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A Microwave Beaming Thruster Powered by 1 MW Microwave

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ABSTRACT

Experiments on a pulsed microwave-beaming thruster were conducted using a 1 MW gyrotron developed by the Japan Atomic Energy Research Institute. Thruster models were launched vertically, and the thrust impulse was estimated from their altitude. As a result, the maximum momentum-coupling coefficient of 345 N/MW was recorded with 0.2 ms pulse width at 1 MW microwave power.

INTRODUCTION

Energy beaming propulsion is expected as an advanced launch system at low cost in near future. The principle of this kind of propulsion system is explained as follows: When a high-power pulsed beam transmitted from the ground based station is focused in the atmosphere, breakdown is occurred near the focus and plasma is formed. The plasma absorbs the following part of the pulsed beam and expands outwards with generating shock waves. The shock wave propagates outwards and reflects on a nozzle surface of a thruster. As a result, impulsive thrust is imparted to the thruster. Since the energy is provided to the vehicle from the ground and an atmospheric air is utilized as a propellant in the air-breathing flight mode, it is not necessary to load neither an energy source nor a propellant on board. For this reason, this type of propulsion system will be able to achieve a high payload ratio at remarkably low launch cost.

Generally speaking, both laser and microwave can be used for the energy beaming from the ground to vehicles, and many experimental and analytical researches have been carried out on laser-powered launchers.[1-3] Myrabo et al. have proposed an axisymmetric thruster named as “Lightcraft,” and spin-stabilized free-flight demonstrations have been accomplished to altitude 100 m.[1] Similar attempt has been also conducted by DLR using a thruster with a parabolic shaped shell.[2] On the other hand, very few studies have been conducted regarding microwave-powered launchers, mainly due to poor directionality of the microwave beam. However it is not necessarily the case when the transmission distance is in the range of 100 km.

Furthermore, microwave has following advantages: The energy conversion efficiency from electricity to microwave can be more than 90% and the development cost of high power microwave generators would be much lower than that of high power laser oscillators. Especially, the phased array technology enables us to realize a single large-diameter coherent beam.[4]

The purpose of this study is to evaluate the performance of pulsed microwave beaming propulsion through thrust impulse measurements. In a series of experiments, vertical flight demonstration was also conducted.

EXPERIMENTAL EQUIPMENTS AND METHODS

Thruster Models

Three models of the microwave-powered thruster were fabricated and tested. A parabola-shaped model made of cupper-plated duralumin was fabricated to assure the precise beam focusing. Diameter of the nozzle exit and focal length of parabola were 90 mm and 15 mm, respectively, as shown in Fig. 1 (a). It weighed 95 g.

Since the duralumin model was too heavy to lift with the microwave power available in this experiment, polymer membrane was used to figure the parabola nozzle as shown in Fig. 1 (b). Although the size and shape of polymer model were the same as the duralumin one, it weighed only 3 g. The technology of membrane-parabola fabrication was originally developed at the National Aerospace Laboratory (NAL) Japan for a sunlight concentrator for solar thermal propulsion.[5]

The relationship between thruster length and thrust performance is another our concern. Therefore, a conical nozzle with a cylinder body of variable length was made as shown in Fig. 1 (c). Its structural material was a thin plastic sheet. The body length was variable from 60 mm to 120 mm, and corresponding model weight was from 9.5 g to 19.5 g. The inner surface of the cone was covered with an aluminum foil. Although it doesn’t focus a microwave beam tightly, plasma was successfully ignited with no miss firing.

Figure 2 shows a photograph of the duralumin parabola model mounted on a thrust stand.

