A01-34556

AIAA 2001-3935

Measured Characteristics of Flow and Combustion in Supersonic Flame/Shock Wave Interaction

Hwanil Huh, Jungyong Kim
Department of Aerospace Engineering
Chungnam National University
Daejeon 305-764, Korea

and

James F. Driscoll
Department of Aerospace Engineering
University of Michigan
Ann Arbor, MI 48109-2118

37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit July 8-11, 2001/Salt Lake City, UT

MEASURED CHARACTERISTICS OF FLOW AND COMBUSTION IN SUPERSONIC FLAME/SHOCK WAVE INTERACTION

Hwanil Huh* **and Jungyong Kim†**
Department of Aerospace Engineering, Chungnam National University
Daejeon 305-764, KOREA

James F. Driscoll‡
Department of Aerospace Engineering, University of Michigan
Ann Arbor, MI 48109-2118

ABSTRACT

Characteristics of flow and combustion in a supersonic combustor were investigated experimentally to understand the effect of shock waves on the supersonic jet flame of the simple geometry. A hydrogen jet flame was stabilized on the axis of a Mach 2.5 supersonic wind tunnel, and to explain why some flames were greatly stabilized, schlieren images, wall static pressures, and pitot pressures were measured. The purpose of this study was to provide database of wall static pressures, pitot pressures and schlieren images for numerical analyst to assess chemistry models of numerical simulations on supersonic flame/shock wave interaction. Also, in order to explain enhancing mechanism of flame stability when shock waves were present, characteristics of supersonic flow in a supersonic flame/shock wave interaction were discussed. Wedge induced shock wave at the fuel nozzle edge and the resulting impinging shock waves on the hot recirculation zone were believed to enhance supersonic flame stabilization.

* Assistant Professor, Department of Aerospace Engineering, Chungnam National University, Member AIAA.

† Graduate Student, Department of Aerospace Engineering, Chungnam National University, Student member AIAA.

‡ Professor, Department of Aerospace Engineering, University of Michigan, Senior member AIAA.

INTRODUCTION

Scramjet-installed airbreathing propulsion systems have the potential advantage over comparable rocket-powered systems. Their advantages are increased payload capability and additional range since oxidizer does not have to be carried for combustion. Recently Pratt & Whitney and the U.S. Air Force have successfully run a hydrocarbon-fueled scramjet engine at hypersonic speeds in freejet test. The first flight of scramjet-powered Hyper-X vehicle is scheduled to operate in mid-June. Scramjet propulsion is the revolutionary technology to be employed in supersonic transport and aerospace mission. With these reasons, researchers are renewably focusing on supersonic combustion studies in scramjet to develop hypersonic airbreathing propulsion system.

One of the most pronounced effects of shock waves on fuel-air mixing has been identified by Marble's researches. Marble reported that the baroclinic torque could create shock-generated vorticity mechanism as a means of mixing enhancement[1]. The oblique shock waves in a scramjet combustor may have the positive effects of enhancing fuel-air mixing and helping to stabilize the flame. Recently, Huh and Driscoll[2] reported that shock waves enhanced the fuel-air mixing and improved the flame stability limit substantially, when optimum oblique shock waves were introduced in a supersonic jet-like flame. The shock waves due to the wedge were expected to create a radially inward/ outward airflow to the flame, additional vorticity and an adverse pressure gradient[2]. Hence, the air entrainment rate and mixing rate will be enhanced near the flame base, which may help stabilization of supersonic flame. Recirculation zones behind the bluff-body can be elongated by the shock waves resulting in the extension of stability limit[3].

Roy and Edwards[4] simulated the complex flame/shock wave interaction experiments conducted by Huh and Driscoll[2,5]. They explained that the process of flame stabilization appeared to be a synergistic balance between inviscid gas-dynamic processes and dissipative/reactive processes. Also, they argue that there exists a self-sustaining mechanism that helps stabilize the flame. In order to explain enhancing mechanism of flame stability when shock waves are present, characteristics of supersonic flow in a supersonic flame/shock wave interaction are discussed.

EXPERIMENTAL METHODS

As shown in Fig. 1 and Fig. 2, a hydrogen fuel jet is injected at sonic speed in the Mach 2.5 air flow using a thick-lip fuel tube, which acts as a bluff body. The combustor is 5.7 cm high at the fuel injection location. The width of the combustor is fixed at 4.06 cm. Length of the combustor window from the fuel injection plane is 27.3 cm. The inner diameter of the fuel nozzle (d_F) is 0.7 cm and the outer diameter is 2.54 cm; therefore, the nozzle lip thickness is 0.92 cm. Combustor sidewalls diverge at 4° from the axis in order to prevent thermal choking[2]. Two identical wedges are mounted on the side walls of the combustor in order to interact the planar oblique shock waves with the hydrogen-air jet like flame as shown in Fig.1 and Fig. 2. The angle of the wedge is 10° to the side-walls and the leading edge location of the wedge is $4d_F$ downstream of the fuel injection plane.

Two kinds of wedges are used to investigate the effect of wedge thickness on the supersonic flame/shock wave interaction. Figure 3 shows the features of the two wedges; the 10° wedge and the slender 10° wedge. Both wedges had the same 10° wedge angle to generate the same shock wave strength. However, the thicknesses of two wedges are different, while their length is fixed at 5.08 cm.

