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The choice of propellants: a similarity analysis of scramjet second stages

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Scramjet-powered vehicles with similar shapes and the same second stage trajectory to orbit are used to establish relationships between the vehicle volume, the vehicle launch mass and the payload mass. It is shown that increasing the fuel density or the payload density can increase the payload mass, while simultaneously decreasing the vehicle launch mass. The maximum payload mass without a volume constraint is found to be half the dry mass. Practical volume constraints are shown to reduce this fraction.

To increase the scramjet thrust, additional propellant is often injected into the scramjet flow. It is shown here that for a hydrogen-fuelled vehicle, replacing this additional hydrogen with neon or with a hydrogen–oxygen mixture can significantly increase the payload and decrease the launch mass. It is shown also, for less rigorous assumptions, that replacing the scramjet hydrogen fuel with a hydrocarbon fuel can have the same effect, such that a vehicle to place a given payload in orbit can be both smaller and less costly.

Keywords: hypersonic vehicle; air-breathing orbiter; scramjet propellants; orbiter scaling; orbiter size variation

1. Introduction

For vehicles that are designed to put a payload into orbit, the mass and volume of the fuel is of critical importance (Hardy 1993; Weingartner 1993; Weinreich *et al.* 1993; Ardema *et al.* 1995). There is a strong incentive to reduce the liquid oxygen (LOX) propellant mass by using an air-breathing system for part of the trajectory and to reduce the fuel volume by using fuels that are denser than liquid hydrogen (LH2). Some studies (Hardy *et al.* 1993; Weinreich *et al.* 1993; Ardema *et al.* 1995) of scramjet-powered vehicles have been made, which show that careful integration of the scramjet into the design is necessary to obtain a worthwhile payload. Here we study more generally the relationship between vehicle volume, payload and launch mass, and suggest ways of improving the performance of scramjet-powered vehicles.

The rationale for using LH2 as fuel for a rocket or scramjet rests with its high specific impulse and its potential for cooling parts of the vehicle. However, the larger engine weight of the scramjet makes it desirable to increase the scramjet thrust by adding hydrogen to the engine flow beyond the stoichiometric burning ratio, or alternatively, in some cases to add inert gases to the flow (Rudakov & Krjutchenko 1990). Hydrocarbons can be expected to provide sufficient cooling up to Mach numbers in excess of 10, giving the potential to replace the stoichiometric LH2 with a hydrocarbon for these Mach numbers. It is then unclear which is the most suitable propellant or mixture of propellants for the vehicle to maximize the payload, or alternatively to reduce the vehicle size and cost.

The performance of different propellants can only be fully assessed by considering their effects not only on the engine thrust, but also on the aerodynamics and structure of the vehicle. Here we concentrate on the aerodynamics and the structure to provide a measure of the potential gains available, and to provide a framework against which the performance of the different propellants for the engine can be judged. The more difficult problem of assessing engine efficiency is not attempted here, but typical values are taken from the literature to enable us to address the important problem of how and whether other fuels may be preferable to LH2 for scramjets.

During the flight to orbit the vehicle will experience a wide range of aerodynamic conditions. In particular, during the latter stages of the flight as orbital conditions are approached, high Mach numbers and low Reynolds numbers will be experienced. However, for the scramjet phase of the flight the maximum atmospheric height is limited by the need of the intake to capture sufficient air, which requires typically a dynamic pressure of *ca.* 70 kPa. At Mach 10 this translates into an atmospheric height of *ca.* 30 km and a Reynolds number of about 10^7 per metre. Thus, low-Reynolds-number flight is not expected during scramjet operation and will be confined to the final rocket-powered phase of the flight, where the aerodynamics are less important as the rocket thrust must be expected to be large compared with the vehicle drag.

The aim of the analysis is to increase the payload mass to orbit for a given launch mass, or alternatively, for a given payload, to reduce the size and/or launch mass of the vehicle. Fundamental parameters of the analysis are a volume ratio and a mass ratio for the vehicle. These are taken to be the payload-mass/dry-mass ratio (r_{m}) and the payload-bay-volume/fuel-tank-volume ratio (r_{v}). Many of the results can be quoted simply in terms of these ratios. There can be uncertainty as to which items represent the payload and which represent the vehicle dry mass. This difficulty is discussed in § 3, and care needs to be taken to ensure valid definitions are used.

2. Similar trajectory vehicles

The method of analysis is to study vehicles that have identical trajectories to orbit. This is either the whole trajectory or the trajectory after some reference condition (e.g. after second-stage launch) where the velocity and altitude are the same. Suppose we have a vehicle with an optimum trajectory to orbit from some reference condition, then a requirement for another vehicle to have the same trajectory is that the vehicle acceleration after the reference condition is the same as the reference vehicle and that it follows the same path. The vehicle acceleration depends on the vehicle thrust minus the drag over the vehicle mass, and hence this must be the same for both vehicles throughout the time of the matching flight.

Suppose the (external) shape of the second vehicle is similar to the reference vehicle but is scaled by a factor l in all directions. Then the volume of the vehicle varies as l^3 and the surface area as l^2. For moderate changes in l the lift and drag coefficients will be very nearly constant, because changes in the friction-drag coefficient will be small. For example, a typical variation of the friction-drag coefficient is given by that of turbulent flow over a flat plate, for which the friction-drag coefficient varies approximately as the minus one-sixth power of the length. In this case an increase of 10% in the length will give a one-third increase in the vehicle volume but only slightly over 1% change in the turbulent friction-drag coefficient. The lift and pressure-drag coefficients remain largely unaffected. There could be some increase in the boundary-layer-induced pressure drag at low Reynolds numbers as the vehicle goes into orbit during the final rocket propelled phase of the flight, but by this time the vehicle drag is small and is greatly exceeded by the rocket thrust. Thus the variation in the integrated drag coefficient must be expected to be well under 1% even for a volume change as large as $\frac{1}{3}$, and the lift and the drag may be taken to vary effectively as l^2. The intake capture area will also vary as l^2; hence if we assume a fuel flow that varies as l^2 to maintain the same scramjet fuel-to-air ratio, then the thrust from the engine must be expected to vary as l^2 also (i.e. the specific thrust is constant). Thus to obtain the same acceleration for this class of vehicles, the vehicle mass throughout the flight (including the initial or launch mass m_t) is also required to vary as l^2.

We also require that the vertical acceleration matches the difference in the lift and weight of the vehicle throughout the flight, including centrifugal effects. As the lift and vehicle mass both vary as l^2, the wing loading will be constant and the vertical acceleration of the scaled vehicle will be the same as that of the reference vehicle, as required.

There could, however, be some problems with vehicle cooling using the fuel flow. The fuel flow varies as l^2, but for some areas of cooling, the required cooling varies linearly with l. Thus the cooling of smaller vehicles may be more difficult. This potential complication is ignored here.

3. Vehicle mass analysis

The vehicle mass is divided into the vehicle dry mass, the payload, the scramjet fuel (including any additive propellants such as oxygen or neon) and the rocket propellants, i.e.

$$m_\mathrm{t} = m_\mathrm{dry} + m_\mathrm{p} + m_\mathrm{s\,fuel} + m_\mathrm{r\,prop}. \tag{3.1}$$

For the case where the vehicle is powered only by a rocket, the scramjet fuel mass $m_\mathrm{s\,fuel}$ will be zero. We have shown that for the vehicle to maintain the same trajectory the vehicle mass and the scramjet fuel rate of flow vary as l^2. For constant rocket-engine efficiency the rocket propellant mass will scale as the total vehicle mass. Hence we have not only that the total mass, but also the various components of vehicle mass, vary as l^2. That is

$$\frac{m_\mathrm{t}}{m_\mathrm{t0}} = \frac{m_\mathrm{s\,fuel}}{m_\mathrm{s\,fuel0}} = \frac{m_\mathrm{r\,prop}}{m_\mathrm{r\,prop0}} = \frac{m_\mathrm{dry} + m_\mathrm{p}}{m_\mathrm{dry0} + m_\mathrm{p0}} = l^2. \tag{3.2}$$

This equation holds throughout the flight to orbit, but of most interest are the launch conditions, and generally we interpret the quantities as referring to launch conditions, unless otherwise stated.

