Future Challenges in Spacecraft Plasma Interactions: Plasma Propulsion and Gas Release

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Spacecraft plasma interactions are getting more important as new propulsion concepts with active plasma and neutral gas sources are introduced. An overview of electric propulsion thrusters and possible spacecraft interactions are shortly discussed. Also new ideas such as interactions with the solar wind and the neutral gas atmosphere for propulsion purposes are presented. Plasma interactions may even play an important role for future launchers were plasmas can reduce atmospheric drag and improve scramjet performance.

1. Advanced Propulsion Challenges

In chemical propulsion, two propellants (fuel and oxidiser) react in a combustion chamber to produce a hot gas, which is expelled through a nozzle (see Fig. 1). Therefore, chemical propulsion systems are limited in their performance due to the chemical energy stored in the reaction partners.

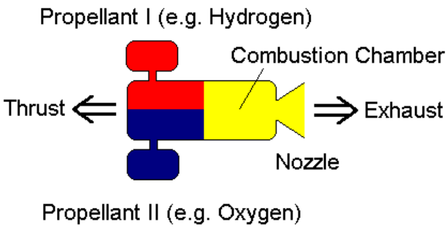

Figure 1 Chemical Propulsion Systems

One category of advanced propulsion systems use energy generated on board the satellite (solar arrays, nuclear power source) to couple with a working fluid or gas. Depending on the power available, performance and propellant utilisation can be drastically increased in this case. One important parameter is the propellant velocity characterised by the specific impulse (velocity divided by Earth gravitational acceleration constant). Since the thrust is given by the mass flow times the velocity, a high specific impulse can reduce the mass flow for a specific thrust value. To achieve such high exhaust velocities, the propellant is the either heated by electric or nuclear means or ionised and accelerated through electrostatic or electromagnetic fields.

Other advanced propulsion concepts use external resources such as the solar wind or the ambient neutral gas atmosphere for propulsion purposes. Some of these concepts are truly enabling technologies for future manned exploration or interstellar missions.

This paper shortly summarises concepts under development, challenges and possible spacecraft interactions of such future propulsion concepts[1].

2. Electric Propulsion

With respect to the type of acceleration, electric propulsion systems are subdivided into electrothermal, electromagnetic, and electrostatic propulsion systems.

2.1 Electrothermal

- **Resistojet:** The propellant (hydrazine, ammonia, water) is flowing through an electric resistor and expelled through a nozzle (see Fig. 2). Although performance is similar to an efficient chemical propulsion system, a resistojet has the advantage of low complexity and the possibility to use a variety of different easy storable propellants.

- **Nuclear Thermal Rocket:** Instead of using an electric heater, a nuclear reactor core can provide a very efficient heat source at very high power and thrust levels. Such nuclear rockets were developed in the 1960's and 1970's in the United States (NERVA program) leading to a fully integrated engineering model. Due to political and environmental constraints, research on this propulsion system is presently very limited.

- **Arcjet:** Very high local temperatures can be generated by an arc discharge through the propellant (e.g. hydrazine, hydrogen). Performance is well above chemical propulsion systems, also high power levels can be processed.

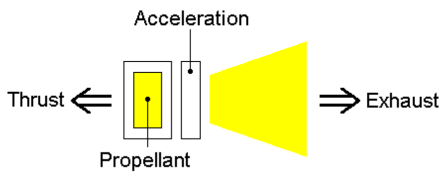

Figure 2 Electrothermal Propulsion

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2.2 Electromagnetic

- **Pulsed Plasma Thruster (PPT):** In this concept, solid Teflon is ablated, ionised and accelerated through a spark discharge. Although the performance is similar to an arcjet thruster, the efficiency of this system is very low (a few percent). However, the simple concept and solid propellant storage makes it very cheap.

- **Magnetoplasmadynamic (MPD) Thruster:** Gaseous (Hydrogen, Ammonia) or liquid fuel (Lithium) is ionised by a high current discharge between a tube shaped anode and rod cathode. The current generates a magnetic field and the propellant is pushed out by the anode field configuration. Very good performance and high thrusts can be produces, one major issue is lifetime limitation due to cathode erosion.

- **Plasma Rocket:** Here, the propellant is ionised and kept inside a magnetic bottle. Additional heating through radiofrequency and microwave fields generate a very hot plasma which can be expelled through a leak in the magnetic field. Very high performance and thrusts at the cost of a very complex system can be achieved. This concept is presently under evaluation for a manned Mars mission.

2.3 Electrostatic

- **Ion Thruster:** Propellant (usually Xenon) is ionised through electron bombardment or radio frequency fields and accelerated through a high electric potential applied to a grid structure at the thruster's exit (see Fig. 3). Very good performance a power needs in the kW range make this thruster attractive for both interplanetary and satellite attitude control applications. NASA launched the first interplanetary spacecraft Deep Space One with an Ion thruster as primary propulsion system in 1998.