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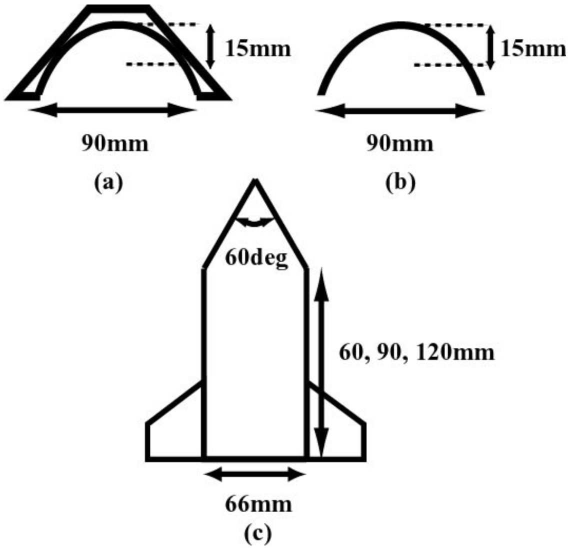

Fig. 1 Thruster Models.
(a) Duralumin parabola model, (b) Polymer membrane parabola model, (c) Plastic cone-cylinder model.

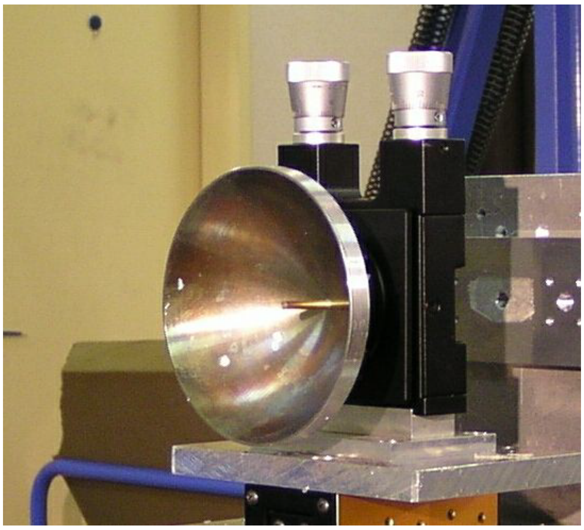

Fig. 2 A duralumin parabola model on a thrust stand.

Microwave generator

The gyrotron microwave oscillator (Fig. 3) developed by the Japan Atomic Energy Research Institute (JAERI) was used in this study.[6] Its specifications are listed in Table 1. This high-power facility was originally constructed as a RF heating device for fusion reactor researches. The pulse width τ is variable from 0.2 ms to 10 s. Output power P is almost constant during the pulse. The microwave was led from the gyrotron to a launch site using a circular corrugated wave-guide. Distance from the outlet window of the wave-guide to the thruster model was 30 cm and the beam waist was 20.4 mm.

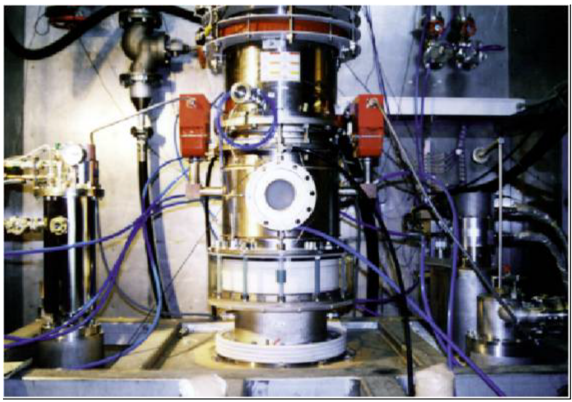

Fig. 3 The 1 MW class gyrotron developed at Japan Atomic Energy Research Institute.

