SIMPLE ESTIMATION OF THE PERFORMANCE OF A LOW POWER ARCJET THRUSTER WITH DIATOMIC GAS AS PROPELLANT

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Abstract

This paper describes the simple estimation of a low power arcjet thruster using a one-dimensional flow model. Discharge power is put into propellant gas as heat input and then the total enthalpy of the propellant gas is increased. In this paper, it is considered that the discharge power is employed not only for elevation of the propellant gas temperature but also for dissociation of it. The thrust and specific impulse which are important performance characteristics of an arcjet thruster were obtained by calculations and compared with experiments. The comparison showed satisfactory agreements with experiments.

Introduction

Arcjet thrusters have attracted much interest as one of the available space propulsion systems for north-south station keeping of spacecrafts. In the design of arcjet thrusters, it is needed to calculate the flowfield inside the thruster for specified thruster geometry and to predict the performance characteristics of it. This is done, in many cases, by the numerical calculations using the axisymmetric Navier-Storkes equations, which needs very long computation time to obtain the steady state solutions. Therefore, in certain cases, numerical calculations are inconvenient as practical design tools. Nothing would be better than quasi one-dimensional calculation, if that could give satisfactory information for the thruster design. On the view of this point, quasi one-dimensional calculations which are available as a simple design tool have been conducted for nitrogen and hydrogen arcjet thrusters and the results of thrust and specific impulse have been compared with experiments.[1,2]. In a previous paper[3], the simple estimation of the performance of an argon arcjet thruster was performed, and the comparison with experiments showed a good agreement. The present work is the extension of the previous work to arcjet thrusters with diatomic gas as propellant.

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Nomenclature

A	:	cross section
F	:	thrust
h	:	enthalpy
I_{sp}	:	specific impulse
$\dot{m}$	:	mass flow rate
P	:	arc power
p	:	pressure
R	:	gas constant
T	:	temperature
u	:	velocity
α	:	degree of dissociation
η	:	efficiency
Θ_d	:	characteristic temperature for dissociation
ρ	:	density
ρ_d	:	characteristic density for dissociation

Subscripts

1	:	entrance of the discharge section
*	:	exit of the discharge section
e	:	exit of the nozzle

Flow Model

The flow inside the thruster nozzle is treated as quasi one-dimensional, and nitrogen or hydrogen is considered as propellant gas. The schematic of the thruster is shown in Fig. 1. The flow model considered here are as follows :

1. The discharge section is located at the throat.
2. In the discharge section, the propellant is heated by Joule heating and at the same time chemical equilibrium is instantaneously established.
3. The energy input is employed not only for an increase in the propellant gas temperaature but also for dissociation and ionization.

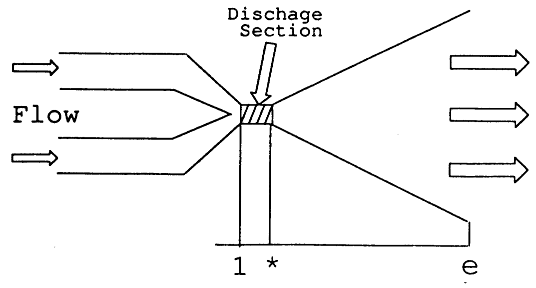

Fig. 1 Schematic of an arcjet thruster

4. After the discharge, the heated, dissociated and ionized gas is isentropically expanded through a nozzle, namely vibrational relaxation and all chemical reactions are considered as frozen.

5. It is assumed that the flow at the exit of the discharge section is sonic.

Basic Equations and Method of Solution

Continuities of flow properties across the discharge section are written as follows :
Conservation of Mass

$$\rho_1 u_1 = \rho_* u_* = \dot{m}/A_* \quad (1)$$

Conservation of momentum

$$\rho_1 u_1^2 + p_1 = \rho_* u_*^2 + p_* \quad (2)$$

Conservation of energy

$$\dot{m}(h_1 + \frac{1}{2}u_1^2) + \eta P = \dot{m}(h_* + \frac{1}{2}u_*^2) \quad (3)$$

Equation of enthalpy

$$h_* = f_1(\alpha_*, T_*) \quad (4)$$

Equation of state

$$p_1 = \rho_1 R T_1 \quad (5)$$

$$p_* = (1+\alpha_*)\rho_* R T_* \quad (6)$$

Law of mass action

$$\alpha_* = f_2(p_*, T_*) \quad (7)$$

Velocity at the exit of the discharge section (sonic velocity)

$$u_* = f_3(\alpha_*, T_*) \quad (8)$$

In principle, nine unknowns (ρ_1, u_1, p_1, ρ_*, u_*, p_*, T_*, α_* and h_*) can be determined from Eqs. (1) to (8) by specifying the diameter at tne discharge section (d_*), mass flow rate ($\dot{m}$), arc power (P), propellant temperature at the entrance of the discharge section (T_1) (hence h_1 is known) and efficiency (η). However, it is quite difficult to simultaneously solve these equations, so that an iteration method has been adopted here. The method is as follows:

1. ρ_1 can be determined from the Eq.(5) for the imagined value of p_1.

