Role of Combustion in Propulsion – are there New Frontiers to Conquer?

H. S. Mukunda.
Department of Aerospace Engineering,
Indian Institute of Science, Bangalore 560 012

Abstract

This paper is aimed at examining a few areas in propulsion involving air breathing and non-air breathing engines that benefit from basic studies in combustion. Newer studies have to contend with substantial development of combustion devices many of which have had the benefit of approximate design approaches and development using intuition backed by consensus rather than rigorous computational back up which otherwise, has been the order of the day in advanced countries. Three areas – droplet atomization, turbulent combustion and high-speed combustion have been taken up for discussion here. The presentation outlines a broad assessment of international status, developments in India and what awaits exploration. Droplet atomization calls for fundamental approach on which much progress has taken place, but more needs to be done. Turbulent combustion, the hot topic of most current day researches, a field that has received little attention in India, except in using models developed elsewhere in the world, in the computational of the averaged equations. It is important that research in India in the area of physics of turbulent combustion must have more intense participation, perhaps from the academic world. The field of high-speed combustion needs to be pursued if the country *decides on building hypersonic cruise vehicles*. Such a development should benefit from the very insightful work carried by Japanese and American researches and should aim initially at building a hypersonic test vehicle flying in an autonomous mode enabling India to be Numero uno country in the world of propulsion.

1. Introduction

I must begin with the expression of a feeling of being privileged to deliver this talk. When I considered how I could make this talk worthwhile for the propulsion community to receive, it was clear that there was a need to balance the aeronautical and space propulsion interests, as the community is composed of both. There are aspects that each group pursues to the exclusion of the other. The main combustion chambers in gas turbine engines experience wide range of operating conditions: pressures of a few atmospheres at the lower end, idling operating conditions at low power implying low pressures and lean mixture ratios, both leading to problems of flame blow off, termed usually as flame stability. Providing a relatively uniform temperature profile at the interface between combustor and turbine is an arduous demand. Emission control on unburnt hydrocarbons (UHC), Nitric oxides (NOx), Carbon monoxide (CO) for engines on civil aircraft poses even more severe constraints on the design. That current day designs meet the current statutory limits and expect to meet the more severe controls in times to come goes to show the extraordinary growth in the technological strength. To a fair extent, it must be stated that the developments have benefited from computational support in achieving the results at costs and time much lower than what would have been possible otherwise. Problems of high frequency instability are usually discussed with reference to afterburner and ramjet combustion, but with much less concern than in the case of the design of liquid rocket engine combustion chamber. The design of gas turbine combustion chamber just as well as other components is aimed at life in terms of hundred to thousands of hours in comparison to a few minutes to perhaps a few hours in the case of rocket engines.

Realization of rocket engines occurs on very different lines. The whole technology of solid propellant manufacture has no parallel in air breathing engine technology and the men involved in these can only exchange pleasantries during breaks at meetings where they could be together; however, even these are rare. Chemistry, the foundation of design of solid rocket propellants is usually dreaded by engineers/scientists involved in other segments and the engineers are often skeptical of the true successes of chemists engineering a propellant with specified combustion characteristics. Admittedly, it is very tough to unravel all the steps in a complex chemistry governing the combustion of large chemical molecules; to add to the woe, physical processes like melting, liquid phase chemical activity are intimately coupled.

The combustion process occurs at very high pressures – tens of atmospheres – in a solid rocket engine is usually enveloped by the propellant itself or a well insulated chamber; the combustion process in a liquid engine also occurring at tens to hundreds of atmospheres needs liquid cooling around the walls which bear some similarity to film cooling processes in gas turbine engines.

Solid rocket engines do not burden the designers with instability due to the presence of metal oxide particles that provide damping; Liquid engines suffer the worst form of high frequency instability and need to be eliminated at the stage of design itself. The intense combustion process with high pressures helping enhanced speed of reactions, with little particulate damping leads to the instability. In an afterburner, the fact that the pressures are much lower (~ a few atmospheres) leads to a far more distributed combustion process and the resulting weaker forms of instability overcome with comparative ease by Helmholtz damping techniques.

Emission problems are not considered an issue with rocket engines.

The flow processes that occur in the port of a solid rocket, in the combustion space of a liquid rocket, and in the nozzles are the features common with those found in parts of gas turbine engines.

