AUTHOR(S): MACLEOD, C. and GERRARD, C.E.

TITLE: A review of air-fuel mixing and alternative methods in scramjets and scramjet-like engines.

YEAR: 2016

Publisher citation: MACLEOD, C. and GERRARD, C.E. 2016. A review of air-fuel mixing and alternative methods in scramjets and scramjet-like engines. Journal of the British Interplanetary Society [online], 69(4), pages 116-126. Available from: http://www.jbis.org.uk/

OpenAIR citation: MACLEOD, C. and GERRARD, C.E. 2016. A review of air-fuel mixing and alternative methods in scramjets and scramjet-like engines. Journal of the British Interplanetary Society, 69(4), pages 116-126. Held on OpenAIR [online]. Available from: http://openair.rgu.ac.uk

A REVIEW OF AIR-FUEL MIXING AND ALTERNATIVE METHODS IN SCRAMJETS AND SCRAMJET-LIKE ENGINES

CHRISTOPHER MACLEOD[1,2] AND CLAIRE E GERRARD[3]
1. *Engineering Section, Lews Castle College Campus, University of the Highlands and Islands, Castle Grounds, Isle of Lewis, HS2 0XR, UK.*
2. *School of Engineering, The Robert Gordon University, Garthdee House, Garthdee Road, Aberdeen, AB10 7QB, UK.*
3. *School of Computing, The Robert Gordon University, Garthdee House, Garthdee Road, Aberdeen, AB10 7QB, UK.*

This paper reviews work on two aspects of scramjet and similar ducted hypersonic propulsion. The first of these is air-fuel mixing techniques - the problem of mixing is considered the most intractable in scramjet design. The second aspect is the use of innovative techniques to supplement mixing or provide an alternative to combustion altogether. The paper outlines the mixing problem and reviews both classic treatments and newer, more innovative, work. In the light of this it also outlines conclusions and points out gaps in current knowledge and areas where more research is needed.

Keywords: Scramjet, Mixing, Hypersonic, Propulsion, Space-plane, literature review

1. INTRODUCTION

The case for Scramjet-powered trans-atmospheric vehicles has been made eloquently by many commentators [1, 2] and there is no need to restate it here. However, there are numerous technical challenges to be overcome and, although there have been some successes in recent experimental programs, extended flight under Scramjet power remains elusive.

Some of these challenges are about the design of the inlet and exhaust topologies - at different speeds these systems have different optimal geometries. This means that their shapes need to change throughout the flight envelope and the machinery to do this could add substantially to the weight of the design. However, these concerns have been successfully overcome in other aerospace vehicles and it is generally agreed that the most demanding technological problems in Scramjet technology lie in fuel-air mixing and to a lesser extent combustion.

At high Mach numbers, drag values are very large and it is difficult to add further kinetic energy to an already energised air-stream. This means that the engine is finely balanced in terms of its thrust and drag components and a low-drag performance is essential for success. It may be understood from this that good conversion of the fuel's chemical energy is essential; yet at high Mach, air passes through the engine in around a millisecond - meaning that the fuel must mix with the air, burn and release its energy in a few tens of microseconds [3]. To achieve maximum extraction of energy, the fuel must be mixed stoichiometrically, at the molecular level, during this time. This must be done in such a way that it does not disrupt the flow enough to cause an increase in drag. The mixture must then be burnt, but without the aid of the flame-holding structures, used at lower speeds - as projections into the duct would cause form-drag. Finally, all this must be done without disrupting the conditions at the inlet.

The aim of this paper is review current work on air-fuel mixing techniques. Combustion research will also be covered where the problems cross over - but this aspect is generally thought to be connected closely with the mixing problem and is more tractable. Innovative techniques to supplement mixing or to provide an alternative to combustion altogether in scramjet-like systems will also be covered. The paper first outlines the mixing problem and the physical limits it poses; it then reviews both classic treatments and newer, more innovative, work. In the light of this, conclusions and areas where more research needs to be done and gaps in current knowledge are highlighted.

2. THE MIXING PROBLEM

The classical approach to fluid mixing is outlined in Heiser and Pratt *et al*. [1], using work from Pai [4]. However, this treatment doesn't cover the important topic of compressible flow well - this is covered in Segal [2] and in more detail in Slessor [5] and others [6–9]. It is not the purpose of this section to reiterate these treatments but to point out the fundamental limits that they impose on practical engines.

No matter how well mixed a flow is at the macroscopic level, only diffusion can provide a stoichiometric mixture *at the molecular level*. Unforced diffusion is controlled by Fick's Law [10], which in this case (in one dimension) may be written as:

$$J = -D_{FA}\frac{\partial C}{\partial y} \qquad (1)$$

Here D_{FA} is the diffusion coefficient or diffusivity of the fuel into the air (or vice-versa) measured in m^2s^{-1}, y is distance in m and C is the concentration of the air (C_A) or fuel (C_F) - depending on which one is being measured, often in (mols)m^{-3}. The result J is the flux of substance diffusing, in this case in (mols)$m^{-2}s^{-1}$.

Finding accurate values of measured diffusivity of fuel into air at the pressures and temperatures of a typical scramjet engine is almost impossible. Heiser and Pratt [1], in their calculations, use the dynamic viscosity μ to obtain a value for diffusivity:

$$D_{FA} = \frac{\mu}{S_C \rho} \tag{2}$$

Where ρ is the density in Kgm^{-3} and S_C is the Schmidt number, μ in Nsm^{-2} is given approximately for air by:

$$\mu = 1.46 \times 10^{-6} \frac{T^{\frac{3}{2}}}{T + 111} \tag{3}$$

The weakness of this approach is that it assumes a constant value for S_c - which is known to vary. Nether the less, by assuming a value of $S_c \approx 0.2$ - a typical measured value of hydrogen in air, useful results can be obtained as illustrated below; for other fuels, typically $S_c \approx 1$.

An alternative approach is to derive an expression for D_{FA} directly from kinetic theory [11]. One such formula in SI units is:

$$D_{FA} = \frac{3}{8nd_{FA}^2} \sqrt{\left(\frac{kT(m_F + m_A)}{2\pi m_F m_A} \right)} \tag{4}$$

Where n the number-density of molecules, k is Boltzmann's constant, T is absolute temperature, m_F and m_A are the masses of the fuel and air molecules (obviously an average value for air) and d_{FA} is the average diameter of a molecule in the system, given by:

$$d_{FA} = \frac{d_F + d_A}{2} \tag{5}$$

Putting in the various constants for hydrogen and air, equation 4 reduces to:

$$D_{FA} = \frac{5.63 \times 10^{18} \sqrt{(665 \times T)}}{n} \tag{6}$$

And n may again be calculated by kinetic theory:

$$n = \frac{p}{kT} \tag{7}$$

Where p is the pressure, again all parameters are in SI units.

The disadvantage of this method is that the typical assumptions of Kinetic Theory are applied (for example, assuming that gasses are perfect and molecules are spherical).

Calculated values from both these methods are tabulated in Table 1. For these calculations and others like them the widely quoted (and very typical) engine design published by Billig [12] and discussed in Anderson [13] is used. The parameters given are at the injectors, just before combustion.

The values calculated by continuum and molecular methods in this case differ by less than 4.2% up to Mach 15 and then diverge to a maximum of 27.7% difference in extreme conditions. The accuracy of these values may also be compared against the few available measured figures for similar gas parameters in the literature, some of which are given in Mills [14] at up to 2000K. In the case of the Kinetic Theory calculations this differs by less than 1.5% and by around 30% in the case of the continuum calculation.

Turning now to calculating the penetration of the fuel into the air stream by diffusion, there are several roughly equivalent approaches to this given in the various references. Heiser and Pratt quoting Pai [4] give the approximate thickness of the mixing layer δ as:

$$\delta \approx 8\sqrt{\frac{D_{FA} x}{u}} = 8\sqrt{D_{FA} t} \tag{8}$$

Where u is the convective velocity, in this case the velocity of the stream, assuming both fuel and air are moving in the same (axial) direction together. The axial distance down the duct is x and t is the time interval being considered.

