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AERODYNAMIC ASPECTS OF SATELLITE PROTECTION BY UPSTREAM EJECTION

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ABSTRACT

A recently proposed method of reducing the fuel required to maintain a satellite in a low earth orbit has previously been tested by direct simulation computations of the rarefied flow using only a simple hard sphere collision model. It is shown here that similar results are found using a more realistic collision model, the variable diameter hard sphere. The simulations show that low earth orbit can be maintained with a significant reduction of the fuel requirement compared to that required for conventional rocket thrusters. The method is only effective for Knudsen numbers less than about 40, that is it relies on an effect which appears in the transition regime as free molecular flow is approached. Computations also show that the method is suitable for protection of sensitive satellite borne equipment, that is for providing "purging gas flows".

NOTATION

A = area of disc/satellite
A_r = area of rocket exhaust
A_2 = area of ejection nozzle
C_D = drag coefficient
d = diameter of sting
D = diameter of disc/satellite
Kn = Knudsen number = λ/D
l = length of sting
m = mass of molecule
n = number density
R_f = mass flux ratio = $m_2n_2A_2U_2/m_1n_1AU_1$
T = temperature
U = stream velocity
V = exhaust velocity of rocket
α = centre angle of ejection from sting
δ = angle of divergence of ejected molecules
λ = mean free path
σ = molecular diameter

Subscripts
1 = class 1 molecules (freestream)
2 = class 2 molecules (ejected)
r = reaction rocket molecules

INTRODUCTION

A satellite in a low earth orbit experiences significant aerodynamic drag as it passes through the low density atmosphere. Presently, rocket thrusters are used to provide forward thrust to overcome the drag on the satellite. The fuel for the rockets must be carried onboard, and therefore represents either a payload mass penalty or a determinant on the life of the satellite. For this reason, any means of reducing the mass of fuel which must be carried is welcome. Stalker (1987) first proposed that by ejecting a gas upstream from the satellite surface normal to the oncoming freestream, it may be possible to reduce the drag and thus the mass of propellent that needs to be carried in order to maintain a low earth orbit. The analysis that Stalker presented depended on an assumption that allowed the collisions between ejected molecules and freestream molecules to occur in a zone that was able to be moved far from the satellite's surface. An analytical analysis based on the mean free path of ejected molecules was developed (Cathcart & Macrossan, to be published) which indicated that the collision zone was unable to be moved far from the satellites surface, and that the total drag on the satellite would increase rather than decrease. These findings were reinforced by Monte Carlo simulations of the flowfield which clearly show the collision zone to be close to the satellite surface and that the total drag on the satellite was slightly greater than the drag on the satellite in the absence of upstream ejection.

Stalker's analysis did indicate, however, that if the collision zone could be moved from the satellite surface, significant savings could result. A sting equipped with a diverging nozzle is suggested that could telescope out in front of the satellite. A first collision analysis applied to a point source of ejected molecules some distance upstream from a satellite revealed that negligible post collision scatter onto the satellite occurs when the point source is removed a distance of four satellite diameters (4*D*) from the satellite. This indicates that little or no improvement would result for a sting length longer than this because of the increased chance that further collisions would reflect a previously deflected molecule back into the satellite's path.

Monte Carlo simulations using a hard sphere molecular model have indicated that substantial mass savings are possible, with up to a 50% reduction in the mass of propellent that needs to be stored to maintain orbit. These results are compared in this paper to simulations using a more realistic molecular model.

The efficient scattering of freestream molecules facilitated by the sting mounted ejection system indicates that a purging gas flow based on the same concept should provide a high level of protection of sensitive satellite borne instruments from contamination by the freestream. The degree of protection enabled is also investigated here using the Direct Simulation Monte Carlo method.

DIRECT SIMULATION MONTE CARLO METHOD

The Direct Simulation Monte-Carlo (DSMC) method (Bird, 1976) models the gas by some thousands of simulator molecules in a computer. The position coordinates and velocity components of each molecule are stored and modified with time as molecules are followed through representative collisions and boundary interactions in simulated space. The flowfield is divided into a computational network of small cells which facilitates the choice of potential collision pairs and the sampling of the macroscopic flow properties.

