Theoretical Concepts of Drag Mitigation of Space Vehicles in stagnation point and side-long before Entering the Space by Injection of Plasma Jet

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For aerospace vehicles flying at hypersonic speed there is always a trade-off between their thermal protection and the propulsive requirement. This motivates researchers around the globe to search for technologies that would be used to minimize the propulsive requirement, thereby effectively reducing the wave drag in actual missions. Various methods such as retractable aero-spikes, counter flowing supersonic jets, concentrated energy deposition and plasma injection from stagnation point have been tried by different research group, for reducing the wave drag at hypersonic speeds. Counter flow plasma injection from the stagnation region of the blunt body in particular is exciting since it can give the combined effect of counter flow jet and energy.

The velocity needed to achieve the Earth's orbit is about 27,350$^{km}/_{hr}$. The velocity needed to escape the Earth's gravity and send a spacecraft to the Moon or another planet is about 40,200$^{km}/_{hr}$. One way to reduce the effect of gravity is to take off in an easterly direction from a position close to the equator. This adds the Earth's velocity to that produced by the rocket. From Cape Canaveral this adds about 1,450$^{km}/_{hr}$ to the rocket's speed [1].

The hypersonic vehicles, such as space shuttles and spacecraft, flying at hypersonic speed generates strong bow shock ahead of nose before reaching the space. Among a number of design requirements, the reduction of bow shock is the major challenge in the design of space vehicles, i.e., rockets, space shuttles, etc. The dynamic pressure on the surface of the blunt body can be reduced by creating low pressure in front of the blunt body by injecting argon plasma jet. Undoubtedly, by this method a space shuttle or rocket would escape from the Earth's gravity with more velocity and weaker bow shock.

Considerable theoretical and experimental efforts have been devoted to the understanding of shock waves and bow shocks in supersonic/hypersonic flows. Various approaches to develop wave drag-reduction technologies have been explored since the beginning of high-speed aerodynamics. In the following, a few of those are discussed.

Buseman [2] suggested that geometrical destructive interference of shock waves and expansion waves from two different bodies could work to reduce the wave drag. However, the interference approach is effective only for one Mach number and one angle-of-attack, which make the design for practical implementation difficult.

Using electromagnetic forces for the boundary layer flow control have been suggested as possible means to ease the negative effect of shock wave formation upon flight [3]. However, an ionized component in the flow has to be generated so that the fluid motion can be controlled by, for instance, and introduced $J \times B$ force density, where J and B are the applied current density and magnetic flux density in the flow.

Thermal energy deposition in front of the flying body to perturb the incoming flow and shock wave formation has been studied [4, 5 and 6]. Heating of the supersonic incoming flow results in a local reduction of the Mach number. This weakens the shock wave by increasing the shock angle (i.e., moving the shock front upstream). Although this heating effect is an effective means of reducing the wave drag and shock noise in supersonic and hypersonic flows, it requires a large power density to significantly elevate the gas temperature [6]. It is known that use of the thermal effect to achieve drag reduction in supersonic flight does not lead to energy gain in the overall process. Thus, this is not a practical approach for drag reduction purposes, but it can be a relatively easy approach for sonic boom attenuation [4]. Direct energy approaches have been applied to explore the non-thermal/non-local effects on shock waves. Katazen and Kaattari [7] investigated aerodynamic effects arising from gas injection from the subsonic region of the shock layer around a blunt body in a hypersonic flow. In one particular case, when helium was injected at supersonic speed, the injected flow penetrated the central area of the bow shock front, modifying the shock front in that area to be conical shape with the vertex at much farther distance from the body (at about one body diameter). Laser pulses [8-9] could easily deposit energy in front of a flying object. However, plasma generated at a focal point in front of the model had a bow radius much smaller than the size of the shock layer around the model, and its non-local effect on the flow was found insignificant.

Plasma has the potential to possibly offer a non-thermal modification effect on the structure of shock waves. Appartaim et al. [10] further show that the plasma effect increases with an increase of the atomic weight of the plasma (generated in noble gas), unambiguously, excluding the thermal effect to be responsible for the observed shock acceleration.

The study of the plasma effect on shock waves was inspired by the observation of a wind tunnel experiment conducted by Gordeev et al. [11]. High-pressure metal vapor (high Z) plasma, produced inside the chamber of a cone-cylinder model by exploding wire off electrical short circuit, is injected into the supersonic flow through a nozzle. A significant drag reduction was measured, which was too large to be accounted for by the thermal effect alone. A brief history of the development of this work was reported in an article published in the Jane's Defence Weekly [12].