The variation of the air molar fraction across the duct width at distance y from the centre as:

$$Y_A = \frac{1 + erf\left(\frac{4y}{\delta}\right)}{2} \tag{9}$$

Where:

$$Y_A = \frac{C_A}{C_A + C_F} \tag{10}$$

And the error function is:

$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \tag{11}$$

TABLE 1: *Comparison of Calculated Diffusivity.*

Free stream Mach N°	Temp (K)	ρ (kg/m^3)	μ_{air} (Ns/m^2)	D_{FA} (cm^2/s) S_c = 1 (note 1)	D_{FA} (cm^2/s) S_C = 0.2 (note 2)	n (#/m^3) × 10^{24}	D_{FA} (cm^2/s) (note 3)
5	700	1.24	3.33	0.27	1.35	27.3	1.41
7	810	0.563	3.65	0.65	3.25	12.4	3.32
10	1090	0.39	4.37	1.12	5.6	8.65	5.53
15	1600	0.238	5.46	2.3	11.5	5.25	13.02
20	2260	0.105	6.62	6.3	21.5	2.33	29.64

Notes: (1) Values calculated by Heiser and Pratt's method using equation 2 for most fuels (see text). Values are given in cm^2/s for convenience to convert to m^2/s divide by 10000. (2) Values calculated by Heiser and Pratt's method for hydrogen and air. (3) Values calculated from Kinetic Theory using equation 4 or 6, for hydrogen and air.

Similar formulae are given in other references, for example [15]:

$$C_{F(y)} = C_{F1}\frac{C_{A1}+C_{F1}}{2}\left(1+erf\left(\frac{y}{2\sqrt{D_{FA}t}}\right)\right) \qquad (12)$$

Where $C_{F(y)}$ is the concentration of the fuel at distance y from the centre of the duct; the values C_{F1} and C_{A1} are the initial concentrations of fuel and air before mixing.

Figure 1 shows the diffusive penetration of the fuel into the airstream verses the distance along the duct which the flow has travelled at various axial free-stream velocities. Data is again taken from the injection and mixing section of Billig's design, using equation 8. These figures assume that the fuel is moving at the same speed as the flow and therefore that there are no compressibility issues.

As can be seen, by the time the flow moves down the duct by, for example 25 cm, the penetration is only a few millimetres.

The importance of these figures is this: Whatever type of macro-mixing is used to bring the fuel into close contact with the flow (injectors, vortex-generators, struts, pylons, etc.), it must result in the fuel and air being macroscopically mixed to the distances shown in Fig. 1 - as only diffusion can "finish the job" and ensure mixing at the molecular level.

Consider now the effects of compressibility on the problem. Where the fuel and air streams meet, a discontinuity forms. If the streams are relatively supersonic, this takes the form of a shockwave. The shock is an area of high energy and density and effectively a barrier to penetration and therefore diffusion. Even before shockwaves form, a region of increased compression exists, which can have a similar effect [5]. To quantify the amount of compression at the boundary between the flows, many authors define a relative speed for the flow components (essentially shifting the frame of reference from the laboratory to that of the free flow). This is often termed the convective Mach number Mc. A common definition for two flows is:

$$M_c = \frac{u_1 - u_2}{a_1 + a_2} \qquad (13)$$

Where u_1 and u_2 are the speeds of the flows under consideration and a_1 and a_2 are the speed of sound in these flows.

Figure 2 is plotted from the data presented in Slessor [5], and shows the effect of compression. In this graph, the spatial rate of increase of the shear layer thickness is labelled δ' and the growth rate of the layer at $M_c = 0$ is labelled δ'_0 (sometimes called the incompressible growth rate):

$$\delta' = \left.\frac{d\delta}{dy}\right|_{\delta=f(M_c)} \text{ and } \delta'_0 = \left.\frac{d\delta}{dy}\right|_{M_c=0} \qquad (14)$$

So the term δ'/δ'_0 is the rate of change of the mixing layer, normalised to the incompressible case.

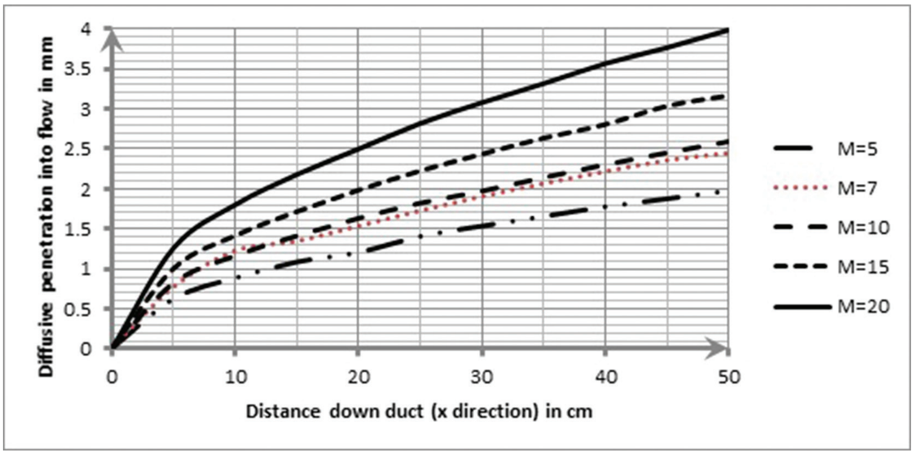


Fig. 1 Penetration of fuel into air-flow.

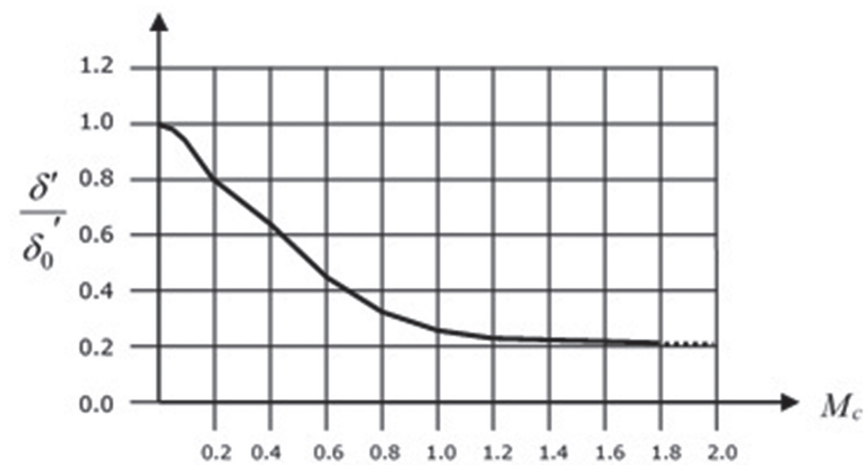


Fig. 2 Graph generated from data presented in Slessor *et al.* [5].

It can be seen from the graph that the amount of mixing decreases rapidly with increasing *Mc* and the distances shown in Fig. 1 should be adjusted downwards accordingly. The figure tends asymptotically to a value of around $\delta'/\delta'_0 \approx 0.2$, particularly for $M_c > 1$. Therefore, for maximum mixing rate, the velocities of fuel and air should match and, in the worst case, the mixing layer growth is only one fifth of its maximum possible value. A curve fit to the graph [2] gives:

$$f(M_c) = 0.2 + 0.8e^{-3M_C^2} \tag{15}$$

This graph can also be used to estimate reasonable values of excess velocity applied to the streams in order to induce, for example, turbulence. As an illustration, consider a simple rule of thumb that diffusive penetration of say 90 or 95% of the maximum is desirable, equation 15 may be rearranged to give:

$$M_C = \sqrt{\frac{\ln\left(\frac{f-0.2}{0.8}\right)}{-3}} \tag{16}$$

Setting $f = 0.9$ (for 90% mixing) and $f = 0.95$ (for 95%) gives connective Mach numbers of $f = 0.9$, $M_{(90\%)} = 0.211$ and $f = 0.95$, $M_{(95\%)} = 0.147$. These would correspond to 136 ms^{-1} and 95 ms^{-1} at Mach 10.