Two choices of the collision probabilities in the simulation were used. The first and most simple was the Hard Sphere (HS) molecule which represents molecules with a constant total collision cross section and assumes that post collision scattering is isotropic in the centre of mass frame of reference. The second, and arguably more realistic model was the Variable Hard Sphere (VHS) molecule for which the collision cross section of pairs of molecules varies according to their relative speed of collision. The post collision scattering is the same as for hard spheres.

Bird's "standard VHS" model (Bird, 1991) yields the following equation for the molecular size σ_{ref} at a reference temperature T_{ref}

$$\sigma_{ref} = \left(\frac{15(mkT_{ref}/\pi)^{1/2}}{2(5-2\omega)(7-2\omega)\mu_{ref}} \right)^{1/2} . \tag{1}$$

In this equation, k is the Boltzmann constant and μ_{ref} is the coefficient of viscosity of the gas being modelled at the reference temperature. The effective collision diameter is then related to the relative velocity of collision c_{r} by

$$\sigma = \sigma_{ref} \left(\frac{\{2kT_{ref}/(m^* c_r^2)\}^{\omega - 1/2}}{\Gamma(5/2-\omega)} \right)^{1/2} , \tag{2}$$

where m^* is the reduced mass $= m_1 m_2 /(m_1 + m_2)$. The theoretical viscosity coefficient of the VHS gas is proportional to temperature raised to a constant power ω, and with a suitable choice of ω can match the real gas viscosity over a range of temperature.

DRAG REDUCTION FOR SATELLITES IN LOW EARTH ORBITS

DSMC Flowfield

The satellite was represented as a flat disc at rest in the chosen reference frame, aligned normal to an oncoming freestream (Fig.1). The sting was modelled as an finite width beam of diameter *d*, and length *l*, protruding from the front surface of the satellite.

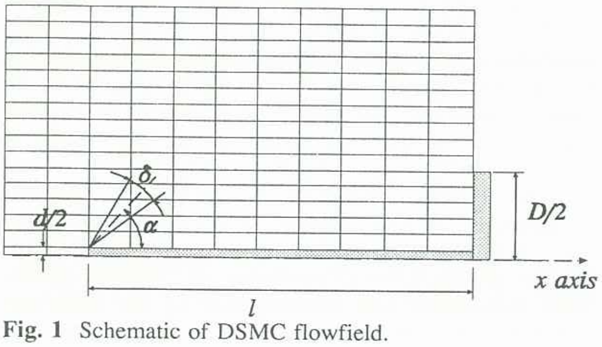

Fig. 1 Schematic of DSMC flowfield.

The jet is simply modelled as an axisymmetric point source located on the exterior of the sting. The angle of ejection (α) and the angle of divergence (δ) can be specified as desired. The computational flowfield measured 6 satellite diameters in the x direction and 2 satellite diameters in the radial direction with a maximum of 60 cells in the x direction and 30 in the radial direction. The satellite surfaces were assumed to be at the same temperature as the freestream and to reflect all incoming molecules diffusely, with full thermal accommodation.

Monte Carlo simulations were made with freestream conditions appropriate to a low earth orbit with an upstream Knudsen number (λ_∞/D) of 1.6. For simulations investigating drag reduction, the ejected molecules were assumed to be identical to the freestream molecules. The direction of ejection, velocity of ejection, and number flux of ejected molecules were varied according to what was thought practicable in order to find a combination that provides the best results, that is the least mass requirements to maintain the orbit velocity. We are therefore primarily interested not in drag reduction, but the mass savings of propellant made possible by upstream ejection coupled with a normal reaction rocket.

Percentage of Mass Required

The total mass flux in order to maintain flight is comprised of the mass flux of ejected molecules $m_2 n_2 A_2 U_2$ and the mass flux for a reaction rocket to overcome the residual drag, which is the vector sum of the aerodynamic drag caused by molecules hitting the disc, and the reaction from the ejection process. The standard reaction rocket must balance the residual drag, that is,

$$m_r n_r A_r V^2 = \tfrac{1}{2} C_D m_1 n_1 A U_1^2 . \tag{3}$$

Typical low earth orbit speeds are 7.6 km/s while exhaust velocities of simple controllable reaction rockets are approximately 1.9 km/s. Therefore putting $U_1/V \approx 4$,

$$m_r n_r A_r V = \tfrac{1}{2} C_D m_1 n_1 A U_1 \left(\frac{U_1}{V} \right) \approx 2 C_D m_1 n_1 A U_1 . \tag{4}$$