Air is injected at static temperature of 284 K and stagnation pressure of 6.44 atm as shown in Table 1. These conditions correspond to the pressure at the combustor with the flight Mach number of 6 at an altitude of 30 km, where atmosphere temperature is 223 K and pressure is 0.01 atm. Wall static pressures, pitot pressures as well as Schlieren photographs are measured.

RESULTS AND DISCUSSION

Mixing-enhancing mechanism

Figure 4 explains the possible importance of baroclinic torque mechanisms as a means of mixing enhancement[1]. As will be shown in Fig. 5, there are several shock wave/supersonic flame interaction locations. Ratner, et al.[6] reported that sometimes locally extinguished flames were found to be reignited at the downstream of shock wave/flame interaction location.

Supersonic flame/shock wave interaction

There are four locations where shock waves may influence the supersonic flame, as in Fig. 5.

Location A: Lip-shock-Wave (Nozzle-edge-shock wave)

As is shown in Fig. 6(c), there are 3-D Prandtl-Meyer expansion waves at the fuel nozzle edge in the mixing case. However, in combustion case, the waves leaving the fuel nozzle edge seems to be compression waves in Fig. 6(b) . The arc which sweeps across the jet is evidently the trace of its intersection with the glass wall. These shock waves are probably due to the strong volumertric expansion from the central recirculation zones as evidenced by the sharp increase of wall static pressures in Fig. 6(a) and 9(a). This outwardly expanded viscous layer may acts as an "equivalent body"[7]. Therefore, this viscous layer displacement effects cause supersonic air passage to be narrowed and shock waves occurred at the fuel nozzle edge. These shock waves tend to decelerate air and increase air density and air temperature. Moreover, these shock waves eventually interact with the top wall boundary layer.

Location B: Shock wave-boundary layer interaction

In Fig. 6(b), there appears to be two shock waves near the leading edge of the wedge. One is a reflected shock wave from the separated wall boundary layer, another is a wedge shock wave[4]. It seems that the wedge shock wave may be "diffused" by a boundary layer thickening or separation and the turning really begins at the nozzle-edge-shock wave reflection. In other words, the shock waves may be communicating through the boundary layer[8]. These two shock waves tend to redirect the air and fuel toward the centerline.

Location C: Recompression shock waves

There appears to be recirculation zone after step, and compression waves at the end of recirculation zone eventually coalesce into recompression shock waves at downstream locations as shown in Fig. 7(b). These recompression shock waves tend to redirect the air and unbunrned fuels toward the centerline.

Location D: Mach disk

Recompression shock waves grew to Mach disks when fuel equivalence ratio is increased from 0.035 to 0.052, as shown in Fig. 7(b) and 7(c). Wall static pressures at the centerline shows sharp increase at X/d_F of 25 in Fig. 7(a). Wall static pressure contours in Fig. 10(a) shows similar results. At the downstream of this Mach disk, flow tends to be decelerated greatly and temperature and pressure of the mixture will be increased significantly. These may help some unburned fuels reignited and increase combustion efficiency as reported by Ratner, et. al [6].

Effect of wedge thickness

A slender 10° wedge is used to investigate the effect of wedge thickness on the supersonic flame/shock wave interaction. Figure 8 shows schlieren pictures of a supersonic flame when the slender 10° wedge is used. There appears to be 3-D Prandtl-Meyer expansion waves at the fuel nozzle edge in combustion case of Fig. 8(b). This is different from the previous result that the lip-shock wave[nozzle-edge-shock wave] appears when 10° wedge is used. This is probably due to wider downstream combustor area which may allow the volumetric expansion without generating nozzle-edge-shock wave. However, the effect of wedge thickness on the supersonic flame/shock wave interaction is yet to be concluded.

Pressure measurement

Figure 9 and Figure 10 represent wall static pressure contours, for the fuel equivalence ratio(ϕ) of 0.035 and 0.051, respectively. With combustion, wedge affects the wall static pressure in the upstream region ($X/d_F<10$) and in the downstream region ($X/d_F>10$) in different manner. In the upstream region where flame-stabilizing mechanism is important, pressures are greater for wedge case as we compare Fig. 9(a) with Fig. 9(c). In the downstream region which is important for combustion efficiency, pressures are lower for wedge case. In this region, expansion waves from the step create a radial outflow of fuel away from the central reaction zone, which reduces the residence time and results in decreased combustion efficiency as reported by Ratner, et al.[6].

Normalized pitot pressure contours are shown in Fig. 11, 12, and 13. Heat release increases the pitot pressures near wall as in Fig. 13, while in the center (within the flame: see Fig. 9) heat release tends to decrease the pitot pressure. However, the effects of heat release on the pitot pressure distributions are not clear.

CONCLUSIONS

Flow and combustion characteristics of a supersonic jet flame/shock wave interaction are measured in order to explain enhancing mechanism of flame stability when shock waves are present. The major conclusions of the present study are as follows.

1. There are four locations where shock waves influence the supersonic flame. Among them, the nozzle-edge-shock wave and the resulting two impinging shock waves on the hot recirculation zone are believed to enhance supersonic flame stabilization – the resulting higher fluid densities, higher temperatures, the long particle residence times, and elongated recirculation zones due to strong adverse pressure gradient all together enhance supersonic flame stabilization.

2. When wedges are positioned, wall static pressures near the flame stabilizing recirculation zone are higher, while in the downstream region wall static pressures are lower than no wedge case. These well coincide with the previous reports of the flame stabilizing mechanism and the decreased combustion efficiency, when shock waves were present at ambient room air temperature.

