Fuel-Air Mixing in the ASPIRE Hypersonic Engine

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Fuel-Air Mixing in the ASPIRE Hypersonic Engine

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Abstract

This paper outlines the experimental verification of the key central concept in an innovative airbreathing hypersonic scramjet like engine. The engine, called ASPIRE, uses a rotating section and discrete fuel injection to achieve effective air-fuel mixing. The results show that the mixing mechanism works exactly as predicted in previous theoretical papers and should result in an optimal air-fuel mixture. Further discussion of engine design, efficiency, testing and combustion mechanisms is also presented.

Keywords

Scramjet, air-fuel mixing, hypersonic, propulsion, ASPIRE

1. Introduction

ASPIRE (Airbreathing Supersonic Pellet Injection Rotary Engine) is an innovative scramjet-like hypersonic airbreathing engine for use in spaceplanes and other launch vehicles. Its development and evolution have been outlined and chronicled through a series of papers in JBIS [1-3]. These previous papers describe theoretical calculations and Computational Fluid Dynamic (CFD) simulations aimed at demonstrating the feasibility of the engine. This paper presents physical experimental verification of the key engine concept – the air-fuel mixing mechanism. It is therefore a critical milestone in ASPIRE's development.

In the sections below the background of the work is described. This is followed by a discussion of the experimental results and their significance. Further insights into the engine's efficiency and the combustion process are described. Finally, how it might be implemented and tested are covered.

2. Background and previous work

The detailed background to the engine concept is discussed extensively in our previous papers - thus it will only be covered briefly here. The reader is referred to this earlier work [1-3] for an in-depth analysis.

2.1 The air-fuel mixing problem in scramjets

Most authorities consider poor air-fuel mixing to be the greatest impediment to achieving a practical and efficient hypersonic airbreathing engine [4,6]. There are several reasons for this:

Firstly, at the most basic level, fuel injectors are usually wall or strut-mounted and the fuel is simply swept away before it has a chance to penetrate deeply into the engine-duct and mix properly (at a free-stream speed of Mach 5, the air speed at the fuel injectors is over 1100 m/s). Secondly, the injectors can create a low-pressure region which tends to trap fuel close to the duct wall. Finally, there is often a shockwave present between the fuel and airflow, and this prevents effective diffusion and mixing. Figure 1 shows some of these features (note however, that the real situation is more complex and subtle - and varies with injector type and topology).

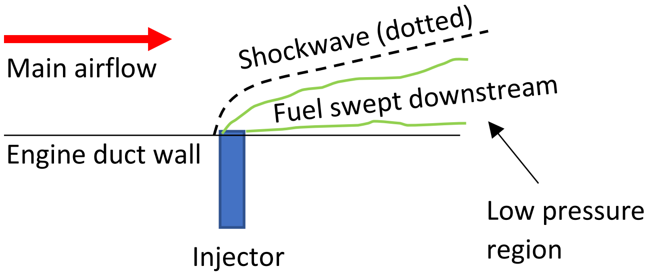


Figure 1, Some typical flow features preventing good air fuel mixing with a conventional injector.

2.2 Original rotating nosecone concept

The original idea behind ASPIRE was firstly to shut off or divert the airflow away from the main engine duct. The fuel can then be injected into the duct in the form of solid pellets, liquid drops or gas capsules - all of which are henceforth referred to as “pellets” for simplicity (although the term “discretized fuel” is perhaps better). The airflow is next switched back into the duct with precise timing - so that the pellets are still travelling through the duct volume when the air hits them. The resulting flow engulfs the pellets and overtakes them (by virtue to their inertia). Finally, the pellets disintegrate in the flow, releasing their fuel-load, which is distributed through the mixing volume. The concept is shown in figure 2.

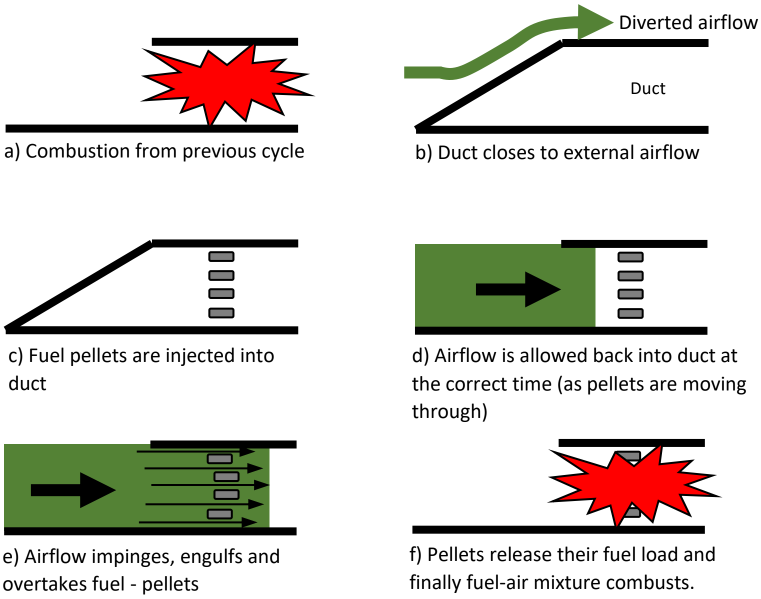


Figure 2, Conceptual sketch of air-fuel mixing mechanism.

An analogous situation that can help the reader to visualize the idea is shown in several online videos – see reference [5] for a YouTube example. In these, a high-speed camera films the collision of a bullet (analogous to the airflow) with a “Prince Rupert’s drop” (a piece of hardened glass, analogous to the fuel pellet). The bullet hits the glass drop and breaks apart before there is any perceivable movement of the drop. In this case, even though the bullet has huge momentum (much more than the airflow would have in an engine) the inertia of the glass drop means that it easily engulfs and overtakes the drop.

The next stage in the development of this concept was to design an efficient and low-loss mechanism to turn the airflow on and off. After considerable calculation and thought, it was decided that a rotating sculpted nosecone could do the job. The nosecone had a series of air intakes on its periphery and these effectively functioned as a valve to turn the flow on and off.

2.3 Improved concept with internal rotating parts

Although the nosecone concept showed promise, having the entire nose rotate in a hypersonic flow was hardly elegant or efficient and potentially caused practical engineering problems. A more refined solution eventually presented itself. This was to have a series of “wedges” rotating on a collar inside the engine (this whole collar-wedge assembly will henceforth just be referred to as “the wedges”). This concept is shown in figure 3. Not only is this a simpler system from a practical point of view, but the velocity inside the engine at the point where the wedges are situated is much less than at the nosecone (around Mach 2.4 in a Mach 5 free stream engine). This makes testing the system considerably easier, and the external nosecone itself is now just a fixed compression surface.

