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Overcoming Fuel-Air Mixing Issues with Pulsed Scramjets and Pelletized Fuel

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In this paper the concept of a pulsed Scramjet using pelletized fuel is examined. The aim is to overcome the main technical problem inherent in more traditional designs – poor air-fuel mixing. In this new paradigm, airflow is diverted away from the main engine duct and fuel pellets are injected at timing intervals which ensure that they are evenly distributed throughout the mixing volume. The main airflow is then permitted to enter the duct and the inertia of the pellets allows the air to envelop and then vaporise them - and so their fuel load is evenly spread through the duct volume. The paper outlines the basic concept and calculations and simulations are used to demonstrate its feasibility.

Keywords: Scramjet, Mixing, Capsules, Pellets, Pulsed, Solid fuel, PDE

1. Introduction

Many commenters [1,2] have eloquently made the case for Scramjet powered space-planes. However, there are numerous technical challenges to be overcome and although there have been some successes in recent investigations, extended flight under Scramjet power remains illusive.

Some of the challenges concern the design of the inlet and exhaust systems - which, at different speeds, have different optimal topologies. This means that their shape needs to change throughout the flight envelope and the machinery to do this could add substantially to the weight of the design. However, these problems 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 also 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 unacceptable 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 [1].

2. The mixing issue in traditional Scramjet topologies

Only diffusion can provide the necessary microscopic mixing across the fuel-air boundary and achieve a stoichiometric mixture *at the molecular level*. Unforced diffusion is controlled by Fick's Law [4], which in this case (in one dimension) may be written as:

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

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, usually in $(\text{mols})\text{m}^{-3}$. In this case, the result J is the flux of substance diffusing, in $(\text{mols})\text{m}^{-2}\text{s}^{-1}$.

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

$$D_{FA} = \frac{\mu}{S_c \rho} \quad (2)$$

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

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

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 (for other fuels, typically $S_c \approx 1$), useful results can be obtained as illustrated below.

An alternative approach is to derive an expression for D_{FA} directly from kinetic theory [5]. One such formula in SI units is:

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

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.

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

$$D_{FA} = \frac{5.63 \times 10^{18} \sqrt{(665 \times T)}}{n} \quad (5)$$

Again, n may be calculated from kinetic theory and 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 below, for the parameters given at the injectors, just before combustion, in Billig's engine [6,7] (a very typical standard engine-design used for reference calculations in many papers).

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) $\times 10^{24}$	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

Note 1: Values calculated by Heiser and Pratt's method using equation 2 for most fuels (see text). Values are given in cm²/s for convenience, to convert to m²/s divide by 10000.

Note 2: Values calculated by Heiser and Pratt's method for hydrogen and air.

Note 3: Values calculated from Kinetic Theory using equation 4 or 5, for hydrogen and air.

Table 1, Comparison of calculated diffusivity.

The values calculated by continuum and molecular methods in this case differ by less than 4.2% up 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 at similar gas parameters in the literature, some

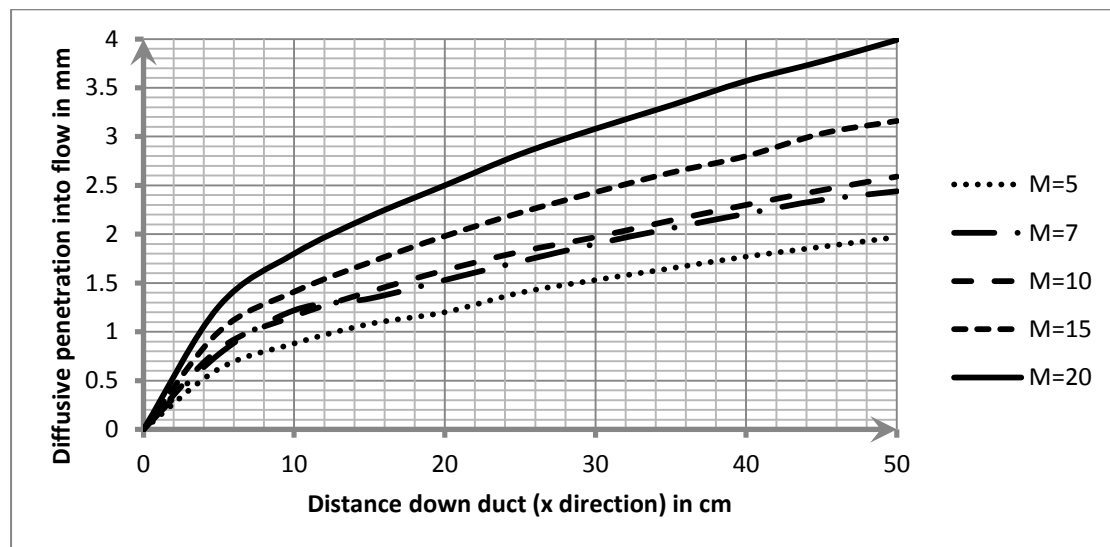
of which are given in Mills [8] at up to 2000K. In the case of the Kinetic Theory calculations this differs by less than 1.5% and by around 30% in the case of the continuum calculation.

