# Numerical Simulation of Microwave Plasma Thruster Flow

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**Mao-lin Chen[*], Mao Gen-wang[†], Yang Juan[‡] and Xia Guang-qing[§]**

Northwestern Polytechnical University, Xi'an, shannxi, 710072, China

**Abstract: Microwave plasma thruster (MPT) is a kind of electrothermal propulsion devices. It is very attractive for future application, with moderate specific impulse, long lifetime and slight plume contamination. Like other electrothermal propulsion thrusters, MPT has a high stagnant pressure about 1 to 5 atm. Transportation of propellant gas in microwave resonance chamber and convergence part of nozzle remains with continuum flow. But for the high expanding rate of the divergence part of nozzle, pressure descends quickly along the nozzle by expanding and is about hundreds Pascal at the outlet of nozzle Transportation of propellant gas around the outlet of nozzle and plume field belongs to transitional flow and free molecule flow.**

**N-S equations were solved with axisymmetric model, to show the distribution of flow field of nozzle and calculate the performance of thruster for 100W MPT with different propellants such as Helium, Nitrogen and Argon. Results show that the thrust changes not a half with various propellants, being 23.6mN for Helium, 26.5mN for Nitrogen and 24.8mN for Argon; while the specific impulse has great disparities. The specific impulse is 565.2 seconds when using Helium as propellant, 243.7 seconds for Nitrogen and 180.2 seconds for Argon. The conclusions of simulation are accordant to experience results.**

**The Direct Simulation Monte Carlo (DSMC) method was used for plume simulation, while Variable Hard Sphere (VHS) model was chosen for the effect of molecules and Random Sample Frequency (RSF) method was chosen for the sampling of collision molecules. Using the outlet parameters of nozzle calculation as the inlet condition of plume field, the distribution of temperature, pressure, gas density and velocity were gotten. Simulation results show that the density, pressure and temperature all reduce along the flow direction and radial direction; the axial velocity increase along the flow direction but decrease along the radial direction, while the radial velocity increase along the radial direction but decrease along the flow direction, for the farther expanding of propellant gas.**

## I.  Introduction

Microwave Plasma Thruster is a kind of electric propulsion, with characteristic of moderate specific impulse, wide thrust scale, high efficiency, non cathode erosion and well compatibility with

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[*]  Mao-lin, Chen, Dr., College of Astronautics, chmaolin@gmail.com
[†]  Geng-wang, Mao, Prof., College of Astronautics, maogenwang@nwpu.edu.cn
[‡]  Juan, Yang, Prof., College of Astronautics, yangjuan@nwpu.edu.cn
[§]  Guang-qing, Xia, Dr., College of Astronautics, goldmas@163.com

aircraft. It is considered to be a good device for the attitude control and position keeping of satellites. Some Institute in USA and the Northwestern Polytechnical University in China has studied this device for many years (Ref. 1, 2).

The working pressure of MPT is very high, while the pressure of environment is relatively low. Propellant gas expands tempestuously in the nozzle, and the whole flow region of MPT involves continuous flow, transitional and free molecular flow. To get the accurate distribution of the whole flow region, axi-symmetry model of nozzle was given, and solved. Results of nozzle simulation were set to be the input condition of plume region and distribution of plume was calculated.

## II. MPT

The operation principle of MPT is converting electric energy to microwave energy by microwave power source, then resonance with the propellant in discharge chamber to produce plasma flow with high temperature and high pressure. The plasma flow is accelerated by a nozzle and ejects in a high speed to generate thrust.

## III. Nozzle flow simulation

The nozzle of MPT has a large expand ratio, about 25 to 100. It is considered to be continuous flow along the nozzle, which can be solved with N-S equations.

### A. Calculation model

Ignoring the gravity of propellant gas, the chemistry reaction and heating radiation, the N-S function can be express as (Ref. 3):

$$\frac{\partial}{\partial t}(\frac{U}{J}) + \frac{\partial}{\partial \xi}[(\xi_z F + \xi_r G)/J] + \frac{\partial}{\partial \eta}[(\eta_z F + \eta_r G)/J] + \frac{H}{J} = 0 \tag{1}$$

The meaning of *U, J, F, G, and H* is defined in Ref. 4.

