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REFLECTIONS ON DEVELOPMENTS IN THE AREA OF SUPERSONIC COMBUSTION

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ABSTRACT Research into supersonic combustion has occurred in spurts – in the mid sixties when the major understanding and development of rocket engine combustion was complete, then in the late eighties with the NASP project in the USA, and somewhat more consistent work in several countries in the last decade. Early enthusiasm on building systems was interrupted in the late eighties by the results on reducing mixing in high mach number streams with concomitant effects on the engine size and this led to studies on the causes for such a feature and methods of causing enhanced mixing. It is the author's view that the development efforts may have been cognizant of these features, but do not seem to have been influenced greatly by these. It is also the author's view that the design of a scramjet combustor can generally ignore the "scare of reduced mixing at high Mach numbers", hints of "introducing an isolator between the intake and the combustor would be necessary", and "design for high degree of combustion, but not complete", but follow the traditional lines of providing arrangements for flame holding, and combustion in the fluid body more than near the wall to reduce wall heating and friction, limit the intrusions in to the high speed fluid body to reduce pressure losses and optimize the geometry and fuel introduction scheme through computation of supersonic flows with heat release to achieve the objectives.

1. Introduction

Curran (2001) traces early work on supersonic combustion to 1946, but ignores a major experimental study by Marquardt Corporation in 1964. This study presents the details of an experimental scheme and results on model combustor that are not very different from those attempted in recent times. Till the middle of eighties, it was thought that the limitations of realizing a hypersonic combustion based vehicle was related to the details of design, some thing that would be worked out when a project gets undertaken with suitable funding. In 1986, the work by Papamoschou and Roshko (1988) expanding on the earlier work of Ikawa and Kubota (1975) showed that the mixing layer growth reduces in high speed flows with the growth rate depending on "convective Mach number" that is derived based on the difference in speed between the streams and acoustic speed (mean between the streams in one simple approach). This created a major upheaval in the combustion community; suddenly, it was thought that the mixing rate between the fuel and oxidant streams would form the primary impediment in the design of such combustion systems. A number of laboratories engaged themselves in the design of better mixing devices – backward facing step, ramps of various forms, cavities, and pylons. They were explored for their mixing efficiency. The most recent survey (Seiner et al, 2001) is a good description though its study does not provide clarity on a possible choice. In developing scramjet based vehicles, it is not always clear that ground tests are cheaper than flight tests particularly when the very expensive facility creation has to be begun. Hence one looks forward to benefiting from flight tests. There have been three flights based on supersonic combustion in recent times. The Russian collaboration with French scientists as well as NASA has resulted in four flight tests. These use a rocket booster to achieve the appropriate Mach number and then initiate the supersonic combustion device. Amongst these tests, supersonic combustion seems to have been established in one case with adequate data. In other cases, either the flights were unsuccessful or the combustion process was subsonic even though supersonic combustion was intended. The American vehicle X – 43 had a problem at the end of rocket boost phase unrelated to the supersonic combustion phase and test was aborted. The Australian experiment had a small segment of supersonic combustion in the return trajectory of a rocket based vehicle. Thus an enthusiastic designer feels the absence of successful autonomous flights based on supersonic combustion system. It is in this light that the present author believes that one should not add to perceived impediments if their value in the development is only minor. The discussion below is an attempt to present some realistic assessments and also analyze the failures that have occurred in the recent past as a guideline for the future.

