A99-45530

AIAA-99-4878

INFLUENCE OF EM DISCHARGES ON HYPERSONIC VEHICLE LIFT, DRAG, AND AIRBREATHING THRUST

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Abstract

This investigation revealed that the influences of electric or electromagnetic discharges from hypersonic vehicle noses propagate downstream over the entire extent of the vehicles and through their engines - affecting not only nose drag, but temperatures, pressures, and total vehicle thrust, drag, and lift. Nose drag reducing discharges increase airflow captured by airbreathing engines for increased thrust and cause higher lifting and thrusting pressures to be exerted upon the curved aft undersurfaces of typical hypersonic craft to increase their lift, and to significantly increase their ratio of lift-to-drag. Increased engine thrust reduces ascent time to reduce ascent propellant consumption, while increased lift/drag ratio significantly increases cruise range. Thus, drag-reducing em discharges - if they can be achieved without excessive electric power consumption - could significantly enhance the ascent and cruise performance of hypersonic craft.

Introduction

Early plasma dynamic investigations in the U.S. (1) and more recent ones in Russia (2, 3) have indicated that significant drag reduction can occur when hemispherical noses are bathed by high speed airflow that is weakly ionized by discharges that involve plasma formations by electric arcs or by laser or microwave radiation. Such discharges usually extend into regions upstream of the bow shock waves that form about vehicle noses at supersonic speeds. And, when velocity was measured, higher than expected sound speed was observed within the localized regions were airflow was perturbed. There is no current consensus as to the source of such anomalous drag and sound speed changes, and full replication of the reported Russian results have not yet been obtained by investigators in other countries. However, more and more flow features of the Russian results have been observed as more and more experiments - such as in (4) - have been performed - and as more expertise in generating electric and electromagnetic discharges have been gained.

If significant nose drag reductions can be achieved with electric/electromagnetic discharges occurring upstream of vehicle noses, downstream effects of the discharges on other vehicle characteristics are also of interest to vehicle designers. Thus, the influence of nose drag reducing discharges on the total lift drag and thrust of high speed craft has been investigated by the authors, using Computational Fluid Dynamics (CFD) techniques.

Methodology

For simplicity, a 2-D vehicle representation (which did not include vertical and horizontal tail surfaces) of a generic vehicle which is typical of a hypersonic airbreathing aircraft or a Single-Stage-to-Orbit (SSTO) vehicle was used, together with solution of the Euler equations - which determined only the inviscid component of the vehicle's aerodynamic characteristics. The Euler equations were solved by an "Approximate Factorization" algorithm whose numerical procedure used 2nd order time accuracy and 4th order spatial differencing to compute external flow about the entire vehicle and internal flow within the airbreathing engine (5). Heat addition to simulate supersonic combustion of hydrogen was modeled by adding a source term to the energy equation - equivalent to First Law or Rayleigh line heat addition. Figure 1 shows the generic vehicle configuration and the airbreathing engine flow-path that was assumed. Here, a blunter nose that which may be technically possible with active cooling or advanced materials was configured in order to reduce or eliminate the need for active nose cooling and to provide ample volume for an electric or electromagnetic discharge device. And Figure 2 shows the extent of the discharge - compared to that of the vehicle itself.

Since reports of significant increase in sound speed within weakly ionized plasmas are often associated with reports of significant nose drag reductions, drag reducing discharges were modeled by sound speed disturbances in regions in the forward vicinity of vehicle noses. At a given altitude above earth, local sound propagation speed within a given gas is

