Self-Field MPD Thruster with Atomic and Molecular Propellants

E. Fischer, Z. Rozkwitalski*, and F. K. Kneubühl
Physics Department, ETH, CH-8093 Zürich, Switzerland

Received 5 March 1985/Accepted 24 April 1985

Abstract. This study is devoted to the design, the operational characteristics and optimization of a self-field magnetoplasmadynamic (MPD) arc in view of its applications as a thruster and as a plasma source for recombination lasers. Its principal characteristics, i.e. its terminal voltage $V_{e1}$ and the exhaust speed $u_e$ as functions of the square of the discharge current $I$ divided by the mass flow rate $m$ are determined experimentally for atomic propellants. On the basis of measured diagrams $V_{e1}$ versus $(I^2/m)$ our discharge configuration is found to be well comparable to those applied by other laboratories. However, in order to further increase the specific impulse, these devices should make use of propellants of low molecular weight. Therefore, we also show that these thrusters can be operated in a quasi-steady mode for atomic as well as for molecular propellants, e.g. $H_2, N_2, O_2$. Existing theories and interpretations of observations on atomic propellants are reviewed and, if possible, extended to explain the experimental results obtained with molecular propellants. In the framework of these extended theories the high-power limit of a stable operation is well understood.

PACS: 34, 52

Research on electromagnetic propulsion devices benefits by the interest in higher exhaust velocities of future thrusters for interplanetary missions. Magnetoplasmadynamic (MPD) arcs represent one approach to such devices. They produce thrust by ionizing an incoming propellant and by accelerating the resulting plasma by electrothermal and electromagnetic forces. The physical background and the basic concepts underlying the field of electric propulsion are outlined in [1].

In self-field devices the electromagnetic forces result from the interaction between the current and its self-induced magnetic field. Since the self-magnetic force $F$ depends quadratically on the arc current $I$, the exhaust velocity $u_e$ and the specific impulse $I_s$ are proportional to the parameter $(I^2/m)$

$$F = n u_e = b I^2,$$

$$I_s = u_e/g = (b/g) \cdot (I^2/m),$$

where $m$ is the mass-flow rate, $b$ the self-field electromagnetic thrust coefficient derivable from an electromagnetic stress tensor, and $g$ the standard acceleration of gravity. Therefore, it is of advantage to operate these thrusters at high current levels and low mass-flow rates. Yet, from the early beginnings of experiments with self-field MPD arcs, one surprising result has been the fact that for a fixed propellant and a given geometry of the electrodes, there exists a maximum of $(I^2/m)$ beyond which undesirable effects occur, e.g. insulator and electrode ablation accompanied by terminal voltage fluctuations. For a better understanding of these phenomena as well as of the acceleration mechanisms theoretical calculations and detailed experimental investigations have been performed. In the following we summarize the relevant studies on this topic.

The acceleration processes in MPD arcs dominated by the self-induced magnetic field were studied theoretically by Devillers [3]. In order to describe the plasma he used a multi-fluid formulation. He has found by computer analysis in agreement with experiments that supersonic solutions exist only in a narrow range of
relevant parameters such as electric field, mass-flow rate, and electron temperature. He emphasized the role played by Alfvén's critical velocity

$$u_c = \left(2eV_iN_0/M\right)^{1/2}, \quad (3)$$

where $V_i$ indicates the ionization potential, $M$ the molecular weight of the propellant, and $N_0$, Avogadro's number. The importance of $u_c$ is due to the fact that for all possible solutions of the multi-fluid problem the exhaust velocity $u_e$ of argon proved to be very close to $u_c$.

