Satellite Protection and Drag Reduction using a Purging Gas Flow

Author's version of 'Satellite Protection and Drag Reduction using a Purging Gas Flow',
G. P. Cathcart and M. N. Macrossan, *Rarefied Gas Dynamics 19, Proceedings of the 19th International Symposium*, Oxford, 25-29 July 1994, vol 2, (*eds.* J. Harvey and G. Lord), Oxford University Press, 1995, pp. 1380-1386. ISBN 0 19 856535 6

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1995

Abstract

The DSMC method has been used to determine the contamination (impingement of atmospheric molecules) and the aerodynamic forces on a cold satellite when a protective 'purge' gas is ejected from a sting protruding ahead of the satellite. Forward ejection of the purge gas provides the greatest protection for a given mass of purge gas and the aerodynamic drag can be significantly reduced, thus compensating for the backward reaction from the forward ejection. If the purge gas is ejected backward from the sting (towards the satellite) the ejection provides thrust and the net retarding force can be reduced to zero. Contamination can be reduced and the mass of purging gas used is less than the mass of conventional rocket propellant required to maintain the orbit of an unprotected satellite.

1 Introduction

Satellite borne experiments and cryogenic optics in space infrared telescopes can be adversely affected by contamination from atmospheric gases. For example, atomic oxygen, which is common at altitudes above 110 km, can react with thin organic films, advanced composites and metallised surfaces [1] resulting in lost or degraded sensor performance. Many space infrared telescopes require the mirror surface to be cooled to temperatures below 100 K in order to reduce background radiation and help monitor dim targets [2]. Atmospheric gases can condense on the mirror at these low temperatures, leading to reduced spatial resolution and a reduction in the sensitivity of the telescope. These undesirable effects can be overcome by providing a purging flow of a non-condensing gas to clear incoming freestream molecules from the satellite's path [3]. Although massive purging may result in very little contamination, large amounts of purge gas can represent a severe payload penalty and the purge gas can build up in the region close to the cryogenic optics, resulting in unacceptably high heat transfer rates. The use of a sting or

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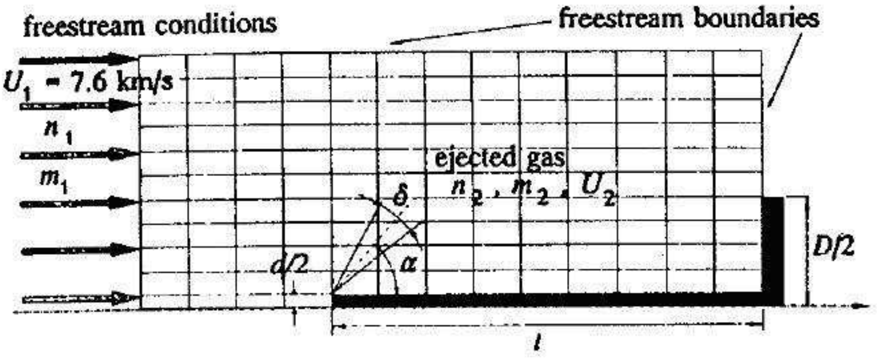

Figure 1: Schematic of DSMC flowfield including sting and ejection geometry

remote nozzles to inject the purge gas upstream of the mirror surfaces can result in good clearance of freestream molecules as well as little build-up of the purging gas near the mirror. Another advantage is that the purging gas, by deflecting high speed freestream molecules from the path of the satellite, provides an aerodynamic drag reduction. Here we use the Direct Simulation Monte Carlo Method [4] to investigate the use of a remote nozzle to provide the purging gas.

2 Molecular Scattering Model

All molecules were represented as standard VHS molecules [5] with reference diameters chosen to make the model gas viscosity match the theoretical Chapman-Enskog viscosity evaluated at 1000 K for a Lennard-Jones potential with appropriate constants for air, helium and neon [6]. Collision diameters varied as $g^{\omega-\frac{1}{2}}$, where ω was 0.642, 0.65 and 0.65 for air, helium and neon respectively [7]. For the sake of simplicity molecular energy modes such as rotation, vibration, ionisation and chemical energy were ignored.

