Design and Initial Operation of an Experimental Simulator of Magnetic Sail

Ikkoh FUNAKI*, Hidenori KOJIMA**, Yukio SHIMIZU*, Yoshinori NAKAYAMA*** ,
Kyoichiro TOKI**** ,Hiroshi YAMAKAWA* and Suetsugu SHINOHARA*

Abstract : In order to simulate the interaction between the solar wind and the artificially deployed magnetic field produced around a magnetic sail spacecraft, a laboratory simulator was designed and constructed inside the space chamber (2 m in diameter) at ISAS. As a solar wind simulator, a high-power magnetoplasmadynamic arcjet is operated in a quasisteady mode of ~ 0.8 ms duration. It can generate a simulated solar wind that is a high-speed (above 20 km/s), high-density (10^{17} -10^{19} m^{-3}) hydrogen plasma plume of ~ 40 cm in diameter. A small coil (2 cm in diameter), which is to simulate a magnetic sail spacecraft and can obtain 1.9-T magnetic field strength at its center, was immersed inside the simulated solar wind. Using these devices, the formation of a magnetic cavity (~8 cm in radius) was observed around the coil. In order to successful simulate the plasma flow around the coil (simulated magnetic sail spacecraft) in the laboratory, the reflection of the plasma flowing toward the coil at the boundary of the magnetic cavity should be clearly observed.

Keywords : Magnetic Sail, M2P2, Laboratory Simulation, Magnetoplasmadynamic Arcjet

1. Introduction

A magnetic sail (MagSail) is a unique interplanetary propulsion system. To propel a spacecraft in the direction leaving the Sun, a MagSail produces a large-scale magnetic field to block the hypersonic solar wind plasma flow[1]. When the MagSail is in operation, as shown in Fig.1, charged particles approaching the current loop (coil) are decelerated/deflected according to the B-field they experience, forming a magnetosphere (or a magnetic cavity) around the coil current. The solar wind plasma flow and the magnetic field are separated by the magnetopause, at which ions entering the magnetic field are reflected except near the polar cusp region where the ions can enter deep into the magnetic cavity. Due to the presence of the magnetosphere, the solar wind flow is blocked, creating a drag force, which is transferred to the coil current through electromagnetic processes[2]. Thus the spacecraft is accelerated in the direction of the solar wind.

The force on the current loop depends on the area that blocks that solar wind. By increasing the size of the magnetosphere, the blocking area can be larger, providing a larger thrust. Therefore, the force exerted on the coil of the MagSail can be formulated as,

* ISAS/JAXA
** University of Tsukuba
*** National Defense Academy
**** Tokyo University of Agriculture and Technology

$$F = C_d \frac{1}{2} \rho u_{sw}^2 S \tag{1}$$

where C_d is thrust coefficient, $1/2\rho u^2$ is the dynamic pressure of the solar wind, and S is the area of the magnetosphere, defined by, $S = \pi L^2$; where L is the characteristic length of the magnetosphere derived afterwards in Eq.(4). In Eq.(1), ρ is the density of the solar wind, u_{sw} the velocity of the solar wind. From Eq.(1), correlation between L and F is derived. The original MagSail by Zubrin required a spacecraft design with a large hoop coil of 100 km in radius to form 1000-km-radius blocking area (which corresponds to 10-N-class thrust)[1]; however, the dimension of the coil is too large to realize. In order to circumvent this problem, we have attempted to design a a smaller MagSail and examined its thrust characteristics. In Fig. 2, both C_d and F values are derived and estimated from numerical studies in Ref.[3], which incorporated the effect of ion gyration in the magnetic field. A reference case ($C_d = 3.6$, which is derived from the MHD simulation) are also plotted for comparison because the MHD limit is expected to determine the upper limit of thrust production. It is noted that the thrust of 0.25 N is obtained for L=30 km. This is a very large thrust in comparison with usual electric thrusters. Notice that the engine used for HAYABUSA provides only 0.02 N for a 500-kg asteroid explore[4]. If such Magsail propulsion can be used for a 1-t-class deep space explorer, that will drastically reduce the mission trip time to reach the outer planets and will gain payload weight because Magsail provides large thrust but requires no fuel[5]. To evaluate the technical feasibility of small Magsail, thrust characterization is very important.

