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Numerical simulation of air-breathing nanosecond laser propulsion considering subsonic inflow and multi-pulse

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ABSTRACT

The model of paraboloid point focusing laser thruster is adopted to investigate numerically the air-breathing nanosecond laser propulsion under subsonic inflow and multi-pulse condition. The influence of pulse number and subsonic inflow on propulsive performance is analyzed. The simulation results indicate that the average impulse coupling coefficient C_{mn} decreases significantly with the increasing of pulse number because the air in the nozzle cannot recover to the initial state, but the trend becomes smooth due to the similar flow field before subsequent pulse. When the Mach number increases, the multi-pulse C_{mn} falls down at the same number of laser pulse. It shows that the faster subsonic inflow, the higher air drag and the shorter time of interaction between the shock wave and the thruster.

1. Introduction

Air-breathing laser propulsion is deemed to be an innovative concept for propelling micro/nano/pico satellites into earth orbit with low cost and launch-on-demand in aerosphere in the future. The great advantages are the infinite specific impulse and the high payload ratio because of the separation of propulsive and energy system. It makes the technology become the research hotspots in the field of aerospace.

Laser propulsion has achieved sufficient researches as it is put forward by Kantrowitz [1]. In the past decades, the propulsion mechanism based on static and single pulse becomes clear through theoretical research, numerical simulation, etc. [2,3]. At present the research has entered a new stage considering inflow and multi-pulse [4–9].

On the basis of the previous study under static condition, numerical simulation of air-breathing multi-pulse laser propulsion by nanosecond laser pulse under subsonic condition is performed to analyze the influence of pulse number and subsonic inflow on propulsive performance in this paper.

2. Computational model

2.1. Thruster model

Fig. 1 presents the geometry of the laser thruster that is made from glass adopted in this paper. The equation of the inner surface is $y^2 + z^2 = 2px$, with parabolic parameter $p = 10$, focal distance $f = 5$ mm, bottom radius $R = 15$ mm and height $H = 11.25$ mm. The inner surface of the paraboloid point focusing laser thruster is not only the system of laser receiving and focusing, but also the nozzle of producing reversal thrust.

The software Gambit was used to generate the grids. In order to simplify the grid generation and the processing difficulty of the boundary conditions, the whole computational field was divided into three zones, zone I for inner field and zone II and III for outer field, as shown in Fig. 2. There, the far field of zone II was supposed to be the subsonic outflow boundary condition, and the far field of zone III was supposed to be the subsonic inflow boundary condition. Besides, the distance to the outflow boundary was enough to reduce the non-physical wave reflection.

2.2. Numerical method

A cell-centered finite volume scheme is adopted in the numerical investigations, using the 2-D Navier–Stokes equations as the

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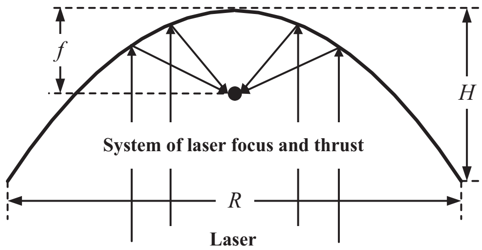

Fig. 1. Schematic structure of thruster.

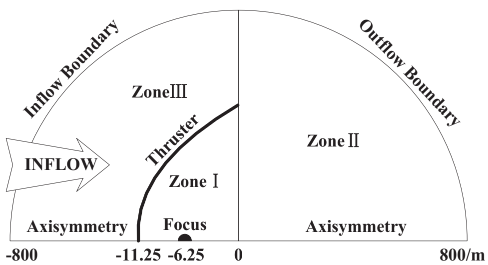

Fig. 2. Computational zones.

governing equations ignoring the viscous and mass force. The equations are as follows:

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial z}+\frac{\partial G}{\partial r}=\frac{\partial M}{\partial z}+\frac{\partial N}{\partial r}+S \tag{1}$$

