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Analysis of Scramjet Flight Trajectories with Oxygen Enrichment

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Abstract

Scramjets are proposed as a second stage for a multi-stage access-to-space system. At present the upper limit of scramjet operation is expected to be Mach 12-14. Use of oxygen enrichment is a possible method for increasing the speed and altitude of scramjet operation. This paper involves mission analysis of scramjets using oxygen enrichment. It follows on from Smart & Tetlow [5], in which trajectory studies of a three-stage rocket-scramjet-rocket access-to-space system were conducted. These calculations indicated that the net thrust (scramjet thrust - vehicle drag) of a hypersonic vehicle with three scramjet engine modules was reduced to very low levels above Mach 12. The current work examines the use of oxygen enrichment in the scramjet to increase net thrust above Mach 10. Results of the study indicate that an important effect of oxygen enrichment is to allow scramjet powered vehicle operation at higher altitude.

Nomenclature

C_D	drag coefficient
C_L	lift coefficient
D	drag (N)
F	uninstalled thrust (N)
f_{st}	stoichiometric ratio
h	altitude (km)
I_{sp}	specific impulse (s)
L	lift (N)
m	mass (kg)
M	Mach number
p	pressure (kPa)
q	dynamic pressure (kPa)
T	temperature (K)
u	velocity (m/s)
w	mass flow rate (kg/s)
w_{cap}	capture width (m)
α	angle-of-attack (º)
φ	equivalence ratio
η	efficiency
ζ	flight path angle (º)

Introduction

In the hypersonic regime, scramjets offer significantly higher specific impulse than rockets, and are thus envisioned as a key component in next generation access-to-space vehicles. The work described in this paper follows on from that by Smart & Tetlow [5], which investigated a low-Earth-to-orbit (LEO) trajectory for a vehicle in which scramjet engines were included as the second stage in a three-stage rocket-scramjet-rocket configuration.

The first stage of the vehicle investigated by Smart & Tetlow [5] was a solid rocket, which boosted a 3000kg scramjet vehicle to an altitude of 27km travelling at Mach 6 and a flight path angle ζ = 0º. The second stage scramjet powered vehicle was a waverider on which three Rectangular-to-Elliptical-Shape-Transition (REST) engines designed for flight at Mach 6-12 (RESTM12) [4] were installed. Finally, the third stage liquid fuelled rocket, which was housed in the scramjet vehicle payload bay, accelerated the payload to a 200km circular orbit. The baseline trajectory calculated allowed the scramjet vehicle to climb to an altitude of 37.15km and M = 11.73 before the engines shutdown after 273 seconds consuming 1356kg of hydrogen fuel. This trajectory was chosen to maintain a dynamic pressure in the range 50-100kPa, which was accomplished by keeping the angle of attack between -4º and -5º. At these angles-of-attack, the waverider did not utilize its high lift capability; as such a key result obtained from the work was that for low density hydrogen fuelled vehicles, high lift-to-drag (L/D) ratios are not as important as low drag.

The work in [5] was continued by Weidner [6], where a second vehicle configuration was also investigated and trajectories were manually optimised. Also, [6] included a change to the thrust calculation, resulting in slightly diminished performance of the engine compared to that in [5]. The initial conditions at scramjet take-over remained the same. For the waverider, Weidner calculated a trajectory that took the vehicle to an altitude of 32.5km and Mach 11.0 after operation for 400 seconds consuming 800kg of fuel. Again, the waverider was flown at an angle of attack in the range of -4º and -5º in order to keep dynamic pressure constant at 50kPa. In this orientation the vehicle L/D ratio was less than one for much of the flight time. As such, the waverider did not operate efficiently.

A second vehicle configuration was investigated in [6]; referred to here as the NASA wing-cone vehicle (WCV). The WCV was designed for efficient packaging rather than high L/D, and did show significant improvement over the waverider. The same optimisation procedure was carried out resulting in a trajectory that allowed the scramjet to climb to an altitude of 35.5km at Mach 11.8 after 400 seconds of operation consuming 725kg of fuel. The WCV was operated at angles-of-attack between 1º and 2º in order to keep the dynamic pressure constant at 50kPa. In contrast to the waverider, this range of angle-of-attack was closer to the design range of the vehicle, which allowed it to operate in a region where the L/D ratio was always larger than one.

It would be desirable to operate the scramjet stage for a longer period, continuing to gain altitude and speed, so as to delay the onset of the third stage. This could be accomplished by increasing the engine thrust and/or reducing vehicle drag. Oxygen enrichment is proposed as a means to augment the engine thrust near the point where scramjet shutoff would occur. This paper investigates possible trajectories for the access-to-space mission outlined in [5] and [6] while including the use of oxygen enrichment as a thrust augmentation technique in the high Mach number regime.

