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# Technical Notes

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## Effects of Ramp Side Angle in Supersonic Mixing

T. M. Abdel-Salam,* S. N. Tiwari,† and T. O. Mohieldin‡
*Old Dominion University, Norfolk, Virginia 23529*

### Introduction

In recent years, a significant amount of high-speed combustion research has been directed toward optimization of scramjet combustors and in particular on the efficiency of fuel–air mixing and reaction taking place in the engine. Considerable fundamental research has been conducted in response to the increased interest in the development of scramjet propulsion systems. A critical element in the design of the scramjet engine is detailed understanding of the complex flowfield present in different regions of the system over a range of operating conditions. Constraints on system size and weight have led to the need to improve technology for analyzing and designing such systems. To design lighter weight and shorter supersonic combustors, significant amounts of experimental and numerical research have been directed toward injector design that must produce rapid mixing and combustion of the fuel and air. Injector design and the flow disturbances produced by injection also should provide a region for flame holding, resulting in a stable piloting source for downstream ignition of the fuel. Critical issues regarding fuel injection and mixing in a scramjet combustor are discussed in detail in the literature.[1–9] Hydrogen combustion has been investigated by Gauba et al.[5] with an unswept ramp fuel injector and by Baurle et al.[6] with a swept ramp fuel injector. The mixing flowfield of an unswept ramp has been investigated experimentally by Donohue and McDaniel[7] and by Laufer et al.[8] The main objective of the work to be described is to study numerically the effect of changing the side angle of the compression ramp on the mixing process.

### Physical Model

The ramp fuel injector is designed to maintain high mixing efficiencies with a minimum total pressure loss for high combustor Mach number applications. The injector design relies heavily on large-scale streamwise vorticity in the supersonic primary stream to mix injectant from near parallel injectors. Three compression ramps are considered for the current study with different side sweep angles. The ramps have a 10-deg compression angle and three side angles, 0 (unswept), 5, and 10 deg. In all cases, the fuel jet diameter and ramp height are kept constant and are equal to 2.7 and 5.0 mm, respectively. The jet is inclined at a 10-deg angle parallel to the ramp surface (in the three ramps) to keep the jet direction parallel to the airflow direction. The unswept compression ramp has an aspect ratio of 1.0. As reported by Nickol,[9] the aspect ratio of 1.0 demonstrated the most rapid downstream decay of maximum injectant mole fraction, and it is the most effective mixer among the three different aspect ratios. The ramps are located in a constant area duct with a rectangular cross section of 30.4 mm width and 18.1 mm height. To be able to compare the results with the existing experimental results, the geometry for the 10-deg swept ramp is selected to be similar to that of Donohue et al.[10]

### Boundary and Initial Conditions

In the present study, the numerical analysis was carried out using the computational fluid dynamics (CFD) code FLUENT. Further details of the numerical methods used in FLUENT may be found in Ref. 11. The governing equations for this study are the Navier–Stokes equations. The turbulence model used is the renormalization group (RNG) $k$–$\varepsilon$ model as described in Ref. 12. A fully developed turbulent flow is assumed for the air inlet and the fuel jet. Table 1 shows the boundary conditions at the inlets. No-slip conditions are used along the combustor walls. All walls are assumed adiabatic, requiring the normal derivative of temperature to vanish. Along the supersonic inflow boundaries, uniform conditions are used for both the freestream and the jet. The symmetry condition is used for the centerplane of the ramp. Initial conditions are obtained by specifying freestream conditions throughout the flowfield. For the present study, unstructured grids have been used with approximately 300,000 grid points. This is a relatively small number of grid points compared with what would normally be used if structured grids were applied.

### Results and Discussion

The validation of CFD codes depends on experimental data obtained in carefully controlled experiments. The primary limitation of CFD is that it is dependent on appropriate modeling of the mixing and combustion.[13] The numerical results are compared with experimental data of Donohue et al.[10] and Hartfield et al.[14] Also, the results are compared with the numerical results of Mao.[15] The comparisons are available in Ref. 16.