To calculate the penetration of the fuel into the air stream by diffusion, there are several roughly equivalent methods given in various references [9]. A common approach is to use the formulae in Heiser and Pratt [1] (quoting Pai [10]). They give the approximate thickness of the mixing layer δ as:

$$\delta \approx 8\sqrt{\frac{D_{FA}x}{u}} = 8\sqrt{D_{FA}t} \quad (6)$$

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

Graph 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 velocities taken from the injection and mixing section of Billig’s design. These figures assume that the fuel is moving at the same speed as the flow and therefore there are no compressibility problems – in practice the compressibility issue can mean that the penetration is only 20% of this value in a worst-case scenario [2,11].



Graph 1, Penetration of fuel into air-flow at various free-stream Mach numbers.

As can be seen, by the time the flow moves down the duct by, for example 25cm, 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 within the distances shown in graph 1, as only diffusion can “finish the job” and ensure mixing at the molecular level.

3. Basic principle of Pulsed Scramjet

Almost all published scramjet designs assume the insertion of a gas into the airflow from some variation of port, ramp or strut injector. These generally can’t achieve good mixing for the reasons outlined above (in the case of ports and ramps) or generate too much disruption and drag (in the case of struts and other projections deep into the duct). There is however an alternative to this scenario and this is explained below and shown stylistically in figure 1.

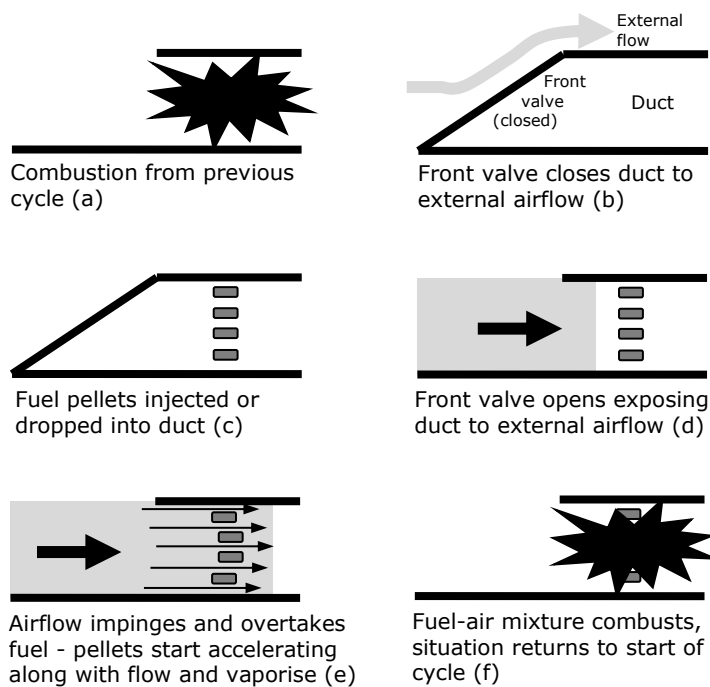


Figure 1, Diagrammatic representation of cycle.

