Evaporation and combustion characteristics of Al-decane droplet under laser excitation

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1 Introduction

With the development of aero-engine, higher requirements for high energy density fuel have been put forward. Aviation kerosene is one of the most commonly used hydrocarbon fuels for engines. Although it is known as a fuel with a high mass calorific value, its low density leads to a low volume calorific value. To meet the demand of high energy density fuel for engine in the future, metal particle additive is a way to increase the energy density and volume calorific value of hydrocarbon fuels, and the ignition and combustion performance can be improved effectively. Nano-aluminum particles are used as metal additives for hydrocarbon fuel because of their high energy density, fast chemical reaction rate and easy ignition. The addition of aluminum particles to hydrocarbon fuel can not only reduce the ignition temperature and ignition delay time, but also increase the ignition probability [1-5].

In this paper, n-decane, oleic acid and aluminum particles are used as fuel, surfactant and metal additives, respectively, and Al-decane droplet with 1%~15% Al NPs is obtained. Infrared laser is applied as an external excitation, and the evaporation and combustion characteristics of Al-decane droplet are investigated.

2 Experimental method

The experimental setup is displayed in Fig. 1. The fuel droplet is placed on a thermocouple (TC1) to measure its temperature. The temperature data are stored in the computer with a data acquisition card (Altai USB 2080 DAQ) at a sampling frequency of 100Hz. The laser generator in the experiment is IPG YLR-100-1064-LP, which can produce infrared laser with wavelength of 1064nm at a constant power of 0~100W. When the laser shines on the droplet, the droplet absorb energy, heat up and evaporate. The evaporation process is recorded by two cameras, including a high-speed camera equipped with a microscopic lens and a Canon HF200 HD camera with 5319 frames/s and 60 frames/s, respectively. By the microscopic lens, evaporation process of the droplet can be obtained, as shown in Fig.1(b). However, the point on the droplet surface, that illuminated by the laser, is too small to be observed. Fig.1(c) and (d) are local magnification of the laser point before laser emission and after laser emission, respectively. In Fig.1(c), the red spot has no energy and is only used as the guiding direction. When the laser is started, a white spot can be found on the droplet surface, as shown in Fig.1(d).

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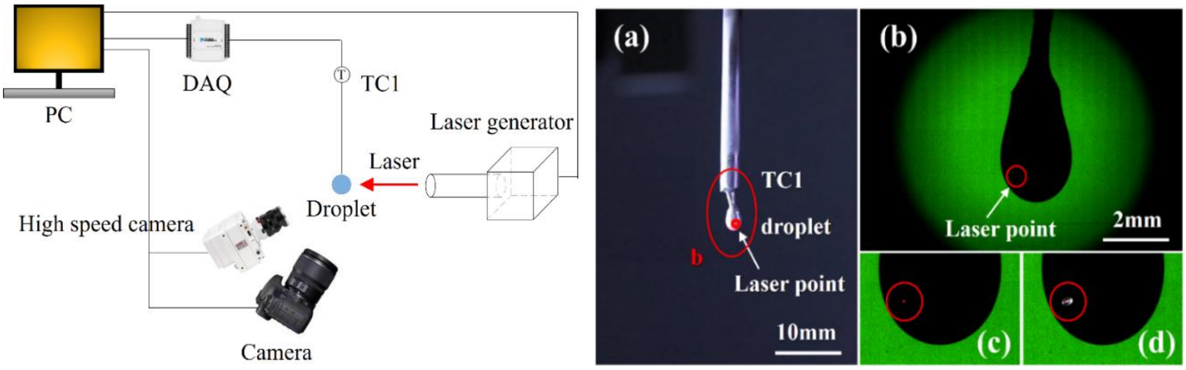


Fig.1 Schematic of experimental setup(left). Schematic of a droplet illuminated by laser(right). (a)Picture of droplet; (b)Droplet picture under microscopic lens; (c)Local magnification of the droplet at the laser point (before laser emission); (d) Local magnification of the droplet at the laser point (after laser emission).

