NUMERICAL SIMULATION OF THE FREE MOLECULEMICRO-RESISTOJET FLOW

IEPC-2007-204

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

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Abstract: A numerical model of flow field distribution and performance prediction of the Free Molecule Micro-Resistojet (FMMR) was created. The influence of difference nozzle kinds, propellant kinds, working pressure and heating temperature on the performance of FMMR was studied. Results of calculation and analysis show that, FMMR with divergence-cross nozzle has great performance improvement than equal-cross nozzle, for thrust increasing 38% and specific impulse increasing 23% maximally; and convergence-divergence-cross nozzle has 21% thrust increase comparing with divergence-cross, but no effect on special impulse enhance. The propellant kind has no effect on thrust, while specific impulse rapidly increases with the decreasing of propellant molecular weight. The specific impulse of FMMR increases with the heightening of working pressure and heating temperature, and thrust increases with the heightening of working pressure but decreases with the heightening of heating temperature.

I. Introduction

The Free Molecule Micro-Resistojet is a micropropulsion device created especially for the propulsion needs of micro-satellite and nano-satellite (Ref. 1). It offers several distinct advantages over conventional microthruster concepts for attitude control and station keeping maneuvers. The FMMR combines MEMS fabrication techniques with simple, lightweight construction consisting of only a polysilicon thin film heating element at a temperature T and a long exhaust nozzle (Ref. 2). Thrust is generated by ejecting heated propellant molecules out of the nozzle. The FMMR operates between 50 and 500Pa (Ref. 3). Because of the low operation pressure, the propellant has a large mean free path inside the expansion nozzle. With the small expansion slot width on the order of 100 μm, a Knudsen number of about unity is maintained inside the thruster.

The design of nozzle is one of the most important parts for FMMR contrive. Convenient to be fabricated by deep fluting technique, the nozzle is designed in planar symmetry structure. There are two kinds of nozzle, equal-cross nozzle and divergence-cross nozzle being used in principle and validating experiments.

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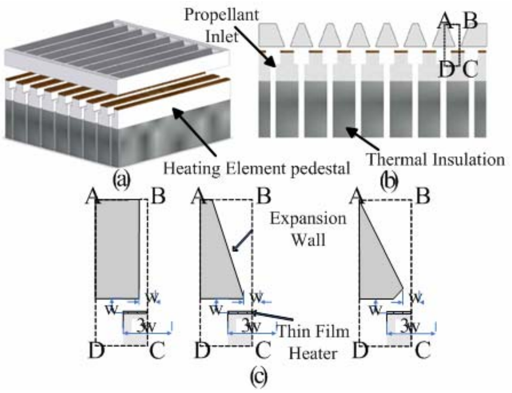
Because of the small scale of FMMR, and low work pressure, theories for normal nozzle design are not fit for the FMMR nozzle design. In this paper, using DSMC method, the gas flow in equal-cross nozzle, divergence-cross nozzle, as well as convergence-divergence-cross nozzle were simulated, and the influence of nozzle kinds on thruster's performance was analyzed.

The FMMR has a large scale of propellant selection, a large scope of plenum stagnation pressure from 50 to 500Pa, and a large scope of heating temperature from 300 to 500K. To evaluate the influence of propellant kinds, heating temperature and plenum stagnation pressure on the performance of FMMR, the gas flow with different conditions was simulated and the performance parameters such as mass flow, thrust and specific impulse were calculated.

II. Numerical Method and Calculation Model

The Direct simulation Monte Carlo Method (Ref. 4) 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.



(a) Integration structure (b) Schematic of cross section (c) Three kinds of nozzle cross section

Figure1: Structure of FMMR

Fig.1 shows the structure of FMMR and the cross section of three different kind nozzles. Simulation in this paper is for one propulsion unit, in which the wide of nozzle throat w is set as 100 μm, and the wide of heating film chip is $3w$ width.