There is a tendency by development groups to use intuitive approaches, shortcuts, and statements of generalization of experiences to make decisions on new designs. Equally well, academic groups tend to examine “fundamental” questions, many times the results of which can at best adorn journals with little possible impact on development. Such attitudes cannot be easily modified unless the both groups attempt to find some common ground. The academic must relate the understanding derived from deeper exploration to the reality. The development engineer must be aware of the limitations of the “short cut” and should desist from swearing by the approach taken, however successful it be in a limited range of application and be willing to consider talking to the academic before crisis arises (at which time he will need to do it against will, many times, even though such interaction may not be useful).

In this backdrop, what I wish to do is to examine three aspects: Liquid atomization processes, turbulent combustion and high-speed combustion. It is realized that each of these areas enjoys extensive literature and what I wish to say will account for this fact.

2. Liquid atomization processes

The need to understand liquid atomization processes goes beyond aerospace applications and includes general mechanical engineering, chemical process engineering, and others. Yet the seriousness of the atomization process is felt very strongly in aerospace applications. The general feature that the vaporization time varies as the square of the drop diameter coupled with the need to complete the combustion process in as small a space as possible provides the motivation to atomize the liquid to as small a drop size as possible. Of course, there are circumstances like in liquid rocket engines, where a sharp heat release implies greater chance of high frequency instability and in these cases the drop size distribution is made deliberately coarse by reducing the pressure drop across the injection system. The question which one wishes to answer positively is: can we predict the drop size distribution given the injector geometry and flow parameters – essentially, the pressure drop across the injection head and the properties of the fluid. For a long time the question itself was not raised. Most scientists were happy to answer subsidiary questions. What is the drop size distribution as a function of injection system? Towards this extensive experiments were performed and lots of data collected. Experimental techniques have improved dramatically in the last two decades and non-intrusive optical techniques have been developed and used to obtain drop size distributions in cold flow as well as in selected combusting flows. In this class of studies many Indian efforts figure – those at NAL, GTRE and IISc (National Aerospace Laboratories, Gas Turbine Research Establishment, Indian Institute of Science all at Bangalore) and LPSC (Liquid Propulsion Research Centre at Trivandrum). It is not clear whether the data have had any definitive influence on the development of combustors. However, development of correlations has occurred. Internationally, such class of studies has been reported as well. More importantly, in the last ten to twelve years, there have been many insightful studies reported in the area of modeling the atomization process. The two primary methods of atomization – pressure atomizers as well air blast atomizers have been extensively explored. There are other areas related to impingement-based atomizers that have not been explored at all. The fundamental processes for atomization have been largely understood; yet there are areas that need exploration. In the group of subjects that have been largely understood are: At low aerodynamic force dominated regime, surface tension forces are responsible for pinching of drops, where the drop size corresponds to the wave length which has the largest linear growth rate (in a linear instability study involving surface tension). As aerodynamic forces increase, the wavelengths grow along the jet surface largely by Tollmein-Sclichting mechanism. At low relative velocities between surrounding gaseous medium and the liquid, the pinching off of drops occurs over the diameter of the jet itself. At higher speeds (increasing Reynolds number for fixed gas and liquid and fixed diameter of the jet), drops are pealed off from the surface; hence, the drop diameters are smaller than the jet diameter. At very high speeds, the drops are formed nearly instantaneously, perhaps with a combination of processes occurring very fast. While surface tension is primarily responsible for the atomization in the first two regimes discussed above, it opposes the peal off from the surface and in the last case, its role is yet unclear. While there have been attempts to classify the above regimes on the basis of Weber number, there appears no universality in the description.

