ELECTROMAGNETICALLY ACTIVATED HYPERSONIC DUCTS

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This paper explores the use of Electromagnetic Radiation as an alternative to combustion in Scramjet-like hypersonic engines. The radiation is absorbed by the flow, heating it and thereby providing an alternative to the heat derived from combustion in the Scramjet. The advantages and disadvantages of this system are explored and theoretical results are presented illustrating typical radiation pathlengths at different frequencies. Suggestions for further theoretical and practical work are also made.

Keywords: Scramjet, electromagnetic heating, electromagnetic activation

1. INTRODUCTION

The Scramjet has been touted for many years as the method most likely to break the rocket's monopoly on access to space and thereby make such access affordable. However, despite recent successes in programmes like HyShot, HyCause and the X-43A, extended flight under Scramjet power remains elusive.

There are several causes of these problems, some are due to the design of the inlet and exhaust topology - because at different speeds, these shock-wave or Isentropic fan systems have different geometries. This means that for efficient compression or expansion, their shapes need to change throughout the flight envelope and machinery to do this could add substantially to the weight of the design. However, despite these concerns, probably the most demanding challenge in Scramjet technology lies in fuel mixing and combustion.

At such high velocities, drag values are very large and it is difficult to add further kinetic energy to the 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 [1]. 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 (disruptions to the boundary layer may be particularly important in this respect [2]). Next, the mixture must be burnt, but without the aid of the flameholding 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, which may cause engine unstart [3]. It can clearly be seen why the technology is on the edge of practicality and the situation is not helped by the lack of published data, much of which is hidden in the military domain [2].

The idea behind Electromagnetic Activation (EMA) is that instead of a combustion system, electromagnetic radiation is injected into the engine in the position where mixing and combustion would normally take place and this radiation directly stimulates the air molecules, increasing their internal energy and therefore heat. The topology of the engine remains basically the same as for a conventional Scramjet design as shown in Fig. 1.

There are many published designs for Scramjets and so this paper will not concern itself with the aerodynamic design of the system since this is basically the same for EMA as for combustive systems. Instead, a well known published design will be used as the basis for discussion and the paper will deal mainly with the Electromagnetic part of the system.

2. ADVANTAGES AND DISADVANTAGES OF EMA

There are several potential advantages of using EMA compared with combustion in a hypersonic engine.

The first advantage is that the individual molecules are directly energised by an effect travelling through the engine at the speed of light and so most of the problems associated with mixing and combustion times in traditional systems are negated. The radiation crosses a 1 m wide duct in less than 4ns and even the longest radiation pathlength discussed below (which is 18.1 km) is transversed in about 61μs - during which time, the flow, even at Mach 25, has moved only about 50 cm. The actual activation times of molecules are measured in a few nanoseconds for rotational activations and picoseconds for electronic ones [4].

Another advantage is that no fuel or other substance is being injected into the stream causing disruption - with its associated loss of momentum and the addition of shock systems and drag [1, 2]. Related to this, there are no injector mechanisms disrupting the flow - the radiation can be injected through a mechanically continuous window into the duct (and of course, there is no need for any contrivance corresponding to a flameholder). Suitable ceramic windows (for example Titanium Nitride) are available for the 61GHz band and already routinely used in high power microwave systems.

The third advantage is the controllability of the system. Radiation can be switched on and off easily as well as its

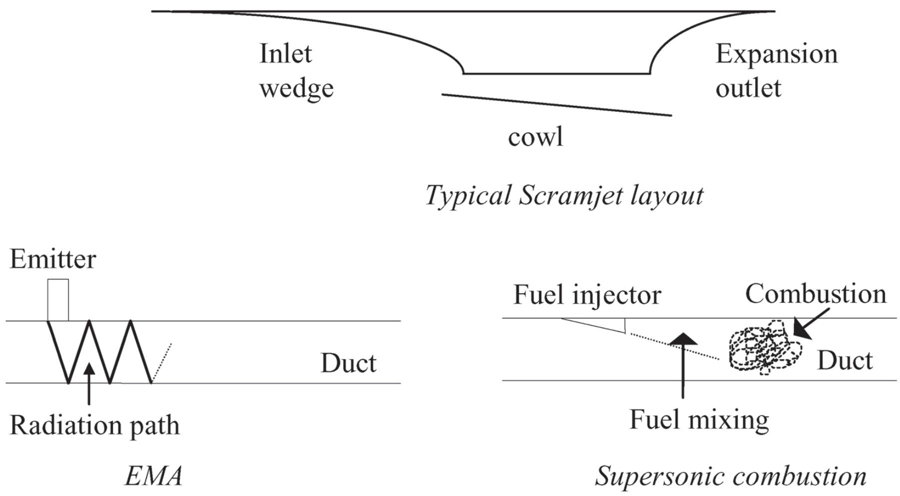


Fig. 1 Typical Scramjet layout - comparison of Supersonic combustion and its alternative - EMA.

intensity varied. Because there is no flame to "blow out", the system is potentially much more stable, without the "unstart" problems associated with combustion (and because the system does not need to support combustion and there is no fuel to disassociate or degrade, it should be possible to operate over a much wider range of pressures and temperatures). This controllability extends to flexibility in the addition of the radiation to the flow which can be easily be done in several stages or more gradually if necessary, thus again avoiding disturbance to the flow - for example strong shocks or disruption of the boundary layer.

A further point is that, at some frequencies at least, both nitrogen and oxygen molecules can be activated directly and the effect is not just restricted to oxygen as in combustion. Because there is no fuel being burnt, there is also no sooting in the duct.

Fifthly, the amount of kinetic energy which can be added to the flow is potentially greater than for combustion because the energy imparted is not subject to the limitations of chemical reactions. Energy can also be added even when the molecules have disassociated into component atoms or become ionised as discussed later - this can make the flow much hotter than is possible using combustion.

Finally, there are a some lesser advantages which are worth noting. One of these is the ease of testability of the system. Because of the fast activation times, the flow is essentially "at a standstill" as energy is added, making figures obtained from static experiments directly applicable to high speed flow. Related to this is testing in transient situations, like shock tubes, which because combustion is not being supported and the short time scales involved, will again give test results directly applicable to real systems.

