Journal of the Energy Institute 87 (2014) 383–392

Contents lists available at ScienceDirect

Journal of the Energy Institute

journal homepage: http://www.journals.elsevier.com/journal-of-the-energy-institute

Study of the characteristic of diesel spray combustion and soot formation using laser-induced incandescence (LII)

Xiaobei Cheng*, Liang Chen, Fangqin Yan

School of Energy and Power Engineering, Wuhan 430074, China

ARTICLE INFO

Article history:
Received 5 March 2013
Accepted 23 July 2013
Available online 2 April 2014

Keywords:
Diesel spray combustion
LII
Constant volume combustion vessel
Flame lift-off length
Soot concentration

ABSTRACT

In this paper, the planar images of diesel spray combustion flame and soot formation were measured and analyzed by using LII, in a constant volume combustion vessel. The effects of combustion flame and fuel–air mixing characteristics on soot formation and distribution of soot concentration were studied at different conditions. The result indicates that, with increase in ambient temperature and pressure, the ignition delay of diesel fuel is shorter. The increase of ambient temperature and pressure and the reduction of injection pressure shorten the diesel flame lift-off length. The lower the ambient temperature and pressure, the weaker LII signal intensity. At the same ambient temperature and pressure condition, the higher the diesel injection pressure, the smaller the soot production in diesel jet spray, and soot particles are primarily produced in the relative fuel-rich region, which is encompassed by the flame surface front at the downstream of the diesel jet.

1. Introduction

Soot particles have already become one of the most important air pollution index of urban air quality, and they also have a significant negative effect on the local and global climate change through their role in high-altitude cloud formation [1–4]. Soot particles smaller than about 300 nm are known to penetrate deep into the lungs and alveoli, and due to this location and their physico-chemical properties, are seriously harmful to human health [5,6]. The internal combustion engine is the main reason of serious particles pollution in the atmosphere. As a result of the increased awareness of soot as a pollutant, as well as tighter emission legislation worldwide, the topic of soot formation and oxidation and their interaction with transport processes continues to be the focus of research activities. For turbulent diffusion combustion in diesel engines, the characteristics of ignition and fuel–air mixing have a very important effect on soot formation and concentration distribution. Because of variation of temperature and soot concentration in diffusion flames, the processes of soot formation and oxidation, and chemical reaction are very complex, and due to the complexity of the interactions of the various boundary conditions in diesel engines, further research on the effect of the characteristics of ignition and fuel–air mixing on soot formation and oxidation is needed, to get substantially more detailed information about soot formation and oxidation in diesel fuel combustion process.

For the research of soot formation and oxidation and their interaction with transport processes, the non-invasive, instantaneous and spatially resolved optical measurement techniques based on laser or other additional light source should be used to observe and investigate the processes of soot formation and oxidation in hydrocarbon-air flames. In many studies laser light scattering and light extinction measurements have been used to provide information on soot characteristics, including soot concentration and primary particle diameter size [7–12]. Though with the advantage of relatively low cost and ease of application, the methods suffer from various limitations and several disadvantages, such as line-of-sight averaging in extinction measurements and interferences of shadows and scattered light [13], and sensitivity of the detected signal to molecular absorption and fluorescence [14]. Two-color method, which is considered as an useful optical diagnostic tool, can obtain not only the information about the transient temperature field but also the two-dimensional distribution of soot concentration [15,16]. But the methods above can only obtain average results of soot concentration and particle size distribution in the direction of optical path.

* Corresponding author. Tel.: +86 27 87543458; fax: +86 27 87540724.
E-mail addresses: chengxiaobei@sina.com (X. Cheng), epchenliang@gmail.com (L. Chen), 532039613@qq.com (F. Yan).

http://dx.doi.org/10.1016/j.joei.2013.07.001
1743-9671/

LII has been considered in numerous studies to be an emerging and useful method for making reliable spatially and temporally resolved measurements of soot concentration and primary soot particle size [17–19]. Compared with other optical diagnostic methods, such as light extinction and light scattering, LII can obtain the transient two-dimensional distribution of soot concentration and soot particle size, and has high time and spatial resolution. Combined with high-speed photography, LII is an advanced optical diagnostic technique and provides a powerful implement for investigating flame construction of diffusion combustion and the processes of soot formation and oxidation.