The injectant mole fraction crossflow distribution for the three side angles is shown in Fig. 1. The fuel is injected from the base region of the ramp and is mixed into the freestream air by the ramp-generated vortices. Figure 1 compares the results of the three ramps at two axial locations from the ramp front face, $X/H = 0.5$ and 8, where $H$ is the ramp height. The effect of the vortices created by the ramp side angle becomes very clear downstream of the ramp. Near the injector plane at $X/H = 0.5$, both the swept ramps show wider spread than that of the unswept one. At this location, the 5-deg swept

**Table 1 Freestream and injectant conditions**

| Parameter | Freestream conditions | Injectant conditions |
|---|---|---|
| $P_0$, kPa | 262 | 248 |
| $T_0$, K | 300 | 300 |
| $P$, kPa | 33.5 | 50.24 |
| $T$, K | 163 | 189 |
| Mach number | 2.0 | 1.7 |
| Turbulence intensity, % | 1.6 | 5 |

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*Graduate Research Assistant, Department of Mechanical Engineering, School of Engineering and Technology. Student Member AIAA.

†Eminent Professor/Scholar, Department of Mechanical Engineering, School of Engineering and Technology. Associate Fellow AIAA.

‡Professor, Mechanical Engineering Technology Department, School of Engineering and Technology. Member AIAA.