The upshot of all this is clear, although unpalatable. In a practical Scram system, for good air-fuel mixing, even under optimal conditions, the fuel injection system must ensure that the air and fuel are in macroscopic contact within a few millimetres to allow molecular diffusion to take place before combustion.

3. CLASSIC TEXTS AND GENERAL COVERAGE OF BASIC PROBLEMS AND SOLUTIONS

The most widely used and referenced standard text on scramjets is the book by Heiser, Pratt, Daley and Mehta [1]; this covers all the theory at a basic level. A newer book which covers similar ground is Segal [2]. Curran and Murthy's edited collection of papers in book form is also very popular [16]. The basic aerodynamic theory is covered in Anderson [17] and the development of scramjets in their historical context by Curran [18]. Other important papers on general topics are listed in the references [19-21].

There are also a number of general and highly cited reviews of mixing itself. All the technical issues discussed in these will be outlined in the next section, with reference to particular techniques – however, they still serve as useful overviews, which should be read before embarking on the more detailed papers. Of these reviews, the most general and cited is the paper by Seiner, Dash and Kenzakowski [22], this contains information on some interesting concepts, not well covered elsewhere. The more modern short review by Pandey is also well worth reading [23]. Bogdanoff [24] covers injectors well. Other smaller reviews, including Drummond [3] and similar papers, comparing several different strategies, are listed in the references [25-30].

4. REVIEW OF MIXING METHODS

The following sections break the topic of mixing methods into individual techniques, identifying the important papers in each case.

4.1 Simple Injectors

The wide-ranging review papers discussed in the previous section, particularly Heiser *et al*. [1], Seiner *et al*. [22] and Boganoff [24], cover the topic of basic injectors in detail. In general, the topologies studied fall into one of several categories, shown in Fig. 3.

Early papers focused on injection through simple holes (often referred to as ports). These generally injected fuel at right angles to the airflow as shown in Fig. 3a; this is known as Normal Injection. The idea was that the large velocity difference between the fuel and air would induce bulk turbulent mixing. However, a strong shock forms between the fuel and air (shown by the dotted line in the figure) and, as noted previously, this is a major barrier to diffusion. The normal shock thus formed quickly speeds up the fuel and only after this happens does good mixing occur – which can be well down-stream of the initial contact point.

To overcome this problem, and also to take advantage of the fuel's own momentum, designers quickly started to inject fuel at a more advantageous angle to the air-flow using ramp injectors, as shown in Fig. 3b. Two basic types have been well investigated. The first is generally referred to as a Compression Ramp, shown in Fig. 3c. This is because a shock (compression) wave occurs where the ramp projects into the flow (at point A in the diagram); this is followed by an expansion wave at the ramp tip. The other general topology is referred to as an Expansion Ramp and is shown in Fig. 3d. Here the shockwave is avoided by keeping the injector flat and the expansion wave dominates. Both types have their advocates, although most studies show better results from the expansion type.

Another area which has received attention, particularly in compression ramp designs, is the shape of the back portion of the injector as shown in Figs. 3e and 1f (in these diagrams, the injector is shown from above). Sweeping the profile like this causes swirl or vortices in the stream behind the injector – this increases macroscopic mixing and better results have been reported from these shapes. The topic of induced swirl is addressed in more detail in the sections below.

In addition to the standard coverage of simple injectors, several studies have considered other aspects of these in more detail. Work by Gruber and his co-workers [31] compared different nozzle shapes in ramp injectors, concluding that elliptical shapes worked well. Fuller et al compared several ramp types and found that some designs of aerodynamic ramp produced significantly better penetration of the fuel into the airflow [32]. Inoue and Aso [33] consider the advantages of making the injector nozzles into slotted shapes.

Moving away slightly from the standard injector types, a number of researchers have considered how mixing could be made more effective by employing more radical alterations to their operation. One injector type which falls into this category uses a pulsed fuel stream instead of a continuous one. Such injectors often use a resonance in their structure to produce the effect. Milton and Pianthong [34] and Steiner [22] consider these systems, although any definitive conclusions are somewhat lacking. Drummond covers co-axial injectors [3] and MacLeod discusses how free-stream kinetic energy may be used to reduce compression issues [35]. It should be noted that, in his review paper, Seiner [22] considers some interesting and unusual schemes not discussed elsewhere.

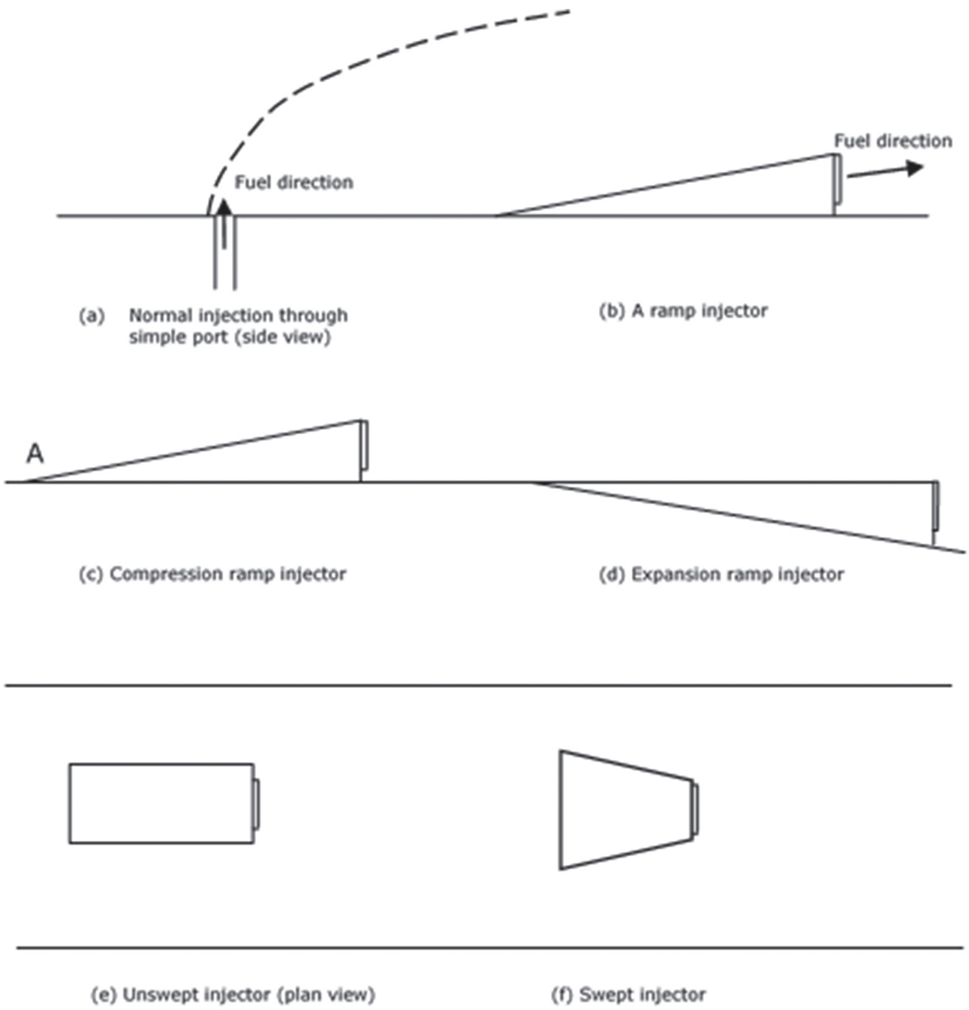


Fig. 3 Simple fuel injectors.