In order to experimentally demonstrate the magnetic sail, we developed an experimental simulator of the magnetic sail that operates in a space chamber. In this paper, after describing the experimental simulator of the MagSail, some preliminary experimental results are presented.

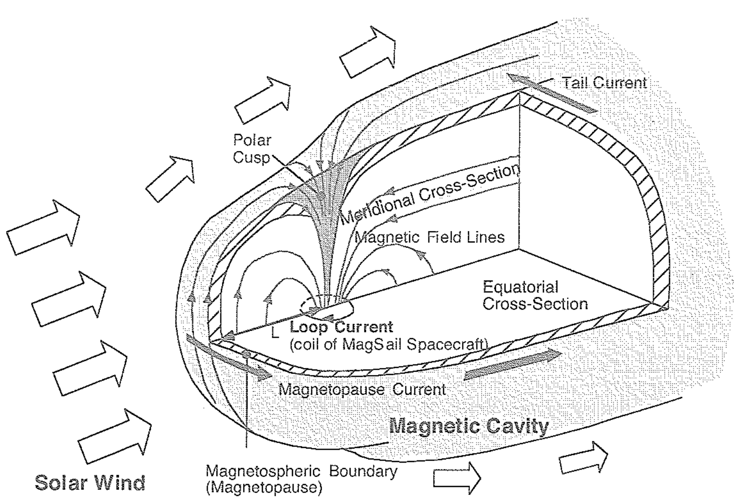

Fig 1: Schematic of Magnetic sail.

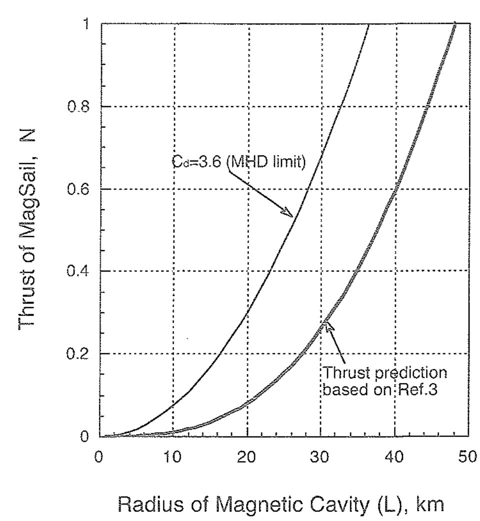

Fig 2: Thrust estimation of small MagSail.

2. Scaling Parameters of MagSail

Because the density of the solar wind plasma flow around a Magsail is very small, the particles in plasma are collision-less and their movement separates the plasma region outside the magnetic cavity and the region inside the magnetic cavity. Simplified picture of this boundary is depicted in Fig.3. When a magnetic dipole M is located at the center, there is a balance between the total internal (magnetic) and external (plasma) pressures at the boundary:

$$n\, m_i\, u_{sw} = \frac{\left(2B_{mp}\right)^2}{2\mu_0} \tag{2}$$

where n is the plasma number density, m_i ion mass, u_{sw} velocity of the solar wind, $2B_{mp}$ the magnetic flux density at the boundary, μ_0 the permeability in vacuum. The magnetic flux density B_{mp} of the dipole at position r is expressed as,

$$B_{mp} = \frac{\mu_0 M}{4\pi r^3} \tag{3}$$

hence the detachment distance of the boundary from the dipole center, L, is derived as follows.