Table 1 Specifications of the JAERI gyrotron

Frequency	110/170 GHz
Output Power P	ca. 1 MW
Pulse Duration τ	0.2 ms - 10 s
Output mode	Gaussian (TEM_{000})
Electrical efficiency	50%

Thrust Impulse Measurement Methods

Thrust impulse was measured by three methods using horizontal and vertical beaming setups. The horizontal beaming setup is shown in Fig. 4. Duralumin parabola model was mounted on a linear-motion-guide (LM-guide) rail, which restrains its movement only in the thrust direction. Thrust impulse was measured with a load cell force transducer set behind the duralumin model. Since characteristic response time of this measurement system is one order of magnitude longer than the beam pulse width, thrust impulse (time integrated thrust) was deduced from the maximum of output signal of the force transducer. Calibration was conducted using an impulse hammer.[7]

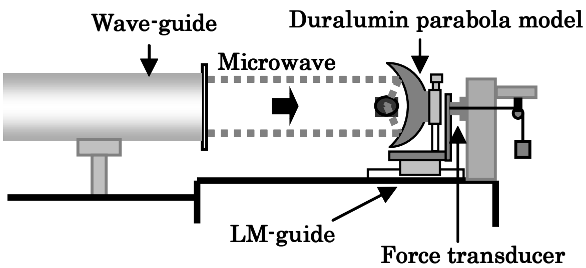

Fig. 4 Horizontal beaming setup.

The vertical beaming setup is shown in Fig. 5. The altitude h was measured with a laser displacement sensor, and its initial velocity v_0 was estimated by analyzing the images of thruster motion taken by a high-speed video camera. The cone-cylinder model placed on the launch stand is shown in Fig. 6.

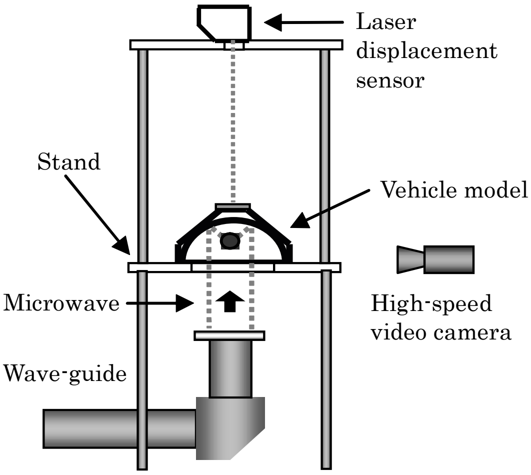

Fig. 5 Vertical beaming setup.

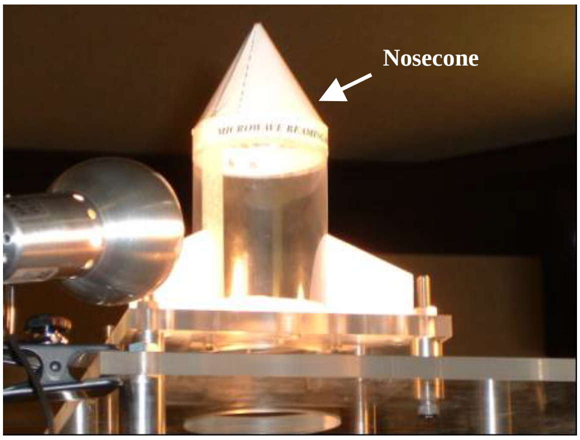

Fig. 6 A cone-cylinder model mounted on a stand.

Thrust impulse I is a function of h or v_0 as,

$$I = M\sqrt{2gh} = Mv_0 \qquad (1)$$

where M and g are the thruster mass and gravitational acceleration, respectively.

RESULTS AND DISCUSSION

Plasma Observation

The plasma emission was observed using high-speed video camera, whose exposure time is 55 μs. Figure 7 shows the observed plasma just after the microwave irradiation.

The plasma was propagated towards the radiation source absorbing the microwave energy. The speed of plasma front propagation was 540±15 m/s at 540 kW and 700±20 m/s at 840 kW. Plasma had gone out of the nozzle exit even with τ=0.2 ms, which was the shortest pulse width available in this experiment.

Therefore, a long cylinder body is expected to serve for confining plasma within it and to help effective conversion from the plasma pressure to thrust impulse.

Figure 8 shows a picture of plasma generated and confined in the cylinder body.