4.2 Injectors Introducing Swirl or Turbulence

Many authors have published theoretical and experimental evidence to indicate that inducing swirl, vortices or turbulence into the flow can aid mixing. This makes intuitive sense as it causes enfolding of the components, thereby inducing macroscopic mixing and facilitating fuel-air contact to the critical dimensions shown in Fig. 1. Such effects can be induced by the injector shape as mentioned above in the case of swept injectors. Heiser *et al*. [1] discusses swirl, turbulence and the advantages they give in general terms. There are also many papers dealing with the concept in more detail. Although it is an early work, one of the most highly cited and comprehensive papers in the field is that by Swithenbank and Chigier [36]. This considers the topic using both theoretical detail and experimental results and covers various ways of inducing swirl and turbulence and the effects of this – substantial increases in mixing are reported. Similar, more modern papers, mostly arriving at similar conclusions (although some report no substantial improvement), are listed in the references [37-40]. Two slightly more unusual contributions are those from Cutler and Johnson on pairs of swirling jets [41] and from Povinelli and Ehlers [42] on injection from a base plate.

4.3 Early and Staged Injection

Another variant on simple injection is to introduce the fuel earlier into the system to allow it more time to mix. Several papers have suggested this, most of them using injectors in the intake compression ramp. A good example of this type is reported by Gardener *et al.* [43]. Here a block of injectors are placed on the intake; the results indicate that doing this could reduce the length of the engine. Similar work using pylons was reported by Guoskov *et al.* [44]. Vinogradov *et al.* provides an overview [45]. The issue of premature ignition of the fuel-air mixture is a major problem with these methods and is discussed in most of the papers. Related to these concepts are papers on staging the injection process along the axis of the engine – sometimes injecting heavier and lighter fuel at different positions [46-48]. Interestingly, there is very little discussion of the logical conclusion of this class of idea – injecting the fuel into the flow well ahead of the intake, using a pole or spike-like structure; there is certainly work which can be done on this – particularly if it combined with innovative flow paths and engine structures [49].

4.4 Fins, Pylons and Struts

Fins are aerodynamic protrusions into the engine duct. They may be introduced for a number of reasons, for example to control the flow parameters - often by inducing swirl or turbulence. They may also be supplied with fuel and used directly as injectors as shown in Fig. 4.

As shown in the diagram, different fin types are often the

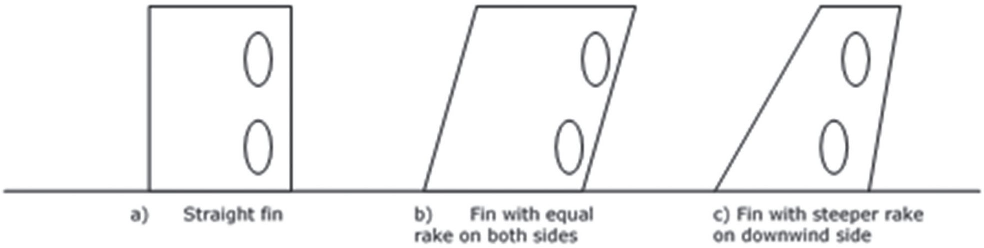


Fig 4 Commonly reported fin topologies.

subject of experiment. The elliptical shapes show typical placement of injector ports on the structures. A good example of this type of work, claiming an increase in mixing efficiency is by Aguilera et al [50]. Longer fins merge with struts, which are discussed below. A variant of fins are pylons – this term tends to refer to fin-like structures with injection ports placed directly behind them, as shown in Fig. 5.

The aim is to provide even finer control of the flow directly associated with mixing. A paper discussing this is by Doster *et al*. [51].

When fins and pylons extend substantially into the duct (often all the way across it) they are generally termed struts. Similarly to fins and pylons, these can be used to either control the flow or as part of an integrated injection system. The main issue with all protrusions into the duct are aerodynamic losses - often wave drag due to generated shocks or just simple viscous friction. The paper by Tam *et al*. [52] explores various issues with different strut shapes using CFD and reports that those with a constant leading-edge angle and raked trailing edge produce good results.

When the idea of fins, pylons and struts is taken to its logical conclusion the result is the Strutjet engine. This concept is more important than this bland sentence might imply for two reasons: Firstly, unlike the other concepts discussed so far, it addresses the challenge presented by the figures in Fig. 1 directly – by physically injecting the fuel into the system at a finer resolution over the cross-sectional area of the duct. Secondly, the struts are configured not to merely inject the fuel, but also to compress and channel the flow as shown in Fig. 6 – the engine therefore presents itself as a complete solution to the Scramjet problem. As shown in the diagram, regular struts extend across the intake, guiding and compressing the flow as well as injecting fuel into it.

A good overview of the Strutjet is given by Campbell in Curran's book [16] and also in other articles [53, 54]. The losses mentioned above are a real issue with these systems and tend to be glossed over somewhat in the papers. Moving away from the pure Strutjet concept (but taking its lessons to heart), one possible way of overcoming these problems and still affording good injection area coverage would be to use very fine or thin injector grids or meshes, perhaps fabricated with modern ceramics or similar advanced materials - this area is relatively unexplored in the literature.

4.5 Shockwave Enhanced Mixing

As outlined in the section on mixing and shown in Fig. 2, shockwaves can be one of the main problems in mixing – the compression region between fuel and air is a major obstacle to

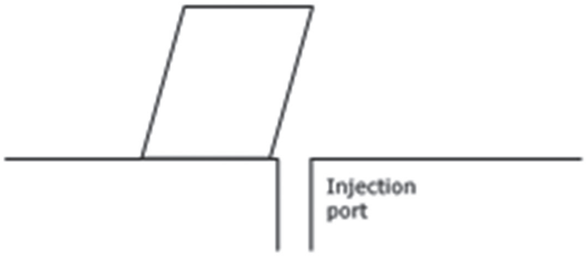


Fig. 5 Structure of a typical Pylon.

good penetration. However, several papers discuss how they may be harnessed to enhance mixing by forcing the components into each other. In most of these cases, the shock is outside the main mixing region and results in pressure waves which cause local instability and better mixing. Very careful placement of the shock-producing structures is required in these cases, as illustrated by the work of Kim *et al*. [55] and Mack and Steelant [56], both of these papers report improvements in mixing, as do most similar papers listed in the references [57], which include work on using oscillating shocks [58] and contoured duct walls [59] to produce the desired effect.

4.6 Cavities and Resonance

By carefully constructing the shape of the mixing or combustion areas of the duct it is possible to induce oscillations in the flow pattern [60]. This is typically done through the introduction of resonant cavities or a similar feature. An interesting example is reported in a paper by Quick *et al*. [61], where an upstream acoustic cavity in the mixing section is coupled with a downstream cavity in the combustion area. The paper reports that this combination increases mixing efficiency. The extensive MSc thesis on the topic by Nemeni [62] contains useful detail on cavity systems.