The objective of the present work is to apply LII method to the measurement and analysis of flame structure of diffusion combustion, and the transient two-dimensional distribution of soot concentration in the combustion process of diesel spray. The experiments were performed at different initial conditions that approach a realistic diesel combustion cycle, in an optically accessible, constant volume high-temperature, high-pressure combustion vessel. The measuring method of soot formation and oxidation in the constant volume combustion vessel using LII together with high-speed photography was proposed. And the effects of different ambient conditions and diesel injection pressures on the distribution of soot concentration were studied. And, in the present work, the high-speed photography method is used in conjunction with the LII method originally to measure and analyze the effects of the characteristics of ignition and fuel–air mixing on soot formation and the distribution of soot concentration synchronously, at different ambient conditions and diesel injection pressures.

2. LII theory and methodology

As early as 1977, Eckbreth proposed the concept of hot particles heated by laser [20]. In 1984, Melton indicated that LII signal intensity was almost proportional to soot concentration, and the technology of hot particles heated by laser, which could be applied to the measurement of the distribution of soot concentration had great potential [21]. Over the past decades, many scholars had deeply researched the applications of LII. Takayuki Ito and co-workers investigated the soot-formation process in diesel jet flame in 2004, using a detailed kinetic soot model implemented into the KIVA-3V multidimensional CFD code and 2D imaging by use of time-resolved laser-induced incandescence [22]. In 2009, Desgroux and co-workers studied soot concentration in low-pressure methane/oxygen/nitrogen flat flames using laser-induced incandescence (LII), and performed calibration by cavity ring-down spectroscopy (CRDS) [23]. Bladh et al. [24] investigated primary soot particle sizes in a premixed flat ethylene/air flame at different heights, by use of two-color LII together with other diagnostic techniques: transmission electron microscopy (TEM) combined with thermophoretic sampling for soot particle sizing, and rotational CARS for measurements of gas temperature. Narayanaswamy and Clemens [19] performed an experimental research to study the soot–turbulence interaction in the soot-formation region of turbulent non-premixed co-flowing ethylene/N_2 jet flames, and soot volume fraction field was obtained using LII.

Laser-induced incandescence has become a popular technique for measurements of soot concentration and particle size. The principle of LII is briefly described as below. LII involves heating particles up to typically around 4000 K with a high-power pulsed laser of several nanoseconds duration followed by cooling down until they reach thermal equilibrium with the combustion environment, and analyzing the thermal radiation from the hot particles, and it is used to obtain the two-dimensional distributions of soot concentration. The incandescence, LII signal, emitted by hot particles, is proportional to soot concentration, as shown in Equation (1).

$$S_{LII} \propto \frac{8\pi c^2 hE(m)}{\lambda^6} d_p^3 \exp\left(-\frac{hc}{\lambda kT}\right) \tag{1}$$

where c is the speed of light; h is the Planck constant; $E(m)$ is the refractive index function of soot; λ is the wavelength of the light; d_p is the diameter of soot particle; k is the Boltzmann constant; T is the particles temperature.

After hundreds of nanoseconds, the particles temperature gradually decreases to the flame temperature, and the radiation signal emitted by the hot particles will disappear slowly. An intensified charge coupled device (ICCD) camera with bandpass filters is used to receive the LII signal. A narrow band interference filter with transmitting wavelength range of 425–475 nm is placed in front of the camera to prevent detection of laser light scattering from soot particles and to reject most background luminosity. To obtain the absolute soot concentration, some optical methods, such as light extinction [10,11,25], are used to calibrate the LII signal intensities and to obtain absolute values of the local soot concentration. However, there are some differences between measurement condition and calibration condition in actual soot measurement of diesel jet flame. The differences including gas temperature, particles component, ambient pressure and so on will cause a larger error of the calibration results. Smallwood et al. [26] proposed the two-color LII method to perform the quantitative measurement of soot concentration. The principle of the two-color LII method is that two-color method is applied to measure the temperature of hot particles heated by laser, then through the functional relationships among particles temperature, LII signal intensity and soot concentration, the absolute value of soot concentration is obtained.

3. Experimental apparatus

This experiment was performed in an optically accessible, constant volume high-temperature, high-pressure combustion vessel. A schematic diagram of the experimental setup is shown in Fig. 1.

