Extended Abstract submitted to
19th ICDERS, July 27 - August 1, 2003 Hakone Prince Hotel, Hakone, Kanagawa, Japan

Combustion and Flow Oscillations in Scramjet Engines with Perpendicular Injection of Hydrogen in Air

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Abstract

Perpendicular fuel injection in a channel type combustor is a simplest form of scramjet combustor configuration widely used in many experimental studies. A number of numerical studies have been carried out for this configuration, and most of them are focused on the fuel/air mixing, combustion and propulsion efficiencies. However a little is known for flow and combustion instabilities inside the supersonic combustor. Thus, a comprehensive numerical study is carried out to investigate the flow evolution and flame development in a supersonic combustor with perpendicular injection of hydrogen in air. The formulation treats the complete conservation equations of mass, momentum, energy, and species concentration for a multi-component chemically reacting system. It also accommodates a finite-rate chemical kinetics mechanism of hydrogen-air combustion GRI-Mech. 2.11[1], which consists of nine species and twenty-five reaction steps. Turbulence closure is achieved by means of a k-ω two-equation model [2]. The governing equations are spatially discretized using a finite-volume approach with MUSCL-type TVD scheme, and temporally integrated by means of a second-order accurate implicit scheme [3~5].

Most of the experimental supersonic combustor configuration uses a hole-type fuel injector. But, present study considers two-dimensional combustor configuration with a fuel injection slit to ensure the grid resolution necessary to capture the flow field details. The supersonic combustor consists of a flat channel of 10 cm height and a fuel-injection slit of 0.1 cm width located at 10 cm downstream of the inlet. A combustor configuration with a cavity is also considered to identify the role of the cavity in comparison with the combustor without cavity. The cavity of 5 cm height and 20 cm width is installed at 15 cm downstream of the injection slit. A total of 936×160 grids are used for the main-combustor flow passage, and 159×161 grids for the cavity. The grids are clustered in the flow direction near the fuel injector and cavity, as well as in the vertical direction near the bottom wall. The no-slip and adiabatic conditions are assumed throughout the entire wall boundary. As a specific example, the inflow Mach number is assumed to be 3, and the temperature and pressure are 600 K and 0.1 MPa, respectively. This combustor inlet condition is roughly equivalent to flight Mach number 5

to 6 at 20km altitude, although the exact condition depends on the inlet configuration. Gaseous hydrogen at a temperature of 151.5 K is injected normal to the wall from a choked injector.

A series of calculations were carried out for the combustor configuration without a cavity and with a cavity by varying the fuel injection pressure from 0.5 to 1.5 MPa. This amounts to changing the fuel mass flow rate or the overall equivalence ratio for different operating regimes. The corresponding equivalence ratios are 0.167, 0.33 and 0.50. Figure 1 and 2 shows the instantaneous temperature fields in the supersonic combustor without and with cavity at four different conditions at a same instance from the start of the fuel injection. The dark blue region represents the hot burned gases. At the fuel injection pressure of 0.5 MPa, the flame is stably anchored, but the flowfield exhibits a high-amplitude oscillation. At the fuel injection pressure of 1.0 MPa, the Mach reflection occurs ahead of the injector. The interaction between the incoming air and the injection flow becomes much more complex, and the fuel/air mixing is strongly enhanced. The Mach reflection oscillates and results in a strong fluctuation in the combustor wall pressure. At the fuel injection pressure of 1.5 MPa, the flow inside the combustor becomes nearly choked and the Mach reflection is displaced forward. The leading shock wave moves slowly toward the inlet, and eventually causes the combustor-upstart due to the thermal choking. The cavity appears to play a secondary role in driving the flow unsteadiness, in spite of its influence on the fuel/air mixing and flame evolution. Further investigation is necessary on this issue. Figure 3 shows temporal evolution pressure at probe 7 (10 cm behind the injector) for four difference cases. The pressure oscillation increases with respect to the equivalence ration and presence of cavity. The major oscillation frequency is the order of 20kHz.

