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# Air Breathing Processes in a Repetitively Pulsed Microwave Rocket

Yuya SHIRAISHI[1], Yasuhisa ODA[2], Teppei SHIBATA[3] and Kimiya KOMURASAKI[4],
*The University of Tokyo, Kashiwa, Chiba 277-8561, Japan*

*and*

Koji TAKAHASHI[5], Atsushi KASUGAI[6] and Keishi SAKAMOTO[7]
*Japan Atomic Energy Agency, Naka, Ibaraki 311-0193, Japan*

**The Microwave Rocket is a propulsion system powered by a millimeter-wave beam. In this research, a 170GHz high power gyrotron was used as a microwave source. A pressure history was measured in a cylindrical thruster model with a forced breath system and thrust impulse was estimated from the measured pressure histories at the thrust wall. As a result, dependency of thrust impulse on the partial filling rate of breathed air was obtained. When the partial filling rate is less than unity, that means the air in the cylinder was not fully replaced by fresh air, the impulse decreased with the pulse counts. The prediction by an analytical engine cycle model based on a Pulse Detonation Engine model showed a good agreement with the measurement.**

## Nomenclature

$A$ = cross section area of thruster
$a$ = sonic speed
$C_m$ = momentum coupling coefficient, a ratio of thrust to input power
$c_p$ = constant pressure specific heat
$f$ = pulse repetition frequency
$F$ = thrust
$I$ = thrust impulse
$I_{single}$ = thrust impulse in a single pulse operation
$L$ = thruster length
$M$ = flow Mach number
$p$ = pressure
$P$ = microwave power
$S$ = average microwave power density in a cylinder. $S=\eta P/A$
$T$ = temperature
$U$ = propagation velocity of a shock wave or an ionization front
$u$ = flow velocity
$u_0$ = flow velocity of the breathed air
$\rho$ = density
$\eta$ = fractional absorption of microwave energy by a plasma column

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[1] Graduate Student, Department of Advanced Energy, Kashiwa-no-ha 5-1-5, Non-member.
[2] Graduate Student, Department of Advanced Energy, Kashiwa-no-ha 5-1-5, Non-member.
[3] Graduate Student, Department of Advanced Energy, Kashiwa-no-ha 5-1-5, Student Member.
[4] Association Professor, Department of Advanced Energy, Kashiwa-no-ha 5-1-5,Member.
[5] Researcher, Plasma Heating Laboratory, Mukoyama 801-1, Non-member.
[6] Researcher, Plasma Heating Laboratory, Mukoyama 801-1, Non-member.
[7] Group Leader Researcher, Plasma Heating Laboratory, Mukoyama 801-1, Non-member.

## I. Introduction

Microwave Rocket is a propulsion system which obtains propulsive power from a microwave beam transmitted from the ground. The vehicle is not necessary to load an energy source and complex components such as a burner and turbo pumps on it. Because the construction cost of the beam station can be redeemed during multiple launch counts, a high payload ratio at a low launch cost is expected. [1]

The thrust generating principle of Microwave Rocket is as follows. Microwave power density is increased around a focal point in the thruster and the energy concentration causes a breakdown of air. The plasma is swollen by absorbing microwave energy and makes pressure waves. Oda et al. evaluated thrust performance of a conceptual thrust model powered by a 1MW single pulse. The momentum coupling coefficient $C_m$ was 400N/MW. [2] Its repetitive-pulse operation is described using a thrust generation model resembling a Pulse Detonation Engine (PDE) model: A PDE produces thrust by a high pressure gas generated behind a detonation wave in an air-fuel premixed gas. In Microwave Rocket, microwave supplied from the cylinder outlet ignites plasma in the vicinity of the thrust wall and is absorbed by plasma in the cylinder. While a microwave pulse is supplied and an ionization front propagates, a shock wave is driven toward a thruster outlet. When the shock wave passes a thruster outlet, an expansion wave starts to propagate towards the thrust wall and the hot air to be exhausted. On the thrust wall, the high pressure is kept constant until an expansion wave reaches the thrust wall. Thrust is computable with the time integration of the pressure history on the thrust wall. [3][4] By supplying repetitively pulsed microwave, Microwave Rocket obtains a repetitive thrust impulse. However, $C_m$ decreased in the repetitively pulse operation because of the hot air remained in the thruster.[5]

In this research, repetitive pulse operation with a forced breath system is tested. This system is simulating gas intake during the rocket mode or the ramjet mode of the Microwave Rocket flights. Thrust performance is evaluated from a pressure history measurement inside the thruster.