The cycle starts by shutting-off the airflow into the scramjet duct as shown in figure 1b). This can be accomplished by a rotary nose-cone valve [12], as discussed later. Next, pelletized fuel is injected or dropped into the duct as shown in 1c). The fuel may be in the form of solid-fuel pellets, liquid-fuel drops, gas capsules or a mixture of these. However, in all cases, the drop or injection sequence and timing is arranged so that the pellets are evenly spaced in the duct volume with the appropriate spacing (as illustrated in graph 1) immediately prior to the next stage. Next, the

duct is opened as shown in 1d) and air rushes in, surrounding and accelerating the falling pellets as shown 1e). Because the pellets have a higher density than the airflow and are initially stationary (relative to the airflow, along the axis of the duct), their inertia means that the airflow overtakes and envelopes them – but provided that they have been injected correctly, they are distributed throughout the airflow volume. Finally, in 1f), the heat and friction of the impinging airflow heats the pellets and they vaporise, mixing their contents with the flow which then ignites. As will be explained later, both vaporisation and ignition can be assisted by other technologies.

It should be noted that, although combustion typically (depending on the engine design), occurs in pulses, because the airflow is always hypersonic, this system has more in common with a standard Scramjet than with a Pulse Detonation Engine (PDE) [13]. The aim is to design the nose-cone valve to give minimum disruption to smooth hypersonic flow - and the combustion phase could potentially take place in either an open or a closed duct. A stylised side-view of the engine concept, showing two ducts, is given in figure 2.

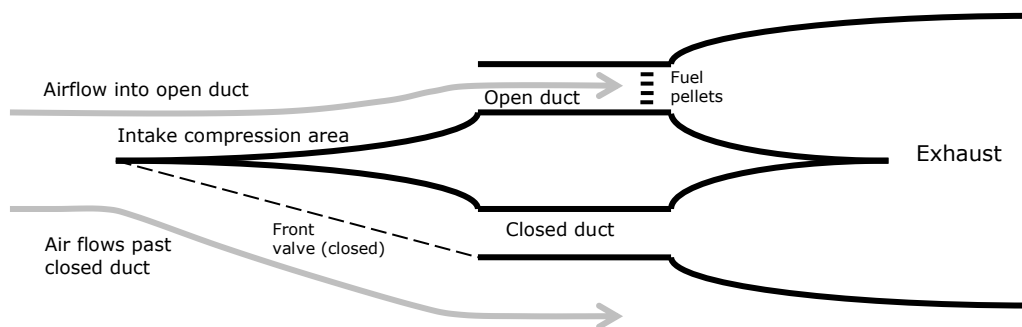


Figure 2, Side view of engine concept.

4. Further consideration of basic idea

The situation in which a pellet finds itself after impingement of the incoming air is extremely complex. The velocity v of a pellet (or its increase in velocity, if it is already moving), which is subject to a force producing an acceleration a , over a distance s , is:

$$v = \sqrt{2as} \quad (7)$$

The force causing this acceleration is due to the pressure difference across the pellet. It is the complex nature of this pressure force which makes the situation difficult to accurately assess.

The total pressure at any point is the sum of the static pressure and the dynamic pressure (fluid momentum):

$$p_{total} = p_{static} + \rho \frac{v_{airflow}^2}{2} \quad (8)$$

To simplify matters the discussion here refers to the face of the pellet which is perpendicular to the flow (the velocity is obviously, more generally, a vector). This equation is correct in the most general sense – however, in isentropic compressible flow, density is not a constant [7] and the total pressure is given as a function of Mach number M and γ the ratio of heat capacities:

$$p_{total} = p_{static} \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\gamma / \gamma - 1} \quad (9)$$

As can be seen from equations 8 and 9, this pressure will drop as the pellet speeds up, eventually tending towards constant density and equation 8 in its simple sense - when the speed of the pellet and flow nearly match. However, this formulation does not tell the full story either. Shockwaves will form around the pellets and these could be either oblique or normal depending on pellet shape and flow speed, figure 3.

