Journal of Nuclear Research and Applications

Research Paper

DOI: 1024200/jon.2022.1016

Cited in: https://jonra.nstri.ir

Received: 6 April 2022, Accepted: 17 April 2022

Design and Construction of a 2.45 GHz Microwave Electrothermal Thruster

S. Fazelpour[1*], H. Sadeghi[2], A. Chakhmachi[1], R. Amrollahi[2]

[1] *Plasma Physics and Nuclear Fusion Research School, Nuclear Science and Technology Research Institute (NSTRI), P.O. Box: 14155-1339, Tehran, Iran*

[2] *Energy Engineering and Physics Department, Amirkabir University of Technology, P.O. Box: 159163-4311 Tehran, Iran*

ABSTRACT

A microwave electrothermal thruster (MET thruster) has been constructed, consisting of a microwave plasma chamber 12 cm long and 8 cm in inner diameter and a micronozzle 10 mm long with 1 mm in diameter. The microwave plasma is produced by 2.45 GHz microwave frequency at a power of 1 kW, and the feed gas is Ar at a pressure of 10^-3mTorr. Microwave energy is transmitted into the cavity and electrons sre connected to the wave's electric field. Thus, the electrons are accelerated by microwave electric fields. Microwave plasma discharge is formed based on the interaction of electrons with neutral gas particles. Then, the plasma acts as a resistive load and absorption of microwave energy, raises the temperature of the gas or plasma. Gas heating increases the gas pressure and is released through the nozzle. The plasma density and electron temperature are 2.35×〖10〗^17 m^(-3) and 1.2 eV, respectively. The thrust and specific impulse are 10 mN and 100 s.

Keywords: Microwave plasma, Electrothermal, Thruster, Spacecraft

I. Introductions

One of the ideal systems for providing low thrust and high specific impact, used in many space missions, is microwave electrothermal thrusters (MET). The Microwave Electrothermal Thruster (MET) is an electric propulsion device that converts microwave energy into thermal energy [1,2].

Based on the advantages and capabilities of these systems, many researchers in the last three decades in this field have studied, designed, and performed them empirically and theoretically.These types of electrodeless thrusters play an essential role in space space missions due to their two properties, which are:

- limitation of electrode erosion problems
- Ease of speed control in electrodeless motors

So, The MET system was conceived to eliminate the handicaps of Resistojets and DC Arcjets. The microwave electrothermal thrusters have low power consumption, small dimensions, and long lifetime operation [1-4].

Plasma characteristics in a microwave electrothermal thruster were studied using a fluid mode by Yildiz. In this report, using Comsol software using the finite element method, they studied the plasma density based on changes in cavity radius, chamber length, cavity temperature, and pressure [5]. On the other hand, Yildiz and his colleagues numerically studied the electric field distribution and power absorption in the cavity to intensify a microwave electrothermal thruster. Using a two-dimensional symmetric model, they investigated the effect of cavity length, antenna length, and separator plate thickness on wave power absorption in the MET

**Corresponding Author name:* S. Fazelpour

E-mail address: samanehfazelpour@ymail.com

thruster at the Bogazici University Space Technology Laboratory [6].

They also geometrically optimized the cavity to intensify a 2.45 GHz microwave electrothermal thruster. In this regard, their scientific reports have investigated the distribution of electric field in the resonant cavity, which is important for starting and maintaining plasma discharge in a microwave electrothermal thruster system [7].

The development and optimization of an 8 GHz microwave electrothermal thruster were performed experimentally by Blum et al. [8]. This type of thruster was simulated using an ammonia or hydrazine combination and optimized by changes in its components such as antenna depth, injector size, nozzle size, and components.

Geo et al. [9] used Camsul software to model a 20-watt microwave electrothermal thruster with a frequency of 14.5 GHz. In their scientific report, the group inserted a dielectric cup into the cavity to investigate the effect of cup characteristics on changes in resonant frequency and electric field strength.

Abaimov et al. [10] modeled a microplasma electrothermal thruster using Comsol software. This type of trust is developed for the mission of 3U and larger CubeSats. In this trust, the cavity resonant frequency is 17.8 GHz, and the input power of the wave is 10 watts.

This paper constructs and tests a microwave electrothermal thruster with 2.45 GHz frequency at power 1 kW. In Section II, the experimental setup of the work is represented. Section III deals with results and a discussion of the thruster. The work is concluded in Sec IV.