An analytical engine cycle model based on a shock wave propagation in a cylinder shape thruster with a forced breath system for impulse recovery is proposed. The fresh air is provided from a high pressure air tank through fast-reacting valves and tubes set on the thrust wall side to replace the hot air using. The partial filling rate is defined as

$$\frac{\text{Replaced air volume}}{\text{Cylinder volume}} = \frac{Au_0/f}{LA} = \frac{u_0}{Lf} \tag{1}$$

The performance dependence on this parameter was investigated.

Fig.1 shows a schematic view of a shock wave propagating through the cylindrical thruster. The region #1 is filled with standard atmosphere at rest. A normal shock wave propagates through the region #1. This normal shock is followed by a plasma region, a rarefaction wave, and a thrust pressure region. In the plasma region, microwave energy is assumed to be absorbed at the constant pressure. Although pressure decreases through a rarefaction wave, the pressure is still higher than ambient pressure. Relations among the properties ρ, $u$, $p$, and $T$ are shown as follows: [6]

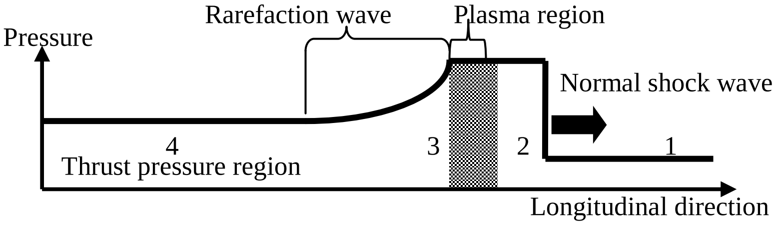

**Figure1. Schematics of pressure distribution and heating region**

Normal shock wave relations:

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{2+(\gamma-1)M_1^2} \tag{2}$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_1^2 - 1\right) \tag{3}$$

$$\frac{T_2}{T_1} = \left[1 + \frac{2\gamma}{\gamma+1}\left(M_1^2 - 1\right)\right]\left[\frac{2+(\gamma-1)M_1^2}{(\gamma+1)M_1^2}\right] \tag{4}$$

Plasma region relations:

$$p_2 = p_3 \tag{5}$$

$$\rho_2 u_2 = \rho_3 u_3 \tag{6}$$

$$T_3 = T_2 + \frac{\eta S}{c_v u_2 \rho_2} \left( = T_2 + \frac{\eta S}{c_v u_1 \rho_1} \right) \tag{7}$$

Rarefaction wave relations:

$$\frac{p_4}{p_1} = \frac{p_3}{p_1} \left[ 1 - \frac{\gamma - 1}{2} M_{3C} \right]^{\frac{2\gamma}{\gamma - 1}} \tag{8}$$

$$M_{3C} = \frac{u_3 - u_1}{a_3} \tag{9}$$

In the pulse repetition condition, initial temperature at the hot remained air region in the thruster $T_{1\ \mathrm{hot}}$ equals $T_4$:

$$T_{0hot} = T_4 \tag{10}$$

The microwave beam power profile was nearly Gaussian and its beam waist was slightly bigger than the radius of a plasma column as shown in Fig. 2. Then the fractional power absorption $\eta$ by the plasma is estimated at 0.49 by integrating the Gaussian profile from axis to the plasma column radius. Reflection, scattering, and transmission are assumed negligibly small. The absorption power density $S$ averaged over the cylinder cross section can be expressed by $S = \eta P/A$.