4.7 Observations on Mixing Methods

From a careful reading and comparison of the available papers, some interesting conclusions are forthcoming. These can be summarised by the following points: Firstly, the experimental base-line mixing-rates reported for simple diffusion are generally similar to those calculated theoretically in the first section of this paper. Secondly, most reliable papers on mixing enhancement, no matter which system they use to induce greater macroscopic mixing, usually report a similar (around one order of magnitude) increase on this base-line figure. Papers which report much larger increases are generally theoretical work and when this is reduced to practicality the words "disappointing"

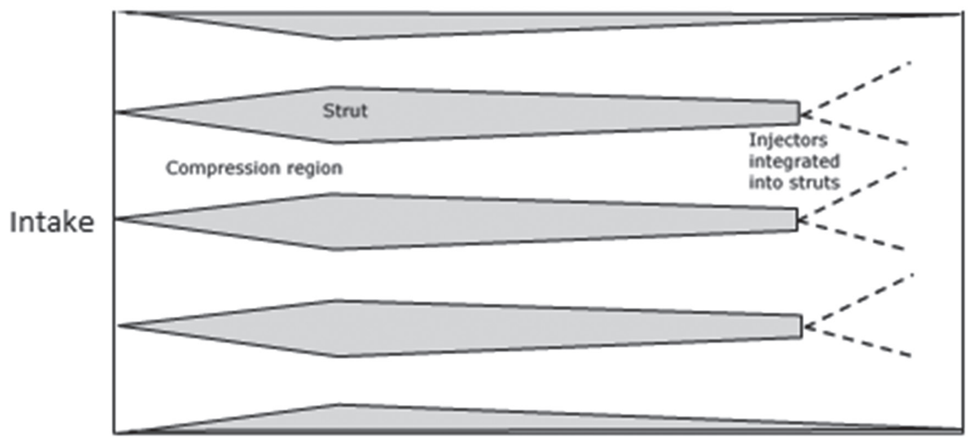


Fig. 6 Intake of Strutjet engine, plan view.

often appear in their conclusions – this often seems to be because of an under-appreciation of compressibility issues. We might summarise this situation by saying that most of the methods above do enhance mixing - but generally by a very similar, fairly predictable, amount. Furthermore, this amount is generally not enough to make such an engine practical.

There are a couple of exceptions to this general rule: The first is the Strutjet. Here the fuel is physically injected over a finer cross-sectional area and so, although the mixing obeys the same rules as stated above, the physical arrangement is such that the fuel ends up infused over a larger volume. The real issue with this engine lies in the unanswered questions about its losses. Leading on from this observation, as stated above, the injection of fuel from fine grids or very thin, razor-like injectors should prove fruitful grounds for further research. Similarly, the injection of fuel earlier into the engine and exploration of the more extreme possibilities of this may be interesting.

From this discussion it should be obvious that many of the papers above offer "more of the same" – that is, injection from wall-mounted devices, as a prescription for fuel-air mixing. Unfortunately, over the last fifty years this has proved time and again quite inadequate. It seems fairly obvious that more radical ideas, both in terms of engine topology and system-energy relationships are required - and it is these which are reviewed below.

5. REVIEW OF ALTERNATIVE INNOVATIVE TECHNIQUES

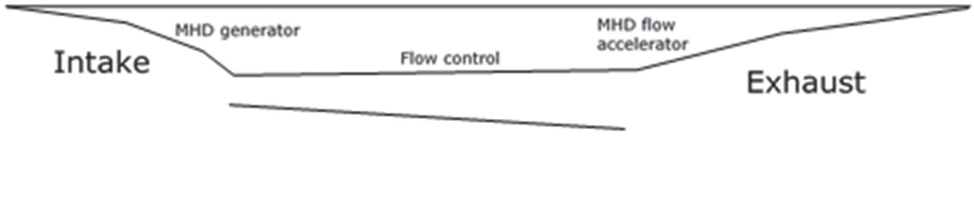
It has been stated that, should alternative sources of energy become available (or better ways of storing and releasing it), then completely new (and mostly unexplored) possibilities for trans-atmospheric engines will become feasible [63]. In the discussion below, some of the techniques reviewed are unfeasible with current power supplies (however, none of the core ideas are outside the bounds of current technology, other than this). They are included, however, because it may be possible to combine them with other techniques to produce a *multimodal* engine – that is, one which couples two or more originally different ideas together into a working system.

5.1 Ionisation and MHD Control of Flows

There is a great deal of interest in ionising the incoming airflow (forming a plasma) and then using ideas from Magneto Hydro Dynamics (MHD) to control it. This technique would potentially afford three advantages: Firstly, it could allow the generation of electricity from a slowing flow (usually at the intake). Secondly, magnetic or electric fields could be used to control the flow parameters. Finally, the stream could be accelerated, again using electric or magnetic fields, to achieve thrust. A generalised MHD system is shown in Fig. 7.

This general structure is discussed by Park *et al*. [64]. Control of flows and generation of energy are considered in a number of papers [65-67]. There is also some work on other ideas based on similar technologies - for example for reducing friction by generating a "plasma shell" around the aircraft [68]. The advantages of the system in general are its elegance and that it can be combined with combustion and other systems to provide several obvious hybrids. The disadvantages are twofold: Firstly, the requirement for a high-power source. Even in the system above, losses mean that energy must either be provided from a source to supplement that obtained by the generator, or an efficient energy reclaim must be in operation (which is unlikely, given the technical problems of reclaiming anything from hypersonic flows). The second and trickier problem is that of ionising the flow in the first place. Several methods have been considered for this including lasers, electron beams and electrical discharges of several types – however, none of these have proved practical so far. Conventional rockets would seem to be logical test-bed for such systems (and indeed it could also be applied to increase the efficacy of these), but this option does not seem to have been widely suggested so far.

Fig. 7 Use of MHD in Scramjet-like systems.



5.2 Electrical and Electromagnetic Heating and Control

A number of other methods of electrically heating or controlling hypersonic flows have emerged from time to time. Some of these involve heating the flow using resistive devices or an arc discharge [69-72]. Almost all of the ideas assume that a large power supply is available, as discussed above. Another idea is to use microwave energy to heat the flow directly [73, 74], to control mixing and combustion [75] or to heat an ionised flow [76]. Electrostatic and magnetic systems have also been considered in a similar context [77]. There are obvious connections between this work and the MHD systems mentioned in the previous sections. Other connections have not been fully explored yet - in fusion technology, microwave radiation, ohmic heating (heating by running large currents through the plasma), induction coils and particle beams are all used to heat or control the plasma [78]; however the application of these to MHD propulsion systems has not been researched in detail.

Laser heating systems have also been considered and these can operate in a number of different forms. There are several research projects using enclosed systems and external ground-based lasers (sometimes called lightcraft) [79]. Although these systems do not generally use ducts or internal laser systems, there is no reason why they should not in principle – although the stream generally needs to be seeded with an absorbent material [80], ultraviolet lasers can heat the air directly [73].

A number of other innovations, connected to the systems mentioned above, are worthy of mention. One is the use of high-efficiency fuel-cells to power electrical systems [80, 81]. Another is to control the flow to generate a Gas Dynamic Lasing (GDL) effect - which can be used to extract and move heat energy or ionise flows [35]. This could be useful both in MHD systems and also in providing ionised "arc paths" filling the volume of the flow for electric arc discharge systems (as could other laser systems). One final area is the use of plasma-torch systems for the initiation and maintenance of combustion [82, 83].

5. Solid Fuelled Engines

In recent years there have been a number of papers on solid-fuelled scramjets published. Most of this work is currently clustered on a research grouping around Haifa in Israel. These systems usually consist of the solid fuel arranged coaxially around the air duct. Work includes theoretical studies [84] and experimental research [85, 86]. The summary paper by Gany [87] is a useful starting point for further study. A great-deal of work can still to be done in this field - for example, the solid fuel could be vaporised using electric or microwave heating. The idea could also be combined with the principle behind strutjets so that the structure of the struts themselves provide fuel for the engine.

Another area which is likely to produce fruitful future research is the use of solid fuel pellets (or liquid/gaseous/composite capsules). These could be used in a pulsed system (or, for example, one with a rotating sculpted inlet/nose-cone) and injected with the correct timing into the engine duct when the airflow is switched off or rarefied as shown in Fig. 8, so that they fill the duct volume. If the airflow is then switched back on, it will envelop and atomise the pellets – distributing their fuel-load throughout the volume. Another alternative is to ballistically project suitably designed pellets into a continuous stream [90]. The same system could be applied to mixing any other active substance into the stream (for example GDL, MHD or electrically active substances). Several related systems have been considered at a basic level in a number of papers by Bates [88].

