Characteristics of droplets ejected from liquid glycerol doped with carbon in laser ablation propulsion*

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The characteristics of droplets ejected from liquid glycerol doped with carbon are investigated in laser ablation propulsion. Results show that carbon content has an effect on both the coupling coefficient and the specific impulse. The doped-carbon moves the laser focal position from the glycerol interior to the surface. This results in a less consumed glycerol and a high specific impulse. An optimal propulsion can be realized by varying carbon content in glycerol.

Keywords: laser plasma, propulsion, liquid, characteristics

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1. Introduction

In laser plasma propulsion, liquid propellants are considered as optimal materials because they significantly enhance the thrust compared with the solid target materials.[1–5] And many experiments have been performed to investigate the interaction of the laser pulses with liquids and liquid-containing materials.[6–9] For all liquid materials, however, a serious splashing behavior results in a very low specific impulse. This is essentially due to the fact that the splashing of the liquid causes laser energy to be consumed for droplet formation instead of high velocity plasma acceleration. In order to enhance the specific impulse, a small container or droplet, as well as doped-liquids is used. Shadowgraph images revealed that the splashing behavior could be controlled by the viscosity of liquid propellant.[6] Furthermore, in the experiments carried out in the present work, carbon-ink-doped water is used as the liquid propellant and 19 s of specific impulse is achieved.[7] Considering both the doping method and the liquid viscosity, the carbon-doped glycerol has been proposed recently to reduce the splashing and to enhance the specific impulse.[2,3] In these papers, only the shadowgraph images revealing the time evolution of the splashing were described. A few publications were involved in the study of the characteristics of droplets ejected from the carbon doped glycerol. In particular, there are a few reports on the measurement of droplet characteristics regarding the coupling coefficient, specific impulse, angular distribution and ablation pressure as well as the relationship between them.[10] These parameters can help us to clarify the effect of the doped-carbon on the propulsion.

In this present paper, the characteristics of the droplets ejected from the liquid glycerol doped with carbon ablation by nanosecond pulse laser are measured. Based on the laser focal position, laser energy, and plasma luminescence, the effects of doped-carbon on propulsion are discussed.

2. Experiments

The container used in the experiments is an aluminum cuboid with dimensions of 3 mm×8 mm×5 mm. A cavity with a depth of 2.5-mm and a diameter of 1.5-mm within the cuboid is used as a container to hold the liquid glycerol. Laser pulses are directly focused by a lens (f = 200 mm, ϕ = 50 mm) into the cavity bottom. The pulse laser used has a wavelength of 532 nm, a duration of 10 ns, and a maximum energy of approximately 250 mJ. The target velocity is measured by a photo-electric device. The schematic of target velocity measurement is shown in Fig. 1. A He–Ne laser source is used as the probe beam, which propagates to the target surface and falls into an angle prism. After the angle prism, the beam returns and then two probe beams are obtained. A small wire with a diameter of 185 μm is fixed beneath the target bottom to simulate the target vibration. After the laser ablation, the wire with the target passes through the two probe beams. Two time signals are recorded by an oscilloscope. The target velocity is the ratio of the distance between the two beams Δl to the time span Δt as recorded by the oscilloscope. In this device, only one He-Ne laser source and one photodiode are used, making the adjustment of the mechanism easy to realize, compared with the two parallel probe beams device.[11,12]

A glass layer of 1 mm in thickness and 50 mm in diameter is placed 45 mm away from the target surface to serve as a

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receiving screen. From the distribution area of droplets on the receiving screen, the ejection angle can be estimated. A force sensor is placed gently on the back surface of the aluminum cuboid to record the ablation pressure. From the amplitude of the signal recorded by an oscilloscope, the pressure force can be calculated. The carbon content values in glycerol are 0.1, 0.5, 1, 3, and 5 wt%. To exactly control the liquid glycerol volume, a micro-liter syringe with a precision of 0.5 μL is used. Under this condition, a good repeatability is ensured. For measuring the consumption mass caused by the laser ablation, the glycerol is directly weighted before and after ablation by a balance with a precision of 0.01 mg.

