PREDICTION OF THE AERODYNAMIC PERFORMANCE OF RE-USABLE SINGLE STAGE TO ORBIT VEHICLES

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ABSTRACT

Re-usable single stage to orbit launch vehicles promise to reduce the cost of access to space, but their success will be particularly reliant on accurate modelling of their aero-thermodynamic characteristics. Non-equilibrium effects due to the rarefaction of the gas in the atmosphere are important at the very high altitudes at which lifting R-SSTO configurations will experience their greatest thermal load during re-entry. Current limitations in modelling the behaviour of the gas and hence in capturing these effects have a strong impact on the accuracy with which the thermal and aerodynamic loading on the surface of the vehicle can be predicted during this design-critical flight regime. The problem is most apparent in the presence of strong shock interactions, and this is likely to exacerbate the problem of aerodynamic characterisation of re-usable single stage to orbit vehicles, especially given design pressures towards increased geometric complexity compared to historical spacecraft designs, and hence the complexity of the shock structures that the vehicle will produce in high-speed flight. The development of this class of vehicles will thus very likely be paced by the development of the specialised modelling tools that will be required to account fully for the properties of the gas at the high speeds and altitudes that are characteristic of their re-entry into the atmosphere of the earth.

INTRODUCTION

Practical embodiment of the re-usable single stage to orbit (R-SSTO) concept in a future space launcher is seen as having the potential to reduce significantly the cost of access to space. The argument for the R-SSTO concept is generally made on the basis of the advantages of an airline-like economic model, in which the cost of the vehicle can be amortised over multiple flights, rapid turnaround and scheduled service allow high vehicle productivity, and the possibility of continuously updating the component failure statistics of a fleet of vehicles during operation reduces the cost of assuring safety and reliability. Although several attempts have been made in the past to develop such technology, few R-SSTO vehicles have proceeded beyond conceptual design stage, and none has flown successfully. This state of affairs arises principally because of the difficulty of designing such a vehicle to have a payload mass fraction that approaches anything near being practically useful.

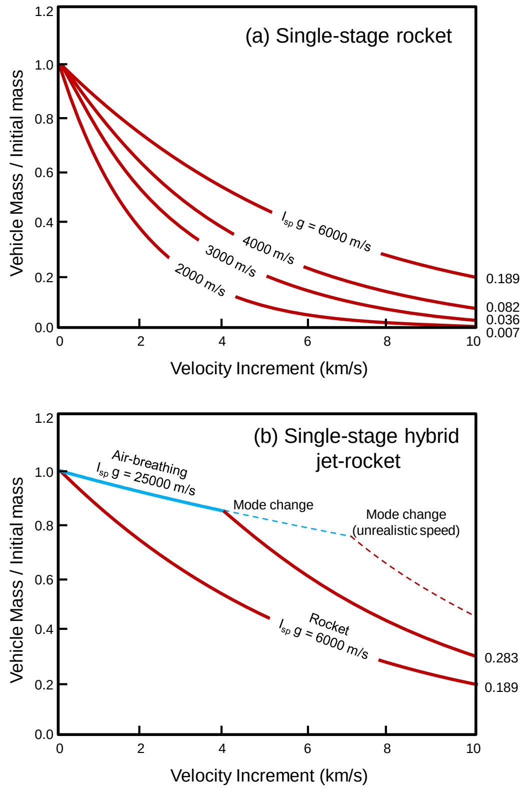


Figure 1. Velocity increment as a function of empty mass - rocket and hybrid systems compared.

The technical argument reduces to one of the specific impulse of the propulsion system. The X-33 programme showed that use of a conventional rocket-based propulsion system, even one with the best specific impulse currently attainable, forces the system to have a structural efficiency which is exceedingly difficult to achieve with current technology [1]. A somewhat simplistic analysis via the Rocket Equation gives the velocity increment imparted to a rocket-propelled vehicle at burnout, as a function of the empty mass fraction of the system, as shown in Fig. 1a. Given that to attain low earth orbit requires an effective velocity increment from the earth's surface of about 10km/s, it is commonly held that the empty mass fraction for a rocket-based SSTO system is limited to not much greater than 0.10. This imposes either very severe constraints on the maximum allowable payload or alternatively on the structural mass of the vehicle.

The principal hope for the future of SSTO vehicles is thus seen to be the development of hybrid propulsion technology that exploits, at least at low to intermediate altitudes, the very high specific impulse that is achievable with air-breathing jet engines [2]. The somewhat artificial example shown in Fig. 1b illustrates how hybrid propulsion can increase very effectively the empty mass fraction of a SSTO vehicle compared to the equivalent rocket-propelled system. Of course the benefits of hybrid propulsion must be offset against the increased mass of the more complex propulsion system itself and thus it is likely that even SSTO vehicles with hybrid propulsion will still require innovative structural design that is somewhat in advance of current aircraft or spacecraft practice. An important observation for the discussion that follows is that the ratio of thrust to weight of all practically-conceivable hybrid propulsion systems (at least in air-breathing jet mode) is less than unity, necessitating almost universally a lifting configuration for the vehicle. Optimisation to include the low-speed, low altitude flight regime generally results in a configuration that is very different to that of space vehicles that have been designed in the past (see Fig. 2) - even those that have been designed to have a lifting configuration. It is well worth bearing in mind though that the relatively simple geometry of these earlier craft was borne out of a well-justified scepticism regarding the ability of contemporary analysis techniques to characterise properly the aerodynamics of vehicles with any greater geometric complexity.