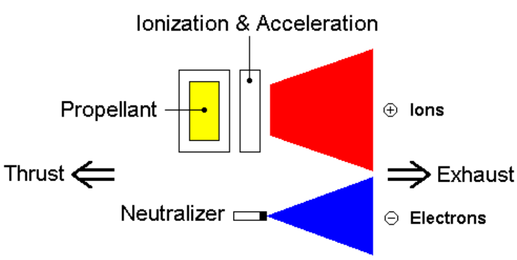

Figure 3 Electrostatic Propulsion

- **Hall Thruster:** Electrons are kept inside a magnetic field configuration around a ring shaped anode to ionise the propellant (Xenon). A potential difference between the anode and a cathode, which provides the electrons, accelerates the generated ions. Performance is between Ion thrusters and Arcjets, power requirements are very attractive (around 1.5 kW). This thruster is currently considered for a variety of satellite platforms and will be launched on SMART-1, the first European mission to the moon, as a primary propulsion system in late 2002.

- **FEEP and Colloid Thruster:** FEEP (Field Emission Electric Propulsion) uses liquid metal as propellant (usually Indium or Cesium) inside a slit or on the surface or a needle. If a high electric potential is applied with respect to an accelerator electrode, metal ions are created through field ionisation and accelerated by the same field. Colloid thrusters use glycerol instead of liquid metal and emit charged droplets instead of metal ions. FEEP and Colloid thrusters create μN thrust with resolutions in the sub μN range. This is an enabling technology for ultra-precise attitude control required for missions such as LISA.

3. Thruster Spacecraft Interactions

As we have seen, electric propulsion thrusters create a plasma and neutral gas environment (depending on the ionisation efficiency). In addition, both plasma and neutral components can undergo several types of collisions (charge-exchange, Coulomb, recombination, etc.) which can modify this environment again. Charge-exchange collisions between fast ion beams and thermal neutrals are of most interest since they create slow velocity ions that can distribute around the spacecraft causing sputtering and contamination (see Fig. 4).

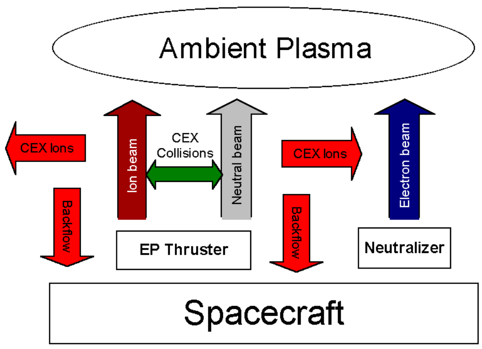

Figure 4 Spacecraft Thruster Interactions

Possible neutral spacecraft interactions are:

- Condensing optical systems
- Absorption/reflection of light

Possible plasma spacecraft interactions are:

- Contamination, sputtering and erosion of spacecraft surfaces
- Degradation of solar arrays
- Influence on measurements (plasma, etc.)
- Spacecraft charging
- Influence on communication

In order to investigate these phenomena, all electric propulsion thrusters are tested and characterised in vacuum chambers with a variety of plasma sensors (Langmuir probes, Retarding-Potential-Analysers, etc.). However, since chamber walls cause secondary electrons and modify the plasma flow and electromagnetic field configuration, they can not resemble fully experiments in space. Since space experiments are very expensive, modelling and numerical simulation has evolved as a very valuable tool to predict electric propulsion thruster performance and spacecraft interactions. As an example, Fig. 5 shows the plasma environment produced by a Hall thruster around the SMART-1 satellite using a Particle-In-Cell (PIC) simulation technique[2].

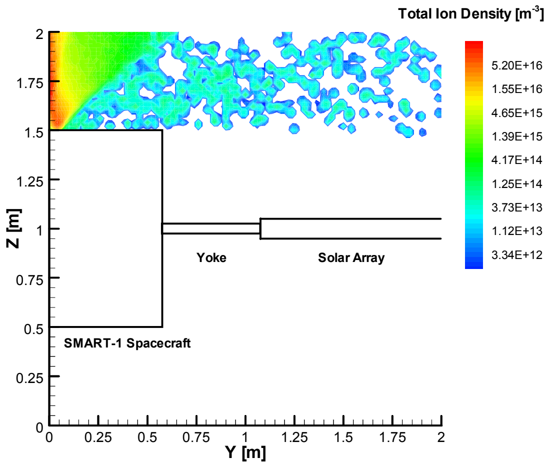

Figure 5 SMART-1 Thruster Spacecraft Interaction Modelling

4. Propulsion by Interaction with the Solar Wind or Ambient Neutral Gas Atmosphere

Propulsion concepts which require no or only very little on board propellant are very appealing. One possibility is to use the solar wind which is travelling at speeds ranging from 300 – 800 km/s which is very high compared to the fastest man made spacecraft Voyager which has a present speed of about 17 km/s.