In the other wind tunnel experiments, the results showed that the shock front increased dispersion in its structure and/or standoff distance from the model when plasma was generated ahead of a model either by off-board/on-board electric discharges [13-20] or by off-board microwave pulses [21]. Exton et al. [18] applied a seeding approach to generate plasma in front of the baseline shock front by the on-board microwave pulses, however, the plasma was too weak to introduce any visible effect on the shock wave. Baryshnikov el al. [16] investigated the relaxation time of the shock structure, attributed to the existence of long-lived excited states of atoms and molecules in the gas, is additional evidence of the presence in the plasma of effects other than those thermally induced.

Malmuth *et al* [22] studied both experimentally and numerically the effect of counter flow plasma jet on the aerodynamic augmentation of a blunt body. They conducted experiments at free stream Mach numbers 2·0, 2·5 and 4·0 and were able to measure the pressure distributions over the model in the presence of the plasma jet. Like a conventional counter flow jet, two stable operational modes, a short penetration mode (SPM) and a long penetration mode (LPM) are also found in case of a plasma jet . The greatest drag reduction is found to occur in the moderate LPM regime. Ganievet et al [23] studied experimentally the possibility of reducing drag by injecting plasma from body surface. They performed experiments in a supersonic vessel type V-I wind tunnel at different free stream Mach numbers (2·0-4·5), prechamber pressures (2·5-18·5 atmosphere) and Reynolds number per meter ($3{\cdot}2 \times 10^7$-$8{\cdot}4 \times 10^7$) and showed reduction in model drag in all conditions. Fomin et al [24] conducted experiments with counter flow plasma jet on cylinder cone model at hypersonic Mach number 6·0. They could record the changes in the flow pattern as well as the drag reduction of the model in the presence of plasma jet. Shang [25] performed both experimental and numerical investigation for plasma injection from a hypersonic blunt body for drag reduction. The experiments were conducted in a Mach 6·0 open jet blow down tunnel. From his studies he found that the drag reduction is mostly derived from the inviscid-viscid interaction of the counter flow jet and thermal energy deposition.

Now in this study, it has been proposed that reducing dynamic pressure by creating low pressure in tip and all-around sidelong of a space rocket can be practical by injection of plasma. Fig 1 shows velocity Pathlines near a blunt body at hypersonic ~ 6 Mach. In order to make launching with more velocity and neutralizing bow shocks and shock waves, which are generated by incoming flow, the bow shock mitigation in tip of space shuttle by injection of counter flow plasma jet and aerodynamics drag reduction at all around sidelong of space shuttle by plasma spray is an efficient solution (before entering to vacuum space). The plasma injection at all around the space shuttle sidelong has three primary goals: 1) Bow shock mitigation in front of space shuttle before reaching the space (and so results in increasing of space vehicles velocity). 2) Eliminating likely shocks and incoming flows around space vehicle's sidelong at different atmosphere layers before reaching space. 3) Results in reducing bow shock and drag flow and possibly a net energy savings to minimize fuel volume and then make launching easier.

Experimental results of bow shock mitigation by injecting counter flow argon plasma in front of a blunt body at hypersonic flow conducted in a shock tunnel test section are used from D. Mahapatra's experiment and we utilize some of its details for our proposal [26]. Experimental results show that plasma injection in tip of a blunt body deflects the incoming flow and its interaction with bow shock has a maximum reduction of ~28% in the drag. ~28% reduction in drag means that the velocity and thrust of blunt cylinders like rockets, space shuttles, etc. can be increased and the amount of liquid fuels (used for, for example, space shuttle’s thrust) and the volume of the external tank and the solid rocket boosters can be reduced by this technique proportional to ~ 28% drag force reduction.

Experimental results of prior studies, as is shown in Fig 2, show that in hyper/supersonic speeds drag force would be easily reduced by plasma injection technique. For example, D. Mahapatra's experiment [26] showed that the reduction of drag by counter flow argon plasma jet interaction could be derived from the possible contributions by favourable counter flow jet and bow-shock interaction, thermal energy deposition by plasma jet, electromagnetic effect and non-equilibrium effect produced by the plasma jet. Theoretical investigations have been performed to study the effect of counter flow plasma injection on aerodynamic drag of a hemispherical blunt cylinder model in IISc, hypersonic shock tunnel. It is found that at higher pressure ratio there is a significant reduction of drag in presence of plasma. A maximum reduction of ∼28% in the drag is observed for a pressure ratio of 72· 5 and supply power of 1· 8KW, which is going to be still more if the decreased mass flow rate because of plasma temperature is taken into account. From the study it can be found that the reduction of drag is because of the combined effect of jet-bow shock interaction and energy addition by plasma jet. Figure 2 shows that how counter flow plasma jet interacts with bow shock of blunt tip body. A brief drag reduction analysis is presented at Fig 3B.