After the laser is started, it continues to shine with a constant power until the droplet evaporates completely. The laser power is determined by setting the energy percentage α of the laser generator. The energy percentage α of the laser can be set from 12% to 100%, and corresponds to laser power of 0W and 100W, respectively, and the relationship between them is linear. Therefore, the relationship between energy percentage α and laser power P can be determined as follows:

$$P = 113.64\alpha - 13.64$$

In the experiment, five energy percentages are used, which are 20%, 40%, 60%, 80% and 100%, and the corresponding laser power is 9.1W, 31.8W, 54.5W, 77.3W and 100.0W.

3 Results and discussion

In this section, Al-decane droplet is discussed, and effects of aluminum content and laser energy on evaporation characteristics of these droplets are investigated, respectively. The Al-decane droplet is mixture of the n-decane, OA, and the aluminum particle. Aluminum particle is used as metal additives, and oleic acid is used as surfactant. In the Al-decane droplet, mass fraction of the aluminum particle is the same quality as mass fraction of the oleic acid. Experiments are carried out at 20-100% laser energy and 1%~15% Al NPs.

Under laser excitation, Al-decane droplet with 1%~15% Al NPs can be observed different experimental results, which can be classified into the following three conditions: evaporation only, micro-explosion and combustion, as shown in Fig.2. Taking Al-decane droplet with 5% Al NPs as an example, at 20% laser energy, only the evaporation process can be observed, the same as the other two droplets. However, at 40% and 60% laser energy, the evaporation process of the droplet is accompanied by obvious micro-explosion phenomenon, and when the laser energy rises to 80% and 100%, not only the evaporation and micro-explosion can be observed, but also the droplet can be ignited by laser and a flame is formed. Combustion involves evaporation and micro-explosion, and micro-explosion involves evaporation. In the case of 5%Al NPs, at 20% laser energy, only pure evaporation process can be observed, while at 40% and 60% laser energy, there is a micro-explosion can be observed, and when the laser energy rises to 80% and 100%, the droplet is ignited by the laser. These three situations are shown in Fig. 3. For the pure evaporation process shown in (a), no violent behavior is detected in the droplet evaporation process, which only occurs at low laser energy and low aluminum particle mass fraction, and the evaporation process is relatively slow. For the micro-explosion shown in (b), when the droplet is radiated by the laser, the droplet distorts and deforms, and the surface shows strong mobility. Due to dramatic temperature rise of the aluminum particles in the droplet, the surrounding droplet around the particle evaporates quickly and will be ejected from inside the droplet.

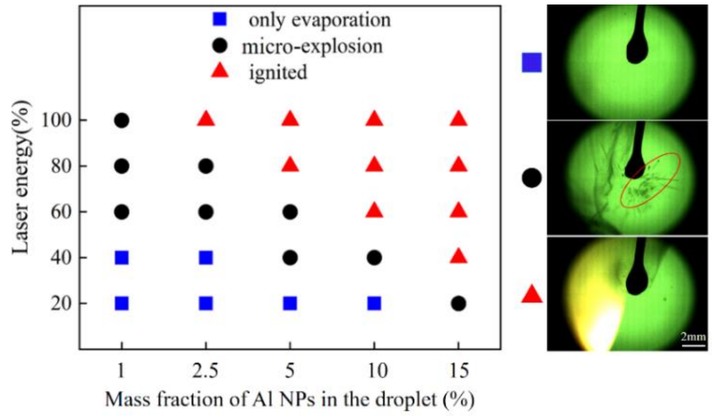
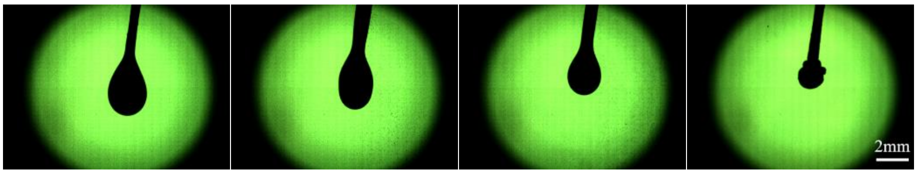


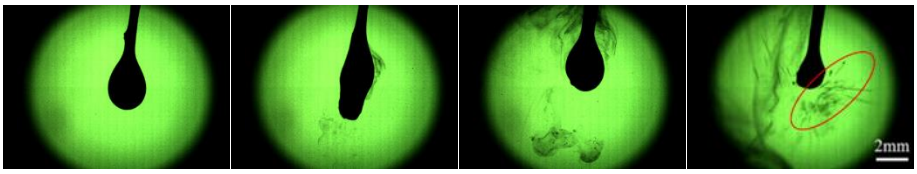
Fig. 2 Evaporation and combustion characteristics of Al-decane droplet

For the combustion process shown in (c), at t=357.2ms, many bright points appear around the droplet, which are the aluminum particles heated by the laser. At the same time, a flame is formed to blow away the black smoke around the droplet. The combustion only occurs at high laser energy and aluminum content. Micro-explosion acts as an intermediate transition between pure evaporation and combustion.