II. Theory

- **Wave Heated Discharge Theory**

The electric and magnetic fields in the electric propulsion plasmas obey Maxwell's equations formulated in vacuum-containing charges and currents. Maxwell's equations for these conditions are as follow,

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \quad (1)$$

$$\nabla \times \boldsymbol{B} = \mu_0 \left(\boldsymbol{J}_P + \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t}\right) \quad (2)$$

$$\nabla, \boldsymbol{E} = \frac{\rho}{\varepsilon_0} \quad (3)$$

$$\nabla, \boldsymbol{B} = 0 \quad (4)$$

where, ρ is the charge density, and $\boldsymbol{J}_P$ is the current density in the plasma. ε_0 and μ_0 are the permittivity and permeability of free space, respectively. $\boldsymbol{E}$ and $\boldsymbol{B}$ are the electromagnetic field quantities.

Considering the Boltzmann equation and applying the Maxwell distribution function, the electron motion equation is expressed by:

$$\frac{\partial \boldsymbol{v}_e}{\partial t} = -\frac{q}{m_e}\boldsymbol{E} + \nu_m \boldsymbol{v}_e \quad (5)$$

where, m_e is the mass and ν_m is the collisional frequency of an electron. Finally, the electromagnetic wave equation in plasma derived from Maxwell's equations can be shown by:

$$\nabla \times \mu^{-1} \nabla \times \boldsymbol{E} = (\omega^2 \varepsilon_0 \varepsilon_r - j\omega\sigma)\boldsymbol{E} \quad (6)$$

Solving this equation using the appropriate boundary conditions leads to a wave-particle power transfer as below:

$$Q_{rh} = \frac{1}{2} real(\boldsymbol{J}, \boldsymbol{E}) \quad (7)$$

where, $\boldsymbol{J}$ is the displacement current density.

- **Plasma and Electron Transport**

The Boltzman equation is used to describe an electron's transport properties. Calculating the moments of the Boltzmann equation for conserved quantities, the fluid dynamic equation can be derived. Therefore, the governing equations reduce to a three-dimensional, time-dependent equation. In this case, the fluid equation for the electron density describes the average momentum and energy of the electron with spatial and temporal dependencies. The change rate in an electron is obtained by:

$$\frac{\partial n_e}{\partial t} + \nabla, \boldsymbol{\Gamma}_e = \mathrm{R_e} - (\boldsymbol{u}, \nabla) n_e \quad (8)$$

where, $\boldsymbol{\Gamma_e}$ is the electron mobility and is given by $\boldsymbol{\Gamma_e} = -(\boldsymbol{\mu_e}, \mathbf{E})n_e - \nabla(D_e n_e)$, and $D_e = \boldsymbol{\mu_e}\mathrm{T}_e$ is the electron diffusivity. It is worth mentioning that the mobility and diffusivity of the electron can be in either scalar or tensor forms. Also, $\boldsymbol{u}$ is the velocity vector. $\mathrm{R_e}$, on the right side of the equation is related to the electron sink. The rate of changes in density is shown by

$$\frac{\partial n_\epsilon}{\partial \mathrm{t}} + \nabla, \boldsymbol{\Gamma_\epsilon} + \boldsymbol{E}, \boldsymbol{\Gamma_\epsilon} = \mathrm{S_{en}} - (\boldsymbol{u}, \nabla)n_\epsilon + \frac{(Q + Q_{gen})}{q} \quad (9)$$

where, $\boldsymbol{\Gamma_\epsilon}$ is the energy mobility and can be written as $\boldsymbol{\Gamma_\epsilon} = -(\boldsymbol{\mu_\epsilon}, \mathbf{E})n_\epsilon - D_\epsilon, \nabla(n_\epsilon) = \frac{5}{3}\boldsymbol{\mu_e}$, and $D_\epsilon = \boldsymbol{\mu_\epsilon}\mathrm{T}_e$ is the energy diffusivity. Again, the energy mobility and diffusivity can also be in either scalar or tensor forms. $\mathrm{S_{en}}$ is related to the electron sink due to inelastic collisions. Q_{gen} is a generalized heat source and Q is the heat flux by conduction.

The growth or loss rate of the plasma density, $\mathrm{R_e}$, is determined by the plasma chemistry. If M is the reaction that results in an increase or decrease in the plasma density, $\mathrm{R_e}$ will be obtained by:

$$\mathrm{R_e} = \sum_{j=1}^{M} x_j k_j N_n n_e \quad (10)$$

In this equation, k_j is the reaction rate of the jth type, x_j is the mole fraction of the target species for reaction j and N_n is the density of neutral atoms.

III. Experimental

The MET system includes two endplates (nozzle and antenna), plasma, and a dielectric separation plate. A diagram of the MET thruster is shown in figure 1[11].