Undoubtedly, thus, proper aerodynamic characterisation and design will play an important role in producing a successful future R-SSTO vehicle. Indeed, both ascent and descent pose a set of demanding requirements on the accuracy with which the aerodynamic performance of the vehicle needs to be characterised during its design, but for rather different reasons. Mis-prediction of aerodynamic drag and lift during ascent to orbit has a direct impact on the sizing of the vehicle for a given payload capacity in much the same way as for conventional expendable launcher technology, except that the impact of uncertainty in the aerodynamic characterisation of the vehicle will have a much more severe effect on the viability of an SSTO vehicle with already marginal payload performance.

For R-SSTO vehicles, however, the very requirement that the vehicle be re-usable poses an unique but obvious additional structural mass penalty given the systems that need to be provided to allow the vehicle to re-enter the earth's atmosphere and to be recovered intact for re-launch. Items such as the wings can be exploited usefully for at least part of both the ascent and descent trajectory if the configuration of the vehicle is suitably optimised, but a particularly significant and somewhat unavoidable structural mass penalty is introduced by the thermal protection system (TPS) that is ordinarily required only during descent to deflect or dissipate into the atmosphere the energy gained by the craft during ascent. The current

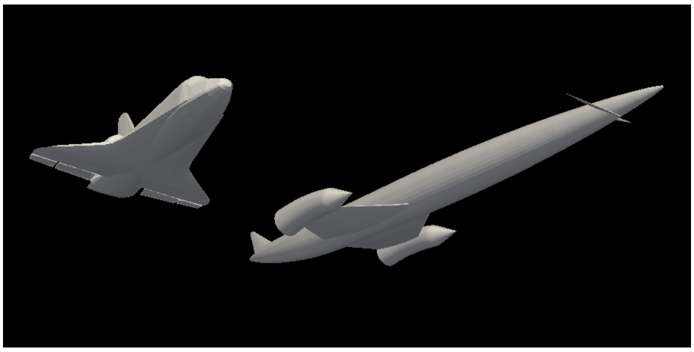


Figure 2. The configuration of a historical re-usable craft (Shuttle, at left) compared to a proposed R-SSTO vehicle (Skylon, at right).

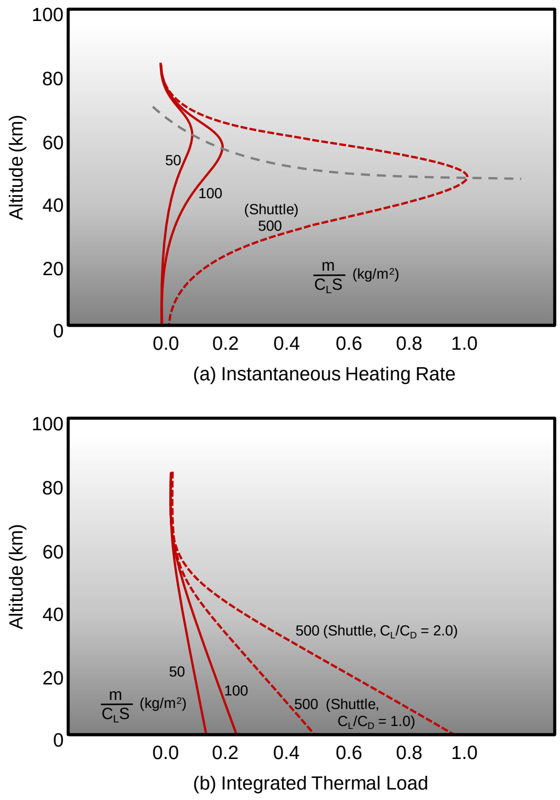


Figure 3. Thermal transfer to a lifting vehicle during re-entry as a function of altitude.

generation of materials that are capable of resisting the temperatures of re-entry are structurally rather inefficient (having a low strength to mass ratio or being brittle or sensitive to impact) and hence to reduce the overall mass of the craft in order to achieve a worthwhile payload mass fraction there is strong design pressure to operate close to the boundaries of existing materials technology. R-SSTO vehicles have limited luxury, for instance, to exploit ablative systems or other simple TPS technologies requiring extensive post-flight refurbishment without destroying the economics of the vehicle or its operational flexibility. One of the principal lessons of the Shuttle programme was indeed how sensitive the economics of an ostensibly re-usable vehicle could be to the robustness and maintainability of its TPS [3].

Mis-prediction of the aerodynamic heating during re-entry is thus a particularly serious problem in the design of an R-SSTO vehicle given that any predictive uncertainty must be accommodated by over-design of the TPS, or, in the case where the heating of the vehicle is over-predicted to the point where indications are that the thermal load cannot be accommodated by a passive system, complex and expensive palliative measures, for example a switch to an active TPS (where for instance the surface of the vehicle is cooled by recirculation of fuel), may be introduced unnecessarily. All of these measures add to the structural mass and reduce the payload that the vehicle is able to carry into orbit.