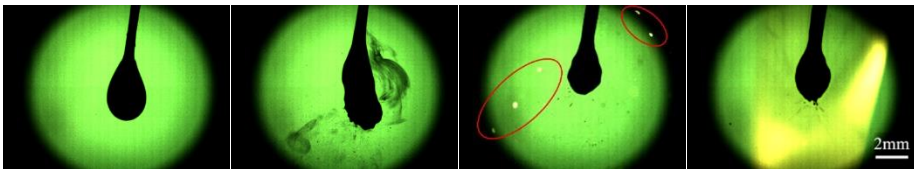
t=0s t=2.256s t=3.01s t=3.76s

(a)Only evaporation（Decane+5%OA+5Al NPs, laser energy of 20%）



t=0ms t=18.8ms t=282ms t=1380.3ms

(b)Micro-explosion（Decane+5%OA+5Al NPs, laser energy of 60%）



t=0ms t=56.4ms t=357.2ms t=445.9ms

(c)Ignited（Decane+5%OA+5Al NPs, laser energy of 100%）

Fig. 3 Evaporation process of Al-decane droplet. (a) Evaporation; (b) Micro-explosions; (c) combustion.

Normalized evaporation curves are shown in Fig. 4. At 20% laser, evaporation of the droplet follows D^2 law and only evaporation occurs during lifetime when aluminum mass fraction is 10% or below. However, when aluminum mass fraction is 15%, evaporation curve of the droplet is obviously different due to an obvious oscillation, which is caused by distortion and deformation of the droplet. Fig.4 (a) marks the corresponding moment of the first micro-explosion, which occurs in the early life of droplet.

