Magnetoplasmadynamic Rocket for Deep Space Exploration

by Gonit Sora - Saturday, February 01, 2014

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Magnetoplasmadynamic Rocket or thruster (MPDT), the name once existed in science fiction, now proven to be the most powerful form of electromagnetic propulsion. Magnetoplasmadynamic thruster, also called Lorentz Force Accelerator or MPD Arc-jet (so called in Japan) has extreme theoretical capability to convert megawatts of electrical power into thrust, making it the prime candidate for the next generation of space rocket capable of delivering cosmonauts or robonauts to Mars, Saturn, asteroids or into deep space. MPDT creates thrust expelling plasma. So far, theoretically MPDT can process more power and create more thrust than currently available any kind of electric propulsion system.

Magnetoplasmadynamic thruster uses Lorentz force to generate thrust. Generally an ionized fuel is inserted into an acceleration chamber, where magnetic and electric fields are created using power source. Then the ion particles are propelled by Lorentz force resulting from the interaction between current flowing through the plasma and extremely applied magnetic field.

By principle there are two main types of MPD thrusters: Applied field and Self field thrusters. Applied field thrusters have magnetic rings surrounding the exhaust chamber to produce magnetic fields. In Self field thrusters there's a cathode through the middle of the chamber. Hydrogen (or Hydrazine), Helium, Xenon, Neon, Argon, & Lithium can be as propellants, while Lithium comes out with condensation problems, non-condensable hydrogen so far has given the best results.

Basically MPD consists of two metal electrodes. Rod shaped cathode at the centre and a cylindrical anode structure that surrounds the cathode. When a high electric arc is applied between the anode and the cathode, the cathode heats up and emits electrons. And the emitting electrons collide and ionize the propellant gas to create plasma. The electric current running through the cathode creates a magnetic field; this self induced magnetic field interacts with electric current flowing from the anode, through plasma to cathode producing a Lorentz force. This force pushes the plasma out of the structure. To produce more thrust, external magnetic fields are applied (applying solenoids) around the exhaust nozzle section. An externally applied magnetic field creates a swirling motion in the incoming plasma jet. This swirling energy is converted into axial energy leading to increase in thrust by the magnetic nozzle diverging field's outline.

As we increase the external magnetic field, the thrust of an MPD device increases. Total thrust in an MPD thruster can be found by the vector sum of the four force sources:

I) $latex F_{thermal}$ **:** The force as a result of gas-dynamics & expansion at the nozzle area.

II) $latex F_{swirl}$: The discharge current crossing the magnetic field simultaneously results in an azimuthal force component that puts the plasma into rotation, which is considered an important source of energy addition. This energy can be partly converted into thrust energy.

III) $latex F_{hall}$: As the discharge current crosses the applied magnetic field, azimuthal currents are induced that yields axial and radial Lorentz (j x B) forces, of which the axial component directly accelerates the plasma while the radial component confines the plasma and builds up a pressure hill, respectively. This energy again can be partly converted into thrust energy.

IV) $latex F_{self}$: The interaction between the radial component of the primary current and the induced azimuthal magnetic field gives a self-magnetic acceleration.

The primary elements of a magnetoplasmadynamic thruster are: cathode unit, anode section, insulator between the cathode and anode, solenoid, insulator between cathode heater and cathode case. The components are assembled as shown in the figure (i).

Fig. (i) : Applied Magnetic Field MPDT Engine geometry.

MPDT had demonstrated its capability to provide Specific Impulse (Isp) in the range of 1500-8000 sec. and thrust efficiencies 30-40% or above. The exhaust velocity range is beyond 110,000 m/s, triple the value of current Xenon based thrusters and 20 times better than liquid rockets. An MPD rocket can make a manned mission into Mars in around 50 days while it takes more than 8 months for conventional chemical rockets.

Applied field MPDT (or AF-MPDT) was experimented and developed (in laboratory scale) in Russia, former USSR, Germany, USA & Japan since 1970s between the power levels of 1 kW to 130 kW. Some of the experimental data are given below:

Discharge current: 100-200 (upto 1500) A

Maximum applied magnetic field: 0.05-0.1 T

Propellant mass flow: 5-50 mg/s for Ar, Li, He, Kr, Xe, H2, N2, NH3

Ambient pressure: 10-0.05 (upto $latex 10^{-4}$) Pa

Discharge voltage: (50 to) 100-150 V

Thrust: 200-2000 mN

Specific Impulse: 15-35 km/s

Thrust efficiency: 20-40%

More efficiency can be obtained by using H2 or He as a propellant. However efficientices are low for gaseous propellants (especially Ar) compared to the alkali ones (Li mainly). Propellant’s atomic mass and applied magnetic field both collectively play important role in the efficiency of AF-MPDT.

X-16 thruster of 1970s from DLR Stuttgart were able to achieve 251 mN thrust level with a magnetic field of 0.6 T at a current of 80 A and 145 V voltage that resulted 7 mg/s mass flow rate. It had an efficiency of 38.8% and 36 km/s exit velocity. X-13 thruster also from DLR Stuttgart investigated the effect of magnetic induction on thrust measurement. It concluded with the significant improvement of thrust efficiency with applied magnetic field larger than 0.1 T compared to self-field MPDT.

Moscow Aviation Institute & NASA-JPL jointly developed an AF-MPDT that demonstrated power level up-to 130 kW and current of 1700-2100 A. With maximum applied magnetic field of 0.09 T it concluded with a mass flow rate of 75-90 mg/s. This experiment demonstrated the possibility to increase the Specific Impulse up-to 50-55 km/s and thrust efficiency of 50-55% at 200 kW power level.

VASIMR (Variable Specific Impulse Magnetoplasma Rocket) is an electrodeless thruster under the same principle of MPDT, conceptualized and in development by former NASA astronaut Franklin Chang-Diaz. VASIMR uses radio-waves to ionize and heat propellants.

Fig. (ii) : A conceptual spaceship by the author to another planet or deep space mission with thruster (MPDT) module, nuclear or MHD power system, crew module & radiation shield.

Fig. (iii) : The complete MPDT module with proper shielding.

Several problems are there on full scale development and operation of MPDT. It requires power in the range of hundreds or kilowatts (or megawatts for better efficiency) that current solar arrays are incapable to produce. One possible option is to use nuclear reactors. But many controversies and safety matters are there using nuclear reactor in space, while Roscosmos and Kurchatov Institute are planning to develop a megawatt scale nuclear powered spaceship in collaboration with other nuclear capable nations. Magnetohydrodynamics is an alternative option but with many engineering challenges. Once these problems are overcome, MPDT will open a new frontier of space exploration and humans' everlasting urge for ultimate knowledge of the cosmos.

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