Faeth (1996) has presented some correlations of experimental results of a few features of aerodynamic effects with Weber number (Figure 5 of his paper), he also indicates that predictions depart from the correlations and these are not significant, even though the first look suggests that the departures are significant. However, there seems to be agreement between two independent studies – Vingert et al (1995) and Faeth (1996) that several aspects of the primary atomization processes are yet unclear. The studies that have progressed from conservation equations towards droplet atomization have occurred in the last twelve years and they are far and few. The work by Rizk and Mongia (1991) towards this uses several empirical elements. The film thickness is correlated to various geometric and flow parameters both for airblast and pressure atomizers. However, recent work by Jang et al (1998) and Sakman et al (2000) on the computational fluid dynamic calculation of the pressure atomizer has obtained the film thickness at the end of the injector as a function of several parameters. *Such studies can fortify/modify the simple correlations based on experiments.* In the work of Rizk and Mongia, the atomization process is simulated by determining the ligament length from earlier stability studies and these ligaments being taken to become spherical droplets of the same volume. Then secondary atomization processes are expected to takeover. *Again the process of the sheet break-up into ligaments needs simulation.* Since the process covering the conversion of sheets to droplets is complex, studies have been made invoking concepts of information theory – idea of maximum entropy characterizing the state of a complex system with discrete states – on the conservation equations to derive the shapes of drop size distributions. These studies by themselves are very interesting; however, they do not seem to have much of a growth path. The only way the field will grow, it appears, will depend on the enhanced physics that would be brought into clarifying the individual processes – sheet thinning through the injector, surface instabilities through aerodynamic interaction, drop peal off through nonlinear three-dimensional wave growth, drop-to-drop interactions downstream (see for instance, Asheim, et al, 1988), drop-to-turbulence interactions, etc. While a fair amount of effort has gone on in downstream processes, the attention paid to early processes needs to be enhanced. *This area also promises to be exciting since it is the elementary phenomena that are being investigated and the generality of their impact will be substantive*. It is simply that virtually no attention has been paid to these in India till now and the field awaits invasion.

3. Turbulent combustion

Turbulent combustion is an even better trodden area attracting the best of the talents in the world to meet the challenges of the as yet impregnable subject of turbulence. So much has been examined with so many tools - experimental, analytical and computational, with very significant residual dissatisfaction amongst peers in the field that I hope to make use of a recent review by Bilger (2000) and make some additional observations. If we simply tabulate the efforts that have gone into obtaining the mean field of a turbulent flow including combustion, these will be: RANS (Reynolds Averaged Navier-Stokes Equations) with a hierarchy of models from zero-dimension to two equation models, additional equations for Reynolds stress – all supposed to work well in certain class of applications. There does not seem complete agreement amongst peers even on what will work where, so much so the partially educated reviewer might take any position – favorable to unfavorable on assessing the validity of the results of a specific computation. Inclusion of reacting flow brings in several scalars – temperature being the primary one, compositional variables whose number depends on the number of species one wishes to include in the examination. The fact that even in low speed combusting flows density varies significantly (by a factor of 4 to 10), it has been found more appropriate to average quantities with density as a multiplying factor – leading to Favre averaging scheme (in high speed compressible flows as well, Favre averaging becomes relevant for similar reasons). In recent times, other developments like probability density function (pdf) methods and conditionally averaged approaches have been proposed. The most prominent in this line is the Large Eddy Simulation (LES) approach known to be computationally prohibitive at present, but likely to be practical in about five years during which period, the computational speed also would have risen. The field of LES is currently undergoing significant metamorphosis with very insightful work on the possible reasons for its success despite the theoretical basis found shaky.

Predicting reactive turbulent processes in reciprocating engine combustion is distinct from those in gas turbines and rocket engine combustors. In the case of reciprocating engine, the combustion process is dominated by wrinkled laminar flame. Turbulence will affect the prediction of the wrinkled flame area. If in addition the effects due to stretch and curvature are added, the picture of the combustion process in a reciprocating engine is reasonably complete. In combustors of gas turbine and rocket engine, the scales of turbulence lead to invasion of the flame structure and hence the more complex approaches are needed to model the reactive turbulence behavior.