The present study features detailed resolution of the flow and flame dynamics in the combustor, which was not typically available in most of the previous works. In particular, the oscillatory flow characteristics are captured at a scale sufficient to identify the underlying physical mechanisms. Much of the flow unsteadiness is not related to the cavity, but rather to the intrinsic unsteadiness in the flowfield, as also shown experimentally by Ben-Yakar e al. [6]. The interactions between the unsteady flow and flame evolution may cause a large excursion of flow oscillation. The work appears to be the first of its kind in the numerical study of combustion oscillations in a supersonic combustor, although a similar phenomenon was previously reported experimentally.

References

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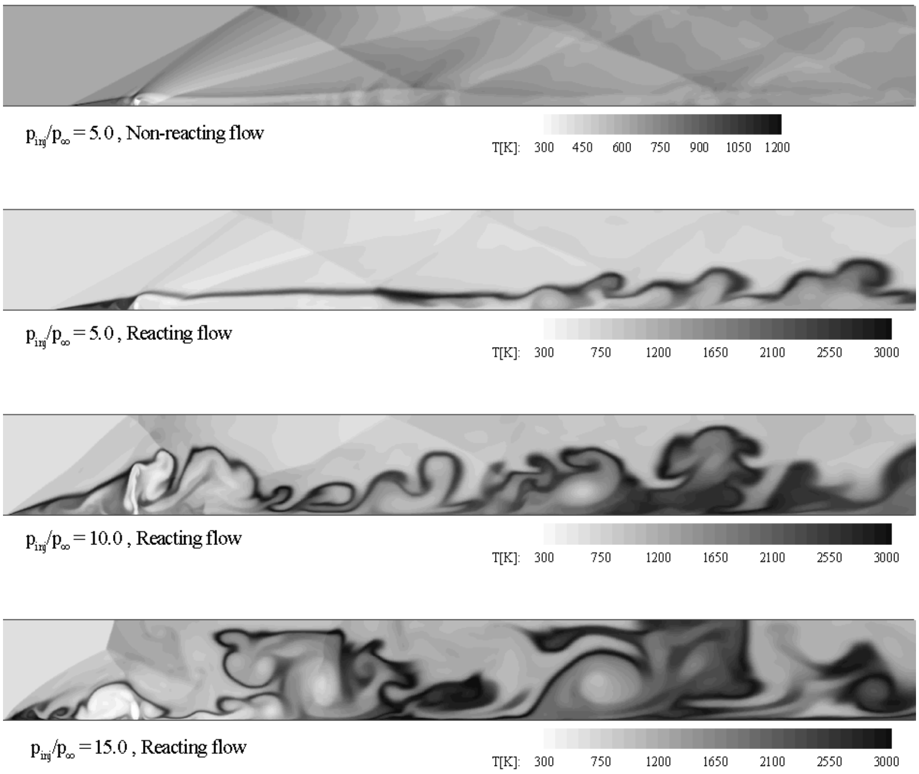

