Design and performance analysis of reflecting ring focusing system for laser propulsion

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A reflecting ring focusing system for laser propulsion has been designed. A paraboloidal reflector of higher order is constructed to focus the laser energy on a ring which can produce a tire liked ignition region in the thruster. Considering the angle of laser incidence and reflector's coarseness, mathematic models of the focusing performance have been set up through ray tracking method. Moreover, numerical simulations of the shape, size, energy density and spatial characteristics of ignition wire are carried out in order to know the ring focusing system's superiority. The results show that the ring ignition region with a radius of 49 mm produced by a ring focusing system is about one order of magnitude larger than that produced by single point focusing system, which makes the heating of the work substance much more uniformly. Also, the ring focusing system has a better coarseness endurance.

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Laser propulsion will serve as an alternative propulsion system for ground-to-orbit launch systems in the near future[1,2]. Since energy is long-distance transmitted from the ground or laser base in space to the vehicle, receiving and focusing of laser beam become the key for thruster's performance[3]. Single-point focusing systems[4,5] adopt parabolic reflectors or collecting lens to focus laser energy on a single point in thruster. In this focusing model there is not enough time to exchange energy, which causes energy waste[6]. Multi-point focusing scheme is proposed to solve this problem[7].

In this reflecting ring focusing system, as shown in Fig. 1, one main component is a paraboloidal reflector of higher order, which is used to focus the laser beam on a ring to form a ringlike "ignition" region. The paraboloid is designed with the rotation of the parabola $(x-R)^2 = -2p(z-H)$ around z-axis,

$$\left(\sqrt{x^2+y^2}-R\right)^2 = -2p(z-H), \quad (p>0), \tag{1}$$

where R and H are underside radius and highness of the paraboloid, respectively, p is the parabolic parameter. The paraboloidal reflector is as shown in Fig. 2.

Because of machining technology, the coarseness problem exists inevitably on the reflector surface. A sine function has been added to the paraboloidal equation to simulate the coarseness case, as shown in Fig. 3. The modified equation is as

$$\left(\sqrt{x^2+y^2}-R\right)^2 - 2pA\sin\left(2\pi k\sqrt{x^2+y^2}\right) = -2p(z-H), \tag{2}$$

where A and k are the amplitude and frequency parameter of coarseness.

Ray tracking method has been adopted in the research, and the essence of this method is dispersing the laser beam into a group of parallel laser rays and then researching spatial distributing status of each reflected ray to confirm the focusing region.

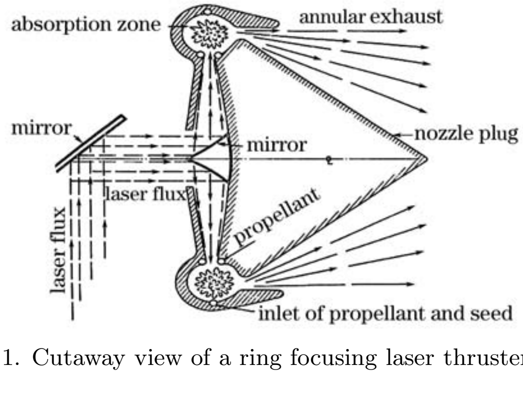

Fig. 1. Cutaway view of a ring focusing laser thruster.

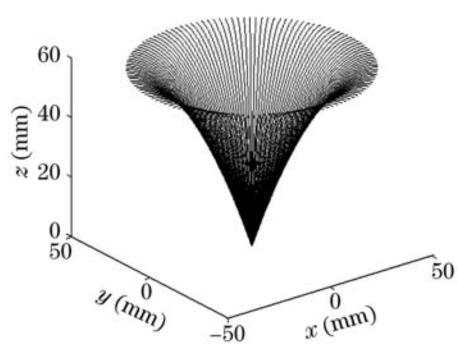

Fig. 2. Sketch map of a paraboloid reflector.