The intermolecular potential was assumed to be a variable hard sphere. Energy redistribution between the rotational and translational modes was performed in accordance with the Larsen-Borgnakke model. The reflection of molecules on the surface was performed in accordance with the CLL model. And a momentum-dependent relaxation number $\sigma = 0.8$ was used (Ref 5).

Supposing u_i to be the normal velocity component and v_i , w_i to be the other two components, a suitable reference frame in which we can make w_i equal to 0 can also be found. Then, the velocity of molecule after collision with the wall can be solved by the equation below.

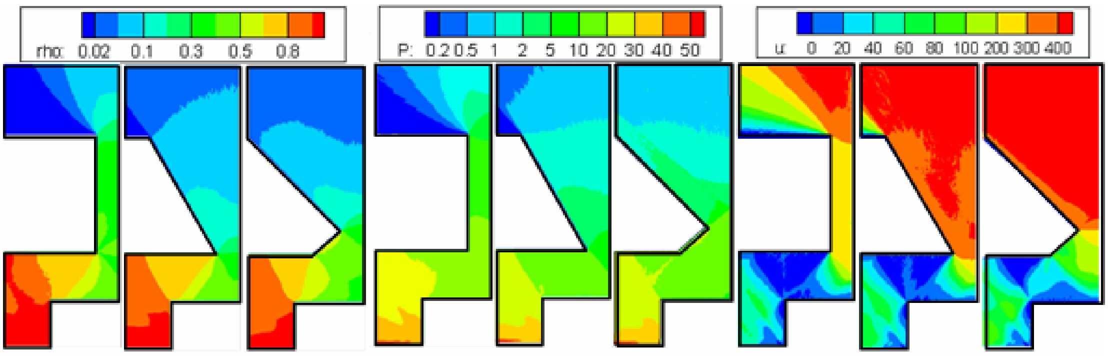
$$\begin{cases} \bar{v}_r = (1-\sigma)v_i, \bar{u}_r = (1-\sigma)u_i \\ r_1 = \sqrt{-\sigma(2-\sigma)\ln R_1}, r_2 = \sqrt{-\sigma(2-\sigma)\ln R_2} \\ \theta_1 = 2\pi R_3, \theta_2 = 2\pi R_4 \\ v_r = \bar{v}_r + r_1 \cos\theta_1 \\ w_r = r_1 \sin\theta_1 \\ u_r = \sqrt{\bar{u}_r^2 + 2r_2\bar{u}_r \cos\theta_2 + r_2^2} \end{cases}$$

Here, R_1, R_2, R_3, R_4 are four random numbers from 0 to 1, and u_r, v_r, w_r are the three components of molecule velocity after collision.

III. Result and Discuss

A. Flow field distribution

Using vapor as propellant, the flow in equal-cross nozzle, divergence-cross nozzle and convergence-cross nozzle were simulated, while the relative density, pressure and velocity distribution were given in Fig. 2.



(a) Density distribution (b) Pressure distribution (c) Axial velocity distribution

Figure 2: Simulation results of equal-cross, divergence-cross and convergence-divergence-cross nozzle

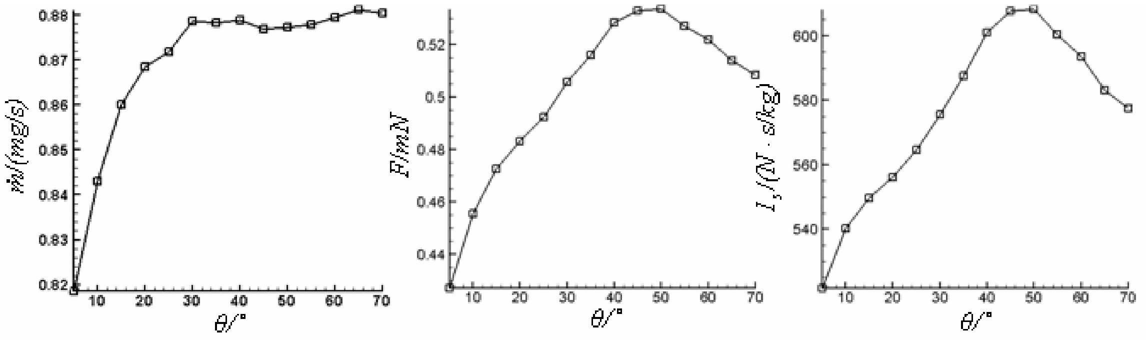
The density and pressure decrease along the flow direction. The grads of density and pressure in near plume field are biggish for equal-cross nozzle, but very small for divergence-cross nozzle and convergence-divergence-cross nozzle. The gas velocity increases along the flow direction and has large grads in the narrowest cross section.

