Solid-like ablation propulsion generation in nanosecond pulsed laser interaction with carbon-doped glycerol*

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A solid-like propellant of carbon-doped glycerol ablated by a nanosecond pulsed laser is investigated. The results show that the specific impulse increases with increasing carbon content, and a maximum value of 228 s is obtained. The high specific impulse is attributed to the low ablated mass loss that occurs at high carbon content. More importantly, with increasing carbon content, the properties of the doped glycerol approach to those of a solid. These results indicate that propulsion at the required coupling coefficient and specific impulse can be realized by doping a liquid propellant with an absorber.

Keywords: laser plasma, propulsion, liquid, specific impulse

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1. Introduction

As a new type of propulsion technology, laser plasma propulsion can be used in small satellites to fulfill many new tasks.[1–3] With this technology, the target surface is irradiated by a laser pulse, a plasma with a super-sound speed is induced and a thrust force is generated. In this process, the properties of the propellant have a significant effect on the thrust. Propellants including metals, polymers, liquids, and other compound materials have been extensively investigated.[4–6] A relatively low laser intensity is required for solid propellants, and a high specific impulse, accompanied with a low coupling coefficient, is easily obtained. In the case of liquid propellants, severe splashing occurs and a very low specific impulse of only a few seconds is generated, accompanied by a high coupling coefficient.[7,8] Therefore, morphology similar to a "jelly" with properties between those of a solid and liquid, is anticipated, which can be manipulated to yield the desired specific impulse and coupling coefficient. Until now, many attempts have been made to obtain desirable values of these parameters such as by using a high-viscosity liquid and doping with an absorber to reduce the splashing.[9,10] Glycerol is often adopted as the liquid because it has high viscosity and it is colorless and odorless. To further increase the viscosity and enhance the laser absorption, carbon black often serves as an absorber, and images reveal that the splashing is almost eliminated as indicated in Refs. [5] and [11]. However, a maximum carbon content only up to 5% has been considered in previous studies and a specific impulse of only a few seconds was obtained.[11–13] At such carbon content, the splashing volume is significantly lower than that of pure glycerol, but the specific impulse is still low due to the properties which is consistent with the scenario of a liquid. Therefore, a systematic study of carbon-doped glycerol with high carbon content, is essential to reduce splashing and further enhance the specific impulse.

In this paper, carbon-doped glycerol with a maximum carbon content amount of 31% is tested, and the corresponding specific impulse coupling coefficient and ablation efficiency are measured. Based on these results, a composite propellant with properties falling between those of a liquid and solid is discussed.

2. Experiments

The container used in the experiment is an aluminum cuboid with dimensions of $3 \times 8 \times 5$ mm^3. A cavity with a depth of 1.2 mm and a diameter of 2.0 mm is used to hold the liquid glycerol. Figure 1 shows the schematic of experimental setup for two crossing beams to measure the target velocity laser pulses are focused by a lens ($f = 250$ mm, $\Phi = 40$ mm) into the bottom as shown in the inset. To protect the optics, a glass layer is placed in front of the focal lens. The pulsed laser used in the experiment has a wavelength of 1064 nm, pulse duration of 10 ns, and maximum laser pulse energy of approximately 600 mJ. The target velocity is measured by using a photo-electric device as shown in Fig. 1.[11,14] A He–Ne laser beam is used as the probe beam, which is returned by two mirrors and composed of two probe beams. After laser ablation, two signals are recorded by using an oscilloscope. The target velocity is calculated as the ratio of the distance between the two beams (Δl) to the time width (Δt) between the two signals.

The experiment is performed at room temperature. A compound is obtained by adding the carbon black into the liquid glycerol. Prior to ablation, this compound is dispersed by

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magnetic stirring for 10 min. The resulting mass loss of the compound is directly measured by a balance with a precision of 0.01 mg. The mass loss data are averaged by five repeated measurements. The carbon content amounts under test are 5, 8, 10, 15, 20, 25 and 31 wt%. The viscosity of the compound increases with increasing carbon content. A maximum content of 31% is realized in the current condition. For higher carbon content, homogeneous dispersion of the compound is prevented.

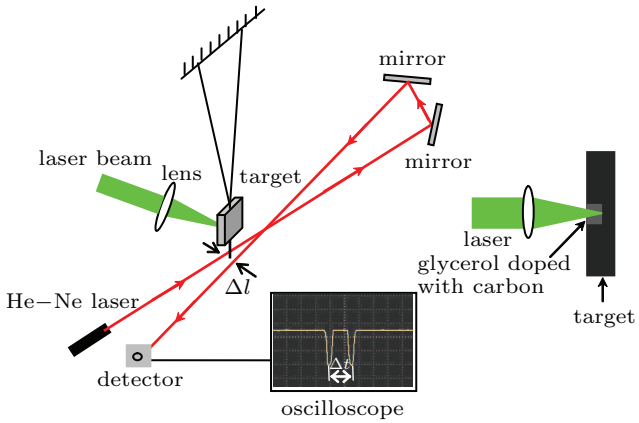


Fig. 1. (color online) Schematic of experimental setup for two crossing beams to measure the target velocity. The inset is the schematic of laser pulse focus into the cavity bottom.