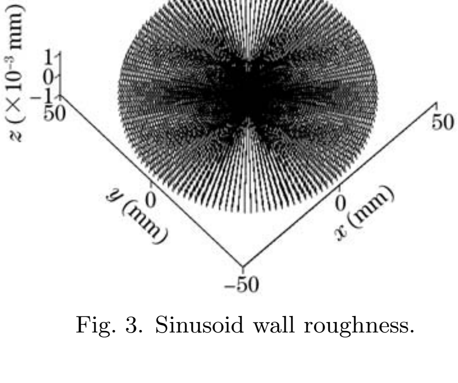

Fig. 3. Sinusoid wall roughness.

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Incidence ray is dispersed into a group of parallel rays, because the paraboloid is of z-axial symmetry, and the random angle of incidence is equivalent to incidence paralleling xoz plane.

Suppose θ is the angle between a random incident ray and x-axis, and $M(x_0, y_0, z_0)$ is the incident point of this ray on the reflector, the equation of this incident ray is

$$\begin{cases} \dfrac{x - x_0}{\cos\theta} = \dfrac{z - z_0}{\sin\theta} \\ y - y_0 = 0 \end{cases}, \quad \theta \in \left(0, \frac{\pi}{2}\right]. \tag{3}$$

Direction vector of this incident ray is $\vec{L}_1 = \{l_{11}, l_{12}, l_{13}\} = \{\cos\theta, 0, \sin\theta\}$. Equation (1) is transformed as

$$f(x, y, z) = \left(\sqrt{x^2 + y^2} - R\right)^2 + 2p(z - H). \tag{4}$$

Suppose $\vec{L}_2 = \{l_{21}, l_{22}, l_{23}\}$ is the normal vector of paraboloid at point $M(x_0, y_0, z_0)$, then

$$\begin{cases} l_{21} = \left.\dfrac{\partial f}{\partial x}\right|_{M(x_0,y_0,z_0)} \\ l_{22} = \left.\dfrac{\partial f}{\partial y}\right|_{M(x_0,y_0,z_0)} \\ l_{23} = \left.\dfrac{\partial f}{\partial z}\right|_{M(x_0,y_0,z_0)} \end{cases}. \tag{5}$$

Suppose $\vec{L}_3$ is the direction vector of reflected ray, we can set $\vec{L}_3 = \{l_{31}, l_{32}, 1\}$.

$\vec{L}_1$, $\vec{L}_2$ and $\vec{L}_3$ exist in the same plane according to the law of reflection, then

$$\begin{vmatrix} l_{31} & l_{32} & 1 \\ l_{11} & l_{12} & l_{13} \\ l_{21} & l_{22} & l_{23} \end{vmatrix} = 0. \tag{6}$$

Angle of incidence is equal to angle of reflection, so

$$\frac{\vec{L}_1 \cdot \vec{L}_2}{|\vec{L}_1| \cdot |\vec{L}_2|} = -\frac{\vec{L}_2 \cdot \vec{L}_3}{|\vec{L}_2| \cdot |\vec{L}_3|}. \tag{7}$$

We can get l_{31} and l_{32} by solving simultaneously Eqs. (6) and (7). There are two forms for $\vec{L}_3$ in the solution. One is in proportion to $\vec{L}_1$, which should be discarded. According to the direction vector and reflecting point, the reflection equation can be gained. Consequently, the point of intersection $M'(x', y', z')$ between the reflected ray and the plane $z = c$ can also be achieved,

$$\begin{cases} x' = x_0 + (c - z_0) l_{31} \\ y' = y_0 + (c - z_0) l_{32} \\ z' = c \end{cases}. \tag{8}$$

The average power of each dispersed incident ray is $P_0 = P/N$. P is total power of incident laser beam; N is the number of dispersed ray. Energy loss of reflection is ignored.