B. The influence of the nozzle kinds

The thrust, specific impulse and mass flowrate were calculated for equal-cross nozzle. Using vapor as propellant, the heat film temperature being 600K, stagnation pressure being 50 *Pa*, the performance parameters thruster unit (with 1 meter long) were: $\dot{m} = 0.777 mg/s$, $F = 0.384 mN$, $Is = 493.93 N \cdot s/kg$.

a) Analysis of divergence-cross nozzle

The engineering experience to take half divergence angle of nozzle as 15 to 30 degree is not suitable for the FMMR nozzle design, because of the rarefaction in the flow channels. The relation between thruster's performance and half divergence angle was given in Fig.3, by the flow simulation with different half divergence angles θ.



(a)Mass flow (b) Thrust (c) Specific pulse

Figure 3: The relation between half divergence angle and thruster performance

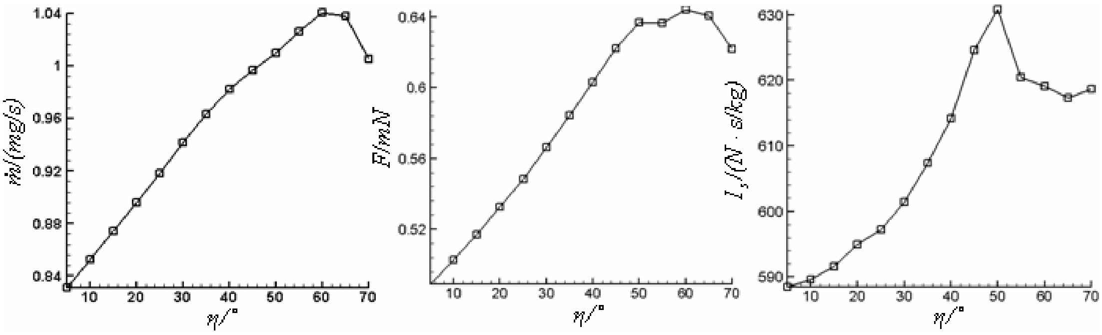
Fig.3 shows that the performance of FMMR can have a great improvement by using the divergence-cross nozzle than equal-cross nozzle, for the mass flowrate increasing 14%, thrust increasing 38% and specific impulse increasing 23% maximally.

The mass flowrate, thrust, and specific impulse increase while the half divergence angle increases, when $\theta < 30^\circ$. The mass flowrate gets its maximum at $\theta = 30^\circ$, and changes not half when $\theta > 30^\circ$. The thrust and specific impulse get their maximum at $\theta = 50^\circ$, and decrease while θ keeps on increasing.

The maximal specific impulse is 638.18 $N \cdot s/kg$ when $\theta = 50^\circ$. It is accordant to the reference 2 in which $Is = 668 N \cdot s/kg$ when $\theta = 45^\circ$, and reference [6] in which $Is = 650 N \cdot s/kg$ when $\theta = 54.74^\circ$.

b) Analysis of convergence-divergence-cross nozzle

To improve the performance by increase the chance of molecule entering the flow channels, the convergence-divergence-cross nozzle were introduced and the flow simulation for this kind of nozzle were also completed. Here, the width of the inlet of divergence part was set as 100 μm, and the half divergence angle was set as 45°. The relation between thruster's performance and half convergence angle was shown in Fig. 4.