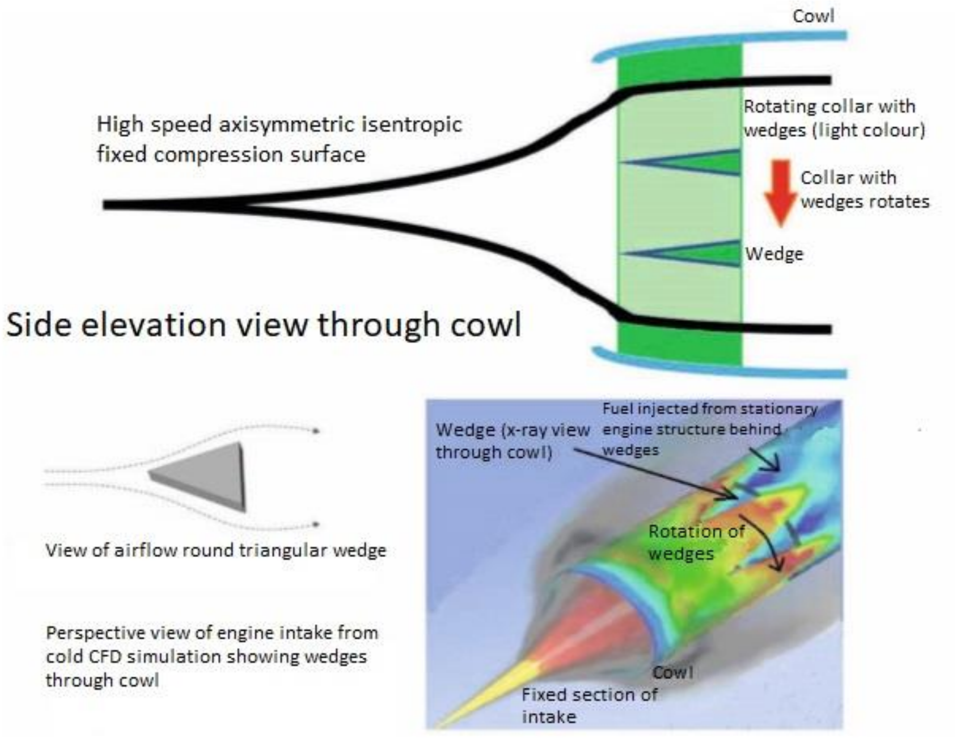


Figure 3, Arrangement of rotating wedges in ASPIRE.

Although this topology produces a similar result to the original idea, the physical principle is somewhat different. As air flows around each wedge, it generates a "dead space" of stagnant air behind it. This can be seen clearly in the CFD simulation shown in figure 4 as the blue area behind the moving wedge (which is in a Mach 10 airstream - details of this are in our previous paper [3]). Note that although there is an area of recirculation shown behind the wedge, this is a relatively gentle phenomenon.

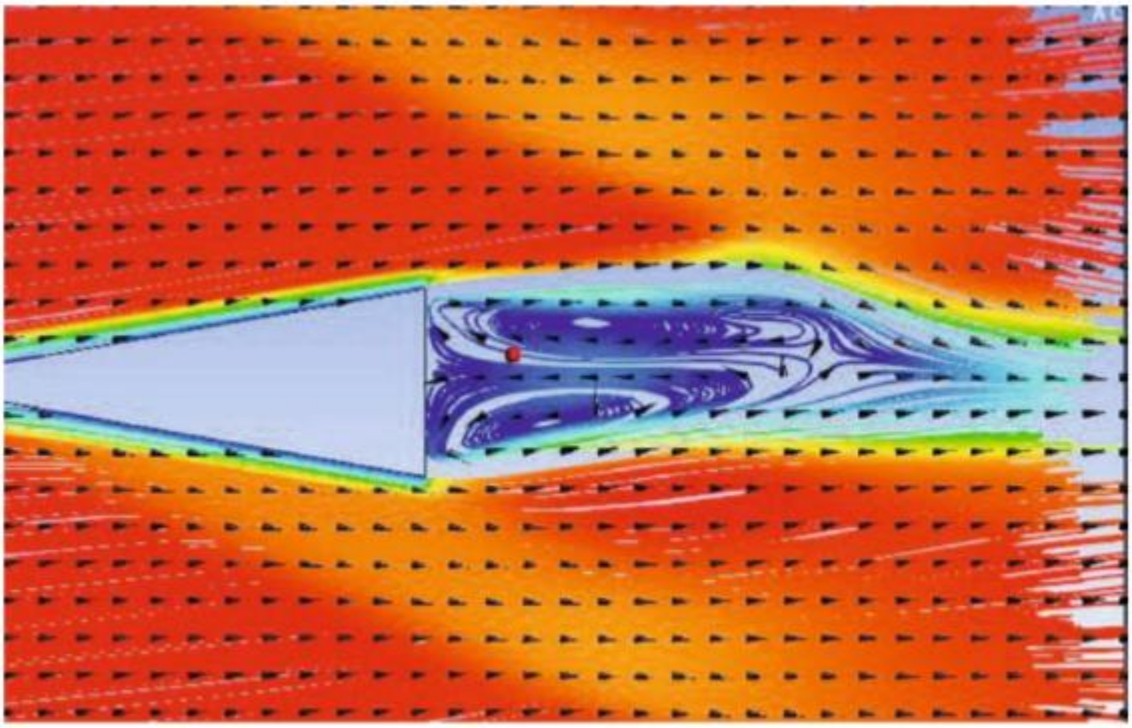


Figure 4, The "dead space" (in blue), behind a moving wedge.

Pellets can then be injected into this dead-space from the stationary engine frame (so the wedges are moving on their rotary collar, but the injectors are stationary). The pellets move freely through the dead-space, unencumbered by the main flow, but get engulfed by the stream when they reach the edge of the wedge - this is shown in figure 5. Of course, in a real engine there may be many hundreds of pellets.

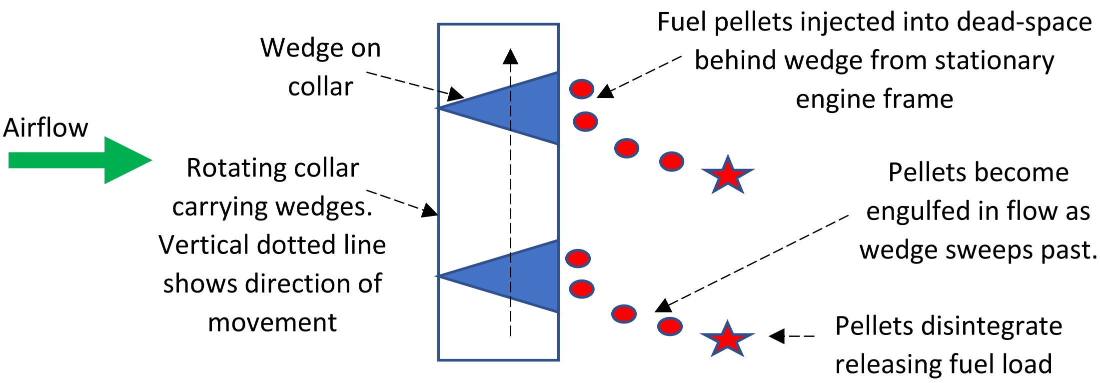


Figure 5, Principle of operation.

It should be mentioned that the wedges do not have to be triangular – this is merely a convenient shape for fabrication, CAD, testing and simulation purposes. Other shapes are discussed in our previous paper [3] and in the sections below.

2.4 Previous papers

The work summarised briefly above is fully reported in our previous papers. The first of these [1] explains the original concept and outlines several possible solutions to the valve mechanism. These include the rotating nosecone idea. The second paper [2] expands and refines the nosecone design and explores the acceleration and general dynamics of the pellets in detail. The third paper [3] outlines and develops the rotating wedge idea and explores this through a series of CFD simulations.

The idea is also outlined, and placed in a wider research context, as part of a general review of scramjet technology [6]. A non-technical explanation of the engine was carried in the magazine *Analog* [7]. Most of these papers can be found online by searching for their titles.