In the analysis of turbulent combustion, one of the important approaches is the flamelet theory. In this theory, it is assumed that the flame is thin – whether the flame is of diffusion or premixed kind. Its genesis is that the activation energy of the reactions is high and hence the principal reactions occur close to the highest temperature. A significant and powerful group of senior researchers have been addressing this subject over the last four decades. While these approaches have considerable value in providing insight, some of the promoters of the field have been so euphoric as to ignore certain essential realities. Typical activation parameter (the ratio of activation energy to the product of universal gas constant and adiabatic flame temperature) considered large from accuracy standpoint would be upwards of 10. Values of the order of 20 are considered more acceptable. Some comparative results on heat release in propagating flames of Methane, propane and hydrogen with air are now presented. It must be realized that these fuels are canonical fuels. Methane and Propane represent straight chain hydrocarbons that have been extensively used in studies to understand the aero-thermo-chemistry in many practical situations. If one were to obtain the equivalent activation parameter for Methane – air, Propane – air and Hydrogen – air systems, the results are as shown in the Table 1. These have been obtained by requiring that the heat release profiles of the propagating flame between an equivalent single step reaction should match in a a well defined manner with that from full chemistry. Figure 1 shows the plots of heat release profiles with the normalized temperature for both single step chemistry and full chemistry (see Mishra et al, 1994 for details). While in the case of methane flames, the peak of the heat release occurs at temperatures close to the adiabatic temperature, a feature required to be satisfied by asymptotic theories, the way it happens for the stoichiometric case – with a hot tail in the case of full chemistry defies simple simulation. Also the fact that significant heat release occurs over a temperature range implies that the flame would be reasonably “thick”.

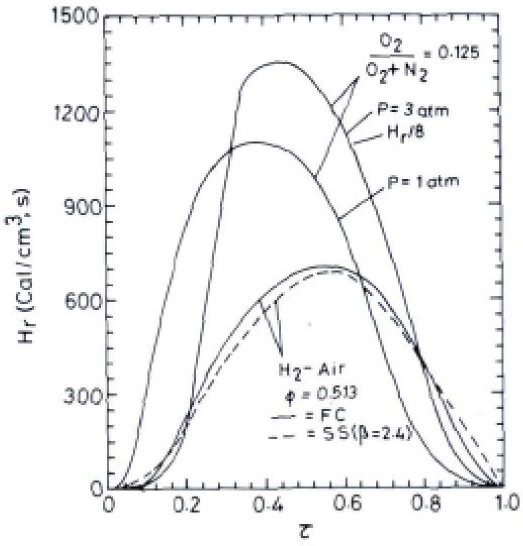


Fig. 1a Volumetric heat release rate with non-dimensional temperature for hydrogen-air flames (from Mishra et al, 1994)

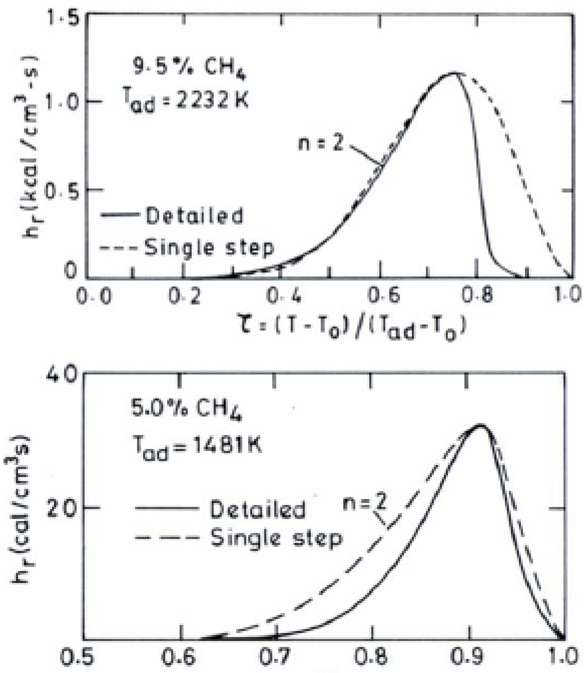


Fig. 1a Volumetric heat release rate with non-dimensional temperature for hydrogen-air flames (from Mishra et al, 1994)

Table 1

Case	Eq. ratio	b = E/RTad
Methane -air	1.0 (stoich)	6.3
Methane - air	0.5 (lean)	15.3
Propane - air	0.78 (lean)	7.0
Propane - air	1.55 (rich)	8.0
Propane – air	1.0 (stoich)	6.0
Hydrogen – air	1.65	2.3

In the case of lean flame, the conditions of good fit between the simple and full chemistry cases are good and the results of asymptotic case can be taken to be reasonable. *In the case of Hydrogen – air system, the peak of the heat release occurs at nearly half the adiabatic flame temperature and heat release occurs over a wide temperature range. It departs from expectations of asymptotic theories the largest*. An examination of the literature indicates that the proponent groups have been holding the fort for longer than can be argued to be appropriate (see Editors, 1994, for instance, particularly the articles by Candel, et al, and Williams). Bilger has concluded in his recent paper (Bilger, 2000) "Advances in Laser diagnostic measurements and DNS are now producing a mounting body of evidence that these concepts have limited validity in problems of practical interest for both premixed and non-premixed flames", a point of view we nurtured over the last eight years through the results described above. Admittedly, the basis needed to establish our point might have been simple, but, perhaps, putting these across needed far more evidence than we have presented and this is what Bilger has brought out.

