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Investigation on plume expansion and ionization in a laser ablation plasma thruster

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ABSTRACT

The laser ablation plasma thruster is a novel electric propulsion thruster, which combined the laser ablation and electromagnetic acceleration. In order to investigate the plume expansion and ionization in the laser ablation plasma thruster which was difficult to obtain from experiments, the two-dimensional heat conduction model and fluid dynamics model were established. The heat conduction model was established to calculate the target ablation, taking into account temperature dependent material properties, phase transition, dielectric transition and phase explosion. The fluid dynamics model was used to calculate the plume properties, taking into account ionization, plume absorption and shielding. The good agreement between calculated and experimental data validated our model, while the plume velocity, temperature and electron number density were predicted by using the numerical method. The calculated results showed that the plume uniformly expanded into the ambience with a mushroom shape, and the peak values of plume velocity, temperature and electron number density fraction were distributed at the front of the plume. The ceramic tube limited the radial expansion of the plume, and enhanced the velocity, temperature and ionization degree nearby the wall, due to the interaction between the plume and the wall. Otherwise, the effects of laser fluence on plume properties and thrust performance of the thruster were investigated utilizing the numerical model.

1. Introduction

As a member of electric propulsion thrusters (EPTs), pulsed plasma thruster (PPT) has a broad prospect on small satellites for its advantages of small, compact, low-mass, and high specific impulse [1]. Though significant progress has been made during the half century, there are still many problems restrict the development of PPT. The main limitation is its low-thrust efficiency, often around 10–15%. Therefore, the improvement in the thrust efficiency of PPT are on top of current needs.

Early in the year 2000, Horisawa et al. proposed a laser-assisted plasma thruster (LS-PPT), in which a laser-induced plasma was induced through laser beam irradiation onto a solid target and accelerated by electrical means [2]. From then on, a series of fundamental studies of laser-electric hybrid acceleration systems were conducted [3–9]. Compared with the traditional PPT, the LS-PPT combines the laser ablation with electromagnetic acceleration means, which can significantly enhance the thrust performance. However, the phenomenon of "late ablation" is still inevitable in the LS-PPT, which significantly reduces the thrust efficiency of the thruster. In order to overcome the shortage of "late ablation", a novel laser ablation plasma thruster (LA-PPT) has been proposed in our previous work [1]. The LA-PPT separates the laser ablation from electromagnetic acceleration through a ceramic tube. As shown in Fig. 1, the LA-PPT consists of a pair of rectangular electrodes, a ceramic tube and a insulator. The propellant is placed inside the ceramic tube. Because of the unique structure of this thruster, almost all types of solid matter can be applied as the propellant, such as metals, polymers and so on. The experimental results show that, with the use of metallic propellant, a specific impulse of approximate 8000s and thrust efficiency of about 90% are obtained [1]. Hence the LA-PPT is a promising candidate for small satellites propulsion, and the physical mechanisms of the thruster should be further investigated. The working process of the LA-PPT can be divided into two stages: laser-induced ablation and plasma-induced discharge. The ablation plume expansion and ionization in the ceramic tube is the combination of the two stages, and it is crucial to understand the working process of the LA-PPT. However, the ablation plume expansion and ionization is difficult to be experimentally investigated, especially when it occurs in a ceramic tube. Therefore, we utilize numerical method to investigate the plume expansion and ionization in the ceramic tube.

