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Computational Study on Effects of Shockwave on Combustion and Injected FuelBy Unconventional Positioning of Injectors

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ABSTRACT: *A scramjet is a variant of a ramjet air-breathing jet engine in which combustion takes place in supersonic speeds. The scramjet is composed of three basic components; a converging inlet, a combustor and a diverging nozzle. Due to the nature of their design, scramjet operation is limited to near hypersonic speeds. While scramjets are conceptually simple, actual implementation is limited by the extreme technical challenges. This is why scramjet has drawn the attention of many researchers. Interaction between shockwave and combustion is very important for supersonic combustion. Isolator is key element to withstand the high pressure due to combustion, to avoid the flameout and to avoid unstart of the inlet. This paper focuses the progress of work to model a shockwave and its interaction with combustion. The purpose of the work is to improve CFD capabilities for predicting the shockwave which in-turn improves the combustion efficiency in SCRAMJET. There are two different positions for fuel injectors. The resultant flow reaction between the fuel and incoming fluid (i.e., air) is simulated and the results are presented.*

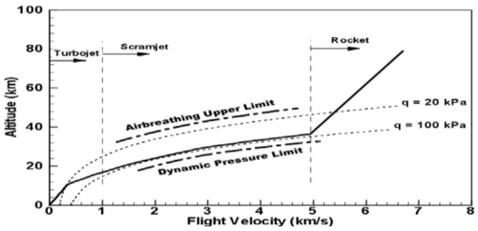
Index terms: *Supersonic combustion, Flame holder, scramjet, shockwave impingement*

I. INTRODUCTION

A scramjet (supersonic combustion ramjet) is a variant of a ramjet air breathing jet engine in which combustion takes place in supersonic flow. As in ramjets, a scramjet relies on high vehicle velocity to forcefully compress and de-accelerate the incoming air before combustion (hence ramjet), but whereas a ramjet de-accelerates the air to subsonic velocities before combustion, airflow in a scramjet is supersonic throughout the engine. This allows the scramjet to efficiently operate at extremely high speeds: theoretical projections place the top speed between 12 Mach (9,100 mph; 15,000 km/h) and 24 Mach (18,000 mph; 29,000 km/h). In recent years, the research and development of scramjet engine has promoted the study of combustion in supersonic speeds. Extensive research is carried out over the world for realizing the scramjet technology with hydrogen fuel with significant attention focused on new generations of space launchers and global fast-reaction investigative missions. However, application for the scramjet concept using high heat sink and hydrogen fuels offers significantly sophisticated mission potential for future military tactical missiles. Scramjet being an air-breathing engine, the performance of the missile system based on the scramjet propulsion is envisaged to enhance the missile range and payload weight. Super-sonic combustion ramjet engine for an air-breathing propulsion system has been realized and demonstrated by USA on ground and in flight. X-43 vehicle used H_2 fuel. Hydrocarbon fuel scramjet engine is still under study and research.

For a scramjet traveling at speeds greater than Mach 5 and at altitudes in the flight corridor of Fig. 1, significant compression and heating of the air is required. For an airframe-integrated scramjet, both the inlet and vehicle fore-body share this task. A multitude of different forebody/inlet configurations have been developed by many researchers, each designed to generate a specified level of compression over a range of flight Mach numbers. The performance of such compression systems can be separated into two key parameters; (1) capability, or how much compression is performed, and (2) efficiency, or what level of flow losses does the forebody/inlet generate during the compression process.

Figure 2 shows a schematic of the internal flowpath of an airframe-integrated scramjet with particular reference stations highlighted. In observance with the convention of Heiser & Pratt, station 0 is in the freestream flow ahead of the vehicle, and area of a stream-tube A0 captures the airflow processed by the engine.



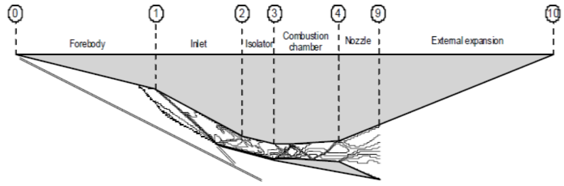


Fig 1. Hypersonic Airbreathing flight corridor **Fig 2. Flow stages in Scramjet engine**

Station 1 be the downstream of the vehicle fore-body shock. Station 2 is at the throat of the inlet, which is usually the least possible area of the flow-path, and the length between stations 2 and 3 is referred to as the isolator. Station 3 represents combustor start (where fuel is added), and air and fuel is mixed and burned by the end of the combustor at station 4. An internal expansion in nozzle up to station 9, and an external expansion at the end of the vehicle to station 10.