Viscosity term is indicated as:

$$\tau_{rr} = -\frac{2}{3}\frac{\mu}{\text{Re}}(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} + \frac{v}{r}) + 2\frac{\mu}{\text{Re}}\frac{\partial v}{\partial r}$$

$$\tau_{\theta\theta} = -\frac{2}{3}\frac{\mu}{\text{Re}}(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} + \frac{v}{r}) - 2\frac{\mu}{\text{Re}}\frac{v}{r}$$

$$\tau_{zz} = -\frac{2}{3}\frac{\mu}{\text{Re}}(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} + \frac{v}{r}) + 2\frac{\mu}{\text{Re}}\frac{\partial u}{\partial z} \tag{2}$$

$$\tau_{rz} = \tau_{zr} = \frac{\mu}{\text{Re}}(\frac{\partial v}{\partial z} + \frac{\partial u}{\partial r})$$

And heat exchange term is indicated as:

$$\dot{q}_r = \frac{1}{(\gamma - 1)\text{Re}}\frac{\mu}{\text{Pr}}\frac{\partial T}{\partial r}$$

$$\dot{q}_z = \frac{1}{(\gamma - 1)\text{Re}}\frac{\mu}{\text{Pr}}\frac{\partial T}{\partial z} \tag{3}$$

Here Pr is Prandtl number.

For the real flow is turbulence, the coefficients of viscosity and heat exchange term can be expressed as:

$$\mu = \mu_L + \mu_t \tag{4}$$

$$\frac{\mu}{P_r} = \frac{\mu_L}{P_{r_L}} + \frac{\mu_t}{P_{r_t}} \tag{5}$$

In this paper, $P_{r_L} = 0.72$, $P_{r_t} = 0.9$.

## B. Simulation results

### a) Distribution in whole nozzle

Characteristic parameter distribution in whole nozzle of 100W MPT was simulated and results were shown in Fig 1. Characteristic parameters such as pressure, density, temperature and Mach number change not a half in the convergence part of nozzle. Pressure, density and temperature fall along the axial direction in the divergence part of nozzle, while the Mach number enhances. The axial velocity increases along the axial direction and decreases along the radial direction. Distribution of temperature, Mach number and velocity both axial and radial, definitely show the existing and influence of surface layer.
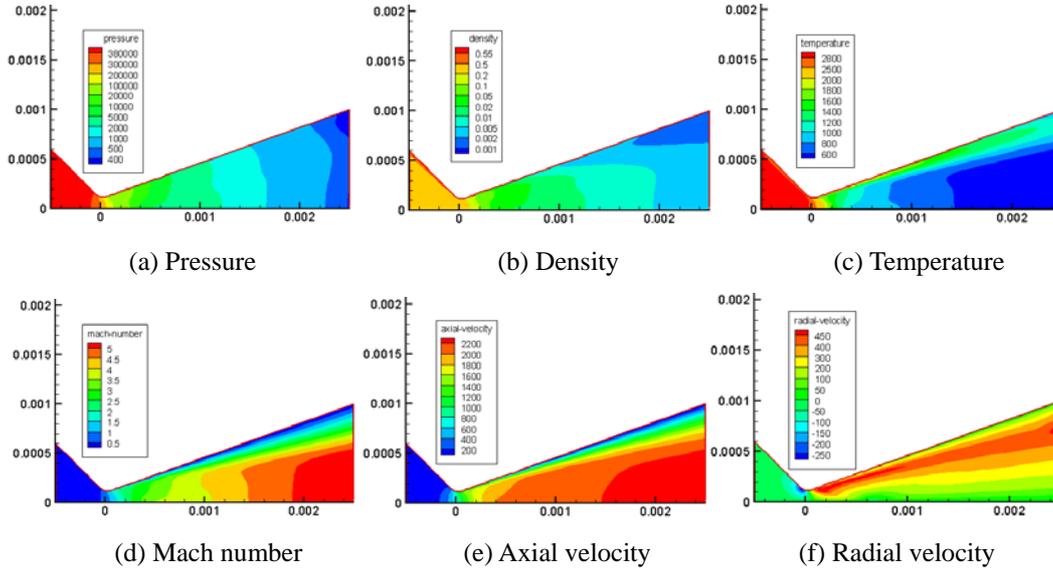


