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COMPUTATIONAL STUDY ON SUPERSONIC MIXING ENHANCEMENT BY CAVITY-INDUCED FLOW OSCILLATIONS

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Abstract*- This paper presents cavity-induced oscillations exhibited by supersonic internal flow past a square cavity with modified wall geometry at leading edge in order to make out optimal geometry for applications in supersonic fuel-air mixing enhancement. A computational investigation has been carried out to determine the effect of oscillation induced by a supersonic flow past a square cavity with a leading edge plate at a Mach number 1.83 at the cavity entrance on supersonic mixing enhancement required for supersonic combustion ramjets. Cavity-induced oscillations are observed at the flow region downstream of the trailing edge of the cavity where fuel-air mixing is supposed to take place. The unsteadiness in the flow field and the formation of feedback loop in the cavity causes the pressure oscillations that would be helpful in mixing the fuel with air. Increased amplitudes of oscillations are observed at the same flow region downstream of the cavity by changing the geometry of the front wall of the square cavity. Therefore, enhancement of mixing is expecting due to this larger oscillations due to cavity with modified front wall geometry.*

Keywords: Mixing enhancement, Supersonic flow, Cavity-induced oscillations

1. INTRODUCTION

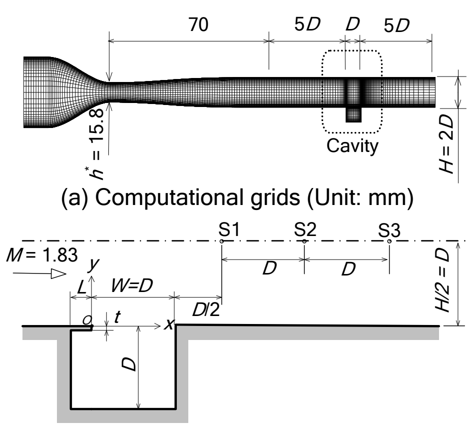
The main components of high speed transportation vehicles are supersonic air breathing engines. As the flow speed is very high, the time available for fuel injection, air-fuel mixing, and combustion is very low. For efficient combustion in high speed transportation vehicles, a successful fuel injection system should provide the facility of mixing the fuel with air streams within a very short time. Nowadays, the enhancement of supersonic mixing has become one of the most important issues in the development of high speed transportation vehicles such as scramjet engine. Techniques to enhance supersonic mixing can be primarily categorized as passive and active according to the requirement of the external energy input to the flow. Active control technique of supersonic mixing enhancement is a mechanical or physical means of controlling the flow and it can offer better performance for a wide range of flow conditions. A major issue with active control techniques is understanding the time-dependent behavior of the supersonic flow as well as the added weight and complexity of actuators or systems. In passive mixing enhancement a geometrical device is placed in or adjacent to the flow in order to modify the flow to produce the desired results. The passive control techniques do not require external energy and are simple and inexpensive compared to the active ones. Again, the passive technique seems to offer more robust operation due to its lack of moving parts and relatively low weight penalties. These techniques include ramp injectors, lobed strut, tabs, swirlers, chevrons, steps and cavities. Seiner et al. [1] has presented a review of the history of implementing such fuel-air mixing enhancement technique in scramjet engines.

Cavity based mixing enhancement have attracted considerable attention in recent times in supersonic combustion scramjets community [2-6]. Yu and Schadow [2] suggested for the first time that the cavity-induced flow oscillations could be used to enhance the mixing in supersonic combustion. In their experimental investigation, they used a cavity-actuated forcing technique for increasing the spreading rate of compressible shear layer successfully. Sato et al. [3] studied the effects of pressure waves generated from a wall mounted cavity and reported that the pressure waves aided the enhancement of mixing process effectively. Nenmeni and Yu [4] examined the effects of duct confinement on cavity-induced supersonic mixing enhancement under various stagnation pressures. In their method, they mounted a rectangular cavity on the duct wall upstream of a gas injector, and the cavity and the injector are on the same wall of the rectangular duct. The also used schlieren method for visualizing the flow fields and measured the effects of cavity length-to-depth ratio and the relative ratio between the duct height and cavity depth. Anavaradham et al. [5] conducted an experimental investigation to determine the effect of liquid injection on the acoustic field generated by confined supersonic oscillatory cavity flow. Handa et al. [6] studied experimentally the effects of cavity induced flow oscillations on the supersonic mixing enhancement. They determine the effects of oscillation frequency on the mixing enhancement by varying the length-to-depth ratio of the cavity. Visualizing the flow by schlieren method and laser-induced acetone fluorescence, they revealed that the mixing was enhanced most successfully in the flow field that oscillation occurred at the highest frequency. The focus of this paper is to determine the effectiveness of passive way of mixing enhancement by using leading edge plate or sub-cavity near the front wall of a square cavity subjected to supersonic flows.