To separate the payload and dry mass in equation (3.2), we need to assess how the dry mass will change with the vehicle scaling. The scaled vehicle retains the same shape and wing loading as the reference vehicle; hence the length of the structural elements can vary linearly with the vehicle length, and the structure mass part of the dry mass will then vary as l^3. There may be other components of the dry mass that vary in a different manner with the vehicle size, so that the dry mass is more generally expressed as a polynomial in l, i.e.

$$\text{dry mass} = a_0 + a_1 l + a_2 l^2 + a_3 l^3 + \cdots \tag{3.3}$$

with the major coefficient expected to be a_3. The a_0 coefficient represents components that do not change with vehicle length (e.g. the crew members (if any), their cabin and the control system computers) and a_2 represents components that scale as l^2 (e.g. tank insulation). The other coefficients (a_1, a_4, etc.) are assumed to be small throughout and are best gathered together with the a_3 term to give a term of form l^n where n is close to 3. Often the a_0 and a_2 terms are also sufficiently small to be included with the l^n coefficient, giving

$$\frac{m_{\mathrm{dry}}}{m_{\mathrm{dry0}}} = l^n. \tag{3.4}$$

If the a_0 and a_2 coefficients are larger, they are included separately in the analysis by careful redefinition of the dry mass and payload. To accommodate the a_2 term, the dry mass and the total mass in equation (3.1) are defined to be the total of the masses without this a_2 term, that is without the insulation mass and any other components of the dry mass which vary as l^2. Because the total mass varies as l^2, removing this mass from consideration in the total mass and dry mass terms makes no difference to the analysis. The accommodation of the a_0 term is straightforward because it does not give any change in mass on scaling, so a_0 can be included with the payload, again without altering the analysis. Thus we have as definitions of $m_{\mathrm{t}}, m_{\mathrm{dry}}$ and m_{p}

$$m_{\mathrm{t}} = \text{total mass} - a_2 l^2, \tag{3.5}$$

$$m_{\mathrm{dry}} = \text{dry mass} - a_0 - a_2 l^2 = m_{\mathrm{dry0}} l^n, \tag{3.6}$$

$$m_{\mathrm{p}} = \text{payload mass} + a_0. \tag{3.7}$$

Substituting for m_{dry} in equation (3.2) and rearranging gives the payload mass as a function of the launch mass for a vehicle scaled in such a manner as to maintain the same trajectory to orbit, i.e.

$$\frac{m_{\mathrm{p}}}{m_{\mathrm{p0}}} = \frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}\left(1 + \frac{1}{r_{\mathrm{m0}}} - \frac{1}{r_{\mathrm{m0}}}\left(\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}\right)^{(n/2)-1}\right), \tag{3.8}$$

where r_{m0} is the payload mass over the dry mass for the reference vehicle (i.e. $m_{\mathrm{p0}}/m_{\mathrm{dry0}}$).

The variation of the payload with vehicle mass, as given by equation (3.8), is shown in figure 1 for the case $r_{\mathrm{m0}} = \frac{1}{3}$. The reference condition is indicated by the circled point at $m_{\mathrm{t}}/m_{\mathrm{t0}} = 1$, $m_{\mathrm{p}}/m_{\mathrm{p0}} = 1$. We see from the continuous curve showing $m_{\mathrm{p}}/m_{\mathrm{p0}}$ that as the vehicle launch mass falls the payload mass *increases* and reaches a maximum before declining with any further decrease in the launch mass.

An important parameter is the ratio of the payload mass to the vehicle mass (r_{m}). The change in r_{m} for the scaled configurations is shown by the stippled line in figure 1 to *increase steadily with reducing vehicle mass*. Any point on the payload curve could have been chosen as the reference configuration in our example, by taking the appropriate value of r_{m} as r_{m0}. The payload curve would then be the same as the curve shown with the appropriate scaling to the new reference point.

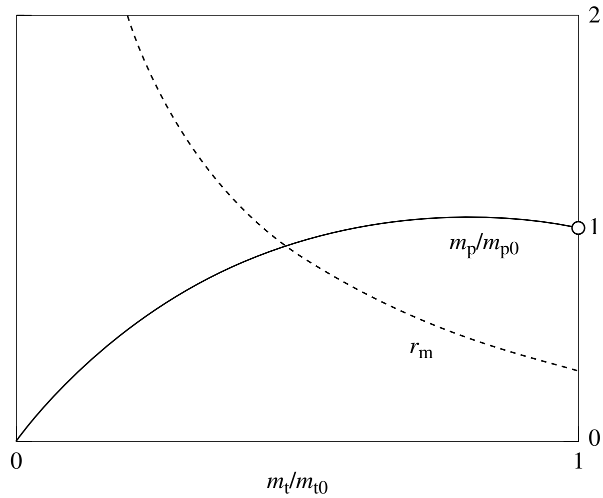

Figure 1. Payload variation with vehicle mass ($m_{p0} = \frac{1}{3}$).

Returning to the variation of payload mass as expressed by m_p/m_{p0}, we can find the rate of change of payload with vehicle mass by differentiating equation (3.8), to give

$$\frac{\mathrm{d}(m_p/m_{p0})}{\mathrm{d}(m_t/m_{t0})} = 1 + \frac{1}{r_{m0}} - \frac{n}{2r_{m0}}\left(\frac{m_t}{m_{t0}}\right)^{(n/2)-1}. \tag{3.9}$$

That is, near the reference vehicle condition (when $m_t/m_{t0} = 1$), the incremental change in payload with launch mass is given simply by $1+(1-\frac{1}{2}n)/r_{m0}$. For a payload mass less than the dry mass (i.e. $r_{m0} < 1$) and n close to 3, under the present type of scaling the payload will increase with decreasing vehicle mass until we obtain a maximum payload.

The condition for the payload to be a maximum is easily found from equation (3.9) by setting the gradient $(\mathrm{d}m_p/\mathrm{d}m_t)$ to zero, i.e.

$$\left(\frac{m_t}{m_{t0}}\right)_{\mathrm{opt}} = \left(\frac{2}{n}(1 + r_{m0})\right)^{2/(n-2)}. \tag{3.10}$$

Putting this value of m_t/m_{t0} in equation (3.8) gives

$$\left(\frac{m_p}{m_{p0}}\right)_{\max} = \left(1 - \frac{2}{n}\right)\left(\frac{1 + r_{m0}}{r_{m0}}\right)\left(\frac{2}{n}(1 + r_{m0})\right)^{2/(n-2)}, \tag{3.11}$$

which for $n = 3$ reduces to

$$\left(\frac{m_p}{m_{p0}}\right)_{\max} = \frac{4}{27}\frac{(1 + r_{m0})^3}{r_{m0}}. \tag{3.12}$$

That is, for a given vehicle with a known ratio of payload to dry mass, we can immediately assess the maximum increase in payload that can theoretically be achieved when the vehicle is scaled so as to maintain the same trajectory to orbit.

Before introducing the volume constraints necessary for a practical vehicle, we determine the ratio of the payload mass to the dry mass (r_{m}) for the maximum-payload vehicle. Any vehicle on the similarity curve may act as a reference vehicle. Suppose we choose the maximum-payload vehicle as reference. Then the left-hand side of equation (3.10) has value 1, and the value of r_{m} at the maximum from the right-hand side will be $\frac{1}{2}n - 1$. That is, when $n = 3$, the maximum payload is half of the dry weight. Whether this optimum ratio can be realized depends upon other vehicle constraints, as will be shown. Whatever other constraints are applied, however, the maximum-payload vehicle remains of interest, because it gives a measure of the payload foregone by applying these other constraints.

4. Vehicle volume analysis

With the linear scaling of the structure used here, the internal volume of the orbiter varies as l^3. The major volume components are the propellant volumes and the payload-bay volume, with most of the smaller components fitting into the spaces surrounding these structures. Thus we may assume that the sum of the payload-bay volume and the propellant-tank volume will vary as l^3. Note that the constraint is applied to the volume of the payload bay and not to its shape, with the result that the scaling can cause changes in the payload-bay and propellant-tank shapes. The tanks hold both the scramjet fuel and the rocket propellants. Thus for the volume of payload and propellant tanks we have

$$V_{\mathrm{t}} = V_{\mathrm{p}} + V_{\mathrm{tank}} = V_{\mathrm{p}} + V_{\mathrm{s\,fuel}} + V_{\mathrm{r\,prop}} \tag{4.1}$$

and the tank volume for the scaled vehicle is given by

$$V_{\mathrm{tank}} = V_{\mathrm{t0}} l^3 - V_{\mathrm{p}} \tag{4.2}$$

with the reference-tank volume, V_{tank0}, given when $l = 1$ by $V_{\mathrm{t0}} - V_{\mathrm{p0}}$. To maintain the same trajectory with the same type of fuel, we have seen that the fuel-mass flow scales as the vehicle mass and l^2, such that the required tank volume also scales as l^2. Then rearranging equation (4.2) and substituting for l we have

$$\frac{V_{\mathrm{p}}}{V_{\mathrm{p0}}} = \frac{1}{r_{\mathrm{v0}}} \frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}} \left((1 + r_{\mathrm{v0}}) \sqrt{\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}} - 1 \right), \tag{4.3}$$

where r_{v0} is the payload volume over the total propellant-tank volume of the reference vehicle, i.e.