Oxygen Enrichment

Oxygen enrichment is seen as a means to augment the thrust of the scramjet powered stage of a launch vehicle at the point where standard scramjet operation no longer provides enough thrust to overcome the vehicle drag. As it is intended for use only at this key phase of the mission, the implementation and use of oxygen enrichment should not adversely affect the overall performance of the vehicle.

Oxygen enrichment is the premixing of oxygen with fuel prior to injection into the engine core flow. It is best used in high Mach number and/or high altitude flight regimes, where net thrust is low. At these conditions, the effects of poor mixing efficiency and in the latter case the low mass flow rate of air through the engine can be mitigated by employing enrichment, thus increasing the available thrust.

There are several parameters to describe the level of enrichment, each with its own usefulness and applicability for a given situation. In this work, the amount of enrichment will be quantified by the freestream addition percentage (addition%), which is the percentage of additional oxidizer injected compared to the available freestream oxygen [2]

$$addition\% = \frac{w_{oxygen,enriched}}{w_{oxygen,\,freestream}} \cdot 100 \tag{1}$$

The freestream addition percentage also quantifies the amount of additional fuel that can be burnt by the premixed oxygen. For example, starting with an equivalence ratio $\varphi = 1.0$ and employing enrichment at addition% = 20, more fuel can be added such that the equivalence ratio is increased to $\varphi = 1.20$.

Of course, the benefits of oxygen enrichment come at the expense of carrying oxidizer onboard the vehicle, which potentially reduces the available payload mass. However, the ability to operate the scramjet stage of the vehicle for longer periods to delay the onset of the rocket stage can potentially increase the payload mass. Despite the need to carry oxidizer, enrichment is favourable to the earlier use of a rocket for one because the enriched scramjet can still have "better specific fuel consumption or specific impulse because the combustion energy release is spread out over more fluid" [1]. The proper use of oxygen enrichment will have to be evaluated in the context of the overall vehicle design and mission objectives.

Vehicle Description

The NASA WCV shown in Figure 1 and described in [3], is characterised by a 5° half-angle conical fore-body, which acts as a compression ramp for the scramjet. It has a cylindrical mid-body and 9° half-angle truncated conical aft-body. The vehicle is scaled to allow for the installation of three RESTM12 engines, each with w_{cap} = 0.76m, which results in a reference area of 24.01m2, a length of 16.33m and diameter of 2.10m.

The aerodynamic data for the WCV [3] is shown in Figure 2 to Figure 4. The nominal angle-of-attack for the operation of the WCV with the REST engines installed was 2 degrees, at which the L/D for the WCV ranges between 2 and 3.