Grid has been marked off in plane $z = c$, the grid coordinates are (x_i, y_i), $(i = 1, 2, \cdots, n_x; j = 1, 2, \cdots, n_y)$, and the cross area of each grid section is $r_0 \times r_0$, where r_0 is small and N is large enough. The n is assumed as the reflected point sum located in zone $\{(x_i, x_{i+1}), (y_i, y_{i+1})\}$ and $e_{ij-}\text{flux} = \dfrac{nP_0}{r_0^2}$ as energy density of point of intersection (x_i, y_i).

There is a focal plane $z = c_0$ when the incident laser beam is parallel with the main axis of focus system. Spatial characteristics of energy in ring focusing system can be investigated by formation of plane pencil around the plane $z = c$. It is very important for numerical simulation of energy transmission in thruster.

Numerical simulations are carried out based on mathematic models proposed above. Correlative parameters are shown in Table 1.

Ignition wire and energy density on plane $z = 50$ mm for laser beam with different incident angles are exhibited in Fig. 4. The average energy density in ignition wire exceeds 10^7 W/cm^2. The case of normal incidence is shown in Fig. 4(a). A ringed wire with the radius of 49 mm occurs on focal plane $z = 50$ mm and the average energy density reaches 10^8 W/cm^2. The ignition efficiency is 100%. Abruption of ignition wire and decrease in

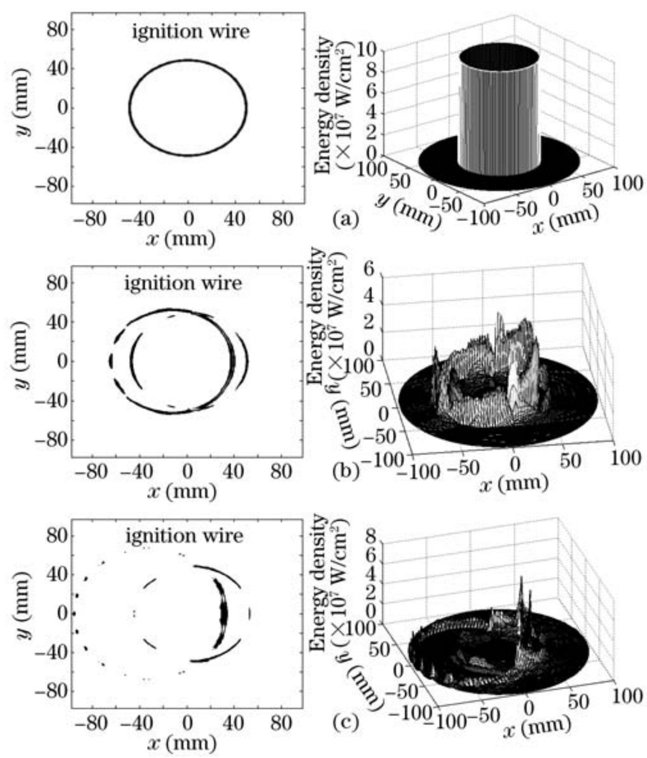

Fig. 4. Ignition wire and energy flux density in $z = 50$ mm, for laser beam with (a) normal incidence, oblique incidence with an angle of (b) 10° and (c) 20°.