3. The effects of wedge thickness are investigated. The slender wedge results in different wave pattern near the fuel nozzle area which is important in supersonic flame stabilization. Increased downstream combustor area is believed to change wave pattern. However, the effect of wedge thickness on the supersonic flame/shock wave interaction is yet to be concluded.

ACKNOWLEGEMENT

This work was partially supported by grant No. KOSEF2000-1-305-002-3 from the basic research program of the Korea Science & Engineering Foundation.

REFERENCES

1. Marble, F. E., "Gasdynamic Enhancement of Non-Premixed Combustion," Proceedings of the Combustion Institute, Vol. 25, pp. 1-12 (1994).
2. Huh, H., and Driscoll, J. F., "Shock–Wave-Enhancement of the Mixing and the Stability Limits

of Supersonic Hydrogen-Air Flames," Proceedings of the Combustion Institute, Vol. 26, pp. 2933-2939 (1996).

3. Kim, J., Huh, H., Yoon, Y., Jeung, I. And Choi, J., "Effects of Shock Waves on a Supersonic Hydrogen-Air Jet Flame in a Model SCRamjet Combustor", The 2nd Asia-Pacific Conference on Combustion, Tainan, Taiwan, May 9-12 (1999).
4. Roy, C. J., and Edwards, J. R., "Numerical Simulation of a Three-Dimensional Flame/Shock Wave Interaction," AIAA Journal, Vol. 38, No. 5, pp.745-754 (2000).
5. Huh, H., Driscoll, J. F., "Measured Effects of Shock Waves on Supersonic Hydrogen-Air Flames," AIAA Paper 96-3035, the 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Lake Buena Vista, FL, USA, July 1-3, (1996).
6. Ratner, A., Driscoll, J. F., Huh, H., and Bryant, R. A., "Combustion Efficiencies of Supersonic Flames," J. of Propulsion and Power, Vol. 17, No. 2, pp. 301-307 (2001).
7. Ferri, A. "Review of SCRAMJET Propulsion Technology," J. of Aircraft, Vol. 5, No. 1, pp. 3-10 (1968).
8. Marble, F. E.(Caltech), Personal Correspondence.