It was alluded to earlier that any practical R-SSTO vehicle will most likely be designed to be capable of relatively high lift to drag ratio, at least at low speed during jet-mode operation, and of course with concomitant benefits for the ferry capability and cross-range performance of the vehicle during its recovery. Despite the unavoidable deterioration of aerodynamic performance with increasing Mach number, a reasonably high lift-to-drag ratio can be expected to persist to the hypersonic speeds that characterise re-entry where it can be exploited to allow significant flexibility in the design of the trajectory of the vehicle. Design for re-entry requires a careful balance of the instantaneous heating rate experienced by the vehicle against the overall thermal load that is absorbed into, or needs to be dissipated from, the vehicle structure. As shown in Fig. 3, increasing the lift produced by the vehicle shifts the maximum deceleration and peak heating rate to higher within the atmosphere, allowing a lower peak heating rate, but operation at a high lift-to-drag ratio

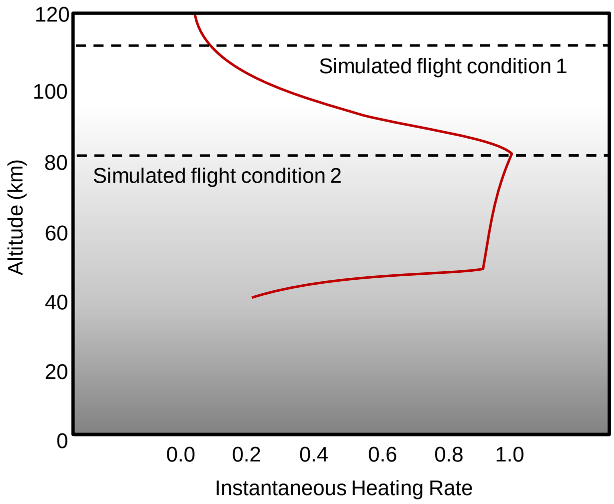
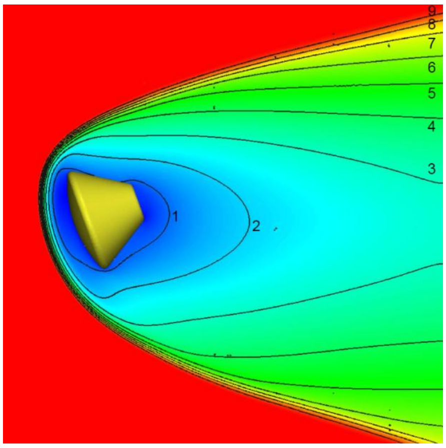
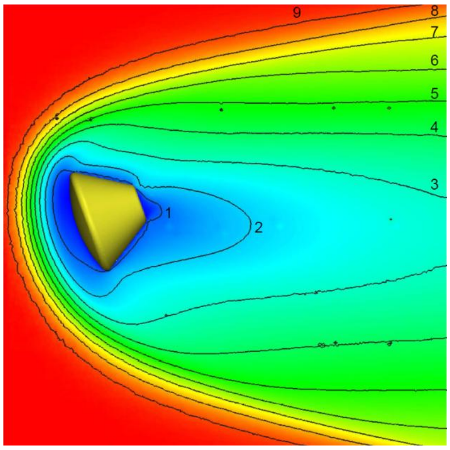


Figure 4. Predicted heating rate for Skylon as a function of altitude.



(a) Continuum-based calculation



(b) DSMC calculation

Figure 5. Comparison of continuum and DSMC calculations of the flow over a blunt re-entry vehicle under rarefied flow conditions.

increases the time of flight and hence the overall thermal load on the vehicle. Given the arguments presented earlier, the material properties of the TPS are likely to dominate, driving the design towards maximum deceleration at the highest altitude that is consistent with the limits on the aerodynamic performance of the vehicle at the hypersonic speeds that are characteristic of re-entry.

The advantage of a vehicle that is capable of a high lift-to-drag ratio is that its drag and lift can be varied considerably by changing its attitude (and bank angle). The vehicle can be flown at high incidence to the oncoming flow during the most critical parts of the re-entry trajectory, creating both high lift and high drag and thus reducing very effectively both the maximum heating and thermal load. Once the regime of peak heating has been traversed, the pitch attitude of the vehicle can then be reduced to increase its lift-to-drag ratio and thus to optimise its performance for its subsequent recovery to the surface. Given the fundamental applicability of this mode of operation to the R-SSTO concept, this paper will concentrate on the problem of characterising the aerodynamics of R-SSTO vehicles in the critical high-altitude hypersonic re-entry regime where the craft experiences the highest heating rate and, for the reasons discussed, is likely to be operating at high lift and thus at high incidence and thus also with high drag.

One of the vehicles that is intended to exploit this mode of operation is Skylon, a R-SSTO concept that is under development by Reaction Engines Ltd., a private UK company [4]. Innovative hybrid engine technology allows the ascent of the vehicle to be split into an initial air-breathing segment, followed by a transition to a rocket-propelled trajectory at a Mach number of 5 and an altitude of 28500m (for the C1 configuration of the vehicle). Following delivery of its payload into low orbit, the vehicle re-enters the earth's atmosphere at high incidence and, in much the same fashion as the Shuttle, follows a gliding descent to the surface. The angle of attack of the vehicle is to be controlled during descent to maintain the temperature of the skin of the vehicle at or below 3000˚F, yielding the expected schedule of heating rate with altitude at the nose of the vehicle shown in Fig. 4 [5].