Since the solar wind consists of charged particles, a magnetic dipole can deflect the solar wind creating thrust. The main drawback is, that the solar wind has a very low density which requires either very high field strengths or very large magnetic fields to create useful thrust for standard size spacecraft.

Presently, there are two different concepts:

- **Magnetic Sail:** A superconductor ring with a diameter of several kilometres and the spacecraft in the middle was suggested by Robert Zubrin and Dana Andrews to create a large high field strength magnetic dipole. Obviously, the major technical difficulties are cooling of this superconductor, the large structure and weight.

- **Mini-Magnetosphere (M2P2):** A very elegant way proposed by Robert Winglee[3] is to produce a large scale magnetic field by a magnetic dipole on board the spacecraft and to inject a plasma (e.g. Argon, etc.) produced by a Helicon device (radiofrequency plasma generator). Since the plasma increases the magnetic permeability, the magnetic field expands with the plasma to a few kilometre diameter. In fact this concept produces a mini-magnetosphere which interacts with the solar wind. Presently, modelling and experimental efforts are underway to estimate the expansion of the magnetic field. About 20 kilometres seem to be possible, which would be large enough to produce significant thrusts for interplanetary exploration missions.

Another "external" propellant is the neutral gas atmosphere in low orbit (around Earth, Mars, etc.). This neutral gas be ionised and accelerated by electromagnetic fields. In Low-Earth-Orbits, power-to-thrust ratios of 80 W/mN seem to be achievable.

5. Future Launchers using Plasmas for Propulsion and Drag Reduction

Plasma interactions can even play an important role for future launcher applications.

5.1 Advanced Drag Reduction

It is well known, that a pointed noise in opposite to a blunt noise decreases the drag load towards the vehicle considerably. This is applicable to aircraft at hypersonic speeds up to several Mach. However, a spacecraft needs to reach about Mach 25 for orbit insertion. Since a pointed noise receives all major heat at the tip of the noise where the insulating heat shield is very thin or non-exiting, such high launcher velocities would cause a burn through and destruction of the heat shield. That is why vehicles gaining very high velocities have a blunt noise which distributes the heat load over the surface at the cost of increased drag.

If the heat transfer zone could be moved away from the vehicle, much less heat would have to be

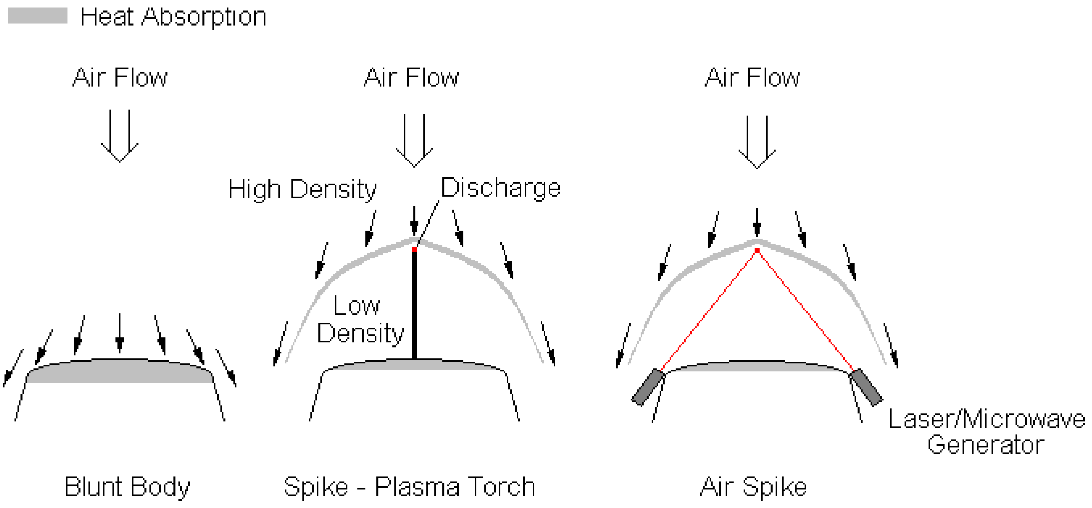

Figure 6 Advanced Drag Reduction

absorbed by the blunt noise. One way of doing this is to expell part of the rocket exhaust in front of the vehicle. This technique is actually used for very high speed Russian torpedos (Shkval) in water. However, for very high velocity flight this seems not to be practible. Another idea is to trigger a very hot plasma discharge in front of the vehicle on a spike (plasma torch) to generate a shock wave that will redirect the air flow and absorb part of the heat load. An illustration is shown in Fig. 6. Inside the bow shock, the air has a lower density reducing the drag load to the blunt surface. An even more radical concept was suggested by Leif Myrabo and Yu Razier to use a laser or microwave generator to focus energy and create a plasma discharge similar to the plasma torch but avoiding the physical spike structure (and avoiding the heat load to it). Although the principle is feasible, the amount of power necessary to operate such lasers are much to high at the moment to be practical.