As shown in Fig 1, in the front of the blunt body, the drag force is low but in the circular sidelong, drag has considerable increase, which means that if plasma injection applied in the all-around sidelong, we will have a considerable drag reduction in overall. It is this paper proposal to apply plasma injection at not only tip of space shuttle but also its circular sidelong. The schlieren technique makes it possible to study both the tip and the surface profile of blunt body that inject plasma spray to its around incoming air to reduce drag; thus, it is obvious that the volume of propulsion systems of space shuttle would be decreased proportional to whole drag reduction. At Fig 3A a plasma spike has specially been designed to inject plasma spray into the incoming air all around sidelong of space shuttle. This model should be designed to have the tip, plasma spikes and the body of the model as the two electrodes for gaseous discharge, which are separated by a ceramic insulator. In fact the plasma spike is introduced at a location in sidelong of the model by an on-board electrical discharge. The breakdown voltage should also be provided by a power supply. As shown in Fig 3C, it is estimated that when the emission of plasma reaches the peak, the incoming flow would considerably interacts with plasma emission and then by continuous plasma peak emission, drag force is reduced 50% at all around a space shuttle.

As shown in figure 3D, a plasma torch is device for generating a directed flow of plasma. In a DC torch, the electric arc is formed between the electrodes (which can be made of tungsten) and the thermal plasma is formed from the continual input of carrier/working gas, projecting outward as a plasma jet/flame. The quality of plasma produced is a function of density (pressure), temperature and torch power (the greater the better). It is better to utilize Argon for ionization because it needs low energy for plasma generation. For example, applying this method for Soyuz5, the design of a scale model of Soyuz5 must include the inbuilt plasma torch in tip (stagnation point) and manoeuvrable plasma torches systems designed around the model. The geometrical homogeny, kinematical homogeny and dynamical similarity of the model must be completely corresponding to the real Soyuz5 then we can observe the drag reduction.

From the study it can be found that the reduction of drag is because of the combined effect of jet-bow shock interaction and energy addition by plasma jet. As shown, in the front of the blunt body, the drag force is low but in the circular sidelong, drag has considerable increase, which means that if plasma injection applied in the all-around sidelong, we will have a considerable drag reduction so it is estimated (before reaching to space) that the continuous produced spray-like plasma and plasma jet would deflect the incoming flow ~50%; thus, minimizing the volume of propellant system a space shuttle and resulting in increasing velocity, with the minimum usage of propellant proportional to a maximum reduction of ~50 % in the drag. Theoretically, creating low pressure in stagnation point and all-around of the blunt body results in reducing dynamic pressure. We have the power and density of the plasma injectors so it can be derived the amount of decreased dynamic pressure and then we can calculate the amount of reduced drag and increased thrust force.