In this paper, the geometry of Skylon is used, with the kind acquiescence of Reaction Engines, simply as an aerodynamic shape that is representative of current R-SSTO configurational thinking and that is complex enough to manifest some of the detailed aerodynamic issues that are likely to be experienced by advanced R-SSTO launch vehicles once they reach production. Although many previous studies comparing aerodynamic models of varying fidelity have been published in the context of relatively simple vehicle shapes, the hope of the present work is to take the discussion to the point where resolution of detailed specific aerodynamic problems, generally of an interactional nature, can yield the difference between a viable and non-viable design. Nevertheless, it is important to bear in mind, given the inherent limitations in the scope of the present study (as shall shortly be made clear), that no inference can reasonably be made from the results presented below regarding the practicality of Skylon itself.

Figure 6. Flow structure generated by the R-SSTO vehicle flying at Mach 21 at 114km altitude.

AERODYNAMICS AT HIGH ALTITUDE

The flow over a vehicle moving through the atmosphere can always be modelled by appealing to the fundamental principles of momentum interchange and mass and energy conservation. Although it is known that the gas in the atmosphere is composed, at microscopic level, of discrete particles, a useful approximation arises if the particulate nature of the gas can be suppressed and instead the atmosphere can be treated as a continuum. Indeed, this continuum approach is at the root of many very successful approaches to modelling the gas flow around air- and spacecraft, for instance those using the Navier-Stokes equations, and yields good correlations with measured data over a wide range of practically-relevant operational conditions.

The extent to which a gas flow can be treated as a continuum is traditionally gauged by a parameter known as the Knudsen number, defined as the ratio of the mean free path of the gas particles to a characteristic length scale of the vehicle. The mean free path of the gas particles that constitute the atmosphere of the earth changes however, from about $8x10^{-8}$m at the surface to roughly 0.45m at 100km, as the density of the gas in the atmosphere decreases with altitude [6]. As the Knudsen number increases, the rarefied, non-continuum, particulate-like behaviour of the gas becomes ever more important in defining the aerodynamic characteristics of the vehicle.

Because of the concomitant rarity of molecular collisions, the principal effect of rarefaction is to allow any non-equilibrium in the partition of energy between the various degrees of freedom possessed by the gas particles (e.g. translation, rotation and vibration), for instance such as induced by passage of the gas through a shock wave or contact with a solid surface, to persist for longer, or equivalently for further downstream, than they would in a less-rarefied flow. Non-equilibrium within the gas has the principal effect of modifying viscous forces and thermal transfer at the surface as higher-order transport phenomena become relatively more important, while in the flow away from the surface, shock waves tend to become broadened and diffuse so that their associated temperature and density profiles are smeared over considerable distances compared to the case in a less-rarefied flow.

Non-continuum gas behaviour can be accommodated to some extent in conventional continuum-based approaches to modelling the aerodynamics of aero-space vehicles, for instance by incorporation of a finite slip velocity between the gas and any solid surfaces that are immersed within the flow. Accommodation of those non-continuum effects that occur in the flow away from surfaces is a challenging problem, however. For this reason, analysis of gas flows in the non-continuum regime is most naturally conducted using specialised computational techniques that are derived from a statistical mechanical representation of the behaviour of the individual particles comprising the flow. The most successful of these techniques is undoubtedly the Direct-Simulation Monte Carlo (DSMC) approach, originally proposed by Bird [7] in the

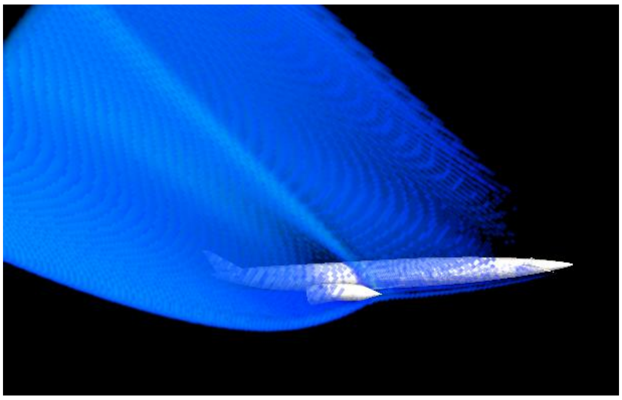


Figure 7. Flow structure generated by the R-SSTO vehicle flying at Mach 25 at 82km altitude.

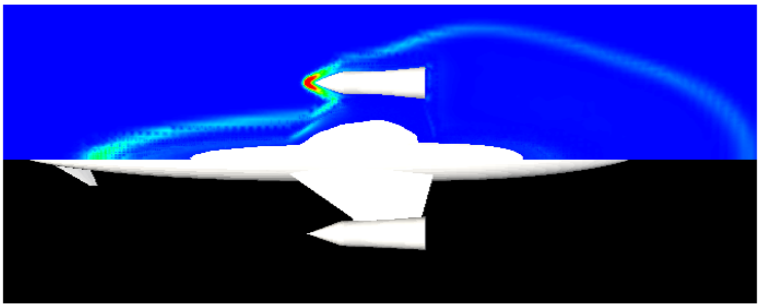


Figure 8. Section through the shock structure produced by the R-SSTO vehicle flying at Mach 25 at 82km altitude, showing multiple shock interactions just below the wing surface.