$$r_{\mathrm{v0}} = V_{\mathrm{p0}} / V_{\mathrm{tank0}}. \tag{4.4}$$

We are now able to consider the variation of payload volume with payload mass: that is, the permissible payload density for the vehicle. In figure 2 the payload mass is again shown as a function of vehicle mass for $r_{\mathrm{m0}} = \frac{1}{3}$ by the continuous line. If for the reference vehicle, the payload-bay volume is a quarter, a half, three-quarters or equal to the fuel-tank volume, then the variation of $V_{\mathrm{p}}/V_{\mathrm{p0}}$ with $m_{\mathrm{t}}/m_{\mathrm{t0}}$ is shown by the stippled lines coming from the reference vehicle point at $(1, 1)$. We see that the payload volume decreases rapidly with vehicle mass until it becomes zero at some finite vehicle mass, which for $r_{\mathrm{v}} = \frac{1}{2}$ is just less than the maximum payload condition. Thus a major constraint preventing the reduction of the vehicle launch mass while

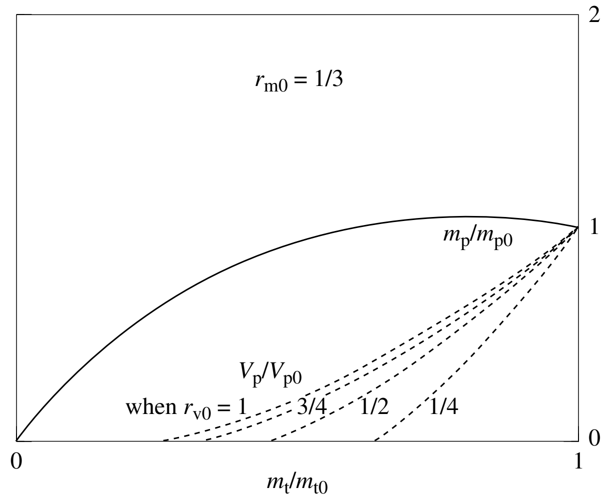

Figure 2. Payload-bay volume variation with vehicle mass for various r_{v0}.

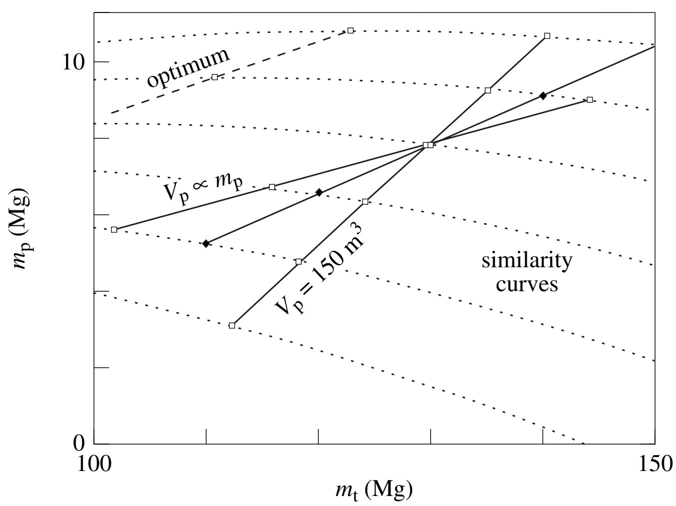

Figure 3. Variation of payload with vehicle mass for various payload-bay volume assumptions.

increasing the payload mass is the requirement to stow the fuel and payload. As payload volume and fuel volume are largely interchangeable, there is considerable incentive to use a denser fuel or payload, or to use a more efficient tank arrangement within the vehicle.

(*a*) *Multiple reference vehicles*

Suppose we have knowledge of more than one vehicle having different shapes and different trajectories to orbit. For example, the performance of a set of second-stage scramjet orbiters (L. H. Townend & R. A. East, personal communication) is shown by the black circles on figure 3 for vehicles of launch mass 110, 120, 130 and 140 Mg, respectively. Each of the reference vehicles has a different shape and trajectory, but we may reasonably interpolate between them to obtain a sequence of reference vehicles. Any of these reference vehicles can then be used by the similarity analysis to estimate the effects of varying the launch mass while keeping the trajectory, fuel type and vehicle shape (but not size) constant. By applying the similarity analysis to a sufficient number of these vehicles, the (payload versus vehicle mass) space of figure 3 can be carpeted with vehicles of known payload volume and tank volume. This carpet is shown on figure 3 by the many dotted curves plotted across the figure. The reference configuration in each case is obtained from the intersection of the dotted line with the interpolated line through the four reference vehicles given.

As the mass of the payload varies we can now assess the effect of different constraints on the payload volume. For example, we can keep the payload-bay volume constant, let the payload-bay size vary linearly with the vehicle size or let the payload-bay size vary linearly with the payload mass (referred to as the constant payload density condition). Suppose we consider the 130 Mg vehicle and keep the payload volume constant at 150 m^3. Then by picking off this value on the similarity curves from the other reference vehicles we can obtain the change in payload with vehicle mass. This line is shown on figure 3 as the steepest line, showing that as the vehicle mass reduces, the payload mass rapidly becomes smaller. Thus the potential for reducing the vehicle size is very limited under this constraint. Alternatively, if we permit the payload-bay volume to vary as the vehicle size, then we obtain the line through the reference values, indicating that this was a parameter in their selection. Perhaps the most reasonable criterion is to vary the payload-bay size with the payload mass. The variation of the payload with the vehicle mass is then given by the least steep of the three lines; but the payload mass still falls with the vehicle mass. This demonstrates the dominating influence the fuel and payload-bay volume requirements have on the payload mass. Each of these variations in payload-bay volume is so restrictive as to eliminate any indication of the increase in payload with decreasing vehicle mass which was found when there were no volume constraints applied. The maximum payload with no volume restrictions is shown by the dashed line in the top-left hand corner of figure 3.

The important variations in the payload mass and payload-bay volume obtained by scaling the vehicle to maintain the same trajectory are given by equations (3.8) and (4.3). From these equations we have shown that a reduction in the vehicle size (and mass) may increase the payload mass, but the payload-bay volume is rapidly reduced. It is important then to specify the highest practical payload 'density' for the vehicle, and to consider increasing the fuel density.

(*b*) *Fuel-density change*

Equation (4.3) and the subsequent results assume the vehicle uses the same fuel throughout the scaling. Suppose, however, we substitute another fuel, which is equivalent to the original fuel in that it gives the same thrust for the same mass flow, but that the fuel is denser. Then the ratio of the tank volumes required is given by

$$V_{\mathrm{tk}} = \frac{V_{\mathrm{s\,fuel0}}\rho_{\mathrm{s0}}/\rho_{\mathrm{s}} + V_{\mathrm{r\,prop0}}\rho_{\mathrm{r0}}/\rho_{\mathrm{r}}}{V_{\mathrm{s\,fuel0}} + V_{\mathrm{r\,prop0}}}, \tag{4.5}$$

where ρ_{s} and ρ_{r} are the new bulk scramjet fuel and rocket propellant densities. Then the value of V_{tank} for a scaled vehicle with the replaced fuel becomes $V_{\mathrm{tk}}V_{\mathrm{tank0}}l^2$, and the payload-bay volume is given similarly to equation (4.2) by

$$\frac{V_{\mathrm{p}}}{V_{\mathrm{p0}}} = \frac{1}{r_{\mathrm{v0}}}\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}\left((1+r_{\mathrm{v0}})\sqrt{\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}} - V_{\mathrm{tk}}\right). \tag{4.6}$$

Note that this equation gives the payload-volume variation for a denser fuel via V_{tk} and a vehicle size change via $m_{\mathrm{t}}/m_{\mathrm{t0}}$ where r_{v0} refers to the original reference vehicle. Assuming the same three constraints on the payload-bay volume, we consider first the constant payload density case, when $V_{\mathrm{p}}/V_{\mathrm{p0}} = m_{\mathrm{p}}/m_{\mathrm{p0}}$. Equating equations (3.8) and (4.6), with $n = 3$, gives the vehicle mass change with fuel density as

$$\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}} = \left(1 - \frac{r_{\mathrm{m0}}(1-V_{\mathrm{tk}})}{r_{\mathrm{v0}} + r_{\mathrm{v0}}r_{\mathrm{m0}} + r_{\mathrm{m0}}}\right)^2. \tag{4.7}$$

Substituting this value in equation (3.8) for payload mass gives

$$\frac{m_{\mathrm{p}}}{m_{\mathrm{p0}}} = \left(1 - \frac{r_{\mathrm{m0}}(1-V_{\mathrm{tk}})}{r_{\mathrm{v0}} + r_{\mathrm{v0}}r_{\mathrm{m0}} + r_{\mathrm{m0}}}\right)^2\left(1 + \frac{1-V_{\mathrm{tk}}}{r_{\mathrm{v0}} + r_{\mathrm{v0}}r_{\mathrm{m0}} + r_{\mathrm{m0}}}\right). \tag{4.8}$$

For the usual case where r_{v0} is less than $\frac{1}{2}$, equations (4.7) and (4.8) show that increasing the fuel density (so $V_{\mathrm{tk}} < 1$) both decreases the launch mass m_{t} and increases the payload mass m_{p}.