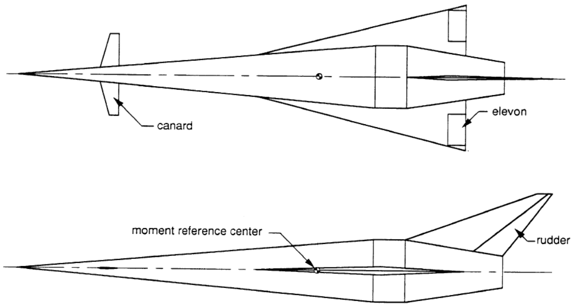

Figure 1 – NASA wing-cone vehicle

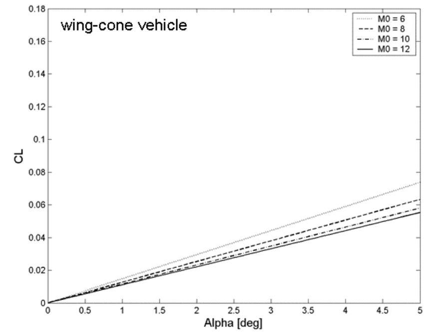

Figure 2 – NASA WCV C_L

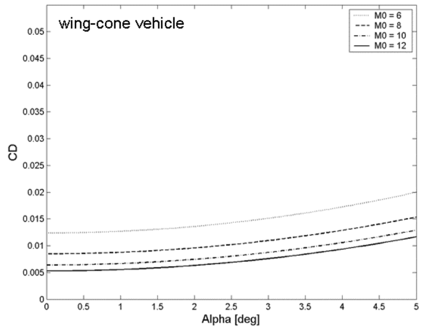

Figure 3 – NASA WCV C_D

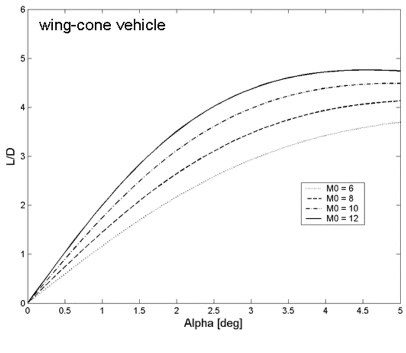

Figure 4 – NASA WCV L/D

Trajectory Simulation

CADAC [7] is a set of FORTRAN programs used to calculate vehicle trajectories based on the vehicle aerodynamic data and engine characteristics. As it is setup for this work, the user inputs an angle-of-attack profile from which CADAC determines the forces on the vehicle, propulsion system behaviour and resulting flight trajectory. In [6] the trajectories were manually optimised, which refers to choosing an angle-of-attack profile to obtain the highest altitude and Mach number at scramjet shutoff. The process is one of trial and error, qualitatively observing the response in Mach number and altitude based on changing angles-of-attack i.e. it is not automated. The main constraint on the optimisation is to keep the dynamic pressure at an acceptable level. In [6] this meant keeping dynamic pressure constant at 50kPa. In the current work, both the case where dynamic pressure is maintained at 50kPa and that in which dynamic pressure is allowed to fall to a lower value are investigated. The former allows for direct comparison with Weidner's results, while the latter explores the benefits of oxygen enrichment in the high altitude regime. At present no other parameters are optimised.

Propulsion Module

The propulsion module used for this study follows the form outline in [5], and was developed from the calculated performance of a fixed geometry, hydrogen fuelled, REST scramjet engine that had a design point of M_0 = 12.0, but remained operational down to M_0 = 6.0. This engine will be referred to here as the RESTM12 scramjet and is considered to be a near-term configuration that could be envisaged to fly within the next 5-10 years.

During a trajectory calculation, CADAC makes calls to the propulsion module to obtain the specific thrust, specific impulse, and equivalence ratio of the engine for a particular flight velocity, angle-of-attack and altitude. The RESTM12 scramjet was designed to operate at $q_0 \sim 50$ kPa in conjunction with a vehicle fore-body compression equivalent to that generated by a 6^o wedge. Analysis of the WCV vehicle fore-body over the Mach 6-12 flight regime indicated that at $\alpha = 2^o$ it generates a similar pre-compression. The engine was therefore installed on the vehicle so that its thrust vector was parallel with the velocity vector when the vehicle was at $\alpha = 2^o$. The operational angle-of-attack range for the engine was assumed to be +/- 3 deg. about the nominal, so that the angle-of-attack limits for the vehicle were set to $\alpha = -1^o$ and $+5^o$.

Two different propulsion modules were used in this study; (1) gaseous hydrogen fuel only, and (2) gaseous hydrogen fuel with oxygen enrichment at addition% = 20. The databases for both modules were created for the RESTM12 flowpath using the compression, combustion and nozzle expansion models described [5]. These were based on calculations performed for M_0 = 6.0, 8.0, 10.0 12.0 and 14, at vehicle α = -2.0, 0.0,+2.0, +4.0 and +6.0 degrees, and q_0 = 50 kPa. For module (1), all calculations were performed with $\phi = 1.0$, except for the M_0 = 6.0 calculations, where the engine reached its operability limit at $\phi < 1.0$. Module (2) was identical to (1), except that at $M_0 > 10$ oxygen enrichment was added and fuel equivalence ratio was increase to $\phi = 1.2$. Both modules included calculations of engine performance at over-sped conditions up to M_0 = 14. Figure 5 shows contour plots of specific thrust and specific impulse for module (2).