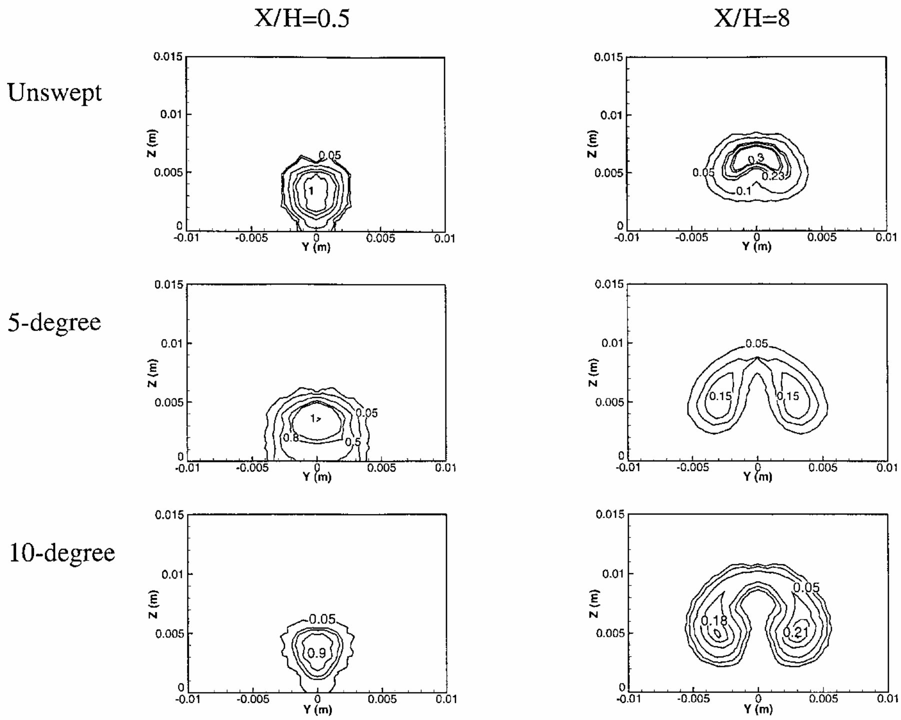


**Fig. 1 Crossflow plane injectant mole fraction contours.**

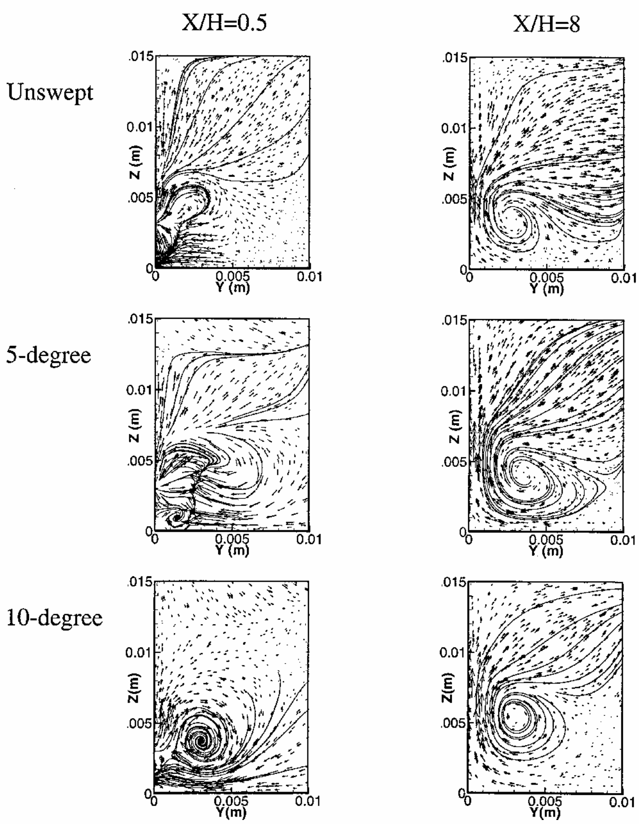


**Fig. 2 Crossflow plane velocity vectors and streamlines.**

ramp shows better spread than the 10-deg swept ramp. Downstream of the injector at $X/H = 8$, kidney-shaped plumes are seen for the two swept ramps while still not formed in the unswept ramp. Also, the spread of the injectant is wider in the 10-deg swept ramp than in the other two ramps. This is due to the effect of the ramp side sweep angle.

Figure 2 shows the streamwise vorticity illustrated by the velocity vectors in two crossflow planes. The design goal of the ramp configuration is for the axial vortices to entrain the central fuel jet, ultimately leading to downstream mixing. The vortices are generated

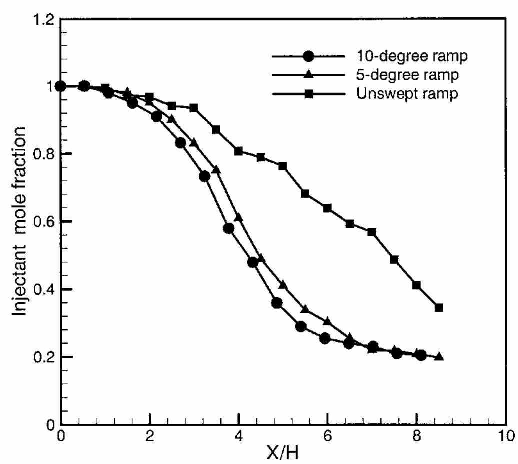


**Fig. 3 Decay of maximum injectant mole fraction.**

by the pressure gradient between the ramp surface and the ramp sides. The relative strengths can be seen clearly. As would be expected, the 10-deg swept ramp has the stronger vortex followed by the 5-deg swept ramp; also the location of the vortex center moves outward from the centerline and downward to the side walls. In the $X/H = 0.5$ plane, the two counter-rotating pair of axial vortices are seen in the 10-deg ramp, and they slightly appear in the 5-deg ramp, whereas they are not seen in the unswept ramp. Downstream of the ramps the vortices become weaker.

The mixing rate of the three ramps is illustrated in Fig. 3. Figure 3 shows the axial decay of the maximum injectant mole fraction for the three side angles. It can be seen that as the distance from the ramp base increases the maximum mole fraction decreases rapidly in the two swept ramps as compared to the unswept ramp. All ramps show almost the same mixing rate from $X/H = 0$ to 2.0. Dwonstream of the injector at $X/H = 6.0$, the mole fraction reduces to about 23% of its maximum value for the 10-deg swept ramp, whereas it reduces to 60% of its maximum value in the unswept ramp case. Farther downstream, at $X/H = 8.0$, these values become 20 and 32%, respectively. Note that the difference in the mixing rate between the two swept ramps is not significant. The effect of increasing the ramp side angle from 5 to 10 deg has a slight effect on the mixing rate, whereas the difference between unswept and the 5-deg swept ramps is remarkable. One would expect the 5-deg swept ramp to