(a)Mass flow (b) Thrust (c) Specific pulse

Figure 4: The relation between half convergence angle and thruster performance

The mass flowrate and thrust have a further enhancement than divergence-cross nozzle, after introducing the convergence part, for thrust increasing 21% and mass flowrate increasing 19%

maximally. And the specific impulse is almost the same with the divergence-cross nozzle.

The thrust, specific impulse and mass flowrate increase quickly along with η increasing, when η is small. The specific impulse gets its maximum at $\eta = 50^\circ$, then has a little fall to the level equal to the divergence-cross nozzle. The thrust changes not half after $\eta = 50^\circ$, and has a little fall when $\eta = 60^\circ$. The mass flowrate gets its maximum at $\eta = 60^\circ$, then declines. The specific impulse of convergence-divergence-cross nozzle is smaller then divergence-cross nozzle while $\eta < 40^\circ$. It boils down to the molecule momentum losing by collision with the wall when convergence angle is too small.

C. The influence of propellant kinds

Many gases can be used as the propellant of FMMR. Nitrogen and argon are good propellants for validating experience, while hydrogen, helium and vapor are more attractive for their high specific impulse (Ref. 6, 7). The experiences with helium and nitrogen have done by the group of Ketsdever in University of Southern Clifornia, and using vapor as propellant is in their plan (Ref. 1). The results of their experiences are given in Tab.1, when heating temperature is 573K and stagnation pressure is 50 *Pa*.

Table 1: experimental results of FMMR performance in several typical propellants

Propellant	H_e	N_2
Mass flow（m*g/s*）	0.43	1.00
Thrust (*mN*)	0.68	0.60
Specific Impulse (*N·s/kg*)	1581	600

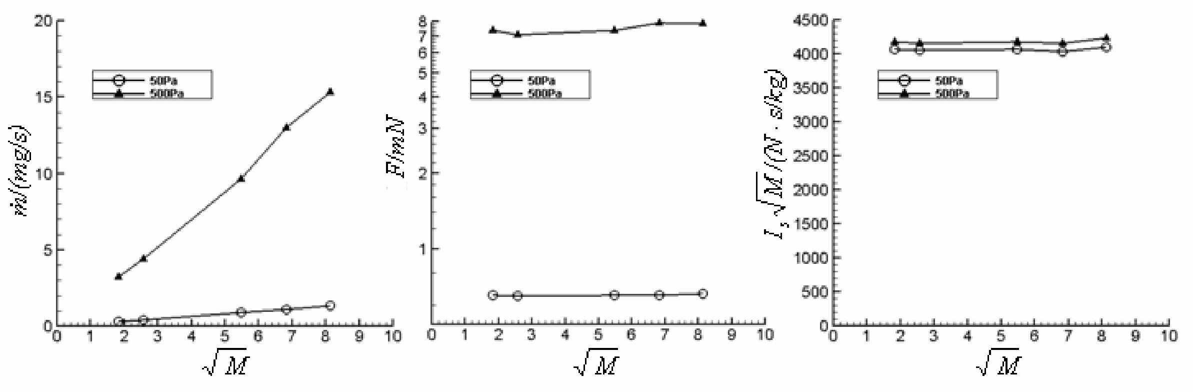
To analyze the influence of the propellant kings on thruster’s performance, the parameters including thrust, specific impulse and mass flowrate with hydrogen, helium, nitrogen, vapor and argon were calculated in the condition of heating temperature being 573K and stagnation pressure being 50 *Pa*. Calculation results show in Tab.2.

Table 2: Computation results of FMMR performance in several typical propellants

Pressure *(Pa)*	Propellant	Mass flow（m*g/s*）	Thrust (*mN*)	Specific Impulse (*N·s/kg*)
50	H_2	0.29305	0.65276	2227.47
	H_e	0.41294	0.64982	1573.64
	H_2O	0.87681	0.65276	744.47
	N_2	1.10341	0.65354	592.29
	A_r	1.31634	0.66216	503.03
500	H_2	3.22613	7.38401	2288.81
	H_e	4.37867	7.06904	1614.43
	H_2O	9.65258	7.38401	764.98
	N_2	12.97348	7.91593	610.16
	A_r	15.33033	7.84789	519.92

Simulation results of helium and nitrogen are accordant with experience data when the stagnation pressure is 50 *Pa*.