(a) Pressure  (b) Density  (c) Temperature

(d) Mach number  (e) Axial velocity  (f) Radial velocity

**Fig1. Characteristic parameter distribution in whole nozzle (with propellant N$_2$)**

### b) Distribution at the outlet plane

Characteristic parameter distribution at the outlet of nozzle, which would be set as the inlet condition of plume region, was packed up and shown in Fig 2. Pressure at the outlet plane of nozzle is about 350~400Pa. The rapidly dropping of pressure near the nozzle wall is caused by over expanding of N$_2$. The density of ejected gas is about 0.0035 kg/s, and has a undulation near the wall. The temperature at the outlet plane is about 440K, and higher near the wall. The axial velocity is about 2200m/s, and drops by the wall.
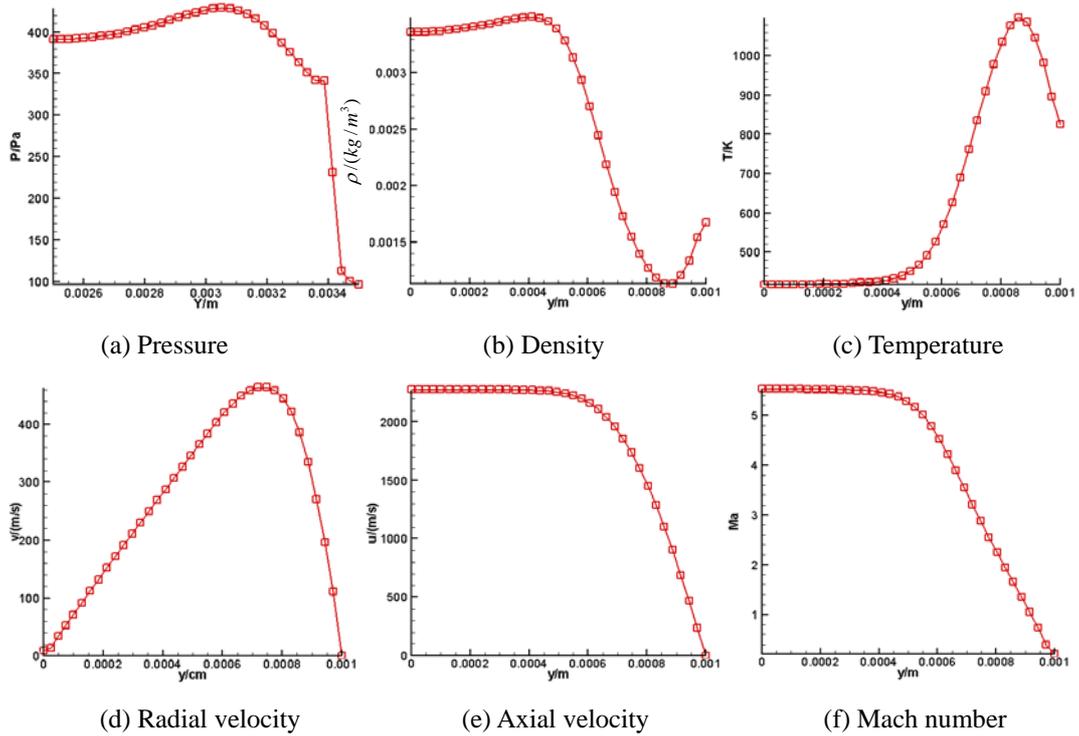
|  |  |  |
|:--:|:--:|:--:|
| (a) Pressure | (b) Density | (c) Temperature |



|  |  |  |
|:--:|:--:|:--:|
| (d) Radial velocity | (e) Axial velocity | (f) Mach number |

**Fig2. Characteristic parameter distribution at the outlet of nozzle (with propellant $N_2$)**

#### c) Performance with difference propellants

To verify the correctness of simulation model, results of calculation and experiment with several difference propellants were given in Tab 1.