$$L = \left(\frac{\mu_0 M^2}{8\pi^2\, n\, m_i\, u_{sw}}\right)^{1/6} \tag{4}$$

This boundary is usually called a magnetopause, on which the two charged particles, ions and electrons, impinge. The external space is considered as magnetic field-free. Because of their heavier mass, the ions tend to penetrate more deeply into the magnetic field than electrons. This sets up a charge separation, thus the outward pointing polarization field restrains the ions. Before they can be deflected by the magnetic field, they are returned by this polarization field. The electrons, however, experience the Lorentz force and gain energy in the polarization field. The transverse velocity component of the electrons accounts essentially for the electric current in the interface, which in case of the magnetopause is usually referred to as Chapman-Ferraro current. In the artificial case of equal external velocity, u, of the incident ions and electrons, the combined penetration depth, δ, is of the order of the geometric mean of the electron and ion gyroradii. If one uses Eq.(2) and replaces u/B_{mp} by the geometric mean gyro-radius at the magnetopause, one finds a thickness of the order of the plasma skin depth δ as

$$\delta = c/\omega_p \tag{5}$$

where c is the light velocity, ω_p the plasma frequency. δ is referred to as the thickness of the magnetopause in this paper. From Eq.(5), δ in the solar wind plasma depends only on the plasma density, hence it is calculated as $\delta \sim 1$ km. Thus, to reflect almost all the ions impinging on the magnetopause, $\delta/L << 1$ is required. Otherwise, ions enter far into the magnetic cavity, leading to small C_d. Therefore, $\delta/L << 1$ is the first condition necessary for MagSail.

The second condition is related to the ion gyration radius at the magnetopause:

$$r_{Li} = \frac{m_i u}{e 2B mp} \tag{6}$$

In order for the plasma to behave like a fluid, $r_{Li}/L << 1$ is required. To simulate a small MagSail, since $r_{Li} = 71$ km, a range of $0.1 < r_{Li}/L < 1$ is targeted for 0.2 −1 N class thrust as is depicted in Fig.2. These conditions are summarized in Table 1 with two conditions requiring a super sonic plasma flow as well as a collisionless plasma flow (i.e., magnetic Reynolds number, $R_m >> 1$). The design parameters for our laboratory simulation is also listed in Table 1.

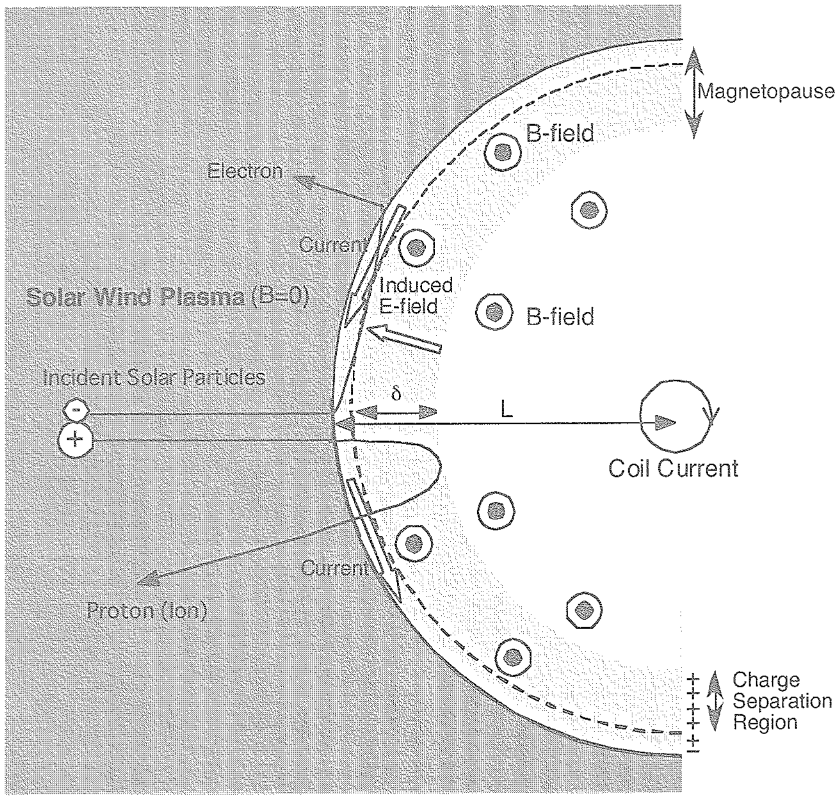

Fig 3: A schematic illustration of the trajectories of charged particles at the magnetopause; ions and electrons incident normally on a plane boundary layer when the polarization electric field due to charge separation is present.