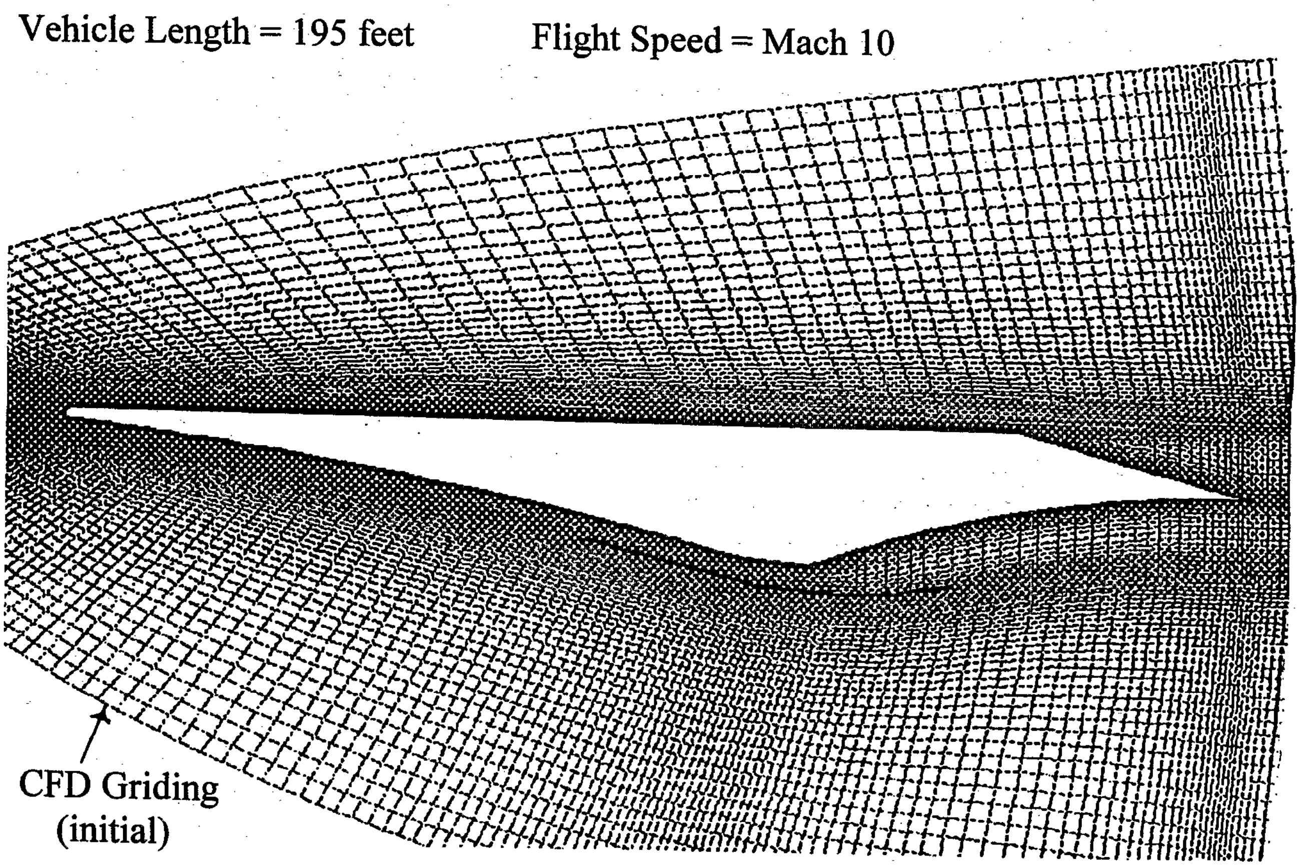

Figure 1 - Hypersonic Airbreathing Vehicle Configuration

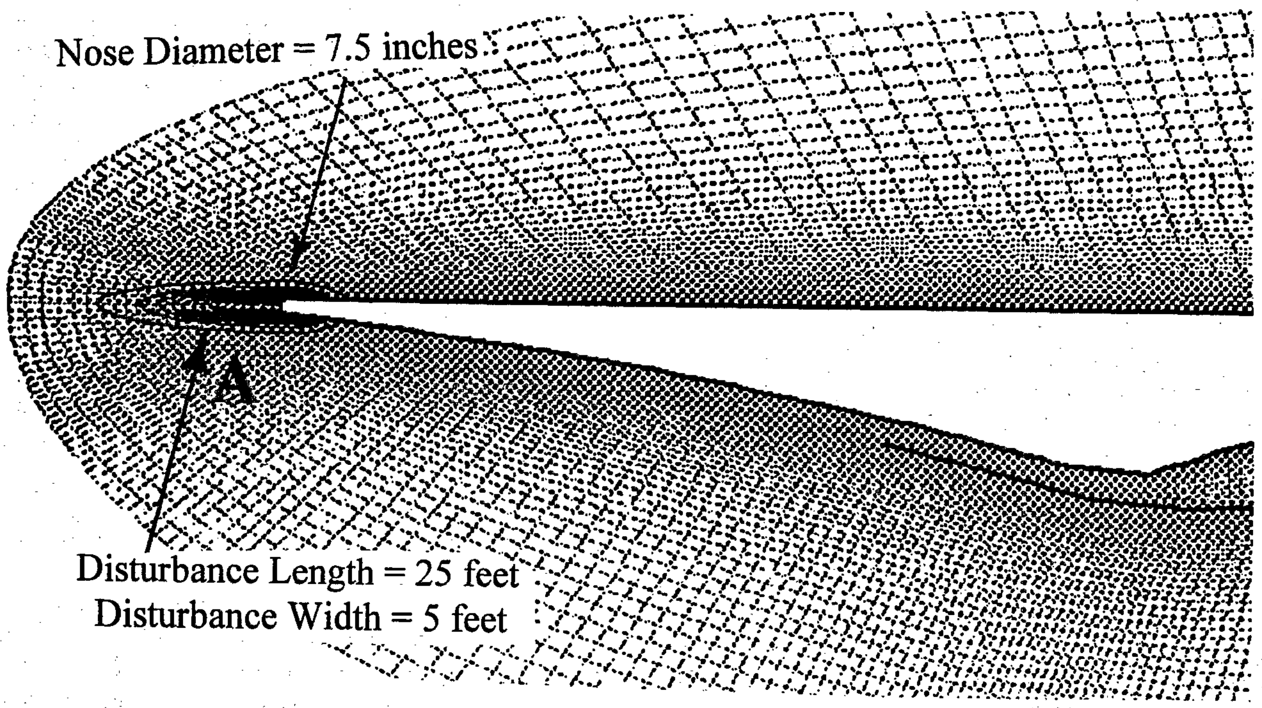

Figure 2 - Region of EM Discharge and Ionized Plasma

determined by the product of γRT, where: γ is the ratio of specific heats for the gas; R is determined by the electrical and physical nature of the gas; and T is the static temperature of the gas. And all of these quantities can, of course, be changed within local regions where electric/electromagnetic discharges have ionized and/or heated oncoming airflow. In this respect, some reported instances of significant nose drag reduction have involved significant airflow temperature increase while other drag reduction instances have not. For these latter instances, changes in local sound propagation speed is presumably determined primarily by changes in γR - by changes in the energy storage and dissipation characteristics (γ) of the gas and/or changes in its electrical-physical structure (R).

The effect of discharges from noses on supersonic airflow within regions near the vehicle was simulated by perturbing R and γ within a localized region of given size and shape, and discharge intensity within the region was modeled by a gaussian variation in the magnitude of the γR disturbances. The γR perturbations did not attempt to replicate actual em discharges achieved in experimental work, but they captured many of the observed features associated with supersonic drag-reduction in weakly ionized plasmas such as: precursor pressures generated significantly ahead of the bow shock; increased bow shock thickening and stand-off distance; and reduction in shock intensity. Two levels of perturbation intensity were considered, corresponding to discharges capable of causing moderate and strong local changes in the energy storage/dissipation and/or electrical/physical characteristics of the gas. These perturbations are shown in Figure 3 and Figure 4.

Theoretical and experimental drag reduction investigations such as (6) show that γR increases of 60 to 180 percent can occur within the vicinity of spheres bathed by supersonic airflow - with these increases occurring for free stream static pressures of 45 and 6 Torr. And (6) proposes that such γR changes, which occur at constant gas kinetic temperature, are associated with changes in the "internal potential energy of binding of air neutral particles". Figures 3 and 4 show the regions of perturbed γR in the vehicle nose vicinity that were used in our CFD analysis - and which would be presumably caused by electric/electromagnetic discharges of modest and strong intensity from the vehicle nose. Changes in γR as high as about 90 percent are seen to be associated with the moderate discharge, while changes as high as 180 percent are associated with the strong discharge.

A fairly broad band of drag reduction values for a diverse range of configurations and discharge types, intensities, shapes and sizes have been reported in the literature, with theoretical and experimental values of supersonic nose drag reduction in the 20-35 percent range cited in references such as (7,8), and nose drag reductions - in the 50-60 percent range are described in references such as (9,10). In this respect, a nose drag reduction of 24 percent was found to be associated with the moderate intensity discharge of Figure 3, while a 30 percent nose drag reduction was associated with the strong intensity discharge of Figure 4.

