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Technical Notes

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Effect of Laser-Induced Upstream Cylindrical Blast Waves on a High-Velocity Rocket

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Nomenclature

A = reference area for drag
a = sound speed, nominally 340 m/s at sea level
C_d = drag coefficient
D = vehicle diameter used to calculate drag.
E = electrical blast wave energy per pulse, J
I_{sp} = specific impulse, 300 s or 3000 m/s
V_{ex} = rocket exhaust velocity, nominally 3000 m/s
V_m = velocity of missile
ρ = density

Subscript

∞ = freestream

I. Introduction

THIS technical note reports on blast wave theory calculations of the reduction of density on the axis of an electrical line discharge upstream of a supersonic vehicle that creates a cylindrical blast wave and consequent effects of reduction of drag due to the decreased air density ahead of the vehicle, see Fig. 1 where the points represent values obtained using the Sedov V parameter. The normalization is with respect to conditions immediately behind the blast wave. This is different than concepts to weakly ionize the air in front of a hypersonic vehicle to affect drag reduction [1]. Detailed numerical calculations by Kremeyer et al. [2] indicated drag reductions up to 85%, but the results are in dimensionless form and the senior author was unable to furnish conversion constants. However, there appears to be good agreement on the electrical energy needed to create the blast wave. A difference is that in [2], the rocket power was the product of the rocket thrust and the rocket velocity. In the present work, the propulsive power is the rate of expenditure of chemical energy to overcome the drag, which for most rockets consists of the product of the drag and the specific impulse (in meters per second). Thus, the rocket power in [2] is less than the propulsive power presented herein, which does not account for the differences in the results, that is, the drag reduction reported herein is less than reported in [2].

The proposed technique is based on the observed phenomena of ultrashort pulse length (femtosecond) lasers. When a collimated beam is propagated into air, its high electric field causes self-focusing of the air, which causes increases in the electric field. This causes ionization of a narrow column or filament in the air, which is electrically conducting, and for which the length can be meters or hundreds of meters, depending on the pulse energy, until the energy in the laser pulse is diminished by the photon energy that goes into ionization [3]. As proof of the concept that a cylindrical shock wave can be generated by this mechanism, an ionized filament was aimed at a sphere charged to 500 kV and this electrical energy was discharged through the filament. Based on the size of the sphere, it was estimated that 20 J were discharged.

In the present concept, a laser onboard the vehicle would irradiate the air ahead of it in a short pulse. This would form the filament. Then a pulsed electrical energy source would be discharged through the filament and create a cylindrical blast wave of finite length that reduces the air density ahead of the vehicle that reduces its drag (see Fig. 2). The details of conducting through the un-ionized air near the vehicle to the ionized filament are ignored in this analysis (perhaps an electron beam is used to create a return ionized path from the vehicle to the ionized filament).

II. Analysis

The cylindrical blast wave similarity theory of Sedov is used [4,5]. The details are contained in [6]. Conceptually, the blast wave extends only a certain distance in front of the vehicle, determined by the

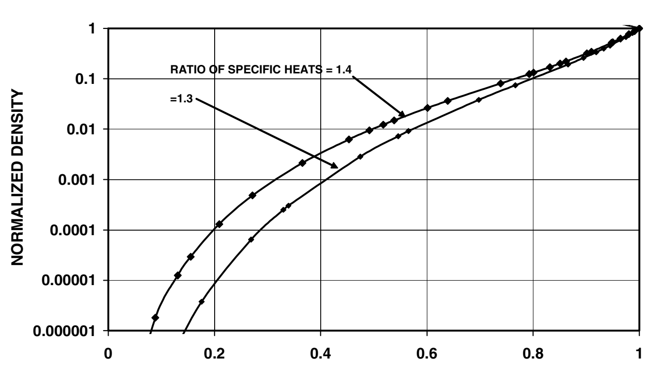

Fig. 1 Density behind blast wave, log scale with $\gamma = 1.4$ and $\gamma = 1.3$, showing that the density becomes very small at small radii.

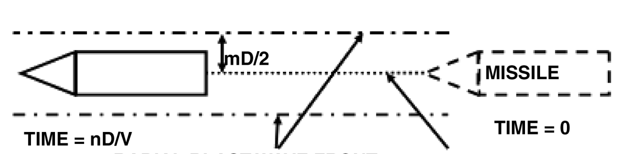

Fig. 2 Schematic of using laser-induced electrical discharges to create a blast wave ahead of a rocket [1].