Table 1: Scaling parameters of a plasma flow around MagSail.

	MagSail in space	Design target of MagSail in our laboratory experiment
Size of magnetic cavity (stand-off distance), L	10-50 km	< 0.1 m
Ratio of ion Larmor radius to L, r_{Li}/L	1 to 10	1 to 10
Ratio of thickness of magnetopause to L, δ/L	< 0.1	< 0.3
Magnetic Reynolds number, Rm	$> 10^5$	3-15
Mach number	8	1-5

3. Experimental Apparatus and Preliminary Results

Our newly developed simulator consists of a high-power magnetoplasmadynamic (MPD) solar wind simulator and a coil simulating MagSail's coil, both of which are operated in a pulse mode. In our preliminary experiment (Fig.4), a coil of 20 mm in diameter was located in the downstream of the MPD arcjet to produce up to 1.9 T magnetic field strength at the center of the coil. Into this magnetic field, a plasma jet from the MPD arcjet was introduced to observe possible interactions.

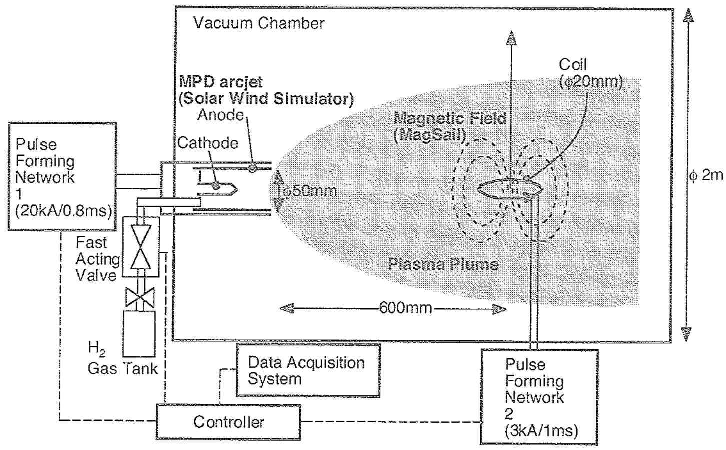

Fig 4: Experimental Setup.

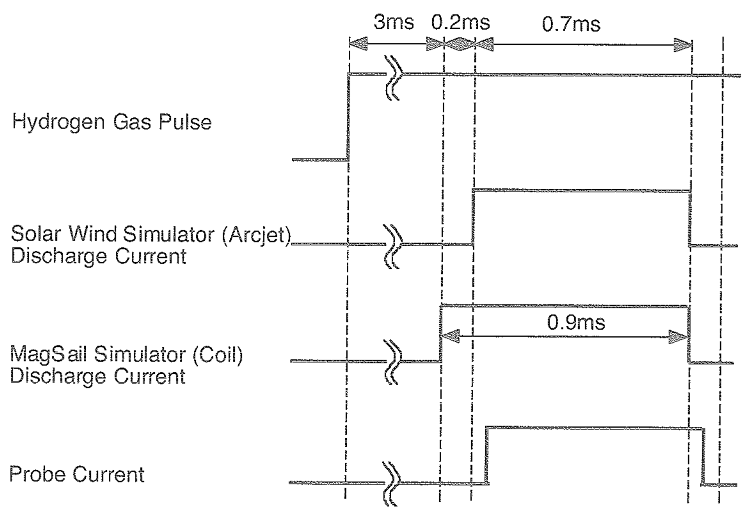

Fig 5: Sequences of Event.