Malliaris et al. [4–6] reported the experimental investigation of quasi-steady MPD propulsion at power levels in the range of 1–10 MW. As propellants they examined all noble gases, $N_2$ and $NH_3$ for different electrode configurations. Two operational regimes with respect to the parameter $(I^2/rh)$ could be distinguished. In the overfed regime, i.e. for values of $(I^2/m)$ smaller than a critical value $(I^2/m)_{crit}$, a stable discharge was reported. In the starved regime, i.e. $(I^2/m)_{crit} > (I^2/m)$, large terminal voltage oscillations were measured, and the operation of the thruster was erratic. For a fixed discharge arrangement $(I^2/m)_{crit}$ varied roughly as the inverse square root of the molecular weight $M$. In addition, at the critical value of $(I^2/m)$ the available specific impulse was found to increase linearly with $(I^2/m)_{crit}$. From assumptions which will be discussed in Sect. 2.3., the analytical expression

$$(I^2/m)_{crit} = u_e/b \quad (4)$$

was derived. Equation (4), though not thoroughly understood, fitted the experimental findings quite well.

Furthermore, in conjunction with (2), it yielded an upper limit for the specific impulse $I_S$ which depends only on geometrical factors of the electrode arrangement and the kind of propellant.

Detailed experimental studies not only on the shape of the anode and the cathode and their relative position [7–9], but also on the injection of the propellant and the resulting exhaust plume structures were performed at Princeton University by Jahn et al. [10–14]. With improved electrodes and insulators they observed satisfactory arc operation at specific impulses somewhat beyond the limits proposed by Malliaris et al. in [5]. In addition, they demonstrated the Alfvén critical speed $u_c$ not to be an ultimate limit of the attainable exhaust velocity. They showed that the onset of voltage fluctuations does not define a unique limiting value of $(I^2/m)$. They suggested this phenomenon to be associated primarily with cathode phenomena rather than with interelectrode flow processes.

Finally, Hügel presented a two-dimensional description of the anode mechanisms of high-current self-field MPD arcs [15]. In a first step he calculated the current density and the magnetic field with the aid of potential theory and Maxwell's equations. He obtained a system of partial differential equations for the plasma flow by taking into consideration also the standard set of basic fluid dynamic equations, i.e. equation of state, continuity equation, conservation of momentum and energy, as well as Ohm's law. He included Joule heating and electromagnetic forces, yet neglected heat conduction, radiation and viscosity. He found that, as a consequence of the self-magnetic forces, the particle density near the anode decreases with increasing $(I^2/m)$ and reaches zero for a critical value $(I^2/m)^*$. In the arc this particle starvation is compensated by raising the anode-fall voltage. This leads first to higher drift velocities of the electrons and to field ionization near $(I^2/m)^*$. In addition, the balancing of the particle density near the anode suggests a $M^{-1/2}$ dependence of $(I^2/m)^*$ for different gases, i.e.

$$A = I^2M^{1/2}/m = \text{const} \quad (5)$$

Therefore, it was proposed to use $A$ as a scaling parameter for self-field MPD thrusters. These results were reported to be in good agreement with measurements on a continuous self-field MPD arc with argon, krypton, and xenon as propellants [2].

Until now, the dominant research on self-field MPD accelerators reported has been performed with noble gases as propellants. Since these gases are expensive and because the maximum available specific impulse scales as $M^{-1/2}$, propellants of low molecular weight should be favoured, e.g. $H_2$, $N_2$, $O_2$. In addition, these gases are common and a well developed technology exists for their storage and liquefaction. After determination of the characteristics of our electrode configuration with noble gases as propellants we therefore have investigated the parameter regime in which our MPD accelerator can be operated in a steady state with these diatomic molecules as propellants.

1. Apparatus

In order to avoid severe problems with gas handling or heat transfer MPD arcs run in the megawatt power range are usually operated in a pulsed mode. The pulse duration is chosen to allow the discharge current $I$ and the terminal voltage $V_m$ to reach quasi-steady values [16].

The power supply of our MPD accelerator consists of a six-section LC-ladder network of 1.2 mF total capacitance capable of storing 15 kJ at 5 kV. The network is designed to supply single non-reversing pulses of currents up to 5 kA for 1 ms, 10 kA for 0.5 ms, or 25 kA for 0.25 ms depending on charging voltage and line configuration. An electrolytic ballast resistor