

Analysis of Fuel Mixing Characteristic in Supersonic Combustor with Injection Pressure and Existence of Cavity using Modal Decomposition Method

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1 Introduction

In supersonic combustion where non-premixed turbulence combustion is dominant, the duration of flow in the combustor is less than 1 ms due to rapid flow speed. So, fuel-air mixing is one of the most important issues. Among the various methods for propellant mixing, cavity have been applied to most supersonic combustors because they have the advantage of being able to cause mixing effects at low cost. Many studies have been conducted to confirm how various geometric forms of cavity such as L/D, size and ramp angle, affect the propellant mixing. These mixed propellants exhibit a very complex flow behavior, so it is difficult to analyze the mixing tendency for geometry of cavity, operating conditions or the shape of the combustor.

In this study, we analyzed propellant mixing characteristics of supersonic combustors by operating conditions and existence of cavity using modal decomposition method. The modal decomposition method used in the analysis of this study is DMD(Dynamic Mode Decomposition) that can observe us the dynamic characteristic of flow, presented by Schmidt[1].

2 Simulation model and Numerical approach

The supersonic combustor considered in this study is shown in Fig. 1. This Divergent nozzle type supersonic combustor is quite similar to the Hyshot test model which is channel type combustor except for the cavity and consists of a cowl under the intake, a main chamber and cavity. The incoming air flow to the combustor with 10 cm height is set to Mach 3 at 600 K and 0.1 MPa. The fuel, gaseous hydrogen, is injected vertically through a choked 0.1 cm width slot nozzle to the combustor at a distance of 14 cm from the inlet. The fuel temperature is 151 K, and for the inject exit pressure are 0.5, 0.75, 1.0, and 1.5 MPa. This is 5, 7.5, 10 and 15 times the pressure of air 0.1 MPa, respectively.

In the two-dimensional coordinate system, momentum, energy and chemical conservation equations in which the flow and chemical reaction are fully coupled are used as the governing equations. This governing

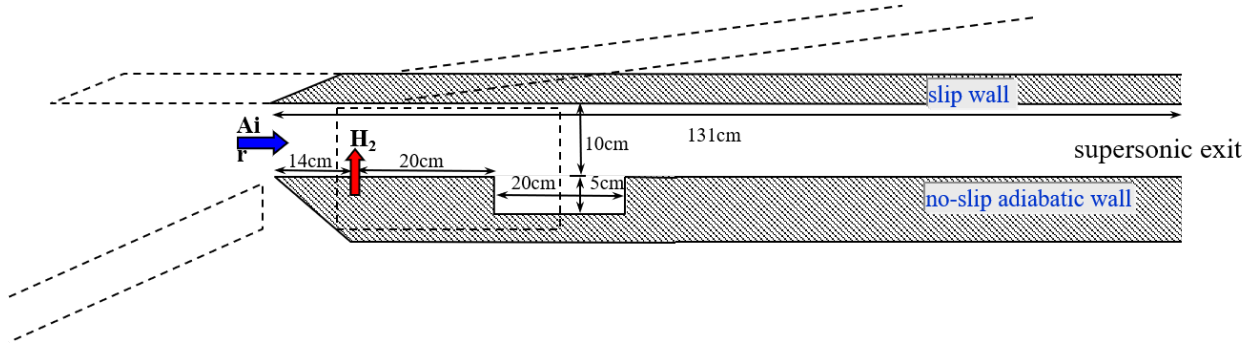


Figure 1. Configuration of scramjet combustor[2]

equations were treated numerically using a finite volume method, and the convection term was formulated using Roe's FDS. Mentor's SST (Shear Stress Transport) model and GRI-Mech 3.0 chemical kinetic mechanism which has 8 species (H , H_2 , O , O_2 , H_2O , OH , H_2O_2 , HO_2) and 25 reaction steps was used as turbulent and chemistry model, respectively. Grid resolution of a main chamber, cavity and cowl is 800×160 , 159×161 , 50×50 . Detailed description of governing equation and numerical approach are documented in previous work[3].

As mentioned before, the modal decomposition method for analyze the mixing characteristic of propellant used the DMD presented by Schmid[1] relatively recently. The major advantage of this technique is that it can be decomposed into the dominant behavior and its subordinate behavior in the flow over time, using sequential time data for space. The DMD used in this study is a snapshot-based DMD. Growth/decay rate and the frequency of each modes can be achieved as well as the decomposed modes through the calculation process of this method. In addition, it is possible to derive the coherence($E_{i,DMD}$) value, which makes it possible to compare and confirm the energy rankings of each mode[4].