3.1. Combustion vessel

According to the operating conditions of diesel engines, the basic technical requirements of the constant volume combustion vessel are that a 3.0 kW electrothermic wire is used to raise the internal temperature of the constant volume vessel rapidly in a relatively short time and the temperature can be maintained at 920 K; compressed air is used to increase the gas internal pressure of the constant volume vessel rapidly and the pressure can be maintained at 6 MPa, to provide measurement conditions that approach a realistic diesel combustion cycle and achieve the diffusion combustion of diesel fuel in the constant volume vessel. Quartz glasses are installed in the four ports of the constant volume vessel to provide optical access and to permit line-of-sight and orthogonal optical access to the injected fuel jet, the diameter of quartz glasses is 98 mm. And to obtain the diesel jet flame in the constant volume vessel, a fuel supply device and a high-

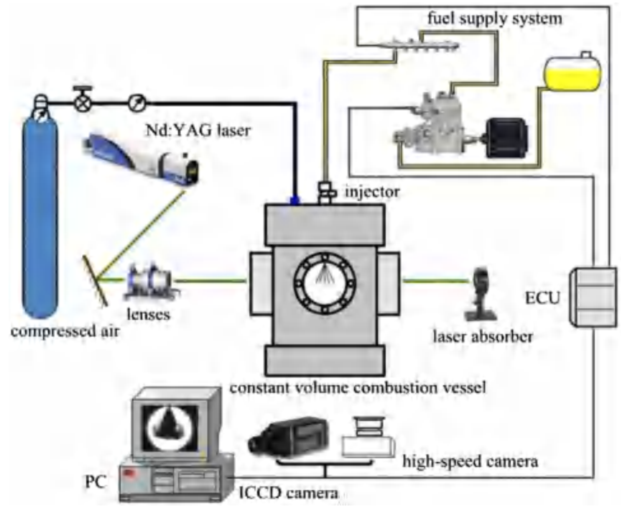

Fig. 1. Experiment measuring system of laser-induced incandescence.

pressure common-rail fuel injection system which could control fuel injection pressure are provided, and the design injection pressure is 160 MPa. In this experiment, direct soot measurements by LII are presented for a range of diesel-like operating conditions with ambient temperatures from 850 K to 920 K, ambient pressure from 3 MPa to 4 MPa, and injection pressures from 50 MPa to 100 MPa. The orifice diameter of the injector nozzle with a single hole is 168 μm. The injection pulse width can be adjusted.

3.2. Laser

The LII signal is excited by a Q-switched Nd:YAG laser (Quantel Brilliant) operating at 532 or 1064 nm, with a repetition rate of 10 Hz and pulse duration of 7–9 ns. In this experiment, the wavelength of 532 nm is preferred because it does not excite undesirable laser-induced fluorescence (LIF) from species such as polycyclic aromatic hydrocarbons (PAHs) associated with soot formation. Too low laser fluences are not recommended because that are not sufficient to heat all soot particles in the probe volume to a uniform temperature close to soot surface vaporization, while too high laser fluences result in increasingly significant modifications of the soot morphology and vaporization [27]. The laser fluence is kept at 0.13 J cm^{-2} in this experiment.

3.3. Lenses

Due to require a laser sheet in the experiment, a homogenous vertical light sheet is formed with a height of approximately 40 mm and a thickness of about 700 μm by a suitable pair of cylindrical negative and spherical positive lenses providing a long focus using a combination of cylindrical and spherical lenses.

3.4. ICCD

Scattering light caused by fuel droplets, soot particles and the constant volume vessel, and laser-induced fluorescence (LIF) emitted from species such as polycyclic aromatic hydrocarbons fluorescence (PAHs) will interfere collection of the LII signal. However, scattering light occurs mainly in several nanoseconds after being excited by laser. And the signal attenuation of laser-induced fluorescence, which occurs mainly in only about 20 ns, is quick, while the LII signal could last hundreds of nanoseconds. So, images detection time of ICCD is delayed and the delay time is 40 ns in this experiment.

An intensified charge coupled device (ICCD) camera applied in this experiment is a PI MAX 2 camera, with the maximum resolution, the minimum gate width and the highest speed of data acquisition being 1024 × 1024, 2 ns and 4 images per second, respectively. And the ICCD can work in multi-triggering mode. The principle of ICCD is that an intensifier, which could change the light signal into the amplified electron streams being sensitive to the device in the back end of CCD, is placed in front of the camera. Thus, weak light could be detected, as well as the LII signals at different initial conditions in the constant volume vessel.

3.5. High-speed camera

In this paper LII signal excited by the pulsed laser in the constant volume combustion vessel is measured. Meanwhile, the diesel jet flame is measured and analyzed by use of the high-speed photograph method. The high-speed camera applied in this experiment is FASTCAM-ultima 512 CMOS, produced by PHOTRON Corporation in Japan. The speed of shoot is 4000 images per second, and the single image pixel is 256 × 256. This high-speed camera is applied to obtain transient two-dimensional images of diesel jet flame in the constant volume combustion vessel at different initial conditions.