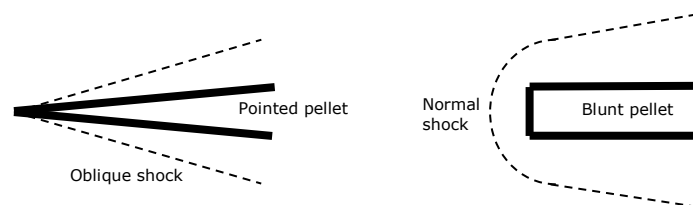


Figure 3, Potential shocks around pellets

The result of these is given by the shock relations [7] (for brevity, not repeated here) - the static pressure, temperature and density of the flow increase, but velocity and total pressure decrease. The situation is further complicated because the many shockwaves formed will interact with each other and the rest of the system. Note that these factors may complicate theoretical calculation but, in general, they aid good mixing of the pellet's load with the air-stream.

In general then, equation 7 becomes:

$$v = \sqrt{2s \frac{Ap_{\text{across pellet}}}{m}} \quad (10)$$

Where A is the cross-sectional area of the pellet presented to the flow and m is the pellet mass.

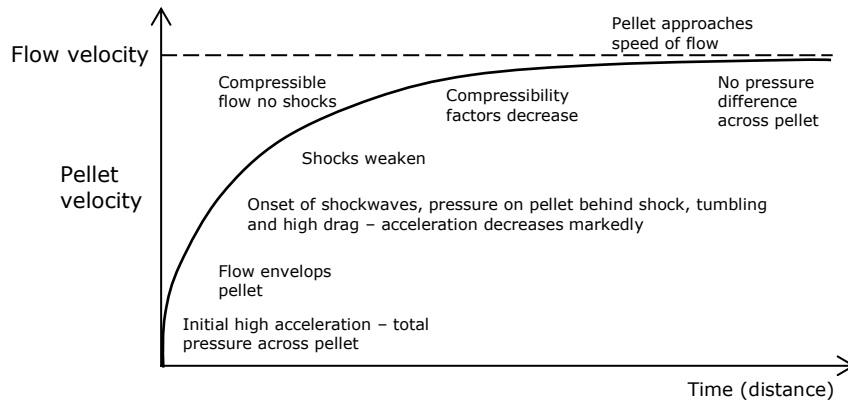
As well as these invisid effects, viscosity will cause the pellet to tumble and be buffeted by turbulent forces.

The consequence of all these variables is that the situation is complex - so modelling or simulation with any great degree of real accuracy is difficult. However, some basic calculations and simulations are possible which show the feasibility of the system, give "ball-park" figures and also illustrate the nature of the forces on the pellets. Consider a group of pellets in an engine travelling at Mach 10 - using Billig's figures [6,7], shown in table 2.

Parameter	Value
Free stream Mach number	$M_{\infty} = 10$
Mach number at fuel injector	$M_{\text{airflow}} = 4.14$
Velocity of airflow at injector	$v_{\text{airflow}} = 2665 \text{ ms}^{-1}$
Temperature of airflow at injector	$T_{\text{airflow}} = 1088 \text{ K}$
Static pressure of flow at injector	$p_{\text{airflow}} = 1.23 \times 10^5 \text{ Pa}$
Density of flow at injector	$\rho_{\text{airflow}} = 0.39 \text{ kgm}^{-3}$

Table 2, Values of airflow for Billig's engine at Mach 10

As an example, let us assume that long thin pellets are injected. These are 1cm long, with the density of methane (CH_4) and with an initial cross-sectional area presented to the flow of 1mm^2 . As the flow hits the pellets, the total pressure (in the sense of equation 9) appears across them. It takes a few microseconds for the flow to overtake the pellets but, during this time, they experience their maximum acceleration - due to a pressure difference of approximately $3 \times 10^7 \text{ Pa}$. They will start tumbling almost immediately - the Reynold's number of the flow around them being in the order of 2.4×10^5 . Shock-waves will also form and these will be complex - due to their interactions and the tumbling nature of the pellets, as previously discussed. In general, the pellet's velocity profile would be expected to be similar to that shown in graph 2 - however, because the onset of all the phenomena described above which, in turn, depend on the structure and composition of the pellets and the shape of the duct, the details and exact profile of the graph will vary widely.



