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Supersonic Combustion of Liquid Hydrogen using Slotted Shaped Pylon Injectors

Gokul.R and Mythri.M.S

Department of Aeronautical Engineering,
Rajalakshmi Engineering College, Thandalam, Chennai, India.

Abstract

Successful supersonic combustion has always been a dream-come true for all sonic enthusiasts for a huge number of applications, prime ones being hypersonic and ballistic missile defense, and air-breathing access to space like SSTOs (Single Stage To Orbit) , reusable rockets, etc. In this paper, liquid hydrogen and its possibility as a fuel for scramjets has been studied. Also, fuel injection and injector jet geometries play a king's role in enhancing the combustion efficiency. A handful of different pylon injector geometries have been referred and studied.

Keywords: Mach number, fuel injection, combustion efficiency, G_{mixing}, OH fluorescence, Specific impulse.

1. Introduction

Man has evolved greatly from stones to metal. Need to dominate the world both with power and technology drove the 20th century scientists to unfold the most challenging arena of engineering- flying piece of metal. Ever since, the invention of the theories of lift and airfoil, flying was made possible, but not efficient. After the categorization of mach numbers, it is quite obvious that man will hop to pioneer high speed propulsion.

Turbojets were invented and put into reality readily for subsonic vehicles. For a supersonic travel, even though enhancing the vehicle aerodynamically and structurally, engines were transformed from turbojets to ramjets. In ramjets, compression was achieved by formation of normal shock, which means the flow turns to be subsonic after the shock wave. This principle will not be friendly enough at higher mach numbers, say in an order of 5 or above. Hence we meet a new tricky technique of combustion, which is going to be at a supersonic speed.

1.1 Supersonic combustion:

A Scramjet engine is well known as hypersonic air-breathing engine in which heat release due to combustion process occurs in a supersonic flow relative to the engine. Hence, the flow velocity throughout the engine remains supersonic. Here, the free stream is compressed by producing inclined (i.e., oblique) shock waves using isolators. At very high speeds, combustion has to be invariably supersonic. Reasons of which are as follows:

- If combusted at a subsonic speed using a normal shock, as in ramjets, the engine will suffer from a very high total pressure loss.
- Also, molecular dissociation will be appreciable, when we conduct combustion subsonically, while the inlet mach is hypersonic.

2. Why Liquid Hydrogen?

Generally, kerosene is the working fuel for any air-breathing aero engine. But for a hypersonic vehicle, (above mach 7 or 8), kerosene does not seem to be a good choice, reasons worth penning. In this paper usage of cryogenic liquid hydrogen (which is at -253 deg C), as a fuel has been studied. Kerosene, which has a high molecular mass, cannot be injected as such, into the incoming air stream. A proper atomization technique is inevitable. Hydrogen, being the lightest of all, does not have to be atomized separately to get ignited, as its auto ignition temperature is 571 deg C. Incoming supersonic free stream has a temperature way higher than this. Moreover, its ignition time – time between injection and ignition, proves to be less compare to kerosene. Thus increasing combustion efficiency and also bringing down the required combustor length. Also beyond a high mach (say > 8 or 9), kerosene reached its flash point easily, making itself incapable to cool the vehicle. Liquid hydrogen, if managed to maintain its cryogenic temperature, will prove to be a good reliable cooling agent. Literature studies reveal that liquid hydrogen reduces the molecular weight of the exhaust gas and thus increases the specific impulse, despite incomplete combustion.

Evidently, one of the main important receiving end of an efficient air-breathing hypersonic vehicle (scramjet powered) is SSTOs (Single Stage To Orbit). Arriving at the LEO (Low Earth Orbit), with a high orbiting speed, has always been with stage propulsion, usually non-air breathing, by carrying oxidizer and fuel separately in tanks. Utilization of an efficient air-breathing scramjet is believed to rocket the payload at one go, i.e., devoid of stages. Employing liquid hydrogen in a scramjet eliminates oxidizer space, thus pushing out a major term in weight calculation.