A second issue in this area concerns the chemistry. Nearly twenty years ago, we felt that single step chemistry would be too inadequate to really help understand features and seek critical comparisons even in a broad sense and the major work on developing a code for determining the flame properties of a premixed flame was started. This code has had contributions to it over a time and it is now perhaps the most robust code for predicting the properties of a premixed flame at any mixture ratio, including the limits themselves (the flammability limits). The approach to solve fluid dynamically complex problems with chemistry has meandered in other ways. Arising out of the idea that capturing turbulent flow with full chemistry is extraordinarily difficult, ideas of reduced chemistry were given birth to by several groups. Combining activation energy asymptotics with rate ratio asymptotics, reduced chemistry models were developed for Hydrogen-air, Methaneair and a few other chemical systems. Though prided greatly by the developers (see Williams in Editors, 1994), it is being realized that the degree of generality over mixture ratio ranges, pressures and ambient temperatures is not adequate and the fashion of reduced chemistry is slowly waning. This position is aided by the advances in the speed of computers over the last two decades, a feature which was clear even to the developers but was pursued as, perhaps, interesting mathematical ventures, which of course they are. Cant (see Editors, 1994) in fact voices ineffectiveness of reduced chemistry approaches in his observations of how things will change in the next twenty-five years. Recent work (see Rightley, 2000) shows that this activity is a minor ineffective subject that will have a natural death in a couple of years.

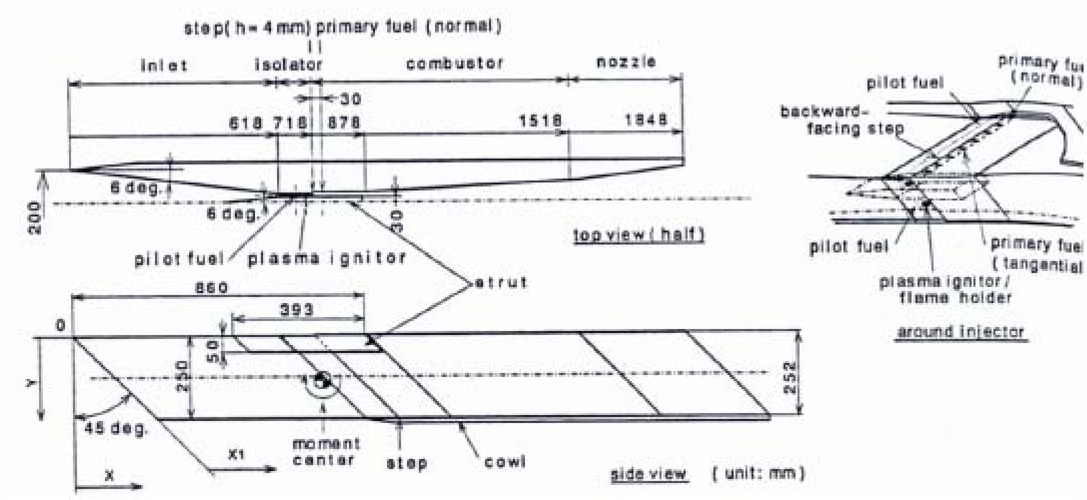
The crucial residual point that remains is to address the question of understanding turbulence. A study of the really vast literature in non-reactive turbulence shows that turbulence appears to have a fair degree of universality – the presence of the Kolmogorov spectrum in a variety of flows including reactive kind, and well defined mean properties. The route taken till now in which the means of fluctuations are modeled in relationship to other mean variables seems to have been beset with so many issues, to resolve which additional complexity is invoked seems to be unending. The pursuit of turbulence seems to be losing elegance and it is becoming increasingly difficult to imagine that the current routes will lead to understanding turbulence at all. It is in this connection that chaos as a route to model three-dimensional turbulence appears still to be relevant. The first step in this approach would be to write the equations for fluctuations, an act performed necessarily, before averaging is done. Instead of averaging the equations leading to Reynolds (or Favre) averaged equations, one must model the behavior of the fluctuations themselves. One standard technique would be to decompose the fluctuations into orthogonal functions (for instance Fourier series/transform) and solve for the coefficients, a procedure that has been dismissed long ago based on the consideration that turbulence involves a wide scale range and it is not captured by this technique. This can partly be overcome by looking at the spectral behavior of the fluctuations and embed into the required fluctuation behavior. There is a crucial issue of describing the phase relationships between different fluctuations. Unfortunately, studies aimed at understanding phase relationships and setting them out into conservation equations have not been there. Some effort in this direction at IISc did not lead to meaningful results. Currently thinking is that one should use wavelets to capture the phase behavior and this will be pursued in times to come. The road is long and it is not clear where it will lead somewhere at all. However, is it not the fun of science?