By using the numerical method to simulate the plume expansion and

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Nomenclature

T_c	critical temperature, K
C	mass fraction
t	time, s
D	diameter, mm
u	axial velocity, m/s
d	dielectric layer, m
v	radial velocity, m/s
E	sum of energy, J/m^3
v_{sur}	surface recession velocity, m/s
F	laser fluence, J/cm^2
W	index of the viscosity
g	characteristic degeneracy
Z	ratio of total collision to inelastic collision numbers
H	volumetric enthalpy, J/m^3
z	axial coordinate, m
h	planck constant, J·s
α	absorption coefficient of the target, 1/m
I	laser intensity, W/m^2
B	absorption coefficient of the plume, 1/m
I_b	Impulse bit, μN·s
δ	initial length of the target, μm
I_n	rate of homogeneous nucleation, 1/(m^3·s)
η	electron number density fraction
IP	ionization energy, eV
ξ, χ, τ	fixed coordinate system
K	thermal conductivity, W/(m·K)
ρ	density, kg/m^3
K_{eq}	equilibrium constant, 1/m^3
Σ	cross section, m^2
k	reaction rate, m^3/s
σ_s	surface tension, N/m
k_1	order of accuracy of numerical scheme
ψ	fraction of ionization area to whole area
k_B	boltzmann constant, J/K
$\dot{\omega}$	mass source, kg/(m^3·s)
L	length, mm

Subscripts

L_v	latent heat of vaporization, J/kg
0	initial
M	molar mass, kg/mol
a	ablation
m	mass, kg
b	boiling
N_1	total number of grids
bac	backward
N_n	number of time steps
c	ceramic tube
n	number density, 1/m^3
d	dielectric layer
p	pressure, Pa
e	electron
p_b	reference pressure, Pa
exp	explosion
p_{sat}	saturation pressure, Pa
f	forward
Q	partition function, 1/m^3
g	gas particle
R	reflectivity
i	electronic energy level
R_c	critical radius, m
l	liquid
r	radial coordinate, m
m	melting
S	source term, W/m^3
p	lume
S_{err}	accumulation of numerical errors
r	reduced
S^{max}	allowable value of total error
ref	reference
s	exposed ablation surface, m
s	specie
s_m	melting phase interface, m
sur	exposed ablation surface
T	temperature, K
Vap	vaporization

ionization in the ceramic tube, the relevant physics of propellant ablation needs to be implemented. The heating process within a propellant material during the irradiation of the laser pulse can be calculated by taking into account temperature dependent material properties, melting, phase transition, dielectric transition, phase explosion, and the reflection of the laser beam at the surface of the propellant [10]. In addition, the ablation plume absorbs part of laser energy, and causes the density, temperature, pressure and components in the ablation plume dramatically vary, which has an significant effect on the thrust performance. During the years, the expansion dynamics of pulsed laser generated plasma plume has been widely investigated through experimental and numerical methods [11–15]. Especially, several models have been proposed to describe the expansion of ablation plume and the formation of plasma in the plume [13]. Aden et al. utilized hydrodynamic equations to describe the plume expansion, which is called hydrodynamic model [16]. Afterwards, the hydrodynamic model had been widely applied to study various laser-solid interactions [17–20]. In order to calculate the laser energy loss caused by plume absorption and shielding, the formation of plasma in the plume were also considered in several hydrodynamic models [14,21–24]. However, most previous models are one-dimensional (1D), which ignore the radial expansion of the ablation plume. As for the LA-PPT, the radial expansion of the plume is limited by the wall of the ceramic tube. This may significantly effect the plume properties in the ceramic tube. Therefore, we establish a 2-D hydrodynamic model to investigate the ablation plume expansion and ionization in the ceramic tube. The numerical model can give insight in the plume dynamics and plasma behavior of LA-PPT, which is sometimes difficult to obtain from experiments.

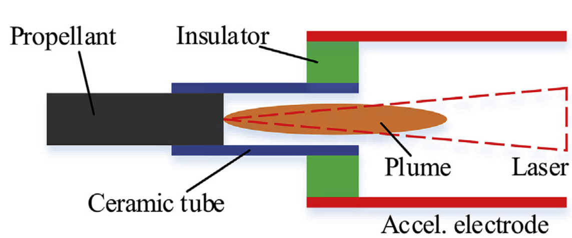

Fig. 1. Schematic illustration of the laser ablation plasma thruster.

In this work, a 2-D model for nanosecond laser ablation of aluminum propellant is presented, which contains the target ablation and plume expansion in the ceramic tube. A 2-D heat conduction model is