2. u_1 is obtained from Eq. (1).

3. The value of u_* is assumed. Initially $u_* = u_1$ is set.

4. ρ_* and h_* are obtained from Eqs. (1) and (3), respectively.

5. The value of α_* is assumed. Initially $\alpha = 0$ is set. T_* is obtained from Eq. (4).

6. p_* is obtained from Eq. (6).

7. α_* is obtained from law of mass action Eq.(7) using T_* and p_*. Then, u_* and p_1 are obtained from Eqs. (8) and (2), respectively.

8. Steps 1 to 7 are repeated until solutions are converged.

We consider that dissociation-recombination is frozen downstream of the discharge section and hence gas constants, specific heat and ratio of specific heats can be set to constants. Therefore, the flow from the discharge section to the nozzle exit is treated as isentropic.

In addition, since the degree of dissociation is expected to be quite low, it is assumed that γ and R are those for molecule, respectively. Properties at the nozzle exit can be determined by using quasi one-dimensional nozzle flow equations. Using quantities at the nozzle exit, thrust and specific impulse are determined by $F = \dot{m}u_e$ and $I_{sp} = F/\dot{m}g$.

To simplify the analysis, an ideal dissociating gas of Lighthill[4] is employed for nitrogen propellant. The following law of mass action for the ideal dissociating nitrogen is employed for Eq. (7):

$$\frac{\alpha_*^2}{1-\alpha_*^2} = \frac{\rho_d}{\rho_*} R T_* \exp(-\Theta_d/T_*) \quad (9)$$

where ρ_d is the characteristic density of dissociation, that varies very slowly in the temperature range from 1000K to 7000K. Therefore, ρ_d may be treated as constant in this temperature range. A recommended value of ρ_d for nitrogen is 130 g/cm^3.

On the other hand, the explicit expression of Eq. (7) for hydrogen is not available, so that a computational code of high-temperature equilibrium hydrogen[5] was employed.

Results and Discussion

Nitrogen propellant

Calculations were carried out for two different mass flow rates and compared with experiments.[1] The diameters of the discharge section and nozzle exit have been taken to be 0.64 mm and 9.5 mm, respectively, to compare with the experiments.

Figures 2 and 3 show thrust vs power at the mass flow rates of 91.6 mg/s and 45.4 mg/s for various efficiencies, respectively. As seen in these figures, the thrust is increased in proportion to power for constant efficiency. It is apparent from Fig. 2 that the calculation for $\eta = 30\%$ is in fairly good agreement with the experiment. At the mass flow rate of 45.4 mg/s, the thrust calculated for $\eta = 25\%$ fairly well agrees with the experiment.

Specific impulse corresponding to Figs. 2 and 3 is shown in Figs. 4 and 5, respectively. As well as the thrust, I_{sp} is increased in proportion to power, showing the feature similar to the thrust. The calculation and experiment are in agreement for the same efficiency as in Figs. 2 and 3, respectively. Hence, it may be mentioned that the efficiency little changes at a constant mass flow rate in the experiment.

Table 1 Performance characteristics of a thruster for N_2 ($\dot{m}$=91.6 mg/s)

P	T_*	α_*	F	I_{sp}
400W	1170K	6.77×10^{-19}	148mN	164s
432W	1250K	1.26×10^{-17}	152mN	170s
450W	1290K	5.65×10^{-17}	155mN	172s
500W	1410K	2.26×10^{-15}	162mN	180s
550W	1530K	5.11×10^{-14}	168mN	188s
600W	1650K	7.41×10^{-13}	175mN	195s
650W	1760K	7.52×10^{-12}	181mN	202s
680W	1830K	2.62×10^{-11}	185mN	206s

Tables 1 and 2 show the temperature (T^*) and degree of dissociation (α_*) immediately downstream of the discharge section along with thrust and specific impulse which have been shown in Fig. 2 and 3. It is apparent that nitrogen is very little dissociated, and hence it may be mentioned that the effect of chemical reactions can be neglected.

Calculated temperatures at discharge section are between 1000 K and 3000 K, so that the model of the ideal dissociating gas proposed by Lighthill may be used in this case.