II. LITERATURE SURVEY

Professor Michael K. Smart [1], studied on challenges in the design of the inlet or intake of these hypersonic air-breathing engines. Kyung Moo Kim et.al [2] worked on the topic of “Numerical study on supersonic combustion with cavity-based fuel injection”, and their findings are – When the wall angle of cavity increases, the efficiency of combustion is improved, but total pressure loss increased. When the offset ratio of upper to downstream depth of the cavity increases, the combustion efficiency as well as the total pressure loss decreases. Yuan shengxue [3] worked on the topic of “supersonic combustion”, and his findings are – The calculation of deflagration in supersonic flow shows that the entropy increment and the total pressure loss of the combustion products may decrease with the increase of combustion velocity. The oblique detonation wave angle may not be controlled by the wedge angle under weak under driven solution conditions and be determined only by combustion velocity. Gruenig and F. Mayinger [4] worked on the topic of “Supersonic combustion of kerosene/h2-mixtures in a model Scramjet combustor”, and their findings are – The essential temperature level is partly achieved by the oblique shock waves in the supersonic flow with increasing combustor area ratio. K. Kumaran and V. Babu [5] worked on the topic of “Investigation of the effect of chemistry models on the numerical predictions of the supersonic combustion of hydrogen”, and their findings are -chemistry of multi-step predicts higher and wider spread heat release than what is predicted by single step chemistry. T. Cain and C. Walton [6] worked on the topic of “review of experiments on ignition and Flame holding in supersonic flow”, and their findings are – Low entry combustor temperature is desirable /essential due to intake and nozzle limitations. Hydrogen and hydrocarbon the optimum temperature /pressures are in regions in which ignition delay is very sensitive to temperature, varying from 0.1ms to >>10ms. At low Mach number and static temperatures but at these conditions combustion results in free subsonic regions with very high turbulence.

A. R. Srikrishnan and j. Kurian et.al. [7] worked on the topic of “An Experimental Investigation of Thermal Mixing and Combustion in Supersonic Flows”, and their findings are – A petal nozzle can achieve nearly uniform temperature and momentum fields by using mixing duct. The performance of a conventional conical nozzle was found to be much inferior to that of the petal nozzle under identical conditions. M Deepu [9] worked on the topic of “Recent Advances in Experimental and Numerical Analysis of Scramjet Combustor Flow Fields”, and his findings are - Increase in jet to free stream momentum flux ratio will result in the increase of jet penetration to free stream for all kinds of jets. Injector orientation plays an important role in the strength of the bow shock, the oblique injector created shocks are being substantially weak compared to transverse injector. Arif Nur HAKIM, Shigeru ASO et.al. [10] worked n the topic of "Experimental Study on Effects of Shock Wave Impingement on Supersonic Combustion", and their findings are the impingement of shock waves enhances the combustion and the separated region induced by shock, which is observed at impingement of stronger shock, could work as flame-holder.

The aim of the current research is to investigate the effects of incident shock wave impingement upstream and downstream of the injector on the flow field, mixing and combustion of a hydrogen jet in comparison with the case that no incident shock is present.

III. POSITIONS OF FUEL INJECTORS

Wall injectors, where hydrogen is injected through the wall (normal or oblique to the main flow) or by ramps mounted to the wall,
Strut injectors, are located at the axis of channel and directly inject the fuel into the air stream core.