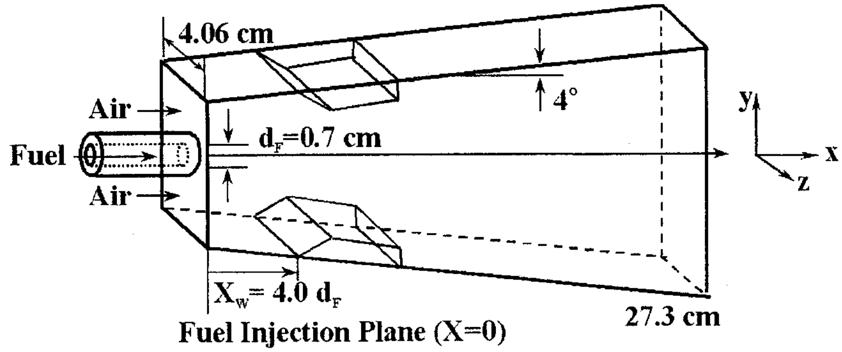


Fig. 1 Schematic diagram of the supersonic combustor

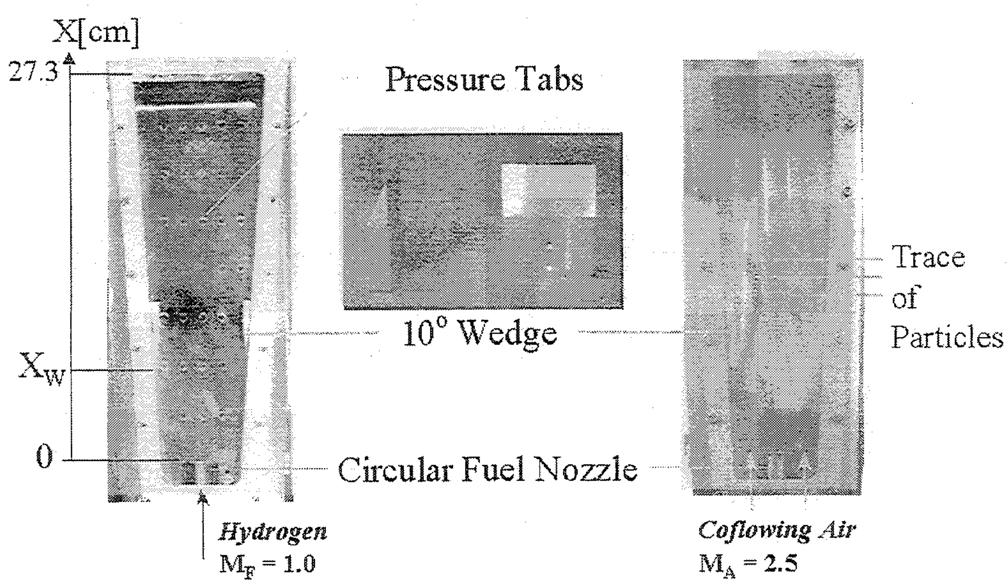


Fig. 2 Photographs of the supersonic combustor and wedges

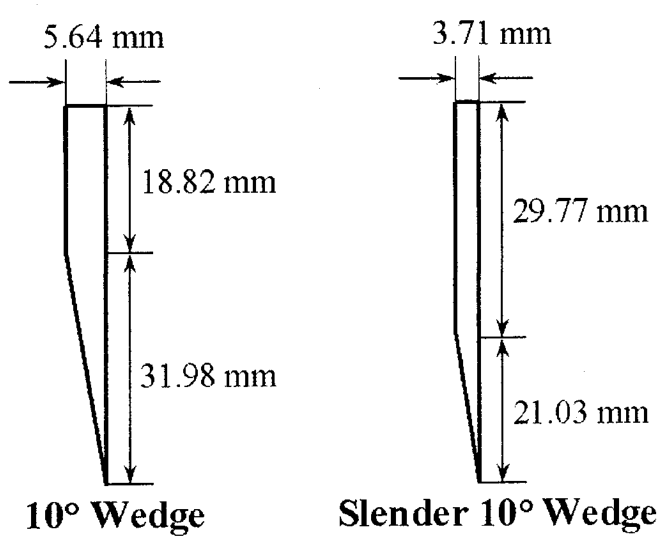


Fig. 3 Schematic of the 10° wedge and the slender 10° wedge

Table 1. Typical boundary condition at the fuel injection (x=0)

Air Mach Number, M_A	2.5
Air Stagnation Temperature, T_{0A} (K)	284
Air Stagnation Pressure, P_0 (atm)	6.44
Air Mass Flow rate, $\dot{m}_A$ (kg/s)	1.06
Fuel Mach Number, M_F	1.0
Overall Equivalence Ratio, ϕ	0.035, 0.051
Maximum Convective Mach Number, M_c	0.45

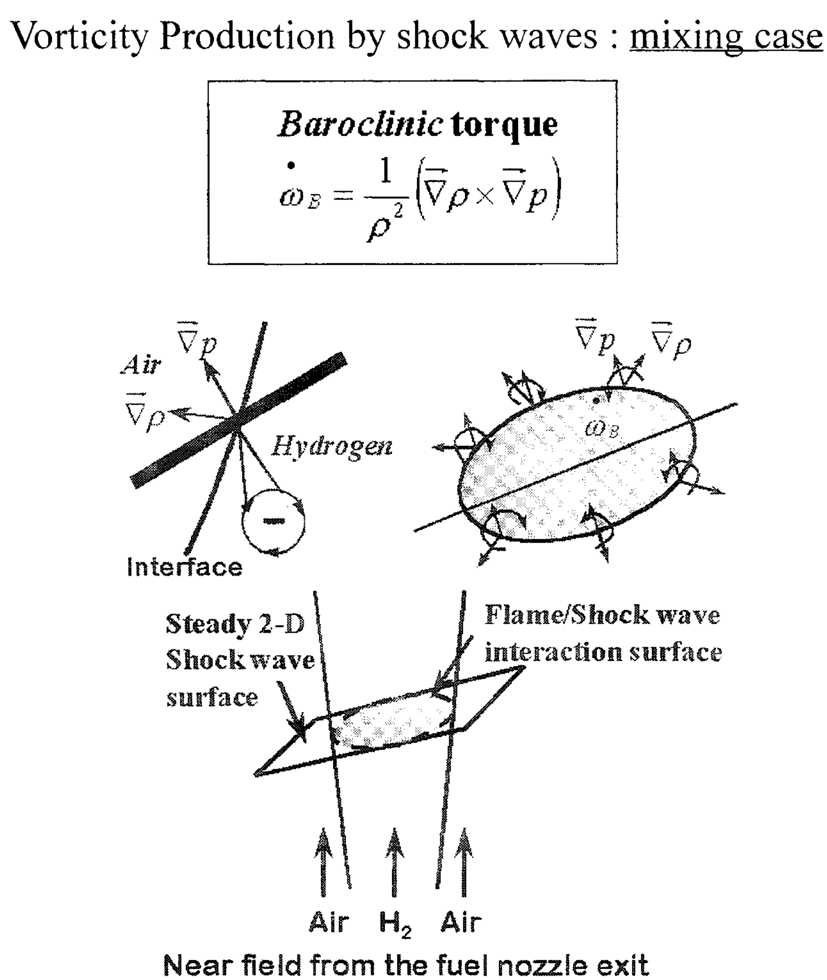


Fig. 4 Schematic illustration of mixing enhancing mechanism

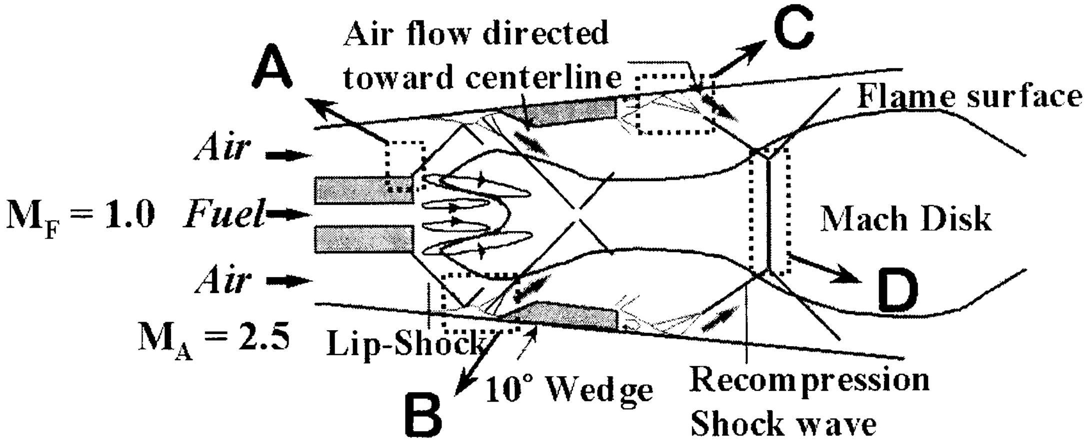


Fig. 5 Schematic illustration of supersonic flame/shock wave interaction [based on Fig. 6]