4. Supersonic Combustion

The subject of supersonic combustion is only forty years old. In the early sixties considerable work was done on supersonic ramjets at Marquardt Corporation in the USA. It was picked as a subject of national technical rejuvenation in the USA with a slogan “New York to Tokyo in three and a half hours” on a vehicle to fly at a Mach number of 27 in the late eighties. This was a project that was being pushed with little groundwork. Subsequent studies in till the early nineties showed that the possible optimum Mach number of flight would be closer to 10 in view of trajectory optimization and possible uncertainty in the net force available for acceleration. As Mach numbers increase, the drag values build up to large values and so would be the thrust. The net force will turn out to be the difference of two large quantities and any possible uncertainty in either of them will affect the available force for propulsion. Many countries –Japan, France, and Russia have major programs in the area of scramjet-based vehicles. Some flight tests have been performed cooperatively between Russia and France. Despite all this effort, the residual fact as of this writing is that no vehicle flying autonomously powered by a scramjet has been realized. The fact that such an event has not occurred despite expenditure of billions of dollars in several countries should also be a pointer to the seriousness demanded of the decision makers if India has to enter the field.

Though much of the early work was done in the USA, very useful and interesting work has been completed in Japan as seen from the open literature. Most of the published work from the USA was related to the fundamentals –inhibition of mixing under supersonic conditions and the enhancement of mixing by devices, mechanical or aerodynamic, examination of the flow behavior through the system by one-dimensional considerations, and computational work related to mixing and combustion in rectangular combustors. The results of tests in model geometries leading to overall performance are classified.

The Japanese work is very valuable on this score. Large groups (between 30 to 40, as can be assessed from the references – Kanda et al, 1997; Mitani et al, 1993; Masuya et al, 1995; Chinzei et al, 1993; Hiraiwa et al, 1995) have done serious experimental and computational studies in the early nineties, partly influenced by the thinking in the USA and produced results which are insightful; but the reality of a scramjet unit which can function with a vehicle and propel seems far-off. These studies are largely on hydrogen fueled combustors. The work of Kanda et al (1997) is very illustrative – measurements of forces and moments on a model system with results of direct implication to design – net thrust of the engine and other forces. Figure 2 shows the sketch of the model taken from the above reference.



The scramjet model used in the experiments of Kanda et al (1997)

Table 2 drawn from the paper by Kanda et al (Table 2 of their paper) is instructive.

Table 2

Test no.	Fuel flow, g/s	Net thrust, N	Lift, N	Pitching moment, N.m
Air only	-	- 1100	300	750
Weak combustion (16d)	36.5	-980	600	500
Intense combustion (19e)	42.6	-250	-200	1700
Unstart (18d)	78.8	-1150	1500	1450

Observations of Table 2 may lead to feelings of depression – no positive thrust from the system. This particular geometry does not have the nozzle extension that is formed by the bottom surface of the aft body. When th additional segment is added one will get good performance. Mitani et al (1993) indicate the possibility of a specific impulse of about 10,000 N.s/kg after analyzing the different loss mechanisms. The essential point in bring out the above table is to illustrate that the design of the elements to obtain positive thrust is not an easy task – certainly not as simple as in low speed air breathing engines or rocket engines.