Tab.2 shows that, along with the increasing of molecular weight of propellant, the specific impulse decreases quickly while mass flowrate increaseing. The kind of propellant has no effect on thrust. At a fixed stagnation pressure and heating temperature, the relation between the performance of FMMR and molecular weight of propellant are given in Fig.5. Here, the x-coordinate is the square root of molecular weight $\sqrt{M}$, the y-coordinate are the mass flowrate $\dot{m}$, the thrust F, and the product of specific impulse and square root of molecular weight $I_s \cdot \sqrt{M}$.



(a)Mass flow (b) Thrust (c) Specific pulse

Figure 5: The relation between propellant molecule weight and thruster performance

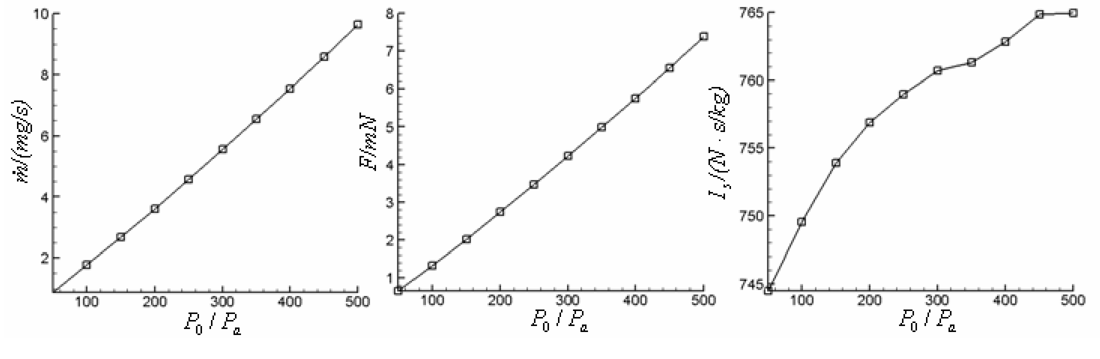
The mass flowrate $\dot{m}$ is nearly direct proportioned with the square root of molecular weight $\sqrt{M}$. Thrust F has no relationship with the propellant kind for it holds on line when propellant changes. The specific impulse is inverse proportioned with the square root of molecular weight $\sqrt{M}$, concluding by $I_s \cdot \sqrt{M}$ being a constant.

D. The influence of the working conditions

The performance characteristics of FMMR are determined by the stagnation pressure and heating temperature, while the structure of nozzle and propellant are fixed. The relations between thruster performance and stagnation pressure, heating temperature were analyzed by flow simulation with divergence-cross nozzle.

a) Influence of the stagnation pressure

Using vapor as propellant and setting heating temperature at 600K, the performance parameters of thruster with stagnation pressures from 50 *Pa* to 500 *Pa* were calculated and showed in Fig.6.



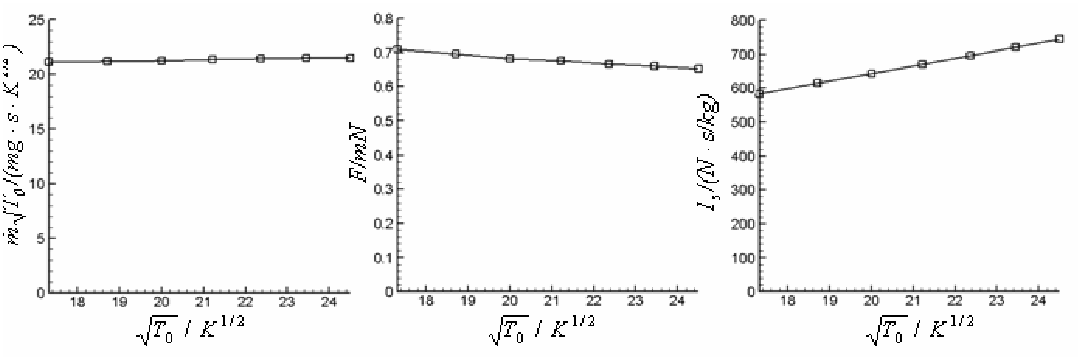
（a）Mass flow （b）Thrust （c）Specific impulse