Hydrogen should be injected in such a way that a good mixing is achieved over a short length resulting in a homogeneous temperature distribution. Local peaks of temperature have to be avoided so as to keep dissociation losses low. An important issue at low flight Mach numbers of a scramjet is auto ignition. Due to relatively low air static temperatures this may become a problem for axial strut injectors which only induce weak shock waves and small recirculation zones down-stream of the strut. Thus the advantage of avoiding normal shock waves may cause problems for a stable ignition.

a) Parallel Injection of fuel

Figure 3 represents the fuel injection parallel to the flow using struts

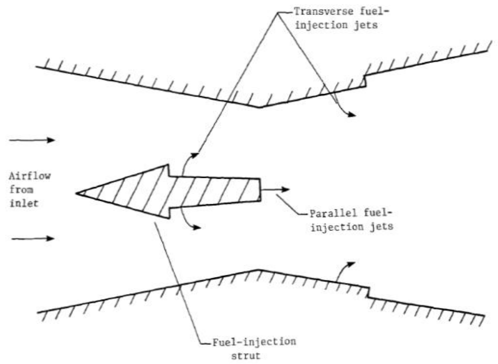


Fig 3. Parallel and transverse fuel injection jets field

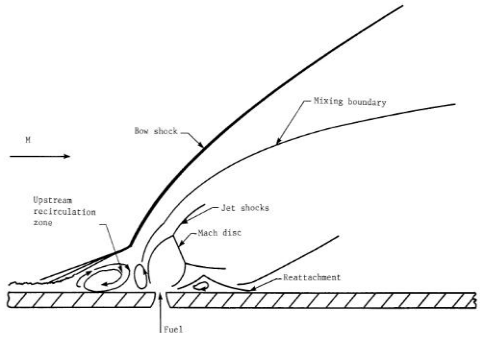


Fig 4. Transverse fuel injection flow

b) Transverse Injection of fuel

Figure 4 presents a more detailed picture of the flow region in the vicinity of a transverse fuel-injection jet in supersonic flow. The temperature and pressure rises which occur at the bow shock of the jet and in the recirculation regions increase as the air flow Mach number increases, and the residence time (extent) in the recirculating regions increases as the extent of jet penetration increases. The residence time of the fuel-air mixture in the bow-shock region will be very short since the mixture expands around the jet flow field immediately after compression in the bow shock. Of course, larger diameter jets will increase the residence time in proportion to the jet diameter. It is quite possible that, for the higher Mach number flows, ignition can be initiated in this region but immediately quenched, or partially quenched, in the expansion around the jet.

c) Downstream Facing Steps With Transverse Injection (Unswept)

As shown in Figure 5, the situation for ignition at transverse jets behind steps may be quite different than for jets alone (on plane surfaces). This difference is primarily because the recirculating zone ahead of the jet is now too rich for good ignition due to the fact that little or no mainstream air is mixed in due to the shielding action of the step.

The extent of the shielding action depends upon the location of the jet downstream of the step. If it is much more than a few step heights (say 5 or 6) downstream, then fuel from the jet may not enter the step region and it may act more like a jet on a plate (the step-separated flow may be reattached well ahead of the jet). Even though the mixture is too rich in the plane of the jet, this type of configuration can be a good ignition source at points in the separated flow on either side of the jet where the mixture is leaner (assuming the jets are not too closely spaced).

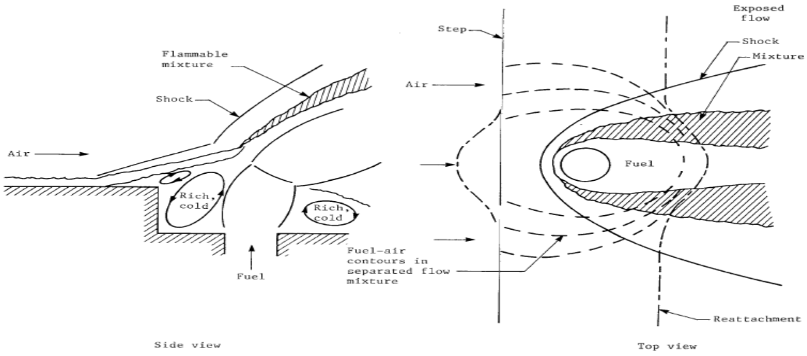


Fig 5. Transverse injection behind unswept steps

IV. COMPUTATIONAL SETUP AND CODE VERIFICATION

In order to validate the implemented numerical method, a problem of transverse injection into supersonic airstream is considered following the experimental configuration of Spaid and Zukoski[11].

