Mechanism for Plasma Propagation Induced by Subcritical Millimeter Wave Based on Detailed Chemical Model

Kanta Hamasaki, Masayuki Takahashi, Naofumi Ohnishi
Department of Aerospace Engineering, Tohoku University
Email : hamasaki@rhd.mech.tohoku.ac.jp

Introduction

Microwave rocket has been proposed as a space transport system capable of drastically reducing launch cost. In this system, a high-intensity millimeter wave beam is supplied from the ground as an energy source, and a thrust is acquired due to a rapid gas heating induced by millimeter-wave discharge. Flight experiment of the microwave rocket was conducted using a 1-MW, 170-GHz pulsed gyrotron [1]. A numerical simulation based on a computational fluid dynamics and plasma transport model reproduced a formation of the plasma structure observed in the experiment at a moderate to high subcritical condition $0.25 < E_{0,\mathrm{rms}}/E_{\mathrm{cr}} < 1$, where $E_{0,\mathrm{rms}}$ is the root-mean-square electric field of the incident millimeter wave and E_{cr} is the threshold electric field for triggering the gas breakdown [2]. However, the breakdown was not maintained at a low-subcritical condition of $E_{0,\mathrm{rms}}/E_{\mathrm{cr}} < 0.25$. In this study, a one-dimensional calculation is conducted using a detailed chemical reaction model in atmospheric air coupled with the conventional model to reproduce the discharge phenomenon obtained at the low-subcritical condition.

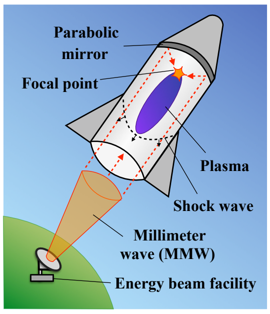

Fig. 1. Conceptual diagram of microwave rocket.

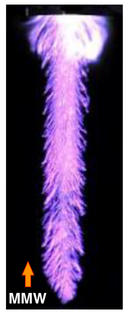

Fig. 2. Photograph of MMW discharge [1].

Numerical modeling

Electromagnetic field propagation model

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \mathbf{H} = \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + J$$

Current density $J = -e n_e v_e$

Absorption energy JE

Plasma fluid model (k = e : electron, p : positive, n : negative ion)

$$\frac{\partial n_k}{\partial t} + \frac{\partial}{\partial x}\left(\mathrm{sgn}(q_k)\mu_k n_k E_{sp} - D_k \frac{\partial n_k}{\partial x} + u n_k\right) = S_k = \sum_r^{r_{\max}} S_{k,r}$$

$$\frac{\partial (n_e \varepsilon_e)}{\partial t} + \frac{\partial}{\partial x}\left(-\frac{5}{3}\mu_e E_{\mathrm{sp}}(n_e\varepsilon_e) - \frac{5}{3}D_e \frac{\partial (n_e \varepsilon_e)}{\partial x} + u(n_e\varepsilon_e)\right) = W_\varepsilon$$

Electron collision reaction rate $k_e(\varepsilon_e)$
Number density n_k

Density source S_k
Energy source W_ε

Compressible neutral fluid model

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho \\ \rho u \\ e\end{bmatrix} + \frac{\partial}{\partial x}\begin{bmatrix}\rho u \\ \rho u^2 + p \\ (e+p)u\end{bmatrix} = \begin{bmatrix}0 \\ 0 \\ W_g\end{bmatrix}$$

Heating source W_g

Density ρ

Thermal reaction rate $k_g(T_g)$

Chemical reaction model

$$\frac{dn_{\mathrm{A}}}{dt} = \sum_j^{j_{\max}} S_{\mathrm{A},j} = \sum_j^{j_{\max}} (a'_j - a_j)\, k_j n_{\mathrm{A}_j}^{a_j} n_{\mathrm{B}_j}^{b_j}$$

For reaction : $a\mathrm{A} + b\mathrm{B} \rightarrow a'\mathrm{A} + c\mathrm{C}$

Conventional model (without detailed chemical reaction)

- Assuming that a composition ratio of N_2 and O_2 are constant as $N_2 : O_2 = 0.8 : 0.2$.
- Considering only 17 electron collision reactions ($e + a\mathrm{A} \rightarrow e + c\mathrm{C}$).

Improved model (with detailed chemical reaction)

- Dry air plasma is composed of 56 molecules $N_2(v$=0-45), O_2, O_3, NO, $N_2(A^3, B^3, a'^1, C^3)$, $O_2(a^1, b^1$, 4.5eV), 6 atoms N, O, $N(^2D, ^2P)$, $O(^1D, ^1S)$, 14 ions N^+, N_2^+, N_3^+, N_4^+, O^+, O_2^+, O_4^+, NO^+, $O_2^+N_2$, O^-, O_2^-, O_3^-, O_4^-, NO^-, and e.
- Considering 331 reactions including electron collision reactions ($e + a\mathrm{A} \rightarrow e + c\mathrm{C}$), thermal reactions ($a\mathrm{A} + b\mathrm{B} \pm \varepsilon_{\mathrm{gas}} \rightarrow c\mathrm{C} + d\mathrm{D}$), and reaction involving excited species.

Under the moderate-subcritical condition ($0.25 < E_{0,\mathrm{rms}}/E_{\mathrm{cr}} < 0.66$)

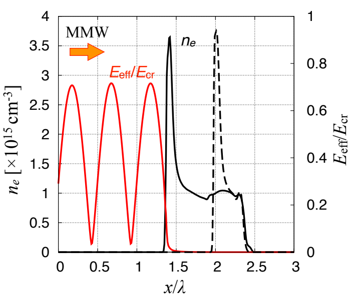

Fig. 3. Distributions of an electron number density n_e (black), and an effective electric field E_{eff} (red) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.41, t=4.7 μs (dot line), 11.7 μs (solid line).