The former idea combines Scramjet technology with methods similar to those used in Pulse Detonation Engines (PDEs). There are several such combinations with this technique, but the subject of PDEs is so large that it requires another paper to itself - the review by Roy *et al*. [89] is a good starting point for further research.

5.4 Innovative Flow Paths

The topic of alternative flow paths has already been mentioned – for example in the work by Gaitonde et al [49]. Several options are outlined in this paper, including a scoop-like inlet structure, termed "jaws" by the authors. Such topologies could make several of techniques already discussed feasible - particularly those involving early injection, by reducing overspill. The same authors have produced a number of other papers on similar themes.

In general most papers stick to the standard ducted or axial versions of the engine, and there is a notable lack of variety in respect of design alternatives. Areas of particular interest, which are not well covered in the literature, include: "open" engine topologies – for example, based on similar principles to open rockets, like the well-known aerospike engine. It may not be possible to achieve the necessary inlet compression ratios using such methods, but combustion and exhaust topologies are a different matter. Likewise, no papers on extended linear engines integrated into lifting surfaces are apparent in the literature. The idea here, which has been discussed in on-line forums, is that an open topology engine is integrated into a carefully designed, contoured, wing-like lifting surface (termed a "scramwing"), and combustion takes place at different positions along this surface, depending on the aircraft's position in the flight envelope – thus eliminating the need for variable-geometry intakes and exhausts. Similarly, ramjet/scramjet combinations (typically, a supersonic core, surrounded by a subsonic periphery flow or vice-versa) are not well researched.

6. CONCLUSIONS

After half a century of research, it seems clear that injecting fuel into a supersonic duct from wall-mounted injectors, and hoping that it will mix sufficiently to provide real trust, is a dead-end. The various methods of mixing enhancement discussed above all produce an improvement on the simple case, but a thorough comparison of the papers shows that they are subject to a similar upper-bound on this improvement, and this is probably not enough to make the engine practical. There are some possible exceptions to this and these need further serious investigation. They are: Strutjets, injection from finely structured grids or meshes and foreword injection combined with more innovative inlet structures.

Combinations of the more radical solutions with other techniques, further downstream, may also yield results – for example, strutjet-like early injection, combined with swirl inducing fins and cavities may induce sufficient mixing. Such combinations have been termed "multimodal" approaches [35] and are not well researched. It is because of the failure

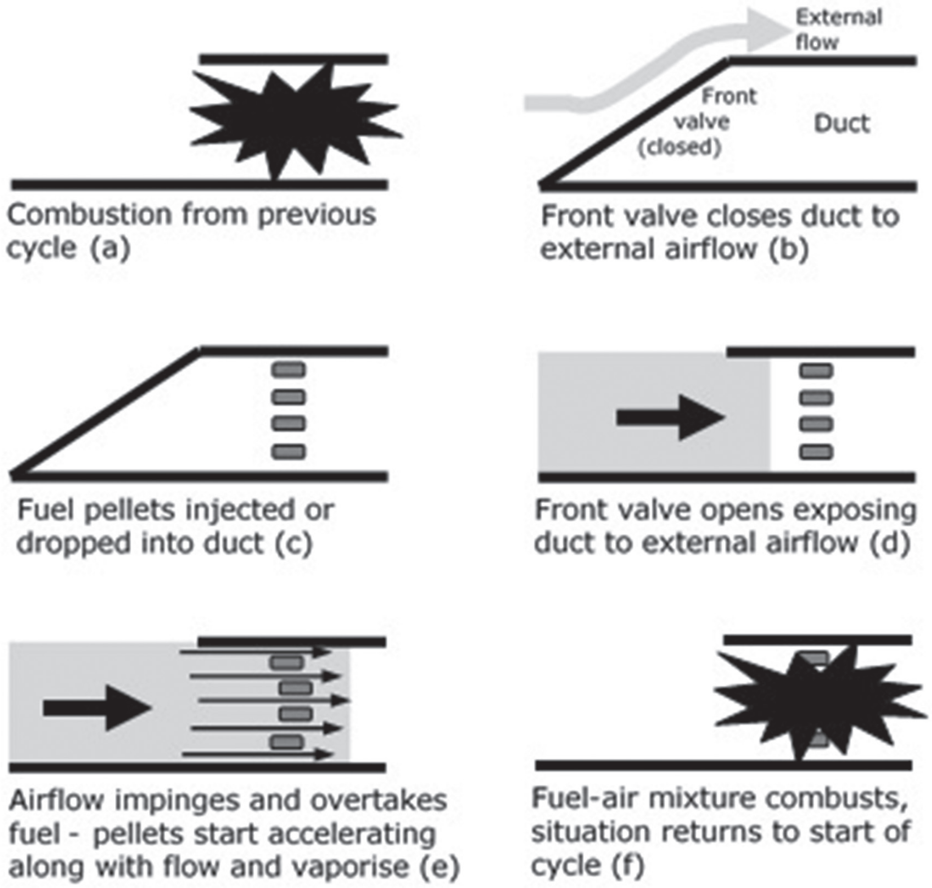


Fig. 8 Use of pelletized fuel.

of traditional methods and the need to consider more radical multimodal systems that the section on alternatives to combustion has been included in the paper.

The techniques illustrated in the latter part of the paper all use similar topologies to the scramjet - that is, they feature hypersonic or supersonic ducts. They have been chosen because they are all possible with current technology, *providing a sufficient power supply were available* (and, as indicted, should such, or a way of storing and releasing high energy, become available in the future, then the prospects for space travel would be transformed). However, papers on these techniques generally do not give them due consideration as part of a (more adventurous) multimodal system, together with combustion. A good example of such would be combining a slowing flow with a GDL effect to ionise a stream in another duct or using MHD generation to remove heat energy from a flow making mixing at lower speeds possible. Using two effects in separate (but coupled) ducts has been termed a "multicompartmental" approach. There are, in fact, around twenty unexplored possible combinations of any two of the major techniques outlined and many more if one includes three or more methods - and several of these look intuitively promising. Some interesting single techniques have also yet to be explored, for example the use of pelletized or encapsulated fuels discussed above. A prospective researcher could to worse than drawing up a matrix of possible combinations as a starting point for his or her work.

REFERENCES

1. W.H. Heiser *et al*., "*Hypersonic Airbreathing Propulsion*", AIAA Education, Washington, 1994.
2. C. Segal, "*The Scramjet Engine*", Cambridge University Press, Cambridge, 2009.
3. J.P. Drummond, G.S. Diskin and A.D. Cutler, "Fuel-Air Mixing and Combustion in SCRAMJETS", *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Indianapolis, USA, 7-10 July 200, Paper AIAA-2002–3878.
4. S.I. Pai, "*The Fluid Dynamics of Jets*", D Van Nostrand, New York, 1954.
5. M.D. Slessor, M. Zhuang and P.E. Dimotakis, "Turbulent shear-layer mixing: growth-rate compressibility scaling", *Journal of Fluid Mechanics*, **414**, pp.35-45, 2000.
6. D. Papamoschou and A. Roshko, "The compressible turbulent shear layer: an experimental study", *Journal of Fluid Mechanics*, **197**, pp.453-477, 1988.
7. M.A. Azim and A.K.M.S. Islam, "Turbulent mixing layer from two nonparallel streams", *The Aeronautical Journal*, **107**, pp.241-248, 2003.
8. S.L. Birch and J.M. Eggers, "A critical review of the experimental data for developed free turbulent shear layers", NASA document SP-321, pp.943-949, 1973.
9. G.L. Brown and A. Roshko, "On density effects and large structures in turbulent mixing layers", *Journal of Fluid Mechanics*, **64**, pp.775-781, 1974.
10. R.B. Bird, W.E. Stewart and E.N. Lightfoot, "*Transport Phenomena*", Wiley, New York, pp.518-525, 2002.
11. E.L. Cussler, "*Diffusion: Mass Transfer in Fluid Systems(2nd ed)*", Cambridge University Press, Cambridge, pp.101-141, 1997.
12. F.S. Billig, "Design and development of single stage to orbit vehicles", *John-Hopkins Applied Physics Laboratory Technical Digest*, **11**, pp.336-352, 1990.
13. J.D. Anderson, "*Fundamentals of aerodynamics (3rd ed)*", McGraw-Hill, New York, pp.538-542, 2001.
14. A.F. Mills, "*Heat and mass transfer*", Irwin, Chicago, p.1181, 1995.
15. Anon (Compressed Gas Association), "*Handbook of Compressed Gases*