As an alternative constraint, let the payload-bay volume scale with the vehicle volume, such that r_{v} is constant and

$$V_{\mathrm{p}}/V_{\mathrm{p0}} = l^3 = (m_{\mathrm{t}}/m_{\mathrm{t0}})^{3/2}, \tag{4.9}$$

giving similarly

$$\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}} = V_{\mathrm{tk}}^2, \tag{4.10}$$

$$\frac{m_{\mathrm{p}}}{m_{\mathrm{p0}}} = V_{\mathrm{tk}}^2\left(1 + \frac{1}{r_{\mathrm{m0}}} - \frac{V_{\mathrm{tk}}}{r_{\mathrm{m0}}}\right). \tag{4.11}$$

Again, decreasing V_{tk} reduces m_{t} and increases m_{p} but at different rates to the constant payload density case.

Finally, consider the constant payload-bay volume case when $V_{\mathrm{p}}/V_{\mathrm{p0}} = 1$. The algebra is more complicated for this simplest constraint. Equation (4.6) becomes

$$r_{\mathrm{v0}} = \frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}\left((1+r_{\mathrm{v0}})\left(\frac{m_{\mathrm{t}}}{m_{\mathrm{t0}}}\right)^{1/2} - V_{\mathrm{tk}}\right), \tag{4.12}$$

which requires the solution of a cubic to give m_{t}, and it is most easily solved numerically.

These changes in the payload and launch mass with the fuel-tank capacity for the three payload-bay volume constraints are shown for a typical configuration in figure 4. The reference configuration is shown at the convergence of all the plots at point 1 on the right-hand axis, and is assumed to have $r_{\mathrm{m0}} = \frac{1}{3}$ and $r_{\mathrm{v0}} = \frac{1}{2}$. As the fuel density increases, the required tank capacity expressed by V_{tk} in equation (4.5) falls. In figure 4, as V_{tk} falls all three curves of payload mass rise initially and those for launch mass fall. The most rapid changes occur for the stippled lines, which represent

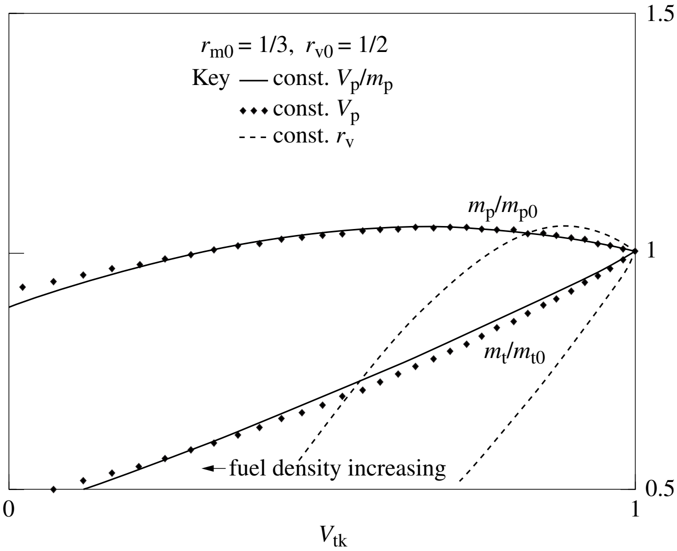

Figure 4. Payload and vehicle launch mass variation with fuel density.

the payload-bay volume changing with vehicle size. The more interesting constraints on constant payload-bay volume and constant payload density are shown by the large dots and the continuous lines, respectively. These still show an increasing payload and falling vehicle mass, but more slowly than for the case where the payload-bay volume changes with vehicle size. As expected, the maximum is equal for all three constraints and it is the same as the optimum payload without any volume constraints.

(*c*) *Fuel change near the reference conditions*

Of particular interest is the change in the payload near the reference condition. At the reference, the incremental change in the vehicle and payload masses in terms of the payload-mass/dry-weight ratio r_{m0} and the payload-volume/tank-volume ratio r_{v0}, can be obtained for the constant density payload constraint by differentiating equations (4.7) and (4.8) and setting V_{tk} equal to unity, i.e.

$$\left(\frac{\mathrm{d}m_t/m_{t0}}{\mathrm{d}V_{tk}}\right)_0 = \frac{2r_{m0}}{r_{v0} + r_{v0}r_{m0} + r_{m0}}, \tag{4.13}$$

$$\left(\frac{\mathrm{d}m_p/m_{p0}}{\mathrm{d}V_{tk}}\right)_0 = \frac{2r_{m0} - 1}{r_{v0} + r_{v0}r_{m0} + r_{m0}}. \tag{4.14}$$

Thus when the payload mass is less than half of the dry mass, the payload will initially increase as the fuel-tank volume decreases. For example, taking typical values of $r_{m0} = \frac{1}{3}$ and $r_{v0} = \frac{1}{2}$, from equations (4.13) and (4.14) a 1% increase in fuel density (equivalent to a 1% decrease in tank volume) will give a $\frac{1}{2}$% increase in payload and a 1% decrease in vehicle mass. Similar results can be derived for the other two constraints. The variation of the vehicle mass and payload with tank size for the reference vehicle with payload-bay volume proportional to vehicle volume (i.e.

$r_v = \text{const.}$) is

$$\left(\frac{\mathrm{d}m_t/m_{t0}}{\mathrm{d}V_{tk}}\right)_0 = 2, \tag{4.15}$$

$$\left(\frac{\mathrm{d}m_p/m_{p0}}{\mathrm{d}V_{tk}}\right)_0 = \frac{2r_{m0}-1}{r_{m0}}. \tag{4.16}$$

Similarly, for the constant payload-bay volume,

$$\left(\frac{\mathrm{d}m_t/m_{t0}}{\mathrm{d}V_{tk}}\right)_0 = \frac{2}{1+3r_{v0}}, \tag{4.17}$$

$$\left(\frac{\mathrm{d}m_p/m_{p0}}{\mathrm{d}V_{tk}}\right)_0 = \frac{2r_{m0}-1}{r_{m0}(1+3r_{v0})}. \tag{4.18}$$

For the constant payload-bay volume when $r_{m0} = \frac{1}{3}$ and $r_{v0} = \frac{1}{2}$, equations (4.17) and (4.18) give values of 1.2 and -0.6, respectively; values that are 20% larger than the constant density payload case. The increase in the payload mass is slightly greater for this latter case, because the increase does not require a bigger payload bay, which in the previous case absorbed some of the released tank volume.

For all three volume constraints, *increasing the fuel density has the double advantage of increasing the payload mass and decreasing the launch mass*, but the amount of change in these masses depends on the constraints applied. However, the largest changes in the payload and launch mass for a given change in the fuel density are given by equations (4.15) and (4.16) for r_v constant.

In the analysis above, changing the fuel density caused both the launch mass and the payload mass to change. To assess the potential payload changes for a *constant* launch mass, we need to know the rate of change of payload with launch mass for an unconstrained vehicle, such as the example shown in figure 3. Using the values from figure 3, the gradient $\mathrm{d}m_p/\mathrm{d}m_t$ has values 0.241, 0.136 and 0.08 for constant V_p, r_v and V_p/m_p, respectively. Then a 1% increase in fuel density gives 5.3%, 6.7% and 1.8% increases in payload for constant V_p, r_v and V_p/m_p. We see that because of the greater sensitivity of the payload to the launch mass for the constant payload-bay volume case, the payload change with fuel volume is large for this case compared with the constant payload density case, again demonstrating the importance of payload density.

(*d*) *Scramjet fuel examples*

As a demonstration of the implications of the analysis, we use the data for different density injectants used as additional propellants in Rudakov & Krjutchenko (1990). The thrust from the engine is increased by adding extra propellant to a stoichiometric hydrogen scramjet, with the parameter B being the ratio of the total propellant mass flow rate to that of stoichiometric hydrogen. The parameter B, as used in Rudakov & Krjutchenko (1990) needs careful definition for various cases.

(i) For the hydrogen-only scramjet, $B = 1$ means air and hydrogen are in stoichiometric proportions. $B = 1.3$ means that hydrogen is supplied at a mass rate 30% greater than the stoichiometric value.