Graph2, Likely form of pellet velocity profile.

Despite all the uncertainty about the details, even at the maximum physically possible pellet acceleration (at the origin of the graph, assuming all the available pressure appears across the pellets), and applying a simple estimate of drag [7], by the time the pellets have moved 10cm along the duct, the air flow has completely enveloped them and moved at least 50cm.

To a certain extent such details may be academic - as it is likely that the pellet will be designed or forced (see next section) to vaporise quickly, after it is enveloped, so that its contents is accelerated by the flow, reducing compressibility issues and increasing mixing rate.

These calculations are confirmed by simulations using the Fluent CFD package. A variety of different pellet sizes and types were modelled in ducts using the standard compressible flow (coupled energy equation) viscous solver and Billig's parameters. These indicate that the figures above are essentially correct - the flow velocities and pressures being as expected and the pellets are enveloped quickly by the flow. Figure 4 shows an example flow-velocity simulation of large pellets, cross-sectional area of 1cm^2 in a 20cm high duct using the parameters shown in table 2, just after the flow has overtaken them. The key on the left of the picture is in ms^{-1} .

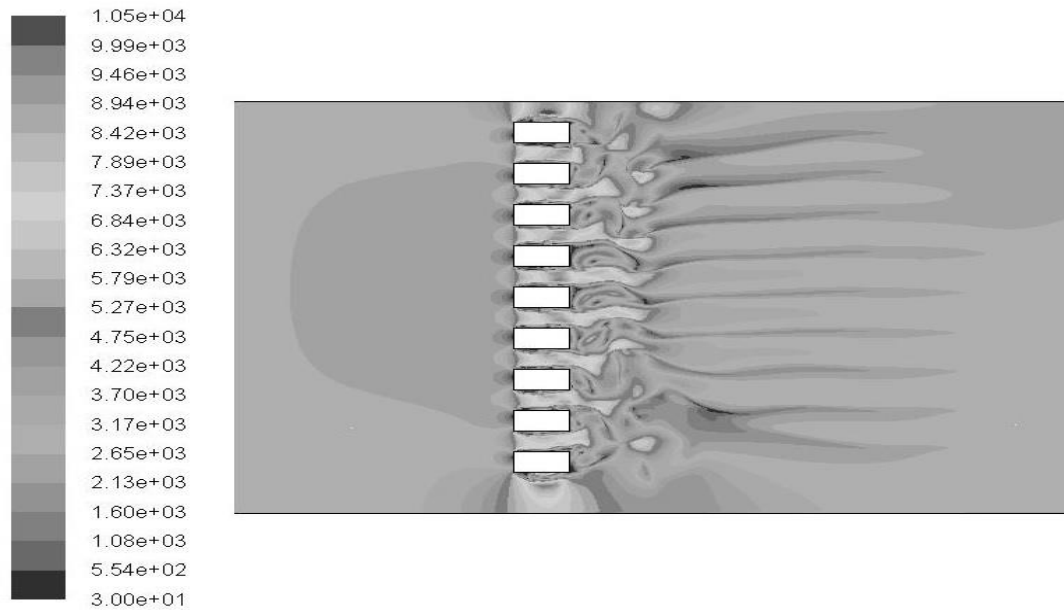


Figure 4, CFD flow-velocity simulation of large pellets in duct.

5. Fuel Engineering and injection timing

A little thought indicates that there are almost endless variations on the theme of injecting pelletized fuel into the duct. The fuel might take the form of solid pellets, liquid droplets or an encapsulated gas – or a mixture of all of these types (or it may be extruded or sprayed into the duct). Furthermore, the individual pellets themselves may have a composite structure – for example a centre comprising a light gas like hydrogen, surrounded by a heavier liquid propellant, in turn encapsulated in a solid or frozen fuel. The pellet might even include an explosive or disruptive core to disperse its contents through the duct volume more effectively. It could also include other materials, aimed at affecting the flow parameters around itself (or combining combustion with other physical phenomena, producing a multimodal effect, as outlined in the conclusions section). The topic of solid fuel in Scramjets, in a more general sense, has been the subject of several Israeli papers in recent years [14].