2. Reduced Mixing at High Mach numbers

Ikawa and Kubota (1975) conducted experiments on a shear layer off a backward facing step from which zone controlled flow of air was introduced to create a zero pressure gradient shear flow. Measurements indicated reduced growth rate. Papamoschou and Roshko (1988) conducted careful experiments on mixing layers and analyzed the data in terms of the ratio of compressible mixing layer growth rate to the incompressible analogue (δ/δ_0) with a quantity called convective Mach number, M_c. For equal speeds of the shear layers, M_c is zero. The quantity (δ/δ_0) reduced with increased M_c asymptoting to about 0.2. The reduction is insignificant up to $M_c = 0.5$. It is also to be noted that the incompressible mixing layer thickness varies with the ratio of speeds of the two streams like $\delta_0 = (\text{constant})\,(1 - r)/(1 + r)$ where r is the ratio of the speeds of the two streams. Thus the compressible mixing layer growth rate is a product of this expression and the reduction due to convective Mach number effect. We can examine the relevance of this expression to practice. Fuel jets from Hydrogen are injected at sonic conditions, say axially, typically at 1200 to 1300 m/s. The air stream speed is typically 1400 to 1600 m/s. The difference in speed between the streams is typically 100 to 300 m/s. At the average acoustic speed of 800 m/s, the convective Mach number is 0.2 to 0.4. If the hydrogen stream is injected normal to the stream, a bow shockwave gets located ahead of the jet, and the subsequent dynamics is related to mixing layer behavior in a more complex manner. In the case of liquid kerosene injection, the tiny droplet cloud (of 20 to 30 microns size, typically), questions of the above nature do not directly apply. By the time drop vaporization occurs, the stream speeds would have come down due to slow heat release. Finally, even as an examination of the mathematical behavior of the mixing layer growth rate keeping the gas stream speed constant, but varying the air stream speed, the compressible mixing layer growth rate shows a peak growth rate at one air stream speed, a feature perhaps not so important considering the earlier mentioned facts, but seems to have been ignored in the literature. The simple message from the above discussion is that it is preferable to keep the convective Mach number at values less than 0.5 to ensure good Mixing rates. Typical growth rates even under adverse circumstances can be set at 1.5 to 2.5^0. It may be noted that subsonic mixing rates are about 4 to 5^0.

Let us examine how to account for the reduced growth rates. The fuel injection system is arranged inside the combustor such that the oxygen in the air stream throughout the cross section is used up in exothermic heat release. If the growth rates are one half of that in a low speed combustion system, one would need to provide twice the number of fuel orifices with reduced spacing so that the entire cross section at the appropriate distance will be filled with combustion gases. Stated differently, the flame length of any jet diffusion flame scales with the diameter of the jet. Thus, if one wishes to retain the same level of physical distance for supersonic combustion as for subsonic combustion, one would reduce the jet diameter suitably. Since the spread rate is also lower, one should provide an appropriate lower spacing to ensure and hence larger number of jets so that the entire space is filled with combustion zone.

The issue of the reduced mixing influencing the design as stated by large number of studies (see Seiner et al, 2001 for the review) appears divorced from reality for several reasons. Many successful developments of supersonic combustion even with liquid fuels took place even before the mixing issue got highlighted (see for instance, Payne, 1975). Since one needs to have some device to inject the fuel – gaseous or liquid and one needs to do with minimum intrusions unlike subsonic flows, one has to use struts or pylons. Use of three-dimensional geometry – like sweptback pylons or struts, and injecting at several axial locations instead of one will help create the desired axial heat release profile so that the inlet-combustor coupling problems will be reduced or eliminated. Further, issues of flame holding are addressed through the choice of the zone just aft of the struts or pylons for creating the necessary flame holding. Thus the problems of mixing highlighted by several scientists seem exaggerated since, the need for introducing some hardware elements for injecting fuel can be combined with the requirements of flame holding and combustion without special devices for this purpose. The work of Avrashkov et al (1990) is an example of such an effort.

One another feature that got uncovered by Marble and colleagues (1990, 1991) during the intense discussions on reduced mixing at high speeds was that the presence of baroclinique torque in hydrogen jets flowing into high speed streams is that if a shock intersects the jet, the fact that there is a pressure gradient normal to the density gradient helps in causing vorticity. This enhances the mixing rate substantially. The suggestion arising out of this study is that the fuel jet path can be arranged such as to intersect shocks from surfaces ahead of the fuel injection zone. Interestingly, it is not clear how one can avoid shocks bouncing from protuberances or edges in a confined supersonic flow. The inevitable conclusion is that mixing related issues would not be a problem since whatever method one might use to inject the fuel, the fuel jets would invariably intersect the compression waves and mixing will get enhanced. This suggestion and solution is valid for hydrogen as the fuel. For kerosene fuel, after the combustion gets initiated, one can expect that the there are high temperature zones separated from low temperature zones and these will provide the necessary density gradient. When these zones are intersected by shock waves, one can expect the "Marble effect" to take over and create enhanced mixing. Thus one finds enhanced mixing mechanisms naturally prevalent in the combustor and it appears that no additional loss producing mixing devices need to be introduced.