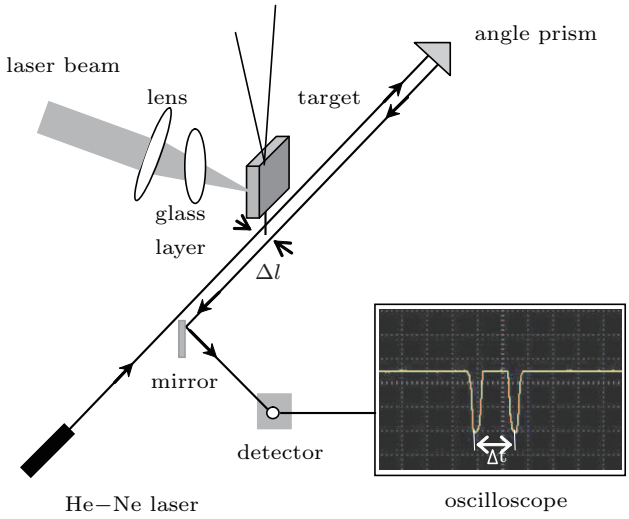


Fig. 1. Schematic diagram of the experimental setup for a He–Ne laser source to measure target velocity.

3. Results and discussion

Figure 2 shows the plots of coupling coefficient and the specific impulse versus carbon content, generated at different carbon content values by a laser with an energy of 14 mJ. The zero carbon content corresponds to pure glycerol. It shows that the coupling coefficient decreases with increasing carbon content. The specific impulse decreases with carbon content increasing up to 1%, but above 1% carbon content, the specific impulse increases. The coupling coefficient is defined as the ratio of the target momentum to the incident laser energy, and the specific impulse is defined as the ratio of the target momentum to the consumed glycerol mass. Therefore, it is deduced that for the same consumed glycerol, the coupling coefficient and specific impulse should follow the same trend. The results obtained in increasing the carbon content from 3% to 5% indicate that this phenomenon is a consequence of a less glycerol consumed. This can be verified by some amount of glycerol that remains in the cavity after ablation as shown in Fig. 3. For pure glycerol, almost all the glycerol in the cavity about 1.6 mg is ejected. With the carbon content increasing to 5%, the consumption mass decreases rapidly and drops down to about 1.1 mg. Under this content, the percentage of the consumption mass to the whole glycerol is about 68%. This is to say, 32% of the glycerol remains in the cavity after ablation. It is known from the definition that the specific impulse is determined by both the target momentum and the consumption mass. The laser pulse cannot penetrate the carbon-doped glycerol. The penetration depth is shorter when carbon content is higher. When the plasma is induced on the glycerol surface, less glycerol is ejected. The less consumption mass results in a low target momentum and coupling coefficient. There, because the mass consumption decreases more rapidly than target momentum, the specific impulse presents an increase trend at high carbon content.

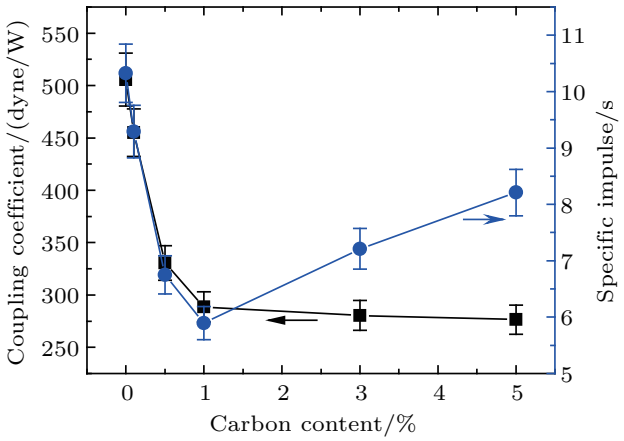


Fig. 2. (color online) Variations of coupling coefficient and specific impulse with carbon content. The zero point corresponds to the pure glycerol. The incident laser energy is 14 mJ in this condition.