2. CFD ANALYSIS

The governing equations are two-dimensional unsteady compressible Navier-Stokes equations coupled with turbulence kinetic energy and eddy viscosity equations. A modified *k-R* (turbulent kinetic energy-eddy viscosity) turbulence model [7-9] is used in this simulation. A third-order TVD (Total Variation Diminishing) finite difference scheme with MUSCL [10] is used to discretize the spatial derivatives and a second order central difference scheme for the viscous terms, and a second-order fractional step is employed for time integration.

Figure 1 shows computational domain of a supersonic flow field with cavity under investigation. The height of the main flow section at the entrance of the cavity is 24 mm. The cavity depth *D* (=12 mm) and its length *W* are the same. S1 in this figure denotes the measuring position of static pressure. The parameters of cavity configurations are summarized in Table 1.



(b) Details of cavity configuration

Fig.1 Computational domain

Table 1: Parameters of cavity configuration

Parameters	*L/D*	*t/D*
Without control	0.00	1.00
Case 1	-0.25	0.25
Case 2	-0.25	0.30

3. EXPERIMENTAL PROCEDURE

Experiments were conducted in order to verify the validity of calculation results. A supersonic indraft wind tunnel [11] where dry air at atmospheric pressure was drawn into a vacuum tank, was used in the present experiment. Test section has a height of 60 mm, a length of 553 mm and a width of 38 mm. A two dimensional Laval nozzle is set in the test section. Variations of static pressure were measured using a pressure transducer installed at the same position as that in calculation. The reservoir pressure and temperature are the same as computational ones.

4. RESULTS AND DISCUSSIONS

4.1 Effects of Cavity on Fuel-Air Mixing

In order to validate the computational code developed for the present numerical simulation, a two-dimensional open square cavity of length to depth ratio = 1.0 at Mach number *M* =1.83 at the cavity entrance was investigated in case without control and the solutions were compared with the present experimental results. The solutions were also compared with the experimental and numerical results of other researchers [12-14]. Figure 2 shows a comparison of the Strouhal numbers *St* among numerical, experimental and theoretical results. Open circle represents the experimental results reported by Zhang and Edwards [12] and Takakura et al. [13]. Solid lines are drawn by using the formulae of predicting oscillation frequencies proposed by Nishioka et al. [14]. Closed circle represents the results of the present simulation and the triangle represents the results of present experiments. The comparison shows a fairly good agreement between the present simulated and experimental results. The results also show a good agreement with the experimental and theoretical results of other researchers [12-14].

Figures 3(a) shows the time history of static pressure at the position S1 inside the cavity for case with a cavity (length to depth ratio = 1) without control. There exists some amplitude of oscillations at the position S1 as

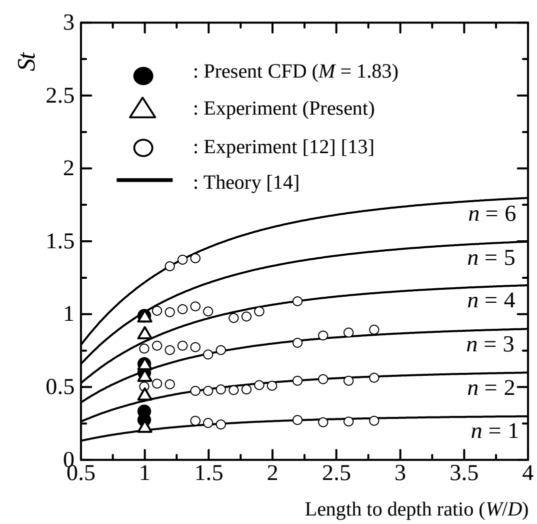
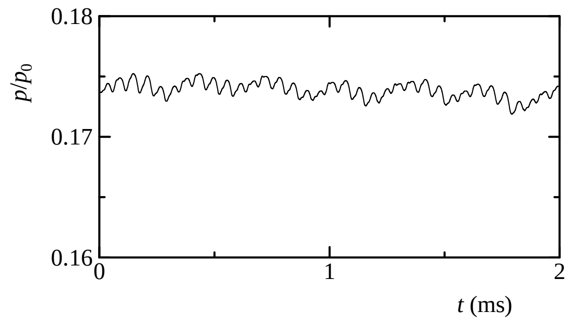
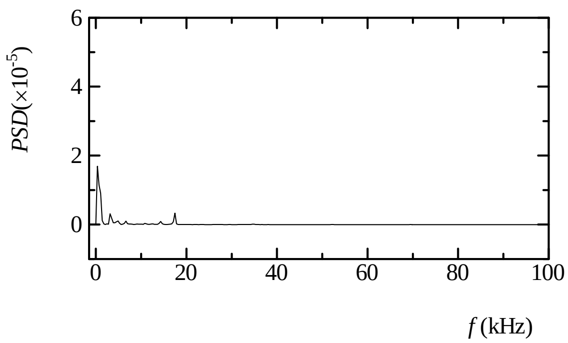