4. Rusults and discussion

4.1. The ignition characteristics of diesel fuel at different ambient conditions

The ignition and combustion characteristics of diesel fuel are shown as in Figs. 2 and 3, respectively. Ambient gas temperatures in Figs. 2 and 3 were 920 K and 850 K respectively, and ambient gas pressure and injection pressure were kept at 4 MPa and 100 MPa. In the combustion images the ignition delay was defined as the time between start of injection and the ignition timing of diesel fuel. At the upstream of diesel jet there was a premixing region of fuel spray, where the fuel concentration was higher and fuel temperature was low, we could see from the figures that, at both initial conditions, there was a non-flame region near the nozzle in diesel spray plume, and the length of the region was slightly longer at the lower ambient temperature: at the ambient temperature of 850 K the length is about 29 mm, while at the ambient temperature of 920 K the length is about 26 mm. At the ambient temperature of 920 K, the ignition timing of diesel fuel was about 0.25 ms, and then the flame developed in the direction of diesel jet, a bright flame could be observed at 0.75 ms; at the initial ambient temperature of 850 K, the ignition timing of diesel spray was about 0.75 ms, a bright flame could be seen at 1.0 ms. Meanwhile, the flame volumetric combustion efficiency at the high ambient temperature condition was higher than that at low ambient temperature condition, this was because atomization and vaporization processes of diesel fuel were accelerated at higher ambient temperature, which resulted in the shorter ignition delay of diesel fuel and the faster combustion rate. And the lower ambient temperature limited the diffusion flame of diesel fuel, which caused slower combustion rate, and then the condition of low-temperature combustion was approached.

In this paper the effects of different initial conditions on the ignition delay of diesel fuel in the constant volume combustion vessel were investigated by the analysis of the lighting flame and pressure rise. The effects of different initial ambient temperature and pressure on the ignition delay are investigated at the injection pressure of 100 MPa as shown in Fig. 4. At the same injection pressure, higher temperature could accelerate the process of breakup, atomization and evaporation of diesel droplets, thus the fuel mixture was rapidly formed that caused the decrease of diesel ignition delay with the increase of ambient temperature. And, at the same ambient temperature, the higher ambient pressure could shorten the ignition delay, this was mainly because that at the high ambient pressure, air density was high and absolute oxygen content per unit of volume was increased. The fuel mixture which was close to the theory equivalent ratio was formed rapidly, resulting in the shorter ignition delay. And then the combustion rate of diesel spray was accelerated, and the temperature in the constant volume vessel was increased rapidly.

4.2. The effects of ambient conditions on the flame lift-off length of diesel fuel

After the autoignition phase is completed, a spray-driven diesel fuel jet becomes a lifted turbulent diffusion flame until the end of injection. The most upstream location of combustion on the spray during injection is referred to as the lift-off length. In the combustion images the lift-off length is the length between the injection nozzle and the most upstream location of flame. Siebers and co-workers [28] have shown that the flame lift-off length has the following power-law relationship to various parameters:

$$H = CT^{-3.74}\rho^{-0.85}d^{0.34}UZ_s^{-1} \tag{2}$$

where H is the lift-off length (mm), C is a proportionality constant, T is ambient gas temperature (K), ρ is ambient gas density (kg m^{-3}), d is orifice diameter of the injector (μm), U is injection velocity (ms^{-1}), and Z_s is stoichiometric mixture fraction to account for effects of ambient gas oxygen concentration on the flame lift-off length, as decreasing with the decrease of ambient oxygen concentration. As there was a region with high fuel concentration, low oxygen concentration and high temperature at the downstream of the lift-off length, the formation