Influence of Discharges on Vehicle Airflow

Figures 5, 6 and 7 show the influence of the moderate and strong e/em discharges on the shock structure that forms about the vehicle nose at Mach 10. For no discharge (Figure 5) pressure waves coalesce into a relatively strong thin shock that stands off a relatively short distance from the vehicle nose. Figure 6 shows that the modest intensity discharge attenuates shock wave intensity, causing the pressure waves to coalesce into a broader region of lesser gradient, and precursor pressures are seen to be created ahead of the shock. And the strong discharge (Figure 7) is seen to increase these effects even more. Thus, although these γR disturbance patterns were not intended to replicate specific electric/electromagnetic discharges achieved in experiments, they appeared to capture the general flow field features and levels of nose drag reductions that are often reported in weakly ionized plasma work.

Figure 8 shows the influence of the moderate and strong discharges on the volume of airflow captured by the vehicle's airbreathing engines. Here, reduced shock wave intensity and increased shock wave bending (toward the vehicle) is associated with increased discharge intensity - which allows more airflow to be captured. Significant increase in engine mass flow (which is proportional to the product of the density and velocity of the air passing through the inlet face) and engine thrust results. And here, increased engine mass flow from the discharges was found to be mainly due to increased density of the ingested air.

Influences of Discharges on Nose Pressures and Temperatures

As might be expected, drag reducing discharges that reduced bow shock intensity were also found to reduce the pressures and temperatures bathing the hemispherical tip of the vehicle nose at Mach 10. And the pressure and temperature reduction extended a significant distance behind the nose tip. No quantitive evaluation of the possible reductions in nose cooling or thermal protection system requirements were made. But, obviously, reduction in aerothermodynamic environment is desirable for the minimization of structural complexity and weight.