Fig.2 Comparison of simulation results with experimental and theoretical results

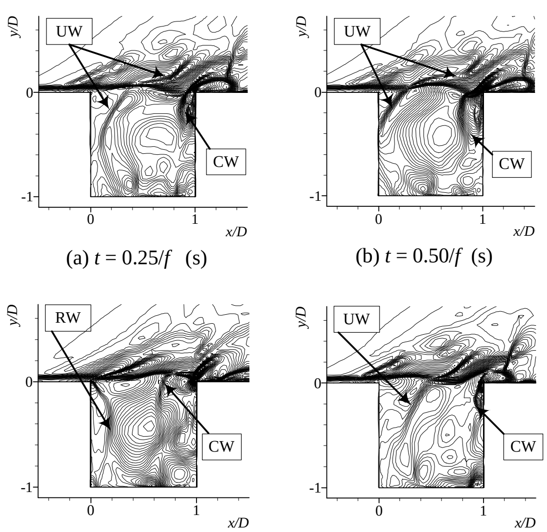


(a) Time history of static pressure



(b) Power spectrum density

Fig.3 Time history of static pressure and power spectrum density (without control)

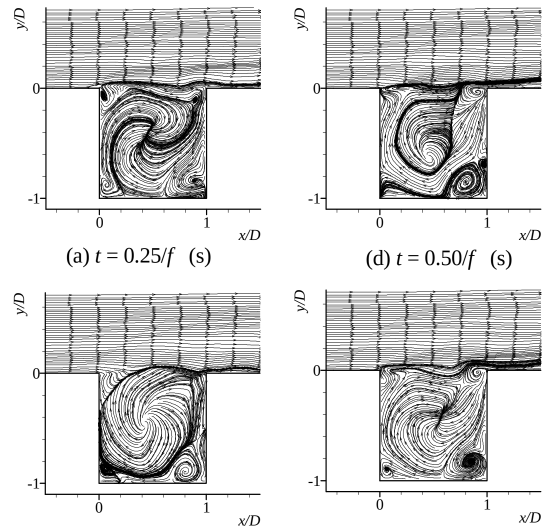


(a) $t = 0.25/f$ (s)
(b) $t = 0.50/f$ (s)
(c) $t = 0.75/f$ (s)
(d) $t = 1.00/f$ (s)

Fig.4 Contour maps of density (without control)

shown in Fig.3(a). Distribution of power spectrum density obtained from the static pressure history is shown in Fig.3(b). There is a dominant frequency at 0.355 kHz in case of cavity without control.

Figure 4 shows contour maps of density during one period of flow oscillations for the cavity without control. It is observed that a compression wave (CW) from the trailing edge of the cavity moves upstream as time proceeds (Fig.4(a)). The upstream compression wave (UW) impinges on the cavity leading edge (Fig.4(b)) and the reflection occurs (Fig.4(c)). The reflected compression wave (RW) disturbs the shear layer near the leading edge of the cavity. This disturbance regenerates instability waves in the shear layer. While the shear layer reattaches at the cavity rear wall, the compression wave (CW) is generated due to the impingement of instability waves on the wall as shown in Fig.4(d). The compression wave thus produced, moves to upstream direction and becomes the upstream compression wave (UW) as shown in the Fig.4(d). This completes the formation of the feedback loop. Therefore, a similar sequence of activities and the formation of typical feedback loop in the cavity were observed in the present numerical simulation that was in a good agreement with those reported by Rossiter [15], Heller and Bliss [16] and Nishioka et al. [17]. The unsteadiness in the flow field due to cavity and the consequent emission of acoustic oscillations would be helpful to enhance the fuel-air mixing process.



(a) $t = 0.25/f$ (s)
(d) $t = 0.50/f$ (s)
(b) $t = 0.75/f$ (s)
(e) $t = 1.00/f$ (s)

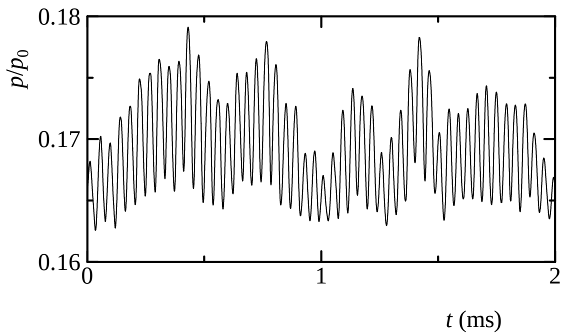
Fig.5 Streamlines (without control)

Figure 5 shows the streamlines of flowfield oscillations in a square cavity without control. There is an unstable shear layer and a single, large vortex in the cavity accompanied by some small vortices in the corner. Therefore, the flowfield inside a cavity can be characterized by flow circulation that increases the residence time of flow entering the cavity. This retardation of flow velocity helps to enhance the mixing process.