The only tasks attempted in India at this time are testing and demonstrating the possibility of combustion at supersonic conditions and the number of people actively working would be not more than about eight including those at National Aerospace Laboratories, Defense Research and Development Laboratory, and work at IIT's and IISc. Some work has begun at VSSC very recently. The work at VSSC will largely concentrate on Hydrogen-fueled system, perhaps for an accelerating mission. Scramjets like their low supersonic counterparts – ramjets, are more suited to cruise missions. For instance, the sustain segment of SAM – 6 (Russia) which is a solid fuel ramjet accelerates very little in its flight. It is even more critical for scramjets. Getting good performance at a single operational point itself is non-trivial. To expect the system to perform over a range of Mach numbers is very difficult if not impossible. One mission contemplated for military application is a scramjet-based propulsion for cruise at Mach 7 using kerosene as the fuel. The classical thinking is that one must have a hydrogen pilot for igniting kerosene on a sustained basis. Systemic issues of carrying hydrogen when one is contemplating avoiding it as a propellant will need to be addressed. This then raises a question as to whether one can avoid hydrogen altogether in the vehicle operations. A few recent studies (Vinogradov et al, 1995; Owens et al, 1997, 1998) have addressed both ignition and combustion aspect of kerosene fuelled scramjets. By and large, they intend resolving the problems with a pilot injection of hydrogen jet at appropriate locations. Several of these studies use a step injector with wall as an inherent component. It is far more desirable to use a strut like configuration in which combustion occurs in the free-stream with reduced heat transfer problems at the walls. Minimizing the heat transfer to the wall calls for reducing if not eliminating bounding walls from being close to high temperature combustion zones. Kay et al (1992) demonstrated an interesting approach in which the a small part of the flow is brought to subsonic conditions in a small cavity enabling better conditions for ignition – temperatures are close to stagnation values and flow may have some recirculation zones. Both these enable ignition of hydrogen easily, and ethylene gas representing kerosene vapor closely. They seem to have stopped short of trying kerosene vapor, but in all probability it would have worked as well. If this approach is chosen, one might not struggle hard with sustenance of combustion in the flow field even if kerosene is the fuel. In a way the earlier work by Owens et al (1997, 1998) may be exaggerating the issues.

There is great deal of earlier work to draw upon to understand what should be done to generate a configuration that is a very good first approximation (for otherwise, the efforts to look for will be very expensive and time consuming) certainly for a single point functioning. There is enough computational work from elsewhere that can be used for comparison and calibration. Computational strength exists today in the country to try and pursue the activity by examining individual configurations, and computing flows without and with heat release, perhaps with as close a modeling of the process as possible including chemistry. There are several guidelines on the problems of kerosene in terms of thermal stability and sooting that one can get from earlier literature (Li et al, 1998, Liang et al, 1998) to configure the system either to inject vapor or boiling liquid.

5. General Remarks

In this paper, I have tried to examine three areas in propulsion relevant to aeronautical and aerospace community from the point of view of what exists today and what needs to be done. In the case of drop atomization, a subject that is of interest to community wider than aeronautical and aerospace, there is need to examine the drop atomization process itself. Though there has been progress on this internationally, there appears considerable opportunity to do innovative thinking and develop models for atomization. This is largely the task of the academic groups. Turbulence research including combustion will continue to baffle people for a long time. There is considerable opportunity to use native skills in thinking in this area. This will an activity restricted mostly to academic institutions.

In so far as the area of supersonic combustion is concerned, firstly, there should be clarity at the national level on the intended magnitude of effort. It was brought out that Japan has a presence in this field with at least 25 senior scientists with enormous facility support and what may be indicated as accomplished after six years of effort is very significant in the scientific sense but only marginal in the sense of having built a vehicle. This area should be taken up only after it is clear that work is definitely needed and when such a decision is made, the groups required to work in close coordination will be as large as 30 to 40 scientists over the next four to five years at which stage one will be clear of the definitions of the vehicle. Accelerating scramjets bring largely pain in the end. Very clearly, cruise scramjets are more likely to succeed and should be examined on paper first before any other activity is begun.