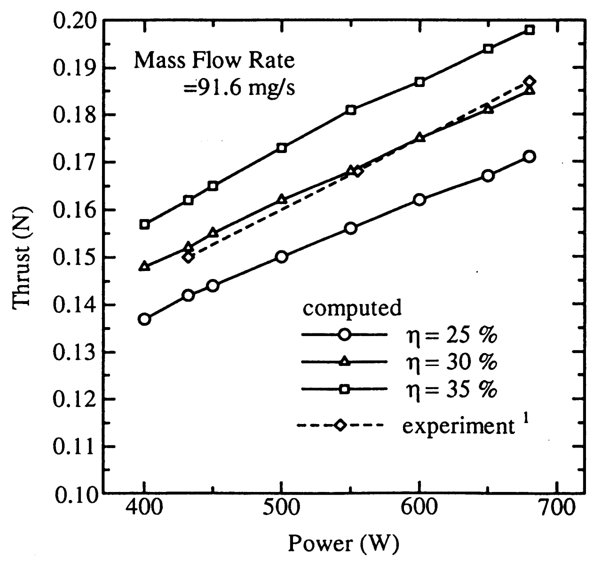

Fig. 2 Thrust versus power for a nitrogen arcjet thruster.

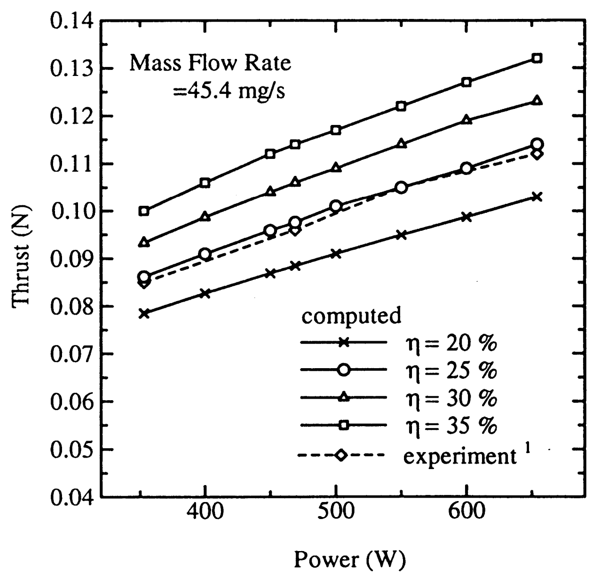

Fig. 3 Thrust versus power for a nitrogen arcjet thruster.

Table 2 Performance characteristics of a thruster for N_2 ($\dot{m}$=45.4 mg/s)

P	T_*	α_*	F	I_{sp}
353W	1630K	7.60×10^{-13}	86.2mN	194s
400W	1820K	2.75×10^{-11}	91.0mN	205s
450W	2020K	6.06×10^{-10}	95.9mN	215s
469W	2090K	1.68×10^{-9}	97.6mN	219s
500W	2210K	7.67×10^{-9}	101mN	226s
550W	2410K	6.41×10^{-8}	105mN	236s
600W	2610K	3.88×10^{-7}	109mN	245s
654W	2830K	2.05×10^{-6}	114mN	255s

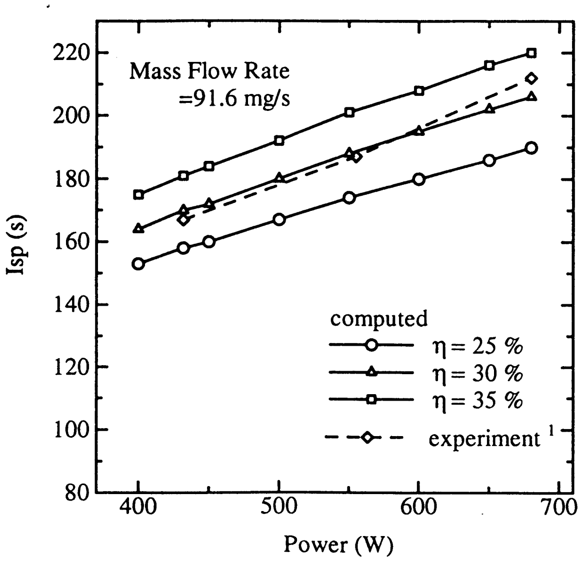

Fig. 4 Specific Impulse versus power for a nitrogen arcjet thruster.