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length of the ionized path. It takes a certain time for this to occur, which is neglected in calculating the change in drag on the vehicle to obtain first-order estimates of the drag and propulsion power reduction. Likewise, it takes a certain time for the pressure to relax back to ambient; this is also neglected. In physical units, the time progression of the blast wave density is shown in Fig. 3. Figure 3 shows that, near the axis, the air density is subatmospheric.

A. Long Electrical Pulse

A long electrical pulse means that the axial length of the blast wave is much larger than the diameter of the missile, so that the pressure can relax back to ambient, and the density will increase before the rocket passes through it (heat conduction is negligible for these short times). The relaxed density is shown in Fig. 4.

With the blast wave, the density around the centerline of the air path is reduced. The drag was calculated by the integration of the cross section area of the rocket of the reduced density and the square of the velocity, taking into account the cone angle. Figure 4 shows the density profile ahead of the rocket with and without pressure relaxation. This was translated into the fractional drag savings in terms of the dimensionless electrical energy (see Fig. 5). For large values of electric energy, the radial density profile in front of the missile is so small that the drag reduction reaches an asymptote of unity. However, for smaller values of the electrical energy, a straight line is observed.

The nominal missile drag coefficient was taken to be 0.134 corresponding to a 15 deg half-angle conical nose. The thrust power was evaluated as the product of the propellant mass flow rate and its chemical energy. A reasonable specific impulse was used, ~300 s, which translates into an exhaust velocity of about 3000 m/s. The propulsion power kinetic energy is the product of the propellant mass flow rate and $\frac{1}{2}V_{\mathrm{ex}}$ [2]. However, there is about an equal amount of residual static enthalpy in the exhaust products, so that the propulsion

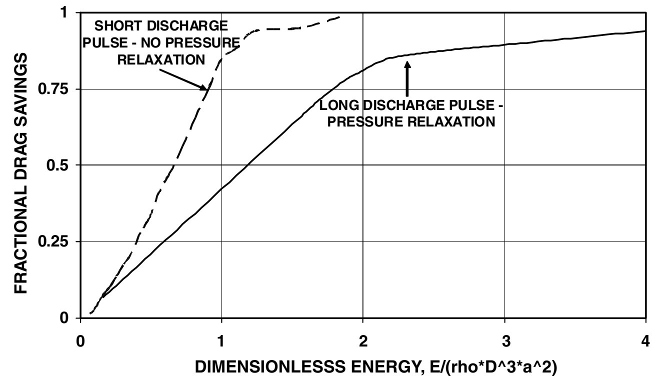

Fig. 5 Fractional drag savings vs dimensionless laser pulse energy.

power is approximated by the product of the drag and exhaust velocity:

$$P_m = \tfrac{1}{2}\rho_\infty C_d A V_m^2 V_{\mathrm{ex}} \tag{1}$$

This is shown in Fig. 6 for two different altitudes.

With the savings in drag, the thrust power reduction can be calculated using the results shown in Fig. 5. The results are shown in Fig. 7 for two different values of the drag coefficient. Note that, for the smaller drag coefficient, the electrical power exceeds the savings in the thrust power for $M = 2$. The total power (propulsion and electrical) is shown in Fig. 8.

An energy savings efficiency was formulated in [1]; it has been modified herein to equal the propulsion power saved, less the electrical power invested, divided by the propulsion power without electrical blast wave drag reduction vs the electrical power needed to cause the blast waves. This is shown in Fig. 9 for blast wave pressure recovery. It is seen that the power savings is negative for $M = 2$, but

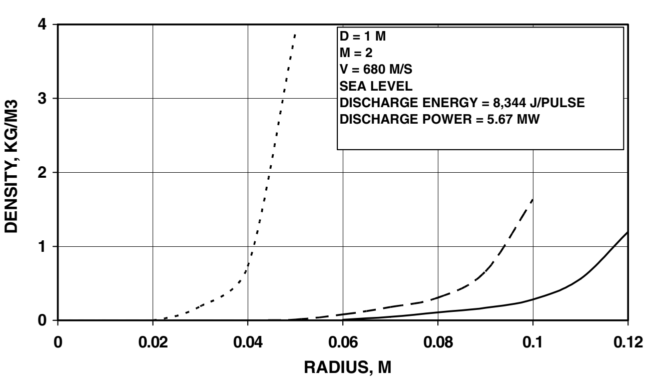

Fig. 3 Progression of density profile with time as blast wave progresses. Times, from left to right, 3.03 × 10^{-5}, 1.21 × 10^{-4}, and 1.74 × 10^{-4} s.