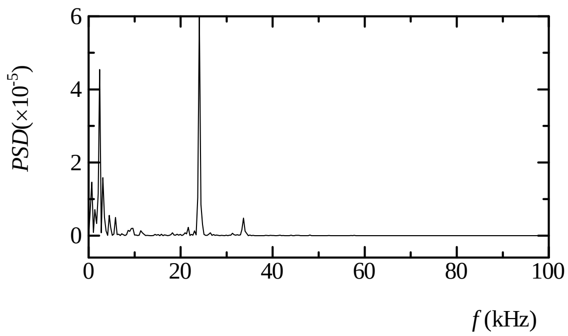
4.2 Effects of Cavity with Thick Plate on Mixing

Figure 6(a) shows the time history of the static pressure at the position S1 downstream of the cavity with control (Case 1). A substantial increase of the amplitudes is obtained when a leading edge plate is introduced in the cavity as shown in Fig.6(a). Distribution of power spectrum density obtained from the static pressure history is shown in Fig.6(b). There are several strong peak frequencies for this case.

Figure 7 shows time history of static pressure and power spectrum density for Case 2. The amplitude showed a similar tendency compared with that of the

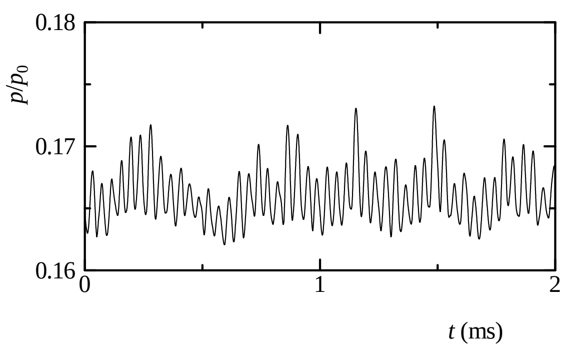


(a) Time history of static pressure

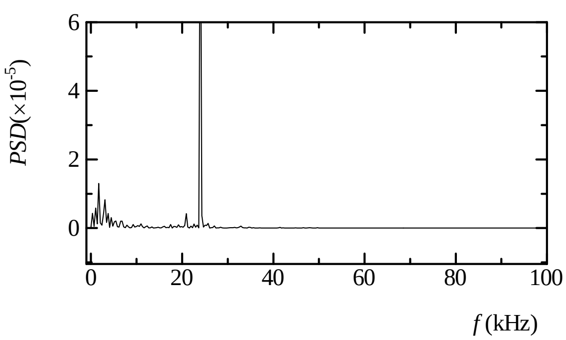


(b) Power spectrum density

Fig.6 Time history of static pressure and power spectrum density (Case 1)



(a) Time history of static pressure



(b) Power spectrum density

Fig.7 Time history of static pressure and power spectrum density (Case 2)

cavity without control and there were some strong peak frequencies for power spectrum density. Therefore, more unsteadiness in the flow field due to cavity with thick leading edge plate and the consequent emission of acoustic oscillations would be more helpful to enhance the fuel-air mixing process.

5. CONCLUSIONS

As the first step of study on the proposed cavity with thick leading edge plate, regarding supersonic air-fulel mixing enhancement, the effects of cavity with and without control on the mixing enhancement were investigated numerically in this study.

The results are summarised as follows:

(1) The unsteadiness in the flowfield due to cavity and the consequent emission of acoustic oscillations are helpful in enhancing the mixing.

(2) The circulation of flow due to cavity increases the residence time of flow entering the cavity and this retarding flow helps to enhance the mixing.

(3) More unsteadiness in the flow field due to cavity with thick leading edge plate and the consequent emission of acoustic oscillations would be more helpful to enhance the fuel-air mixing process.

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7. NOMENCLATURE

Symbol	Meaning	Unit
D	Cavity depth	(mm)
f	Frequency of oscillations	(Hz)
h	Throat height	(mm)
H	Height of main flow section	(mm)
L	Plate length	(mm)
M	Mach number	Dimentio-nless
p	Static pressure	(Pa)
P	Power spectrum density	Dimentio-nless
t	Time	(sec)
W	Cavity length	(mm)
x,y	Cartesian coordinates	(m)