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho \upsilon\\ e_0\end{bmatrix},\quad F=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho u\upsilon\\ (e_0+p)u\end{bmatrix},\quad G=\begin{bmatrix}\rho \upsilon\\ \rho u\upsilon\\ \rho\upsilon^2+p\\ (e_0+p)\upsilon\end{bmatrix},\quad M=\begin{bmatrix}0\\ \tau_{zz}\\ \tau_{zr}\\ u\tau_{zz}+\upsilon\tau_{zr}-q_z\end{bmatrix}$$
$$N=\begin{bmatrix}0\\ \tau_{zr}\\ \tau_{rr}\\ u\tau_{zr}+\upsilon\tau_{rr}-q_r\end{bmatrix},\quad S=\frac{1}{r}\begin{bmatrix}-\rho\upsilon\\ -\rho u\upsilon+\tau_{zr}\\ -\rho\upsilon^2+\tau_{rr}-\tau_{\theta\theta}\\ -(e_0+p)\upsilon-q_r+u\tau_{zr}+\upsilon\tau_{rr}\end{bmatrix} \tag{2}$$

where ρ, p, τ and q are defined as density, pressure, viscous force tensor and heat flux of the fluid, respectively. u and υ are the x, y velocity components; z, r and θ are the parameters of cylindrical coordinate system; e_0 is the total energy per unit volume. The expression is

$$e_0=\frac{p}{\gamma-1}+\frac{\rho\left(u^2+\upsilon^2\right)}{2} \tag{3}$$

Although the temperature becomes very high after air breakdown, air is assumed as ideal gas in these computations, which can be described by

$$p=\rho RT \tag{4}$$

2.3. Initial conditions

In numerical simulation the nanosecond laser is adopted. There, the single-pulse energy E is 18 J, the pulse width t_p is 20 ns and the repetition frequency f is 25 Hz. The environment parameters are shown in Table 1.

Table 1
Parameters of ambient air.

Mach number	Height (km)	Pressure (P)	Density (kg/m^3)	Temperature (K)
0.1–0.9	0	1.01×10^5	1.225	288

3. Results and discussion

3.1. The average impulse coupling coefficient

In air-breathing laser propulsion, one of the most important parameters of propulsion characteristics is the impulse coupling coefficient (C_m), defined as the impulse generated by unit laser energy. For single pulse, C_m can be described by

$$C_m=\frac{I}{E}=\frac{\int_0^t F(t)\,dt}{E} \tag{5}$$

where I is the impulse and E is the incident energy of the laser pulse. For multi-pulse propulsion, the average impulse coupling coefficient (C_{mn}) is emphasized, which can be described by

$$C_{mn}=\frac{I_n}{E_n}=\frac{\int_0^t F(t)\,dt}{nE} \tag{6}$$

where I_n is the total impulse generated by n pulses.

We address the subsonic inflow Mach number from 0.1 to 0.9, with the total computational time t = 0.2 s. Fig. 3 shows the relation between C_{mn} and pulse number in the different subsonic inflow. The computation results indicate that the multi-pulse C_{mn} decreases with the increase of laser pulse number under subsonic inflow, but the changing trend becomes smooth. Take a broader look, when the Mach number increases, the C_{mn} decreases sharply. However, the gap of the different inflow becomes narrow with the increase of pulse number. The influence of subsonic inflow and pulse number on propulsive performance is analyzed in detail as follows.

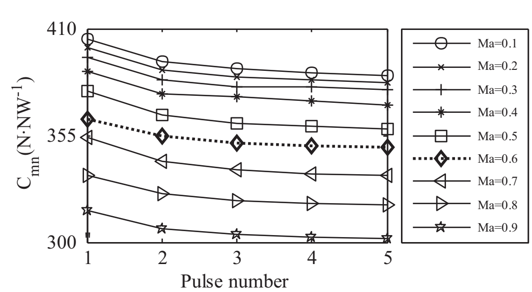

Fig. 3. C_{mn} vs. pulse number in different subsonic inflows.