3.1. Solar Wind and MagSail Simulator

An MPD arcjet was selected and fabricated for the solar wind simulator. The MPD arcjet consists of eight anode electrode rods that are azimuthally equally spaced, a short cathode rod, an annular floating body and insulators. Eight anode electrode rods are made of Molybdenum, 8 mm in diameter and 70 mm in length. A short rod shape cathode is made of thoriated tungsten, 20 mm in diameter and 16 mm in length. These electrodes are able to operate from a low current discharge range to erosive high current discharge range. The discharge chamber of the MPD arcjet is 88 mm in outer diameter, 50 mm in inner diameter and 100 mm in length. The discharge chamber is attached on the space chamber inner wall as shown in Fig. 4.

A fast-acting valve (FAV) allowed us to feed gaseous propellants featuring a rectangular waveform signal. When the FAV is opened, the gas in the reservoir flows through choked orifices of 1.2 mm in diameter. The mass flow rate of hydrogen gas was controlled by adjusting the reservoir pressure, obtaining a gas pulse of about 8 ms duration in the MPD arcjet. After the gas pulse reaches its quasi-steady state, the ignitron of a pulse-forming network (PFN) is triggered. The sequence of operation is summarized in Fig.5. After the gas feed and the magnetic field by the coil (MagSail) reaches a steady state, the firing of the MPD is initiated. The PFN for the MPD arcjet supplies the

Table 2: Parameters of plasma stream and magnetic field strength in laboratory experiment.

Plasma stream form hydrogen MPD solar wind simulator		
	velocity	10-60 km/s
	plasma density	10^{17}-10^{19} /m^3
	electron temperature	5000 - 20,000 K
	radius of plasma stream at the coil position	0.2 m
	plasma duration	0.7 ms
Coil current simulating MagSail in operation		
	radius of coil	20 mm
	B-field at the center of coil	0-1.9 T
	duration of exciting current	0.9 ms

discharge current up to 20 kA with a 0.7 ms flat-topped waveform in a quasi-steady mode. The PFN for the coil supplies rather small current (below 3 kA), and 20-turn-coil is required to produce 1.9 T magnetic field strength at the center of the 2-cm-diameter coil. Operational parameters of these devices are summarized in Table 2, in which the data were acquired from Langmuir probes and the time of flight velocity evaluation. From the data in Table 2, it is easily confirmed that the scaling parameters in Table 1 is mostly satisfied.

3.2. Plasma Flow around the Coil

Figure 6 a) and b) show photos of simultaneous operation of both the solar wind simulator (MPD arcjet) and the MagSail simulator. In Fig. 6, the plasma jet from the MPD arcjet diverges to 40-cm-diameter plasma jet at the coil position, which can be confirmed from this picture as well as from Langmuir probe measurements. In a close-up view near the coil in Fig. 6b, the region around the coil is dark except in the region very close to the coil. Although the boundary between this dark region and the simulated solar wind is not clear enough, the dashed line in Fig.6b may correspond to the boundary, where the plasma flow cannot enter but being reflected. The radius of the magnetic cavity observed was consistent with L defined in Eq.(4), which was about 8 cm in this case, hence it is expected that the plasma flow around a MagSail spacecraft was successfully scaled down and was demonstrated in our new experimental simulator.