There is one major disadvantage to the system and two more minor ones. The major disadvantage is the need for a large power-supply system. At the present time, only nuclear fission is capable of supplying this need and it is not currently politically acceptable to allow reactors to fly. However, in the longer term, other sources of power or different approaches to supply may become available; for example, a practical means of temporary storage and discharge of energy or energy-beam transfer from ground or space generators by Electromagnetic means. The use of combustion, using atmospheric oxygen, to generate power rather than to provide propulsion, is also a possibility.

The other disadvantages include the lack of available data on the radiation absorption of high temperature gases and the nature of their corresponding temperature rises. Also, the lack of radiation sources designed to be suitable for this type of system (particular in terms of low weight). These disadvantages however, are more easily overcome.

These points mean that the method is one which currently belongs to the future - but which has great potential once some of the technical problems are solved.

The following sections consider the technical aspects of the system.

3. ABSORPTION OF RADIATION

Absorption of Electromagnetic Radiation in a gas is given by the Beer-Lambert Law [5]. A constant fraction of the radiation is absorbed per unit distance of the gas crossed; this leads to the exponential relationship shown below.

$$I = I_o e^{-\alpha t} \tag{1}$$

Where I_o is the intensity of radiation entering the gas. I is the intensity at distance t in the medium and the final parameter α is called the Absorption Coefficient.

A complete description of radiation transmission also includes various scattering mechanisms. However, in this treatment, these are ignored, because firstly, the scattering contribution is low in the gases involved and secondly, because the system operates inside a duct, any scattered radiation is confined until absorbed providing the duct length is longer than the average radiation absorption pathlength [6].

There are several different ways to specify the Absorption Coefficient α. It is often given in absorption units per cm. Another common and useful formulation is to specify the Absorption Cross-Section. In this case.

$$\alpha = \sigma n \tag{2}$$

Where σ is the Absorption Cross-Section, usually specified in cm^2, and n is the number-density of absorbing particles (per cm^3). In terms of the fraction of radiation absorbed, equation (1) becomes.

$$\frac{I}{I_o} = e^{-\sigma n t} \tag{3}$$

If we are considering the two main molecules of air, N_2 and O_2, the equation includes a linear superposition of the two resulting terms and becomes.

$$\frac{I}{I_o} = e^{-\sigma_o n_o t} + e^{-\sigma_n n_n t} \tag{4}$$

This equation can be rearranged to give the required path-length for a specified absorption by taking logs of both sides and rearranging.

$$\ln\left(\frac{I}{I_o}\right) = -t\left(\sigma_o n_o + \sigma_n n_n\right)$$
$$\Rightarrow t = \frac{\ln\left(\frac{I}{I_o}\right)}{-\left(\sigma_o n_o + \sigma_n n_n\right)} \tag{5}$$

The resulting equation (5) can be used to calculate the path-length required, for example, for 50% absorption of the radiation ($I/I_o = 0.5$); 90% absorption ($I/I_o = 0.1$) or 99% absorption ($I/I_o = 0.01$).

At lower frequencies and in engineering texts, the absorption is often given in a different form - usually in dB power reduction per km. In a parallel beam, of constant area, this is equivalent to a reduction of intensity, as described above. In these cases, a 3 dB reduction is equivalent of 50% absorption, 10 dB is 90% absorption and 20 dB is 99%.

4. CONTRIBUTION OF ABSORBED RADIATION TO INTERNAL ENERGY OF THE GAS

In general, a molecule can have various forms of Potential and Kinetic Energy associated with its translational speed and rotation, the longitudinal and transverse vibrations of its bonds and the energy levels of its electrons. The total internal energy [7] is given by.

$$\varepsilon_{total} = \varepsilon_{trans} + \varepsilon_{rot} + \varepsilon_{vib} + \varepsilon_{el} \tag{6}$$

Each of these terms has itself got contributions from various degrees of freedom which depend on the shape and complexity of the particular molecule. Energy is continuously transferred and redistributed between these different modes by means of scattering and collisions and the emission and absorption of phonons and similarly of photons.

Each discrete combination of energies is known as a microstate and the combination of available microstates a macrostate. The system occupies a series of macrostates distributed around the most probable, which is that which corresponds to the macrostate containing the most number of available microstates. This provides a means of mathematically calculating the state of the system [7].

At equilibrium the sensible internal energy of the system turns out to be.

$$e = \frac{3}{2}RT + RT + \frac{h\upsilon/kT}{e^{h\upsilon/kT} - 1}RT + e_{el} \tag{7}$$

Where R is the Gas Constant, T is absolute temperature, h is Planck's Constant, k is Boltzmann's Constant and υ is the frequency of vibration.

The first term of equation (7) corresponds to the translational contribution; the second term to the rotational; the third to the vibrational and the final term to the electronic. The electronic term has no simple mathematical form because of the differences in shape and electron energy levels in different molecules. Transfer of energy between these modes is sometimes specified by intermode coupling coefficients.

Energy may be supplied to any of these terms by the absorption of radiation and is redistributed among the others by the mechanisms described above.

5. PATH LENGTH OF RADIATION INSIDE A DUCT

Many sources of EM radiation can be confined into a tight coherent beam (for example radiation emerging from a microwave waveguide, a laser or a fibre-optic). If long path-lengths are required for good absorption, the duct itself can act as a waveguide. In these cases, propagation is by a series of reflections. The geometry of this in a parallel sided duct is shown in Fig. 2.

In this case, the width of the duct is W and the radiation is launched in a tight parallel beam at angle θ to a normal through the duct wall. The path length to the first reflection is L and the distance along the duct to this point is d. Using simple geometry L and d are.

$$L = \frac{W}{\cos\theta} \tag{8}$$

$$d = W\tan\theta \tag{9}$$

From these relationships an expression may be derived for the length of duct, D, required to accommodate a particular total radiation pathlength, L_{tot}, as shown below. Consider first the number of reflections n required to give the total pathlength needed.

$$n = \frac{L_{tot}}{L}$$

Substituting for L in the equation above.

$$n = \frac{L_{tot}}{\frac{W}{\cos\theta}} = \frac{L_{tot}\cos\theta}{W}$$

However, the duct length required for this total pathlength is.

$$D = nd = nW\tan\theta$$

Finally substituting for n and rearranging we have.