The total mass flux for the upstream ejection system is then $m_2 n_2 A_2 U_2 + 2C_D m_1 n_1 A U_1$. By similar reasoning which led to Eq.(4), the mass flux of rocket molecules is

$$m_r n_r A_r V = \tfrac{1}{2} C_{D0} m_1 n_1 A U_1 \left(\frac{U_1}{V} \right) \approx 2 C_{D0} m_1 n_1 A U_1 . \tag{5}$$

to overcome C_{D0}, the drag coefficient in the absence of upstream ejection calculated using the DSMC method. The fraction of mass required for sustained flight using upstream ejection compared with a typical reaction rocket is then

$$\frac{\dfrac{m_2 n_2 A_2 U_2}{m_1 n_1 A U_1} + 2C_D}{2C_{D0}} = \frac{R_f + 2C_D}{2C_{D0}} . \tag{6}$$

Hard Sphere and Variable Hard Sphere Results

The same conditions were simulated using the hard sphere model and the variable hard sphere model. The viscosity of air predicted from the Leonard Jones potentials (Hirschfelder et al., 1954) does not follow a simple power law of temperature below 1000K but does above 1000K. The effective size of VHS molecules is chosen so that the viscosity of the VHS gas matches the viscosity of air at the reference temperature. The collision diameters of the molecules, for a given relative speed of collision, depend on the reference temperature if it is below 1000K, but are independent of the reference temperature if it is chosen to be 1000K or higher. The collisions between the freestream and ejected molecules, which are most important to the simulation for the drag reduction of the satellite, are high energy and therefore high temperature collisions. In order to accurately represent the real viscosity of air for these collisions, the reference temperature T_{ref} was chosen to be 1000K for all VHS simulations.

Investigating the optimal angles of ejection, it was found that ejection perpendicular is favourable compared to direct upstream ejection as there is no backwards reaction on the disc. Furthermore ejection at a downstream angle provides both thrust and drag reduction from impinging molecules. The optimum angle of ejection was found to depend on the collision model. The VHS model predicts that for l/D=4.0 and Kn=1.6, the optimum angle of ejection (α) is 15 deg. with a divergence angle (δ) of 10 deg. compared with α=10 deg. and δ=20 deg. found using the HS model. Although the optimum angles for each case are different, the drag predicted using either method with the two different angles of ejection vary less than 1 percent.

The velocity of the jet was varied from near zero to a maximum velocity of 2 km/s which is an estimate of the maximum velocity able to be achieved using a simple, controllable rocket thruster. With a constant mass flux ratio the drag due to impinging molecules increased with increasing velocity of ejection (Fig.2). The reaction due to ejection however provides more positive thrust with increasing ejected speed. This increase in thrust more than balances the increase in drag caused by impinging molecules and the lowest overall drag coefficient is achieved using the maximum ejected velocity.

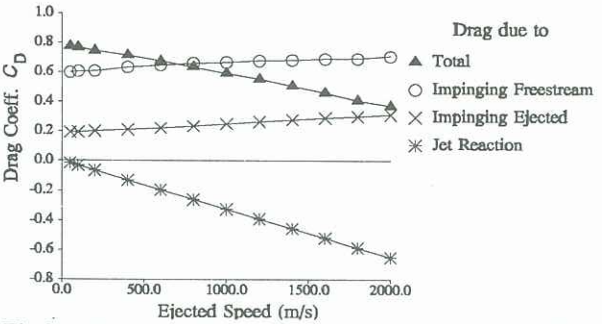

Fig.2 Drag Coeffs vs Ejected Velocity from DSMC method using HS model, mass flux ratio = 1.25.

The mass flux of ejected molecules $m_2n_2A_2U_2$ was varied by altering the number density with the velocity of ejection held constant at 2 km/s (Fig.3).