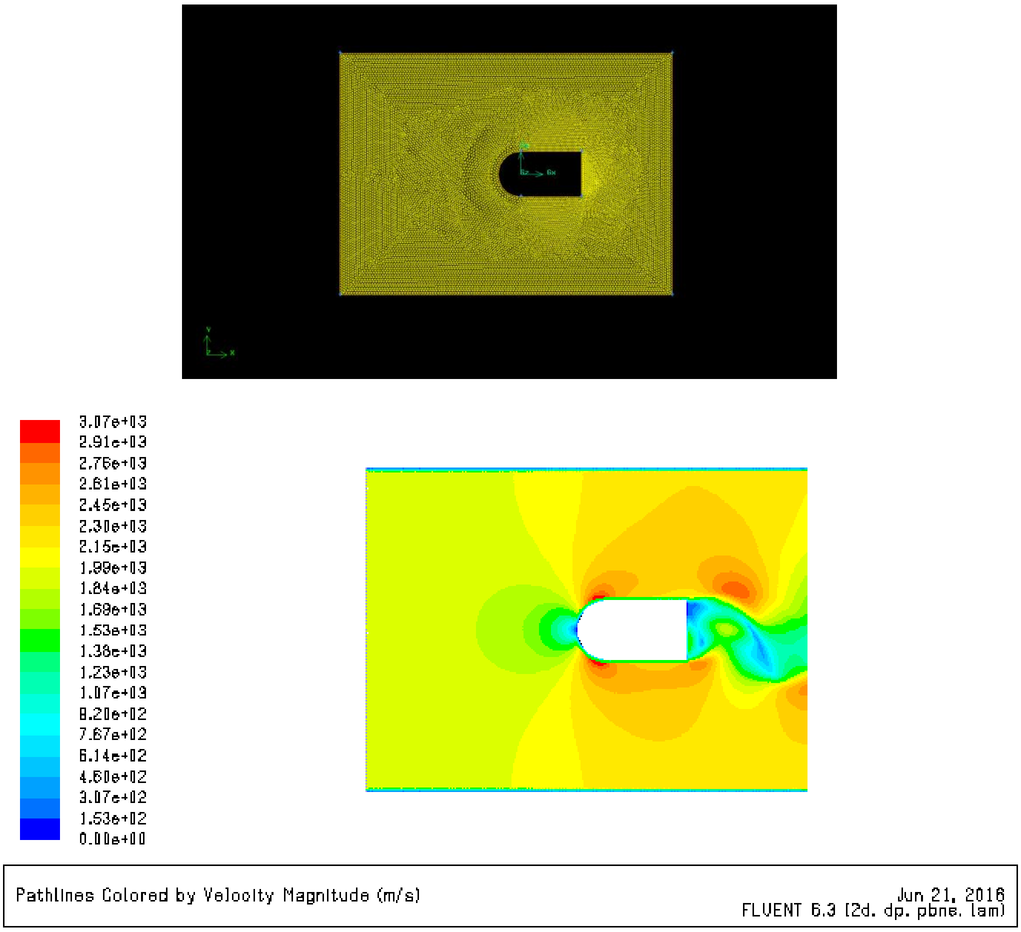
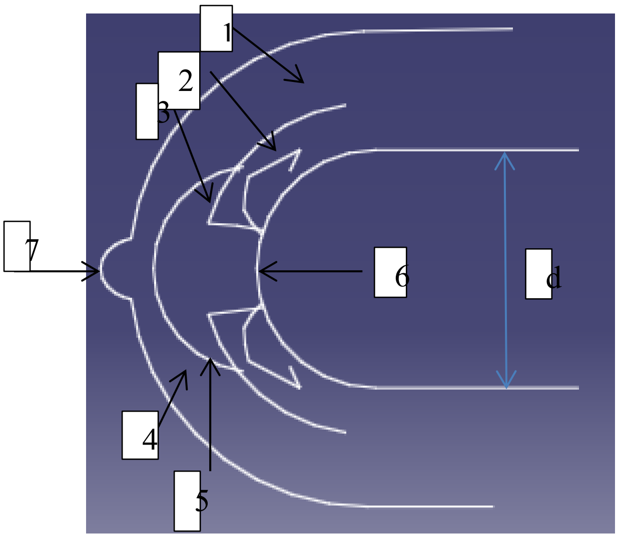


Figure 1. Computational mesh and velocity distribution at hypersonic speeds near blunt body.



(A)

