

Interaction Phenomena in Supersonic Combustors

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1 Introduction

Supersonic combustion ramjet and its combination with rocket engines (so-called Rocket-Based Combined Cycle engines) are expected to be efficient propulsion system both for cruise missions and acceleration missions like launch vehicles [1]. The supersonic flow into the combustor will be decelerated due to heat release, either through oblique shock train to moderate supersonic speed, or through pseudo shock wave system to subsonic speed, the latter called as dual-mode combustion [2]. The oblique shock train can penetrate the injector location with boundary layer separation, so that the airflow can be compressed in prior to heat release. This drastic change in the flow field, in turn, alters the fuel-jet/airflow mixing process [3] to make this combustion phenomena within the supersonic combustor very complicated. Still, the fuel injection is the key control factor especially for the acceleration missions with airflow condition varying from moment to moment. Thus, the interaction between the airflow condition (or combustion mode) and the fuel / airflow mixing process is very important and interesting theme.

In this presentation, combustor tests relating to the above mentioned interactions are described, with emphasis on the change in airflow conditions due to pressure-rise.

2 Combustion in different modes

Figure 1 shows the schematics of the direct connect facility / combustor used for combustion tests [4]. The major target of the tests was to find the effects of several wall-flush-mount fuel injection schemes on combustion phenomena. Supersonic injection through a diamond-shaped orifice with very fair interaction with the supersonic freestream [5] and under-expanded sonic injection through a circular orifice with relatively intensive interaction with the supersonic freestream, were compared, both with identical orifice equivalent diameter (6 mm) so that injection pressure was almost identical for both orifices. Room temperature gaseous hydrogen was injected perpendicular to the airflow. A high-enthalpy airflow with a total temperature (T_0) of $2000\text{ K} \pm 5\%$, and a total pressure (P_0) of $1.0\text{ MPa} \pm 5\%$, was supplied from a vitiation air heater and was accelerated to Mach 2.44 through a rectangular nozzle with the exit cross-sectional area of 51 mm (height) by 94.3 mm (width). Static pressure at the exit of the nozzle was about $0.062 \times P_0$. Oxygen was added to maintain the oxygen fraction of the

vitiated airflow to be $21.0 \text{ vol.}\% \pm 5\%$. The vitiated airflow contained approximately 26 % water vapor in mole fraction. A rectangular combustor was directly connected to the nozzle. The cross-section of the combustor remained constant for 507 mm from the nozzle exit, and then expanded in its height direction at an angle of 1.66 degrees for 635 mm, while the width was constant to be 94.3 mm through the combustor. In basic configuration, center of the orifice was 131 mm upstream of the onset of the diverging duct. In some cases, a 15 mm deep and 90 mm long recess was installed with its upstream-end step at 55 mm downstream of the orifice center which was 186 mm upstream of the onset. The downstream-end (aft-) wall of the recess had 60 degrees of swept-back angle. A portion of the fuel was injected into the recess directly if necessary.

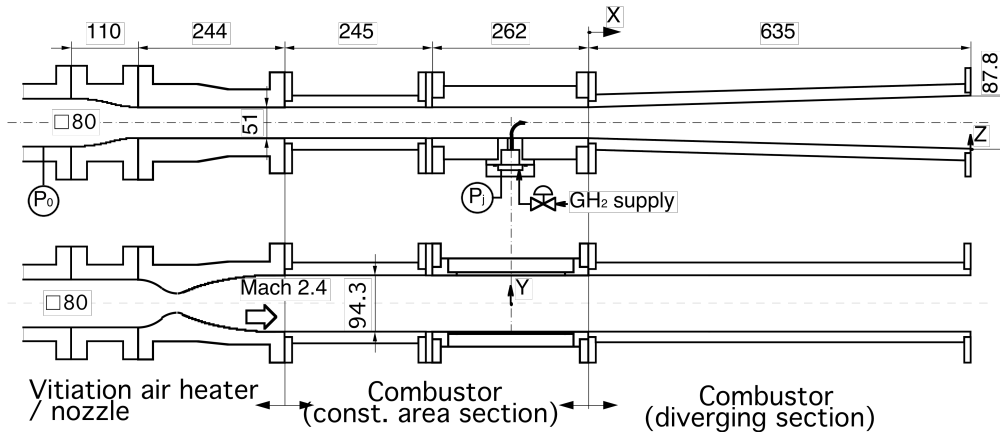


Figure 1. Experimental apparatus

Figures 2 show typical pressure distributions without recess installation. With small fuel flow rate (equivalence ratio; $\phi \sim 0.3$), so called (pure) supersonic combustion was attained with both injection configurations. Pressure level at far downstream portion of the diverging duct was slightly higher with the diamond-shaped orifice because of a better penetration performance with the diamond-shaped orifice as will be shown later. With increased fuel flow rate ($\phi \sim 0.5$), pressure-rise was attained around the circular orifice as the plume through the orifice had more intensive jet / freestream interaction and consequent high-pressure ignition region ahead of the orifice. When the recess and recess injection were applied (results not shown in Figs. 2), almost equally intensive pressure-rise was attained around the orifice. In these cases, the oblique shock train penetrated the orifice location. With higher fuel flow rate ($\phi \sim 0.7$), so-called dual-mode combustion was attained in both orifice cases. One should note that the pressure distributions were almost identical regardless of the injection configuration, so that the injection configurations had no sizable effects on the mixing process under dual-mode combustion.