1970s. The principal differences between DSMC and continuum-based predictions are clearly seen in the example calculation shown in Fig. 5 for the flow surrounding a blunt re-entry vehicle travelling through the earth's atmosphere at a speed of 7.6km/s and an altitude of 100km. Under these conditions one would expect the bow shock located upstream of the vehicle to be thick and diffuse given the rarefied nature of the atmosphere. The diffuse nature of the shock is captured by the DSMC approach but is completely missed by the continuum solver in striving to maintain as compact a shock front as possible. The overall effect is for the continuum-based model (even as in this case with slip wall boundary conditions) to predict a drag coefficient for the vehicle of 1.6, compared to the value of 1.4 predicted by the DSMC approach. One interpretation of these results if applied to the real design environment, where it can be difficult to decide at face value which computational approach yields the better predictions, is that unresolved discrepancies between modelling approaches in this case could well lead to an uncertainty of greater than 10% in the characterisation of the ballistic coefficient of the real vehicle, with direct effect on its predicted performance.

The results that are presented below show how computational predictions of the aero-thermodynamics of R-SSTO vehicles within the high-altitude re-entry regime can be affected very strongly by the characterisation of the properties of the gas through which the vehicle is flying. The uncertainty in prediction of the aerodynamic loads and thermal transfer that is induced by uncertainty in the characterisation of the gas properties will be argued to be exacerbated in R-SSTO vehicles because of the trend towards inherent complexity within their configuration and the resultant increase in the importance of shock interactions - both in creating certain points on the vehicle at which aerodynamic loading and particularly heat transfer is critical, as well as in affecting the flow physics at these critical points in such a way that the prediction of the associated critical flow values is rendered very sensitive to errors in the characterisation of the gas. The DSMC method yields a particularly convenient computational framework for this study since it allows such direct control over the characterisation of the energetic properties of the gas molecules comprising the flow.

COMPUTATIONAL MODEL

The DSMC code used to produce the results presented below is known as dsmcFoam. This new code has been written within the framework of the open-source C++ CFD toolbox OpenFOAM [8]. The main features of dsmcFoam include the capability to perform both steady and transient DSMC calculations for gases consisting of multiple chemical species, to model arbitrary 2D or 3D geometries using unstructured polyhedral meshes and the ability to exploit unlimited parallel processing. The version of dsmcFoam used to produce the results presented below determines the energetics of intermolecular collisions for polyatomic species using the variable hard sphere (VHS) model [7], and, where included within simulations, the phenomenological Larsen-Borgnakke model is used to distribute post-collision energy between the translational and rotational modes of the particles [7]. A series of successful benchmark trials have been carried out which have validated the dsmcFoam code for non-reacting flows [9], and future developments include the implementation of a comprehensive capability to model the chemistry of the reacting flow around a re-entering spacecraft using Bird's quantum chemistry model [10].

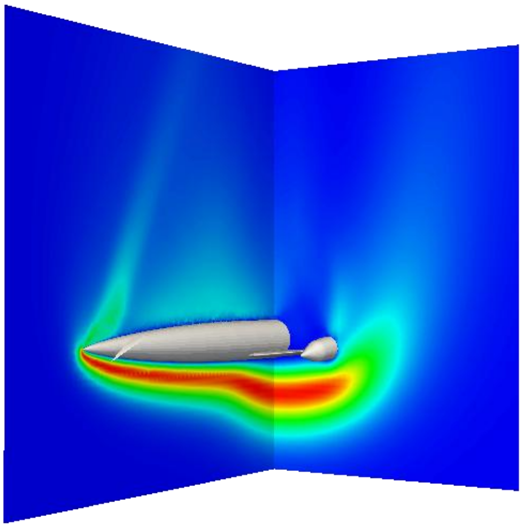


Figure 9. Region of non-equilibrium in the gas surrounding the R-SSTO vehicle flying at Mach 21 at 114km altitude. Red: greatest deviation from equilibrium; dark blue: equilibrium flow.

Two cases were modelled (see Fig. 4) - the first with Skylon at an altitude of 114km travelling at Mach 21 and an incidence of 66˚. At this altitude the mean free path of the molecules in the atmosphere is about 10m, yielding a Knudsen number, based on the length of the vehicle, of the order of 0.1 and hence a flight condition that would be expected to be dominated by the effects of rarefaction within the flow surrounding the vehicle. A second case was simulated with the vehicle at an altitude of 82km travelling at Mach 25 at an incidence of 43˚. This case corresponds to the flight condition that is expected to produce the maximum heating rate on the nose of the vehicle [5]. The mean free path at this altitude is about 0.01m yielding a Knudsen number of 10^{-4} based on the length of the vehicle. Ostensibly, the effects of flow rarefaction should not be important under such conditions. That rarefied gas effects are indeed important under such conditions is one of the key observations of this paper.

The gas surrounding the vehicle was assumed to be a binary mixture composed of 23% O_2 and 77% N_2 by mass. Two sets of simulations were conducted. The first set modelled the gas molecules as possessing only their translational mode of energy storage. A second set of calculations additionally accounted for the rotational inertia of the gas molecules, thus allowing a second mode of energy storage and the possibility of a non-equilibrium distribution of energy between the two modes under suitable circumstances. Of course, the rotational degrees of freedom are just the first in a chain of additional modes of energy storage that may be activated under particular flight conditions. For instance, under the real atmospheric conditions that pertain at the two flight conditions described above, vibrational excitation of the gas molecules as well as dissociation of both oxygen and nitrogen are likely also to contribute to the energetics of the gas. Although the results presented here thus need to be considered as somewhat artificial with regards true predictions of the performance of Skylon, they show very effectively the link, in a relatively uncomplicated context, between uncertainties in characterisation of the energy-containing modes available to the gas and the resultant uncertainty in the aerodynamic characterisation of the system. The reader is left to extrapolate the results presented here to the case where further modes of energy containment are available to the gas. It is very important to realise though for the argument that follows that even after several decades of intense effort, the theoretical basis for describing the energetics of a gas in which these additional modes have been excited is still not fully agreed and indeed is a matter of intensive current research [11-13].