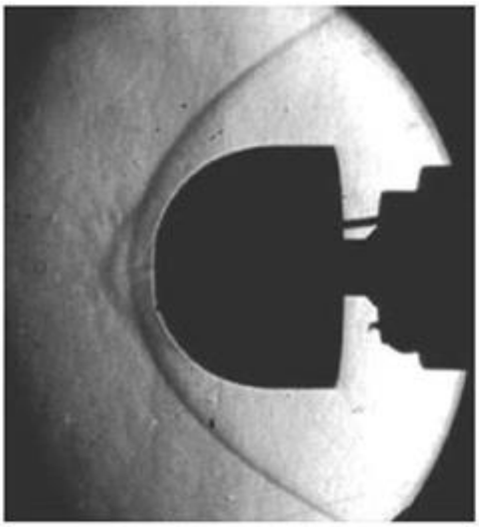
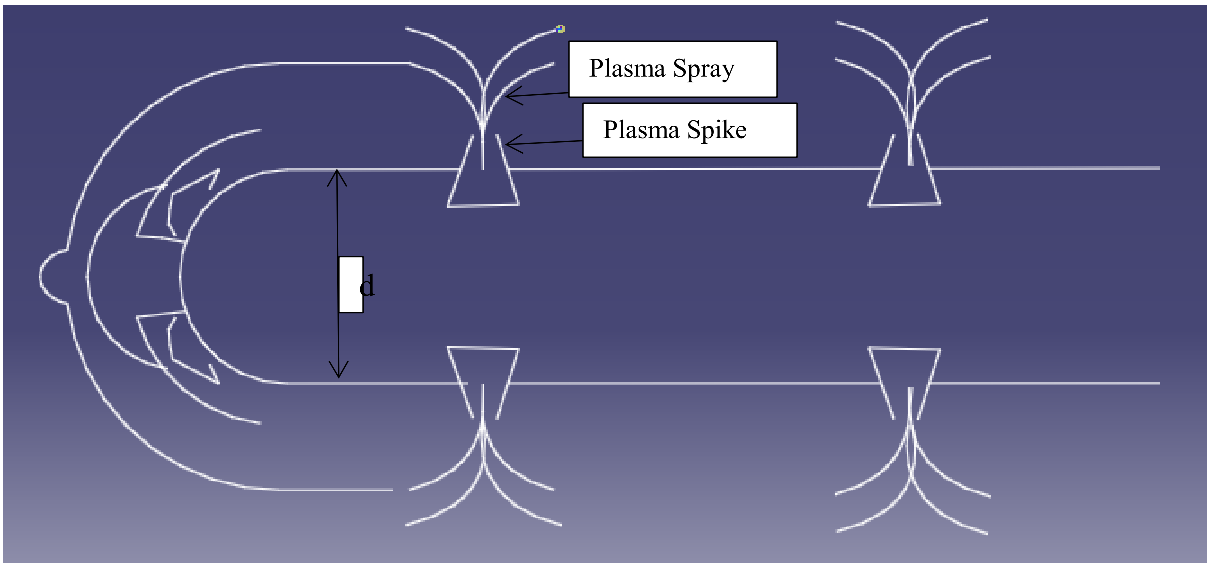

(B)

Figure 2. (A) Schematic of the typical flow features of a counter flow plasma jet. Numbers 1, 2, 3, 4, 5, 6 and 7 are main flow, recirculation region, jet layer, sonic line, interface, plasma jet ($M_j P_j$) and hypersonic flow ($M_f P_f$) respectively. (B) A typical schlieren photograph obtaind from a plasma jet.



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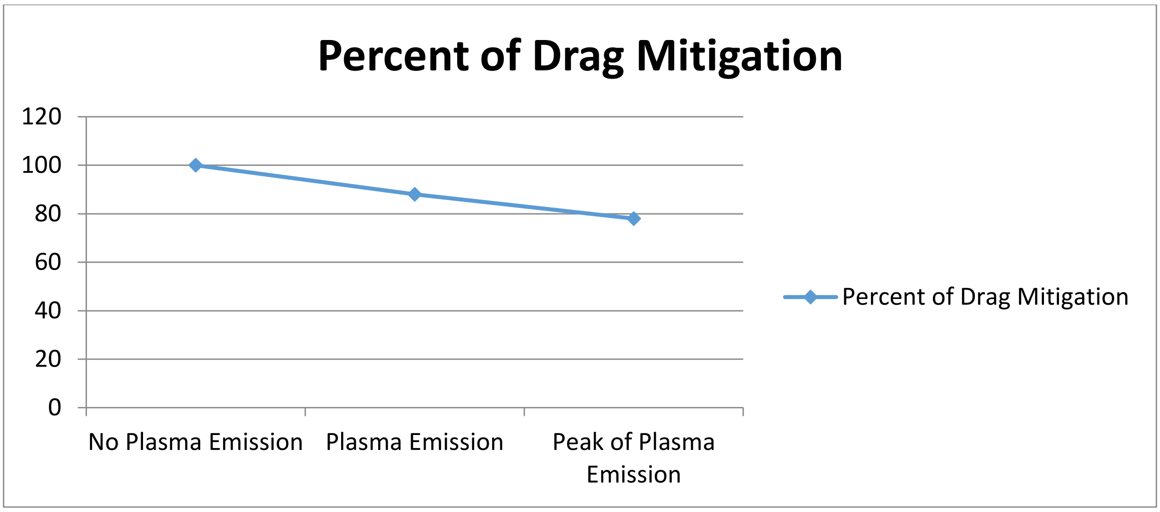