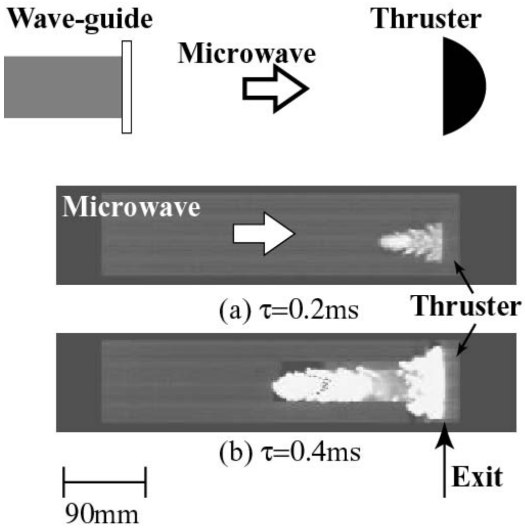

Fig. 7 Pictures of a plasma front propagating upstream of the microwave.

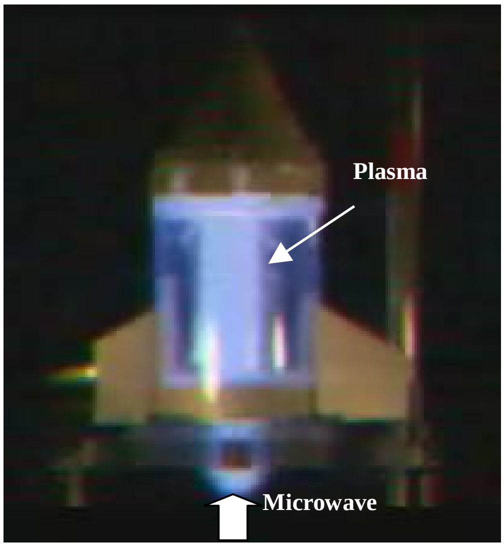

Fig. 8 A picture of plasma propagating within cylindrical nozzle

The history of plasma luminescence for various pulse width is shown in Fig. 9. Duration of plasma illumination was the same as the pulse width, while the intensity was monotonically increased with the pulse width.

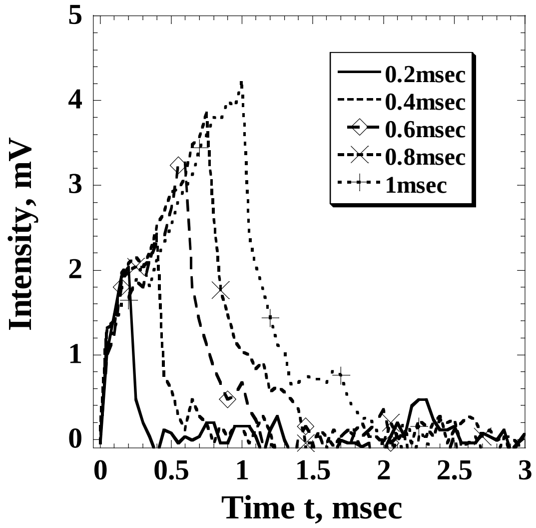

Fig. 9 Plasma luminescence variation for various pulse width of microwave irradiation. *P*=746kW.

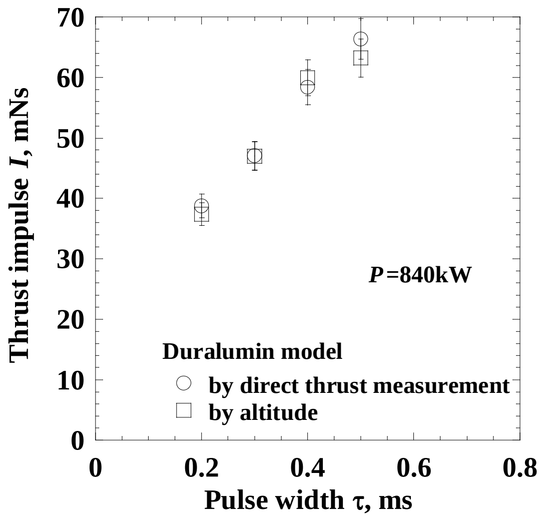

Fig. 10 Correlation between the direct thrust measurement and thrust estimation from the altitude.