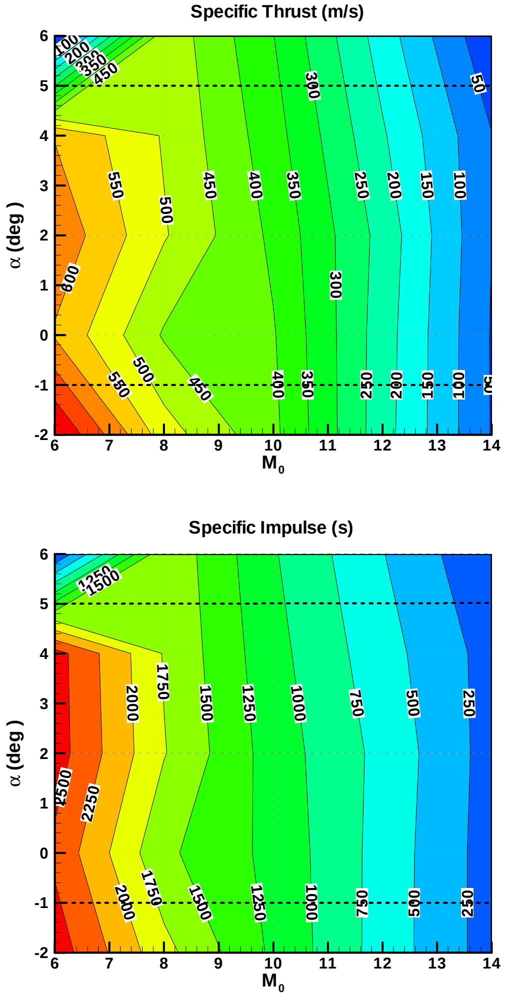

Figure 5 - Contour plots of specific thrust and specific impulse with oxygen enrichment

The calculations used in the database were performed for a single engine with a capture width, w_{cap} = 0.15 m; i.e. at wind-tunnel model scale. It was assumed that the propulsion parameters calculated in this way can be conservatively used for larger engines. A lower limit of q_0 = 30 kPa was placed on the use of module (1) due to kinetic limitations related to low pressures entering the combustor. For module (2) this limitation was lowered to q_0 = 10 kPa, with the assumption that the oxygen enrichment will establish robust combustion even at low dynamic pressure. Three RESTM12 scramjet modules were used for the trajectory calculations discussed in the next section, each with a width of w_{cap} = 0.76 m. This scale allowed smooth integration with the 16.33 m length WCV vehicle.

Results & Discussion – LEO Trajectories

Prior to discussing the trajectories obtained using oxygen enrichment, a baseline un-enriched trajectory is presented. The CADAC thrust module used by Weidner was first adjusted to more accurately reflect the engine performance in over-sped cases, as described in the previous section. The highest performing trajectory calculated using this updated propulsion system description is shown in Figure 6. Figure 6(a) shows plots of the change of Mach number, altitude and dynamic pressure throughout the flight. Figure 6(b) shows plots of the propulsion system thrust and the vehicle lift and drag. Dynamic pressure was maintained near q = 50kPa, for comparison with Weidner's results. However, the flight time was extended such that all 800kg of fuel were consumed. In the end, the scramjet stage was able to reach an altitude of 35.9km at M = 12.19 after 445 seconds of flight. This is a more favourable result than that of Weidner [6], however the use of oxygen enrichment should further improve the outcome.

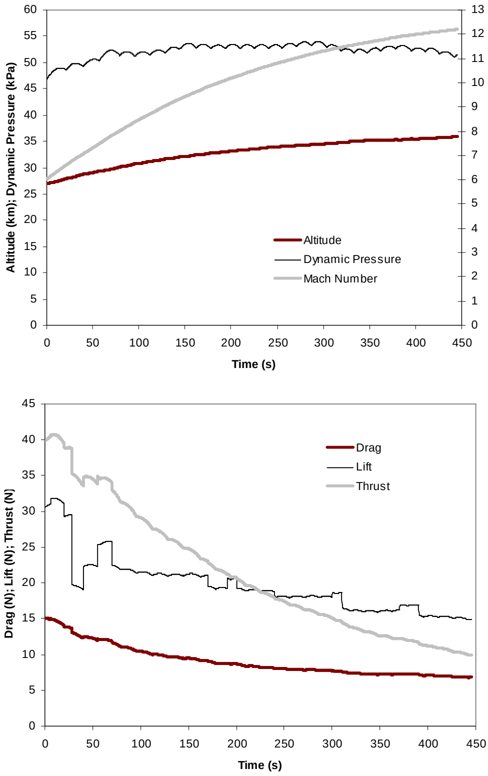

Figure 6 – Un-enriched scramjet baseline trajectory results

As described in the previous section, enrichment is applied and incorporated into the curve fits for Mach 10, 12 and 14. As such, up until approximately M = 8-9 the vehicle will respond to changing angles-of-attack in much the same way as for the un-enriched calculations. Using the previous baseline trajectory as a starting point, the angle-of-attack profile was altered and manually optimised for the enriched scramjet. Dynamic pressure is again maintained near 50kPa. As shown in Figure 7, enrichment did offer some improvement to the un-enriched result. The enriched scramjet climbed to h = 36.12km and M = 12.45 after 400 seconds of operation.