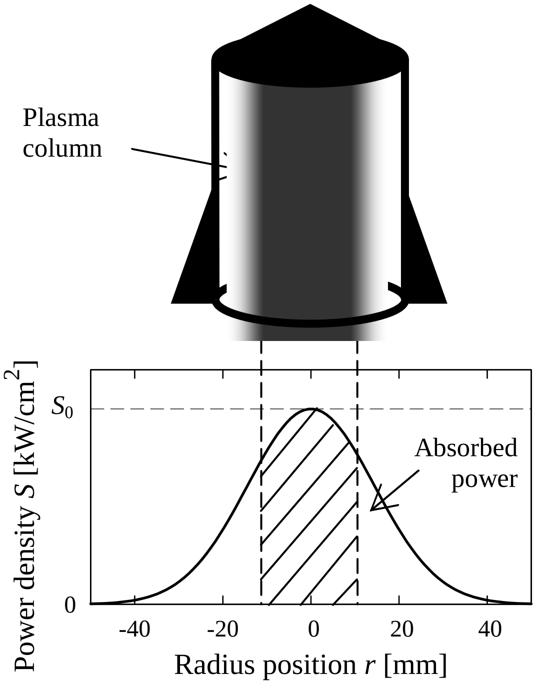

**Figure2. Radial distribution of microwave power density and a plasma column.**

## II. Experimental Apparatus

### A. A Microwave Generator

A 1MW-class 170GHz gyrotron was used as a microwave generator. [7] The gyrotron was developed for high frequency induction heating of an International Thermonuclear Experimental Reactor (ITER) in Japanese Atomic Energy Agency. 1MW operation from 0.1msec to 1000sec is possible about the microwave power. The microwave beam is Gaussian and its beam waist is 20.4mm. [8]

In this study, controlling oscillation mode realized repetitively pulsed operation by modulation to the accelerating voltage of an electron beam. At repetitively pulse operation, the duration and power of each pulse was fixed at about 2msec and 270kW, respectively. The repetition frequency was varied from 20Hz to 50Hz and the maximum operation time is 1sec.

### B. A Thruster Model and Forced Breath System

A cone-cylinder shape thruster model was used as shown in Figs. 3 and 4. It consists of an acrylics cylinder and an aluminum conical reflector which functions as a thrust wall. The thruster length was varied from 0.19m to 0.59m and diameter is fixed at 60mm. Four sets of a tube and a fast-actuating valve are connected from an air reservoir tank to the thruster. The tank pressure is kept at 0.4 MPa and the bulk flow velocity $u_0$ was varied from 2.5 m/s to 10m/s by controlling the number of opening valves.

### C. Measurement Apparatus

A pressure history was measured by two piezo-electric pressure gauges (Kastler's 603B). These gauges were flush-mounted on the cylinder surface as shown in Fig. 4. One is settled near the thrust wall and another is near the outlet of thruster.

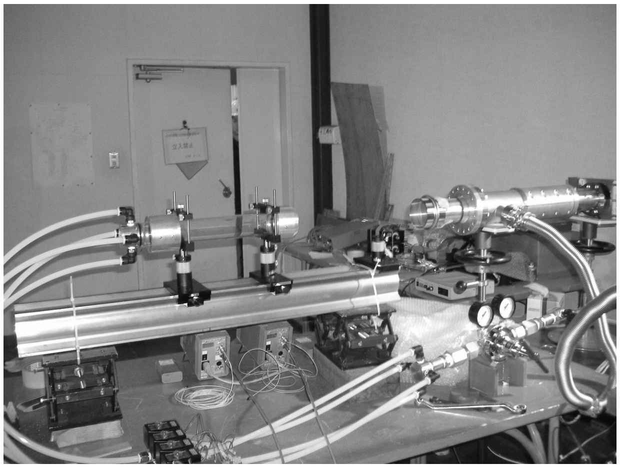

**Figure3. Picture of Thrust Measurement**

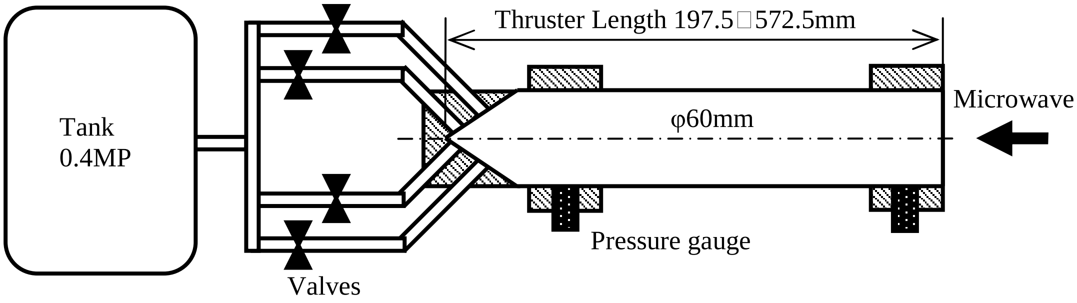

**Figure 4. Thruster model with a breathing system and pressure gauges.**

## III. Experimental Results

### A. Impulse Recovery by Forced Air Breathing

The thrust impulse for each pulse count is shown in Fig. 5. The result with the maximum flow rate case $u_0$=10m/s was compared to the result without air flow. In the case of no flow, the impulse decreased with the pulse counts. On the other hand, in the case of $u_0$=10m/s, thrust impulse was slightly decreased at the second pulse. However, almost steady thrust impulse was obtained at the 3rd pulse and further.