(4th ed)", Kluwer Academic Publishers, Norwell, pp.60-62, 1999.
16. E.T. Curran and S.N.B. Murthy, "Scramjet Propulsion", in *Progress in Astronautics and Aeronautics*, Series V-189, AIAA, Washington, 2001.
17. J.D. Anderson, "Hypersonic and High Temperature Gas Dynamics", AIAA Education, Washington, 2006.
18. E.T. Curran, "Scramjet Engines: The First Forty Years", *Journal of Propulsion and Power*, **17**, pp.1138-1148, 2001.
19. C.J. Jachimowski, "Analytical study of the hydrogen-air reaction mechanism with application to scramjet combustion", NASA-TP-2791, NASA, Hampton, VA, 1988.
20. J.R. Henry and G.Y. Anderson, "Design considerations for the airframe-integrated scramjet", *First International Symposium on Air Breathing Engines*, Marseille, June 19-23 1972. (also available as NASA report).
21. E.T. Curran, W.H. Heiser and D.T. Pratt, "*Annual Review of Fluid Mechanics*", **28**, pp.323-360, 1996.
22. J.M. Seiner, S.M. Dash and D.C. Kenzakowski, "Historical Survey of Enhanced Mixing in SCRAMJET Engines", *Journal of Propulsion and Power*, **17**, pp.1273-1286, 2001.
23. K.M. Pandey, "Recent Advances in Scramjet Fuel Injection – A Review", *International Journal of Chemical Engineering and Applications*, **1**, pp.294-301, 2010.
24. D.W. Bogdanoff, "Advanced Injection and Mixing Techniques for Scramjet Combustors", *Journal of Propulsion and Power*, **10**, pp.183-190, 1994.
25. J.R. Henry, "Recent research on fuel injection and mixing and piloted-ignition for scramjet combustors", *Symposium (international) on Combustion*, **12**, pp.1175-1182, 1969.
26. R.A. Baurle *et al*., "An investigation of advanced fuel injection schemes for scramjet combustion", *36th AIAA Aerospace Sciences Meeting and Exhibit,* Reno NU, AIAA paper 98-0937, January 1998.
27. O. Dessornes and C. Jourdren, "Mixing enhancement techniques in a scramjet", *8th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Norfolk VA, April 1998.
28. S. Murugappan, "*Innovative techniques to improve mixing and penetration in scramjet combustors*", PhD Thesis, University of Cincinnati, 2005.
29. H. Ogawa, "Computational Investigation of Fuel Injection with Various Injector Geometries and Mixing into Hypersonic Crossflow in Scramjet Engines", *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Grapevine, TX, January 2013, Paper AIAA 2013-0115.
30. E.M. Fernando and S. Menon, "Mixing enhancement in compressible mixing layers - An experimental study", *AIAA Journal*, **31**, pp.278-285, 1993.
31. M. R. Gruber *et al*., "Transverse Injection from Circular and Elliptic Nozzles into a Supersonic Crossflow", *Journal of Propulsion and Power*, **16**, pp.449-457, 2000.
32. R.P. Fuller *et al*., "Comparison of Physical and Aerodynamic Ramps as Fuel Injectors in Supersonic Flow", *Journal of Propulsion and Power*, **14**, pp.135-145, 1998.
33. K. Inoue and S. Aso, "A Study on New Ramp Injectors with Slotted Nozzle for Improvement of Supersonic Mixing," *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Fort Lauderdale, 11-14 July 2004, Paper AIAA-2004-4208.
34. B.E. Milton and K. Pianthong, "Pulsed, supersonic fuel jets—A review of their characteristics and potential for fuel injection", *International Journal of Heat and Fluid Flow*, **26**, pp.656-671, 2005.
35. C. MacLeod "Innovative approaches to fuel-air mixing and combustion in airbreathing hypersonic engines", *JBIS*, **66**, pp.178-189, 2013.
36. J. Swithenbank and N.A. Chigier, "Vortex mixing for supersonic combustion", *International Symposium on Combustion*, **12**, pp.1153-1162, 1969.
37. D.W. Riggins and P.H. Vitt, "Vortex generation and mixing in three-dimensional supersonic combustors", *Journal of Propulsion and Power*, **11**, pp.419-426, 1995.
38. D.K. Kraus and A.D. Cutler, "Mixing of swirling jets in a supersonic duct flow", *Journal of Propulsion and Power*, **12**, pp.170-177, 1996.
39. T. Sunami, M. Wendt and M. Nishioka, "Supersonic mixing and combustion control using streamwise vortices," *34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, Cleveland, USA, 13-15 July 1998, Paper AIAA-1998-3271.
40. S-H. Lee and T. Mitani, "Mixing Augmentation of Transverse Injection in Scramjet Combustor", *Journal of Propulsion and Power*, **19**, pp.115-124, 2003.
41. A. Cutler and C. Johnson, "The use of swirling jet pairs to provide rapid fuel penetration in scramjet combustors," *33rd Aerospace Sciences Meeting and Exhibit*, Reno, USA, 9-12 January 1995, Paper AIAA-1995-0099.
42. L.A. Povinelli and R.C. Ehlers, "Swirling Base Injection for Supersonic Combustion Ramjets", *AIAA Journal*, **10**, pp.1243-1244, 1972.
43. A. D. Gardner, A. Paull and T. J. McIntyre, "Upstream porthole injection in a 2-D scramjet model", *Shockwaves*, **11**, pp.369-375, 2002
44. O.V. Guoskov *et al*., "Numerical Research of Gaseous Fuel Preinjection in Hypersonic Three-Dimensional Inlet", *Journal of Propulsion and Power*, **17**, pp.1162-1169, 2001.
45. V.A. Vinogradov, Y. M. Shikhman and C. Segal, "A Review of Fuel Pre-injection in Supersonic, Chemically Reacting Flows", *Applied Mechanics Reviews*, **60**, pp.139-148, 2007.
46. E.H. Weidner and J.P. Drummond, "Numerical Study of Staged Fuel Injection for Supersonic Combustion," *AIAA Journal*, **20**, pp.1426-1431, 1982.
47. K. Kobayashi *et al*., "Performance of a Dual-Mode Combustor with Multistaged Fuel Injection", *Journal of Propulsion and Power*, **22**, pp.518-526, 2006.
48. J.C. Turner and M.K. Smart, "Application of Inlet Injection to a Three-Dimensional Scramjet at Mach 8", *AIAA Journal*, **48**, pp.829-838, 2010.
49. D.V. Gaitonde *et al*., "Integrated Analysis of Scramjet Flowpath with Innovative Inlets", *DoD HPCMP Users Group Conference*, pp.130-137, 2008.
50. C. Aguilera *et al*., "Scramjet Mixing Control Using Fin-Guided Fuel Injection", *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and exhibit*, Denver, USA, 2-5 August 2009, Paper AIAA-2009-5415.
51. J. Doster *et al*., "Pylon Fuel Injector Design for a Scramjet Combustor", *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and exhibit*, Cincinnati, USA, 8-11 July 2007, Paper AIAA-2007-5404.
52. C-J. Tam *et al*., "Aerodynamic Performance of Strut Injection for a Round Scramjet Combustor", *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and exhibit*, Cincinnati, USA, 8-11 July 2007, Paper AIAA-2007-5403.
53. B. T. Campbell, A. Siebenhaar and T. Nguyen, "Strutjet Engine Performance", *Journal of Propulsion and Power*, **17**, pp.1227-1232, 2001.
54. M. Bulman and A. Siebenhaar, "The strutjet engine - Exploding the myths surrounding high speed airbreathing propulsion", *31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and exhibit*, San Diego, USA, 10-12 July 1995, Paper AIAA-1995-2475.
55. J-H. Kim *et al*., "Numerical Study of Mixing Enhancement by Shock Waves in Model Scramjet Engine", *AIAA Journal*, **41**, pp.1074-1080, 2003.
56. A. Mack and J. Steelant, "Mixing Enhancement by Shock Impingement in a Generic Scramjet Combustion chamber", *Proceedings of the European Conference on Computational Fluid Dynamics*, **Vol 1**, pp.531-550, 2006.
57. S. Menon, "Shock-wave-induced mixing enhancement in scramjet combustors", *27th Aerospace Sciences Meeting*, Reno, USA, 9-12 January 1989, Paper AAIA-1989-0104.
58. A. Kumar, D.M. Bushnell and M.Y. Hussaini, "Mixing augmentation technique for hypervelocity scramjets", *Journal of Propulsion and Power*, **5**, pp.514-522, 1989.
59. I.A. Waitz, F.E. Marble and E.E. Zukoski, "Investigation of a contoured wall injector for hypervelocity mixing augmentation", *AIAA Journal*, **31**, pp.1014-1021, 1993.
60. N. Sato *et al*., "Advanced Mixing Control in Supersonic Airstream with a Wall-Mounted Cavity", *Journal of Propulsion and Power*, **15**, pp.358-360, 1999.
61. A. Quick *et al*., "Upstream Mixing Cavity Coupled wtih a Downstream Flameholding Cavity Behavior in Supersonic Flow", 41st *AIAA/ASME/SAE/ASEE Joint Propulsion Conference and exhibit*, Tucson, USA, 10-13 July 2005, Paper AIAA - 2005 – 3709.
62. V.A.R. Nenmeni, "Flow Induced Cavity Resonance for Turbulent Compressible Mixing Enhancement in Scramjets", MSc thesis, University of Maryland, 2002.
63. C. MacLeod and K.S. Gow, "A reconsideration of electrostatically accelerated and confined nuclear fusion for space applications", *JBIS*, **63**, pp.192-205, 2010.
64. C. Park, D. Bogdanoff and U.B. Mehta, "Theoretical Performance of Frictionless Magnetohydrodynamic-Bypass Scramjets", *Journal of Propulsion and Power*, **17**, pp.591-598, 2001.
65. S. Macheret, M. Shneider and R. Miles, "External supersonic flow and scramjet inlet control by MHD with electron beam ionization", *39th Aerospace Sciences Meeting and Exhibit*, Reno, USA, 8-11 January 2001, Paper AIAA-2001-0492.
66. E. Sheikin and A. Kuranov, "MHD Controlled Inlet for Scramjet with Various Configurations of Magnetic Field", *42nd AIAA Aerospace Sciences Meeting and Exhibit,* Reno, USA, 5-8 January 2004, Paper AIAA-2004-1195.
67. S. Macheret *et al*., "MHD Power Generation in Scramjet Engines in Conjunction with Inlet Control," *42nd AIAA Aerospace Sciences Meeting and Exhibit,* Reno, USA, 5-8 January 2004, Paper AIAA-2004-1197.
68. V.L. Fraishtadt, A.L. Kuranov and E.G. Sheikin, "Use of MHD systems in hypersonic aircraft", *Technical Physics*, **43**, pp.1309-1313, 1998.