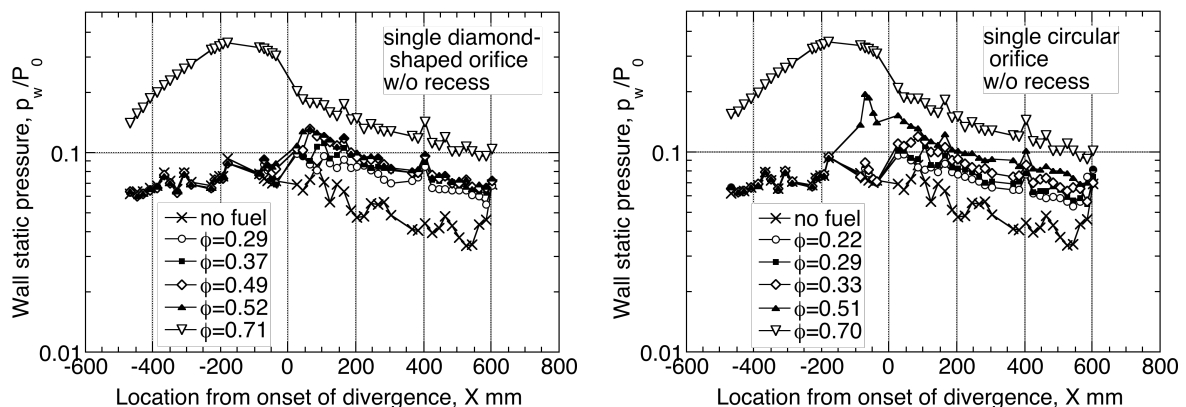


Figure 2. Wall pressure distributions with diamond-shaped orifice (left) and circular orifice (right)

Figures 3 show fuel distributions at the exit of the diverging duct on the symmetry ($Y=0$) plane at $\phi=0.3$. In the pure supersonic combustion case, injection configuration had sizable effects on the fuel distribution, i.e., mixing process, with a larger penetration with the supersonic injection through the diamond-shaped orifice as shown in the past mixing tests [5]. When the oblique shock train penetrated the orifice location, a sudden change in the fuel distribution was observed, the plume core disappeared and spanwise diffusion enhanced. In this case, the injection configuration had little effects on the fuel distribution. Thus, interaction between the fuel jet and the oblique shock train dominated the mixing process.

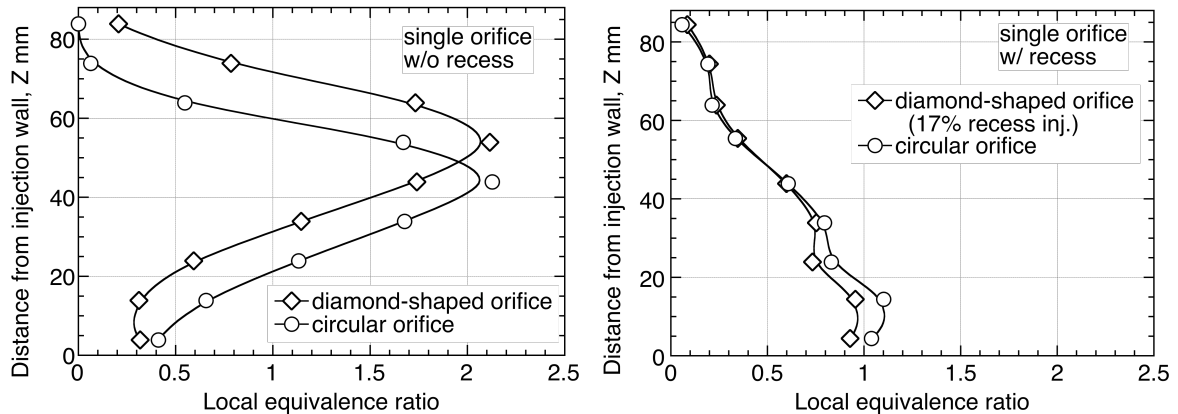


Figure 3. Fuel distributions at combustor exit in the pure supersonic combustion case (left) and in the presence of the oblique shock train penetrating orifice location (right).