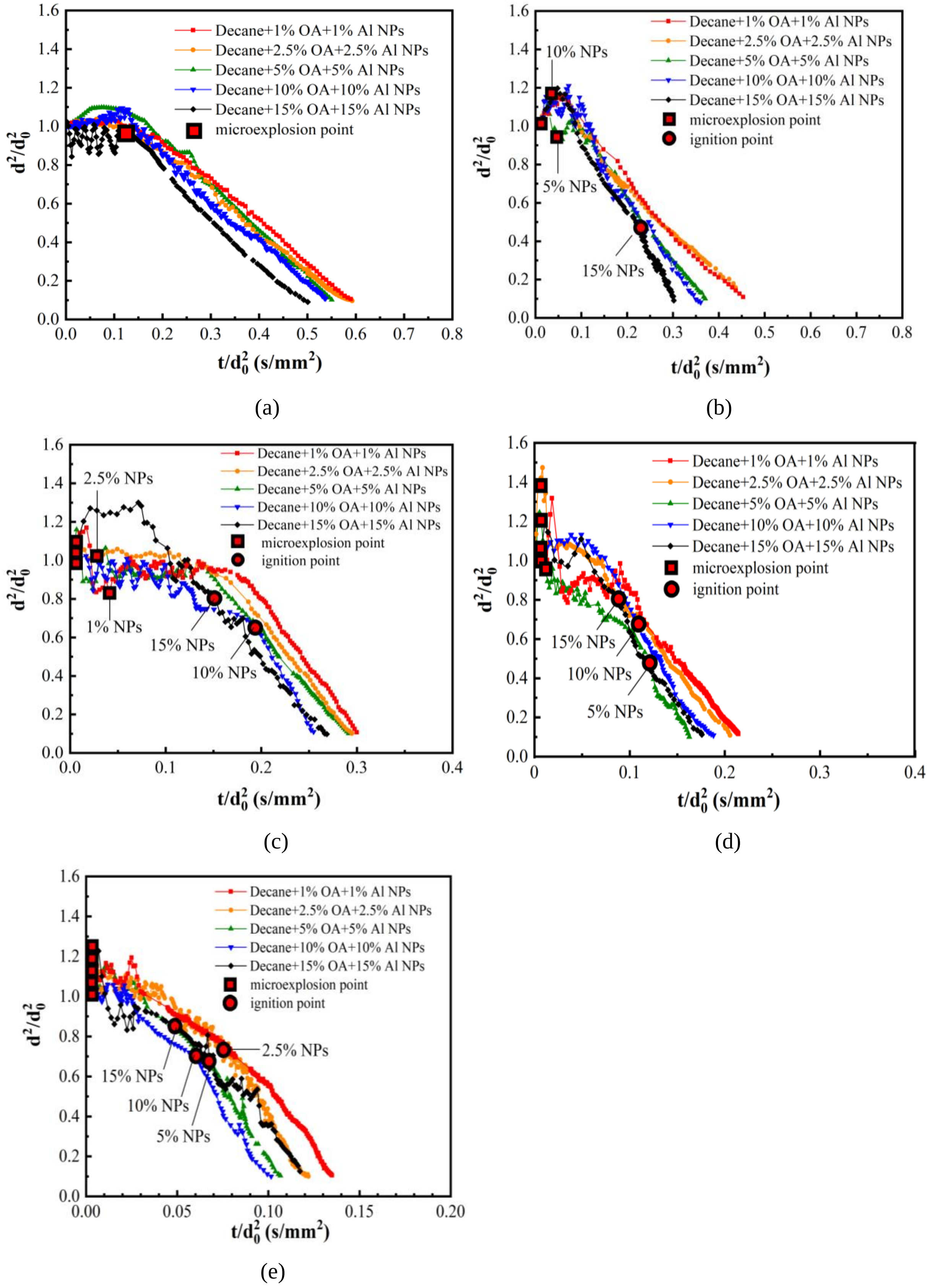


Fig. 4 Normalized evaporation curves of Al-decane droplet. (a) 20% laser; (b) 40% laser; (c) 60% laser; (d) 80% laser; (e) 100% laser

After the oscillation phase, the normalized droplet diameter is reduced linearly. Occurrence of micro-explosion causes the droplet to continuously eject little droplet and aluminum particles, which accelerates mass consumption of the droplet, resulting in a significantly higher evaporation rate. For 40% laser energy in (b), there is only the evaporation process in the Al-decane droplet with 1% and 2.5% Al NPs, and evaporation of these two droplets are the slowest. In the early stage of evaporation, micro-explosion can be observed in the droplet with 5% and 10% Al NPs, and the evaporation rate is obviously higher than the droplet with less Al NPs. At the end of lifetime, the droplet with 15% Al NPs is ignited, which further reduces lifetime of the droplet. In (c), micro-explosions are observed in all droplet as the laser energy rises to 60%. In the droplet with more than 5% Al NPs, no delay is detected between laser irradiation and micro-explosion, which means the micro-explosion occurs immediately when the droplet is illuminated by the laser. The droplet with 10% and 15% Al NPs is ignited at the end of their lifetime, accelerating the mass consumption. By comparing (a) and (c), shape of the curve is clearly different from the previous straight line. In (d), as the laser energy rises to 80%, there is almost no micro-explosion delay time for droplet with Al NPs above 2.5%. The droplet with 5%, 10% and 15% Al NPs can be ignited, resulting in a significantly less droplet lifetime than that of unburned droplet. In (e), as the laser energy increases to 100%, there is no micro-explosion delay time for all droplet, and only the droplet with 1% Al NPs cannot be ignited. The ignition is advanced to middle of the droplet lifetime, and the higher the aluminum content, the faster the combustion rate.

In addition, the evaporation rate constant of the droplet is obtained and shown in Fig. 5. The droplet evaporation rate constant is increased significantly with the increase of laser energy. In addition, the evaporation rate constant of droplet with 15% Al NPs is higher than that of 1% and 2.5% Al NPs, because of more aluminum particles in the droplet with 15% Al NPs. Therefore, addition of the aluminum particles can significantly improve evaporation rate.