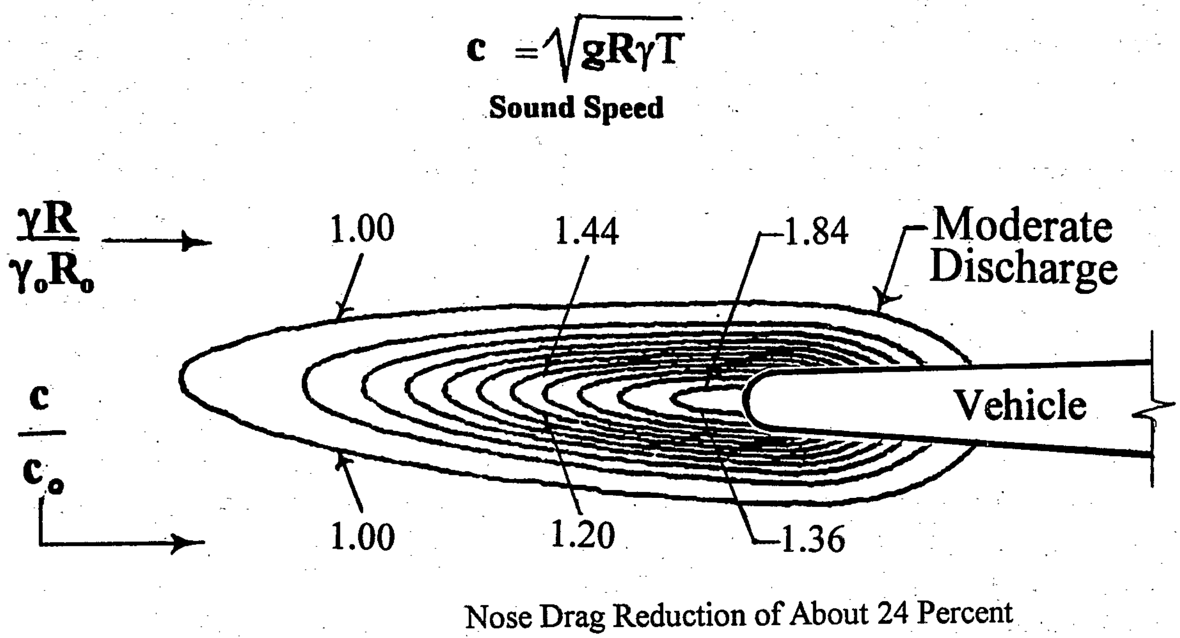

Figure 3 - **Increase in γR within the Moderate Discharge Region**

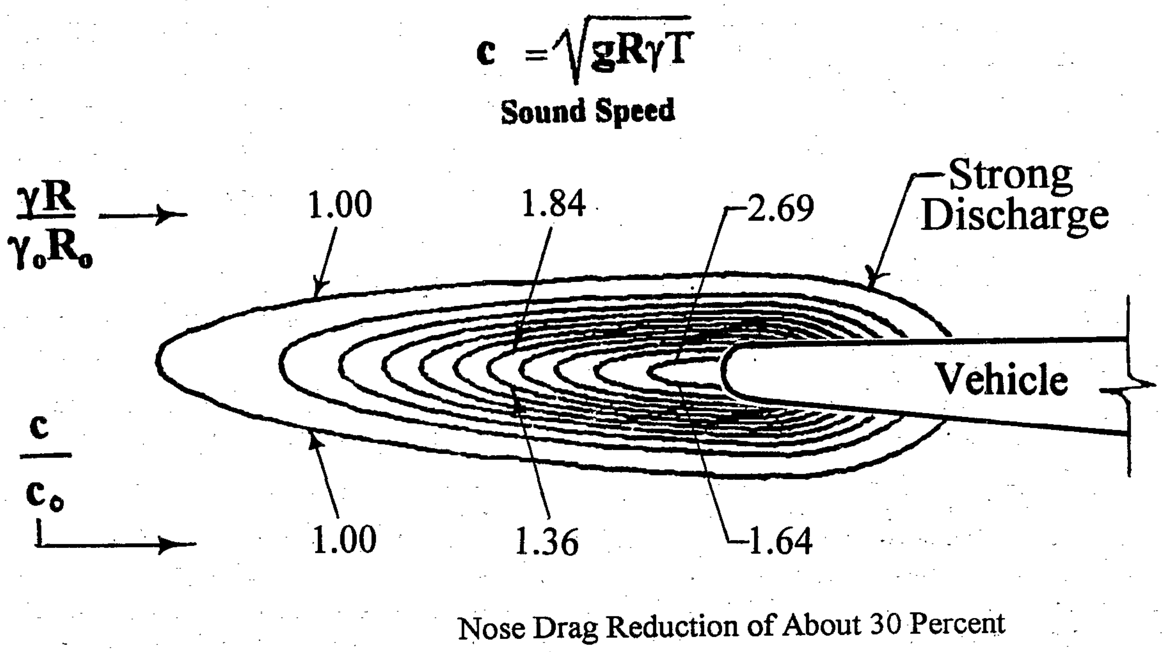

Figure 4 - **Increase in γR within the Strong Discharge Region**

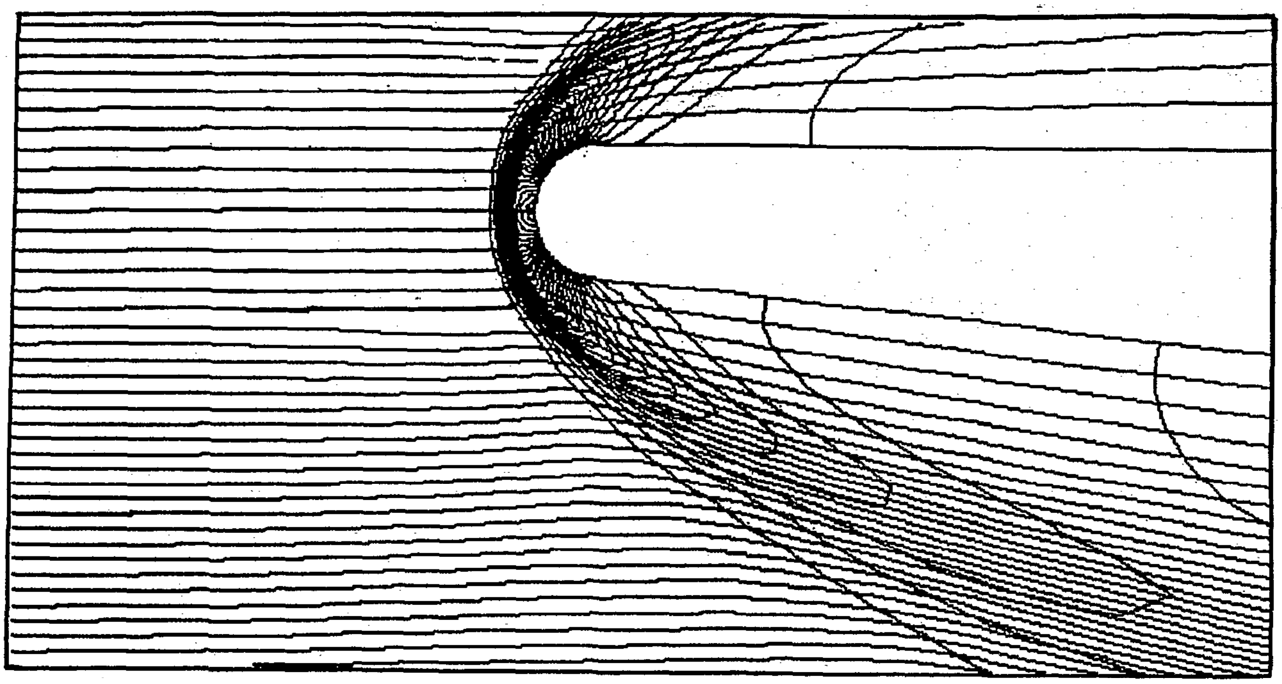

Figure 5 - Streamline and Pressure Contours in the Nose Vicinity without any Drag-Reducing Discharge

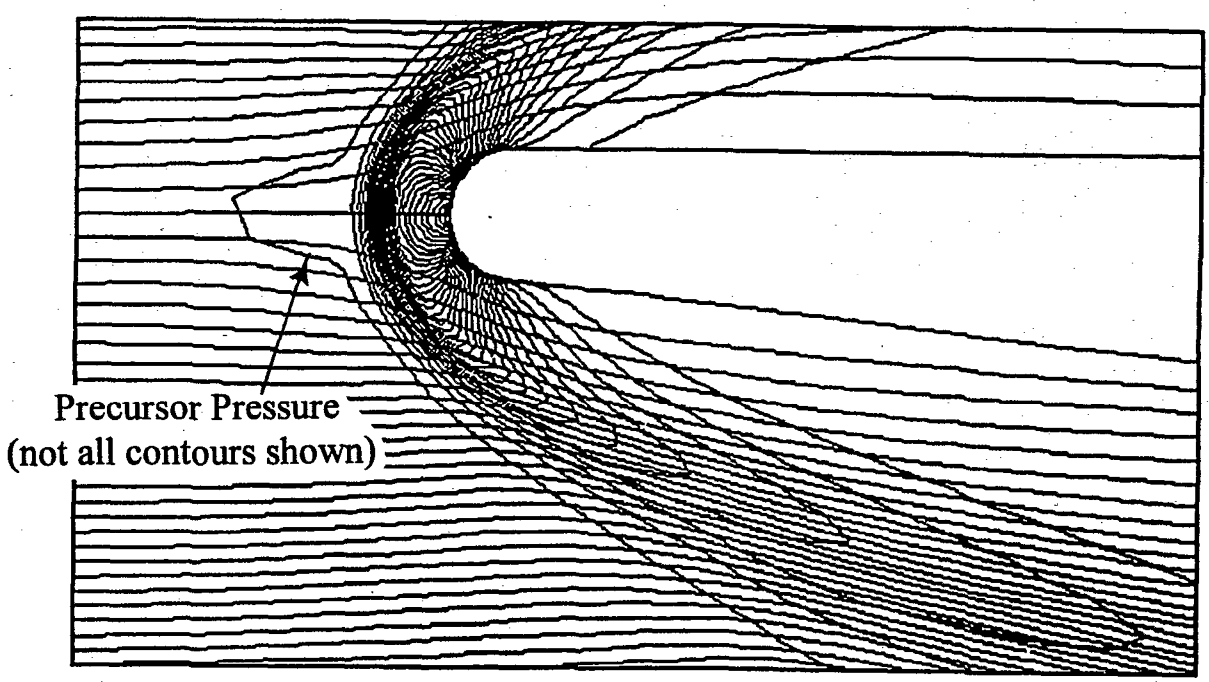

Figure 6 - Streamlines and Pressure Contours in the Nose Vicinity for a Moderate Drag-Reducing Discharge