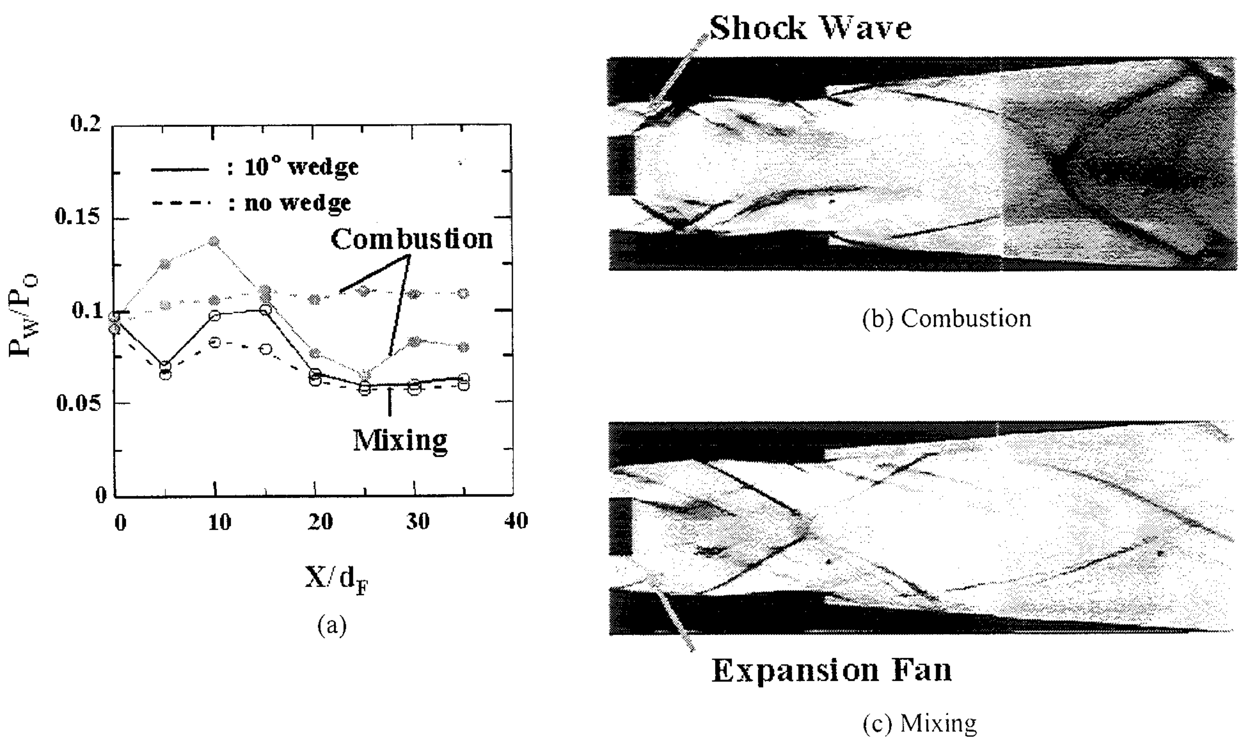
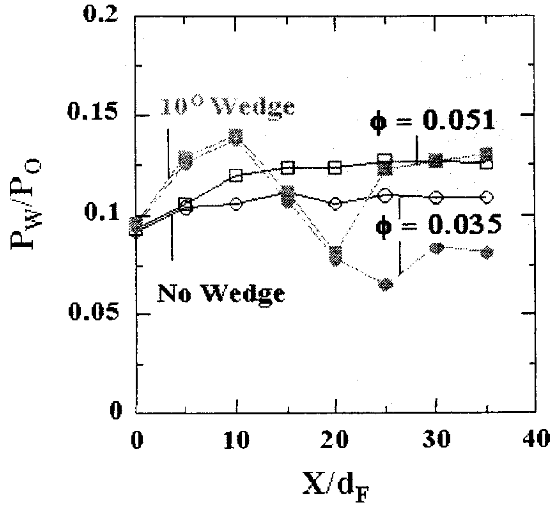


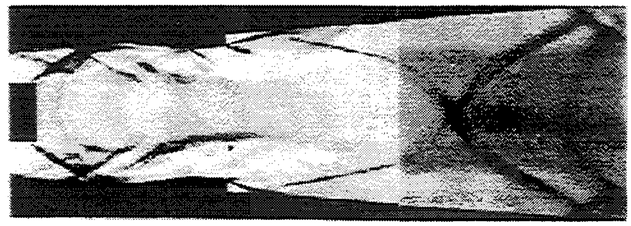
Fig. 6 Effect of combustion on wall static pressures ($\phi = 0.035$)

- -●- - Combustion without 10° wedge —●— Combustion with 10° wedge

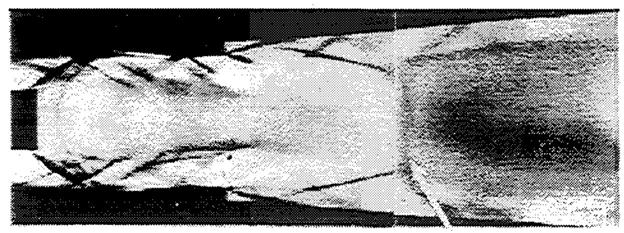
- -○- - Mixing without 10° wedge —○— Mixing with 10°wedge