3 Mixing control under dual-mode combustion by injection scheme

As shown in previous section, perpendicular injection schemes had little effects on the mixing process when shock wave system (either oblique shock train or pseudo shock wave) penetrated the orifice location. However, fuel injection was still the major (or only) possible control device on the engine operation conditions, so that the possibility of mixing control by injection scheme was further pursued. Figure 4 shows the experimental setup. Mixing experiments were conducted with a mechanical throttling to anchor the shock wave system (pseudo shock wave) at a certain location, i.e., injection orifice located at a halfway of the pseudo shock wave. Room-temperature helium was injected into a M2.5, room-temperature airflow. The facility nozzle and combustor was identical to these in the last section, while the diverging duct was removed and a straight duct was added when necessary.

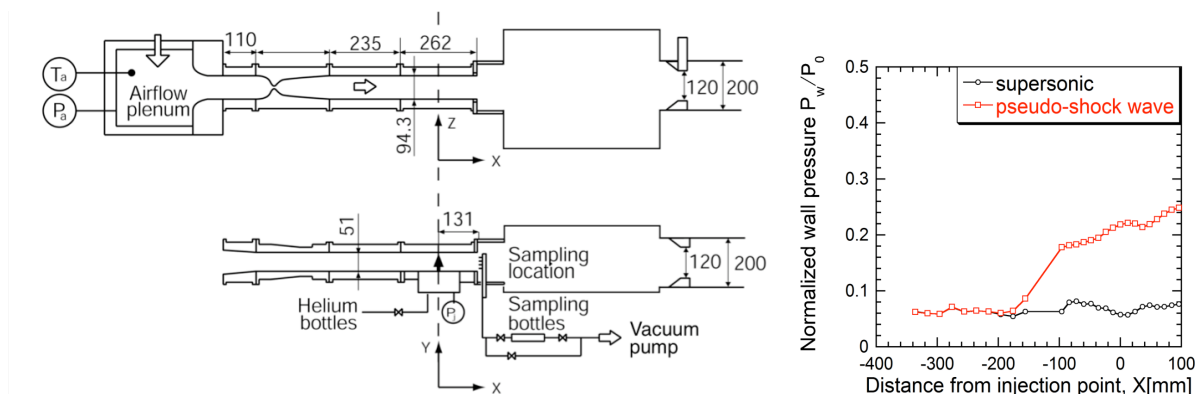


Figure 4. Experimental apparatus (left) and pressure distribution in case with mechanical throttling (right).

Both perpendicular and angled circular orifices (6 mm in diameter) were used for under-expanded sonic injection. The swept-back angle was 60 degrees.

Figures 5 show injectant contour at 131 mm downstream of the orifice center. The left half of each figure shows the contour in the presence of the pseudo shock wave system, and the right half shows that without pseudo shock wave system (i.e., supersonic freestream case). In the supersonic freestream case, the perpendicular injection showed better penetration than the angled injection as shown in previous studies [7]. When the perpendicular plume interacted with the pseudo shock wave system, the contour changed drastically. The plume core penetration was reduced, while the plume extent in height direction was almost identical. The maximum concentration was drastically reduced, showing that the plume diffused in the spanwise direction rapidly. In the case with the angled injection, the maximum concentration was still high though the spanwise diffusion was visible. Both core penetration and extent were reduced. Thus, angled injection can provide different mixing characteristics from the perpendicular injection, and their combination will be effective for mixing control in dual-mode and/or supersonic combustion with oblique shock train penetration.

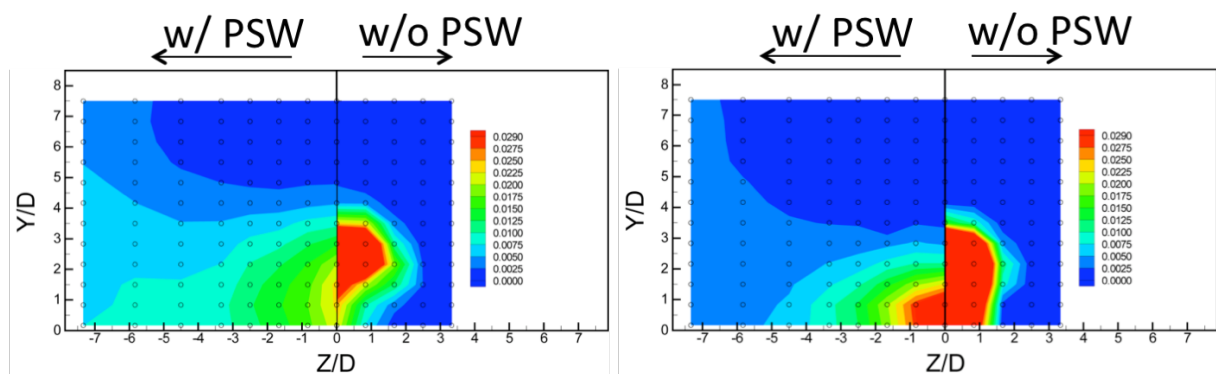


Figure 5. Injectant contour with perpendicular injection (left) and angled injection (right).

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