Numerical investigation on the effects of the laser energy and focal position on the multi-pulses laser propulsion

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Abstract. A detailed parametric study on the air-breathing laser propulsive performance is carried out for multi-pulses. Based on the finite volume scheme, the detailed evolving process of the inner and outer flow fluids is simulated. The numerical models with different focal positions and laser energies are employed to analyze the parameters effect on the multi-pulses impulse coupling coefficient $C_m$. Moreover, the laser frequency is discussed and compared with those calculations. The simulation results indicate that the focal position is one of the main factors to influence the multi-pulses $C_m$ at low frequency. For high frequency, it is beneficial to replenish the air in the nozzle when the focal position locates near the nozzle exit. The influence of the laser energy is similar to the single pulse at low frequency, but at high frequency, the partial filling air in the nozzle causes low $C_m$ by high laser energy. The multi-pulses $C_m$ is lower than that of a single pulse. In the same calculative time, the higher the laser frequency, the higher the impulse value, but the lower the $C_m$.

1. Introduction
Laser propulsion is one of the most innovative propulsion for its high efficiency and specific impulse. To propel the small spacecraft, it must work at a sequence of multi-pulses on certain repeating rate in the air-breathing mode. Several experiments have been done on laser propulsion for spacecraft [1-5]. In 1998, the “Laser Lightcraft” had been flown successfully by air-breathing mode using a pulsed laser at 10Hz [6]. In another indoor experiment, it had been found the impulse coupling coefficients decrease when the laser repetition rate increases [7]. By using the numerical method, the non-equilibrium thermodynamics, unstructured-grid is developed to simulate the flow fluids for the single pulse in the nozzle [8]. A dynamic method was employed to calculate the multi-pulse performance [9]. The detailed parameters such as the nozzle configuration, focal systems laser energy etc. show impact on the multi-pulse propulsive performance. However, more systematic and detailed work is needed to be done.
This paper focused on the effects of the focal position and laser energy on multi-pulse propulsion. The detailed evolving process of the inner and outer flow fluids is simulated to compare with the differences among pulses. Moreover, three repetition rates are employed to analyze the frequency influence. The qualitative results gained in this paper will pave the way for designing the optimal laser thrusters for multi-pulses.

2. Computation method

2.1. The nozzle configuration
An expending cylinder nozzle is chosen which is shown in figure 1. The laser beam is focused to the site \( B \) mm away from the front of the nozzle using a lens. In the simulation, the incident laser pulse width is 7.57\( \mu \)s, the laser beam radio is 45mm and the pulse repetition rate is 20Hz, 50Hz and 100Hz respectively.

![Figure 1. Schematic structure of nozzle.](image)

2.2. Computation method
The cell-centered finite volume scheme is used. A Roe scheme is adopted to estimate numerical flux and the space accuracy is extended to 2nd-order by MUSCL (Monotone Upwind Scheme of Conservation Law) approach with Minmode flux limiter. The time integration performed with the predictor correction method.

2.3. Initial value and boundary condition
The gas is standard, and its physical parameters are as follows, atmospheric pressure \( p_0 \) is 1.01325\( \times 10^5 \)Pa, temperature \( T \) is 288.15K, density \( \rho_0 \) is 1.225kg/m\(^3\).

A two-dimensional axisymmetric computational model, as shown in figure 2, is created to describe the propagation of the inner and outer flow fluids. Structure grid is constructed and high grid density is used in the inner flow region for the actual computation. The wall is defined as a slip boundary and the interface is defined as a continuous overlapping type. The outer boundary is set far enough to suppress the influence of non-physical waves reflected from the boundary and is defined as a subsonic, characteristic condition.
3. Results and discussion

A series of computations have been performed for different focused positions and laser energies. The nozzle numbers are listed in table 1.

Table 1. Nozzle number

| Nozzle number | B1 | B2 | B3 | B4 | B5 | B6 |
|---------------|----|----|----|----|----|----|
| B/mm          | 5  | 10 | 15 | 20 | 30 | 40 |

| Nozzle number | E1 | E2 | E3 | E4 | E5 |
|---------------|----|----|----|----|----|
| E_{in}/J      | 14 | 28 | 42 | 56 | 70 |

3.1. Impulse coupling coefficient for different focused position

The laser energy is 14J. Figure 3 shows the thrust histories for different focused positions. The thrusts are formed at time of 0.6μs, 1.6μs, 3.7μs, 8.8μs, 15.1μs and 18.3μs respectively. The laser energy is deposited at the focused position and plasma is produced near the laser focus. As the blast wave expends, the portion of the wave in contact with the nozzle surface and the impulse is delivered to the nozzle. Therefore, the nearer the focused position to the front wall, the earlier the appearance thrust.

Figure 2. Computational zones near the nozzle. Zone 1 is the inner flow zone; zone 2 and zone 3 are the outer ones.

Figure 3. Thrust histories for different focused positions
Impulse coupling coefficient $C_m$ is one of the important parameters of the propulsive characteristics in pulsed laser propulsion. Here, the multi-pulses is $C_m$ defined as

$$C_m = \frac{I}{nE_m} = \frac{\int_0^{n+1} Fdt}{nE_m}$$  \hspace{0.5cm} (1)$$

where $I$, the total impulse of the $n$ pulses, is achieved through temporal force integrations, $f$ is the laser repetition rate. For $n$ pulses, $C_m$ is the average evaluation of $n$ pulses.