(a)



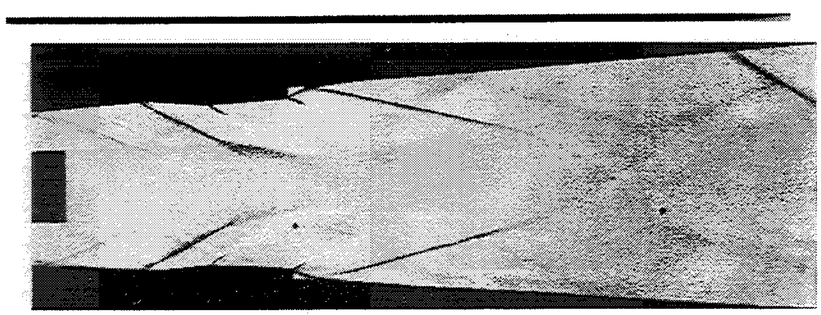
(b) ϕ = 0.035



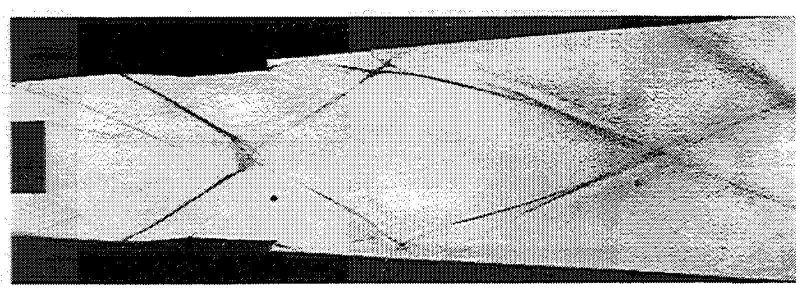
(c) ϕ = 0.051

Fig. 7 Effect of combustion and increased heat release on wall static pressures

■ 10° wedge, ϕ=0.051 ; ● 10° wedge, ϕ=0.035 ; □ no wedge, ϕ=0.051 ; ○ no wedge, ϕ=0.035