$$D = L_{tot}\sin\theta \tag{10}$$

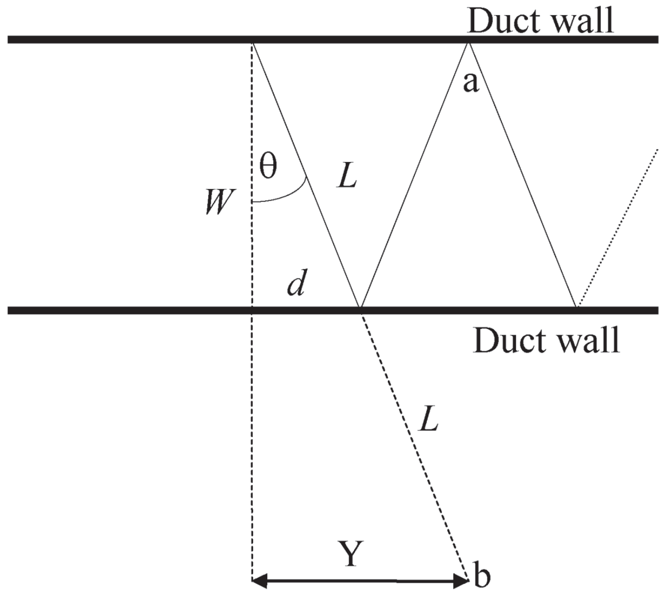


Fig. 2 Path length of radiation in duct.

It may be seen here that *W* has cancelled out in equation (10). The reason for this may be seen from the geometry of Fig. 2. If the duct wall were not in place, the ray would carry on another length *L* to point b. This is exactly opposite point a, where the reflected ray ends up - and so the width of the duct does not enter into the final equation for path length. It is also easy to derive similar expressions for diverging and converging ducts - in the case of the diverging duct the length *D* increases for a particular total path length required, in the case of a converging system it decreases. Note however, that a duct diverging to the right in a similar geometry to Fig. 2 with the radiation fired from the left, becomes a converging duct if the radiation is fired from the right.

6. TYPICAL ENVIRONMENT INSIDE THE DUCT

As mentioned in the introduction, there is no intention here to redesign the many inlet, isolator, combustion and expansion ducts already investigated theoretically and experimentally for Scramjet use. Instead, a typical and well known design will be used. This is based on that published by Billig [8] and discussed by Anderson [9]. The values presented are typical of those given in other published work for Scramjet operation [10, 11] and are shown in Table 1.

The pressures and temperatures given are those at entry to the combustor section for a typical flight envelope. Refer to the original paper or Anderson's discussion of it for a list of all the parameters (velocities, altitudes and pressure and temperature ratios) if required.

These values are typical in that most designs aim to keep the maximum temperature at the start of the combustor below 2000K in order to avoid oxygen dissociation ($O_2 \rightarrow 2O$) which starts around 2500K at a pressure of 1atm and moves downwards towards 2000K or less at lower pressures, Fig. 3. Considerations such as these mean that most designs put the Mach number at the start of the combustor at 0.3 to 0.4 times the free stream number [10, 12]. Another often quoted "rule of thumb" is that the pressure at the same point is between 0.5atm and 10atm. The upper limit being chosen for stress and structural reasons and the lower so that good combustion can be maintained [10]. In this discussion these values will be used as there are many published designs which employ them and they have been calculated to maintain a reasonable thrust and though-engine flow-rate. However, it should be borne in mind that although these values will be used, the EM activated duct potentially has a wider operating range than a conventional Scramjet because conditions conducive to the combustion of fuel do not have to be maintained.

In the discussion below, calculations are based on a perfect gas assumption as opposed to one based on a calorically adjusted gas or a reacting flow. This is a reasonable assumption for temperatures and pressures below those required for oxygen dissociation or other major chemical or physical reactions. In Billig's data these are the temperatures and pressures quoted up to Mach 15, which cause an error of less than 10% in calculated parameters. It is not such a good assumption at the conditions quoted at Mach 20; however, since such extreme conditions within a duct are difficult to predict accurately anyway and little experimental verification exists, the perfect gas assumption is still made; literature indicates that this should be accurate to within 25% in terms of calculated radiation pathlengths [7]. The Oxygen, Nitrogen ratio is also assumed to be 21% to 78%, the other 1% being other gases; again, this holds true except at the highest altitudes.

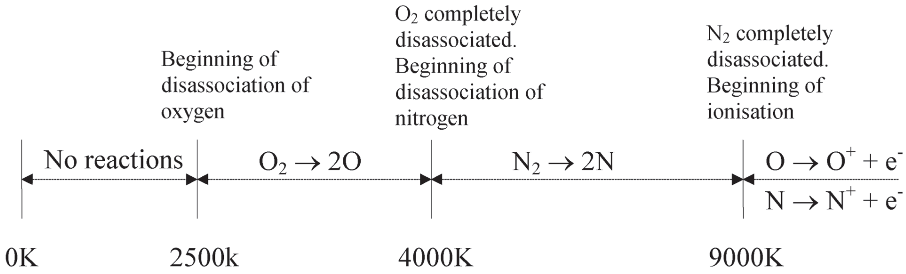
7. ABSORPTION OF ELECTROMAGNETIC RADIATION BY NITROGEN AND OXYGEN INSIDE THE DUCT

This discussion on absorption will, for the moment, confine itself to the two principle components of the atmosphere - molecular nitrogen and oxygen. Molecular nitrogen and oxygen are symmetric diatomic molecules. One result of this is that they normally have no electric dipole moment. Having no moment means that, compared with, for example water, there are less absorption lines in many parts of the spectrum. In fact, in the infrared, where water is strongly absorbing (the mechanism responsible for much of the heating of Earth through solar and reflected ground radiation), oxygen only has a very weak response and nitrogen practically no response at all. Oxygen does have rotational absorption bands in the Millimetre Wave region of the spectrum however - due to its magnetic moment, and these are discussed below. It is also worth noting that an electric moment can be induced by applying an external electric field; however, a fuller exploration of this aspect is left for future work. Nitrogen, in contrast, does not absorb well until the ultraviolet and wavelengths below 185nm.

TABLE 1: *Billig's Calculated Scramjet Parameters.*

Mach number	**7**	**10**	**15**	**20**
Pressure in duct (Pa)	1.31×10^5	1.23×10^5	1.1×10^5	0.69×10^5
Temperature in duct (K)	806	1087	1600	2263

Fig. 3 Dissociation and ionisation in air at 1atm.



8. ABSORPTION AT MILLIMETRE WAVE FREQUENCIES

The first absorption band associated with oxygen or nitrogen in the atmosphere is that caused by the magnetic moment of molecular oxygen mentioned above. This band is centred at a peak of around 61GHz and has the form shown in Fig. 4. As can be seen from the graph, there is also another band centred at 119GHz, but this has a lower absorption than the 61GHz band and is not discussed further here [13].