2.1 OH fluorescence:

The emission of self-fluorescence of a flame consists of thermal fluorescence (thermal excitation of the molecules) and chemiluminescence (production of excited molecules by chemical reactions). By choosing a suitable molecule and knowing their role in the chemical kinetics involved, the kinetical processes can be examined. The highly reactive OH radicals are products of starting and chain branching reactions of the hydrogen combustion process, subsequently serve as reaction partners for the exothermic fuel oxidation reactions and are finally consumed by chain terminating reactions. Therefore the detection of OH self-fluorescence is an appropriate means to determine location and intensity of the reaction zones. Comparing the OH fluorescence of the cases, viz., liquid hydrogen with LOX- liquid oxygen (non air breathing) and liquid hydrogen with atmospheric incoming air (2) we get even more technical insight of the advantage of using the latter in rocketing.

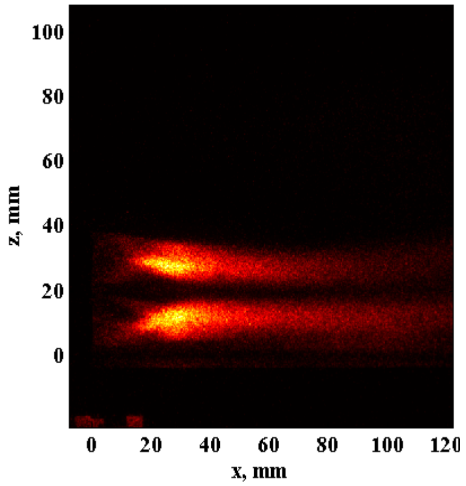

Fig. 1

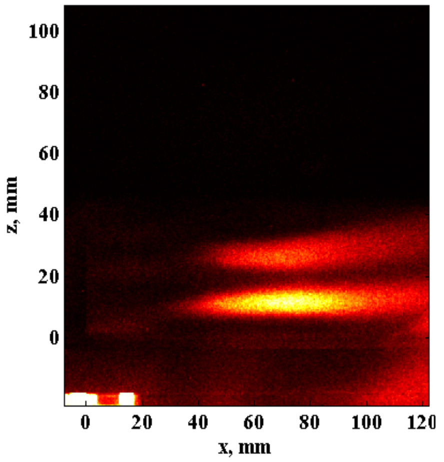

Fig.2

In the above graph, along X axis is the length of the wall of the combustor and along Z axis is the height of the combustor. Figure 1 represents the case of non air breathing combustion (LOX with LH2) and figure 2 represents the case of air breathing combustion (LH2 with atm air). Injector is placed at the origin.

3. Injectors

There are several important issues that have to be troubleshot while designing an efficient fuel injector, especially for supersonic combustion. Some bullet points are total pressure loss, mixing efficiency parameter (G_{mixing}) among which the formal have to be low and the latter-high. Also, careful crafting of the injector will help metering the combustion length and weight down the scale.

3.1Injector Types:

Arriving at the injectors types, there are two main categories, namely, intrusive and non-intrusive. Intrusive ones are those whose geometry is included inside the combustor. Some of the intrusive types are strut, pylons, ramp, etc. On the other hand, non-intrusive ones are those that are not themselves included into the combustor working space. E.g. wall jet injectors.

In this paper with a reference to the paper by C.Gruenig and his co-authors (3), a set of four different pylon injectors have been studied.

4. Pylon Injection

Pylon injection is essentially an injection behind a tall, narrow in-stream body. Injection may be axial, normal, or at any angle relative to the free stream. By injecting the fuel in the center of the flow, with pylons, problem of slow lateral mass transport in supersonic mixing layers is circumvented.

4.1Tested pylon designs: [3]

Various pylon designs have been tested with respect to their mixing and combustion performance. The fuel injection holes of the pylons were designed to give a mach of 1 at the exit. The orifices were sized to give approximately the same fuel mass flow rate for a selected injection pressure range. The chosen pylon designs are shown in fig.3. These pylons allow the study of the effects the injection angle, shape of the injection orifice, and the number of injected fuel jets. Pylons A, C and D inject a single fuel jet. Pylon B injects four jets. Pylons A and B inject circular jets and pylons C and D inject elliptical or slot-shaped jets. Mixing efficiency parameter is interpretated as the inverse of the fuel mass flux. Faster the fuel mass flux decreases along the combustor, better the mixing process.It can be given as, $G_{\text{mixing}} = \frac{A_{\text{jet}}}{\dot{m}_{\text{fuel}}}$.