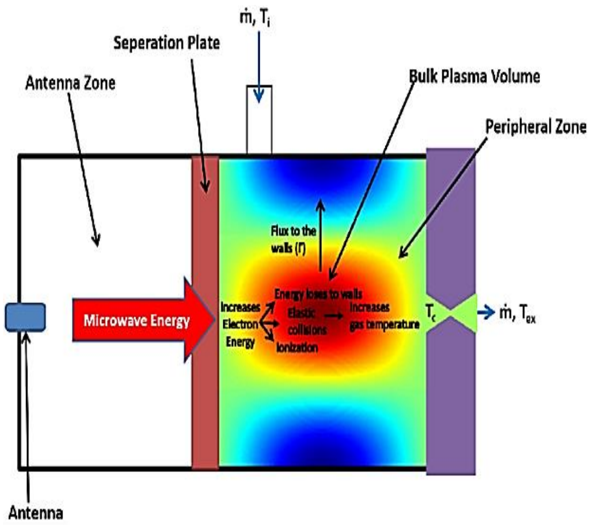

Fig. 1 A diagram of the MET thruster [5].

The physical process of the MET system can also be explained in the following manner:

Microwave energy is transmitted into the cavity and electrons sre coupled to the wave's electric field. Thus, the electrons are accelerated by microwave electric fields. Microwave plasma discharge is formed based on the interaction of electrons with neutral gas particles. Then, the plasma acts as a resistive load and absorption of microwave energy, raises the temperature of the gas or plasma. Gas heating increases the gas pressure and is released through the nozzle [12,13].

The formula for the thrust of MET thruster is given as:

$$\tau = \dot{m}\mathrm{u_e} + (\mathrm{p_e} + \mathrm{p_a})\mathrm{A_e} \quad (11)$$

The formula for specific impulse is given as:

$$\mathrm{I_{sp}} = \frac{\tau}{\dot{m}\mathrm{g}} \quad (12)$$

A schematic view of the experimental setup is shown in figure 2. The MET system parameters are listed in table 1.

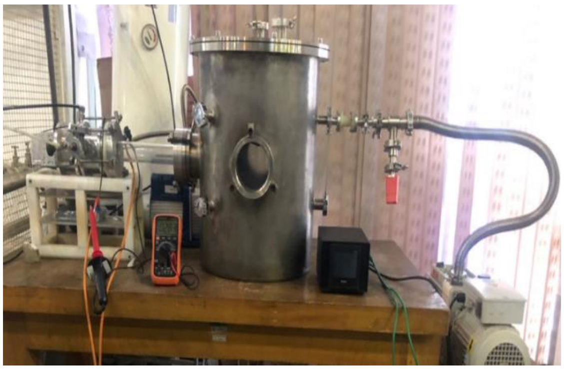

Fig. 2 A schematic view of the experimental setup.

The plasma chamber and cavity are made of aluminum and the nozzle is made of Stainless steel.

Table 1. The MET system parameters

Parameter	Value
Frequency (GHz)	2.45
Power (W)	1
Gas	Argon
Gas pressure (mTorr)	10^-3
Gas flow rate (SCCM)	10-80

IV. Results and discussion

MET thrusters use 2.45 GHz frequency magnetron wave generators because of their availability and low cost [14]. Photos of MET operation and cavity dimensions at 1kW is shown in figure 3. The device's mass is reasonable because the estimated power to mass ratio of a 2-kilowatt propulsion system is 513 W/kg (is 4 kg) and 235 W/kg for an Aerojet MR-512 arcjet propulsion system (is 1.4 kg). Using the Langmuir probe, the plasma density is equal to $2{,}35 \times 10^{17}\ \mathrm{m}^{-3}$ and the plasma temperature is equal to 1.2 eV.

According to the simulation results with COMSOL software, the gas temperature is 3000 K.

According to the chamber's temperature, the special impulse can be obtained [1]. And then, the thrust can be calculated by considering the specific pulse range and power [15]. The measured specific impulse of greater than 100 s and thrust in the range of 10 mN was found for argon in this device.

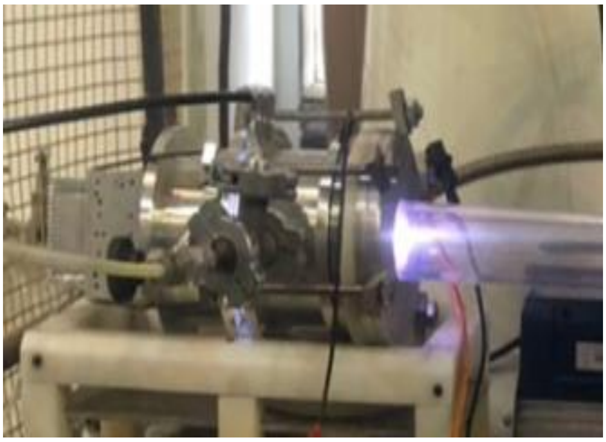

Fig. 3 Photos of MET operation and cavity dimensions at 1kW.