Figure 4 and Figure 5 show the $C_m$ versus pulse numbers in 20Hz and 100Hz. The $C_m$ decreases with the number of the laser pulses. In figure 4, the nozzle B2 gets higher $C_m$ than B4 and B6 after 4 pulses in 20Hz. In contrast, the $C_m$ of the nozzle B2, B4 and B6 get closed after the action of 10 pulses in 100Hz.

![Figure 4. $C_m$ versus number of pulses in 20Hz](image)

![Figure 5. $C_m$ versus number of pulses in 100Hz](image)

Figure 6 shows the multi-pulses $C_m$ versus the focal position. The $C_m$ decreases with the increasing $B$ in 20Hz, and the $C_m$ varies slightly for laser repetition rate of 50Hz and 100Hz. As discussed in our previous work [10], the partial filling rate of the air has a critical influence on the pulse propulsive performance. It is beneficial to breathe the air in nozzle when the repetition rate is low. A strong shock wave is generated in the focus region, and its intensity decays rapidly as the wave expends. At 20Hz, the main factor for the $C_m$ is focus position. So the nearer the focus position to the front wall the higher $C_m$ will be got. The pulse separation becomes shorter as the repetition rate increases, the density of the air in the nozzle decreases with the increasing number of the pulses. When the focus position locates far away from the front wall that means it is near the exit, it is beneficial to breathe the air. Therefore, at 100Hz, as the increasing focus position, the $C_m$ increases slightly.
3.2. Impulse coupling coefficient for different laser energies

Figure 7 shows the thrust histories of the first pulse for different laser energies. As shown, the higher the laser pulse energy, the earlier the generation of a pulse thrust and the higher the pick value. At around 550µs to 600µs, when the shock wave arrives at the exit of the nozzle, the density of the air in the nozzle is low and the shock attaching the outside of the wall generates a negative thrust. After the shock slips away from the exit, the air is breathed into the nozzle and the thrust oscillations

In multi-pulses, the density of the air in the nozzle is important for initiating the air breakdown process and may have a significant impact on the numerical value of impulse coupling coefficient. As the laser repetition rate is 50Hz, the computational times to gain the density information for the 2nd, 3rd and 4th pulse start are at 20ms, 40ms and 60ms respectively. The initial density contours for the 2nd, 3rd and 4th pulse starts in the laser energies of 14J, 42J and 70J are shown in figure 8. The density of the air in the nozzle becomes larger with the number of the laser pulses. In the same pulse, the larger laser energy has the lower density area. That is because the air is exhausted more by higher laser energy and it takes a longer time to replenish the air in the nozzle.
The influence of the laser energy on impulse and $C_m$ for single pulse has been studied widely [2, 5, 8]. Here, we simulate the laser energy impact on $I$ and $C_m$ with laser repetition rate of 20Hz, 50Hz and 100Hz for multi-pulses. The calculation time is 10ms.

Figure 9 and figure 10 show the calculation data of $I$ and $C_m$ for different repetition rates. The impulse is found to be a linearly increasing function at the pulse energy of 14-70J as shown in figure 9. The simulation results are similar to those results on single pulse in reference [2]. Also shown, the “f=100Hz” line gets highest rate of slope. One of the reasons is the higher repetition rate obtains more pulses in the same calculation time.

In figure 10, for the single pulse, the $C_m$ reaches maximum at pulse energy of 40J, and does not grow even decrease slightly at subsequent increasing of the pulse energy. For the multi-pulses, the “f=20Hz” achieves higher $C_m$ than the other repetition rates in the same laser energy, and its curve is similar to that of the single pulse. At 50Hz, the $C_m$ has max peak at pulse energy of 32J, and then decreases at pulse energy of 40-70J. In contrast, the $C_m$ grows slightly with the increasing laser energy at 100Hz. For low laser frequency, the influence of the energy is nearly the same with the single pulse. From the density contours in figure 8, it is found that higher energy causes larger low density area in the nozzle. For high frequency, the time between two pulses is short, so the air in the nozzle is partial filling. Hence, it impacts on the intensity of a pressure force upon the nozzle surface, and further influences the $C_m$. Also from figure 9 and figure 10, it indicates that the higher the repetition rate, the higher the impulse, but the lower the $C_m$.

Figure 8. Density contours for laser energies of 14J, 42J and 70J
4. Conclusions
The focal position and laser energy impact on the propulsive performance of the air-breathing laser propulsion for multi-pulses have been studied. To contrast, three different repetition rates have been modelled to simulate the laser frequency affect.

The $C_m$ decreases with the number of the laser pulses in multi-pulses propulsion. At the low frequency, the focal position is one of the main factors to influence the multi-pulses $C_m$. When the focal position locates near to the front nozzle wall, the high $C_m$ is achieved. As increasing the frequency, the time to replenish air becomes short, so it is beneficial to breathe the air when the focal position near the exit.

The higher laser energy will exhaust more air in the nozzle, and it needs a longer time to recovery the density of the air. The reaches maximum at the energy of 32J, and then decreases at the energy of 40-70J at 50Hz. The curve of $C_m$ at 20Hz is similar to that of the single pulse, but its value is lower than the single one. In the same calculative time, the 100Hz has the most pulse numbers, so it gets the highest impulse, but the lowest multi-pulse $C_m$.

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