Validation of Thrust Measurement Methods

Figure 10 shows the thrust impulse obtained with the duralumin model. Both vertical and horizontal beaming was tested, and a coincidence in measured thrust impulse was obtained by these methods. The thrust impulse couldn't be deduced from v_0 because v_0 was very small and the camera didn't have enough spatial resolution to estimate it.

Figure 11 shows the thrust impulse obtained with the polymer membrane model. The vertical beaming was conducted. Equivalent impulses were obtained from h and v_0. The impulse measurement with a force transducer was impossible because of its poor rigidity.

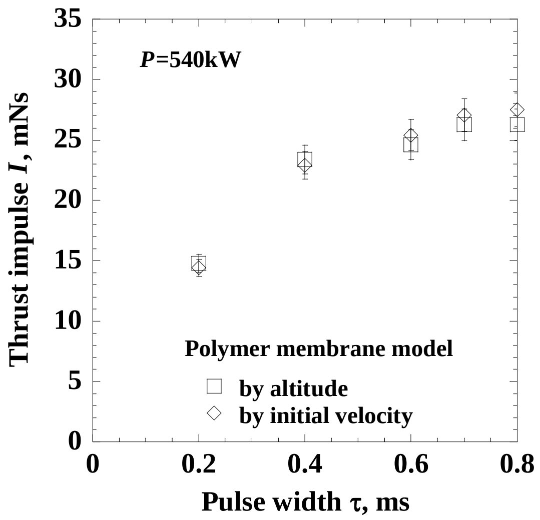

Fig. 11 Correlation of the estimated thrust impulses from the altitude and initial velocity..

Consequently, it was found that these three methods give same thrust impulses.

Performance Characteristics

Figure 12 shows the momentum-coupling coefficient C_m defined as,

$$C_m = \frac{I}{P\tau} \tag{2}$$

The duralumin and polymer membrane parabola models were compared. C_m of the polymer membrane model was about half of that of the duralumin model. This is because the polymer membrane parabola was less rigid than the duralumin one and the shock reflection on the polymer membrane became inelastic.

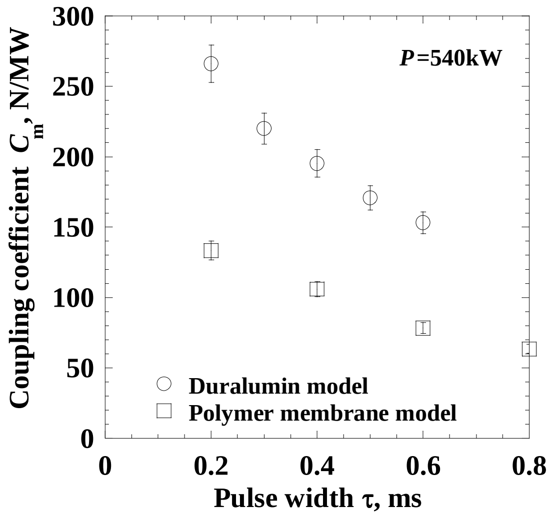

Fig. 12 Momentum-coupling coefficient.

C_m was decreased with τ for both models. This would be because most of the energy in the long pulse case was provided to the plasma outside of the thruster and the pressure of the plasma was not converted to the thrust. It is considered that optimum pulse width for this scale of parabola would be shorter than 0.2ms.

Figure 13 shows the measured C_m for the cone-cylinder model with τ=0.2 ms. It was monotonically increased with L. This indicates that the pressure of the plasma extended toward the radiation source was converted effectively to the thrust by the cylinder body.