Table 1. *Inert gases and other data (after Rudakov & Krjutchenko 1990)*

substance		temperature (K)	density (kg m^{-3}) (tank conditions)	flow ratio r ($M = 10$)
hydrogen	H_2	20	71	1.0
helium	He	4	129	1.0
neon	Ne	27	1206	2.0
argon	Ar	87	1393	2.4
krypton	Kr	120	2418	
xenon	Xe	160	2980	2.7
oxygen	O_2	90	1135	

Table 2. *Stoichiometric combustion of organic liquids*

substance (C_nH_m)		stoichiom. mass ratio	combustion heat (MJ kg^{-1})	density (kg m^{-3})
hydrogen	(LH_2)	1.0	120	76
methane	(CH_4)	2.0	101	300
acetylene	(C_2H_2)	2.6	126	618
JP-7	($C_{12.5}H_{26}$)	2.32	—	793

(ii) For the hydrogen–neon scramjet, $B = 1.9$ means air and hydrogen are in stoichiometric proportions and the neon mass flow is 0.9 times the mass flow of hydrogen.

(iii) For the hydrogen scramjet with oxygen injection, the oxygen is injected in such a way that the hydrogen–air–oxygen mixture is stoichiometric. Thus $B = 2.5$ means that in addition to hydrogen injected at a mass flow to give a stoichiometric mixture with the air, *extra* hydrogen is injected together with whatever oxygen would permit complete combustion of that extra hydrogen, with the total mass flow of injected oxygen and *extra* hydrogen being 1.5 times the mass flow of hydrogen already giving stoichiometric proportions with the air.

In Rudakov & Krjutchenko (1990) the thrust is given for several flow additives, including a hydrogen–oxygen mixture and inert gases, such as helium and neon. The inert gases are studied because of their minimal real gas losses and because some of them can still offer low molecular weight. The thrust increase for helium and hydrogen–oxygen addition at the same mass flow is found by Rudakov & Krjutchenko (1990) to be very nearly the same as that for hydrogen for values of B up to 2.5. For the range of additive mass flow when helium and hydrogen–oxygen give the same thrust as hydrogen, the effect of these additives on the vehicle can be analysed using equations (4.7)–(4.12). Details of these additives are given in table 1. To retain consistency with the results of Rudakov & Krjutchenko (1990), the density of LH2 in table 1 is the boiling-point density at 1 atmosphere pressure. (In table 2, a higher tank density of 76 kg m^{-3} is used (Heiser & Pratt 1994), which is close to the triple-point density (National Research Council 1933).) From table 1, the density of liquid helium is nearly twice that of LH2, whereas the hydrogen–oxygen mixture for complete

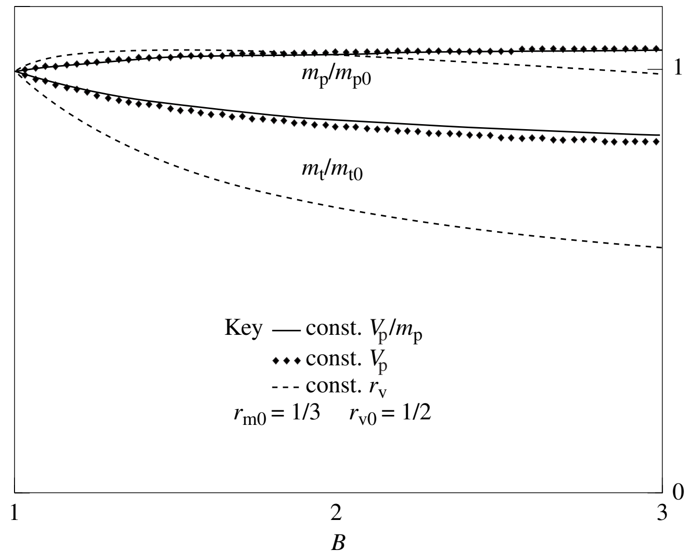

Figure 5. Payload and launch mass ratio for helium additive compared with LH2.

combustion has a density about six times that of hydrogen. For a typical vehicle the scramjet LH2 fuel tankage represents *ca.* 80% of the total tankage, so that V_{tk} from equation (4.5) varies between 1 and 0.64 for liquid helium and between 1 and 0.33 for LH2–LOX, depending on the value of B. Substituting these values in equations (4.7)–(4.12), with $r_{m0} = \frac{1}{3}$ and $r_{v0} = \frac{1}{2}$, gives the payload and vehicle launch mass changes for these additives compared with LH2. The ratios of the payload and launch masses from these equations are shown in figures 5 and 6, for liquid helium and LH2–LOX, respectively. The ratios are plotted against values of B from 1 (representing no additives) to 3 (when the additives are twice the mass flow of stoichiometric hydrogen). There is a small increase in the payload (*ca.* 5% maximum) and a larger decrease in the launch mass. That is, for constant V_p or V_p/m_p, a liquid helium additive equal to the stoichiometric LH2 mass flow (i.e. $B = 2$) gives a launch mass *ca.* 12% below that of the equivalent LH2 additive and an LH2–LOX mixture gives a 20% reduction. To compare payload increases at constant launch mass, a value of $\mathrm{d}m_p/\mathrm{d}m_t$ is required and can again be expected to show that the change for constant payload-bay volume is significantly greater than for constant payload density.

It is clear from the above analysis that the density of the additives injected into the flow is important. Neon, which has a greater density than helium or LH2–LOX, is worthy of investigation. However, the analysis of this section is not applicable, because the thrust from adding neon to the flow is less than that from adding an equal mass flow of hydrogen, which is a requirement of the analysis. The addition of neon and other inert gases, and the prospects of hydrocarbons as fuels, is considered in the following section.

5. Generalized scramjet fuel analysis

The assumptions made previously have enabled reliable predictions to be made of the variation in the payload and vehicle launch mass with vehicle volume, for a restricted

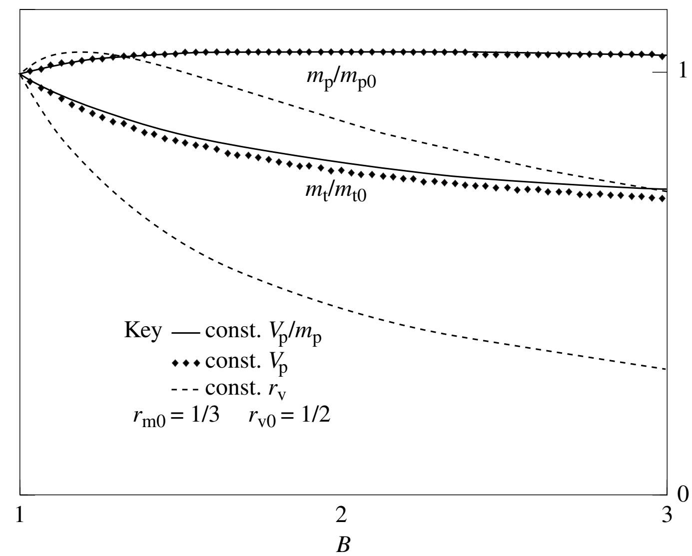

Figure 6. Payload and launch mass ratio for LH2–LOX additive compared with LH2.

range of vehicles that have similar shapes and the same trajectory to orbit. When a change in the fuel requires a different mass flow rate to obtain the same thrust the previous assumptions cannot be fully satisfied. However, it is important to try to assess whether LH2 is the best fuel, even though this may require the use of more approximate assumptions. Here we try to give an indication of which of the likely alternative fuels to LH2 are worth further investigation. More specifically, we try to assess whether using inert fuel additives or hydrocarbons for part of the fuel, instead of LH2, is beneficial in increasing the payload for a given launch mass.

As a means of assessing the relative merits of different fuels, consider, first, two reference vehicles of the same size and shape, of which one uses LH2 and the other uses some alternative fuel or fuel additive with a different mass flow rate to give the same vehicle thrust. We anticipate that this second vehicle will have some spare tankage from the use of a denser fuel, which will enable vehicle size to be reduced in the manner of the previous analysis. The mass flow rate of the alternative fuel, which is necessary to obtain the same thrust as the LH2 used in the first vehicle, will, in general, be a complicated function of the vehicle Mach number and the particular engine characteristics. If, as before, the replacement fuel additive is an inert gas that is used to replace the additional LH2 fed to the scramjet in excess of that for a stoichiometric mixture, then representative values of the relative mass flows can be obtained from Rudakov & Krjutchenko (1990). For example, at Mach 10 the required mass flow of various gases compared with LH2 varies from about the same rate for helium to 2.7 times the LH2 rate for xenon, as shown in table 1.

Alternatively, replacing the scramjet stoichiometric LH2 mass flow with a hydrocarbon, the required mass flow rate of the hydrocarbon for a stoichiometric mixture will vary from twice the LH2 rate (for methane) to about 2.3 times (for kerosene). Mass flow rates for these and a number of hydrocarbons are shown in table 2. Also shown is the approximate combustion heat and the relative density. We see that not only is there a significant increase in the fuel mass flow required to provide the same thrust, but also the combustion heat is typically 10–20% less; thus to give the same thrust, the mass flow may need to be further increased, depending on whether the greater nozzle mass flow compensates for the reduced combustion energy. This will depend on the engine characteristics, but the influence of the ratio r, which is the mass flow for the replacement fuel compared with LH2 mass flow to give the same thrust, can be assessed by considering a range of r from 2 to 3.