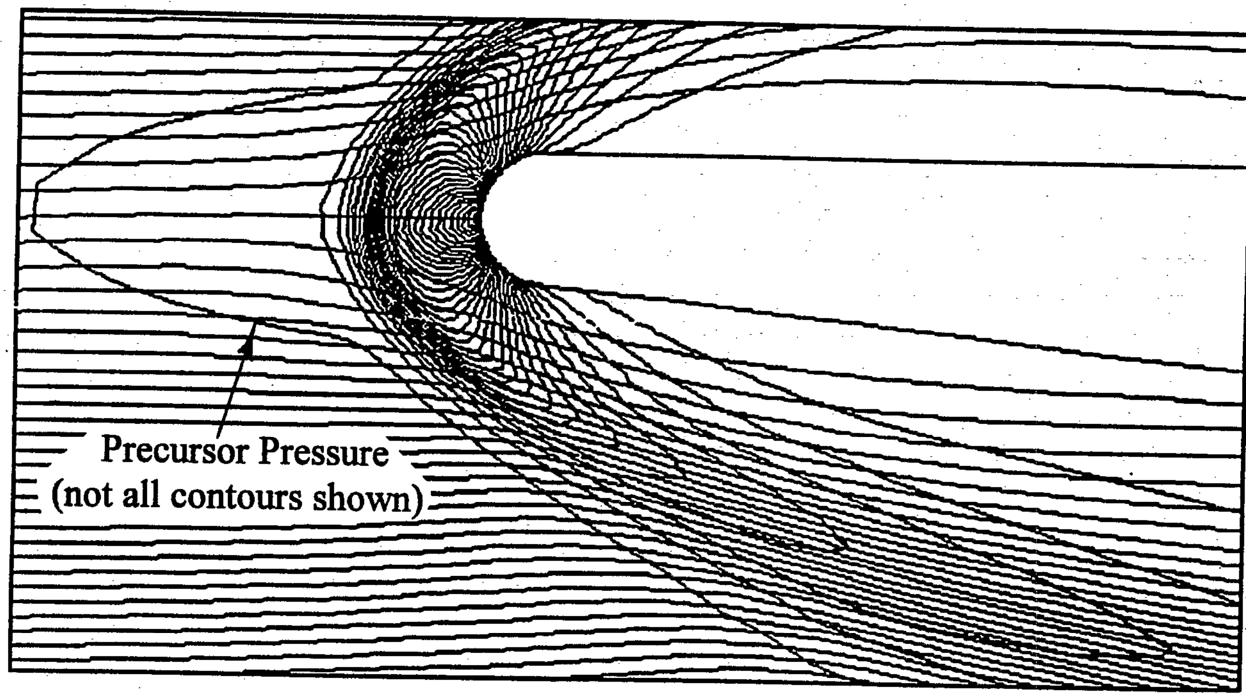

Figure 7 - Streamlines and Pressure Contours in the Nose Vicinity for a Strong Drag-Reducing Discharge

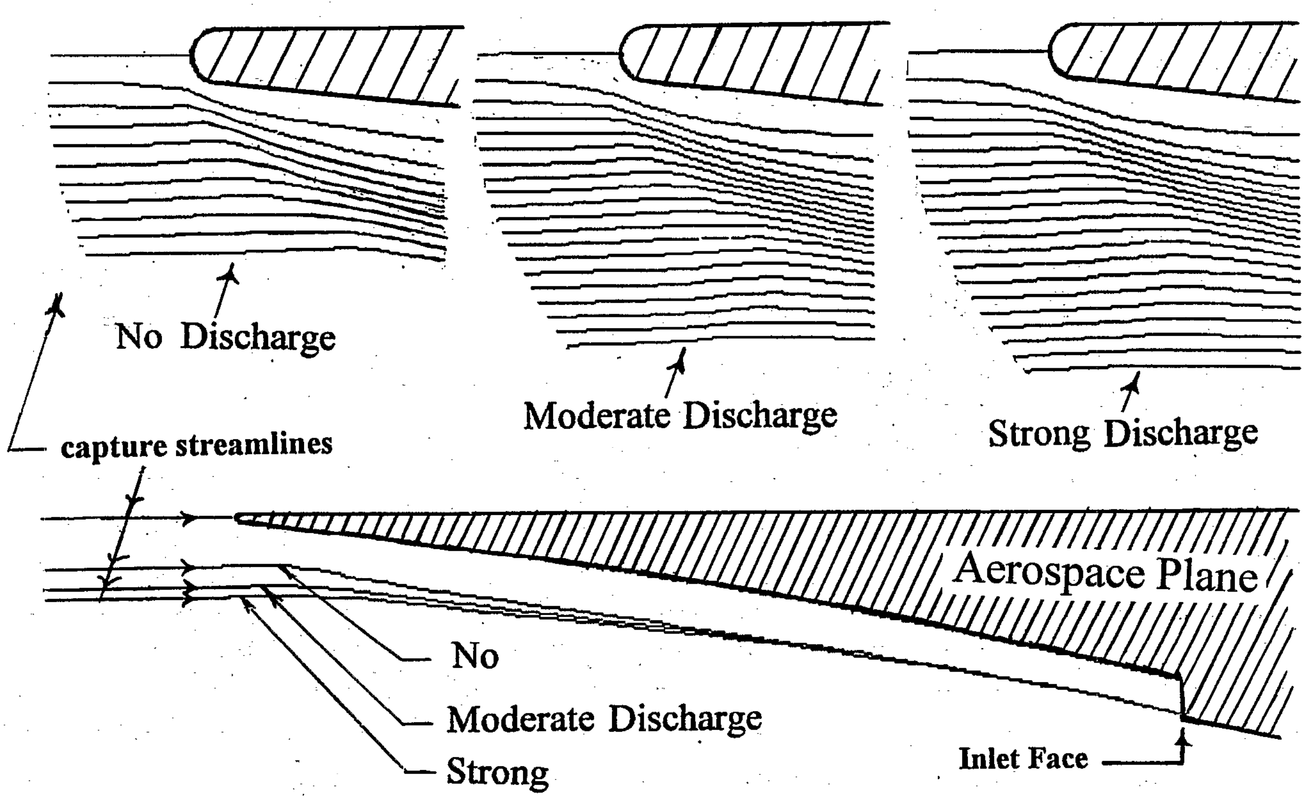

Figure 8 - Influence of Discharge Intensity on Airflow Capture

Influences of Discharges on Exhaust Flow Temperatures and Pressures

As would be expected, vehicle lift was greater and vehicle drag was less during powered flight when the aft undersurface of the vehicle was being acted on by the higher pressures associated with the higher flow temperatures caused by the engine exhaust. Here, typical airbreathing vehicles for earth-to-orbit missions or hypersonic cruise embody undersurfaces that are contoured to continue expansion of the exhaust flow downstream of the engine itself. And the curvature of such undersurfaces is such that the pressures acting upon them possess components in the lift and thrust directions. Thus, the increased engine mass flow caused by drag reducing nose discharges increase engine thrust and this was found to increase the temperature and pressure of the exhaust flow acting upon the aft undersurface. Such higher pressures from nose drag-reducing discharges resulted in higher vehicle lift and lower vehicle drag during powered flight.