Figure 6: The relation between stagnation pressure and thruster performance

Thrust and mass flowrate are nearly direct proportioned with the stagnation pressure, while specific impulse has a small improvement, about 5%, when the stagnation pressure increases from 50 *Pa* to 500 *Pa*. Reason of this enhance is considered to the better directional capability of gas flow, caused by more collisions between the molecules and between molecule and wall, along with the stagnation pressure increasing.

b) Influence of the heating temperature

Using vapor as propellant and setting stagnation pressure at 50 *Pa*, the performance parameters of thruster with heating temperature from 300K to 600K were calculated and showed in Fig.7. Here, the x-coordinate is the square root of heating temperature $\sqrt{T_0}$, and the y-coordinate are the product of mass flowrate and square root of heating temperature $\dot{m}\sqrt{T_0}$, the thrust F and the specific impulse I_s .



（a）Mass flow （b）Thrust （c）Specific impulse

Figure 7: The relation between heat film temperature and thruster performance

It can be concluded that the mass flowrate $\dot{m}$ is inverse proportioned to the square root of heating temperature $\sqrt{T_0}$ from fig.7 (a), for $\dot{m}\sqrt{T_0}$ being a constant. In fig.7 (b), thrust F decreases along with the heating temperature increasing, but not seriously, just drops 10% while the heating temperature changes from 300K to 600K. And in fig.7 (c), specific impulse I_s increases linearly with $\sqrt{T_0}$ increasing, but not be direct proportion.

IV. Conclusions

The gas flow in a Free Molecule Mirco-Resistojet is studied numerically with the direct simulation Monte Carlo method. A reasonable agreement of numerical and experimental data was observed. From the simulation, we have gotten the following conclusions:

(1) The density and pressure decrease along the flow direction. The grads of density and pressure in near plume field are biggish for equal-cross nozzle, but very small for divergence-cross nozzle and convergence-divergence-cross nozzle. The gas velocity increases along the flow direction and has large grads in the narrowest section.

(2) The performance can be great improved by using divergence-cross nozzle than equal-cross

nozzle: the mass flowrate increases 14%, thrust increases 38% and specific impulse increases 23% maximally. Along with the increasing of the half divergence angle, the thrust and specific impulse firstly increase and then decrease. When the half divergence angle is about 45 to 50 degrees, thruster gets its best performance for thrust and specific impulse all gets their maximal value.

(3) The performance can have a further improvement by using convergence-divergence-cross nozzle than using divergence-cross nozzle: thrust increases 21% maximally, but specific impulse has no enhancement. Along with the increasing of the half convergence angle, the thrust and specific impulse firstly increase and then decrease. When the half divergence angle is about 50 degrees, thruster gets its best performance.

(4) The propellant kinds have no influence on the thrust of FMMR. And under the same stagnation pressure and heating temperature, the mass flowrate direct proportion with square root of propellant's molecular weight, while specific impulse inverse proportion with square root of propellant's molecular weight.

(5) The thrust and mass flow are nearly direct proportioned to the stagnation pressure at the identical heating temperature, while specific impulse has a small improvement, about 5%, when the stagnation pressure increases from 50 *Pa* to 500 *Pa*.

(6) At a fixed stagnation pressure, the mass flowrate is inverse proportioned to the square root of heating temperature, while specific impulse increases linearly with its increasing. Thrust decreases along with the heating temperature increasing, but not seriously, just drops 10% while the heating temperature changes from 300K to 600K.

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