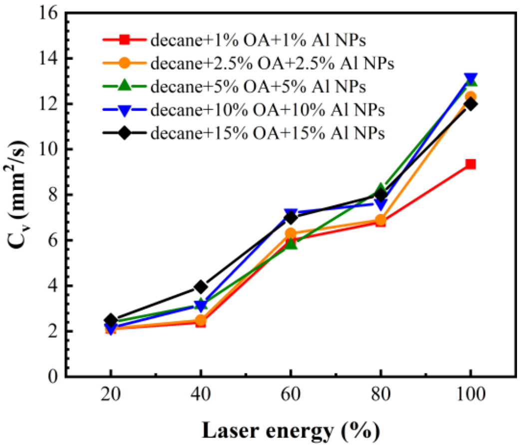


Fig. 5 Evaporation rate constant of Al-decane droplet at different laser energies

The micro-explosion delay time is defined as the interval between the laser emission and the first micro-explosion of droplet. The micro-explosion delay time at different conditions is shown in Fig. 6 (a). It can be found, at the same laser energy, the higher the mass fraction of aluminum particles, the less the micro-explosion delay time. For the droplet with 1%~10% Al NPs, the micro-explosion delay time is decreased with the increase of laser energy, while for the droplet with 15% Al NPs, when the laser energy rises to 40%, the micro-explosion delay time is decreased rapidly to less than 10ms, which means that the micro-explosion immediately occurs when the laser is started. The little delay time can be attributed by the fact, that the higher the laser energy, the more heat the aluminum particles absorb, so that the temperature rises faster to the melting point of the aluminum, and the particles are ejected. In addition, the micro-explosion delay time is decreased with the increase of aluminum mass fraction, because the increase of the aluminum mass fraction improves the distribution density of aluminum particles in the droplet, so that more particles in the droplet can accept heat of the laser radiation, and they are heated to the melting point in a very short time and then ejected.

For the Al-decane droplet that can be ignited, the ignition delay time is defined as the interval between laser emission and the flame. The ignition delay time at different cases is shown in Fig. 6 (b). It can be found that the higher the aluminum mass fraction, the less the ignition delay time, and the ignition delay time is inversely proportional to the laser energy, because the higher the laser energy, the more heat the aluminum particles absorb, so that the temperature rises faster to the melting point of the aluminum, and the particles are ejected. In addition, the increase of aluminum mass fraction improves the density of aluminum particles in the air around the droplet, so that the number of aluminum particles in the range of laser radiation are increased, and the particles are heated and ignited.

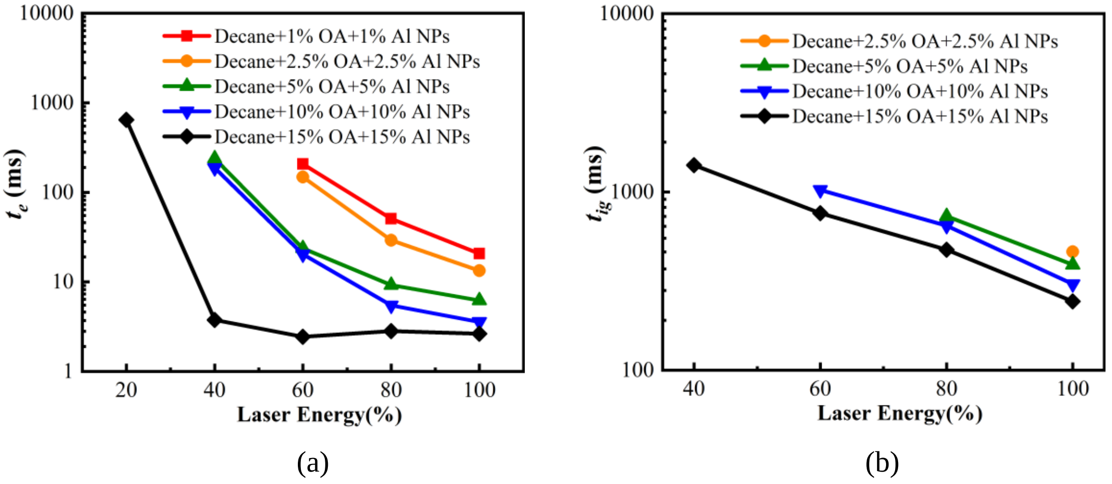


Fig. 6 (a) Micro-explosion delay time of Al-decane droplet; (b) Ignition delay time of Al-decane droplet

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