V. Conclusions

In the paper, we have designed and constructed a microwave electrothermal thruster via a 2.45 GHz microwave plasma source at a power 1 kW.

The results show that this system has a plasma with a density of $2{,}35 \times 10^{17}\ \mathrm{m}^{-3}$ and a temperature of 1.2 eV. According to the simulation results with COMSOL software, the gas temperature is 3000 K. The thrust and specific impulse are 10 mN and 100 s.

References

1. Power, John L. "*Microwave electrothermal propulsion for space*." IEEE transactions on microwave theory and techniques 40.6 (1992): 1179-1191.
2. Diamant, Kevin D., Byron L. Zeigler, and Ronald B. Cohen. "*Microwave electrothermal thruster performance*." Journal of propulsion and power 23.1 (2007): 27-34.
3. Whitehair, S., J. Asmussen, and S. Nakanishi. "*Microwave electrothermal thruster performance in helium gas*." Journal of Propulsion and Power 3.2 (1987): 136-144.
4. Diamant, Kevin, et al. "*Performance measurements of a water fed microwave electrothermal thruster*." 37th Joint Propulsion Conference and Exhibit. (2001).

5. Yildiz, Mehmet S., and Murat Celik. "*Evaluation of Plasma Properties in a Microwave Electrothermal Thruster Resonant Cavity by Using Two Fluid Global Model*." In 51st AIAA/SAE/ASEE Joint Propulsion Conference, p. 3926. (2015).
6. Yildiz, Mehmet Serhan, and Murat Celik. "*Numerical investigation of the electric field distribution and the power deposition in the resonant cavity of a microwave electrothermal thruster*." AIP Advances 7, no. **4** (2017): 045021.
7. Yıldız, Mehmet Serhan, Numan Unaldı, and Murat Celik. "*Geometry Optimization of a 2.45 GHz Microwave Electrothermal Thruster Resonant Cavity*." (2014).
8. Blum, Jacob H., Jeffery R. Hopkins, Michael M. Micci, and Sven G. Bilén. "*Evaluation and Optimization of an 8-GHz Microwave Electrothermal Thruster*." In The 31st International Electric Propulsion Conference (2009).
9. Gao, Enyu, and Sven G. Bilén. "*COMSOL Multiphysics Modeling of a 20-W Microwave Electrothermal Thruster.*" *In Department of Electrical Engineering*, The Pennsylvania State University, University Park, PA, (Excerpt from the Proceedings of the COMSOL Conference 2008 Boston) (2008).
10. Abaimov, M. D., M. M. Micci, and S. G. Bilén. "*A 17. 8-GHz Microwave Electrothermal Thruster for CubeSats and Small Satellites.*" IEPC 2016 (2016).
11. Yildiz, Mehmet Serhan, and Murat Celik. "*Global Energy Transfer Model of Microwave Induced Plasma in a Microwave Electrothermal Thruster Resonant Cavity*." (2015).
12. Sullivan, Daniel Joseph. *Development and performance characterization of a microwave electrothermal thruster prototype*. The Pennsylvania State University, (1995).
13. Brandenburg, John E., John Kline, and Daniel Sullivan. "*The microwave electro-thermal (MET) thruster using water vapor propellant*." IEEE transactions on plasma science 33.2 (2005): 776-782.
14. Takao, Yoshinori, Koji Eriguchi, and Kouichi Ono. "*A miniature electrothermal thruster using microwave-excited microplasmas: Thrust measurement and its comparison with numerical analysis*." Journal of Applied Physics 101.12 (2007): 123307.
15. Brandenburg, John E., John Kline, and Daniel Sullivan. "*The microwave electro-thermal (MET) thruster using water vapor propellant*." IEEE transactions on plasma science 33.2 (2005): 776-782.

How to cite this article
S. Fazelpour, H. Sadeghi, A. Chakhmachi, R. Amrollahi, Design and Construction of a 2.45 GHz Microwave Electrothermal Thruster, *Journal of Nuclear Science and Applications,* Vol. **2,** No. **2, (2022),** P **20-24, Url**: https://jonra.nstri.ir/article_1467.html, **DOI**: 1024200/jon.2022.1016