The conditions of calculate DMD were represented in the table 1. DMD can using the results of each chemical species as well as pressure, speed, density and temperature, but we focused on the fuel H_2 mass fraction results to analyze mixing characteristic of propellant intensively. In this paper, only the DMD result of 0.5 and 1.0 MPa condition will be shown among all results.

Table 1: Condition of calculate DMD

	Without cavity	With cavity
Number of snapshot	298	
Number of iteration between snapshot	500	
Physical time of 1 iteration in solver	6.1×10^{-5} ms	5.9×10^{-5} ms
Physical time of first snapshot	21.4 ms	20.7 ms
Physical time of last snapshot	30.6 ms	29.5 ms
Type of snapshot used	8 case (four inject exit pressure case + w/ or w/o cavity)	

3 Result and Discussion

Instantaneous and time averaged of H_2 mass fraction distribution are shown in Fig. 2. When the fuel inject exit pressure is low, the relatively high H_2 mass fraction is maintained along the bottom of the combustor, but the opposite case represented the high H_2 mass fraction only around the injection point. This tendency

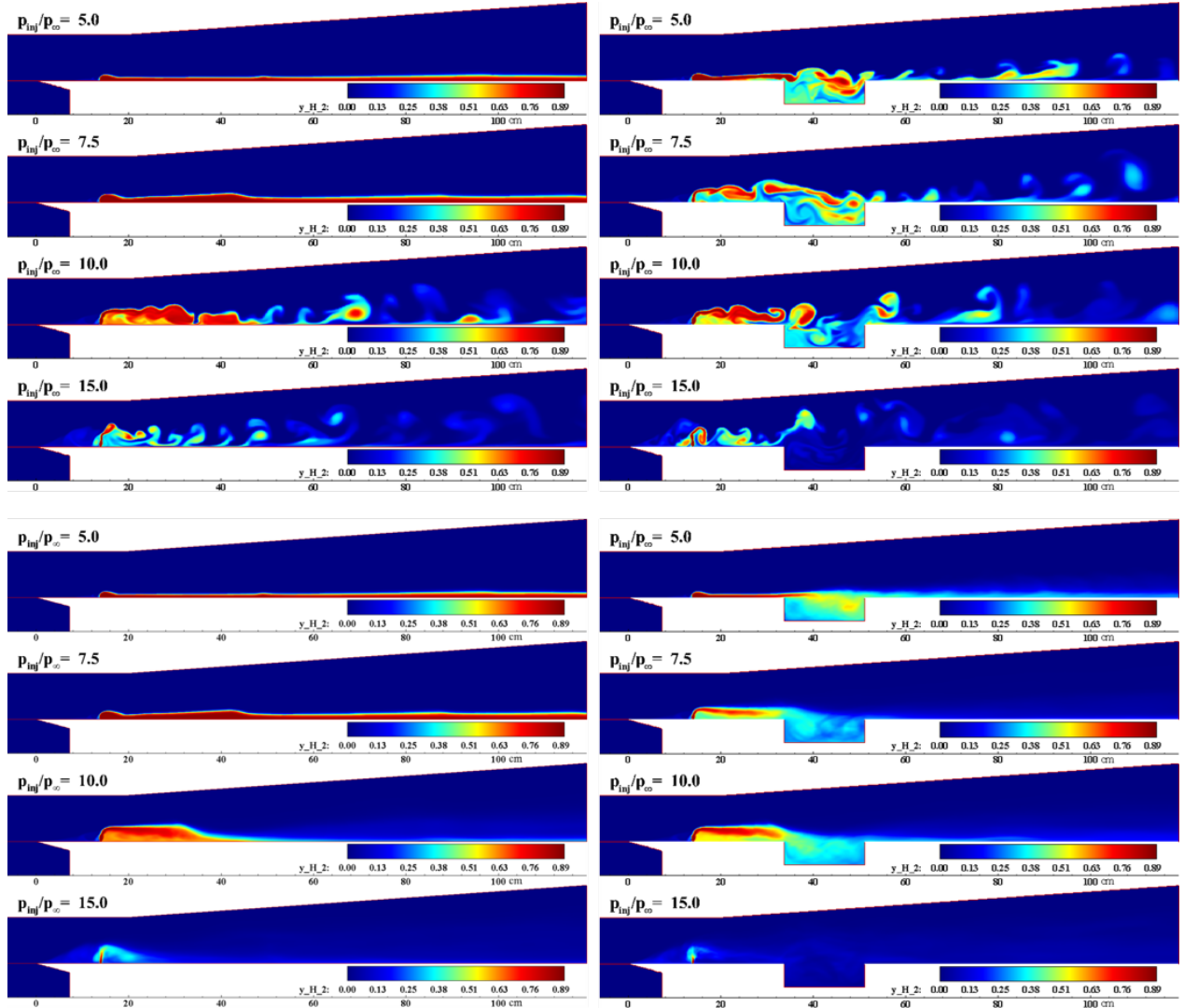


Figure 1. H₂ mass fraction distribution of instantaneous(upper) and time average(lower)