2.5 Engine model used in discussions below

In the sections below, parameters from the scramjet model published by Billig [8] are quoted in discussions. This is a standard engine model used by many researchers in the area. The relevant data are given in table 1.

Free stream Mach number	Altitude (km)	Mixing section Mach number	Pressure ratio	Mixing section pressure (×10^5 Pa)	Mixing section temp (^{0}C)	Mixing section temp (K)	Mixing section speed (m/s)
3	14.6	1.53	8	1.0	140	413	620
4	17.5	1.95	16	1.28	244	517	879
5	20.0	2.36	25	1.37	339	612	1158
6	22.3	2.77	35	1.35	437	710	1454
7	24.4	3.14	47	1.31	533	806	1755
10	29.1	4.14	90	1.23	815	1088	2665
15	34.8	5.50	186	1.10	1327	1600	4239
20	42.0	6.65	314	0.69	1990	2263	5989
27	54.3	7.69	473	0.22	2609	2882	8292

Table 1, Billig's engine parameters, used in discussions.

3. Experimental work

The aim of the following experiments was to verify that the predictions of previous theoretical and simulation work were correct in a physical system. Specifically, the objectives were: Firstly, to confirm that the flow around the moving wedges was as predicted; secondly to check that the fuel moved in the dead-space behind the wedge as expected; and finally, to observe the mixing of the fuel and airstream at the edge of the wedge and again correlate this with predictions.

3.1 Experimental setup and parameters

A small supersonic wind-tunnel was set up to provide experimental test flows. This consisted of a compressor and air-receiver system, which was chargeable to a pressure of 7 bar gauge. The air supply from this could be channelled into a range of circular converging nozzles with throat diameters from 3 mm to 1 cm. The resulting sonic flow was then expanded isentropically to give a uniform stream of up to several centimetres of usable width for a few seconds.

A white-light schlieren / shadowgraph system was constructed to allow shockwaves and other flow details to be observed. An accurate flow Mach number was obtained by placing a small test wedge of triangular cross-section in the stream and measuring the resulting oblique shockwave angles. Temperature could also be measured by placing a razor-thin piece of metal in the flow and using a remote infrared thermometer – however this was not very accurate due to the thermal mass of the metal and the short duration of the flows. Pressure could also be measured using a supersonic pitot tube – again accuracy was limited due to lack of verified calibration and the resolution of the attached pressure gauge. Due to these limitations, temperature and pressure readings were only used to confirm that flow predictions and patterns where approximately correct.

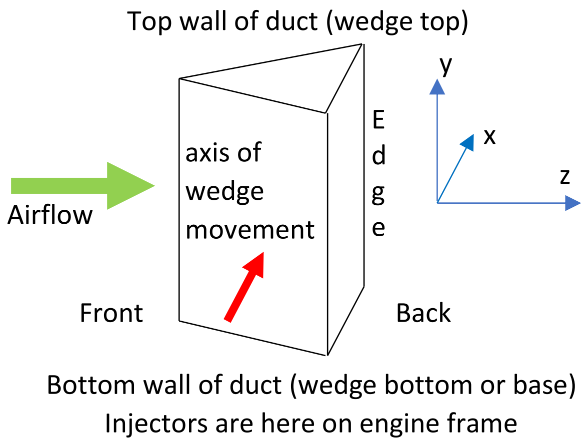
A series of ten runs with the most consistent nozzle were made to test tunnel parameters. These resulted in flow Mach numbers ranging from Mach 1.64 to Mach 1.96 with an average of Mach 1.74. This range is likely to be due to the compressor automatically shutting off at slightly different final reservoir pressures. At the average (Mach 1.74) speed the isentropically predicted flow parameters were static pressure p = 133 kPa, temperature T = 180 K and density ρ = 2.6 kg/m^3. Temperature and pressure measurements confirmed that these values were approximately correct.

These speed and pressure figures correspond to the conditions in the mixing section of a Mach 3 to 4 free-stream engine. However, the flow temperature of an actual scramjet stream is much higher, and this results in a lower density in the flow (around 0.9 kg/m^3 in the Mach 3.5 case). In turn, this means that the mass flow rate per unit area in the tunnel system is approximately 1500 to 1700 kg/sm^2 compared to around 700 kg/sm^2 for a Mach 3.5 free-stream engine. In fact, this flow rate is higher than in any real engine (a Mach 5 free-stream engine is approximately 900 kg/sm^2 and Mach 10 approximately 700 kg/sm^2 according to Billig's figures). Since pellet dynamics depend almost exclusively on fluid momentum, the experimental setup represents a more challenging environment for mixing than in a real engine - with the pellets subject to almost twice the highest fluid momentum forecast. All the experiments shown below were carried out in these conditions.

Given this, and since flow regime in the mixing area does not change over the operating region of the engine (other than becoming more chemically reactive at free-stream speeds above Mach 10), it is very likely that the behaviour observed in the experiments below is qualitatively similar over the range of Mach numbers representative of a real engine. This is discussed in detail in section 4.

A variety of different pellets were used in the tests. These included solid cylindrical organic starch pellets (ρ = 470 kg/m^3), round plastic pellets of various diameters from 0.5 to 10 mm (ρ = 910 kg/m^3) and similarly sized round steel pellets – mainly used to test flow momentum, forces and acceleration (ρ = 7600 kg/m^3). For liquid and droplet experiments, water was used (ρ = 1000 kg/m^3). These materials were chosen to be comparable to a range of likely fuels – for example, common liquid or light solid fuels like kerosene (800 kg/m^3) or liquid cryogenic methane (425 kg/m^3) and heavier solids like RDX (1850 kg/m^3). Solid pellets were injected into the tunnel using compressed air and liquids by means of a controlled plunger. These Injectors were carefully placed to avoid any disruption of the flow in the regions of interest.

In order to make the observations below clearer, directions are defined with respect to the wedges as shown in figure 6. Note that the x, y, z designations below, although they are indicated by arrowed lines, just refer to the axes - not particular directions.



x direction is across the width of the wedge (into the page and along the axis in which the wedge travels).

y direction is up the height of the wedge (vertical on this diagram and in the axis which runs from bottom to top of the duct).

z direction is along the direction of airflow (horizontal on this diagram).

Figure 6, Directions referred to in text.

3.2 Experimental results

Writing constraints preclude a discussion of all the results obtained - those shown below were chosen to illustrate the key outcomes and behaviours. Many of the experiments were filmed and selected footage can be seen online [8].

One important set of experiments was designed to establish how the pellets behaved in the dead-space behind the wedge. Figure 7 shows the arrival of a 0.5 mm diameter, 1 mm long starch pellet, travelling in the x direction at 10 m/s along the back of the wedge. The pellet appears elongated because the camera, filming at 240 frames per second (fps), has blurred its motion. The wedge has a half-angle of 5° and is 15mm long (in the z direction). Notice how the pellet travels parallel to the back of the wedge and is basically unperturbed by the main flow.