3. Results and discussion

Figure 2 shows the dependence of the coupling coefficient and specific impulse on the carbon content. It is found that the carbon content has a significant effect on thrust performance. In fact, when the content increases from 5% to 31%, the coupling coefficient decreases from 72 to 17 dyne/W, whereas the specific impulse increases rapidly from 8 to 148 s. Furthermore the increase and decrease are indicative of the inverse proportionality of these two parameters.[15] A proportional relationship was observed in previous studies for carbon content lower than 5%.[11,13] This is because for such a carbon content, the target momentum is determined mainly by the ejection of un-ionized droplets.

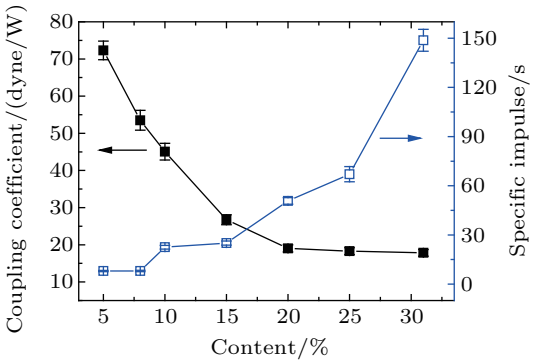


Fig. 2. (color online) Dependence of the coupling coefficient and specific impulse on carbon content.

It is believed that liquids with low viscosity, such as water, ethyl alcohol etc., always present a proportional relationship between the coupling coefficient and specific impulse. For the inverse relationship, it is based on the assumption that the ablation efficiency is constant, and the thrust source is only coming from the plasma itself. For example, for an ablation metal in vacuum environment, an inverse relationship between the coupling coefficient and specific impulse is observed. In the present experiment, with the carbon doping, the ablation efficiency and the thrust source both vary. The interaction process is mainly determined by the liquid splashing rather than the plasma expansion. As the splashing reduces the specific impulse, it also increases the target coupling coefficient. In this case, the coupling coefficient and specific impulse do not follow the inverse relationship.

In addition, it is found that the morphology of the ejection droplet is also correlated with the carbon content. Ablated pure glycerol, consisting of micrometer-sized droplets distributes in a relatively uniform manner. With the carbon content increasing, the variation of the droplet size and number are divided into two stages. In the first stage with the carbon content less than 10%, the droplet size increases with the content increasing. At about 10%, the glycerol becomes obviously viscous. The physical properties are similar to those of a jelly. At such a content amount, the individual droplet begins to agglomerate, and the size increases from a few millimeters to centimeters.

In the second stage, namely the content higher than 10%, especially close to the highest content 31% realized under the present conditions, the physical properties of the carbon-doped glycerol exhibit certain solid-like properties. The number of droplets decreases, and the size decreases to micrometer level again. This means that the splashing volume begins to reduce. Based on this viewpoint, the splashing can be completely eliminated by the carbon doping. It is believed that doping absorber is an efficient method of preventing the liquid propellant from splashing, and enhancing the specific impulse.

Figure 3 shows the dependence of the target momentum and ejection volume percentage on the carbon content. When the carbon content increases from 5% to 31%, the percentage of the ejection volume decreases from 90.8% to 1.2%; whereas the target momentum decreases rapidly from 11.3 g·cm/s to 21 g·cm/s. At low carbon content, the laser pulse can penetrate the glycerol surface and plasma is induced within the glycerol interior. With the plasma expansion, a significant volume of the glycerol is ejected and a high target momentum is generated. With further increase in carbon content, the ejection volume decreases and its effect on the target momentum weakens. This can be induced from a similar tendency of the target momentum and ejection volume varying with the carbon content. Furthermore, it means that at low carbon content, the glycerol ejection contribution to the target momentum is dominant and the plasma itself plays a minimal role. At a high carbon con-

tent level, the target momentum is determined mainly by the plasma rather than by the droplet ejection.

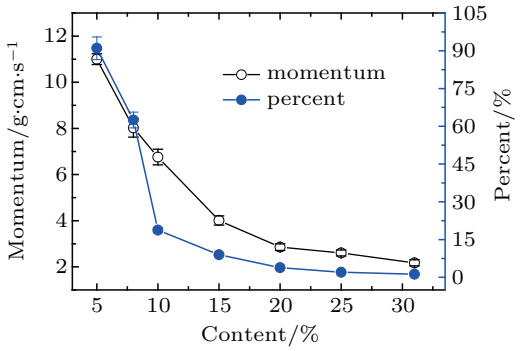


Fig. 3. (color online) Dependence of the target momentum and mass loss percentage on carbon content.