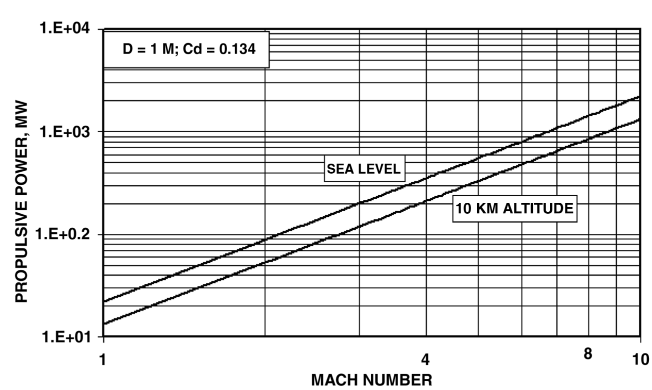

Fig. 6 Rocket thrust power, no drag reduction.

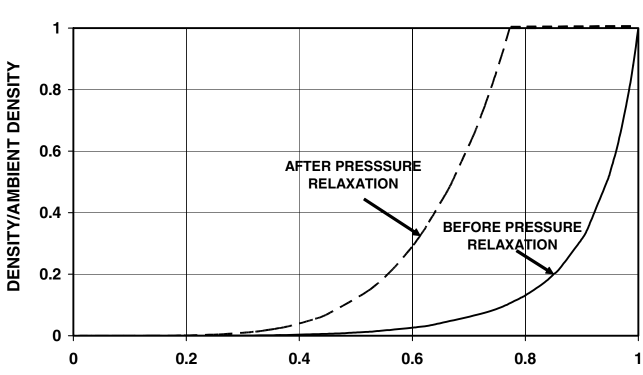

Fig. 4 Density behind blast wave before and after pressure is relaxed to ambient.

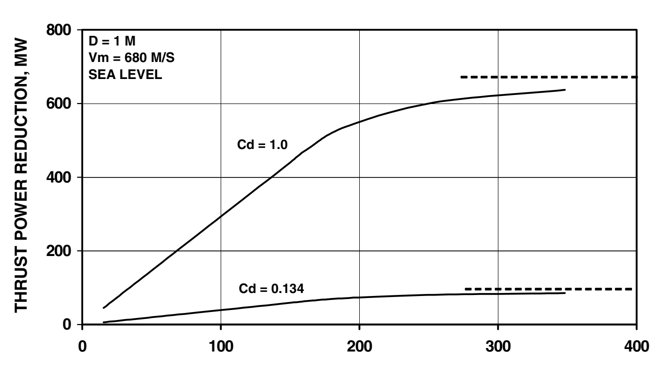

Fig. 7 Thrust power reduction vs electrical power. Dashed line represents 100% thrust power reduction.

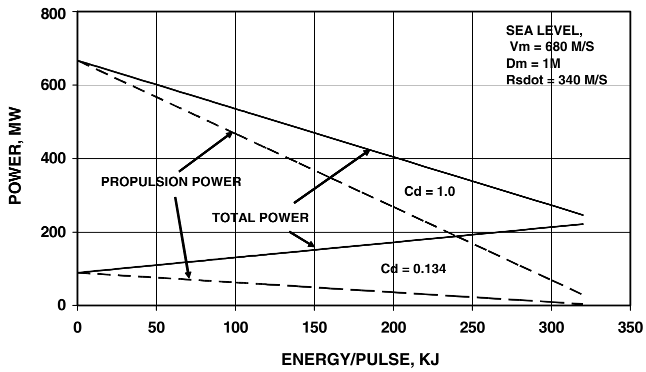

Fig. 8 Total electrical and thrust power as a function of electrical energy per pulse.

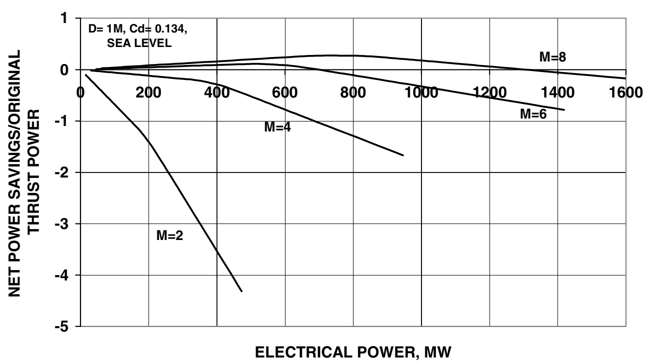

Fig. 9 Fractional power saved vs electrical power, with pressure relaxation.