Therefore, the thrust impulse maintained after second pulse was regarded as the steady impulse in this study.

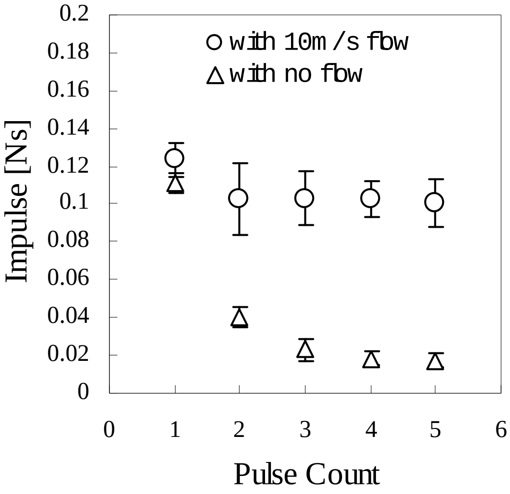

**Figure5. Thrust impulse for each pulse count in repetitive pulse operations. *f*=50Hz and *L*=390mm.**

### B. Impulse Dependence on $u_0$ and *f*

The steady impulses in the repetitive pulse operations *f*= 20Hz and 50 Hz are plotted in Fig. 6. *P* was kept at 300kW with *L*=390mm. When $u_0$= 10 m/s, the steady impulses were almost identical at both repetitive frequencies. However, at *f*=50Hz the steady impulse decreases with the decrease in $u_0$ at 7.5m/s and further, while the impulse was kept high in the range $5\text{m/s} \le u_0 \le 10\text{m/s}$ at *f*=20Hz. It suggests that when the pulse repetition frequency is high, the interval time between the pulses is too short and filled fresh air not sufficient to have full impulse recovery.

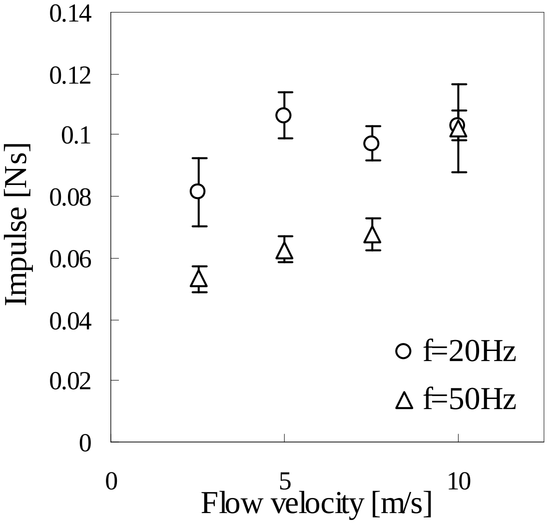

**Figure6. Steady impulse for various $u_0$ and pulse repetition frequencies. *P*=300kW, *L*=390mm.**

### C. Dependence on the Partial Filling Rate

In this sub-section, the filling condition is characterized using the partial filling rate. Measured shock propagation velocity *U* and the thrust impulse normalized by the impulse at the first pulse$I/I_{\text{single}}$ are plotted as a function of the partial filling rate in Figs. 7 and 8, respectively. The predictions by the analytical engine cycle model described in the section I are also plotted by a solid line in the figures. The measurements and computations showed a good agreement. It would be concluded that the Microwave Rocket can operate in a repetitively pulsed mode without performance degradation when the partial filling rate is kept larger than unity. Furthermore, even though the partial filling rate becomes lower than unity, the performance degradation is predictable using the analytical engine model.

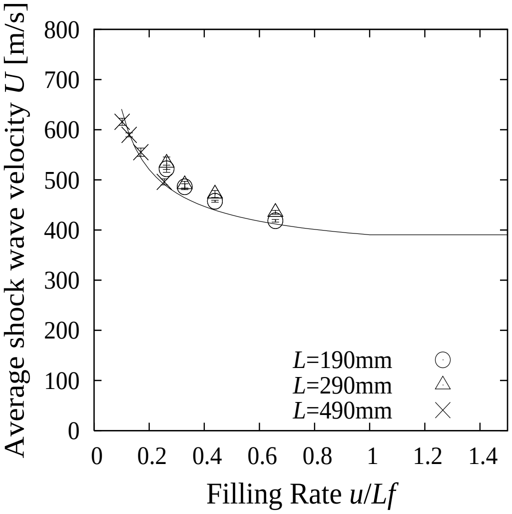

**Figure7. Shock wave propagation velocity dependence on the partial filling rate. Symbols show measurements and a solid line does theoretical prediction.**