The computational domain in this case is a rectangular consists of a flat plate with a slot located 228.6 mm downstream at the bottom of the wall’s leading edge, supersonic inlet at the left with free stream Mach number of 3.5, total pressure of 2.4bar and total temperature of 314K, supersonic outlet at right and finally on top a far-field boundary. The width of the slot is 0.266 mm where a sonic nitrogen jet with total pressure of 3.5bar and total temperature of 290K is injected transversely into the free stream. Three grid systems of 161 × 55, 181 × 65, 201× 85 are generated. The grid density is clustered towards wall and injection port for all grids and relaxed towards top and outlet.

In Figure 6, the surface pressure distribution obtained from all three grid systems are plotted and compared with experimental data. As depicted in Figure 6, apart from the location of boundary layer separation upstream of the injector, convergence of grid is achieved. Since the results obtained by 161x55 grid system are reasonable in comparison with experimental data, this grid system is used for further computations.

V. RESULTS AND DISCUSSIONS

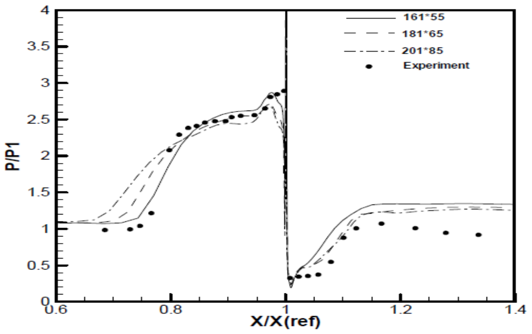
Figure 7 shows the schematic of computational domain which is a rectangular consists of a flat plate, whose length is 180.5 mm, with a slot located 100 mm downstream of the wall’s leading edge at the bottom, supersonic inlet with 2.5 free stream Mach number, static pressure of 29260.7 Pa and static temperature of 550 K and 320K for hot and cold airstreams respectively, at the left and supersonic outlet at the right.

Following the experimental data, the slot width is 0.5 mm where a sonic hydrogen jet with static pressure of 581080.2 Pa and static temperature of 300 K is transversely injected into the free stream.

Experimentally, the oblique shockwave is generated using a wedge which deflects the incoming supersonic flow; it is sufficient to impose the incoming supersonic state on the left side of the top plane while another supersonic state is imposed on the right side of the top plane numerically. This is computed so as to satisfy the Rankine–Hugoniot relations across a shock with the given upstream state and shockwave angle [12].

Figures 8 and 9 illustrate the computed flow field and Mach number contours distribution without incident shock wave. The transverse jet acts like an obstruction on the main flow. A strong jet-induced bow shock is resulted by the blockage.

The obtained numerical results are consistent with those observed experimentally by Ben-Yaker et al. [13] Figures 12 and 13 illustrate the computed flow field and Mach number contours distribution with incident shock wave introduced upstream of the injector. The incident shock wave distorts the flow field drastically and enlarges the recirculation region upstream of the injector.



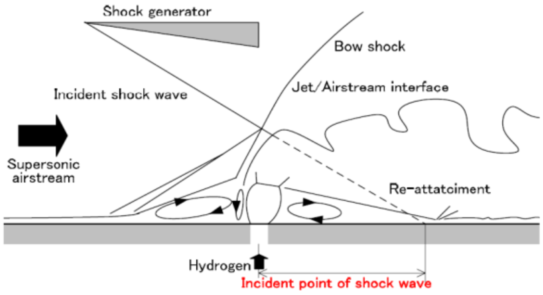
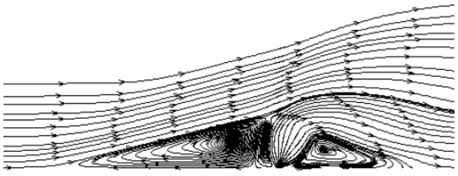


Fig 6.Wall Pressure distribution for transverse injection into airstream **Fig 7. Computational domain**