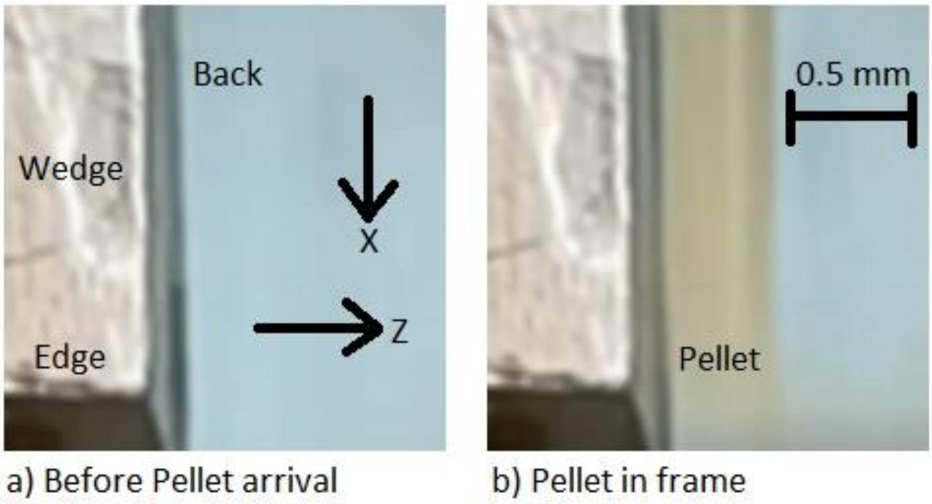


Figure 7, A solid pellet travelling behind a wedge.

To test the dead-space further, a jet of water of diameter 0.5mm was injected at a speed of 1 m/s along the edge at the back of the wedge in the y direction. The idea was to see if the air flow disrupted the jet (the water having a lower integrity than the solid pellet). The jet was placed at various distances from the edge of the wedge (which has the same dimensions as in the previous experiment). Figure 8 shows it 1 mm from the edge. The image is a projection taken in shadowgraph mode.

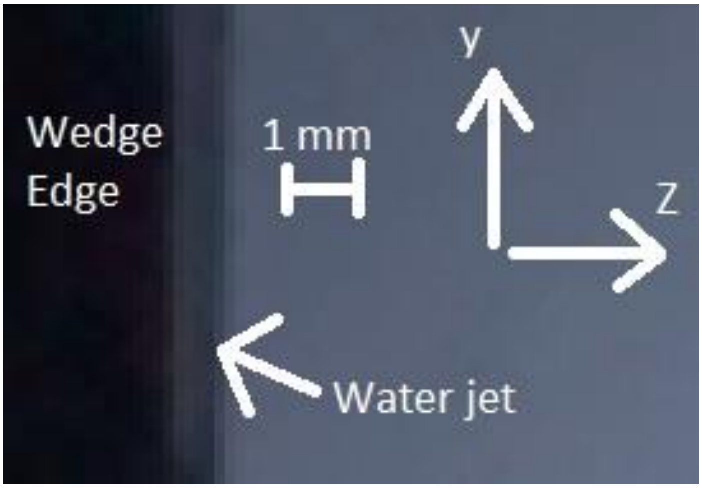
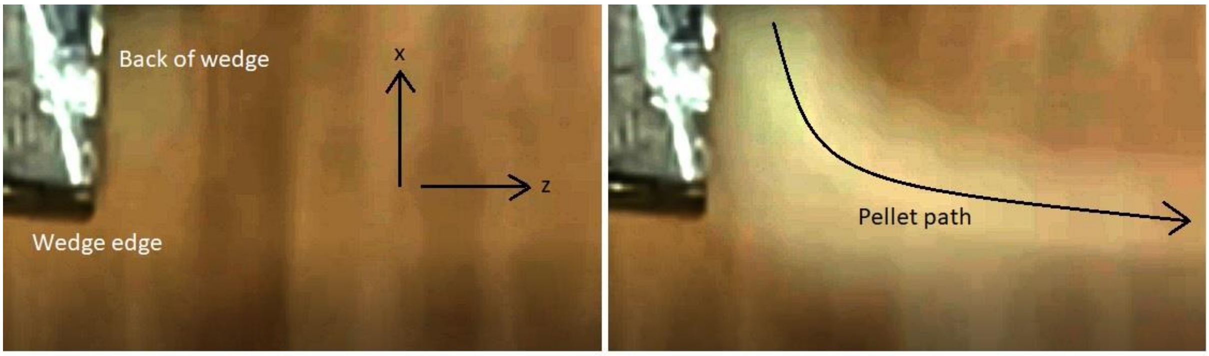


Figure 8, A water jet injected 1 mm from the edge of the wedge in y axis.

As can be seen in the figure, there is little disruption to the structure of the jet (in fact there was little disruption up to a distance of 0.3 mm from the edge). This confirms the findings from the solid pellets. This was also repeated with the round plastic pellets, again with the same result.

Turning now to the pellets' transition from moving in the dead-space behind the wedge into the main supersonic flow just beyond the wedge edge. Figure 9 shows the same setup as figure 7 with the same size of pellet. This time we see the situation as the pellet passes the wedge edge. The two images are stills from the 240 fps video of the event. The pellet appears to get swept backwards by the flow before it leaves the wedge because its forward edge (in the x axis) hits the flow first and drags the rest of the pellet along behind.



a) Wedge before pellet arrives b) Path of pellet leaving wedge

Figure 9, Pellet leaving wedge edge.

Figure 10 shows a wider view of a similar event (filmed in the same direction and with the same setup) – this time showing the ultimate breakup of the pellet. In picture a) the pellet has not yet arrived at the edge of the wedge (which is at the top left of the image). Picture b) shows the pellet arriving through the dead space. Picture c) was taken at a similar time to that in figure 9 – as the pellet leaves the wedge edge. Finally picture d) shows the cloud of "fuel" (starch in this case) vaporising and dispersing in the flow.

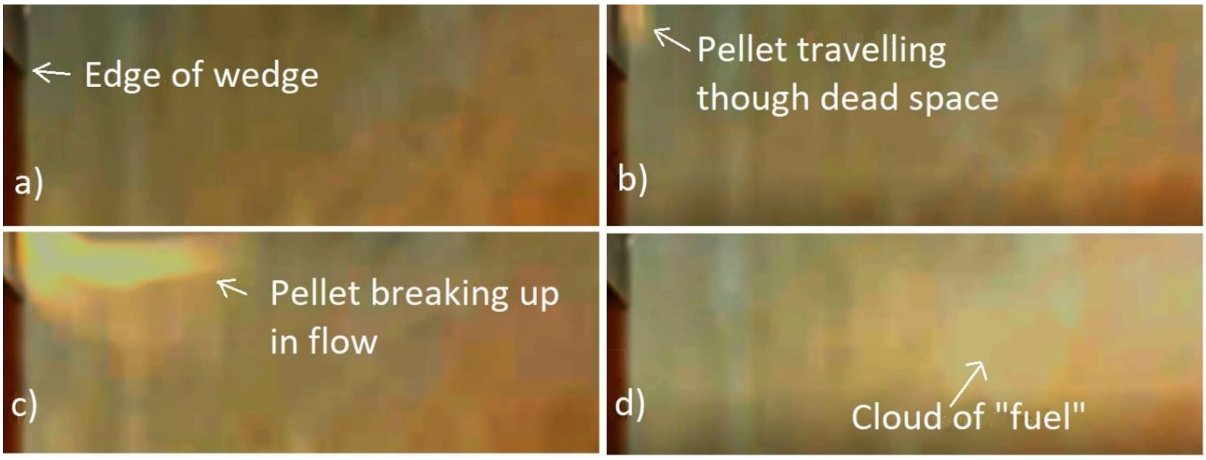


Figure 10, Wider view of pellet leaving wedge and dispersing.

The acceleration of the intact pellet in the flow was observed using the solid plastic and steel spheres - but the combination of Mach number variation, short available uniform flow-length and framerate blurring in the camera made accurate measurement difficult. However, the observed values were of the same order of magnitude as those predicted from the theoretical work reported in our previous papers [2].