It is only appropriate to substantiate the above observations with results from experiments on combustors. Gruenig et al (2000) have conducted experiments in a small combustion chamber (27.5 x 25 mm) using pylons of different shapes and different injection schemes. They have assessed both mixing and combustion performance. These experiments at M = 2.1, static temperature of air of 765 K and of hydrogen of 150 K at a static pressure of 1 atm., show that combustion gets completed in less than 0.6 m from the injection station. The hot air is derived from the combustion of hydrogen and air and the oxygen fraction was accepted at the level of combustion itself – 19 % of oxygen, 8 % water vapor and 73 % Nitrogen. The conditions that are obtained in a practical combustor would be far more favorable in terms of oxygen fraction that would be at least 4 % higher, static temperature (~ 1200 K or better) and the fuel gas temperature would probably close to 600 to 800 K due to hydrogen being used a coolant around the combustor and hence the combustion distances would be even better.

The Japanese group from National Aerospace Laboratories, Kakuda have done excellent work on a variety of injection schemes in rectangular combustion chambers. Only two are cited here In the Mach 6 testing scheme (Kanda et al, 1997), they showed that even without an internal strut, with only wall injection, combustion could be completed in a rectangular combustion chamber with a side step at an equivalence ratio of 0.94 with in a distance of 1.0 m. The injection orifices used were 0.5 mm for pilot fuel and 1.5 mm for main hydrogen fuel injection. The fuel stagnation temperature is 300 K (static temperature would be about 160 K). The combustor Mach number is more than M = 2 and the pressure about 1 atm. The air stream static temperature is close to 800 K. Thus under these conditions, the combustion length has been 1 m and at a free stream speed of 1000 m/s, the combustion time is about 1 ms.

In another study (Mitani et al, 2000) with the same test facility, at M = 2, stagnation temperature of 1431 K, combustor static pressure of 0.023 MPa, ignition and combustion time estimated at 0.9 ms and a length of 0.30 m.

Thus achieving ignition and combustion in Hydrogen based engines at flight Mach numbers of 6 and combustor Mach numbers of 2 to 2.2, seems to be achieved with fuel injection scheme that is very standard with residence time of about a millisecond and combustor lengths of a maximum of 1 m.

3. Isolator between intake and the combustor

Another "cliché" that seems to have got embedded into the literature on supersonic combustors is the fact that isolator as an element between intake and the combustor is essential to prevent inlet un-start under several operating conditions of operation. The isolator is a constant area section from the end of inlet to the start of the combustor. Tomoika et al have expressed the need or otherwise of this element. They have shown that for the geometry and the flow conditions that they experimented with, at an equivalence ratio of 0.34, the combustion process was entirely confined to the combustor region, but at an equivalence ratio of 0.52, pressure rise took place right in the constant area section ahead of the combustor. It would be possible to obtain the same equivalence ratio through staged injection as done by them with the initial injection restricted to a lower value and subsequent injection to account for the total flow. This point is not unknown in the field of supersonic combustors. It has been recognized from a long time that the rate of heat release is fundamental to a proper design of a supersonic combustor. A slow release will prevent inlet – combustor backlash, but a longer combustor; a sharper heat release will create stronger waves ahead of the combustor that may cause inlet un-start in the extreme condition even though combustor may be short. The careful choice of the hardware inside the combustor and the fuel injection pattern can reduce or eliminate the upstream constant area section that will lead to losses with no obvious benefit. It would be easily possible to add additional divergent section if length is not a constraint to manage the inlet un-start problem. In fact it is recommended that calibrated computational tools can be effectively used to eliminate the isolator and manage the combustion process adequately.

4. Design for high degree of combustion, but not complete

This is another consideration that got floated in 1988/1990 largely because of the thinking proposed by Swithenbank and colleagues (1990). This study indicated that any progress in combustion is related to mixing and the final result of thrust from a vehicle is dependent on the pressure losses that occur due to turbulent mixing and pressure rise caused by progress in combustion. His simple analysis showed that optimum in performance is obtained at a combustion efficiency of around 80 %. An examination of his analysis considers combustion efficiency in terms of "oxygen untreated". This analysis has meaning in the specific context only if stoichiometric combustion is presumed. If the combustor were to be run on lean conditions, the analysis as presented cannot be used to draw the conclusions drawn in the paper. The analysis is set in such a simplified framework that the conclusions appear far too sweeping. Interestingly, excepting for the Langley group, the work does not seem to have evoked interest in subsequent work in the field. Even if it is true that one cannot burn a stoichiometric fuel-air mixture to completion in a scramjet combustor for optimum performance, it would be possible to run the system on a slightly leaner mixture and for this case, the theory does not apply. What more, present day computational tools can be used to settle the question clearly and in this sense, the issue is still open. And also, one has to use these tools to do a multi-disciplinary optimization so that one gets the best out of the combination of the combustor and other vehicle elements.

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