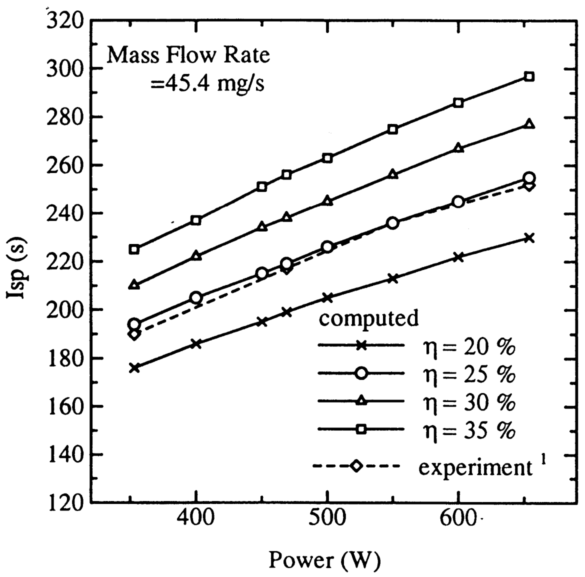

Fig. 5 Specific Impulse versus power for a nitrogen arcjet thruster.

Hydrogen propellant

Calculations for hydrogen propellant were carried out for two different diameters at the discharge section, 0.6 mm and 0.8 mm, and compared with experiments.[2]

Calculated results of thrust vs power are shown in Fig. 6 for $d_* = 0.6$ mm and in Fig. 7 for $d_* = 0.8$ mm. Unlike the results for nitrogen shown in Figs. 2 and 3, the calculation for constant efficiency does not agree with the experiment, that is to say, the calculated thrust shows an increase with power, while the experimental thrust illustrates almost constant for power. The results calculated by using the efficiency given in the paper of the experiments are also illustrated on this figure. The features of the calculated and experimental results are fairly similar. Similar agreement is seen in Fig. 7 for $d_* = 0.8$ mm. Comparisons between calcula-

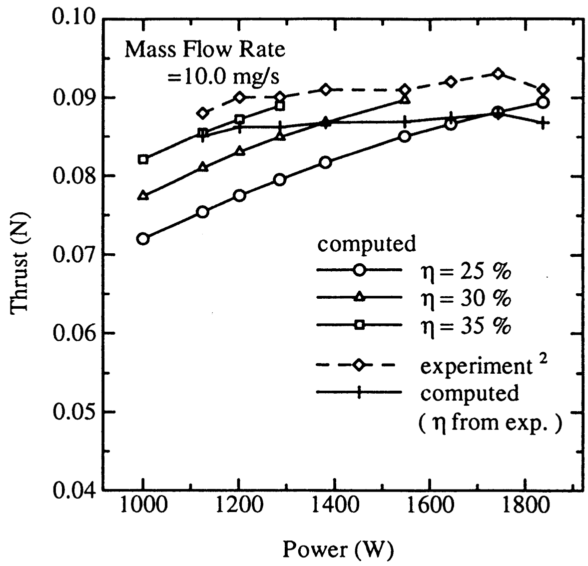

Fig. 6 Thrust versus power for a hydrogen arcjet thruster.

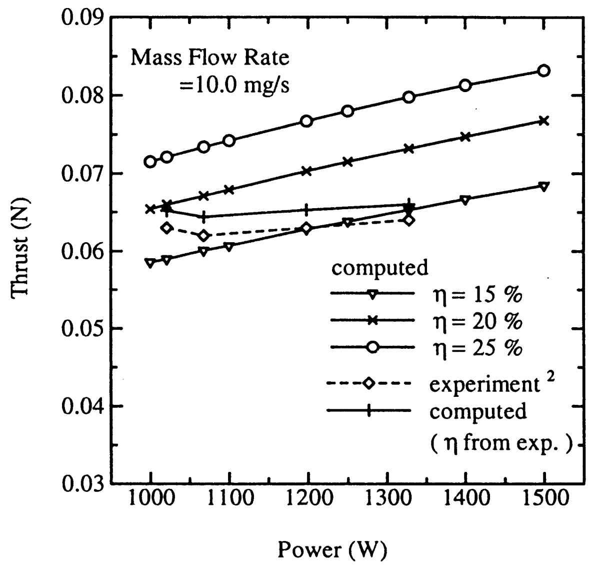

Fig. 7 Thrust versus power for a hydrogen arcjet thruster.

tion and experiment of I_{sp} are given in Figs. 8 and 9. Calculated results obtained by employing variable efficiency given in Ref. 2 give feature similar to the experiments.

Tables 3 and 4 show the temperature (T^*) and degree of dissociation (α_*) immediately downstream of the discharge section along with thrust and specific impulse shown in Fig. 7 and 8. It is apparent that hydrogen is also little dissociated.