Considering the definition of the specific impulse as the ratio of the target momentum to the target mass loss, a high target momentum and a low mass loss will correspond to a high specific impulse. In the present study, these parameters exhibit a similar tendency. However, the mass loss decreasing more rapidly than the target momentum, yields a high specific impulse of 148 s.

The ablation efficiency η is defined as the efficiency of the laser energy conversion into exhaust kinetic energy, which is expressed as follows:[16]

$$\eta = \frac{1}{2} g_0 C_m I_{sp}, \tag{1}$$

where g_0, C_m, and I_{sp} are the gravity acceleration, coupling coefficient and specific impulse, respectively. The ablation efficiencies at different carbon content amounts can be calculated from Eq. (1). The dependence of the ablation efficiency on carbon content is given in Fig. 4. The ablation efficiency increases from 1.8 % to 116% when the carbon content increases from 5% to 31%. This indicates that more energy is converted into kinetic energy for high carbon content. In those conditions, the ablation process is similar to that of a solid target. However, carbon-doped glycerol is a solid-like propellant, which has physical properties of both a liquid and a solid, and these properties can be tailored to fulfill specified requirements.

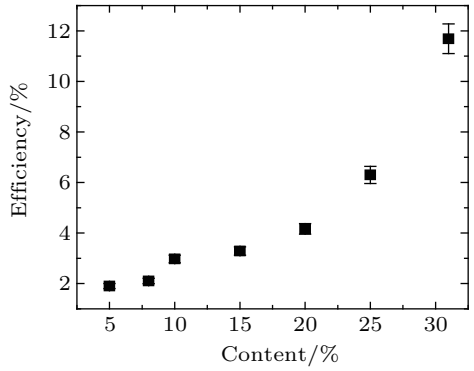


Fig. 4. Dependence of the ablation efficiency on carbon content.

In order to further investigate the thrust performance of the solid-like propellant, figure 5 shows the dependence of the specific impulse and mass loss on laser fluence at the highest content (i.e., 31%) realized in the present experiment. The results illuminate that in addition to an inverse relationship between the specific impulse and the mass loss, a high specific impulse of 228 s is found. According to the definition of the specific impulse as the ratio of the target momentum to the target mass loss, for a solid-like propellant, the mass loss is a few micrograms per pulse, which is the main reason for achieving such a high specific impulse. During the ablation of solid propellant, such as aluminum in atmosphere, a coupling coefficient of only 6–10 dyne/W and a specific impulse about 75–100 s are obtained.[17] These values are both lower than those in carbon-doped glycerol. The values of the specific impulse are related to many factors such as the experimental conditions, laser parameters, and target properties.[18,19]

Furthermore, the specific impulse decreases with increasing laser fluence. This is most probably caused by the plasma shielding effect. Generally speaking, an intense shielding effect shields more laser pulses from interacting with propellant, thereby leading to a low mass loss. However, in the interaction process, the mass loss has two sources: one is consumption in the plasma coupling, the other is the consumption of ejection un-ionization volume. For liquid propellants, the latter plays a dominant role in mass consumption. An intense plasma coupling corresponds to a more powerful counterforce, which leads to the ejection of more un-ionization volumes. This can also be deduced from the tendency of the mass loss in Fig. 5 that it increases from 6 to 15.2 μg per pulse with the laser fluence increasing from 11 to 21 J/cm^2.

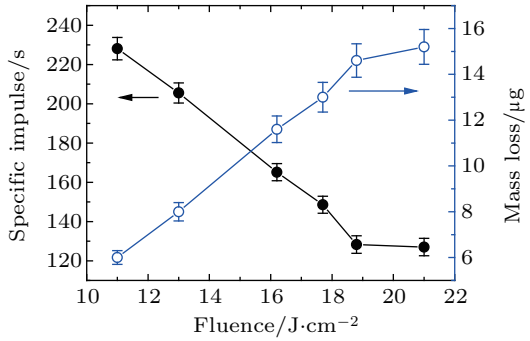


Fig. 5. (color online) Dependence of the specific impulse and the mass loss resulting from each laser on the laser fluence at given carbon content of 31%.

4. Conclusions

Adding an absorber into a liquid to change the physical properties is a new concept aiming at tailoring the coupling coefficient and specific impulse to fulfill specified requirements. In this work, carbon, which serves as an absorber, yields high absorption of the laser energy. Furthermore, the carbon content changes the physical properties of the propellant, which

in general is a compound composed of the liquid and the absorber. When the properties of the compound are similar to those of the liquid, a high coupling coefficient can be supplied. When the properties of the compound are similar to those of the solid, a high specific impulse is obtained owing to a low ablation mass loss. Based on this viewpoint, the required values of the coupling coefficient and specific impulse can be easily realized by adjusting the carbon content.

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