The peak at 61GHz is actually due to a series of several absorption lines between 48 and 71GHz. However, these are merged together due to a phenomena known as "pressure broadening". Pressure broadening is important because it illustrates the energy transfer mechanisms explained in section 4 above. If the air is at a high enough pressure, interactions between molecules involving collisions and scattering transfers kinetic energy and hence momentum from the original rotational activation of the molecules to their translational and vibrational states (see equation 6) and this transfer is responsible for merging and spreading the absorption band. Hence the mechanisms described above are manifest in the shape of the band. Figure 5 shows this diagramatically.

Pressure broadening also gives an indication of the lowest possible pressures at which the system is likely to be effective at this frequency. At room temperature, in the 48GHz to 71GHz band, the lines don't split and become distinct until the pressure drops to about 0.2atm. At this point there is not sufficient energy transfer between kinetic modes to merge the band and hence heating due to absorption is likely to be markedly less effective below this pressure. It should be noted however, that higher temperatures will reduce the pressure at which spreading occurs because the hotter molecules have greater kinetic energy and collide more often; unfortunately there are no published figures for this at millimetre wave frequencies and its calculation using kinetic theory is involved and must be relegated to future work.

At the standard conditions mentioned above, 61GHz radiation has an absorption in air of 16dB per kilometre. This figure corresponds to an absorption of 0.975 or 97.5% of the radiation over 1 km or 99.84% over 2 km. These pathlengths may initially seem long, but if a parallel sided duct, as in Fig. 6, is considered and some simple assumptions made, the actual situation shows the practicality of the system. If the duct is fed, as shown in Fig. 6, with a "fanned" feeder of the standard width of waveguide at 61GHz, which is 0.188 cm (British waveguide type WG25 or American types WR15/RG98), then equation 10 may be applied to calculate the length of duct required.

If it is assumed that the angle θ of the waveguide to the duct is just enough so that the reflected radiation just misses its

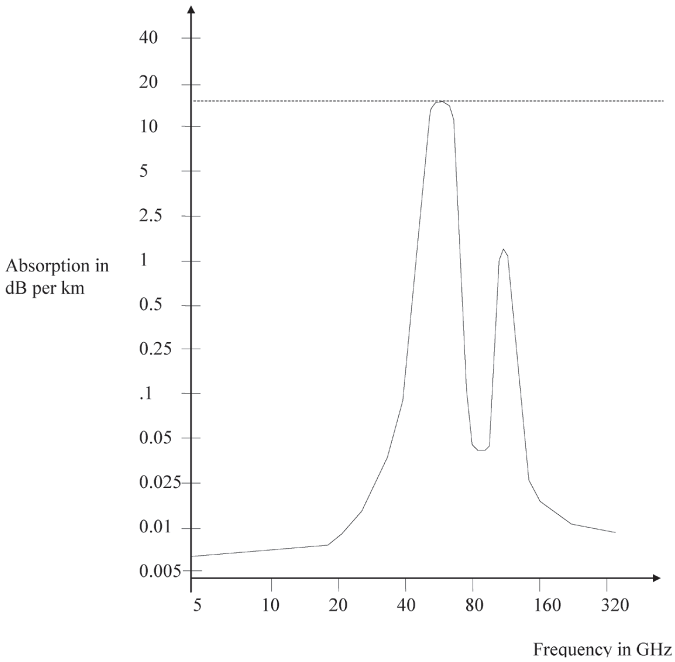


Fig. 4 Absorption by molecular oxygen at US standard sea-level atmospheric temperature and pressure.

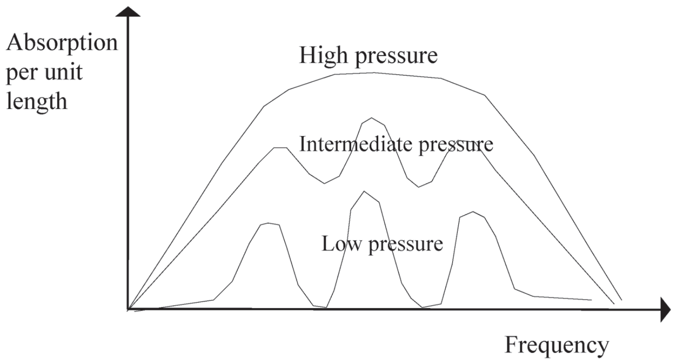


Fig. 5 The effect of pressure broadening on several closely spaced absorption bands.

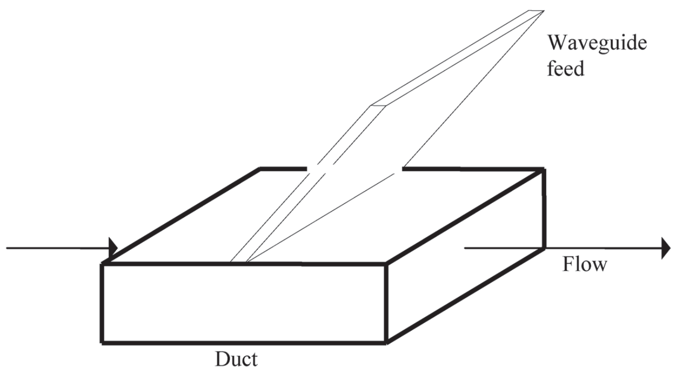


Fig. 6 A simple millimetre wave fan feed to duct.

opening (equals *2d* in Fig. 2), this gives, from equation 9, an angle 0.027° in a 1 m wide duct. Calculating the required duct length for the 1000 m pathlength then leads to a figure of 0.47 m. So it may be seen that long pathlengths do not necessarily need long lengths of duct; it should also be noted that "one way" transmission windows can be set up easily at these frequencies (as can cleverer beam paths), so the assumption above of the radiation missing the feed is not even necessary with careful design. Most metals are good reflectors of these frequencies, which behave similarly to microwaves; reflection is also tolerant of sooting and any duct deposits and heating of the wall surface by the radiation itself is negligible.