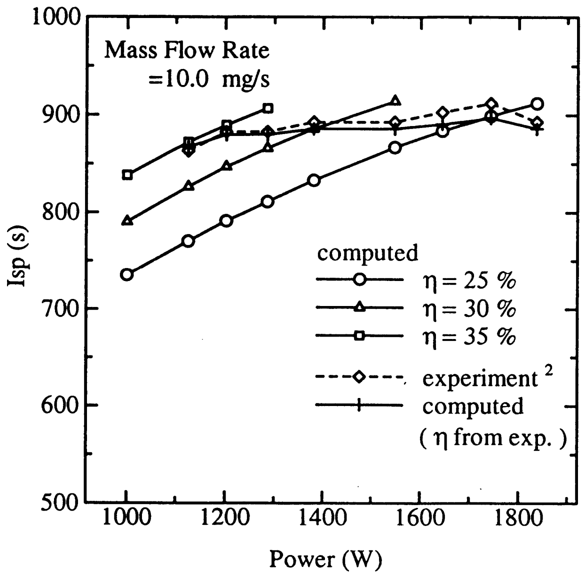

Fig. 8 Specific Impulse versus power for a hydrogen arcjet thruster.

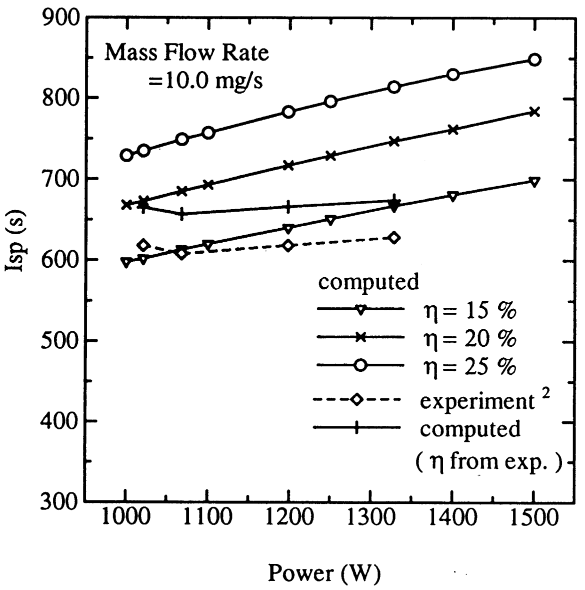

Fig. 9 Specific Impulse versus power for a hydrogen arcjet thruster.

Conclusion

The results obtained in the present work are summarized as follows:

1. The thrust and specific impulse of an arcjet thruster with nitrogen or hydrogen as propellant were obtained by simple calculation.

Table 3 Performance characteristics of a thruster for H_2 (d_*=0.6 mm)

P(W)	η(%)	T_*(K)	α_*	F(mN)	I_{sp}(s)
1125	34.4	2310	5.18×10^{-3}	85.0	867
1202	33.7	2380	7.21×10^{-3}	86.2	880
1286	31.5	2380	7.21×10^{-3}	86.2	880
1381	30.0	2410	8.41×10^{-3}	86.8	886
1547	26.8	2410	8.45×10^{-3}	86.9	886
1644	25.7	2440	9.55×10^{-3}	87.4	891
1743	24.8	2470	1.10×10^{-2}	87.9	897
1837	22.5	2410	8.27×10^{-3}	86.8	886

Table 4 Performance characteristics of a thruster for H_2 (d_*=0.8 mm)

P(W)	η(%)	T_*(K)	α_*	F(mN)	I_{sp}(s)
1021	19.4	1380	2.87×10^{-6}	65.2	665
1068	18.0	1350	1.82×10^{-6}	64.4	657
1198	16.6	1380	3.05×10^{-6}	65.3	666
1328	15.4	1420	4.63×10^{-6}	66.0	674
1500	12.8	1350	1.79×10^{-6}	64.4	657

2. The comparison with experiments showed a good agreement to experiments. Therefore, this calculation can be employed as a design tool.

3. Both thrust and specific impulse were increased with power in a nitrogen arcjet thruster, that is similar to the experiment. However, calculated thrust and specific impulse are increased with power in a hydrogen arcjet thruster, while the experiments show nearly constant thruster and specific impulse.

4. It is apparent from the comparison between the calculation and experiment that efficiency is nearly constant in the nitrogen arcjet thruster and decreased with an increse in power in the hydrogen arcjet thruster.

5. Calculated degree of dissociation is quite low. Therefore, it may be mentioned that most input power is employed for an increase in the propellant temperature.

References

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