The pellets may be disrupted or vaporised by the heat, pressure or friction of the intrinsic duct airflow or by an outside device – for example, by microwave heating [15,16] as shown in figure 5.

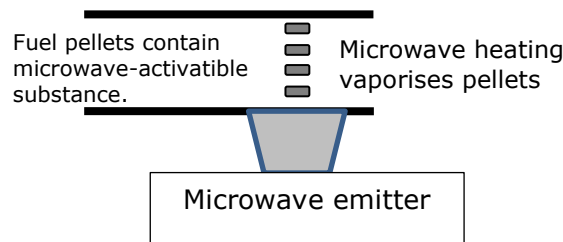


Figure 5, Pellets dispersed by microwave heating.

As explained above, the pellets will probably be designed to vaporise quickly. However, in some circumstances, it may be advantageous to delay their disruption for a more controlled period – for example to control mixing rates. To this end, the pellets might be coated with an anti-ablation compound (such as a thin refractory layer). The aerodynamic properties of the pellets are of critical importance and, in general, they should be small (to reduce the pressure force), but heavy (to increase their inertia). Rough shapes which increase tumbling and drag may also be useful.

Whatever structure and composition is chosen, the object of the system is to get the fuel in contact with the airflow to the dimensions shown in graph 1 - so that it can easily make its final diffusive step. Realistically this means distributing the pellets no more than a few centimetres apart in the stream. Simple calculation of air-fuel ratios shows that, in a duct volume of (say) 1m^3 , this might typically mean around 1000 small round pellets of a couple of millimetres or slightly larger in size – however, CFD simulation shows that a wide range of sizes, structures and spatial distributions are potentially feasible. The pellets could also be distributed through the volume so as to minimise interference from their generated shockwaves and turbulence to the duct walls and hence reduce drag.

The timing of the pellet injection system is obviously critical – it needs to release or propel the pellets into the duct with an accuracy of a few microseconds. This should not present a problem for modern electronic control and sequencing, although the mechanical mechanisms would need careful design.

Very little relevant or related work has been published in the area covered by this paper. However one researcher who has written several interesting articles is Stephen C Bates [17] of the University of Connecticut. He has explored the dynamics of both fuel pellets

and slurries in hypersonic systems (using a more conventional injection system and topology than that outlined here). Bates studied the ablation and breakup of the fuel in the stream, practically and theoretically, pointing particularly to the importance of the ratio:

$$\frac{\rho_i v_i^2}{\rho_a v_a^2} \quad (11)$$

Where i refers to the injected fuel and a to the airstream. His work also confirms the calculations on pellet sizes and numbers mentioned above.

He also points out the advantages of slurries rather than pure liquid, gas or solid materials and how penetration and mixing can be controlled through achieving the correct formulation (particularly of a semi-solid H₂/He mixture). The studies also indicate that the turbulent wake behind the pellet is important in mixing its contents.

6. Other aspects of design

An important aspect of the design, which has not been thus-far discussed, is that of the air-stream switching mechanism. It is not proposed to go into extensive detail about this in the current paper, due to space restrictions. However, it is planned that the topic be covered in a separate paper and a detailed design proposed. Note also that there is extensive discussion of stream-switching in many papers on PDEs - Roy's review paper [13] on this topic is a good starting point for further reading. Our previous paper on forced mixing [12] also discusses the subject at some length.

Having said this, however, there are several important points worth stating or reiterating. In the system above, the calculations assume flow switching of a similar nature to the rotating nose-cone already mentioned. When this is shut, it would form the aerodynamically efficient and stable shape of a pointed cone, producing a shock pattern similar to that shown for the pointed pellet in figure 3 (but obviously on a much larger scale). When the valve is open, the duct appears as a normal scramjet inlet – of which there are hundreds of published designs. Between these two modes, the nose-cone opening would be carefully sculpted to transition from open to shut and vice-versa as smoothly as possible as shown in figure 6. This would probably mean that the pellets would be staggered axially along the duct – so that those furthest from the initial opening would be able to catch up with the ones exposed first.