Having done some basic calculations at standard temperature and pressure to gain a feel of the pathlengths and distances involved, consideration will now be given to pathlengths in real duct conditions. To do this it is better to frame the absorption problem in terms of the Beer-Lambert Law (equation 1) as this allows a more flexible and accurate calculation than the figures quoted above. It should be noted however, that the figures given in the literature and used here, are mostly measured for use in communications engineering and are not as accurate as the absorption cross-sections carefully measured by spectroscopic means - as in the Ultraviolet examples below. Equating the measured loss of 0.975 over 1 km to equation 1 gives a figure for α of 0.0253 where t is in km. Knowing the number density of O_2 molecules in standard air ($n = 5.1731 \times 10^{18}$ #/cm^3) allows, from equation 2, the absorption cross-section to be estimated at $\sigma = 7.1232 \times 10^{-24}$ cm^2.

Using the assumptions outlined in section 6 for Billig's data allows the calculation of number densities of molecules at various Mach numbers as shown in Table 2a.

Table 2b contains the figures for 0.5atm which, as mentioned in section 6, is often taken as the minimum acceptable pressure (at least for combustion). The temperature of 2000K is taken as the temperature limit for the reasons (disassociation) described above - this represents, then, the most extreme (that is disadvantageous) case which most designs present.

Using these data, the path lengths within the duct can now be calculated using equation 5. These are shown in Table 3 for 99% absorption of the radiation.

As can be seen, these pathlengths range from 2.8 km to 15.0 km, with the extreme case of 18.1 km at 0.5atm. As described above, these represent an interesting, but by no means impossible, engineering challenge to accommodate within the engine.

To provide further insight into the behaviour of the system, consider Fig. 7. This represents a graph of pathlengths at different pressures but at fixed temperature (2000K) and illustrates the expected variation of pathlength in these circumstances for 99% absorption.

The other data which can shed some light on the system is that of pathlength against temperature. This is shown in Fig. 8, in this case for 99% absorption at 0.5atm.

9. ABSORPTION AT ULTRAVIOLET FREQUENCIES

At Ultraviolet frequencies, Oxygen and Nitrogen molecules, atoms and ions absorb radiation. This absorption is responsible (along with some other mechanisms like ion generation and recombination) for the conditions in the high thermosphere, which reaches high temperatures (2000K or more) despite being extremely tenuous. The efficiency of absorption explains why these wavelengths disappear quickly even in this low-density medium and have little effect on heating in the atmosphere below (indeed short UV wavelengths are known as "vacuum ultraviolet" because they will only propagate, without appreciable absorption, in the absence of air). In comparison with the situation at millimetre wavelengths described above, the Ultraviolet is more complex as the absorption mechanism is electron energy activation and this is affected by non-linear mechanisms like radiation saturation and phonon scattering. Andrews presents an analysis of heat production due to Ultra-

TABLE 2a: *Number Densities Using Billig's Data.*

Mach	7	10	15	20
Partial pressure O_2 (Pa)	26200	24600	22000	13800
Partial pressure N_2 (Pa)	104800	98400	88000	55200
Density of O_2 (Kg/m^3)	0.125	0.085	0.053	0.023
Density of N_2 (Kg/m^3)	0.438	0.305	0.185	0.082
Number of O_2 molecules per cm^3	2.35×10^{18}	1.64×10^{18}	9.97×10^{17}	4.33×10^{17}
Number of N_2 molecules per cm^3	9.42×10^{18}	6.56×10^{18}	4.01×10^{18}	1.76×10^{18}

TABLE 2b: *Number Densities for Air at 0.5atm and 2000K.*

Species	O_2	N_2
Number density in air at 0.5atm, 2000K (molecules per cm^3)	3.57×10^{17}	1.46×10^{18}

TABLE 3: *Pathlengths at 61GHz for 99% Absorption.*

Mach	7	10	15	20	0.5atm, 2000K
Number density *n* of O_2 (#/cm^3)	2.35×10^{18}	1.64×10^{18}	9.97×10^{17}	4.33×10^{17}	3.57×10^{17}
Pathlength (km)	2.8	4.0	6.5	15.0	18.1

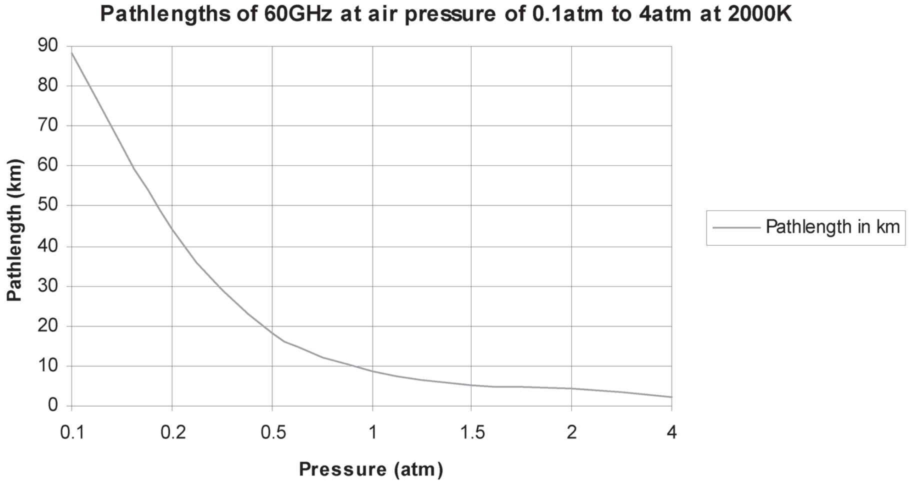


Fig. 7 Variation of pathlength with pressure for 99% absorption.

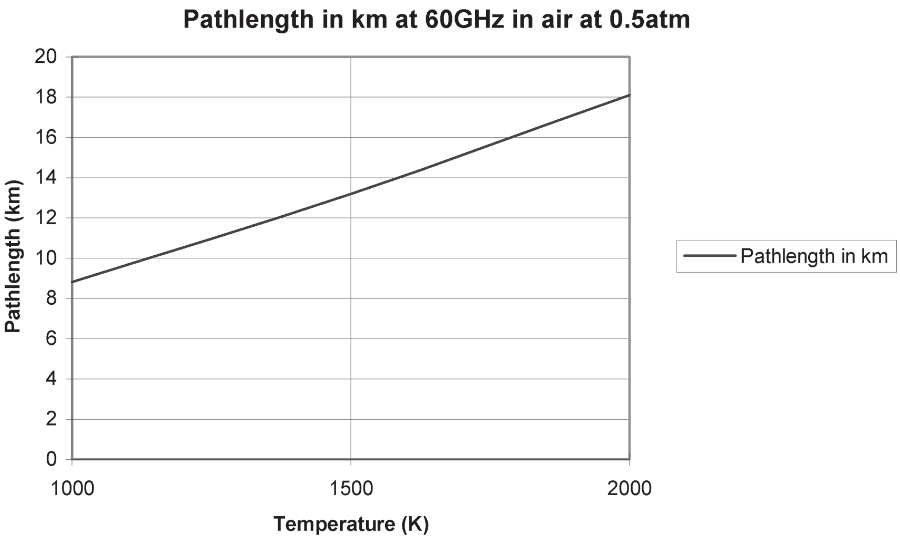


Fig. 8 Variation of pathlength with temperature for 99% absorption.

violet absorption in the upper atmosphere [14]; however, little data has been published regarding the situation with regard to the high temperature gases discussed here and more work is needed to obtain reliable figures.