This is illustrated in Figures 9 and 10 which indicate the regions of high airflow temperature that bathes the aft undersurface of the vehicle for: no discharge at all and for the strong intensity discharge from the vehicle nose. Lighter regions denote higher temperature, while darker regions denote lower. Figure 9 indicates that temperatures of moderate intensity act upon the curved aft undersurface, while Figure 10 indicates that the strong drag reducing discharge from the vehicle nose results in higher temperatures acting upon the most curved portion of the aft undersurface. Since higher pressures - with components in the lifting and thrusting directions - are associated with the higher temperatures, the drag reducing discharges increase vehicle lift and decrease vehicle drag They thus increase the vehicle's lift/drag ratio even more.

Influence of Discharges on Vehicle Thrust, Drag and Lift

Sine the moderate and strong discharges from the nose significantly reduce static pressures acting upon its hemispherical portion and directly behind it. The discharges significantly reduced the drag force acting upon the vehicle nose - as indicated in Figures 11 and 12. But drag reduction for the entire vehicle is seen to be much less during gliding (power-off) flight because the hemispherical nose is not the only major source of the vehicle's drag. Similarly, vehicle lift and lift/drag improvement is seen to be much less than vehicle nose drag improvement during gliding flight - where there is no thrust at all.

During powered flight, the significant increases in airflow capture caused by the moderate and strong discharges result in thrust increases comparable to the nose drag reductions that were achieved. This is indicated in Figures 11 and 12. Moreover, the significant thrust increase resulted in significant increase in the components of the exhaust pressure that act upon the curved aft undersurface of the vehicle in the lift and drag direction. This is seen to result in lift and drag improvements comparable to nose drag improvements, together with improvements in lift/drag ratio that are about twice as much.

Figure 11 indicates that vehicle lift/drag (L/D) ratio improvements for the moderate intensity discharge are of the order of 45 percent - about the same as those predicted in references such as (8). And figure 12 shows that even greater L/D improvements would be possible if a more intense and favorable discharge could be achieved. Increased thrust and L/D minimize drag and gravity losses during airbreathing phases of earth-to-orbit flight, and increased L/D is extremely desirable for hypersonic aircraft because their cruise range is almost directly proportional to the L/D ratio that can be achieved.

It must be emphasized that this investigation does nothing to substantiate the possibility of drag reducing discharges from vehicle noses. But, it provides encouragement that such discharges - if they can be achieved - may provide the additional benefits of increased engine thrust and this may enable significant increases in vehicle L/D.

General Validity of the CFD Analysis

This CFD analysis has been limited in its usefulness by its simplifications. One simplification is neglection of viscous effects such as skin friction drag and boundary layer buildup within the airflow volume captured by the engine inlet. Another is the 2-dimensional representation of a 3-dimensional vehicle and its 3-D flow fields. And still another is simulation of complex supersonic combustion processes by a very simple heat addition model.

Neglecting viscous effects such as skin friction drag - which is typically 30-40 percent of vehicle drag at hypersonic speeds is somewhat compensated by the fact that viscous drag, like wave drag, is reported to be reduced by favorable electric/electromagnetic discharges from vehicle noses. And things such as boundary layer build-up within captured airflow is partially compensated by the fact that it occurs for both discharge and non-discharge cases. Neglecting 3-D effects is partially compensated by the fact that typical hypersonic vehicles tend to be fairly "wide" with respect to their height and length. Such vehicles are

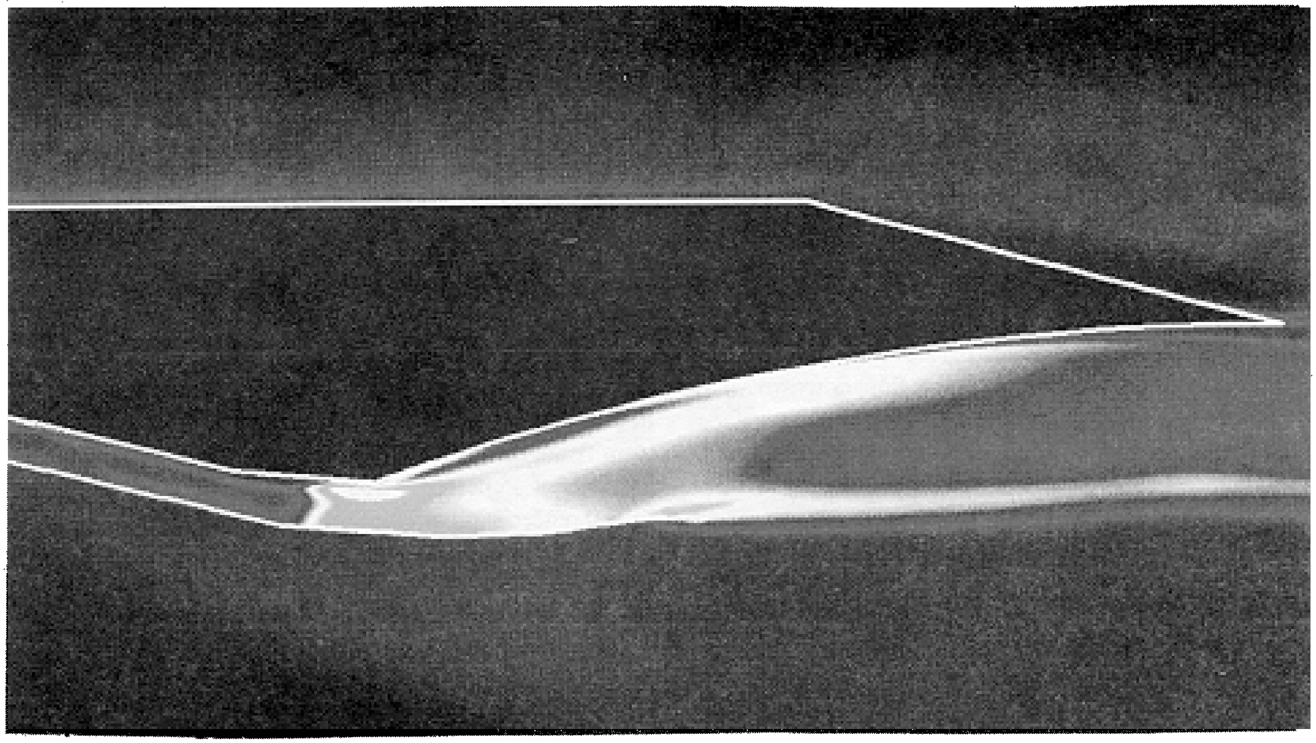

Figure 9 - Temperature Intensity in the Aft Body Vicinity for no Drag Reducing Discharge