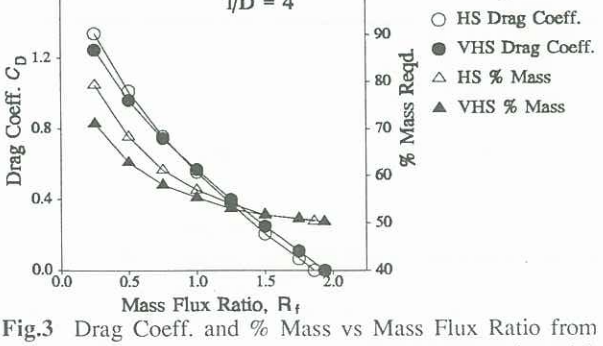

Fig.3 Drag Coeff. and % Mass vs Mass Flux Ratio from DSMC method using HS and VHS, sting length ratio = 4.0

An ejected mass flux of approximately $1.9m_1n_1AU_1$ results in a total drag of zero predicted by both the HS and VHS model, and so provides the capability of maintaining flight solely with the upstream ejection system (that is, without a backwards pointing reaction rocket), and the percentage of mass needed to maintain flight compared with a typical reaction rocket is reduced to just over 50%.

The sting length ratio l/D was varied by altering the length of the sting. Sting length ratios larger than 4 provided little advantage as predicted from the first collision analysis, but the effectiveness of the ejection process was found not to decrease dramatically until the ratio was less than 2. Since it is desirable to use the shorter, rather than the longer sting, the best case using a sting length ratio of 2.0 was investigated. The optimum angles of ejection were found to be the same for both molecular models, that is α = 30 deg and δ = 10 deg. A mass flux ratio of 2.1 for the HS model and 2.4 for the VHS model results in a net drag of zero, negating the need for a reaction rocket, and the total propellant mass needed to maintain flight is approximately 57% and 62% predicted by the HS and VHS model respectively (Fig.4).

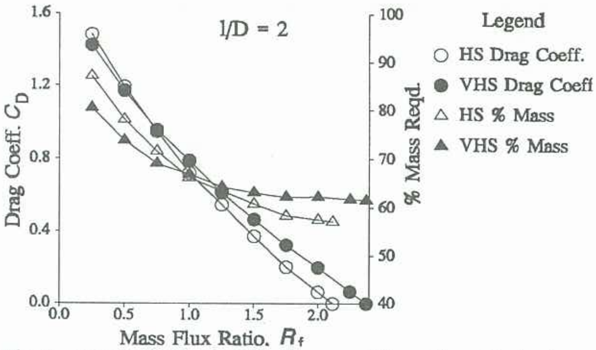

Fig.4 Drag Coeff. and % Mass vs Mass Flux Ratio from DSMC method using HS and VHS, sting length ratio = 2.0

Investigating different altitudes or satellite sizes, different upstream Knudsen numbers were simulated. As the Knudsen number increased, the mass flux required to maintain orbit increased (Fig.5). For Knudsen numbers greater than 40 the predicted savings were dramatically reduced with virtually no savings predicted for Knudsen numbers greater than 250.

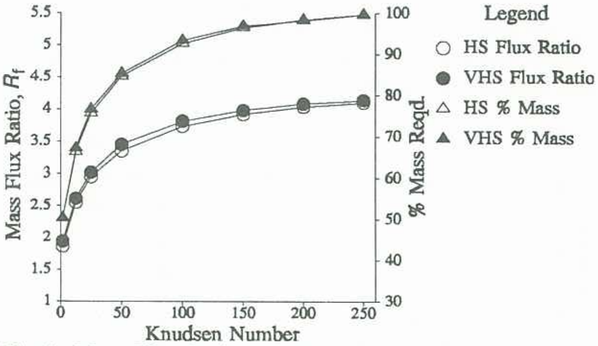

Fig.5 Mass Flux Ratio and Percentage Mass vs Upstream Knudsen Number from DSMC method using HS and VHS. Sting length ratio = 4.0.