Table 1. Correlative Parameters in Numerical Simulations

H (mm)	R (mm)	p	P (MW)	N	r_0 (mm)	c_0 (mm)
60	49	20	200	6272	1	50

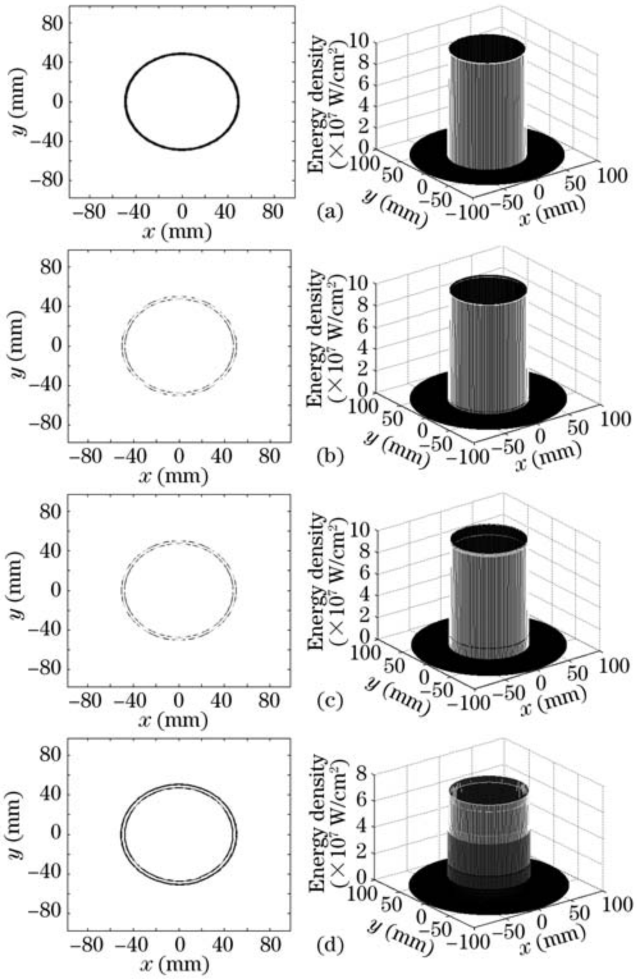

Fig. 5. Ignition wire and energy density in focal plane $z = 50$ mm with laser of normal incidence for (a) $A = 0$, (b) 0.001, (c) 0.01, and (d) 0.1 mm.

energy density are seen in Fig. 4(b), however, ignition can also be done with an efficiency of 75%. When the gradient angle reaches 20°, shown in Fig. 4(c), focal points above 10^7 W/cm^2 decrease farther and the ignition wire becomes discontinuous. The ignition efficiency is 71%. Considering the factors above, the critical incident angle is about 20°.

When the incident laser beam is out of the perpendicular, the focusing energy is no more uniformly distributed in the round ring, but assemble to x-axis, which results in a flat fire area. So, an approximately elliptical cylindrical cavity will greatly increase the energy converting efficiency.

The effects of surface coarseness upon focal performances are shown in Fig. 5. When the amplitude of coarseness $A = 0$, the same as Fig. 4(a), which means the reflector is absolutely clean, laser energy is transformed farthest to kinetic energy of aerocraft. When $A = 0.001$ mm, because of partial scattering of incident laser beam on the reflector surface, some slight abruption of ignition wire has taken place. It seems that there have been two ignition wires, which imposes little effect on the average energy density of ignition wire. When A continuously increases to 0.01 mm, the slight abruption of ignition wire changes little, but takes on great difference on the figure of average energy density, the energy densities of most ignition points keep on around 10^8 W/cm^2, and the others decrease to 8×10^7 W/cm^2. When A reaches 0.1 mm, its effect on focal performance could not be neglected, the ignition wire splits into two parts, two obvious strips of ignition wire have been formed, see Fig. 4(d); the energy density is also divided into two grades, 4×10^7 and 7×10^7 W/cm^2, and a drop of 9% in ignition efficiency takes place.

The effect of reflector coarseness on the focal performance in point focusing system has been researched in Ref. [8]. Conclusions are that when $A = 0.01$ mm the ignition region becomes small obviously and the coarseness has intolerable effect on system. However, the maximum amplitude is about 0.1 mm in our system, which reveals that the ring focusing system has an advantage over the point focusing system.

In conclusion, design and performance analysis of reflecting ring focusing system for laser propulsion are carried out. From the numerical simulations, two results are obtained. Tire liked ignition region with a radius of 49 mm produced by ring focusing system in thruster is about one order of magnitude larger than that produced by spot focusing system, which makes the heating of the working substance much more uniformly. Ring focusing system designed in this research is of certain degree of roughness tolerance. Because of a larger ignition region, the ring focusing system is much better than point focusing system on tolerating surface coarseness.

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