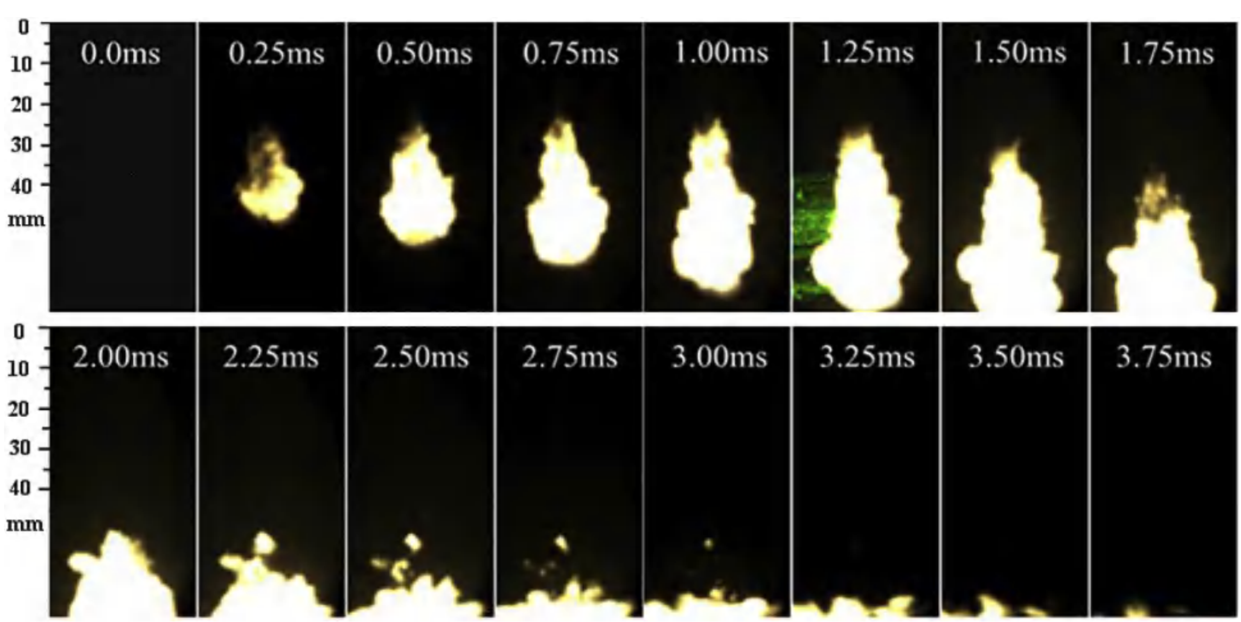

Fig. 2. Ignition process of diesel spray at diesel injection pressure 100 MPa, ambient pressure 4 MPa and ambient temperature 920 K.

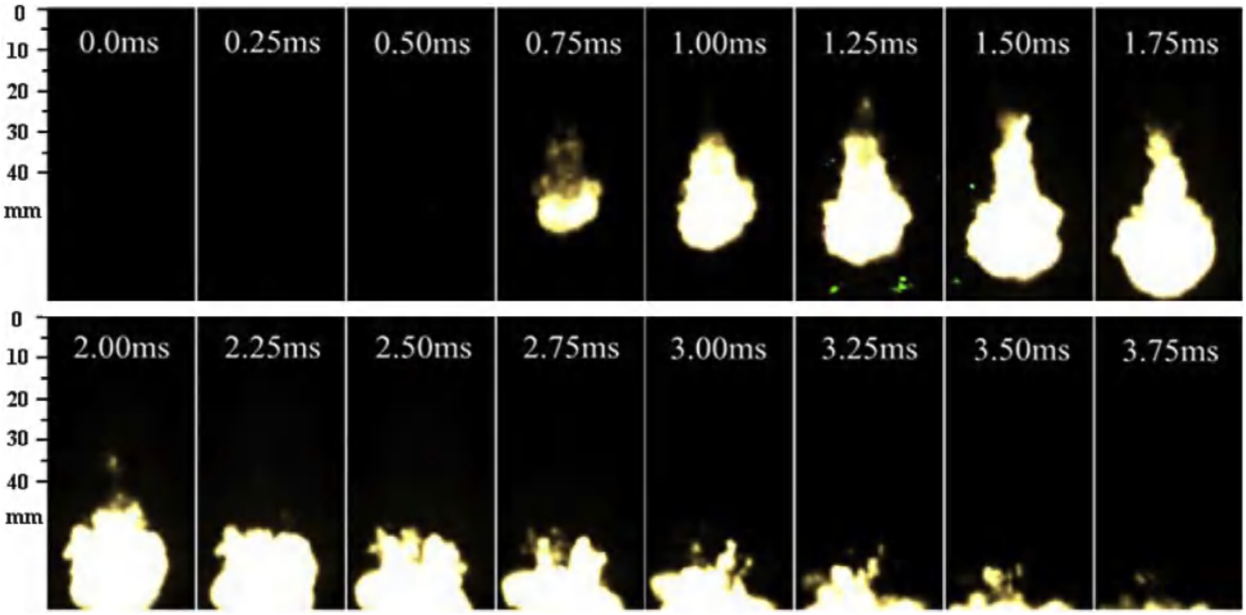

Fig. 3. Ignition process of diesel spray at diesel injection pressure 100 MPa, ambient pressure 4 MPa and ambient temperature 850 K.

and growth process of particle precursors such as PAHs, is easily accelerated at this region. Pickett et al. [29] found that the soot formation and oxidation occurred in the region between the lift-off length and the flame front, where the peak soot concentration occurred and decreased gradually from middle to both ends of the flame. Thus, the flame lift-off length has great effects on the soot formation and oxidation.