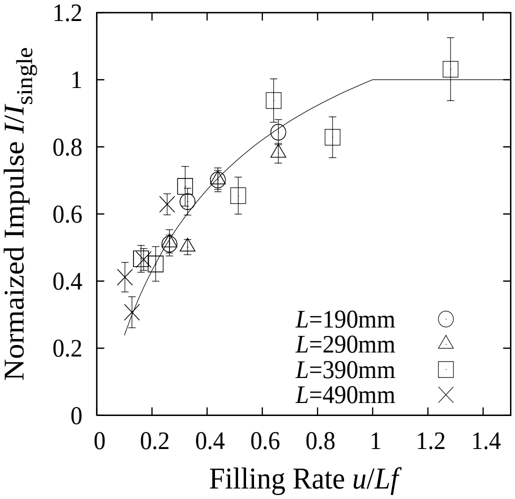

**Figure8. Thrust impulse dependence on the partial filling rate. Symbols show measurements and a solid line does theoretical prediction.**

### D. One-second Repetitive Pulse Operation

Operation of the pulse repetition was carried out for 1 second duration in several conditions. High speed video camera images showed that there was no miss firing for that period of operation. Thrust impulses estimated from the measured pressure histories at the thrust wall and from the trajectory of the thruster mounted on a movable stand showed a good agreement. The measured thrust is plotted in Fig.9.

### E. The Repetitive Thrust for Each Frequency

When the impulse recovery by the forced air breathing is enough, that is the partial filling rate is greater than unity, the averaged thrust $F$ is simply predictable using $I_{\mathrm{single}}$ and $f$ as

$$F = I_{\mathrm{single}} \cdot f \tag{13}$$

Equation (13) is plotted with straight lines in Fig. 9 in the condition of $u_0$= 2.5m/s and 10m/s, $P$= 300kW, and $L$= 190mm, 390mm and 590m. However, when the partial filling rate is less than unity, measured $F$ is smaller than predicted value especially at high $f$ conditions as shown in Fig. 9.

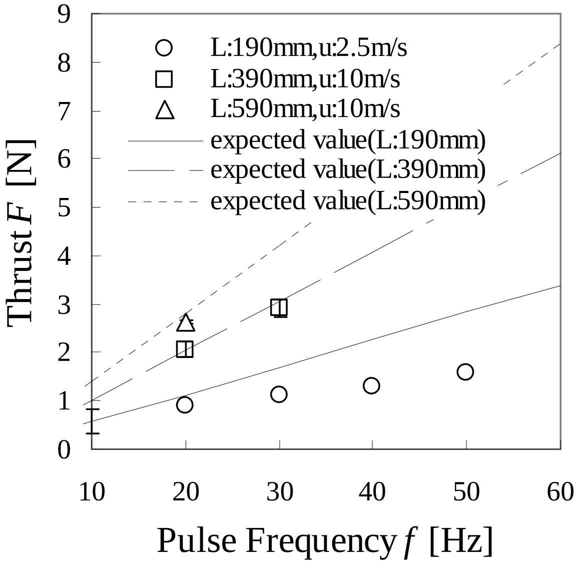

**Figure9. Measured and expected thrust in 1-sec repetitive operations .**

## IV. Conclusions

Repetitive pulse operation with a forced breath system is tested simulating gas intake during the rocket mode or the ramjet mode of the Microwave Rocket flights.

Impulse recovery at the second pulse count and maintenance of the steady impulse in the following pulses were achieved using the forced breath system. Moreover, the impulse dependences on the flow velocity of fresh air in a thruster, pulse repetition frequency, and thruster length were investigated. As a result, these dependences were expressed simply as a function of the partial filling rate which is a ratio of the volume replaced by fresh air during the pulse interval to the thruster volume. The dependence showed that the impulse is fully recovered when the partial filling rate is greater than unity.

The thrust impulse was computed using an analytical engine cycle model based on a Pulse Detonation Engine model. Constant pressure heating in the plasma region was assumed instead of detonation heating. The results show a qualitative and quantitative agreement with the measured results. Using this model, the thrust impulse is predictable even in the cases when the partial filling rate is less than unity.

Moreover, repetitive pulse operations for 1 second duration were conducted. The data of measured time-averaged thrust lay on the lines predicted by the above discussions.

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