3 Freestream Conditions, Satellite Geometry and Reference Flow

We considered orbital flight at a speed of $U_l = 7.6$ km/s at an altitude of approximately 140 km, where the freestream temperature was $T_1 = 350$ K and the number density of atmospheric molecules was $n_1 = 5.226 \times 10^{17}$ m^{-3}. The satellite was represented as a flat disc of diameter $D = 2$ m aligned normal to the oncoming freestream (1). The Knudsen number based on the nominal λ_1 for this altitude [8], was 1.62 and the freestream speed ratio was $S_1 = 16.7$. The axisymmetric computational flowfield measured $6D$, with a maximum of 60 cells, in the x-direction and $2D$, with a maximum of 30 cells, in the radial direction. The sting, which protruded from the surface of the satellite, had a diameter of $d = D/5$, and a length of $\ell = 4D$. Purge gas was ejected at a temperature of 350 K from a point source (in axisymmetric coordinates) on the exterior tip of the sting. The angle of ejection, α, and the angle of divergence, δ, could be specified as desired.

The temperature of the sting surface was set at T_1 and all molecules hitting the sting surface were diffusely reflected. The disk surface temperature was set at 30 K and

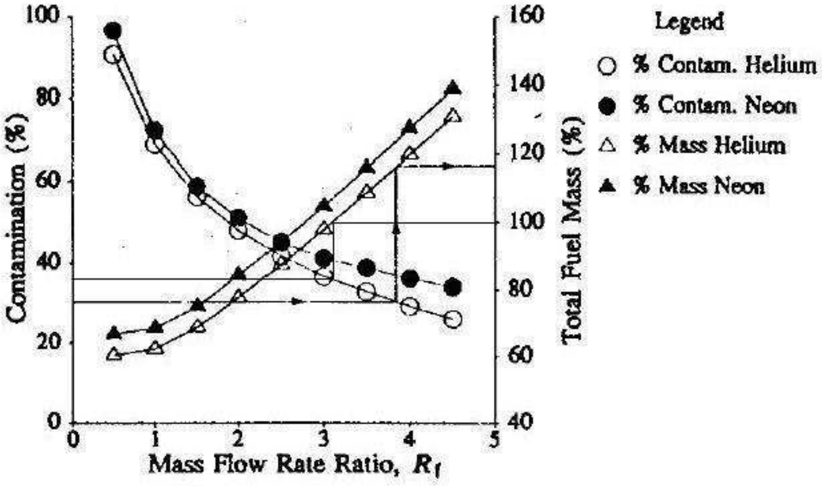

Figure 2: Minimum contamination, and corresponding mass of total fuel (purge gas plus rocket propellant), for a given mass flow rate, R_f, of purge gas. Minimum contamination is obtained with $U_2 = 5$ m/s, $\alpha = 165°$, $\delta = 20°$

all freestream (air) molecules striking it were removed from the simulation to simulate condensation. Purging gas molecules were diffusely reflected from the cold disk.

For no purging gas flow and no sting, the flux of air molecules hitting the cold satellite disk (where they condense), and the associated aerodynamic drag, can be determined analytically from free molecular flow theory. Hence the mass of reaction rocket propellant required to maintain orbit (for no purging gas flow) could be calculated assuming a rocket exhaust speed of 1.9 km/s. These values are used as reference conditions; the number of air molecules reaching the satellite when purging is employed is expressed as a percentage of the reference value and the total mass of purging gas plus reaction rocket propellant required to maintain orbit (hereafter referred to as total mass of 'fuel') is expressed as a percentage of the reference mass of rocket propellant.

4 Maximum Protection for Given Mass of Purge Gas

A large number of simulations were undertaken for a range of ejection speeds and angles. For a given mass flow rate of purge gas, the minimum contamination was found for ejection at $\alpha = 165°$ with a divergence $\delta = 20°$, and an ejection speed $U_2 = 5$ m/s. This combination effectively builds a high density cloud of purging gas molecules near the front of the sting which acts as a barrier to oncoming freestream molecules. Figure 2 shows, for both helium and neon, the level of contamination obtained in this case. The mass flow rate ratio, R_f in the figure, is the mass flow rate of purging gas divided by a reference mass flow rate of freestream molecules, $m_1 n_l U_1 \pi D^2/4$. The figure shows that contamination is reduced as R_f is increased and that helium purge gas provides better protection (less contamination) for a given R_f. Although the heavier neon molecules scatter the air molecules more effectively, the better performance of helium arises from the larger number density of molecules for the same mass flow rate of purge gas.