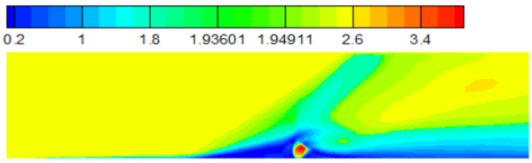
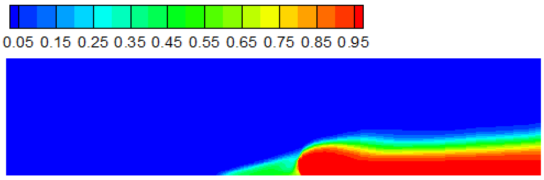


Fig 8.Flow field without incident shock wave **Fig 9.Mach number contours**



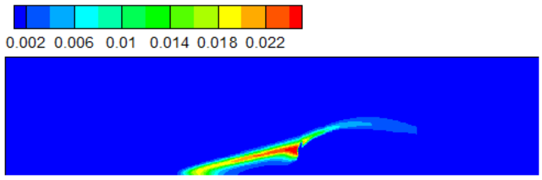


Fig 10.Hydrogen mass fraction contours distribution **Fig 11. OH mass fraction contours distribution**

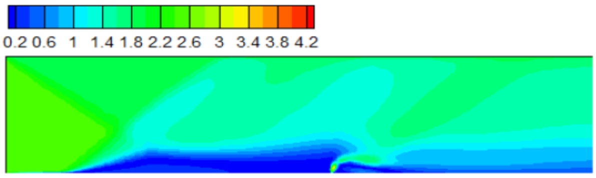
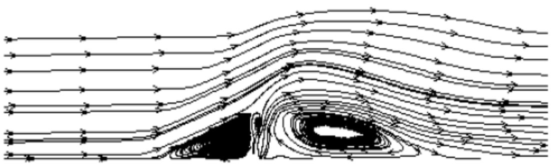


Fig 12.Flow field with incident shock wave ahead of the injector **Fig13.Mach number contours**

Figures 14 and 15 illustrate the computed flow field and Mach number contours distribution with incident shock wave introduced downstream of the injector. The incident shock wave distorts the flow field drastically as in the case where incident shock wave was introduced upstream of the injector. Although the recirculation region upstream of the injector is smaller in this case in comparison with case without incident shockwave, the injected fuel will also be sucked into the recirculation region upstream of the injector in this case. However, as illustrated by OH mass fraction distribution, a sustainable combustion is observed in this case which is consistent with experimental and numerical results obtained by previous researches



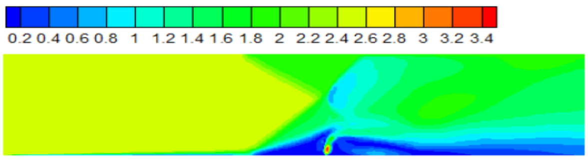
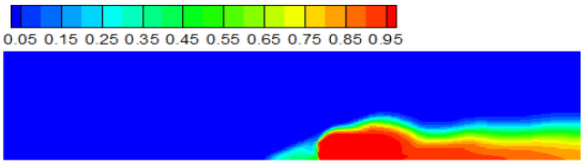


Fig 14. Flow field with incident shockwave downstream the injector **Fig 15.Mach no Contours**



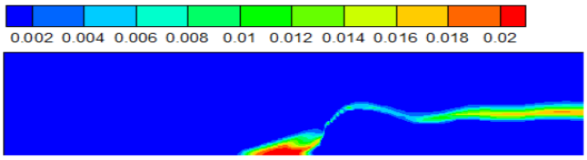


Fig 16.Hydrogen mass fraction contours distribution **Fig 17. OH mass fraction contours distribution**

VI. CONCLUSION

This study reveals that without the impingement of incident shockwave the injected fuel (Hydrogen) is sucked into the recirculating zone just ahead of the injector that would create a suitable zone for auto ignition of hydrogen jet. But the flame will subsequently quenched downstream of the injector which is consistent with the experimental results. When the incident shock wave introduced upstream of the injector, the flow field drastically distorts, and, fuel is no more present in the region of recirculation just upstream of the injector. Therefore flame stabilization could not be achieved in this case. When the incident shock wave introduced downstream of the injector, the stabilization of flame is confirmed which is consistent with previous numerical and experimental observations. The shock wave impingement enhances the combustion and the separated region induced by shock, which is observed at impingement of stronger shock, could work as flame-holder.

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