The results of simulation have a good consistence with experiment dates. From which, the trustiness of simulation model are checkout.

**Tab1. The comparison between calculation results and experiment dates**

| Propellant | Thrust (*mN*) | | Specific Impulse (*s*) | |
|:--:|:--:|:--:|:--:|:--:|
|  | Calculation | Experiment | Calculation | Experiment |
| Ar | 24.8 | - | 180.2 | - |
| He | 23.6 | 24 | 565.2 | 590 |
| $N_2$ | 26.5 | 26 | 243.7 | 230 |

## IV. Plume simulation

### A. Calculation model

The Direct simulation Monte Carlo Method (Ref. 5, 6) uses the motions and collisions of particles to perform a direct simulation of nonequilibrium gas dynamics. Each particle has coordinates in physical space, three velocity components, and internal energies. A computational grid is employed to group together particles that are likely to collide. Collision selection is based on a probability model developed from basic concepts in kinetic theory. The method is widely used for rarefied non-equilibrium conditions and finds application in hypersonic, materials processing, and micro-machine flows.

The intermolecular potential was assumed to be a variable hard sphere. Energy redistribution between the rotational and Random Sample Frequency (RSF) method was chosen for the sampling of collision molecules. The reflection of molecules on the surface was performed in accordance with the

CLL model.

**B. Simulation results**

The simulation of MPT plume has done with $N_2$ and Ar propellants, and the result are shown in Fig3 and Fig4.

**a) Using $N_2$ as propellant**

The pressure, density and temperature fall quickly along axial direction, and drop slowly along radial direction. The velocity both axial and radial change not a half near the center. Away from center, the axial velocity increases along the axial direction and decreases along the radial direction, while the radial velocity do oppositely.
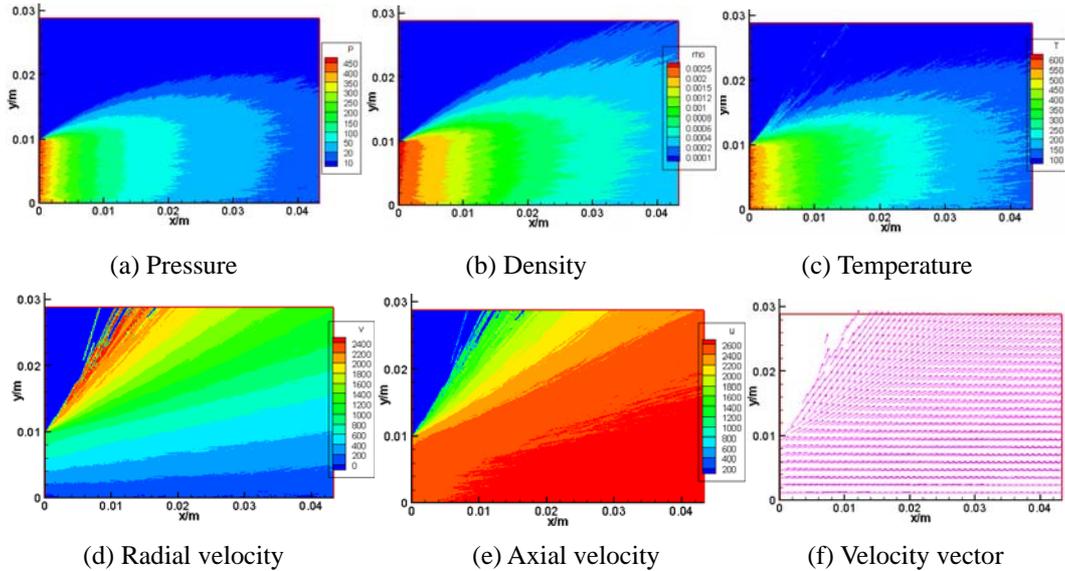