Figure 2 also shows the total mass of fuel (purge gas and propellant) for a given mass flow rate of purge gas. Note that the propellant required to maintain orbit must overcome the drag due to any molecules impinging on the satellite surfaces (as determined from the simulations) as well as the reaction due to ejection of the purge gas in the forward direction. It can be seen that the total fuel mass increases substantially (with little reduction in contamination) as the mass flow rate of purge gas increases above $R_f \simeq 2$. Thus, if near to zero contamination is required, the payload and/or the lifetime of the satellite will be dramatically reduced. However, if 30% contamination is acceptable, it can be seen that there is only a 17% mass penalty associated with providing the purge gas; and if contamination of 35% is acceptable, orbit can be maintained using helium purge gas with a smaller total mass of fuel than if no purging gas system is used at all[1]. This is because the purging gas system reduces the aerodynamic drag on the satellite by more than enough to compensate for the backward reaction (extra drag) arising from the forward ejection of the purge gas itself.

5 Maximum Protection for Given Mass of Fuel

The use of a purging gas as a drag reduction mechanism was suggested by Stalker [9], and it has been shown [10] that its effectiveness is increased if the purge gas is ejected from the sting in the backward direction ($\alpha < 90^\circ$). Although for a given mass of purge gas this is less effective in shielding the satellite, the reaction from the purge gas ejection reduces what we call the residual drag, which is the sum of the total aerodynamic drag on the satellite and sting ± the reaction due to purge gas ejection.

The angle of ejection and mass flow rate of a helium purge gas were varied to achieve a large range of results. It was found that performance was improved by increasing the ejection speed but we limited this to 750 m/s, a typical maximum speed provided by a cold gas propulsion system which is a likely method of supplying the purging gas.

For any given level of contamination, the least total fuel mass was obtained when using an ejection speed of 750 m/s, directed downstream at $\alpha = 5^\circ$, with divergence $6 = 10^\circ$. With this combination of parameters the total fuel mass requirement can be reduced by increasing the mass flow rate of purge gas up to $R_f = 3.28$, at which point the residual drag goes to zero and 37% contamination is achieved with only 82% mass of fuel. To decrease the contamination further, without accelerating the satellite, the mass flow rate of purge gas has to be increased without increasing the reaction due to ejection. This can be done either by increasing the angle of ejection or by reducing the speed of ejection. The latter results in a greater build up of purging gas molecules near the satellite.

Figure 3 shows the effect of increasing R_f with a fixed ejection speed of 750 m/s at an angle of ejection of $\alpha = 60^\circ$. There is a continual decrease of the residual drag coefficient and contamination up to the point where the residual drag goes to zero. Similar results were determined for ejection angles up to 65°. In each case the mass flow rate of purge gas was increased up to the point where the residual drag was reduced to zero; it was found that this provided the best protection (least contamination) for a given total mass of fuel and the fixed ejection speed. Figure 4 shows a summary of these results for different ejection angles. It shows the degree of contamination and the corresponding

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[1] It appears from the figure that this is a little optimistic. For a total mass flux of 100% it appears the contamination is about 37%. MNM, July 2007