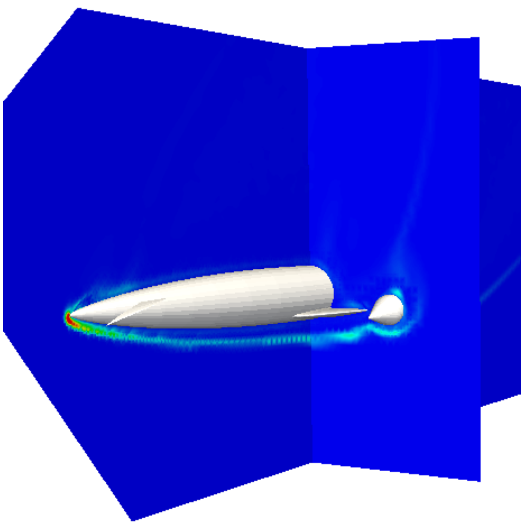


Figure 10. Region of non-equilibrium in the gas surrounding the R-SSTO vehicle flying at Mach 25 at 82km altitude. Red: greatest deviation from equilibrium; dark blue: equilibrium flow.

COMPUTATIONAL PREDICTIONS

Fig. 6 shows the overall structure of the flow field surrounding the vehicle when at 114km altitude. The vehicle is enveloped in a highly diffuse shock envelope that consists of two primary elements. The large effective bluntness of the wing and nacelles results in a roughly

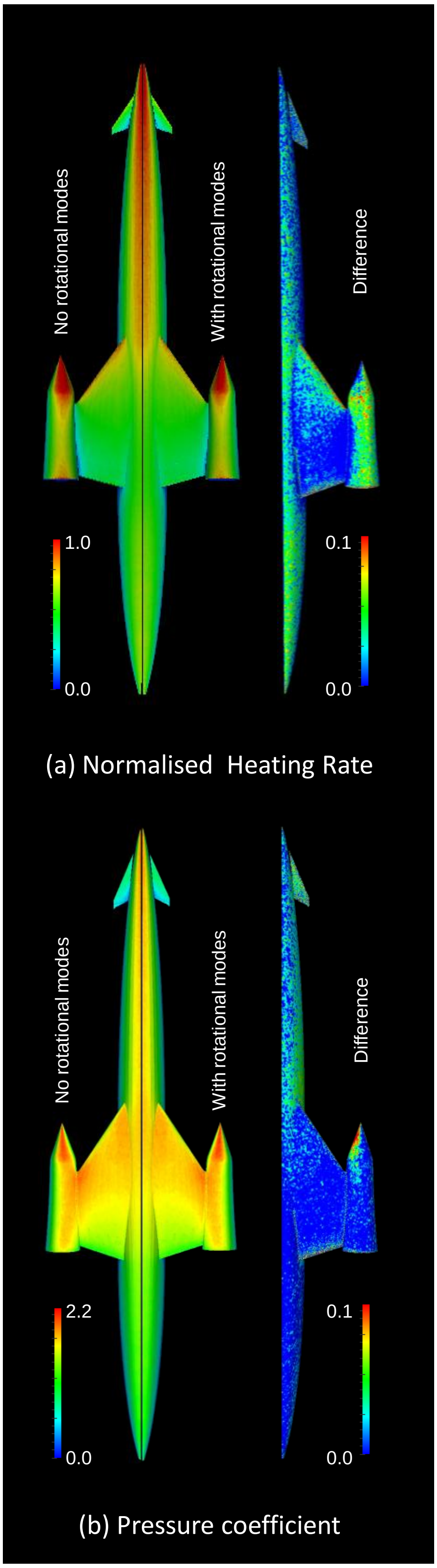


Figure 11. Heating rate and pressure coefficient on the lower surface of the R-SSTO flying at Mach 21 at 114km altitude. Calculations with and without gas rotational degree of freedom compared.

parabolic bow shock structure with a relatively large standoff distance from the body. The forward fuselage, however, presents a very much smaller effective radius to the oncoming flow than the wing at this flight condition. As a result, although the rear fuselage lies within the shock structure that is produced by the wing, the forebody produces a strongly curved shock which lies much closer to the underside of the vehicle than the shock that is produced by the wing. The shock structures produced by the wing and the fuselage interact weakly just forward of the wing-fuselage intersection to form a moderately curved, concave shock front just forward of the wing.

Fig. 7 shows the overall structure of the flow field surrounding the vehicle when at 82km altitude. In this case the shock is very much thinner than at 114km, the standoff distance from the vehicle is generally smaller, and the overall shock geometry results from a rather complex interaction between separate structures that are formed by the fuselage, wings and nacelles. As an indicator of how complex the pattern of shock interactions on the vehicle is at this flight condition, Fig. 8 shows a cross section through the flow just a small distance below the lower surface of the wing, revealing quite clearly the intersection between the various components of the shock structure that envelops the vehicle.