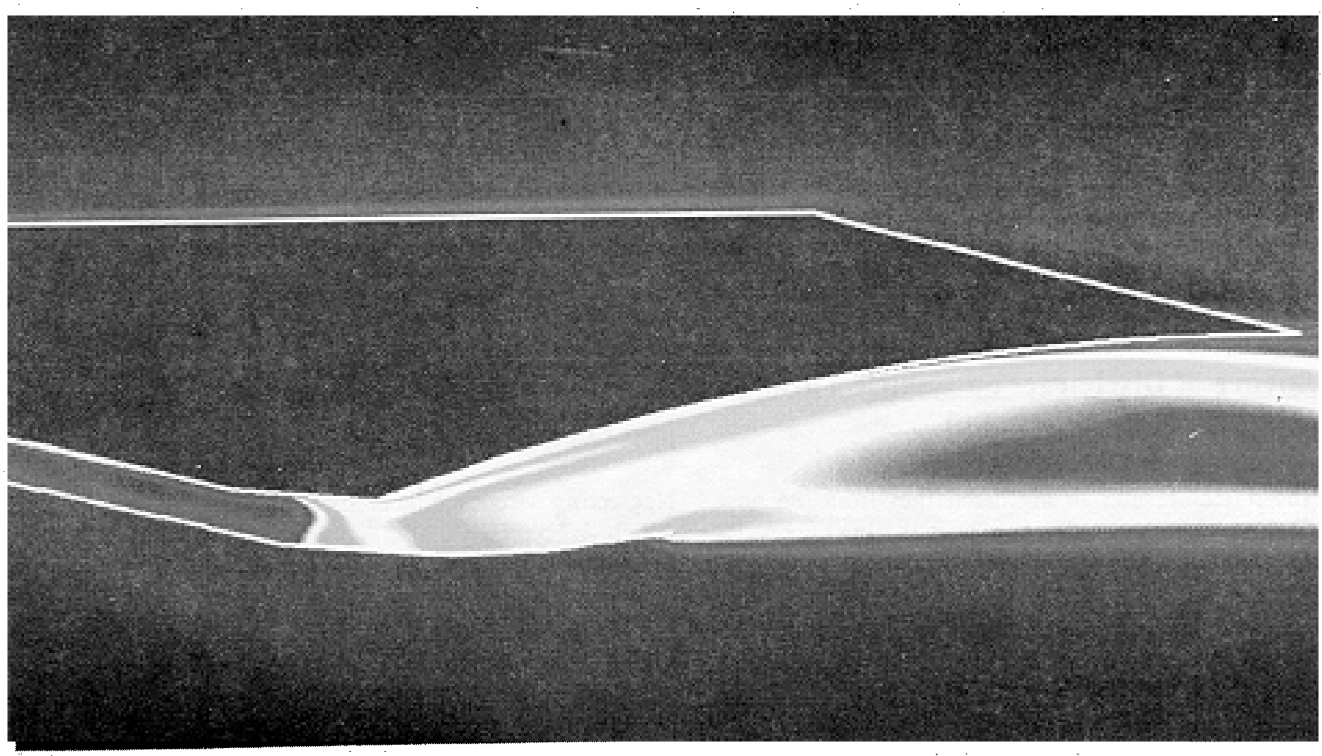

Figure 10 - Temperature Intensity in the Aft Body Vicinity for a Strong Drag-Reducing Discharge