At short wavelengths, disassociation and ionisation occurs and this situation is described at the end of the section. First, however, simple absorption without these complications will be discussed.

The graphs in Fig. 9a and b show the absorption cross-sections of oxygen and nitrogen molecules at ultraviolet wavelengths.

As with the Millimetre Wave examples previously discussed, the absorption pathlengths can be calculated from these data. Table 4 shows the pathlengths required for 99% absorption by O_2 between the wavelengths of 140nm and 200nm.

It can be seen from these tables that the pathlength of UV can be much shorter than for Millimetre waves and by choosing the activation wavelength a wide variety of pathlengths are available. Furthermore, because the graph of absorption cross-sections is smooth between 140nm and 200nm, the response of the system could be finally controlled if a tuneable wavelength radiation source were available. Figure 10 shows this in graphical form.

The situation as the vehicle accelerates through its performance envelope with activation at a fixed wavelength is shown in Fig. 11.

The situation for nitrogen is similar and is shown in Table 5 - although the wavelength response is more of a step function and so the argument for a tuneable source, made above for oxygen, does not apply so well.

As pointed out in the advantages section, activating nitrogen means that heat is transferred directly to approximately 80% of the flow. However, also note that, unlike the situation at 61GHz, at most UV wavelengths, absorption is by both oxygen and nitrogen and so the whole flow is activated.

Finally, before ending the discussion on ultraviolet activation, the effects of disassociation and ionisation can be considered. Ultraviolet, at short wavelengths, first disassociates and then ionises N_2 and O_2 in a similar way to high temperatures. The wavelengths at which this happens are shown in Table 6 below.

It might initially seem that this situation is to be avoided because it requires energy which would otherwise be directed into increasing the internal energy of the flow. However, there are two important points to bear in mind. Firstly, some of the energy is conserved as kinetic and manifests itself in the products. Secondly, recombination reactions also occur - which release energy. If the two were in equilibrium, then energy levels due to disassociation effects would nearly cancel (this is

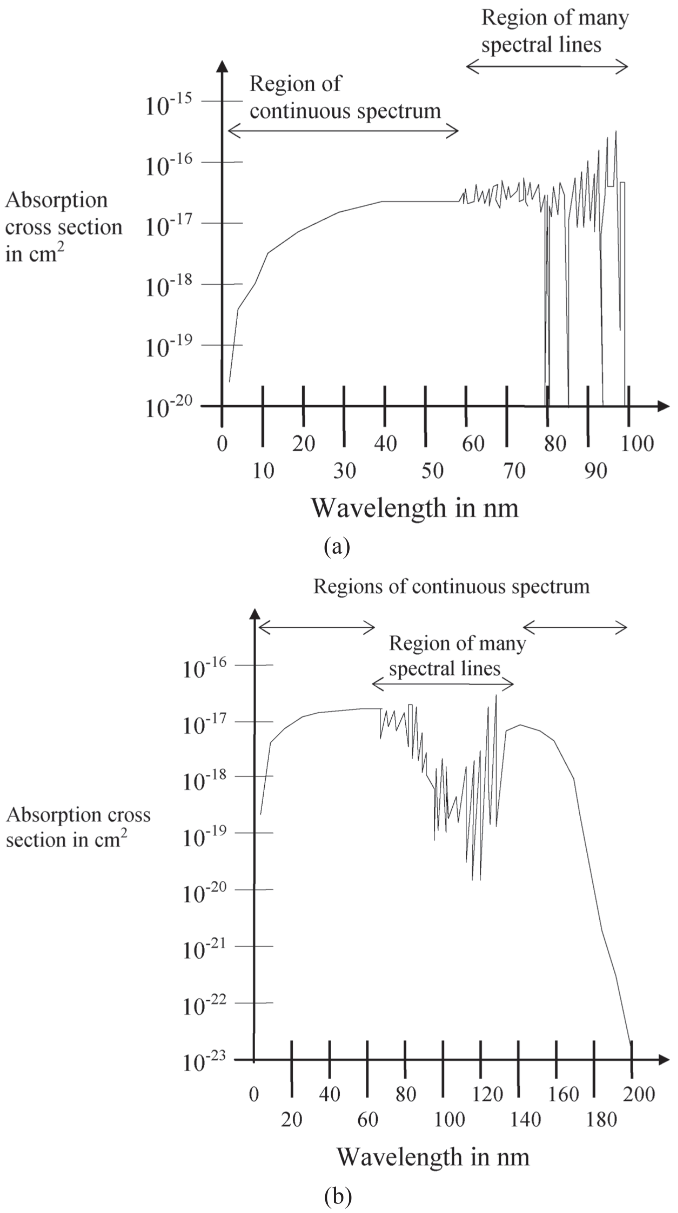


Fig. 9 Absorption cross sections for a) N_2 and b) O_2.

why the contribution to thermosphere heat from these phenomena is not as high as sometimes stated).

However, the most important point to emphasise is that, whether disassociation products appear by means of UV activation or heat, they themselves can be activated by the radiation - an important difference compared to combustion and one of the reasons why it is possible to add more energy to the flow

TABLE 4b: *Pathlengths at 0.5atm, 2000K for 99% absorption by O_2.*

Wavelength (nm)	**140**	**160**	**180**	**200**
Pathlength (cm)	2.58	3.22	2577	5154077

using EMA. To illustrate this Fig. 12 below shows the cross section of atomic oxygen at UV.