Before the experiments were carried out there was some concern that fuel might get trapped in the dead-space because of the low pressure and recirculation present in that region. This proved not to be the case - however it may be seen to a limited extent with very fine droplets injected at low velocity (10 cm/s) as shown in figure 11. In this figure, the edge of wedge has been drawn over to make it clearer - as the vapour obscured it somewhat on the original (shadowgraph) image. The scale is similar to that in figure 9. The darker area is the trapped vapour. This will be discussed in more detail in the next section.

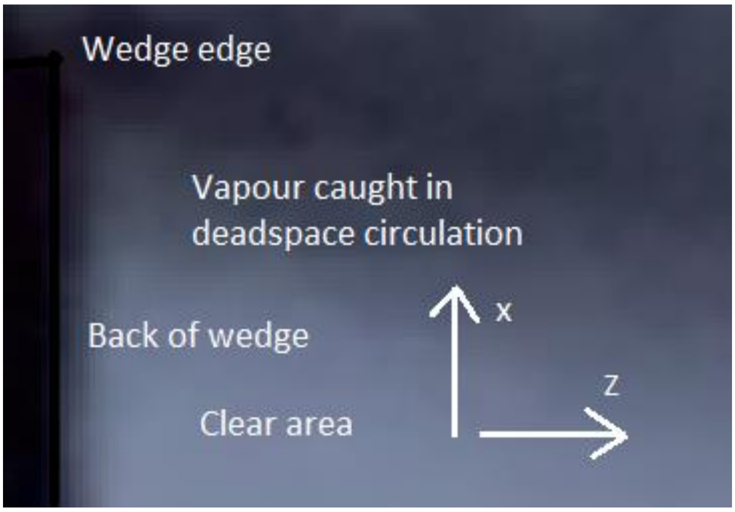


Figure 11, Fine vapour from fluid injection recirculated in dead space behind wedge.

Finally, figure 12 shows a series of images which neatly encapsulate the whole series of experiments. These show a 10 mm long, 5° half-angle wedge, moving at 1 m/s into the page (away from the camera) and passing in front of an injector, injecting water at 1 m/s.

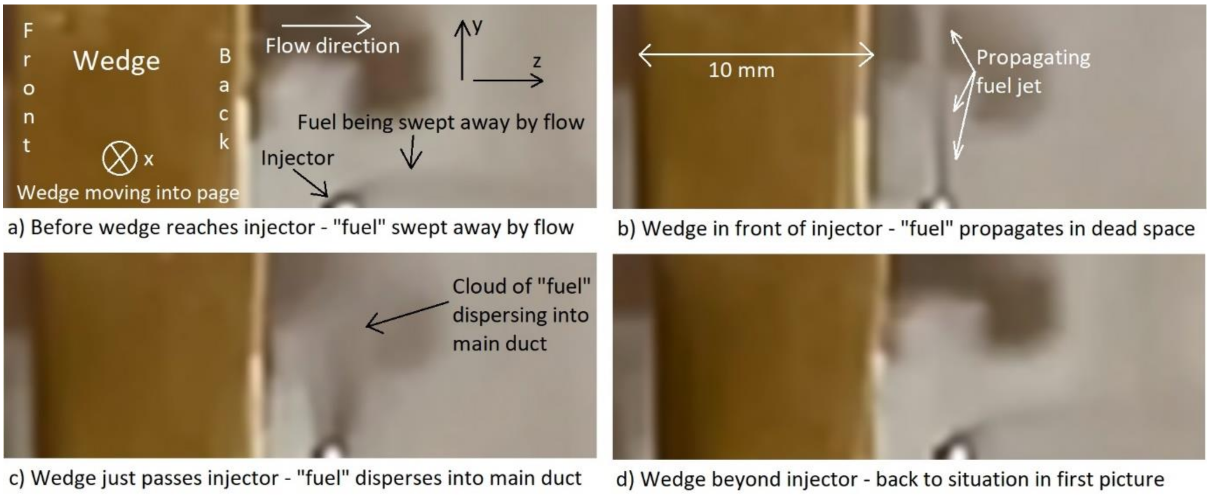


Figure 12, a moving wedge passes in front of a liquid water jet.

Pictures a) and d) clearly show the normal injector situation – with the "fuel" being swept away by the flow before it can mix. Picture b) shows what happens when the wedge moves in front of the injector – the liquid can now move through the dead space behind the wedge and covers the whole height of the duct. Picture c) shows the situation as the wedge just sweeps past the water-jet – the water disperses into the main flow at the wedge edge. This sequence of events is exactly as predicted by the previous theoretical work and simulations.

4. Discussion of experimental results

As mentioned above, the experiments confirm the theoretical predictions and simulations presented in previous JBIS papers [1-3].

For completeness however, two complicating factors should be addressed. The first of these is that the experiments were conducted at a smaller scale than in a full-sized engine; the test size being dictated by the dimensions of uniform supersonic flow available in the tunnel.

As discussed in section 3.1, there is no reason to believe that the system would display qualitatively different or unexpected behaviours at a larger scale, there being no change of flow regime. The aspects of significance which would be different are the Reynold's number (which is approximately 5 x 10^5 in the experiments, compared to around 5 x 10^6 in a moderately sized engine) and the size of the boundary layer around the wedge (this will be about twice the size in the engine). Both these parameters may result in different down-stream mixing attributes for the vapourised fuel (because of different wake turbulence, flow separation and vortex patterns), but neither will affect the basic entry of the fuel from the wedge into the duct. Calculations, simulations and experiments all show that the defining characteristics of a solid pellet's dynamics as it leaves the wedge depend entirely on pellet momentum and the flowrate of the stream.

The second issue to consider is the speed of the flow - corresponding to a Mach 3 to 4 free-stream engine, as described in section 3.1. This is at the lower end of scramjet operation. Again, the practical limitation was the available tunnel flow attributes. For this reason, a thin wedge of half-angle 5° was chosen for most of the tests to maximise down-stream Mach number (10° wedges were also available and produced the expected results). The dimensions of the front shockwave for the average tunnel Mach number are shown in figure 13. The flow pattern at the back of the wedge is not shown in the diagram as it is more complex - comprising of expansion fans at the corners, the wake (dead-space) and reattachment shocks – these are discussed in our previous paper [3].

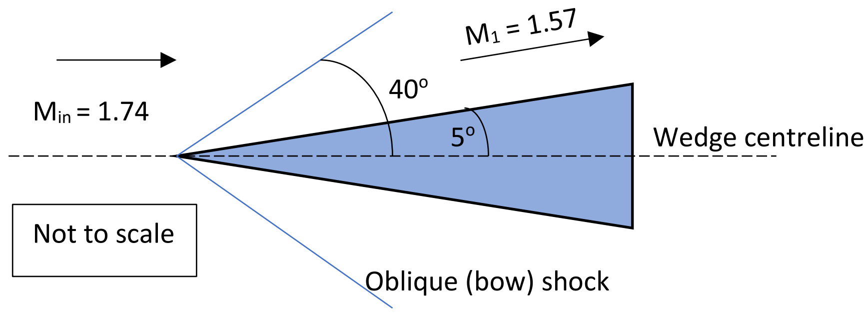


Figure 13, bow shockwave and Mach numbers for a test wedge.