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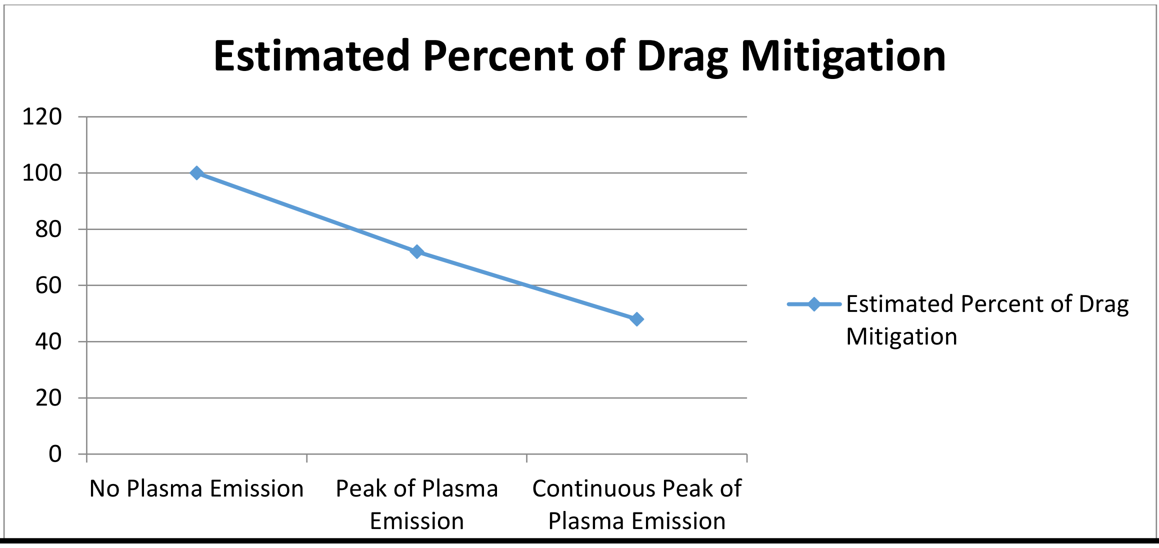

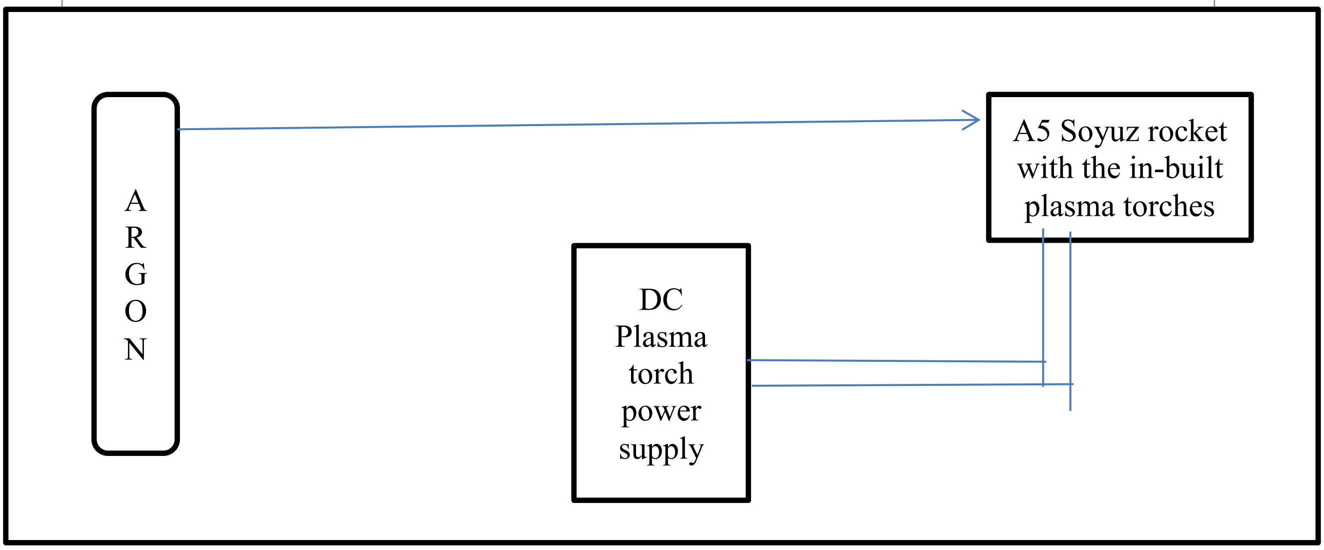

Figure 3 A, B, C and D. Proposed plasma injection in blunt tip and all-around sidelong of space vehicles, Drag force reduction at Much 6.0 and 8.0 conditions, Estimated drag force reduction for space vehicles before reaching space and plasma injection system for A5 Soyuz.

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