10. RADIATION SOURCES

At millimetre wavelengths there are a number of different sources which may be suitable for use in EMA systems. Two well known generators are the Klystron and Magnetron [15]. Both of these are thermonic valves (tubes) which can generate similar large powers at these frequencies. At 61GHz, commercially available devices are capable of delivering up to 0.5MW of power. However, this frequency is not popular in communications systems, due (ironically) to its high path loss and so this power is not representative of the available technology in devices which operate at nearby millimetre wave frequencies. The available powers at these frequencies are continuous powers of around 3MW for large Klystrons and perhaps 6MW for magnetrons. Examples are available with 100MW or more of intermittent power - note however, that there is no need to use single devices. These powers might be compared [16] with 1 to 4MW for a medium sized jet engine and 60MW for a large engine like a Rolls Royce RB211.

Klystrons and Magnetrons are moderately heavy devices, primarily designed for communications systems. Their weight is governed by two factors - one is the heavy magnets they employ to focus and shape their electron beams, the other is shielding to prevent harmful radiation like x-rays escaping and harming their operators (as well as shielding the vehicle occupants, electronics and payloads from the microwave radiation itself). A typical 100MW pulsed Klystron weighs around 300 kg, military versions for aircraft use weigh less - a 3.1MW Magnetron for example only weighs 8.6 kg. From available figures it is likely that a combined duct/generator system (not including the power supply, of course) would weight around 1000 kg or less (a large jet engine, like the RB211 weighs around 3000 kg). Integrating these devices into vehicles, at the design stage, may well save some weight which is necessary for communications work but not for propulsion. It may also be possible to design the duct into the electrical scheme of the device (for example as a cavity).

The other option at millimetre frequencies is the microwave laser or maser [17]. These may have some advantages over other methods in terms of weight and power, and there are quite

TABLE 4a: *Pathlengths for O_2, 99% absorption between 140nm and 200nm.*

Wavelength (nm)	**140**	**150**	**160**	**170**	**180**	**190**	**200**
Cross-section s (cm²)	0.5×10^{-17}	0.1×10^{-17}	4×10^{-18}	9×10^{-19}	5×10^{-21}	1×10^{-22}	0.25×10^{-23}
Path Length Mach 7 (cm)	0.4	2.0	0.49	2.18	392	19596 (195.96 m)	783859 (7.84 km)
Path Length Mach 10 (cm)	0.56	2.8	0.70	3.1	562	28080	1123212
Path Length Mach 15 (cm)	0.92	4.62	1.15	5.1	924	46190	1847611
Path Length Mach 20 (cm)	2.1	10.64	2.66	11.8	2127	106354 (1.06 km)	4254199 (42.54 km)

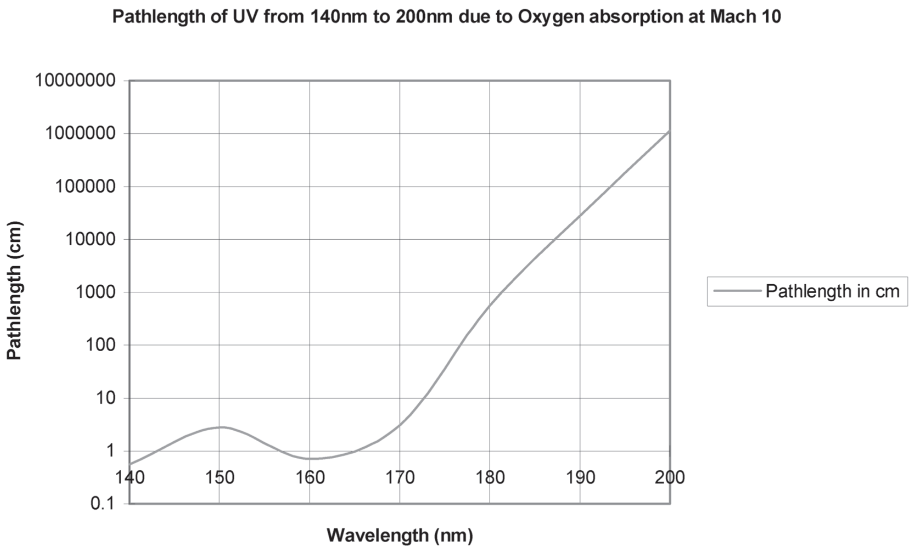


Fig. 10 Graph of pathlength for 99% absorption by O_2 from 140nm to 200nm at Mach 10.

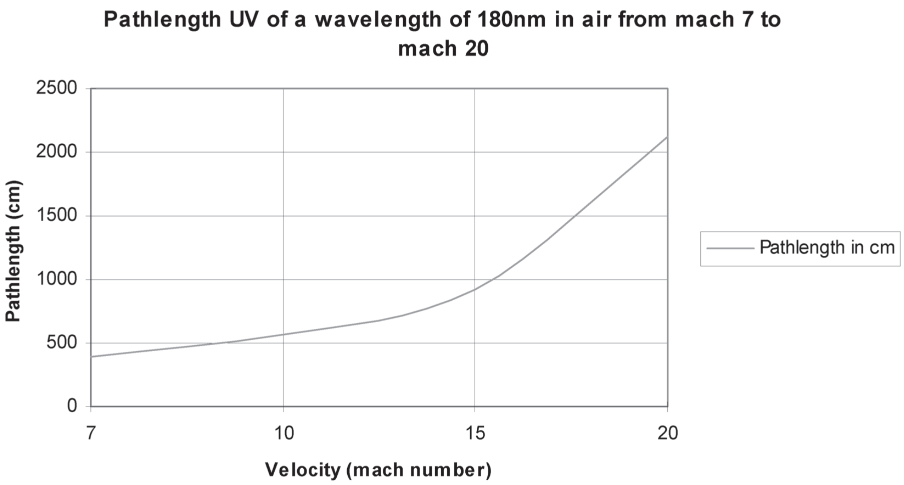


Fig. 11 Pathlength for 99% absorption at 180nm for Mach 7 to Mach 20.