The flame lift-off length of diesel fuel is quantitatively studied in the constant volume combustion vessel at different ambient temperature, pressure and injection pressure as shown in Fig. 5. And in Fig. 5 the images at different initial conditions are all selected at the ignition timing of diesel spray. As could be seen from the figure, at same ambient pressure and injection pressure conditions, the flame lift-off length at the ambient temperature of 850 K was longer than that at the ambient temperature of 920 K. That was because that the lower temperature in the constant volume vessel would inhibit the atomization, vaporization and heat transfer of diesel droplets, and then prolong the physical and chemical ignition delay time, increase the time scale of the chemical reaction. At same initial ambient temperature and injection pressure conditions, the lift-off length at the ambient pressure of 4 MPa was shorter than that at the ambient pressure of 3 MPa. Due to high air density, high oxygen content per unit of volume at the same ambient temperature, the fuel mixture being close to the theory equivalent ratio was formed rapidly. Thus, it can be concluded that at the condition of higher ambient pressure, the shorter lift-off length was acquired.

Fig. 6 shows the effects of initial ambient temperature on the flame lift-off length. Fuel injection pressure considered in Fig. 6 was kept at 100 MPa, and initial ambient pressure was 3 MPa and 4 MPa, respectively. From the figure we could see that, the flame lift-off length decreased with the increase of ambient pressure and temperature. With the analysis of Fig. 4, the trends of the lift-off length of diesel fuel, which decreased with increasing ambient temperature and pressure, were the same as that of the ignition delay. And the lift-off length exhibited a non-linear change with a change in ambient temperature and pressure. The non-linear change demonstrated that the sensitivity of the lift-off length to the changes of ambient parameters was different.

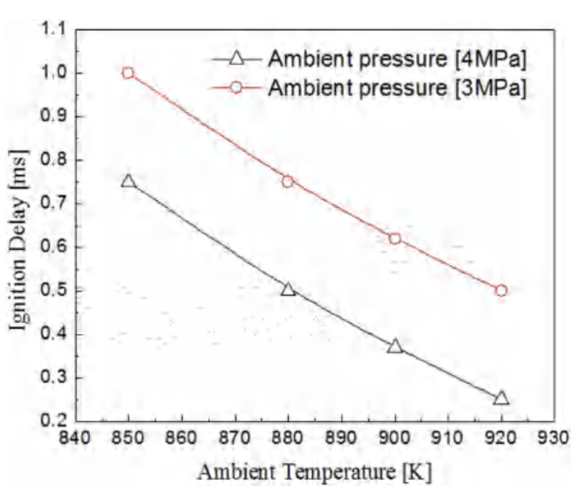

Fig. 4. Effects of different ambient pressure and temperature on ignition delay.

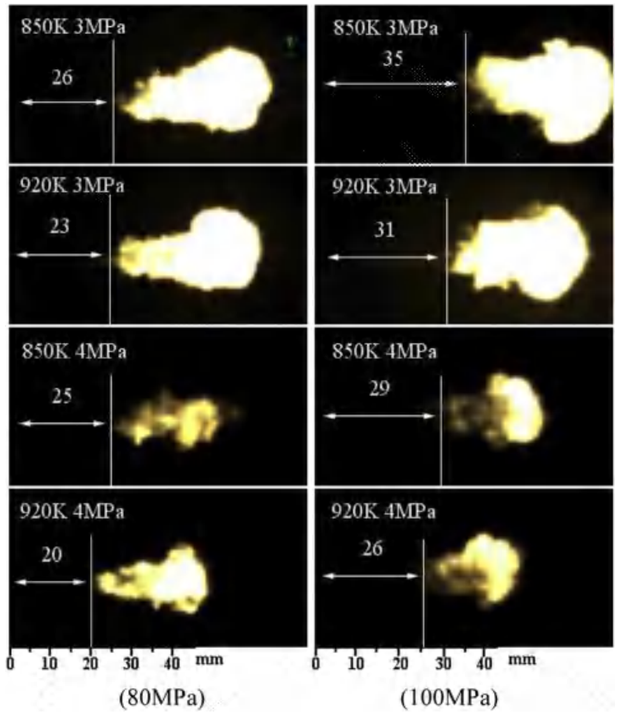

Fig. 5. Effects of different initial conditions on flame lift-off length.