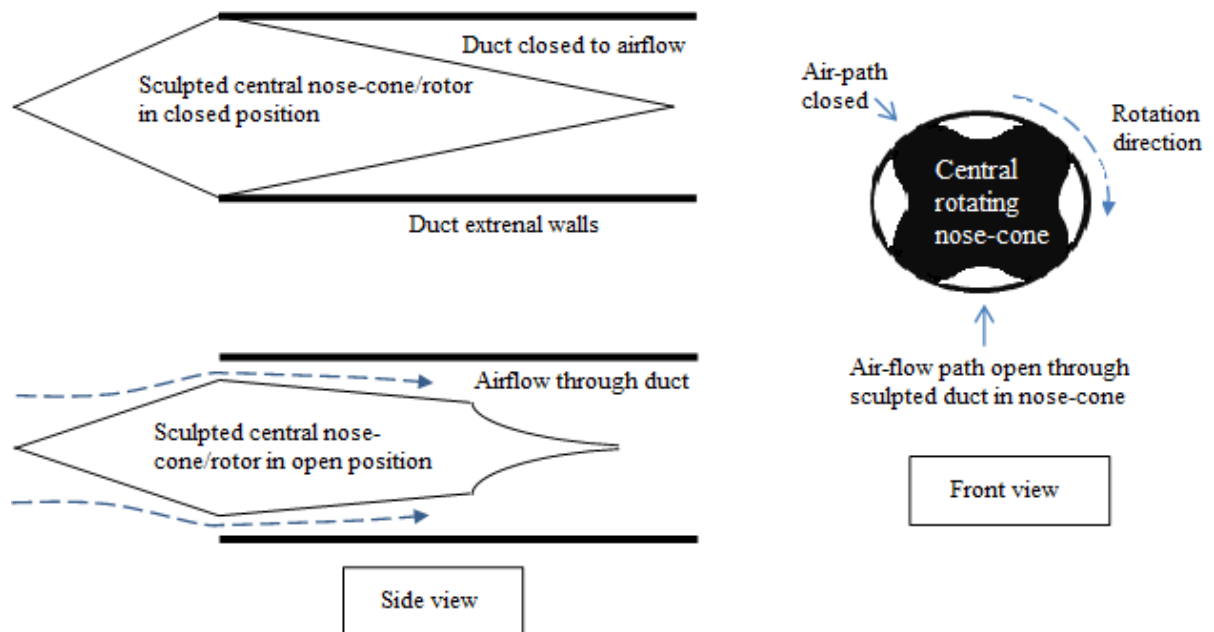


Figure 6, use of a sculpted nose-cone.

The central rotor could be controlled either mechanically or electrically (for example, by being configured as the rotor of an induction motor, with the stator coils being in the duct walls). Providing that the nose-cone is moving sufficiently slowly compared to the airflow speed, it would appear almost stationary to an air particle moving through the duct and therefore like any scramjet intake. Another way to consider the operation of the system is to think of it as producing a continuous rotating flow (rather than a pulsed one) generated by the rotating nosecone. This is shown in a stylised diagram as figure 7. Fuel is then deposited appropriately in the path of the oncoming spiral and is enveloped by it – with careful design this arrangement would allow a non-pulsed combustion.