(a) Combustion



(b) Mixing

Fig. 8 Schlieren photographs for the slender 10° wedge case

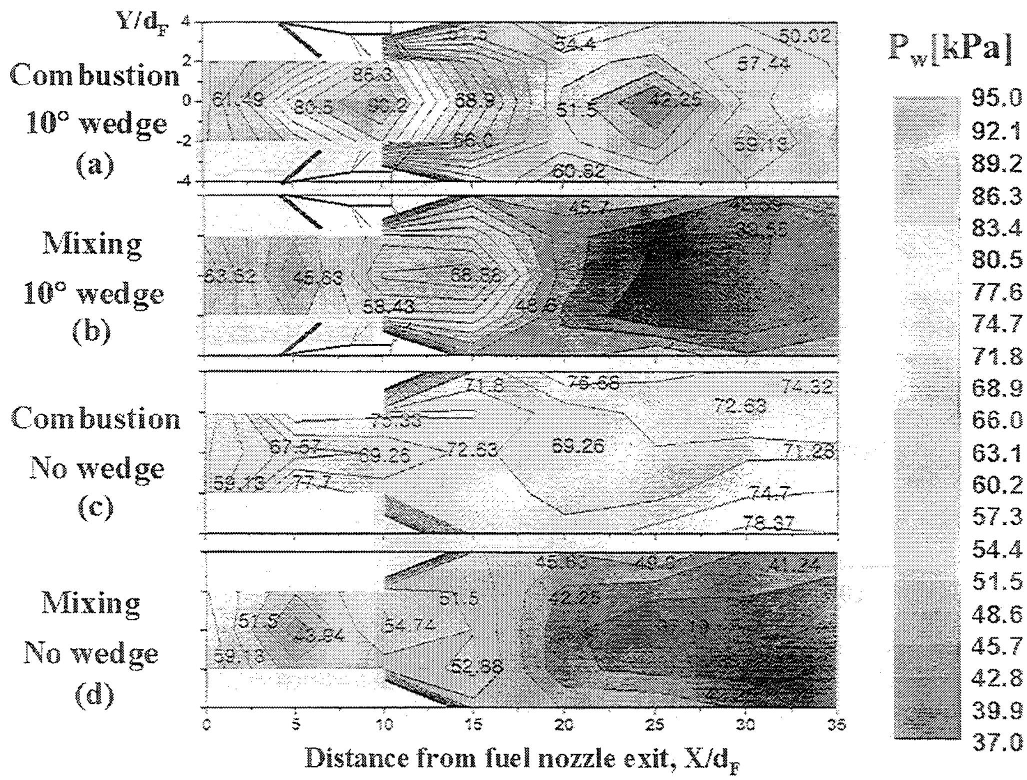


Fig 9. Wall static pressure (P_W) contours. $\phi = 0.035$

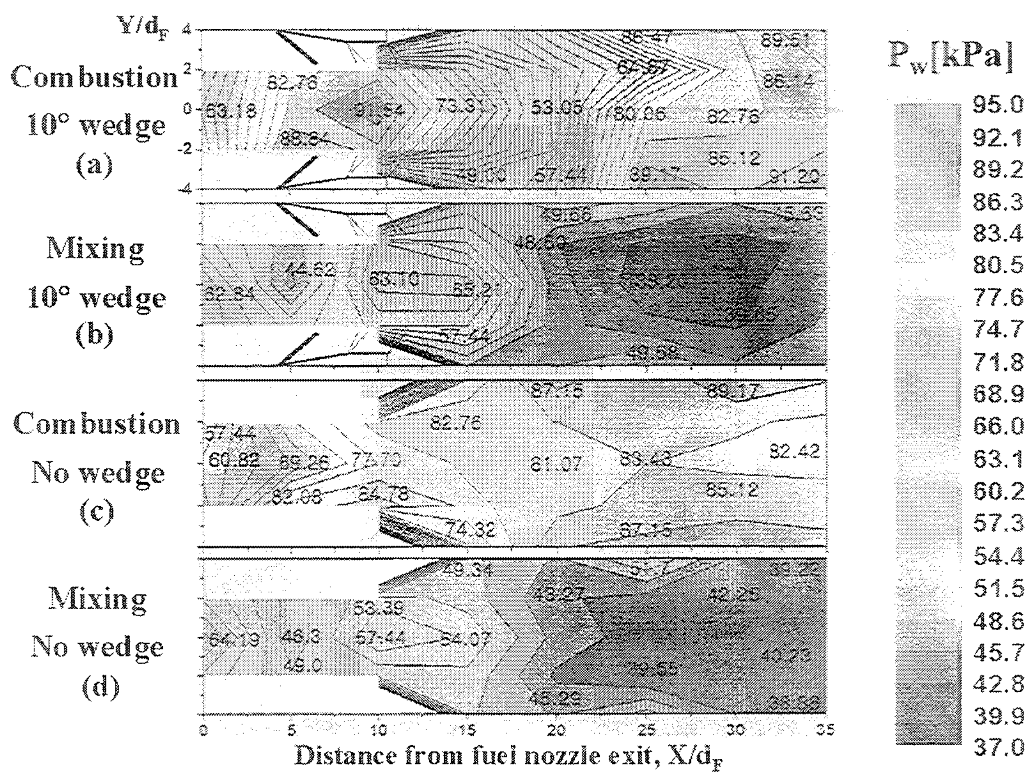


Fig 10. Wall static pressure (P_W) contours. $\phi = 0.051$

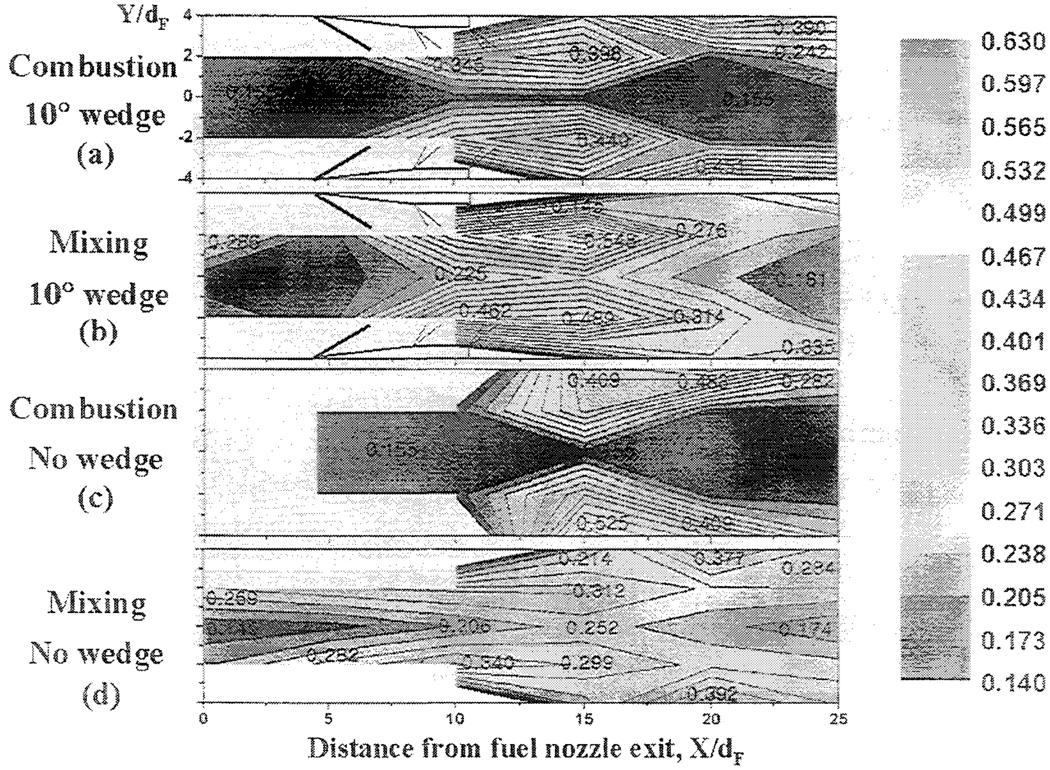


Fig 11. Normalized pitot pressure (P_t/P_0) contours. Z/d_F =0 (center)