For the grounds already outlined, there is no reason to think that these flow parameters would produce a different result at higher Mach numbers (in fact the observed behaviour was the same for all the runs, the fastest of which approached Mach 2). As discussed in section

3.1, the high flowrate in the experiments (because of the low flow temperature) provides more difficult penetration and mixing conditions to the pellet than the flow in an actual engine.

Turning now to the main lessons learned from the experiments. The results underlined two pellet attributes which are vital to achieving good mixing. These are:

- Pellet momentum
- Pellet friability

Pellet momentum in both x and y directions is important. Momentum in the y direction controls the point of pellet emergence from the wedge edge, and in the x direction the pellet's penetration into the flow. This is illustrated in figure 14. Note that the different momentums required do not necessarily imply different speeds – momentum being a vector quantity.

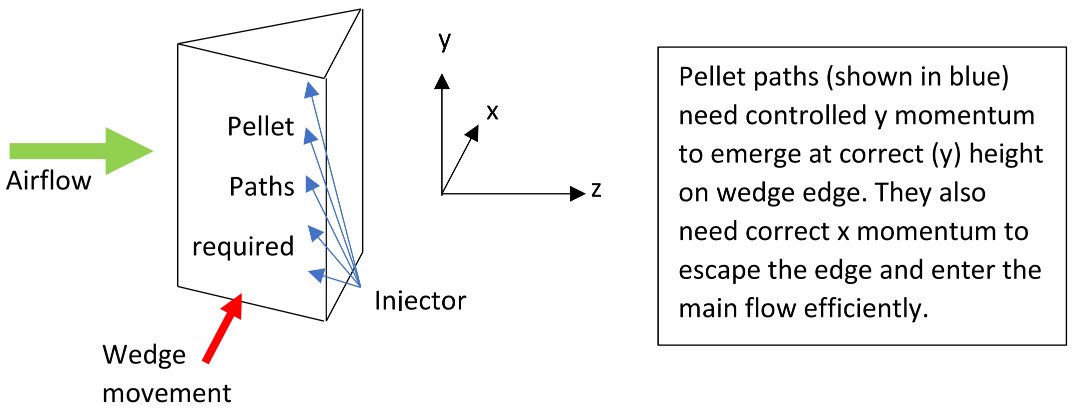


Figure 14, the importance of pellet momentum for correct fuel placement.

The dead-space behind the wedge is a bubble of low pressure. The x momentum works with the pellet's inertia so that this may be escaped correctly, and the main flow penetrated. This low-pressure effect was mentioned in section 3.2 and illustrated in figure 11. An approximate figure for the pellet velocity required to escape the edge of the wedge may be obtained by considering that pressure is equivalent to energy density – so for a pellet moving from an area of low pressure (P_0) into one of high pressure (P_1), the required kinetic energy is:

$$\frac{1}{2}mv^2 > V_p(P_1 - P_0)$$

Or taking the pressure difference as ΔP, the required minimum velocity v is:

$$v_{min} = \sqrt{\frac{2V_p\Delta P}{m}}$$

Where m is the pellet mass and V_p is its volume. Note that for an accurate evaluation, the difference between the dynamic pressure (which only acts on the windward surface) and the static pressure, in addition to friction effects, should be considered.

Momentum analysis also leaves open the possibility of ballistic pellet projection directly into the duct (without the aid of the wedges). This would be more difficult to control and has not yet been investigated in detail - it was discussed briefly in the earlier papers [1, 2].

The requirement for controlled momentum can be used positively in the design of the engine. For example, if pellet injection is driven by a gas (such as hydrogen) or liquid (perhaps kerosene), this driver may itself be a component of the fuel - and can be a cold or cryogenic substance to aid cooling of the hot air behind the wedge [3].

The second important pellet attribute is its friability (integrity). A pellet which breaks up early might not penetrate as far as required into the flow. Similarly, a very hard pellet may maintain its integrity too long to effectively mix its load.

Fortunately, friability is controllable by a wide variety of means - including structure, composition and surface treatments (discussed in earlier papers [2]). A wide variety of gels, mixed fuels, emulsions and solid fuels have already been evaluated for rocketry applications as discussed by Clark [9]. Cryogenics or cooling may similarly play an important part in this aspect – generally the colder the pellet, the harder it is. Cryogenically frozen fuels also allow mixtures of frozen gasses, solids and liquids to be used and may again help control or mitigate the effect of the heat in the area behind the wedge. An example of work in this area is Bates [10] who has done research on cryogenic fuels for scramjet applications and particularly suggests hydrogen-based “slurries”.

5. Further thoughts on wedge design and efficiency highlighted by the experiments

Our previous paper [3] contained some ideas for improvements to the wedge design and the present experiments suggest some interesting possible additions to these.

5.1 Losses and pressure recovery

Any conventional hypersonic airbreathing engine design is very finely balanced in terms of thrust to drag ratio, and therefore losses are of the utmost importance [11]. The current design is no different and must be as efficient as possible.

This is one reason why, despite triangular wedges being useful for testing and validation, they probably wouldn’t be the first choice for a real engine. Although theoretical local pressure recovery and efficiency are high for the thin triangular wedges in the experimental tunnel (approaching 99% for a perfect 5^o half-angle wedge at M_{in} = 1.74 and 98% for a 10^0 wedge), this soon falls at higher speeds (for example, to around 86% in a Mach 10 free stream with a 10^o wedge). It is impossible to get rid of losses completely, as there will always be friction, a boundary layer, turbulence and reattachment - however, wave drag losses could be minimised by adopting an isentropic wedge design as shown in figure 15. The pressure gradient generated at the bottom of the wedge could also be designed to help drive pellets into the main flow.

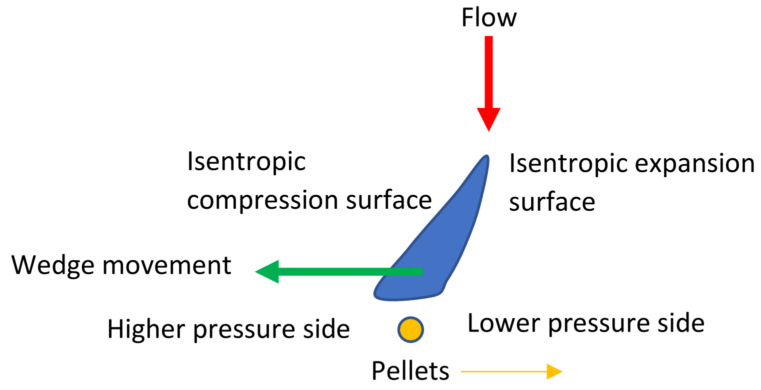


Figure 15, General configuration of an isentropic wedge.

Note that the wedge itself is part of the compression system. For example, in a Mach 5 free-stream engine, the input Mach number at the front of a 10° triangular wedge would need to be Mach 2.82 to produce Billig's ideal mixing section speed of Mach 2.36 at the back.

Some interesting insights into losses can be gleaned from a 2014 paper by J. Liang et al of the National University of Defence Technology in Hunan, China [12]. This paper describes a sophisticated simulation of rotating "ramps" in a scramjet-like engine. Although this may sound superficially similar to the ASPIRE concept, the underlying physical principle is completely different. In the Chinese system, the purpose of the ramps is to act as a "stirrer" or "agitator" to mix fuel that is pre-injected into the duct in front of the ramps from conventional injectors. To achieve this stirring action, the ramps are travelling an order of magnitude faster than the wedges in ASPIRE (which travel relatively slowly [1,2]). The paper presents pressure recovery and efficiency graphs and finds that these fast-rotating components generate a 10% loss over the same structures when stationary. The mixing action is also interesting as CFD results described in our previous paper [3] indicated a similar action with gaseous fuel in ASPIRE.