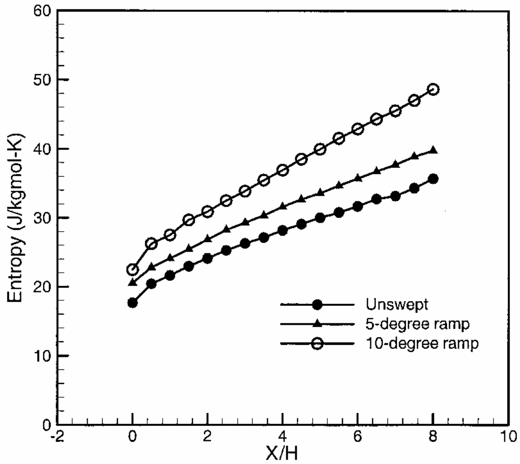


**Fig. 4 Mass-averaged entropy increase.**

be an intermediate case between the unswept ramp and the 10-deg swept ramp. However, the difference between the two swept ramps is not as significant as the difference between the swept ramps and the unswept ramp. This leads to the conclusion that there should be an optimum value after which further increase in sweep will not improve the mixing.

Induced mixing must be traded against losses induced by the mixing enhancement technique. The losses associated with the mixing process are shown in Fig. 4 by presenting the increase of the entropy along the flow direction. The entropy is calculated for all cells at different crossflow planes; then, the mass-averaged entropy is calculated for each plane. As expected, the 10-deg swept ramp shows higher increase in entropy than the other two ramps. Both the unswept ramp and the 5-deg ramp show the same trend. This demonstrates that the 5-deg swept ramp gives high mixing rate and low losses compared to the 10-deg case.

## Conclusions

A numerical investigation has been conducted to study the supersonic mixing in a scramjet engine configuration. Three wall-mounted ramps with different side angles have been used. The study is focused on the effect of the ramp side angle in the enhancement of the mixing process. The numerical results are obtained with the existing CFD code FLUENT and with unstructured grids. Note that the swept angles highly affect the mixing process. The results show clearly that increasing the ramp side angle leads to a better mixing and faster mixing rate. The results also show that further increase of the ramp side angle will slightly improve the mixing rate. The 10-deg swept ramp is a more effective mixer than either the 5-deg or the unswept ramp. However, there is no significant difference between the two swept ramps. Furthermore, the losses associated with the 5-deg swept ramp are less than that of the 10-deg one. Further study is needed with different side sweep angles greater than 10-deg to determine if this increase will lead to further improvement of the mixing process.

## Acknowledgments

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M. Sichel
*Associate Editor*

# Irregular Phenomena of Shock Reflection Transition in a Conventional Supersonic Wind Tunnel

Norikazu Sudani,* Mamoru Sato,† Toshio Karasawa,†
Hiroshi Kanda,‡ and Nobuhiro Toda§
*National Aerospace Laboratory of Japan,*
*Tokyo 182-8522, Japan*

## Introduction

AT a sufficiently high Mach number in steady supersonic flow, three-shock theory permits both regular and Mach reflections in the so-called dual-solution domain of incident shock wave angles. In 1979, Hornung et al.[1] predicted that a hysteresis of the transition between the two reflections would occur if the shock wave angle were adjusted during the steady flow. It was experimentally shown by Hornung and Robinson,[2] however, that the transition occurred at

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*Leader, Transonic Wind Tunnel Group, Wind Tunnel Technology Center, Chofu; sudani@nal.go.jp. Member AIAA.

†Senior Researcher, Wind Tunnel Technology Center, Chofu.

‡Researcher, Wind Tunnel Technology Center, Chofu.

§Senior Staff Researcher, Wind Tunnel Technology Center, Chofu; currently Member of Research Staff, Japan Aero Space Technology, Sendai, Miyagi 981-3133, Japan.