The flame lift-off length at the fuel injection pressure of 100 MPa was longer than that at the fuel injection pressure of 80 MPa as shown in Fig. 5. Fig. 7 shows the effects of fuel injection pressure on the flame left-off length, at initial ambient pressure of 3 MPa and 4 MPa. Generally, the higher the fuel injection pressure, the better the fuel vaporization, which could accelerate the mixing rate of air and fuel. However, the high fuel injection pressure also accelerated fuel droplets speed. Although the total quantity of the air entrainment increased, the speed of the entrained air in the spray was roughly constant. Thus, the distance between the ignition point and the injector nozzle was extended, as well as the lift-off length. Consequently, from Fig. 7 we could see that the lift-off length increased with the increase of fuel injection pressure. This characteristic was important to the design of the combustion chamber of diesel engines. And according to the fuel injection characteristic and the in-cylinder airflow motion, proper selection of the combustion chamber structure and controlling the distribution of ignition points could inhibit the formation of exhaust emissions, such as soot particles.

4.3. Soot formation and the distribution of soot concentration in diesel jet flame

For the relationship of the fuel–air mixture and soot formation and distribution of soot concentration, laser-induced incandescence (LII) was applied to the measurement and analysis of combustion process of diesel spray. To improve the influence of randomness of diesel spray

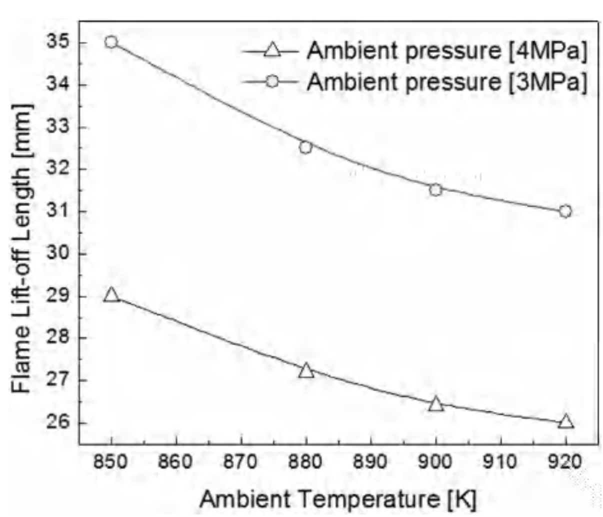

Fig. 6. The change of flame lift-off with ambient pressure and temperature.

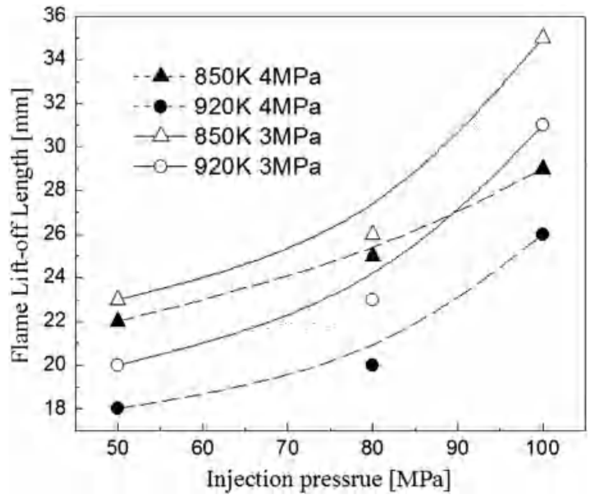

Fig. 7. Effects of different injection pressure on the flame lift-off length.

on the measuring results, 50 images of LII signal intensity for each experimental condition were then averaged and analyzed. And, the range of LII signal intensity was 300–12,000 cd (cd is the international standard unit of luminous intensity, whose full name is candela), in which the boundary of laser sheet could be accurately observed.

The quantity of the entrained air in the premixing stage of diesel spray, the fuel–air mixture, has great impact on soot formation. The percent of stoichiometric air ζ is defined as an expression for the air entrained up to the lift-off location as a percentage of the total air required to burn the fuel being injected. Naber and Siebers give the expression as below [30,31]:

$$\zeta = \frac{10}{3}\left(\sqrt{1+16\left(\frac{H}{\gamma}\right)^2}-1\right) \tag{3}$$

where H is the lift-off length, γ is the characteristic length scale for the spray,

$$\gamma = \sqrt{\frac{\rho_f}{\rho_a}}\,\frac{\sqrt{C_a}\cdot d}{0.66\cdot\tan(\theta/2)} \tag{4}$$

In Equation (4), d is the orifice diameter, C_a is the area contraction coefficient, ρ_f and ρ_a are the injected fuel and ambient gas densities, $\theta/2$ is the measured spreading half-angle of the spray. From Equation (3), we can see that the stoichiometric air ζ is almost direct proportion to the flame lift-off length. The high quantity of the entrained air in the spray caused by the short lift-off length could rapidly reduce the concentration of the fuel–air mixture, which could speed up the formation of the ignition mixture being close to the theory equivalent ratio. Siebers and co-workers [30] introduced that in the lift-off length, large quantities of air entrained up to the lift-off length were mixed with