As a gauge to the degree of non-equilibrium within the flow, Figs. 9 and 10 show the difference between the overall temperature and the rotational temperature of the gas within the flow, calculated from those simulations where the gas was endowed with both translational and rotational degrees of freedom. With the gas in equilibrium, these two temperatures would be expected to be the same. Fig. 9 for the vehicle at 114km altitude shows the flow field surrounding the vehicle to be dominated by the effects of non-equilibrium between the translational and rotational modes of energy storage within the gas. The figure shows clearly how the region of non-equilibrium flow extends all the way through the shock structure to the surface of the vehicle. This is a consequence of the large mean free path of the gas at this altitude and hence the significant distance, as alluded to earlier, that is required for the gas to recover to its equilibrium state after encountering the shock structure upstream of the vehicle. The greatest excursions from equilibrium are to be found in the flow immediately below the forward fuselage and the wing, whereas the flow below the rear fuselage exists in a state that is considerably closer to equilibrium. In addition, plumes of non-equilibrium gas extend backwards along the sides of the nacelles and the forward fuselage, persisting as significant features in the flow well downstream of the vehicle. At 82km altitude (Fig. 10), non-equilibrium within the gas is,

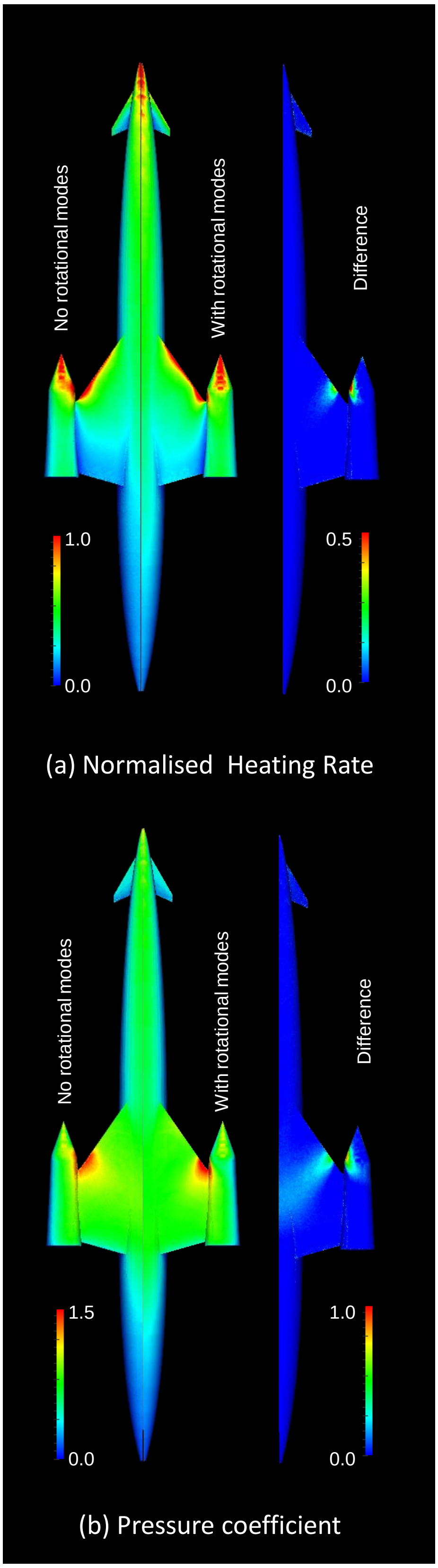


Figure 12. Heating rate and pressure coefficient on the lower surface of the R-SSTO flying at Mach 25 at 82km altitude. Calculations with and without gas rotational degree of freedom compared.

perhaps somewhat contrary to expectation, still an important feature of the flow-field, but it is confined to the very thin layer immediately downstream of the shock structure that envelops the vehicle. The difference in the extent of non-equilibrium within the gas between the two cases shown here is simply because the much shorter mean free path at 82km altitude allows the gas to equilibrate much more rapidly after passing through the shock structure surrounding the vehicle than is the case at 114km altitude. It is important to note that, at 82km altitude, significant deviations from equilibrium are generated particularly at the nose of the fuselage and the tips of the nacelles where the radius of curvature of the shock is comparatively small and thus the effective Knudsen number based on the dimensions of the shock is actually quite large.

Given these observations, it is not altogether surprising that the effect of introducing additional modes of energy storage within the gas on the predictions of the aerodynamics of the vehicle and the heating rate at its surface is markedly different at the two different altitudes. An important observation is that the effects of errors in characterising the energetic properties of the gas are manifest most clearly where the regions of non-equilibrium within the flow around the vehicle come into contact directly with its surface.

Indeed, Fig. 11a shows the predicted distribution of heating rate over the lower surface of the vehicle, normalised to unity at the point of maximum heating rate, with the vehicle at 114km altitude. As expected, the undersides of the fuselage and nacelles, with their reduced radius of curvature relative to the wing, bear the majority of the thermal flux from the gas to the surface of the vehicle. Allowing the gas additional rotational degrees of freedom modifies the predicted distribution of heating rate to the surface, principally on the underside of the nacelles and rear fuselage, but also along the leading edges of the wings. Although the data presented in Fig. 9a show significant statistical scatter, the difference between the two predictions is of the order of 10%. Similar conclusions hold for the distribution of the pressure coefficient over the vehicle surface, as shown in Fig. 11b, but the principal differences between the two predictions are confined to the regions of shock interaction on the inner faces of the nacelles and within the plume of non-equilibrium flow up the sides of the fuselage just forward of the wing. Given the lateral symmetry of the vehicle, these differences result in the incorporation of the additional degrees of freedom of the gas having an effect on the prediction of the lift and lift-to-drag ratio of the vehicle in this flight condition that is in the order of only one percent. The pitching moment about the centre of mass of the vehicle (bearing in mind that, because the vehicle is trimmed, the predicted value is small in any case) is somewhat more strongly affected, with a difference of 14% being observed between the two predictions. As with the traditionally-accepted explanation for the Shuttle pitch moment anomaly [14] it is highly likely that the larger discrepancy in the case of the pitching moment arises from the effect of small differences distributed over the surface of the vehicle being compounded by their distance from the centre of gravity of the vehicle.