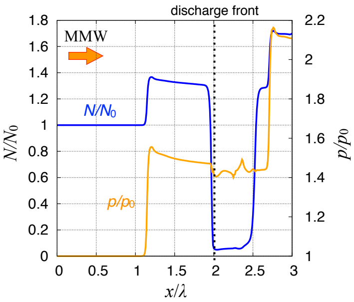

Fig. 4. Distributions of a neutrals number density N (blue), and a pressure p (orange) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.41, t=4.7 μs.

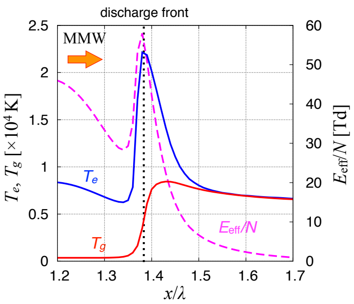

Fig. 5. Distributions of electron temperature T_e (blue), gas temperature T_g (red), and reduced electric field E_{eff}/N (magenta) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.41, t=11.7 μs.

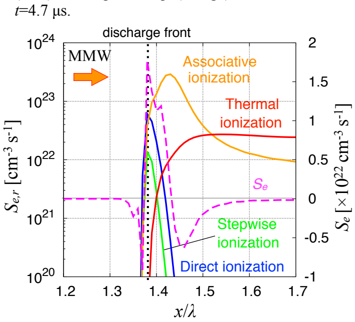

Fig. 6. Distributions of electron density source via several ionization processes $S_{e,r}$ (solid line) , and total electron density source S_e (dot line) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.41, t=11.7 μs.

A discharge front propagates toward a millimeter-wave source (Fig. 3), and a shock wave is driven while increasing the pressure to 1.5-2 atm which is the same value as the experiment [1] (Fig. 4). An electron temperature T_e increases with a decrease in a neutrals number density N by a strong expansion wave, and the discharge front is driven at a position where an T_e peak (Fig. 5) due to a direct ionization and an associative ionization in a collision between O and $N_2(^2P)$ (Fig. 6). A propagation speed of the discharge front is evaluated as 197 m/s at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}} = 0.41$, which is about one fifth of the experiment value [1].

Under the low-subcritical condition ($E_{0,\mathrm{rms}}/E_{\mathrm{cr}} < 0.25$)

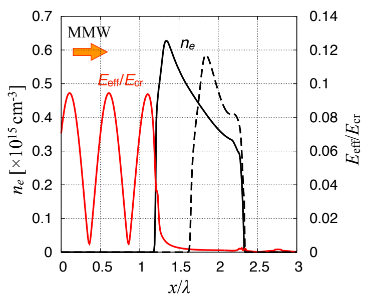

Fig. 7. Distributions of an electron number density n_e (black), and an effective electric field E_{eff} (red) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.08, t=49.4 μs (dot line), 88.2 μs (solid line).

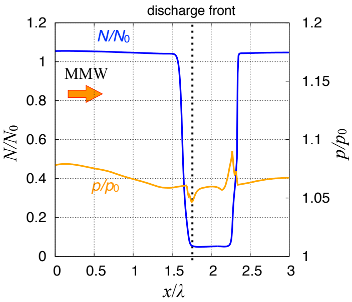

Fig. 8. Distributions of a neutrals number density N (blue), and a pressure p (orange) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.08, t=49.4 μs.

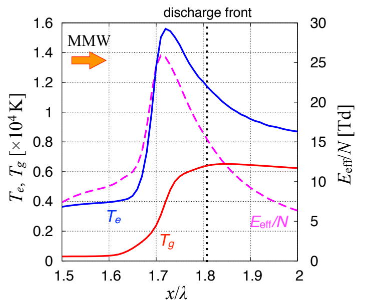

Fig. 9. Distributions of electron temperature T_e (blue), gas temperature T_g (red), and reduced electric field E_{eff}/N (magenta) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.08, t=49.4 μs.

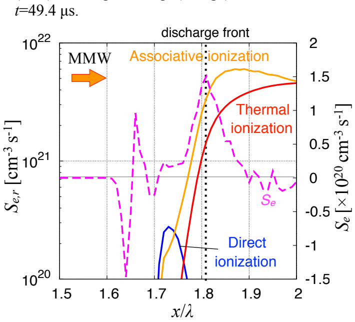

Fig. 10. Distributions of electron density source via several ionization processes $S_{e,r}$ (solid line) , and total electron density source S_e (dot line) at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}}$=0.08, t=49.4 μs.

The discharge development in the direction of the millimeter wave source is reproduced even under the low-subcritical condition (Fig. 7). The discharge is not maintained by the direct ionization process since the electron temperature T_e does not increase sufficiently (Fig 9). Therefore the discharge front is driven by a thermal ionization and the associative ionization at a position where translational temperature of a neutral particle T_g is increasing to about 6000 K (Fig. 10). The propagation speed of the discharge front is evaluated as 57 m/s at $E_{0,\mathrm{rms}}/E_{\mathrm{cr}} = 0.16$, which is half of that observed in the experiment [1].

References : [1] Y. Oda et al., Journal of Applied Physics, Vol. 100, 113307 (2006). [2] M. Takahashi et al., AIP Advances, Vol.17, 055206 (2017).