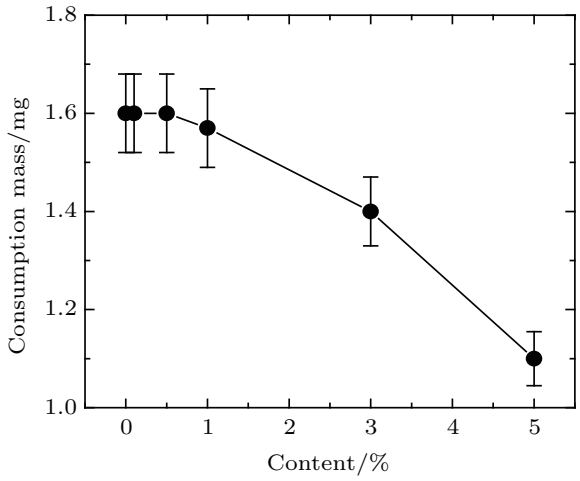


Fig. 3. Consumption mass induced by a laser pulse versus carbon content.

As the laser focal position moves from the glycerol bottom to the surface, laser intensity varies correspondingly. From the definition of laser intensity it follows that under the same laser focal area, the laser intensity is determined by the laser energy. Thus, the coupling coefficient and specific impulse are related to the laser energy as shown in Fig. 4. It

shows that an inverse relationship exists between the coupling coefficient and specific impulse. This is in agreement with the relationship between the coupling coefficient and the specific impulse.[13,14] Meanwhile, the coupling coefficient decreases with laser energy increasing. Therefore, the energies correspond to laser intensities ranging from about 1 W/cm^2 to 6×10^8 W/cm^2. A high laser intensity generates a intense laser plasma, and shields a larger amount of energy from directly interacting with the glycerol. The intense shielding effect results in a low coupling coefficient.[10]

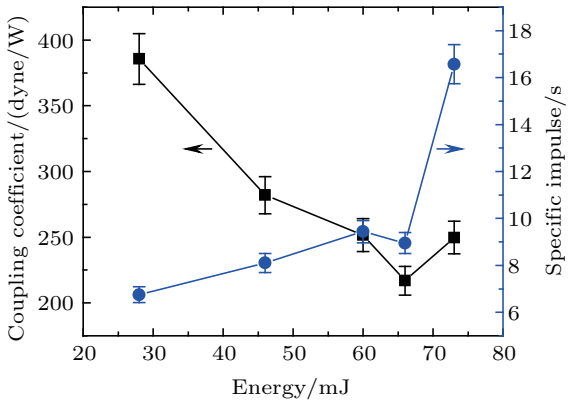


Fig. 4. (color online) Plots of coupling coefficient and specific impulse versus laser energy, with 1% carbon content ablated.

A direct distribution of the glycerol droplets is shown in Fig. 5. The typical images (a)–(f) correspond to carbon content values of 0%, 0.1%, 0.5%, 1%, 3%, 5% respectively. From these images, the distribution area and droplet average size can be estimated. The distribution area decreases as carbon content increases up to 1%. But over 3%, the distribution area increases and large sized droplets are observed. Especially in images (e) and (f), some droplets with a large size appear at the central position. The droplet outlines are not clear because the light irradiation on the glass can penetrate the large droplets. It is believed that with the generation of plasma on the surface, a plasma wave is induced and compresses the glycerol within the cavity.[15] After the compression, the glycerol rebounds and ejects from the cavity. This process is different from that of the plasma generation in the cavity bottom, in which the glycerol is pushed by the plasma expansion and the droplet size is relatively small.

The angle distribution deduced from the distribution area and corresponding ablation pressure are shown in Fig. 6. It shows that as the carbon content increases up to 1%, the angle distribution decreases. But above 1% carbon, the angle distribution presents an increasing tendency. However, on the contrary, the ablation pressure always decreases with carbon content increasing. This is in agreement with the tendency of coupling coefficient in Fig. 2 that high coupling coefficient corresponds to a high ablation pressure.