is prominent when there is without cavity. The performance difference of the fuel mixing can be clearly confirmed by comparing the CFD results for each case of H₂ mass fraction distribution, but there is some limit to analyzing the mixing characteristic in each individual condition. For example, it is expected that different mixing performance will be represent by each condition, especially the presence of cavity, but it is difficult to find certain phenomenon such as the mixing starting point and the strength of mixing. But through the DMD results, it is possible to confirm what meaningful effects the existence of cavity has on the fuel mixing start point. The purpose of this study is to analyze the characteristics of the fuel mixing using mode decomposition method. For the numerical analysis results, only the necessary information is briefly mentioned. For more details, refer to the reference[2][5].

In this paper, it will be only mentioned that the results of 0.5 and 1.0 MPa. The top of contour shown in Fig. 3 and 4 is called Primary mode having a coherence value of 1.00000, and the contour shown sequentially is the first, secondary mode having the next largest coherence value. The Coherence value has some limit that

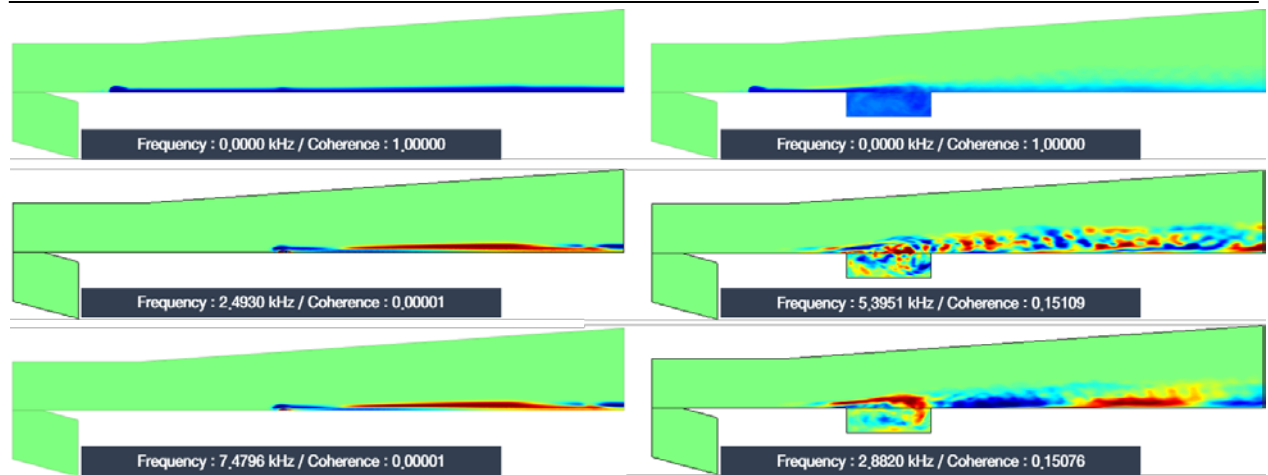


Figure 2. DMD result of 0.5 MPa injection pressure case : without cavity case(left) and with cavity case(right)