Though this is an improvement from the un-enriched case, the real benefit of oxygen enrichment can be seen when the vehicle is flown at higher altitudes and thus lower dynamic pressure. This case was also simulated, and the results are shown in Figure 8. Dynamic pressure was allowed to fall to a minimum of 25kPa once enrichment was turned on i.e. for M > 10. In this case the scramjet achieved a final altitude of 40.7km and Mach 12.23 after 525 seconds of operation. The vehicle was able to climb nearly 50% higher than in the un-enriched case and still reach a Mach number greater than 12.

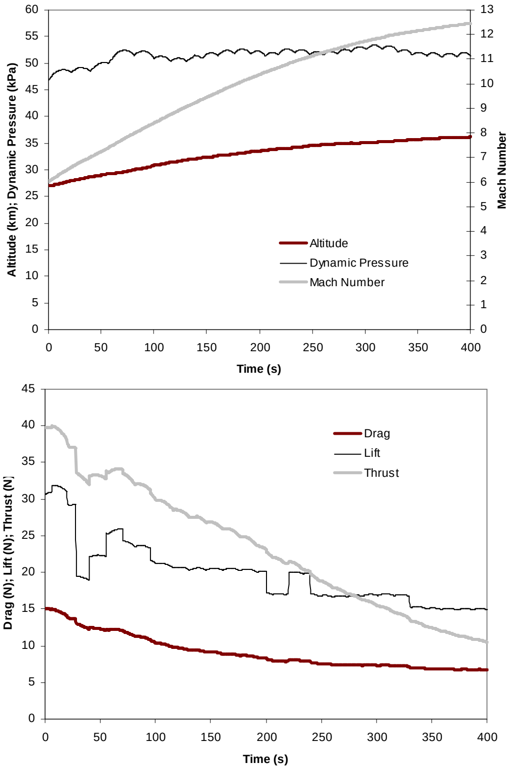

Figure 7 –Enriched scramjet trajectory results – constant dynamic pressure maintained

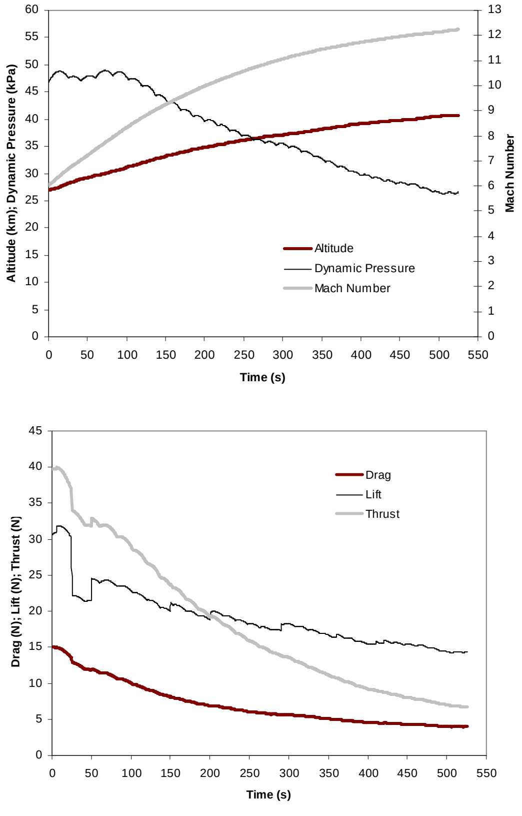

Figure 8 –Enriched scramjet trajectory results – dynamic pressure allowed to decrease

Conclusions

This work investigates the effects of oxygen enrichment on LEO trajectories for a three-stage rocket-scramjet-rocket wing-cone vehicle. In [6] Weidner found a manually optimised trajectory which took the vehicle from Mach 6 and an altitude of 27km to Mach 11.8 and an altitude of 35.5km before scramjet shutoff. This trajectory is improved by applying an updated thrust module which better captures engine behaviour in over-sped situations. Starting with this second trajectory as a baseline, oxygen enrichment is applied at high Mach numbers, where previously thrust fell off significantly, in order to continue to accelerate and gain altitude during this stage of the flight.

For addition% = 20 applied for Mach numbers greater than 10, the scramjet vehicle was able to accelerate beyond Mach 12 to a final shutoff value of Mach 12.23 at an altitude of 40.7km. The scramjet stage operated for 525 seconds and consumed all of its 800kg of fuel.

This preliminary work shows that oxygen enrichment has the potential to extend the upper range of scramjet operation, which in the context of a multi-stage access-to-space vehicle results in a delay in the onset of the final rocket stage. Since the enriched scramjet is potentially more efficient than a typical liquid fuelled rocket, the use of enrichment can increase the payload mass fraction, and further reduce the costs associated with access-to-space missions.

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