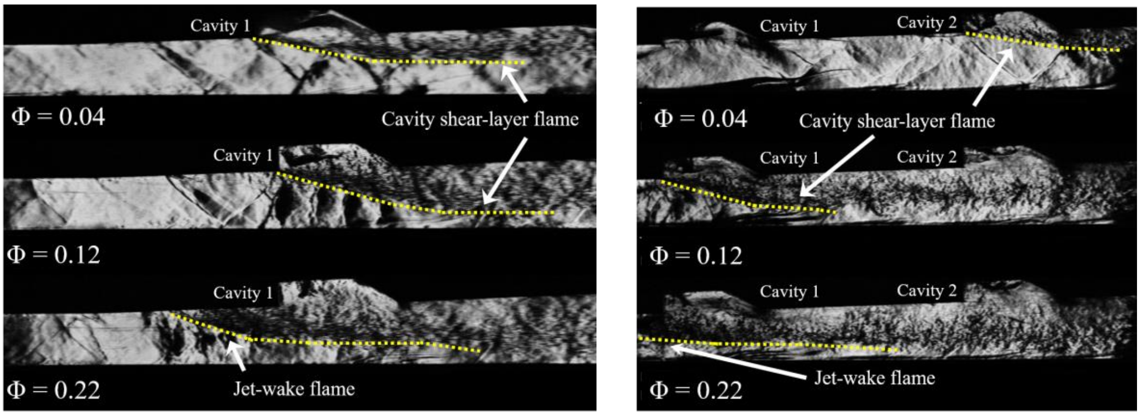

Figure 7: Schlieren snapshots of the tandem cavity case. Left: Ignition by μPDE in cavity 1. Right: Ignition by μPDE in cavity 2.

4 Conclusions

The PNU-DCSC was constructed with a design point of flight Mach number 4.0-5.0 an altitude of 20-25 km. Through the VAH verification test using the wedge, it was confirmed that vitiated air with a Mach number of 2.04 ± 0.04 and a total pressure 1.685 ± 0.072 MPa could be fed to the inlet of the isolator. GH_2 at room temperature was supplied as fuel for the scramjet combustor. The ignition and combustion characteristics of scramjet combustors with single and tandem cavities were investigated using μPDE as an ignitor.

The wall pressure distribution and Schlieren snapshots shows that the pressure from the isolator to the cavity and the peak pressure near the cavity increase as the injected fuel and equivalent ratio increase. The pressure distribution from the cavity to the combustor exit did not show significant differences in all cases. However, in the case of the tandem cavity, when the equivalence ratio is low, the flame does not propagate to the front cavity and the wall pressure near the rear cavity is higher. Through this phenomenon, a high pressure distribution and shock interaction are formed between the wall surface and the flame layer generated by combustion, which increases to a higher pressure as the equivalence ratio increases and develops into a jet-wake flame. It is also seen to lead to an increase in the pressure of the isolator.

Acknowledgments

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