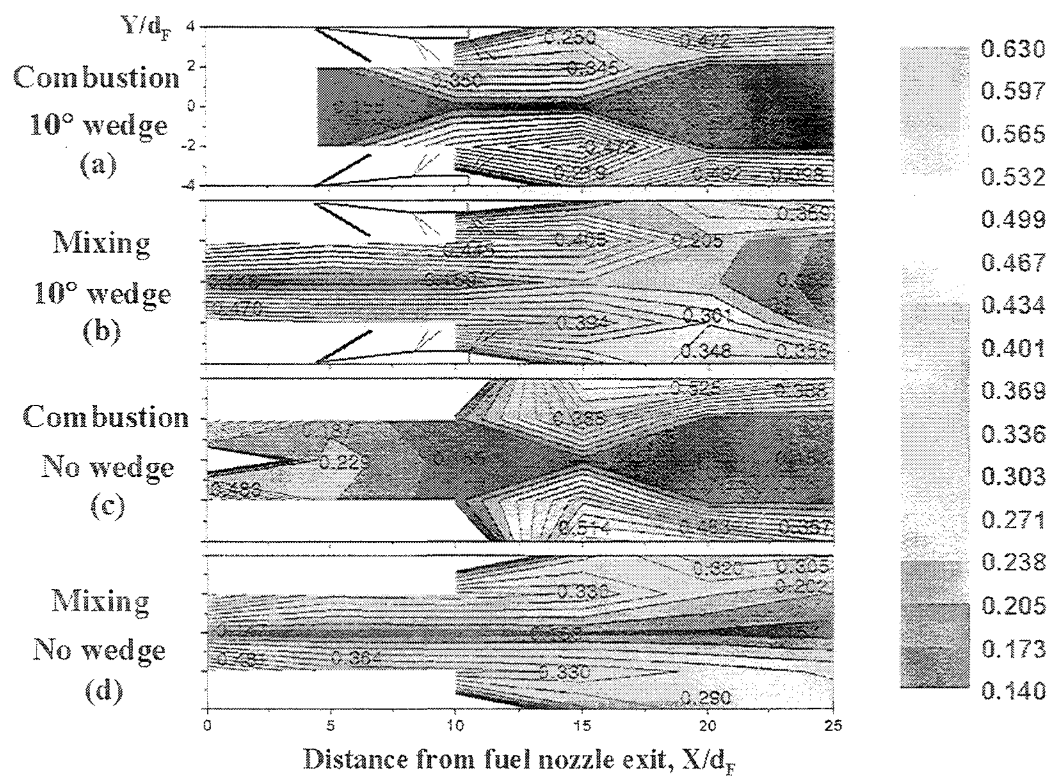


Fig 12. Normalized pitot pressure (P_t/P_0) contours. Z/d_F =1.3 (1/2 center)

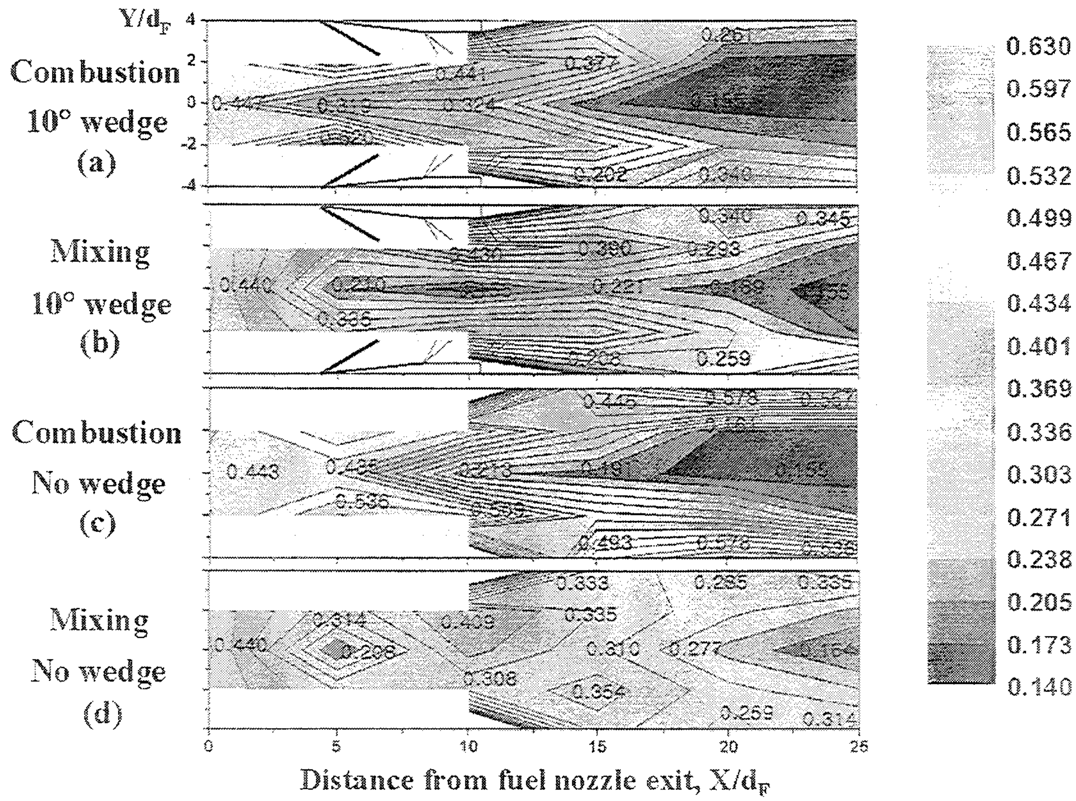


Fig 13 Normalized pitot pressure (P_t/P_0) contours. Z/d_F =2.6 (near wall)