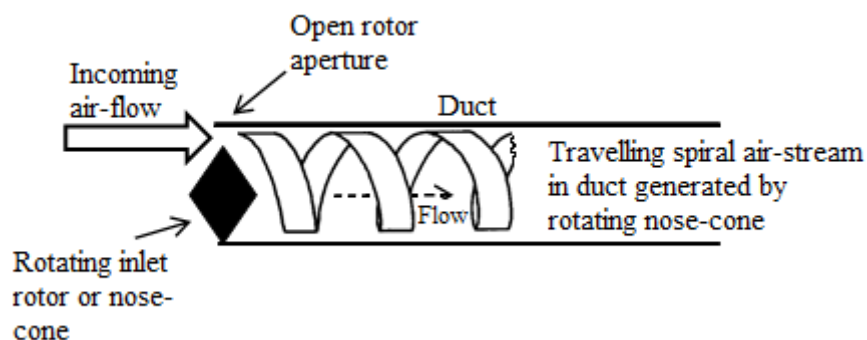


Figure 7, pattern of airflow from a rapidly spinning nose-cone.

The system outlined above is certainly not the only way of switching the flow – for example, a similar valve could be contained within the duct, after the flow has been slowed - and many others are outlined in PDE papers [13] or can be easily thought up.

Whichever design is chosen, in order to provide a more continuous thrust, a “Gatling Gun” type topology may be adopted [12]. Here a series of ducts are used – each at a different stage of the cycle. Figure 8 shows a front view of the nose-cone in a system like this (described in detail in reference 12), using a different configuration from that shown in figure 6 (figure 2 also shows a similar topology, with two illustrated ducts).

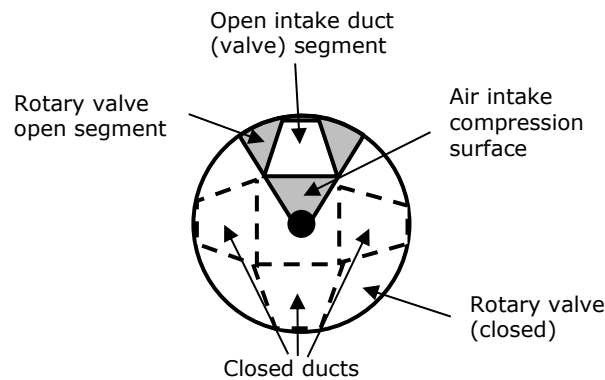


Figure 8, Gatling Gun type nose-cone (front view).

Finally, although not considered in detail here, the possibility of using pelletized fuel with a continuously operating conventional Scramjet topology (without a nosecone) is worthy of further investigation. Suitably constructed pellets could be fired into the stream by some form of gun (which might be conventional, powered by compressed gas, a railgun or could be powered by the stream itself [12]) – this ballistic approach appears not to have received any extensive consideration in the literature. Some systems using oscillating flow or combustion in open ducts could also be suitable for investigation [18].

7. Conclusions

Most papers on Scramjet mixing focus on the injection of fuel from a few standard structures – injectors, struts and pylons. However, despite hundreds of studies and experiments, none of these approaches has yet solved the fuel-air mixing problem and, as graph 1 and an analysis of compression issues shows, they are never likely to. Only a solution which successfully distributes fuel in-situ throughout the airflow is likely to succeed.

Although the system outlined here is more complex than a “standard” Scramjet design, due to the need for moving parts, it could potentially fulfil some of the fundamental mixing requirements which other methods have difficulty with. Basic testing could also be

fairly straightforward, as the fuel could be initially suspended on a very fine wire grid in a shock tube.

The system also lends itself to many other scramjet and hypersonic air-breathing engine related issues, including the introduction into the air stream of:

- Substances necessary for flow-activation in pure MHD and MHD-Scramjet hybrid systems [19]. Either to make ionisation or the application of further energy to the flow easier.
- Electrically conducting substances – which may be used in induction heating, magnetic acceleration, radiation reflection or electrostatic field manipulation of the stream [20].
- Chemical catalysts to aid combustion or similar reaction processes.
- Lasing compounds [12].
- EMA active substances [15]

This list could be extended to include many similar applications and the ideas could also be combined with conventional fuel pellets to produce a multimodal system [12] as mentioned earlier.

The biggest unknown in the system is the airflow switching mechanism and much depends on whether this would cause too much drag or disruption to be acceptable. The authors of this paper hope to publish a study of this in the near future. The likely advantages of such a system, however, make it worthy of further study and the sheer variety of potential variations on the system is exciting in itself.

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