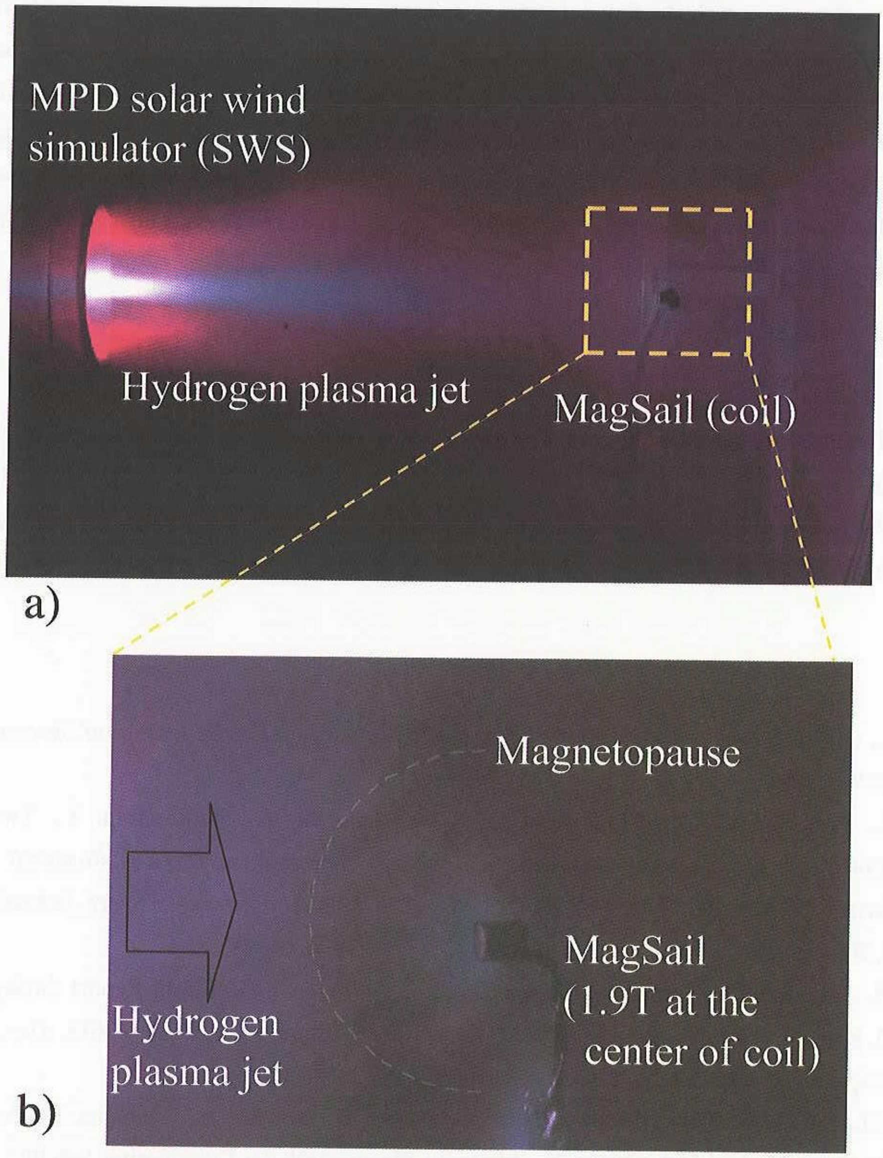

Fig 6: Operation of MagSail in space chamber; a) operation of down-scaled Magsail (right small coil) in hydrogen plasma jet from MPD solar wind simulator (left) , b) close-up view of a plasma flow around the Coil; MPD is operated at a discharge current of 20 kA and a mass flow rate of 0.5 g/s; also, the coil produces 1.9-T magnetic field strength at the coil center. The magnetic dipole axis is normal to the plasma flow.

4. Summary

An experimental simulator of a plasma flow around MagSail was designed and fabricated. A high-density plasma jet above 10^{17}m^{-3} is supplied by a hydrogen MPD arcjet, from which a high-speed plasma jet 20 - 60 km/s is ejected. In case a 20-mm-radius coil with 1.9 T magnetic field strength at the center of the coil was inserted into the plasma plume, a magnetic cavity was observed in front of the coil, which indicates the plasma flow around the properly scaled MagSail was simulated.

The most difficult task in our laboratory simulation is to achieve a collision-less plasma flow. In our simulator, R_m

is still too small to simulate a real situation correctly (see Table 1 and 2). This is primarily due to the fact that the collisional effect of charged particles in our simulated solar wind is quite large. Two possible ways to readily reduce the collision frequency are: 1) to increase the velocity and/or 2) to reduce the density of the jet from the MPD arcjet. The latter method seems easier because the plasma density can be controlled just by adjusting the position of the coil from the MPD arcjet as the density drops at a position away from the MPD arcjet. After tuning the simulator by these methods, a detailed probe measurement of the plasma flow will be conducted to evaluate a momentum change of the simulated solar wind, which is equivalent to the force on the coil of the MagSail.

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