The maximum C_m of 345 N/MW was recorded at τ=0.2 ms, P=1 MW and L=120 mm. This value was comparable to those of laser-powered thrusters.[7-9]

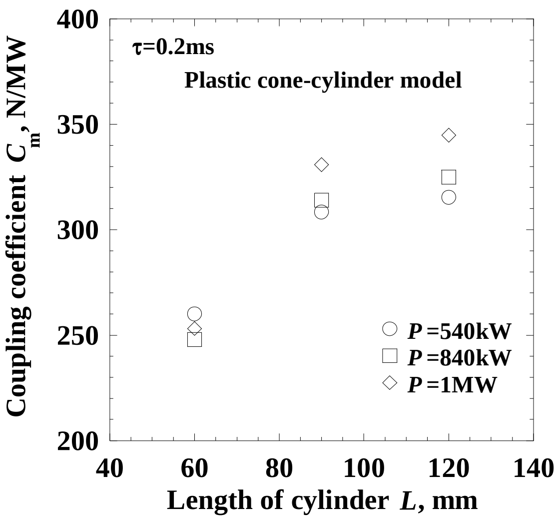

Fig. 13 Momentum-coupling coefficient and thruster length.

CONCLUSION

Using a 1 MW gyrotron, models of a microwave-powered thruster were launched and thrust impulse was measured by three methods. The results showed a good agreement among each measurement method.

The momentum-coupling coefficient was estimated from the measured thrust impulse. As a result, the maximum coupling coefficient of 345 N/MW was obtained with the cone-cylinder model. This value was comparable to those of laser-powered thrusters.

The coupling coefficient will be increased further by optimizing pulse width and thruster length as well as by increasing rigidity of the thruster structure.

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REFERENCES

[1]Myrabo, L. N., "Ground and Flight Tests of a Laser Boosted Vehicle," AIAA Paper 98-1001, 1998.

[2]Schall, W.O., Bohn, W.L., Eckel,H-A., Mayerhofer,W., Riede, W., and Zeyfang, E., "Lightcraft Experiments in Germany," *Proceedings of SPIE, High-Power Laser Ablation III*, Vol. 4065, 2000.

[3]Katsurayama, H., Komurasaki, K., Momozawa, A., and Arakawa, Y., "Numerical and Engine Cycle Analyses of a Pulsed Laser Ramjet Vehicle," *Transactions of JSASS, Space Technology Japan*, Vol. 1, 2003, pp. 9-16.

[4]Benford, J. and Dickinson, R., "Space Propulsion and Power Beaming Using Millimeter Systems," *Space Energy and Transportation*, Vol. 1, 1996, p. 211.

[5]Sahara. H., "Ultra-light Electromagnetic Wave Concentrator with Variable Focal Length and Its Use for Solar Thermal Propulsion," 2002-c-19, 23rd ISTS, Matsue, Japan, May 26-June 2, 2002.

[6]Sakamoto, K., Kasugai, A., Tsuneoka, M., Takahashi, K., Imai, T., Kariya, T., and Mitsunaka, Y., "High power 170 GHz gyrotron with synthetic diamond window," *Review of Scientific Instruments*, Vol. 70, Jan., 1999, pp. 208-212.

[7]Myrabo, L. N., Libeau, M. A., Meloney, E. D., Bracken, R. L., and Knowles, T. B., "Pulsed Laser Propulsion Performance of 11-cm Parabolic 'Bell' Engines Within the Atmosphere," AIAA Paper 2002-2204, 2002.

[8]Bohn, W. L., "Laser Lightcraft Performance," *Proceedings of SPIE, High-Power Laser Ablation II*, Vol. 3885, 2000.

[9]Mori, K., Katsurayama, H., Hirooka, Y., Komurasaki, K., and Arakawa, Y., "An Experimental Study on the Energy Balance in the Repetitively Pulsed Laser Propulsion," AIAA Paper 2003-496, 2003.