An idea explained in our previous paper [3] also helps to elucidate the role of loss in the wedge system. It was pointed out that one possible wedge structure is a tilted flat plate, as illustrated in figure 16.

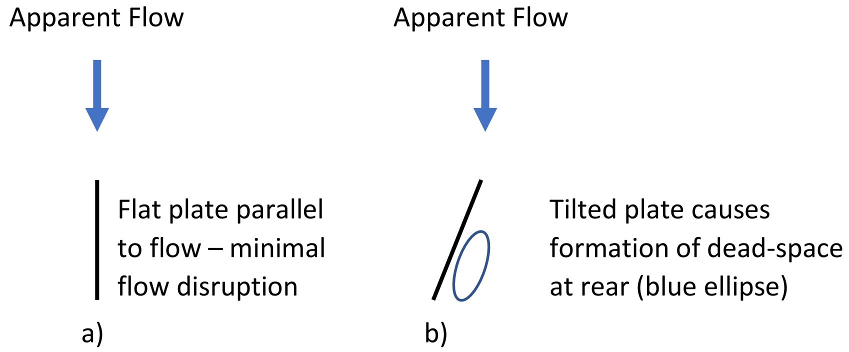


Figure 16, A tiltable flat plate as a "wedge".

In the situation shown in figure 16a, the plate (which is of minimal thickness) is parallel to the flow and causes no disruption. In this situation there is no dead-space, and any injector behind the plate just behaves as in a conventional scramjet system. In figure 16b however, the plate is tilted just enough to introduce a dead-space in which the fuel can propagate. This allows us to view any loss incurred by generating the dead-space as the thermodynamic “cost” of good injection (the increase of flow entropy caused by fuel penetration). The thought-experiment facilitates the development of a figure of merit for injection – as any injection system must disrupt the flow, but the minimum value is when there is just enough dead-space generated to allow the fuel to propagate across the duct.

It may be seen from the argument above that the moving wedge system is not an additional component to the fuel injectors - but is an integral part of their operation.

5.2 Other aspects of wedge design

There are numerous wedge designs possible, and our simulations and experiments indicate that simple designs work surprisingly well. However, some more complex topologies are worthy of consideration as they might help the mixing of lighter fuels like liquids and gases (which will be present as part of the pellet injection system or may be introduced separately).

The earlier discussion of low pressure in the dead-space behind the wedge leads to the conclusion that minimising this may be functionally useful and would also increase pressure recovery. This might be easier to achieve in the curved isentropic type designs discussed earlier, as part of the overall shape. For solid pellets, overcrowding a smaller space may help to facilitate the exit of the fuel into the main duct (and would also minimise the effect of heat behind the wedge). However, for gaseous or liquid fuel it may have greater advantages. As shown in figure 11, light, low-momentum fuel components (like driver gas) can get “stuck” behind the wedge - but a smaller dead-space would help to destabilise these and eject them into the flow. Injecting further back (in the z direction) would also aid this.

Some other ideas worthy of further research include: a) Injecting gas from the back of the wedge into the dead-space to cool it and help eject fuel; b) Injecting from both the top and bottom engine frame; c) Incorporating shaped “deflectors” into the back of the wedge to physically direct the fuel outwards; d) Having a concave or sculpted back to the wedge to control the fluid parameters of the dead-space; e) having fixed post-wedge structures to control fuel mixing (for example a thin “scraper” to remove fuel from the back pressure bubble of the wedge); f) having serrations or other structures on the wedge edges to induce turbulence or destabilise the wake and increase fuel entrainment; g) Studying other types of fuel morphology – such as candyfloss, irregular or spaghetti shaped fuel.

6. Combustion

Since all the results indicate that the ASPIRE fuel mixing system works as planned, some thought now needs to be given to initiating and sustaining combustion in the engine.

A great deal of research has been published on combustion in scramjets – from relatively conventional flame-holders to exotic plasma torches [6,13]. Our previous papers have also addressed this question [3]. Recently there has been much discussion of detonation combustion, particularly involving oblique shocks [14,15].

However, there are also some ideas which the ASPIRE system uniquely facilitates. These include:

- The introduction of chemical combustion initiators along with the fuel as pellets – for example hypergolic, pyrophoric or more complex incendiary compounds [3].
- Similarly introducing substances which can be heated to induce combustion by other means – for example using microwaves, lasers or electromagnetic induction [16].
- Introducing an ignition (heat) source located or originating on the wedge itself – perhaps to ignite the downstream fuel released from another (trailing or leading) wedge.

All these could potentially facilitate the initiation of multiple flame fronts in the flow (and, of course, could be used in combination or with other techniques).

Calculation and simulation of combustion mechanisms is potentially difficult, and it may therefore be necessary to supplement or replace these with experimental data. This could be done in a special wind tunnel setup by using pressurised premixed fuel and air to produce a flow speed and composition similar to that at the combustor. For obvious reasons this is potentially dangerous and thus a safe and controlled automatic system to prime and run the experiments together with containment structures would need to be designed.

However, there is another alternative - outlined in the next section.

7. HyBE

HyBE (pronounced "high bee") stands for ***Hy***personic ***B***ypass ***E***ngine. In this concept ASPIRE is combined with another form of propulsion – for example a rocket engine. The idea is somewhat analogous to the way an afterburner or reheat is used to supplement the performance of some jet engines. However, in this case, ASPIRE is used to supply an air-fuel mixture to enhance the main propulsion.

In a rocket engine, HyBE might take the form of a concentric "skirt" which is added to the vehicle. This houses an ASPIRE front-end that gathers and compresses atmospheric air and then adds fuel using the rotating wedge-based fuel-injectors. The resulting air-fuel mixture is next released into the rocket engine, where it is ignited by the exhaust plume and increases thrust. This combination of ideas is based on hybrid engines discussed in our previous work [17] and is illustrated in figure 17.

Such a system is an ideal test-vehicle and demonstrator for the ASPIRE concept. Even fairly small atmospheric and sounding rockets (including some amateur rocketry) can reach the required speeds of Mach 3 to 6. A suitable single-speed HyBE skirt could be designed to provide measurable thrust-enhancement at a pre-selected Mach-number, thereby providing proof of concept for the whole system. This could be manufactured cheaply using 3D printing or a similar rapid-prototyping method. HyBE effectively removes the combustion problem by using the existing engine plume as a high-energy sustained ignition source. In addition to providing an incremental test and development route to a full ASPIRE engine, a fully scaled up mature version of the concept could bring substantial fuel savings to commercial rocketry.