69. P.J. Wilbur, C.E. Mitchell and B.D. Shaw, "The Electrothermal Ramjet", *Journal of Spacecraft and Rockets*, **20**, pp.603-610, 1983.
70. H. Kolm, "Electromagnetic Propulsion Alternatives," *4th Princeton/AIAA Conference on Space Manufacturing Facilities*," Princeton, USA, 14-17 May 1979, Paper AIAA-1979-1400.
71. R.G. Jahn, "*Physics of Electric Propulsion*", McGraw-Hill, New York, 1968.
72. M. Martinez-Sanchez and J.E. Pollard, "Spacecraft electric propulsion – an overview", *Journal of Propulsion and Power*, **14**, pp.688-699, 1998.
73. C. MacLeod, "Electromagnetically Activated Hypersonic Ducts", *JBIS*, **62**, pp.99-109, 2009.
74. C. MacLeod, K.S. Gow and N.F. Capanni, "Some Practical Aspects of Electromagnetic Activation", *JBIS*, **62**, pp.320-331, 2009.
75. E. Stockman *et al*., "Toward High Q, Evanescent Coupled Microwave Controlled Combustion", *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*, Orlando, USA, 5-8 January 2009, Paper AIAA-2009-0491.
76. S. Satori *et al*., "The development of a microwave engine," 27th *International Electric Propulsion Conference*, Pasadena, USA, 15-19 October 2001, Paper IEPC-01-224.
77. T. Taylor and D. Riggins, "Impact of Electro-Magnetics and Ionization on Mixing and Combustion in Scramjet Combustors", *42nd AIAA Aerospace Sciences Meeting and Exhibit,* Reno, USA, 5-8 January 2004, Paper AIAA-2004-0859.
78. C.M. Braams and P.E. Stott, "*Nuclear Fusion*", Institute of Physics Publishing, Bristol, 2002.
79. L. Myrabo, D. Messitt and F. Mead, "Ground and flight tests of a laser propelled vehicle", *36th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, USA, 12-15 January 1998, Paper AIAA-1998-1001.
80. Y. Minami and S. Uchida, "Water Vapour Propulsion Powered by a High-Powered Laser Diode", *JBIS*, **62,** pp.332-339, 2009.
81. I. Regev and M. Lai, "Hybrid Jet Engine for Unmanned Aerial Systems (UAS) Applications", *51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*", Grapevine, USA, 7-10 January 2013, Paper AIAA-1013-1070.
82. K. Takita, "Ignition and flame-holding by oxygen, nitrogen and argon plasma torches in supersonic airflow", *Combustion and Flame*, **128**, pp.301-313, 2002.
83. Y. Sato *et al*., "Effectiveness of plasma torches for ignition and flameholding in scramjet", *Journal of Propulsion and Power*, **8**, pp.883-889, 1992.
84. R. Ben-Arosh *et al*., "Theoretical study of a solid fuel scramjet combustor", *Acta Astronautica*, **45**, pp.155-166, 1999.
85. A. Ben-Yakar, B. Natan and A. Gany. "Investigation of a Solid Fuel Scramjet Combustor", *Journal of Propulsion and Power*, **14**, pp.447-455, 1998.
86. A. Cohen-Zur and B. Natan. "Experimental Investigation of a Supersonic Combustion Solid Fuel Ramjet", *Journal of Propulsion and Power*, **14**, pp.880-889, 1998.
87. A. Gany, "Accomplishments and Challenges in Solid Fuel Ramjets and Scramjets", *International Journal of Energetic Materials and Chemical Propulsion*, **8**, pp.421-446, 2009.
88. S.C. Bates, "Assessment of Solid Hydrogen Slurry Fueling for an Airbreathing Supersonic Combustor", *Journal of Propulsion and Power*, **20**, pp.793-800, 2004.
89. G.D. Roy *et al*., "Pulse detonation propulsion: challenges, current status, and future perspective", *Progress in Energy and Combustion Science*, **30**, pp.545-672, 2004.
90. C. MacLeod, N.F. Capanni and K.S. Gow, "Overcoming Fuel-Air Mixing Issues with Pulsed Scramjets and Pelletized Fuel", *JBIS*, **68**, pp.354-362, 2015.

(Received 18 May 2015; Accepted 20 July 2016)

* * *