The extra mass of fuel to be carried will require increased thrust for the vehicle to maintain the same trajectory unless vehicle mass can be saved elsewhere. To estimate this extra thrust in the analysis would require more detailed assumptions about the engine performance (see, for example, Heiser & Pratt 1994), but this is beyond the scope of the present paper. However, when only a small quantity of LH2 fuel is replaced, and the substitute fuel is used immediately after second-stage launch, the extra thrust required to accelerate the extra fuel mass is vanishingly small (i.e. it is a second-order effect), and it may be ignored. Note that this approach cannot assess how much LH2 should be replaced, but it can indicate whether it is worth replacing *any* of the LH2 with an alternative fuel; i.e. for a range of vehicles we can assess the relative merits of alternative fuels, and obtain initial rates of payload increase for the new fuel.

The variation of vehicle mass and payload for a replacement fuel or additive with the same thrust for the same mass flow as the original fuel has already been obtained in the previous section under various payload-bay volume constraints. Suppose now that the replacement fuel (or fuel additive) mass flow is r times the original fuel (or fuel additive) mass flow for the same scramjet thrust. Then exchanging a small mass of the original fuel m_0, which has volume v_0 (equal to m_0/ρ_0), for a mass rm_0 of the replacement fuel of volume rm_0/ρ_1, the change in total vehicle mass and total tank capacity is

$$\Delta m = (r-1)m_0, \tag{5.1}$$

$$\Delta V_{\text{tank}} = (r\rho_0/\rho_1 - 1)v_0. \tag{5.2}$$

For the constant density payload vehicle, with the fuel replaced and the vehicle scaled so that the fuel volume matches the available fuel-tank volume, we have, from equation (4.13),

$$\frac{\Delta m_{\text{t}}}{m_{\text{t0}}} = \frac{2r_{\text{m0}}\Delta V_{\text{tk}}}{r_{\text{m0}} + r_{\text{m0}}r_{\text{v0}} + r_{\text{v0}}} + \frac{\Delta m}{m_{\text{t0}}}, \tag{5.3}$$

where the change in tank volume term ΔV_{tk} is given by

$$\Delta V_{\text{tk}} = \frac{\Delta V_{\text{tank}}}{V_{\text{tank0}}} = \frac{(r\rho_0/\rho_1 - 1)v_0}{V_{\text{tank0}}}. \tag{5.4}$$

Hence substituting for ΔV_{tk} and Δm in equation (5.3) gives

$$\frac{\Delta m_{\text{t}}/m_{\text{t0}}}{v_0/V_{\text{tank0}}} = \frac{2r_{\text{m0}}(r\rho_0/\rho_1 - 1)}{r_{\text{m0}} + r_{\text{m0}}r_{\text{v0}} + r_{\text{v0}}} + \frac{(r-1)\rho_0 V_{\text{tank0}}}{m_{\text{t0}}}. \tag{5.5}$$

Similarly, from equation (4.8) for the change in payload,

$$\frac{\Delta m_{\text{p}}/m_{\text{p0}}}{v_0/V_{\text{tank0}}} = \frac{(2r_{\text{m0}} - 1)(r\rho_0/\rho_1 - 1)}{r_{\text{m0}} + r_{\text{m0}}r_{\text{v0}} + r_{\text{v0}}}; \tag{5.6}$$

i.e. for a small fraction v_0/V_{tank0} of the fuel changed, the fractional changes in the total vehicle mass and payload mass are given by equations (5.5) and (5.6). The equivalent equations for the other constraints may be obtained in the same way from equations (4.15)–(4.18).

In figure 3, a typical variation of payload with vehicle mass is shown for vehicles where the fuel remains the same but the vehicle shape is unconstrained. Improved vehicle performance from a fuel change for these vehicles can be achieved if a vehicle, when scaled in the manner proposed here, has a payload and vehicle mass combination that lies to the left of or above the appropriate volume constraint line. The variation of m_{p} with m_{t} for the scaled vehicle is given from equations (5.5) and (5.6), or their equivalents for the other constraints, as

$$\frac{\mathrm{d}m_{\text{p}}/m_{\text{p0}}}{\mathrm{d}m_{\text{t}}/m_{\text{t0}}} = \frac{2r_{\text{m0}} - 1}{2r_{\text{m0}} - \varepsilon}, \tag{5.7}$$

where

$$\varepsilon = (r_{\text{m0}} + r_{\text{m0}}r_{\text{v0}} + r_{\text{v0}})\frac{r-1}{1 - r\rho_0/\rho_1}\frac{\rho_0 V_{\text{tank0}}}{m_{\text{t0}}}, \qquad \frac{V_{\text{p}}}{m_{\text{p}}} = \text{const.}, \tag{5.8}$$

$$= r_{\text{m0}}\frac{r-1}{1 - r\rho_0/\rho_1}\frac{\rho_0 V_{\text{tank0}}}{m_{\text{t0}}}, \qquad r_{\text{v}} = \text{const.}, \tag{5.9}$$

$$= (1 + 3r_{\text{v0}})r_{\text{m0}}\frac{r-1}{1 - r\rho_0/\rho_1}\frac{\rho_0 V_{\text{tank0}}}{m_{\text{t0}}}, \qquad V_{\text{p}} = \text{const.} \tag{5.10}$$

We see that ε depends on the multiplication of three terms. Only the first of these varies for the three different volume constraints. For $r_{\text{m0}} = \frac{1}{3}$ and $r_{\text{v0}} = \frac{1}{2}$, this first term has values of 1, $\frac{1}{3}$ and $\frac{5}{6}$, respectively. The second term depends only on the choice of replacement fuel, with the numerator giving the increase in the mass flow and the denominator the decrease in its volume. Note that when $r = 1$, the conditions are as described in the previous section, and for all constraints the gradient of equation (5.7) has value $1 - 1/2r_{\text{m0}}$. The final term is a reference-vehicle constant, which is the ratio of the mass of LH2 that would fill the total tank volume of the reference vehicle, divided by the reference-vehicle launch mass.

(*a*) *Inert-gas additives*

To demonstrate the effect of these fuel changes, consider first the substitution of the inert gases for the 'additional liquid hydrogen', i.e. when the LH2 replaced is the additional mass flow above the stoichiometric requirement for an LH2 scramjet. For the constant density payload case, substituting the values for different additives from table 1 in equations (5.5) and (5.6) gives the resulting incremental changes in vehicle mass and payload shown in figure 7*a* for a typical vehicle with $r_{\text{m0}} = \frac{1}{3}$, $r_{\text{v0}} = \frac{1}{2}$ and $m_{\text{t}}/V_{\text{tank}} = 500\ \text{kg m}^{-3}$. The LH2-fuelled reference vehicle is represented by the dot at the point $(0, 0)$. The substitution of helium and a hydrogen–oxygen mixture has been discussed in the previous section. These additives have the same fuel mass flow rate for the same thrust as LH2 (i.e. $r = 1$). Thus equation (5.7) with $\varepsilon = 0$ gives the lines of gradient $-\frac{1}{2}$ shown in figure 7; i.e. if for a small fraction f of the total tank volume of the reference vehicle the additional LH2 is replaced by helium (with the appropriate tank-size reduction), we see from the helium vector in figure 7*a* that

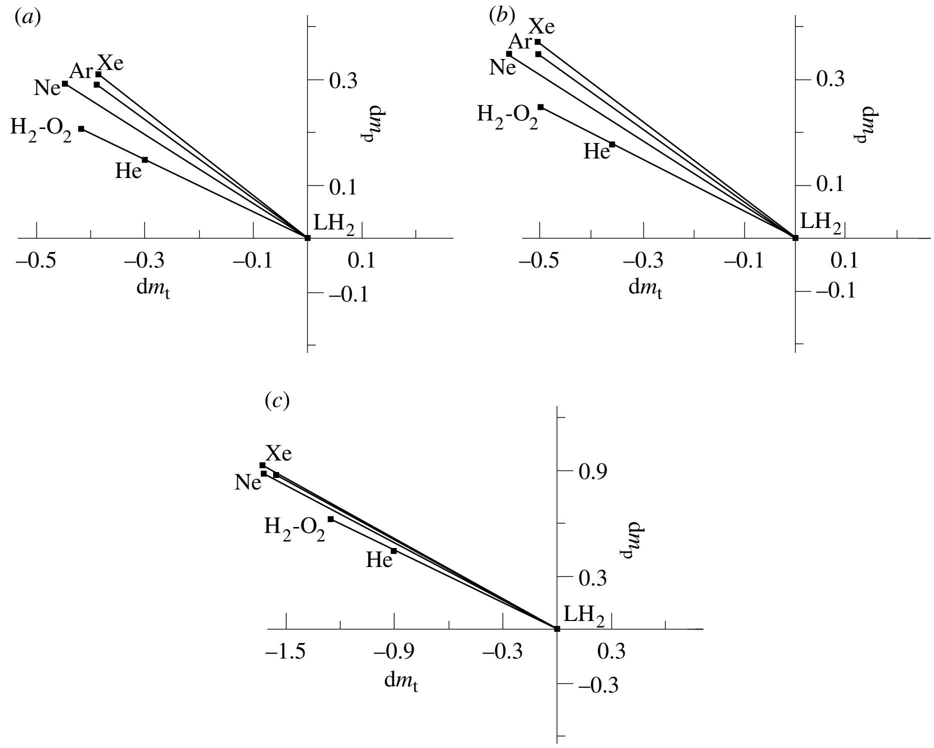

Figure 7. (*a*) Effect of fuel additives replacing LH2 for constant payload density. (*b*) Effect of fuel additives replacing LH2 for constant payload-bay volume. (*c*) Effect of fuel additives replacing LH2 for constant r_v ($r_{m0} = \frac{1}{3}$, $r_{v0} = \frac{1}{2}$, $m_t/V_{tank} = 500$ kg m^{-3}).