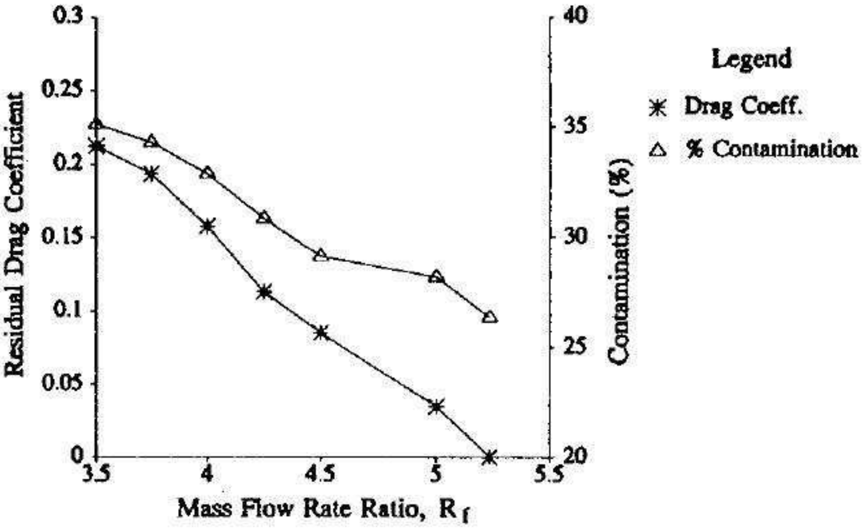

Figure 3: Residual drag coefficient and contamination with backward ejection of helium purge gas with $\alpha = 60°$, $U_2 = 750$ m/s, $\delta = 10°$. The mass flow rate ratio, R_f, is increased until the residual drag is zero.

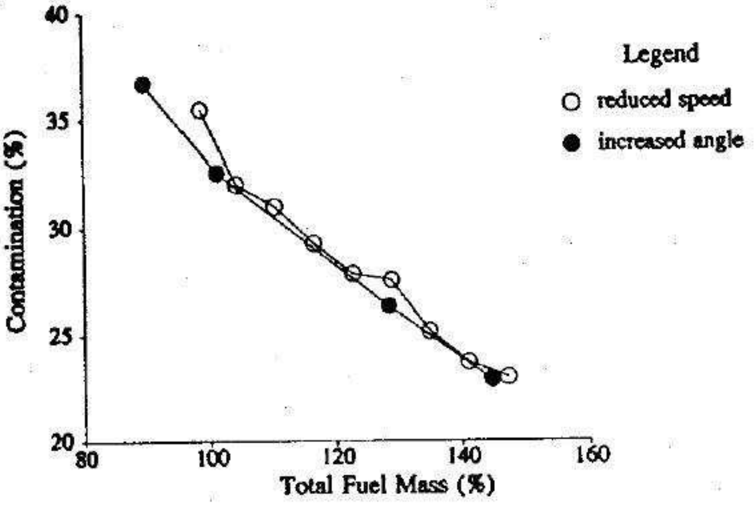

Figure 4: Contamination versus total fuel mass required for increasing flow rates of helium purge gas, with $\delta = 10°$ and: (a) ejection speed = 750 m/s and $5° < \alpha < 65°$; (b) $\alpha = 5°$ and ejection speed < 750 m/s. Residual drag is zero for all cases and the 'fuel' consists of purge gas only.

total fuel mass required when the residual drag is reduced to zero. Note that for zero drag the total fuel consists of purge gas only.

Contamination could also be reduced, without accelerating the satellite, by increasing the mass flow rate of purge gas while decreasing the ejection speed and keeping the angle of ejection fixed at 5°. The mass flow rate was found which resulted in a residual drag of zero. The corresponding level of contamination proved to be the minimum contamination which could be achieved for a given total fuel mass and a fixed ejection angle of $\alpha = 5^\circ$. Figure 4 also shows a summary of these results for a residual drag of zero.

6 Discussion

It has been shown that the incident freestream number flux and the total drag for a cold satellite can be significantly decreased by providing a purging gas ejected from a remote nozzle. The mass of propellant increases as the level of contamination decreases and a compromise must be found between the protection provided and the total mass that must be carried to provide satellite protection and to maintain orbit. It has been shown in section 4 that contamination can be reduced to levels 35% using forward ejection of helium purge gas with no increase in total fuel mass which must be carried (see figure 2). In section 5 it was shown that backward ejection of the purge gas can be used to obtain similar levels of protection for the same total mass of fuel (see figure 4) with the added advantage that, since the residual drag is reduced to zero, propulsion rocket need not be provided to maintain orbit. Two different backward ejection arrangements have been considered which give similar levels of protection for a given mass of total fuel. However it was found that by using a high ejection speed at a high ejection angle there is less build up of purging gas molecules near the cooled surface than if a smaller (more backward) ejection angle is used with a lower ejection speed. Our investigation of the protection of cooled satellite surfaces by using a remote source reveals that there may well be potential for such a system. However, it must be remembered that the simulated flowfield was much simplified, and would not accurately represent the important case of a satellite carrying an infrared telescope which typically has a telescope barrel, and often a sunshade in front of the cooled mirror surface. The implications of these complications have not been considered.

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ISBN 0 19 856535 6