Fig. 1 Snapshots of temperature fields in a supersonic without a cavity

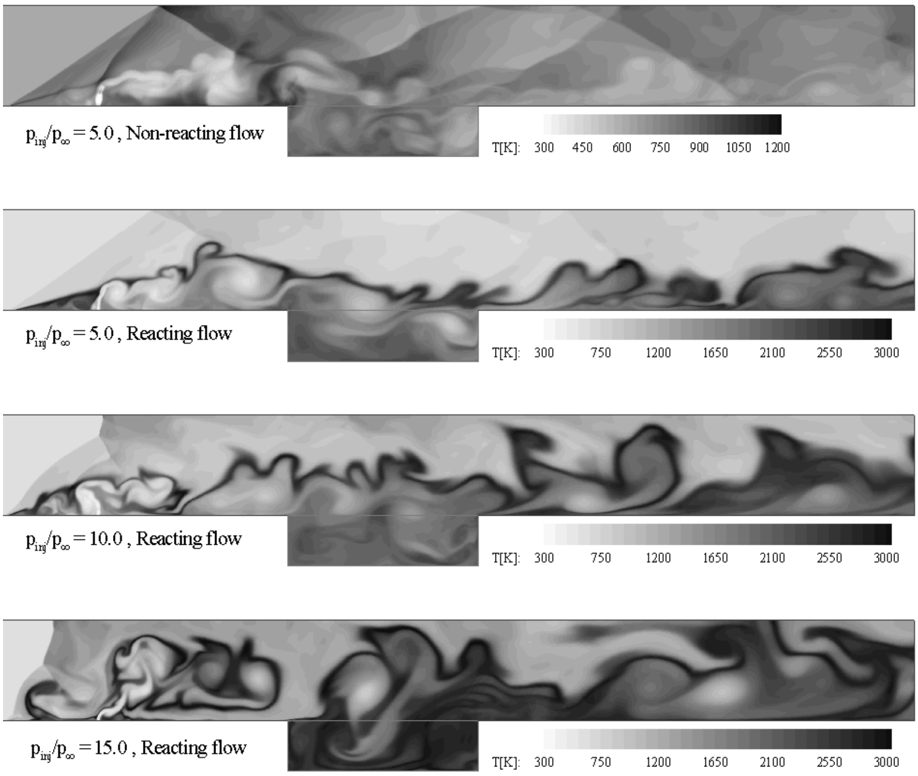

Fig. 2 Snapshots of temperature fields in a supersonic combustor with a cavity

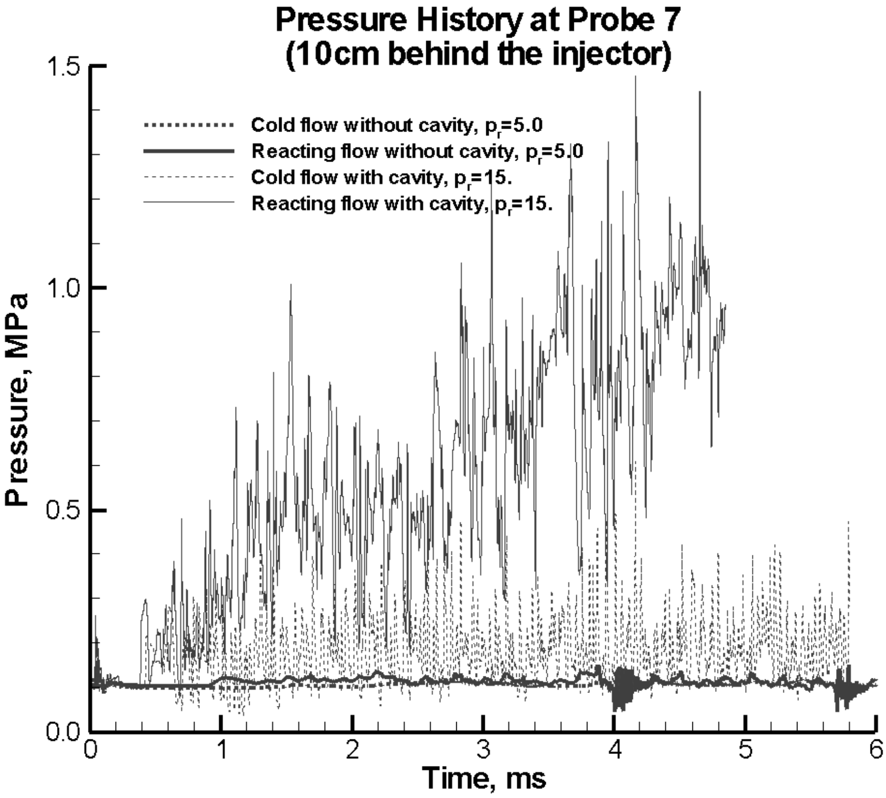

Fig. 3 Temporal evolution pressure at probe 7 (10 cm behind the injector) for four difference cases