a reduction in the total vehicle mass of $0.3f$ and an increase in payload of $0.16f$ is achieved. For the hydrogen–oxygen combination, the changes in the vehicle and payload masses are both *ca.* 40% larger as was seen in the previous section. Using the present analysis other fuels may be compared with these results, but the changes are only accurate to order f^2.

The changes produced by replacing LH2 with the inert gases neon, argon and xenon are also shown in figure 7*a*. The changes for neon can be seen to be larger than for helium or LH2–LOX, even though the mass flow rate for the same thrust is double these previous additives. For a small fraction f of the original tankage volume replaced, the increase in the payload is about $0.3f$ and the decrease in the vehicle launch mass is about $0.45f$ for neon. The changes for argon and xenon can be seen in figure 7*a* to be similar, the main difference being a slightly smaller decrease in the launch mass. The change for krypton is not shown, but lies close to the argon and xenon values.

In figure 7*b* the changes for a constant payload-bay volume are shown to be similar in character to those of figure 7*a*, but slightly larger throughout. The constant r_v case of figure 7*c* is at a different scale to figure 7*a*, *b*, and shows changes that are about three times as large as the previous constraints. This larger change is due to the reduction in vehicle size being accompanied for this constraint by a proportionate reduction in the payload-bay volume.

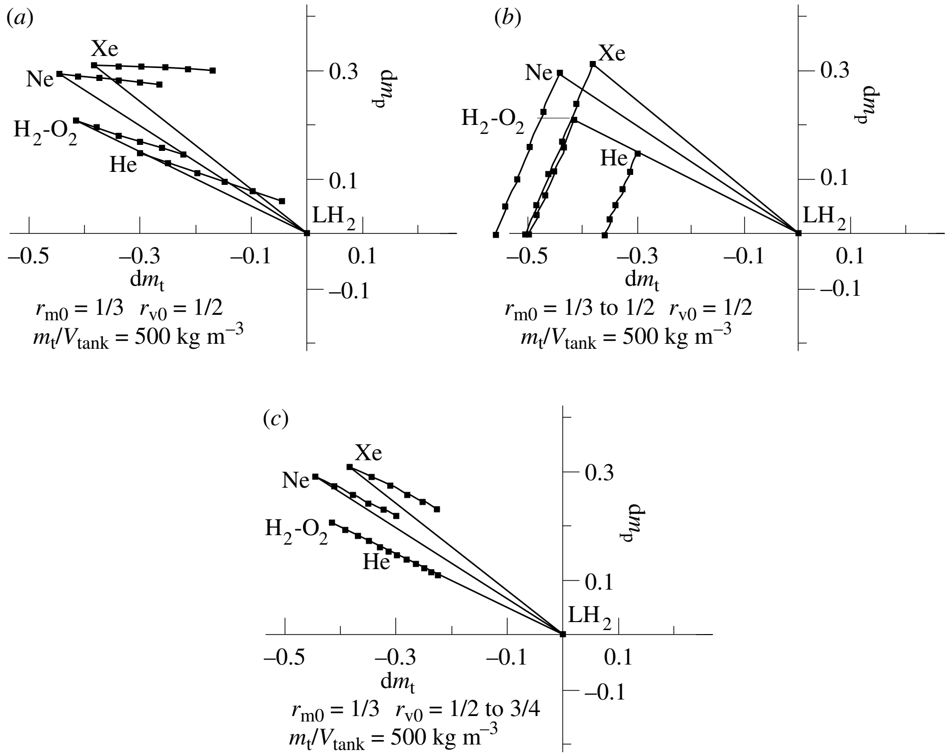

Figure 8. (*a*) Effect of increasing the thrust equivalent mass of the additive fuel in 10% steps. (*b*) Effect of increasing r_{m0} in 10% steps. (*c*) Effect of increasing r_{v0} in 10% steps.

Figure 7 shows that the use of the inert gases or LH2–LOX as additives instead of LH2 has the double advantage of both increasing the payload and decreasing the vehicle mass. The decrease in vehicle mass can also represent a further increase in the payload when $\mathrm{d}m_{\mathrm{p}}/\mathrm{d}m_{\mathrm{t}}$ is positive, as shown for example in figure 3.

(i) *Variation of fuel mass flow for equal thrust*

These encouraging results from fuel additives are based on approximate values of the equal thrust mass flow factor (r) as given in table 1, and thus it is important to assess the sensitivity of the results to changes in this parameter. In figure 8*a* the same vectors as in figure 7*a* are shown (minus the argon vector), to which are added results for increases in the mass of the additive required to obtain the same thrust. The lines emanating from the ends of the original vectors show the variation in the vertices of the vectors with increasing r, with the dots on the lines representing increases of 10%, 20%, 30%, 40% and 50% in r. We see that the payload increase remains largely unaffected, but the vehicle mass change is reduced by these increases in r. However, it is clear that the results are not particularly sensitive to the value of r. An error in r of order 10%, for example, will not significantly affect the conclusions, which remain: (1) the substitution of propellant additives that are denser than LH2 is beneficial; and (2) the potentially most promising additives are neon or LH2–LOX.

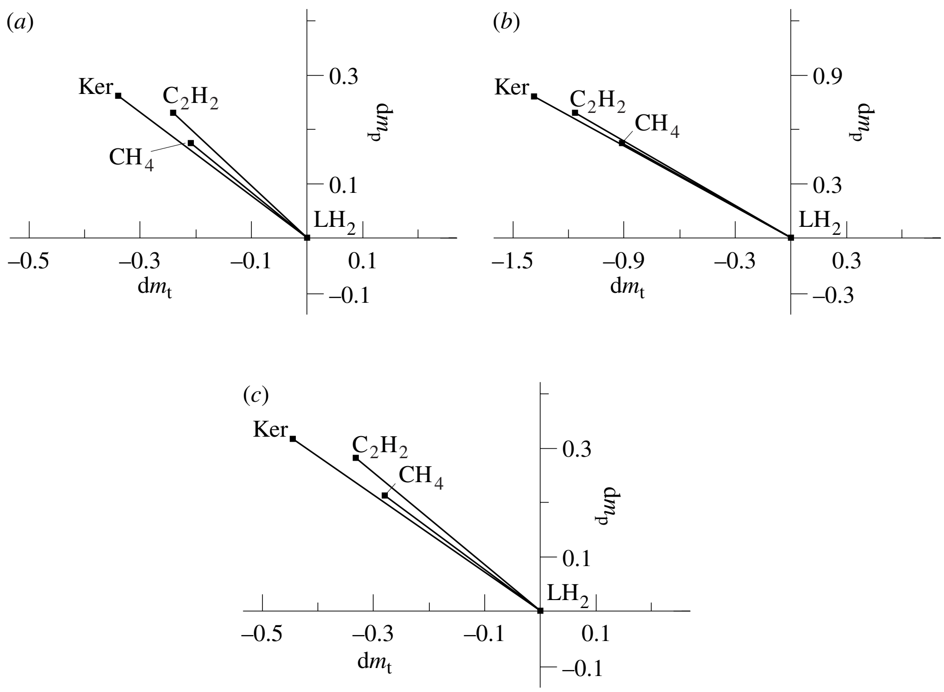

Figure 9. (*a*) Effect of alternative fuel replacing LH2 for constant payload density. (*b*) Effect of alternative fuel replacing LH2 for constant r_v. (*c*) Effect of alternative fuel replacing LH2 for constant payload-bay volume ($r_{m0} = \frac{1}{3}$, $r_{v0} = \frac{1}{2}$, $m_t/V_{tank} = 500$ kg m^{-3}).