G_{mixing} of all the four pylons has been studied and is plotted in the graph in fig.4.

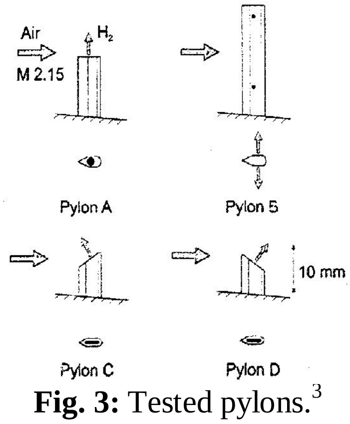

Fig. 3: Tested pylons.[3]

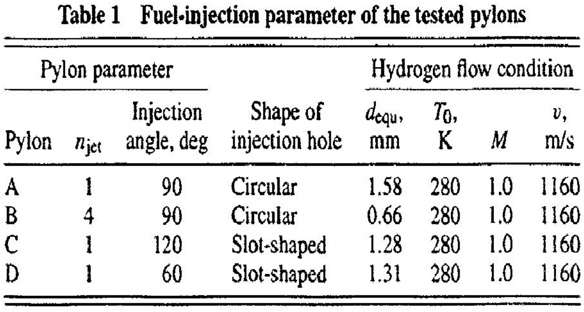

Table 1 Fuel-injection parameter of the tested pylons

Pylon parameter				Hydrogen flow condition			
Pylon	n_{jet}	Injection angle, deg	Shape of injection hole	d_{equ}, mm	T_0, K	M	v, m/s
A	1	90	Circular	1.58	280	1.0	1160
B	4	90	Circular	0.66	280	1.0	1160
C	1	120	Slot-shaped	1.28	280	1.0	1160
D	1	60	Slot-shaped	1.31	280	1.0	1160

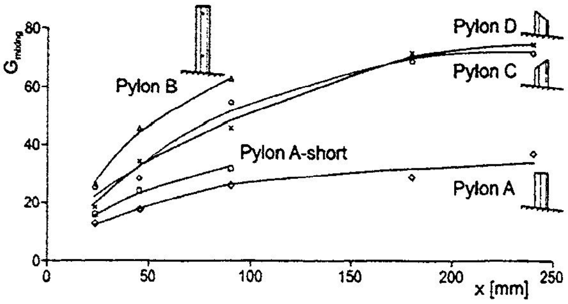

Fig. 4: G_{mixing} of all four pylons.[3]

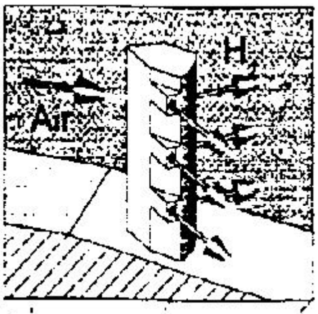

Fig. 5: Optimized pylon(pylon B)[3]

4.2Optimized pylon and its combustion performance: [3]

Based on the results of mixing and combustion experiments, the pylon design is been optimized and is shown in fig.5. The pylon basically consists of a strut that is equipped with six small ramps that inject the fuel with a downstream angle of 30deg. By means of multiple injection orifices, the fuel is spread across the whole duct.

5. Conclusion

From the above collective study, following inferences can be spot-lighted:

i. Utilizing liquid hydrogen as a fuel in scramjets, as well as the active coolant, some serious limitations of employing hydrocarbon fuels can be obliterated.
ii. Liquid hydrogen fuelled scramjet will rapidly reach very high mach numbers(above 8 or 9) so fast and easily , than a hydrocarbon counter part.
iii. In the reffered paper for pylon injection, circular injection jets have been used, solely for budget reasons. If the finance be taken care of, integration of the cross section of pylon C(slot shaped) or D with the optimized pylon(pylon B) - wholly, a slot shaped multi jet pylon, might prove to be the most efficient choice, as it brings two advantages together -

a) Most homogenous fuel distribution across the flow channel(pylon B)
b) Faster expansion than circular jets.(slot shaped ones-pylons C and D)

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