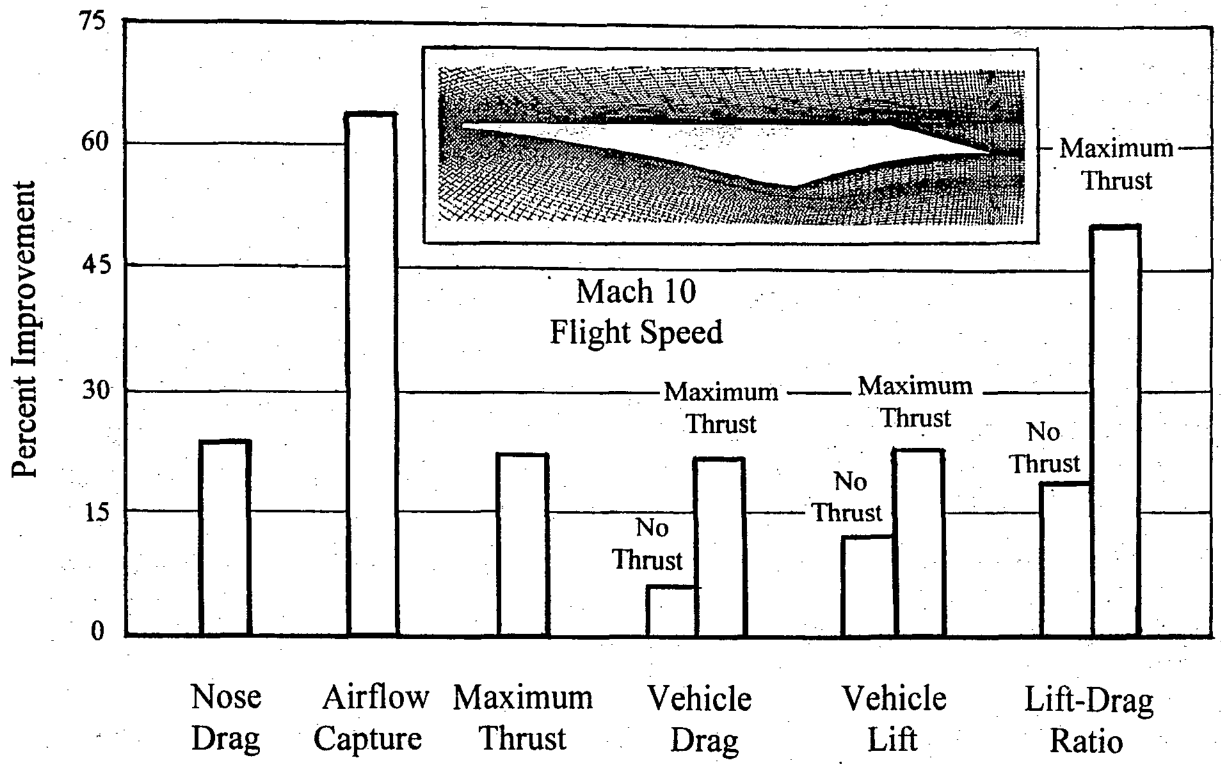

Figure 11 - Influence of Moderate Drag-Reducing Discharge on Drag, Lift, Airflow Capture and Airbreathing Thrust

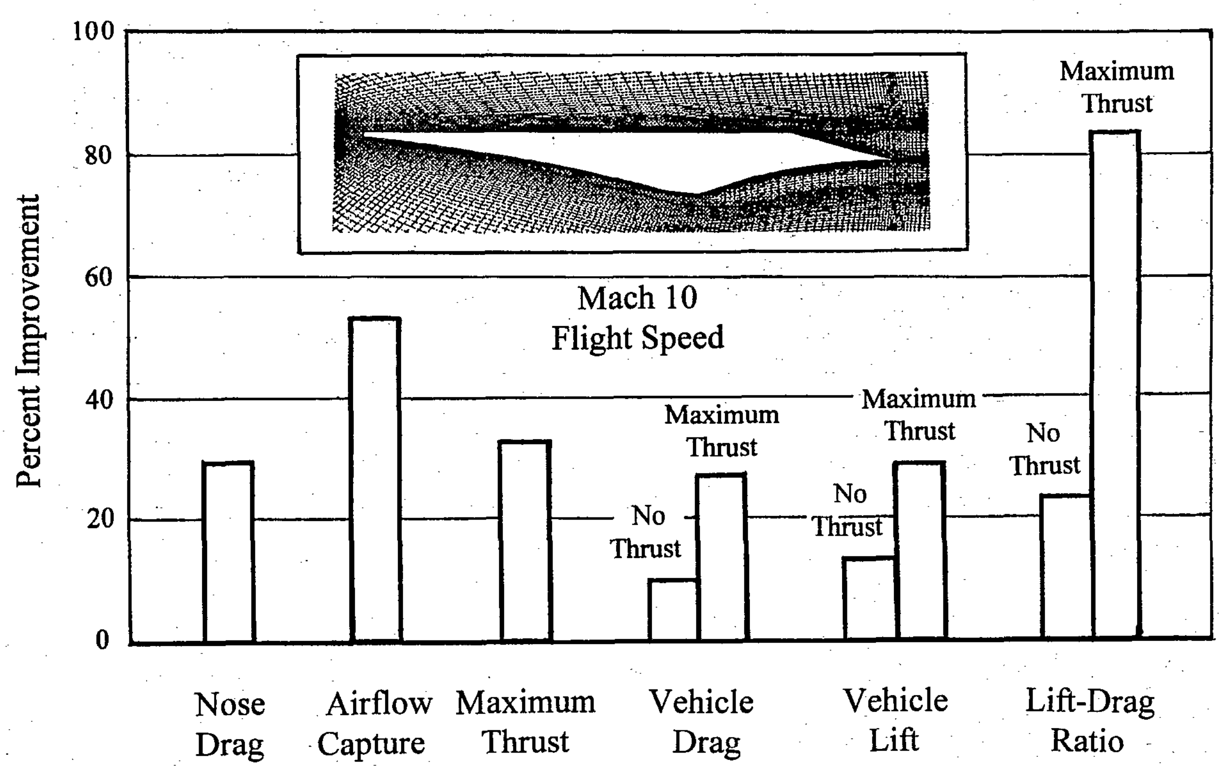

Figure 12 - Influence of Strong Drag-Reducing Discharge on Drag, Lift, Airflow Capture and Airbreathing Thrust

typified by the "Hyper-X" hypersonic airbreathing research vehicle which embodies a broad body whose maximum width is more than half of its length and a broad unswept "spatula" nose. This results in 2-dimensional flow over much of its breadth. As a consequence, references such as (11) indicate that Hyper-X surface pressures do not vary significantly over most of its lateral extent.

The simple heat addition model was found to significantly limit the amount of engine thrust that could be achieved before thermal choking occurred. Here, because this model could not replicate optimal fuel injection, mixing and burning, less than optimal heat transfer prevented achievement of high thrust. Achieved thrust levels corresponded to those that would be associated with Mach 10 cruise at high L/D - not the higher values that would be needed for acceleration during ascent to orbit or to desired altitude for cruise. Nevertheless, a consistent thrust comparison was obtained for the nose discharge and the no nose discharge cases.

Summary and Conclusions

Airflow perturbations corresponding to electric or electromagnetic discharges emitted from the vehicle nose were investigated for Mach 10 flight. Although the perturbations reduced vehicle nose drag by values of the order of 25 percent, drag reduction for the entire vehicle during gliding (power-off) flight was much less because the nose was not the only major source of drag. Nevertheless, modest vehicle drag reductions were accompanied by modest lift increases - which resulted in vehicle lift/drag increases that were roughly comparable to the percentage decrease in vehicle nose drag that the discharges caused.

The nose drag-reducing discharges caused reduction of bow shock intensity and static pressures and temperatures acting upon the hemispherical portion of the vehicle nose. Reduction in the bow shock intensity also resulted in significantly more mass flow capture by the airbreathing engine. And this increased airbreathing thrust during the powered portions of vehicle flight.

The increased thrust associated with the increased mass flow caused by the drag-reducing discharges caused higher pressures in the lift and thrust directions to act upon vehicle undersurfaces that expand exhaust flow aft of the engine nozzle. These higher pressures - which possessed components in the lift and thrust directions - so significantly improved vehicle drag and lift, that vehicle lift to drag ratio improvement of the order of 50 percent (about twice the nose drag improvement) were achieved during powered flight.

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