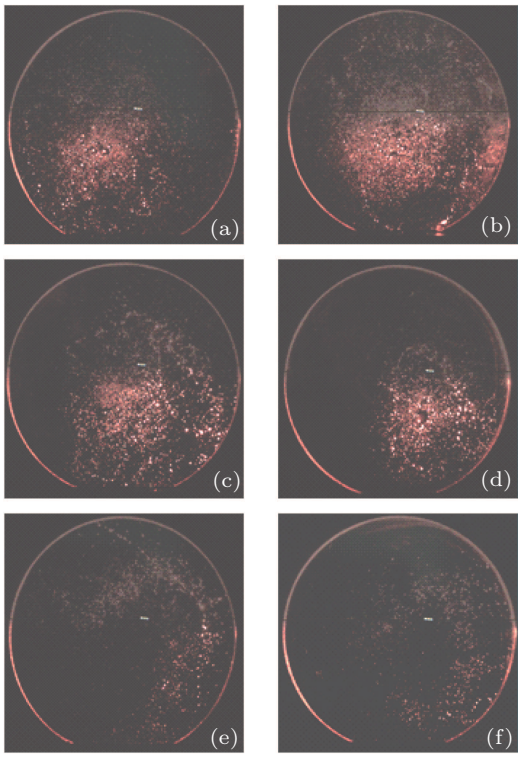


Fig. 5. (color online) Typical images of droplet distribution with carbon content values of 0% (a), 0.1% (b), 0.5% (c), 1% (d), 3% (e), 5% (f).

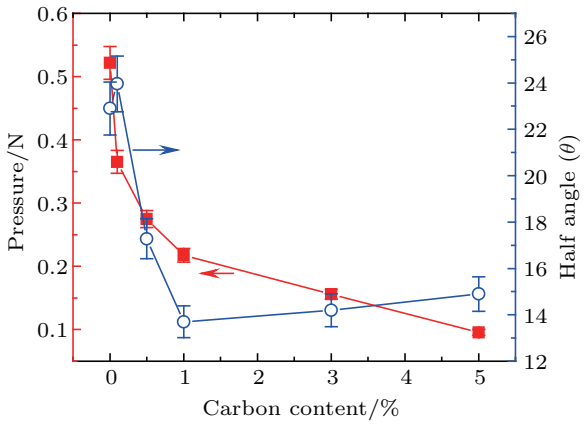


Fig. 6. (color online) Plots of ablation pressure and half angle distribution versus carbon content.

Moreover, when laser pulse is focused into the glycerol, a certain amount of an-ionized glycerol is ejected. In this process, a certain liquid layer can play a role of confinement. Under the confinement ablation, the coupling coefficient has been enhanced by tens of times.[11,14] As the focal position moves from the glycerol bottom to the surface, the confinement ablation becomes weaker. The ablation pressure decreases to approximate 0.1 N.

The plasma luminescence generated at different carbon content is also measured by a photodiode with a picosecond response time, and is recorded by an oscilloscope. The results given in Fig. 7 show that the signal intensities have almost the same values. However, the signal width, namely the luminescence life, is extended from 10.4 ms of the pure glycerol

to 12 ms of 5% carbon content. This indicates that the interaction time of the laser pulse with the glycerol is extended due to the carbon doping. Based on this viewpoint, the higher the carbon content, the higher coupling coefficient is generated. However, as shown in Fig. 2, the coupling coefficient decreases with carbon content increasing. Those results indicate that although the doped-carbon enhances the interaction between the laser pulse and the glycerol, the target momentum and the coupling coefficient are mainly determined by the ejection of the un-ionized liquid. The role of the plasma itself is minimal. For example, the coupling coefficient coming from the plasma in laser-ablated aluminum in vacuum is only 1 dyne/W∼3 dyne/W,[16] which is much lower than 250 dyne/W for laser-ablated aluminum confined by water.[17]