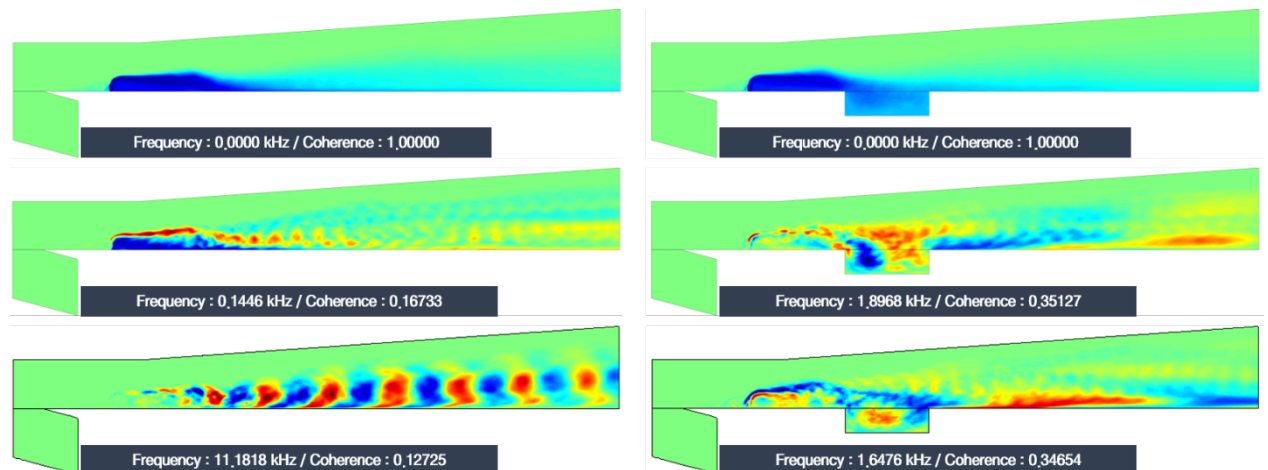


Figure 3 DMD result of 1.0 MPa injection pressure case : without cavity case(left) and with cavity case(right)

inaccurate to indicate the absolute amount of energy each mode has, but it is effective to indicate relative rank.

In Fig. 3, the primary mode of both case exhibits a very similar behavior to the time-averaged result of the numerical analysis. But, except for the primary mode, the first mode which has the next largest coherence value clearly shows the effect of cavity for the fuel mixing. The fuel mixing in the case of a without cavity begins quite far away from the fuel injection point. But in the opposite case, it can be confirmed that mixing start point is relatively get close to the injection point. In addition, from the viewpoint of the homogeneity of the mixing, it can be confirmed that the length of mixing interval is relatively longer when the case of without cavity. From these results, as mentioned earlier, it can be confirm from the DMD analysis that these points which are difficult to see in the results of the numerical analysis such as the starting point of fuel mixing and tendency of the sub-modes.

Also, case of without cavity which is considered to have a relatively low mixing performance based on the previous results lead to the low coherence value. These tendencies appear the same in secondary mode as

well as first mode. There are some inaccuracies in comparing the absolute contain of energy that the modes have, but nonetheless it can be seen that the difference is significant depending on the existence of cavity in the result. In short, if there is no cavity, the fuel mixing starts at a far distance from the fuel injection point, and the mixing performance in the combustion chamber length and height direction is low, and even these has low energy.

Fig. 5 shows the DMD result of the condition that the fuel injection pressure is 1.0 MPa. Although the secondary mode of the no cavity condition is a little lack, both cases, the point at which the mixing begins is closer to the fuel injection point than the result of the 0.5 MPa case. It also shows better mixing performance in the direction of the combustor height, which is a very improved result compared to the 0.5 MPa condition. Both conditions appear to have improved mixing performance compared 0.5 MPa case due to the increase in fuel injection pressure. However, the case of without cavity, there shows a tendency for a kind of uniform perturbation along the combustor height and flow path direction in mixing flow, while the opposite condition is not. Also, as same of 0.5 MPa result, the coherence value of with cavity case has higher then opposite case.

Table 2: Coherence value of DMD mode

	$P_{\text{inject}} : 0.5 \text{ MPa}$		$P_{\text{inject}} : 1.0 \text{ MPa}$	
	W/o cavity	W/ cavity	W/o cavity	W/ cavity
Primary mode	1.00000	1.00000	1.00000	1.00000
First mode	0.00001	0.15109	0.16733	0.35127
Secondary mode	0.00001	0.15076	0.12725	0.34654

4 Conclusion

In this paper, we were conducted a study to confirm the effect of cavity on fuel mixing in a supersonic combustor which has transverse fuel injection. DMD, a modal decomposition method that can capture and divide the dynamic behavior of the flow over time, was applied to analyze the mixing characteristics of the propellant. Through the computational results of the H_2 mass fraction were analyzed by the DMD, the dominant behavior of the fuel mixing was captured by decomposing the primary and sub modes. In the results of the sub modes, first and secondary mode, the effect of the cavity and the fuel injection pressure on the fuel mixture could be confirmed.

Acknowledgements

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