| (a) Pressure | (b) Density | (c) Temperature |



| (d) Radial velocity | (e) Axial velocity | (f) Velocity vector |

**Fig3. The distribution of plume with $N_2$ Propellant**

**b) Using Ar as propellant**

Characteristic parameter distribution of plume while using Ar as propellant, is similar with the results while using $N_2$ as propellant, except the flow region reducing.
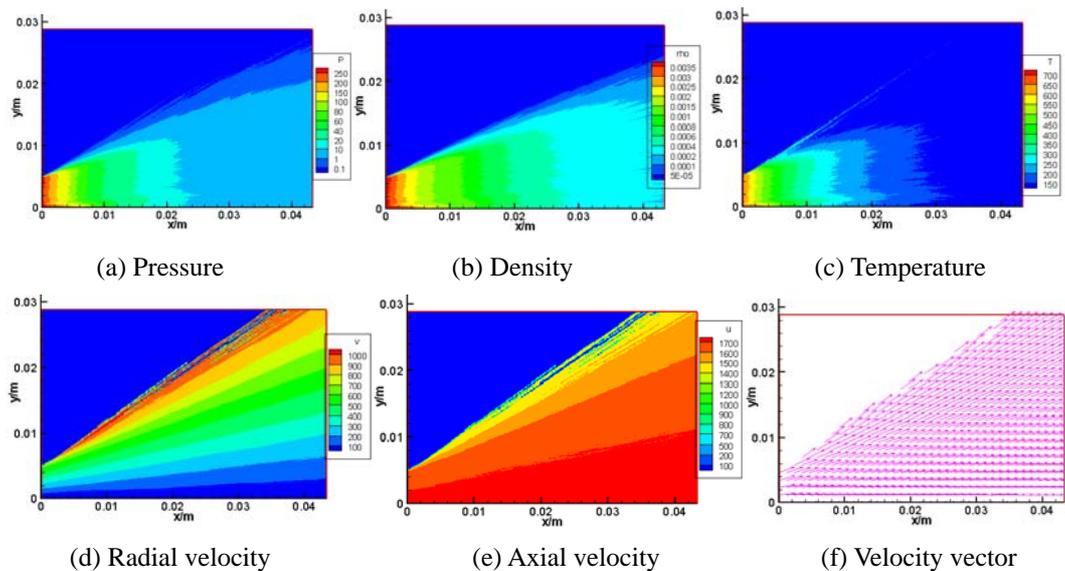


| (a) Pressure | (b) Density | (c) Temperature |



| (d) Radial velocity | (e) Axial velocity | (f) Velocity vector |

**Fig4. The distribution of plume with Ar Propellant**

## V. Conclusions

The flow of MPT nozzle was simulated with N-S equations, and performance of thruster was calculated. Simulation results are accordant to experience dates. The flow in plume field was simulated with DSMC method. Using the outlet parameters of nozzle calculation as the inlet condition of plume field, the distribution of temperature, pressure, gas density and velocity were gotten. From the simulation results, we can conclude that:

(1) In the convergence part of nozzle, pressure, density, temperature and Mach number change not a half; in the divergence part, pressure, density and temperature fall along the axial direction, while the Mach number enhances.

(2) At the outlet plane of nozzle, pressure is about 350~400Pa; density of ejected gas is about 0.0035 kg/s; temperature is about 440K; and the axial velocity is about 2200m/s.

(3) Using difference propellants. thrust of MPT change a little, about 23.6mN to 26.5mN; while the specific impulse has great disparities. The specific impulse is 565.2 seconds when using Helium as propellant, 243.7 seconds for Nitrogen and 180.2 seconds for Argon.

(4) In plume field, the pressure, density and temperature fall quickly along axial direction, and drop slowly along radial direction. The velocity both axial and radial change not a half near the center. Away from center, the axial velocity increases along the axial direction and decreases along the radial direction, while the radial velocity do oppositely.

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