6. References

Droplet Atomization

Asheim, J. P, Kirwan, J. E, and Peters, J. E., Modeling of a hollow cone liquid spray including droplet collisions, Journal of Propulsion and Power, v. 4, pp. 391 – 398, 1988

Rizk, N. K, and Mongia, H. C., Model for air blast atomization, Journal of Propulsion and Power, v. 7, pp. 305 – 311, 1991

Chuech, S. G, Przekwas, A. J, and Singhal, A. K., Numerical modeling for primary atomization of liquid jets, Journal of Propulsion and Power, v. 7, pp. 879 – 886, 1991

Vingert, L, Gicquel, P, Lourme, D, and Menoret, L., Coaxial injector atomization, pp. 145 – 189, Ch. 6, Liquid Rocket Combustion Instability, v. 169, Progress in Astronautics
and Aeronautics, 1995

Faeth, G. M., Spray combustion phenomena, 26th Symposium (international) on combustion, pp. 1593 – 1612, The Combustion Institute, 1996

Jang, S. M, Jog, M. A, Benjamin, M. A., Computational and experimental study of liquid sheets for simplex fuel nozzle, AIAA J, v. 36, pp 201 - 205, 1998

Sakman, A. T, Jog, M. A, Jog, M. A., Jang, S. M., and Benjamin, M.A., Parametric study of simplex fuel nozzle internal flow and performance, AIAA J, v. 38, pp. 1214 – 1218, 2000

Turbulent combustion

Editors - The Next twenty five years – Combustion Science and Technology, 25th Anniversary issue, v.98, p. 217 – 365, 16 articles by leading combustion scientists,

Bilger, R. W., Future progress in turbulent combustion research, Progress in Energy and Combustion Science, v. 26, pp. 367 – 380, 2000

Mishra D. P, Paul P. J and Mukunda, H. S., Stretch effects extracted from propagating spherical flames with detailed chemistry, Combustion and Flame, v. 99, pp. 379 – 386, 1994

Rightley, M. L., Comment on the limitations of a reduced model for the simulation of H_2 – air combustion, AIAA J., v. 38, pp. 188 – 189, 2000

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Kanda, T., Hiraiwa, T., Mitani, T., Tomioka, S., and Chinzei, N., Mach 6 testing of a scramjet engine model, Journal of Propulsion and Power, v. 13, pp. 543 – 551, 1997.

Mitani, T., Ueda, S., Tani, K., Sato, S., Miyajima, H., Matsumoto, M., and Yasu, S., Validation studies of scramjet nozzle performance, Journal of Propulsion and Power, v. 9, pp. 725 – 730, 1993

Masuya, G., Komuro, T., Murakami, A., Shinozaki, N., Nakamura, A., Murayama, M., and Ohwaki, K., Ignition and combustion performance of scramjet combustors with fuel injection struts, Journal of Propulsion and Power, v. 11, pp. 301 – 307, 1995

Chinzei, N., Komuro, T., Kudou, K., Murakami, A., Tani, K., Masuya, G., and Wakamatsu, Y., Effects of injector geometry on scramjet combustor performance, Journal of Propulsion and Power, v. 9, pp. 146 – 152, 1993

Hiraiwa, T., Tomioka, S., Ueda, S., Mitani, T., Yamamoto, M., and Matsumoto, M., Performance of variation of scramjet nozzle at various nozzle pressure ratios, Journal of Propulsion and Power, v. 11, pp. 403 – 408, 1995

Vinogradov, V. A, Kobigsky, S. A, and Petrov, M. D., Experimental investigation of kerosene fuel combustion in supersonic flow, v. 11, Journal of Propulsion and Power, pp. 130 – 134, 1995

Owens, M, Segal, C and Auslander, A. H., Effects of mixing schemes on kerosene combustion in a supersonic air-stream, v. 13, Journal of Propulsion and Power, pp. 525 – 531, 1997
.
Owens, M. G, Tehranian, S, Segal, C, Viogradov, V. A., Flame holding configurations for kerosene combustion in Mach 1.8 airflow, Journal of Propulsion and Power, v. 14, pp. 458 – 461, 1998.

Kay, I. W, Peschke, W. T, and Guile, R. N., Hydrocarbon fueled scramjet combustor investigations, Journal of Propulsion and Power, v. 8, pp. 507 – 512, 1992.

Li, T. X, Zhu, D. L, and Law C. K., Droplet combustion, micro-explosion, and sooting characteristics of several energetic propellants, Journal of Propulsion and. Power, v. 14, pp. 45 – 50, 1998.

Liang, K, Yang, B, Zhang, Z., Investigation of heat transfer and coking characteristics of hydrocarbon fuels, v. 14, Journal of Propulsion and Power, pp. 789 – 796, 1998.