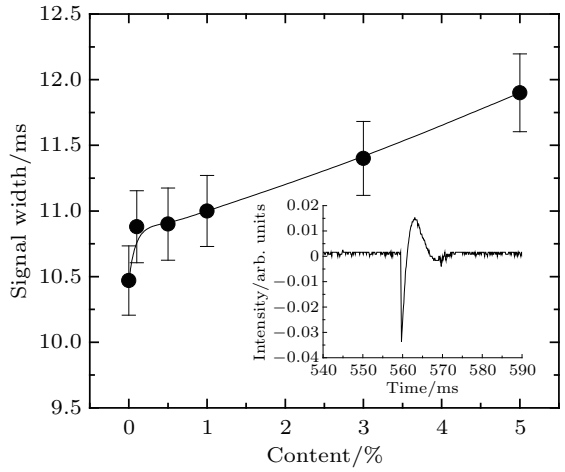


Fig. 7. Time width of the luminescence signal of plasma versus carbon content, with the inset showing a typical luminescence signal.

4. Conclusions

In this work, the characteristics of the droplets ejected from glycerol doped with carbon are investigated through ablation by a nanosecond laser. Because the carbon-doping changes the laser focal position and laser intensity, the coupling coefficient, specific impulse, distribution angle as well as the ablation pressure present a different behavior compared with those in pure glycerol. With carbon content increasing, the laser focal position is varied from the glycerol interior to surface, and less glycerol is consumed, which results in a high specific impulse. Base on this viewpoint, to reduce the splashing volume, high carbon content should be adopted. However, high carbon content corresponds to a low coupling coefficient. Through this process, an optimum coupling coefficient and specific impulse can be chosen by varying the carbon content.

References

[1] Zheng Z Y, Gao H, Gao L, Xing J, Fan Z J, Dong A G and Zhang Z L 2014 *Appl. Phys. A* **115** 1439
[2] Xue Y T, Dou Z G, Ye J F, Li N L, Zhang G Z and Wan Y 2014 *High Power Laser Part. Beams* **26** 101020
[3] Zheng Z Y, Gao H Fan Z J and Xing J 2014 *Plasma Science and Technology* **16** 251
[4] Phipps C R, Baker K L, Libby S B, Liedahl D A, Olivier S S, Pleasance L D, Ruenchik A, Trebes J E, George E V, Marcovici B, Reilly J P and Valley M T 2012 *Adv. Space Res.* **49** 1283
[5] Shi L, Zhao S H, Chu X C, MA L H, Wu J L, Li X L and Li Y J 2009 *Europhys. Lett.* **85** 55001
[6] Fardel R, Urech L, Lippert T, Phipps C, Fitz-gerald J M and Wokaun A 2009 *Appl. Phys. A* **94** 657
[7] Zheng Z Y, Fan Z J, Wang S W, Dong A G, Xing J and Zhang Z L 2012 *Chin. Phys. Lett.* **29** 095202
[8] Zhang Y, Lu X, Zheng Z Y, Liu F, Zhu P F, Li H M, Li Y T and Zhang J 2008 *Appl. Phys. A* **91** 357
[9] Zheng Z Y, Gao H, Fan Z J and Xing J 2014 *Plasma Science and Technology* **16** 251
[10] Li N L, Ye J F and Zhou W J 2015 *J. Prop. Tech.* **36** 1595
[11] Choi S, Han T, Gojani A B and Yoh J J 2010 *Appl. Phys. A* **98** 147
[12] Zheng Z Y, Zhang J, Hao Z Q, Yuan X H, Zhang Z, Lu X, Wang Z H and Wei Z Y 2006 *Chin. Phys.* **15** 580
[13] Phipps C R, Luke J R, Lippert T and Mcduff G G 2003 *Appl. Phys. A* **77** 193
[14] Sinko J E and Phipps C R 2009 *Appl. Phys. Lett.* **95** 131105
[15] Noack J, Hammer D X, Noojin G D, Rockwell B A and Vogel A 1998 *J. Appl. Phys.* **83** 7488
[16] Zheng Z Y, Zhang J, Lu X, Hao Z Q, Yuan X H, Wang Z H and Wei Z Y 2006 *Appl. Phys. A* **83** 329
[17] Zheng Z Y, Zhang J, Zhang Y, Liu F, Chen M, Lu X and Li Y T 2006 *Appl. Phys. A* **85** 441