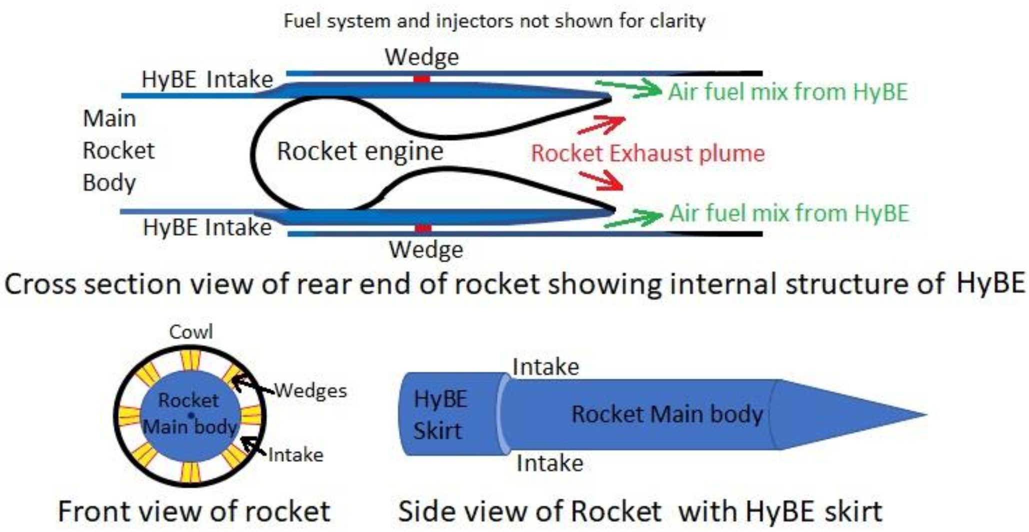


Figure 17, An idealised view of the HyBE concept (not to scale).

The setup shown in figure 17 is a stylised rendering. There are many possible variations. For example, the HyBE air-fuel mixture could be added near the end of the rocket nozzle, as shown in the diagram - or much earlier, just after the engine throat. If this earlier option is pursued, then the HyBE and rocket are best integrated holistically during the development process into a single hybrid unit. This would allow for the best matching of pressures, velocities and flowrates so that the two parts will operate seamlessly together. It is also not difficult to imagine more exotic versions of the system – for example an aerospike configuration. A disadvantage of external-only compression systems is that they change the direction of the flow-path – but even this might be advantageous in some topologies, if harnessed to direct the HyBE output into the rocket plume. A smaller concentric duct might be added beneath the main HyBE intake to swallow the rocket-body boundary layer and perhaps even be configured as a boundary layer ramjet to produce extra thrust from this.

8. Future work, Internet resources and open-source development

The ASPIRE team is currently developing a larger and more comprehensively instrumented supersonic wind tunnel. This will hopefully provide a wider and longer area of uniform flow at speeds up to approximately Mach 3. Such a tunnel will be able to simulate the flow in the mixing area of a Mach 6 to 7 free-stream engine. The larger working volume will also permit bigger wedges or an integrated section of the whole fuel system to be studied. This should allow further refinement of the design and additional information to be gathered about its operation. More CFD work is also planned to investigate promising design variations (such as those outlined in section 5).

Due to the cost and safety implications, there are currently no plans to implement the combustion tunnel outlined at the end of section 6 (unless funding opportunities become available). Instead, the team plans to pursue the HyBE route to development, as outlined in section 7. This represents a clear, manageable and cost-effective roadmap to a full ASPIRE engine - while facilitating the development of a potentially important improvement to traditional rocketry along the way. Initial design work on a rapid-prototyping compatible demonstrator will begin shortly (in parallel with the other investigations outlined).

Thus far, all ASPIRE development data has been shared openly - and in the spirit of continuing in the same vein, a website with comprehensive information and resources has been set up at www.aspire-hypersonic.com. This will also contain a new hardware development management system called “Change the World” (CTW), which has been designed specifically for the project and will be active shortly.

CTW allows academics, students and other interested parties to participate in ASPIRE development by contributing their own calculations, simulations and experiments to the project. The team would like to invite anyone interested to do this. The terms and conditions of use can be found on the website.

9. Conclusions

The experimental verification of ASPIRE’s main concept is a key milestone in its development. The results outlined in section 3 clearly demonstrate that the use of rotating wedges and discrete fuel injection to provide stoichiometric air-fuel mixing is a valid and productive path. They closely align with the predictions of the theoretical and simulation work, with no major surprises evident.

While ignition and combustion are still important topics to be addressed, most commentators consider these to be much more tractable issues than fuel mixing [6,11]. Research also points to many promising approaches to this aspect of operation as discussed in section 6.

The HyBE concept provides an excellent opportunity to address several issues at once: Firstly, it serves as a proof-of-concept demonstrator for the whole ASPIRE concept and as a logical stepping-stone to a fully capable engine. Secondly, it means expensive and difficult simulation and experimental verification of combustion mechanisms can be circumvented (while at the same time providing data on these). Finally, with appropriate development, it may provide additional capabilities to existing rocketry. Enough theoretical, simulation and experimental information has now been gathered to start the detailed design of a demonstrator.

Our current road-map therefore consists of adding to our knowledge base through further simulation and an improved experimental setup while simultaneously embarking on a demonstrator design based on HyBE.

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References

1. C. MacLeod, N. F. Capanni and K.S Gow "Overcoming Fuel-air Mixing Issues with Pulsed Scramjets and Pelletized Fuel", Journal of the British Interplanetary Society, 68(11), pp.354 - 362, 2015.
2. C. MacLeod and M. Murray "ASPIRE – An Innovative Hypersonic Propulsion Paradigm", Journal of the British Interplanetary Society, 72(3), pp. 90 - 101, 2019.
3. C. MacLeod and O. Valentin "Rotary Intakes for Scramjet-like Hypersonic Engines", Journal of the British Interplanetary Society, 73(3), pp. 85-96, 2020.
4. 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, 7-10 July 2002. Paper AIAA - 2002 – 3878.
5. https://www.youtube.com/watch?v=F3FkAUbetWU (time index 3:25) (accessed: 14th November 2022)
6. C. MacLeod and C. E. Gerrard "A Review of Air-fuel Mixing and Alternative Methods in Scramjets and Scramjet-like Engines", Journal of the British Interplanetary Society, 69(4), pp.116 - 126, 2016.
7. C. MacLeod "The new space race: a case for innovation", Analog science fiction and fact, 136(12), pp. 21 – 29, 2016.
8. https://www.youtube.com/watch?v=Mst553BlQ1w (accessed: 14th November 2022)
9. J. D. Clark, "Ignition: An Informal History of Liquid Rocket Propellants", Rutgers University Press, New Brunswick, 2020.
10. S. C. Bates, "Assessment of Solid Hydrogen Slurry Fuelling for an Airbreathing Supersonic Combustor," Journal of Propulsion and Power, 20(5), pp. 793 - 800, 2004.
11. W. H Heiser et al, "Hypersonic Airbreathing Propulsion", AIAA education, Washington, 1994.
12. J. Liang et al, "Numerical Analysis of Rotating Ramps in a Scramjet Engine", 10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Florida, pp. 938 – 943, 2014.
13. Q. Liu, D. Baccarella and T. Lee, "Review of Combustion Stabilization for Hypersonic Airbreathing Propulsion," Progress in Aerospace Sciences, 119, paper 100636, 2020.
14. D. A. Rosato et al, "Stabilized detonation for hypersonic propulsion," Proceedings of the National Academy of Sciences of the United States of America (PNAS), 118(20), paper e2102244118, 2021.
15. C. Li, K. Kailasanath, and E. S. Oran "Detonation structures behind oblique shocks," AIP Physics of fluids, 6(4), pp. 1600-1611, 1994.
16. C. MacLeod, K. S. Gow and N. F. Capanni, "Some Practical Aspects of Electromagnetic Activation," Journal of the British Interplanetary Society, 62(9), pp. 320 – 331, 2009.
17. C. MacLeod "Innovative Approaches to Fuel-air Mixing and Combustion in Airbreathing Hypersonic Engines", The Journal of the British Interplanetary Society (JBIS), 66(5/6), pp 178 – 189, 2013.