TABLE 5: *Pathlengths for N_2, 99% absorption at 98.4nm and 97.5nm.*

Wavelength (nm)	98.4	97.5
Cross-section σ (cm^2)	1 x 10^{-20}	2.8 x 10^{-16}
Pathlength at Mach 7 (cm)	48	1.75 x 10^{-3}
Pathlength at Mach 10 (cm)	70.2	2.51 x 10^{-3}
Pathlength at Mach 15 (cm)	115	4.1 x 10^{-3}
Pathlength at Mach 20 (cm)	261.7	9.34 x 10^{-3}
Pathlength at 0.5atm, 2000K (cm)	315	11.2 x 10^{-3}

TABLE 6: *Disassociation and Ionisation Wavelengths and Energies.*

Species	Disassociation wavelength (nm)	Disassociation energy (eV)	Ionisation wavelength (nm)	Ionisation energy (eV)
O_2	242	5.12	103	12.08
N_2	127	9.76	80	15.58
O	-	-	91	13.61
N	-	-	85	14.54
NO	191	6.51	134	9.25

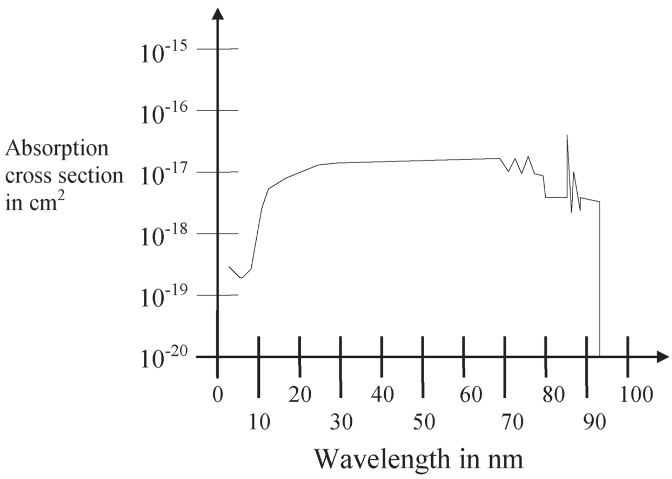


Fig. 12 The absorption cross-section of atomic oxygen in the UV.

a number available at millimetre wave frequencies - including Ammonia, Hydrogen, Rubidium, Ruby, Brandon and others. Many of these provide comparable power outputs to Magnetrons, but are in some cases lighter. Others are capable of much more power - for example 200MW is quoted for a pulsed Cherenkov device. However, it has to be said that the efficiency of these devices is low compared with the thermonic valve equivalents - both Magnetrons and Klystrons routinely exceed 65% efficiency and good devices can approach 80%.

At ultraviolet frequencies there are also both non-coherent devices and lasers available. However, the issue is somewhat more complex here due to the availability of suitable windows and reflecting materials.

Conventional sources include various arc, fluorescing and incandescent devices [18] and Lasers include semiconductor types, solid-state bulk lasers, some fibre-optic lasers, dye lasers, excimer devices, argon and krypton ion and free-electron lasers. Other lasers can also be used with frequency multiplication. Information on the efficiency of these devices is rather limited.

The short pathlengths of ultraviolet systems means that a different topology is possible - one of surrounding the duct with a wrapped system of multiple sources pointing inwards. One can think of this as like surrounding the duct with a ultraviolet "flashlight" or lasing material. Diamond films also show some promise as UV emitters and would have particular material advantages due to their high thermal conductivity and hardness.

11. EXTENSION AND COMBINATION WITH OTHER TECHNIQUES

There are a number of different ways in which the techniques discussed above can be combined with others. One of the most obvious of these is its combination with Magneto HydroDynamic (MHD) systems. This approach, pioneered principally by several Russian teams [19, 20] accelerates the flow by electrical means. Such systems consist of a Plasma Generator (for example an ionising radiation source, electric arc or similar) and a means of magnetically or electrostatically focusing and accelerating the resulting plasma. The ionising portion of the ultraviolet spectrum can be used to generate and heat the plasma as discussed earlier and this may then be accelerated as just described. The MHD approach moves away from the basic structure of the Scramjet, in that the structure of the duct and outlet need to accommodate the focusing and acceleration coils used by the system. A variation of this system is to use another oscillating field applied to plasma to heat it (rather than accelerate it linearly) and then use a more traditional expansion nozzle - this type of heating is commonly found in nuclear fusion reactors and particle accelerators. Such ideas also point the way to systems where several different frequencies are used, exploiting their different characteristics.

There may also be a role for EMA in more traditional Scram type engines. EMA may be applied to the fuel after injection to increase its mixing efficiency or before injection to increase its internal energy. Obviously it may also augment combusted fuel energy in a traditional Scram system (or supply ignition energy to the mixture).

Another extension to the technique is to add a substance to the flow beforehand which is particularly easy to activate. This may seem to negate some of the advantages of having no injection in the system mentioned earlier - however, there is an obvious candidate for such a substance - water. Water, having an electric dipole moment, absorbs over a much wider range of frequencies and more efficiently than nitrogen and oxygen (as most people are aware of, from everyday microwave ovens). Water vapour could be injected ahead of the engine or a film of it coating a surface could be vaporised inside the duct itself. The use of water even makes the techniques discussed here applicable to lower speed scenarios - an EM water activated turbojet for example.

12. DISCUSSION AND CONCLUSIONS

The idea of using a means other than combustion to add energy to the flow in a hypersonic duct is not new. MHD has been reviewed in the sections above and there are other ideas also - for example, the use of acoustic standing waves to add heat [21, 22]. However, the EMA idea is one of the most general, relying as it does on the direct excitation of the particles themselves. It is also probably the most flexible, in that all common atmospheric gases can be activated in this way, potentially allowing for operation in different planetary atmospheres. The figures outlined above show clearly that the engineering challenges in the actual duct itself can be overcome within the limitations of current technology.

Of the various advantages outlined, the three greatest are probably smooth flow through the engine, controllability and virtually instant activation. The disadvantage, for the moment, is the power supply issue. This means that the ultimate importance of this technique probably lies in the future; however, it may still have some significance in the meantime as a means of enhancing fuel-air mixing. It is also clear that (at least in the short term) the Millimetre system has several advantages over the Ultraviolet one - these include the high efficiency of the generators, their low weight and the easy availability of suitable window materials.

There is clearly experimental work still to be done in order to make better estimates of the absorption and heating effect in high temperature, low pressure gasses. This will lead to a better understanding of the losses involved in the system and therefore its efficiency (an understanding of which remains unclear at this point). In particular, careful measurement of gas heating, disassociation and ionisation would be useful. One benefit is that measurement taken in static situations and high-speed flow experiments in shock-tunnels are much more applicable to the system parameters than they are in combustion systems. As discussed in the previous sections there are also numerous enhancements to the technique which would also make for an interesting programme of further work.

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