(ii) *Variation of the reference vehicle parameters*

The results of figures 7 and 8*a* are shown for the reference values $r_{m0} = \frac{1}{3}$, $r_{v0} = \frac{1}{2}$ and $m_t/V_{tank} = 500$ kg m^{-3}. However, they are typical of the results for other values of these parameters. For example, the changes in the performance vectors for the constant density payload case when r_{m0} increases from $\frac{1}{3}$ to $\frac{1}{2}$ (in 10% steps) are shown in figure 8*b*. We see that the main effect is to reduce the incremental increase in the payload, although the vehicle mass reduction remains significant and increases slightly. When $r_{m0} = \frac{1}{2}$ the incremental payload change is zero, as might have been anticipated from figure 1. In figure 8*c*, the changes in the performance vectors with the volume parameter are shown, again for the constant density payload case. As the basic configuration volume parameter r_{v0} increases in 10% steps from $\frac{1}{2}$ to $\frac{3}{4}$, we see that the magnitudes of the vectors are reduced slightly. Similar results hold for the other payload constraints.

(*b*) *Hydrocarbon fuels*

Another fuel change of potential importance is the substitution of stoichiometric LH2 fuel with that of other hydrocarbons. In table 2, the properties of a number of hydrocarbons of interest are shown from methane to kerosene (JP-7).

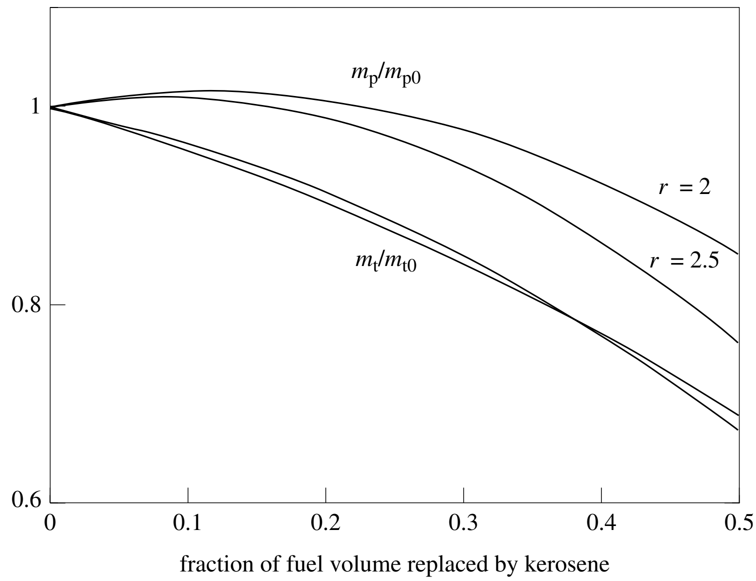

Figure 10. Payload and launch mass change when kerosene replaces LH2.

Suppose again, that following second-stage launch, a quantity of LH2 is replaced by another fuel that gives the same scramjet thrust. Then the changes in launch mass and payload can again be calculated from equations (5.5) and (5.6). These changes are shown in figure 9 for our typical configuration, where the mass flow for the same thrust is based on the approximate mass flows quoted in table 2. Figure 9*a*–*c* shows results for constant payload density, constant payload-bay volume and constant r_v as before. The replacement fuels shown are methane, acetylene and kerosene. We see that acetylene has the potential to give a significant improvement in performance. However, its physical properties make it undesirable as a fuel. The paraffins are more amenable as fuels, and the simplest paraffin, methane, is shown to initially increase the payload by $0.18f$ and decrease the launch mass by $0.21f$. The higher paraffins have similar performance, with a complex mixture of hydrocarbons forming kerosene giving a $0.26f$ increase in payload and a $0.33f$ decrease in launch mass. Clearly, the hydrocarbons have potential for improving the performance and justify further investigation as a scramjet fuel.

Without further analysis it is not in general possible to predict how the incremental performance gains found might translate into more substantial gains when a significant fraction of the LH2 fuel is replaced. However, we can demonstrate quantitatively the effect of fuel substitution by reducing the payload mass to compensate for the increased fuel mass. Although this is probably not an efficient way of accommodating the extra mass, it will serve to demonstrate the type of response expected as the fuel is replaced. A further complication is that the denser fuel is best consumed during the early part of the trajectory, whereas the payload mass affects the complete trajectory. Thus even the fundamental assumption of identical trajectories ceases to be strictly valid as the refuelled vehicle will have greater mass during the early part of the trajectory and less mass during the latter part.

The results are shown in figure 10 for values of r (the equal thrust fuel mass flow

Table 3. *Payloads of second stage scramjet orbiters with a launch Mach number of 7 (after L. H. Townend and R. A. East, personal communication)*

propellant	LH2		LH2 + neon		kerosene
launch mass (Mg)	110	136	110	119	110
payload mass (kg)	4250	7500	6400	7500	7500

ratio) of 2 and 2.5, which span the expected values for kerosene. We see that as the LH2 is replaced by kerosene, the payload at first rises to a maximum and then falls as more of the payload is foregone to compensate for the extra fuel mass. The vehicle mass, however, continues to fall as the vehicle size reduces when using the denser fuel. When *ca.* 20% of the original tank volume has been replaced with smaller kerosene tanks, we see that the payload is close to its original value but the total vehicle launch mass is only *ca.* 90% of the original mass before kerosene substitution.

Although these results indicate the potential for the vehicle performance to change with the propellant, they apply for a limited class of vehicles with the same trajectory and shape and other constraints. Relaxation of these constraints can have a significant effect on the vehicle performance, as has been demonstrated in studies of particular configurations (L. H. Townend and R. A. East, personal communication). For example, payloads for scramjet orbiters with a launch Mach number of 7 are shown in table 3, where the trajectories used are different for the different propellants. These suggest that the initial advantages of hydrocarbon propellants shown earlier can translate into significant increases in payload when the trajectory is tailored to the higher-density vehicle, which hydrocarbons make possible.

6. Conclusions

A restricted class of scramjet orbiters, which have similar shapes and the same trajectories to orbit, is used to establish relationships between the launch mass, the payload mass, the vehicle volume and other parameters of the vehicle. It is found that decreasing the volume by increasing the payload density or increasing the fuel density, has the doubly beneficial effect of increasing the payload and reducing the vehicle launch mass. Hence it is important to consider payload densities that are as large as possible and to investigate denser fuels than liquid hydrogen.

Scramjets commonly use fuel-rich mixtures to increase the thrust. The substitution of helium or a stoichiometric LH2–LOX mixture instead of LH2 for all or part of the additional fuel is shown for typical vehicle parameters to result in an increase in payload of *ca.* 5% while decreasing the launch mass by *ca.* 20%. It has been suggested from engine studies that neon and other inert gases may also be desirable additives. These additives require a greater mass flow for the same thrust and so cannot directly be assessed by the present analysis. However, the incremental gain from the substitution of a small quantity of replacement fuel can be found. This is used to assess whether there is any potential gain from using the inert gases as an additive to enhance the engine thrust, and whether they are likely to be preferable to other additives. It is found that the initial benefits from neon are slightly better than those from injecting an additional stoichiometric mixture of hydrogen and oxygen. The other inert gases are inferior to neon.

Similar considerations apply when replacing the LH2 burnt in the scramjet with a hydrocarbon. It is found that the initial improvement in the performance using kerosene is better than that obtained with methane or acetylene. But substitution of any of them is capable of increasing the payload and decreasing the launch mass compared with LH2, although for practical reasons acetylene would not normally be used as a fuel. More research is needed to assess the best practical combination of fuels to maximize the payload and to allow relaxation of the constraints imposed in this paper. In particular, relaxation of the trajectory and vehicle shape restrictions may permit further improvement and influence the choice of fuel.

Nomenclature

a_0–a_3	dry mass constant coefficients (equation (3.3))
B	total scramjet propellant mass flow over stoichiometric hydrogen mass flow for the incoming air
l	linear vehicle scaling factor
m_{dry}	vehicle dry mass (equation (3.6))
m_{p}	payload mass (equation (3.7))
$m_{\mathrm{r\,prop}}$	rocket propellant mass
$m_{\mathrm{s\,fuel}}$	scramjet propellant mass
m_{t}	vehicle mass (equations (3.1), (3.5))
r	ratio of propellant mass flows for the same thrust
r_{m}	vehicle mass ratio ($m_{\mathrm{p}}/m_{\mathrm{dry}}$)
r_{v}	vehicle volume ratio ($V_{\mathrm{p}}/V_{\mathrm{tank}}$)
V_{p}	volume of payload
V_{t}	volume of vehicle tanks and payload (equation (4.1))
V_{tank}	volume of propellant tanks
V_{tk}	tank volume ratio for fuel density change (equation (4.5))
subscripts	
0	unscaled or reference vehicle

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