PROTECTION OF SATELLITES USING PURGING GAS FLOWS

Purging gas flows have been suggested for protecting satellite borne experiments and cryogenic optics in space infrared telescopes from the freestream (Muntz and Hanson, 1984). For example, the condensation of atmospheric gases (primarily oxygen atoms) on cryogenic optical surfaces could present a serious problem to successful infrared telescope operation by effecting the scattering characteristics of the primary mirror or by causing unwanted absorption features in the infrared spectrum (Simpson and Witteborn, 1977). A way to overcome this is to provide a purging flow of incondensable gas (usually helium or neon) to prevent contamination. Although massive purging may result in very little contamination from condensing gases, there are several reasons why this is not desirable. Firstly, the purge gas must be carried and stored on board. Secondly, the purge gas can build up and cause relatively high pressures in the region close to the cryogenic optics resulting in unacceptably high heat transfer rates. The use of a sting or remote nozzles for providing the purge gas is well suited to these instances as the collision zone is far from the mirror surfaces providing good clearance of freestream molecules as well as little "build-up" of the purging gas in the regions near the mirror. An advantage of using a remote nozzle is that the purging gas provides an aerodynamic drag reduction so the mass of propellent needed for a reaction rocket can be substantially reduced to help combat the mass of purging gas that must be stored.

Simulations of the satellite flight with purging gas flows were obtained using the VHS molecular model with a sting length ratio of 4.0. The protection of the satellite from freestream molecules was investigated using both helium and neon as the purge gas with equal ejected gas mass fluxes. Since neon molecules are much heavier than helium molecules, the number flux of neon was much less than helium, so although neon provides better scattering of the freestream per purging gas molecule, the helium provides better overall reduction of the freestream contamination on a per mass basis. With helium chosen as the purge gas, the angle of ejection and velocity of ejection were investigated. The best results (the least flux of freestream molecules impinging on the surface) were obtained for an ejected velocity of 5 m/s at an angle of ejection of 165 deg. and a divergence angle of 20 deg.

The number flux of freestream molecules onto the surface was compared to the number flux incident for normal flight without the purge gas. The mass flux of ejected molecules was varied with the velocity of ejection held constant at 5 m/s (Fig.6).

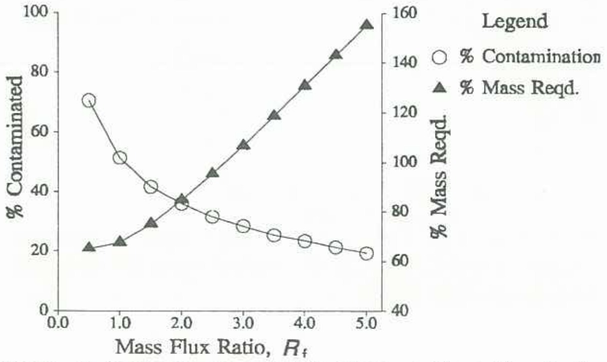

Fig.6 % Contamination and % Mass vs Mass Flux Ratio from DSMC method using VHS. Sting length ratio = 4.0.

The percentage of mass required to maintain orbit by overcoming the residual drag on the satellite using a reaction rocket is also shown. The large drag reduction caused by the scattering of freestream molecules from the satellite path means, for example, for an increase of only 6% of stored propellent (purging gas as well as rocket fuel) contamination is reduced to 28.5% with a mass flux ratio R_f of 3.0.

CONCLUSIONS

Upstream ejection from a sting mounted jet source is suggested as a new method of reducing the thruster fuel required to overcome the aerodynamic drag of a satellite in a low earth orbit. The mean direction of this jet has a lateral as well as a longitudinal component. This is a more effective means of using the onboard fuel than the conventional use of rocket thrusters as the ejected molecules perform two functions: (1) by virtue of the jet's lateral component, collisions between the ejected and freestream molecules divert molecules away from the satellite and reduce the aerodynamic drag, and (2) the longitudinal component of the jet provides thrust to overcome the residual drag. The overall effect is that the orbit can be maintained with a total fuel requirement significantly less than that required for conventional rocket thrusters for Knudsen numbers which are characteristic of the lowest practical earth orbits. The results have been shown to be insensitive to the collision models used, although some care must be taken in selecting the effective cross section of the collision models. The relevant collisions which must be accurately modelled are high energy collisions between the ejected molecules and freestream molecules.

Upstream ejection has also been shown to be a promising means of supplying a purging gas flow, that is a means of protecting sensitive satellite borne equipment from contamination by atmospheric molecules. The scattering of heavy atmospheric molecules is effectively achieved by having a high purge gas density a large distance from the satellite surface. The aerodynamic drag reduction associated with the decrease of impinging high speed atmospheric molecules enables a large percentage of protection to be achieved with a small increase in the total stored onboard mass of propellent needed to provide the purging gas and to fuel a reaction rocket needed to maintain orbit.

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