becomes positive for higher Mach numbers. The plateau is caused by the reduction of drag to essentially zero, after which increasing electrical power has a negative effect on the total power. The peak electrical power for $M = 8$, sea level, is 544 MW. Note that the required electrical power decreases linearly with ambient density, so that, at an altitude of 20 km, the electrical power would be reduced by a factor of $\frac{1}{14}$. The powers needed are also proportional to the square of the missile diameter, so that, for a diameter of 0.5 m, the powers shown would be decreased by a factor of one-fourth. The values for low Mach number are negative in contrast with [1]; this is caused by a different definition: the propulsive power was used herein, whereas the drag power was used in [2]. Also, the peak power savings shown herein is lower. Note that these results are insensitive to altitude because all terms in the ratio are proportional to local ambient density, which is the same for Fig. 10. The curves move slightly to the left with increasing altitude because of decreasing sound speed with altitude.

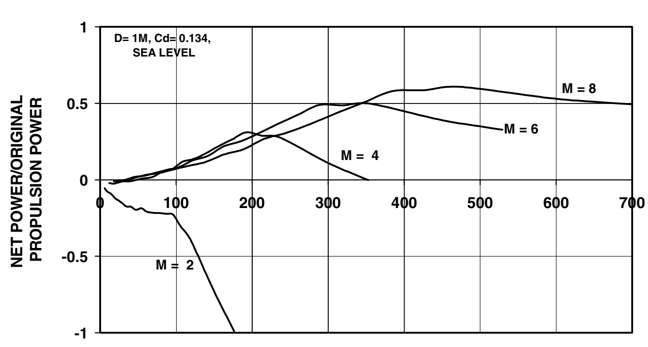

Fig. 10 Fractional power saved vs electrical power, with no pressure relaxation.

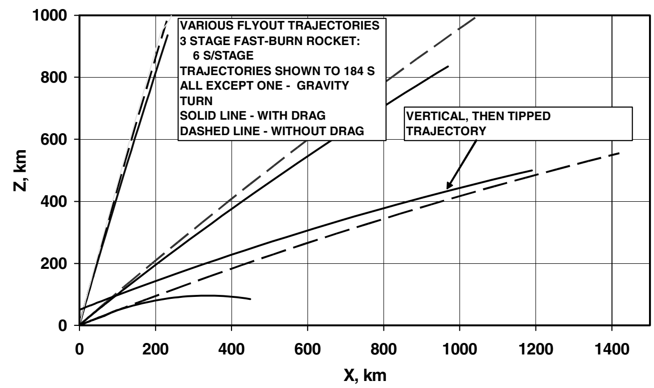

Fig. 11 Impact of drag reduction on fast-burn trajectories.

B. Short Electrical Pulse

The results for the long blast wave suggested that short blast waves should be considered, using the approximation that the pressure and density behind the blast wave do not relax until after the missile has traversed this region. The drag savings are also shown in Fig. 5; it is seen that short blast waves (in the axial direction) that do not have time for pressure recovery nearly double the energy savings compared to long blast waves in which the pressure recovers. Figure 10 shows the resulting energy efficiency. A maximum energy efficiency of about 60% is shown for an electrical power of about 350 MW.

III. Impact on Fast-Burn Rocket Trajectories

The trajectories that suffer severely from atmospheric drag, and which therefore can benefit the most from drag reduction, are fast-burn trajectories from the ground, because they achieve very high velocities within the atmosphere. As an example, calculations were performed for a three-stage rocket, with 6 s burn time for each stage, and using a specific impulse of about 300 s. The drag coefficient was selected as 0.15 and a base diameter of 0.5 m. The total mass was 6759 kg, and a propellant mass loading for the first three stages was taken as 0.88. The results are shown in Fig. 11 for three gravity-turn trajectories. Only in the case of a depressed trajectory was drag reduction important. However, for that case, one additional trajectory was calculated: initially vertical and then tipped over, with a drag penalty for the turn. Here, again, it is seen that it does almost as well as for complete drag reduction. For more practical drag reductions of up to 60%, there may be no net benefit of drag reduction over trajectory shaping. In addition, for these calculations, zero mass addition was assumed for the laser/electrical discharge equipment. In [5], the implications of the power supply on mass are discussed.

IV. Conclusions

A theoretical analysis has been made of the concept presented in [1] of using a repetitively pulsed electrical cylindrical blast wave through a laser-induced ionized path ahead of a rocket. It is found that, for low supersonic speeds, the total power required exceeds the vehicle thrust power for the usual low level of drag coefficient. For very high speeds, there is a slight advantage to adding electrical energy to the upstream air, but the mass of such an electrical supply may be excessive [6]. For ground-based flyouts of high-acceleration rockets, there is very little advantage to drag reduction.

Acknowledgment

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