5.2 Magneto-Hydro-Dynamic (MHD) Concept

If ionised air is passed through a magnetic field configuration (see Fig. 7), the plasma flow can be either accelerated by transmitting a strong current through it, or decelerated generating power at the electrodes. This can be used to increase the performance of a SCRAMJET (supersonic jet) engine.

Scramjet engines suffer from problems of mixing fuel and air at high Mach number speeds. This can be augmented by using a Magnetohydrodynamic (MHD) generator to extract energy and thus slow down the airflow before entering the combustion chamber (see Fig. 8). The energy extracted can be re-injected into the beam by using an MHD accelerator after combustion which speeds up the airflow. In order to operate a MHD the incoming must be ionized. If ionisation takes place

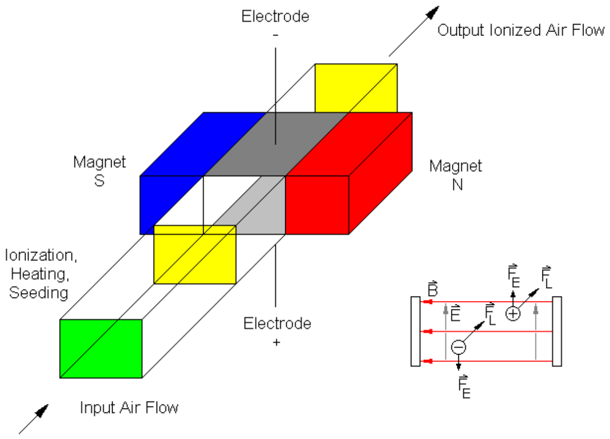

Figure 7 MHD Accelerator/Generator Concept

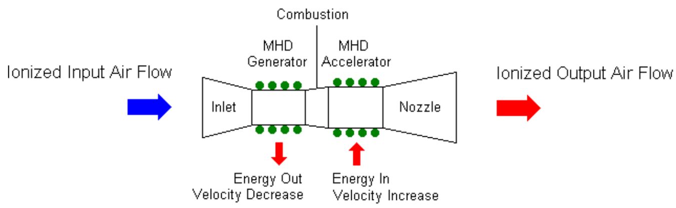

Figure 8 MHD Energy Bypass

in front of the aircraft also air drag is significantly reduced.

This concept of combining advanced drag reduction, scramjet and MHD generator/accelerator was suggested by the Russian Hypersonic System Research Institute (NIPGS) called the AJAX vehicle (see Fig. 9). Ionization of air is done by using a microwave and neutral beam generator on board the vehicle. Since the MHD generator produces the high energy input needed by the MHD accelerator, the high energy need problem

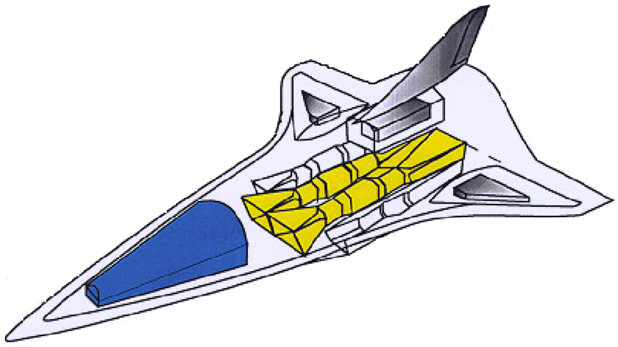

Figure 9   Russian AJAX Launcher Concept

of MHD propulsion is smartly bypassed. Superconducting coils would be necessary for the MHD devices in order to operate effectively. Although the generator/accelerator combination introduces some losses due to imperfect efficiencies (losses are estimated to be 10%), the gain in combustion performance is significant. Calculations for an AJAX vehicle flying at Mach 12 show an energy bypass ratio of 0.28 and increase the specific impulse by 20%. The application of AJAX technology to a SSTO launcher would be very attractive. Numerical studies and MHD test facilities are under development mainly at NASA in the United States. The combination of superconducting magnets, MHD and scramjet technology on a launch vehicle however leaves many areas for active development before this concept can be realised.

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