The situation changes quite dramatically at lower altitude. Fig. 12a shows the normalised distribution of heating rate over the surface of the vehicle when in its flight condition at an altitude of 82km. With the vehicle at lower incidence, the nose of the fuselage, the tips of the nacelles and the wing leading edges are exposed to the highest heat flux from the gas, rather than the underside of the vehicle as at higher altitude. There is strong evidence also that shock impingement is responsible for the formation of localised patches where heat transfer is significantly higher than elsewhere on the surface of the vehicle, for instance on the inner surfaces of the nacelles and the wing leading edges. Allowing the gas to have additional rotational degrees of freedom reduces significantly the predicted heat transfer in these regions of impingement - to the extent for instance that the thermal flux at the hot spot on the inner surface of the nacelle is halved, and that at the wing leading edge is reduced by about 25%. The pressure coefficient (Fig. 12b) exhibits similar behaviour, and again allowing the gas to have additional rotational degrees of freedom reduces significantly the predicted pressure coefficient in the regions of shock impingement near the wing-nacelle junction. The overall effect of these differences is to reduce the predicted lift coefficient for the vehicle, and also its lift-to-drag ratio, by approximately 10%, compared to the values obtained when the gas is allowed only translational degrees of freedom. The pitching moment about the centre of mass of the vehicle is even more dramatically affected, however, with a calculated discrepancy between the two cases of close to 50%.

DISCUSSION AND CONCLUSIONS

Non-equilibrium effects due to the rarefaction of the gas are important at the high altitudes at which lifting R-SSTO configurations are most likely to experience the greatest thermal transfer from the surrounding atmosphere into their structure - even, as suggested by the results presented here, under conditions where a simplistic analysis via an overall Knudsen number for the vehicle would imply that this should not be the case. The results presented above show that uncertainty in the characterisation of the energy containing modes of the gas can have a significant effect on the quantification of both the thermal transfer to the surface of the vehicle and the local aerodynamic loading. Although demonstrated here only for the rotational mode of the gas, the results are suggestive of the likely effect of the further uncertainties that are known by the community to exist in the characterisation of the additional modes of energy storage within the gas, in particular vibration and dissociation, which, although not modelled here, are undoubtedly excited under the real atmospheric conditions that pertain within the critical high-altitude regime that is encountered by R-SSTO type vehicles that exploit their lifting potential to ameliorate their thermal loads during re-entry.

The results presented above thus yield, firstly, an important reminder that analysis of the likely importance of non-equilibrium in the flow surrounding a vehicle using the Knudsen number needs to be treated with extreme care. It can be inappropriate to define just one length-scale that characterises all the physics of the flow around the vehicle that has anything other than the simplest of geometry. Indeed, the simulations suggest that the major uncertainties in predicting local heat transfer and aerodynamic loading at the surface of the vehicle, at least those that result from uncertainties in the characterisation of the gas, are largely confined to regions of shock interaction or to where elements of the configuration are immersed directly in those regions of the flow over the vehicle that are removed furthest from equilibrium. In considering the effects of localised shock impingement on surface heating, it is relatively certain that the dimensions of the shock itself are more critical in gauging the importance of non-equilibrium effects within the flow than the overall length of the vehicle itself. The results presented above caution very strongly that the argument extends too though to the characterisation of the overall loads or the aerodynamic coefficients of the vehicle, even if regions of non-equilibrium are localised. This is because even ostensibly local and small-scale discrepancies in the prediction of the heating rate or aerodynamic loading at critical points on the vehicle can contribute strongly to errors in characterisation of the overall aero-thermodynamic properties of the vehicle.

Secondly, the importance of these smaller-scale effects leads inevitably to the conclusion that the pressures towards increased complexity in the configuration of R-SSTO vehicles compared to spacecraft that have been designed in the past could render them more susceptible to errors in aerodynamic characterisation, particularly if any increase in configurational complexity results in a more complex and interactive shock structure surrounding the vehicle. The designs of the past have traditionally been configured to produce as simple a shock structure under operational conditions as possible, and wherever shock interactions have occurred they have generally had unforeseen and deleterious effects. Given the present state of the art in computational prediction, a sensible design strategy would still seem to be to strive to eliminate these interactions as far as possible through careful integration of the various elements of the configuration. Although complete elimination of such interactions is undoubtedly not entirely consistent with the requirement that the R-SSTO configuration be optimised for a very broad range of flight conditions, their existence remains as a distinct element of risk to the success of this class of vehicles. Computational tools that can model properly the range of energy containing modes that are available to the gas, especially under the rarefied, non-equilibrium flow conditions that characterise the re-entry of R-SSTO vehicles into the earth's atmosphere, are under intense development, but significant additional work is required to include and verify the models for modes such as vibration, dissociation and chemical reaction. It is the authors' firm conviction that the R-SSTO concept will continue to apply the greatest incentive to the development of such tools, and hopefully the point will be reached very soon where these tools become useful adjuncts to the design process.

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