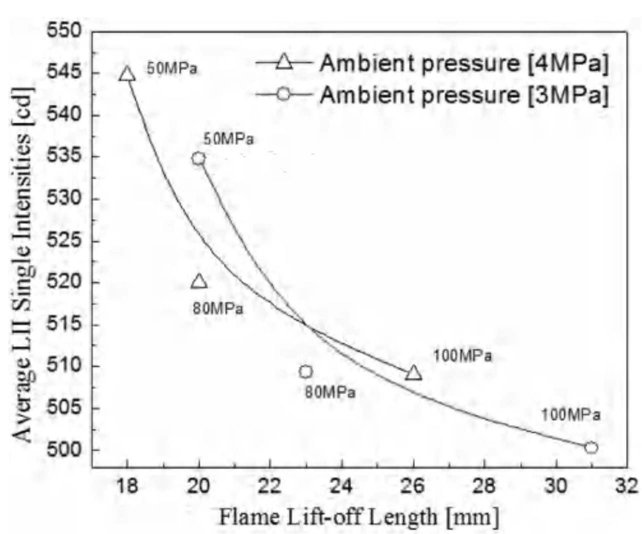

Fig. 8. LII signal intensity corresponding with different flame lift-off lengths.

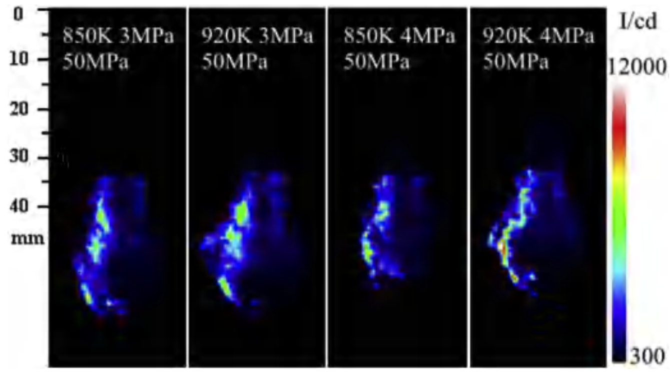

Fig. 9. Two dimensions images of LII signals at different ambient temperature and pressure.

diesel fuel, the quantity of the air entrained which determined the equivalence ratio in the in-cylinder fuel-rich region was about 20% of the total air required to burn the fuel being injected. And when the percentage of the air entrained into the lift-off length was 38%, soot particles would be barely formed.

Fig. 8 shows the average LII signal intensities in transient two-dimensional images, which are chose at 1.8 ms after diesel fuel is injected, at the ambient temperature of 920 K and different ambient pressure. From Figs. 8 and 6 we could see that, the shorter the lift-off length, the bigger the LII signal intensity which was proportional to the soot concentration. Thus, the number of soot particles in the combustion process of diesel spray at this condition was more. However, with the increase of the flame lift-off length, the sensitivity of the LII signal intensity to soot concentration was reduced, as observed in the figure.

The two-dimensional images of the LII signal intensity are shown in Fig. 9, at the injection pressure of 50 MPa and different ambient temperature and pressure. As shown in Figs. 9 and 10, under the influence of the increase of ambient temperature, the quantity of air entrained to the lift-off length was increased with the decrease of the lift-off length, and the ignition location was closer to the injector nozzle. With the development of the flame at the downstream of diesel jet, the region of the high temperature and lack of air amounts could cause that the rate of soot formation was higher than the rate of soot oxidation. Then a large amount of the soot precursor produced by the pyrolysis of diesel fuel could not be further oxidized which resulted in the soot particles being relatively numerous, thus the greater LII signal intensity at the high ambient temperature was observed in the figures. In contrast, at the lower ambient temperature, with increase of the lift-off length and the quantity of air entrainment, the equivalence ratio in the flame region decreased, thus the soot formation was inhibited at this condition.

From Figs. 10 and 11 we could see that at the higher fuel injection pressure, the same ambient temperature and pressure, the LII signal intensity was weaker, which represented the smaller soot concentration in diesel spray. At the same ambient temperature and pressure, the soot formation in the spray decreased about 7% with the increase of diesel fuel injection pressure from 50 MPa to 100 MPa. The result was consistent with that in Fig. 7. Because the high injection pressure could cause not only the better atomization and vaporization of diesel spray but also the longer flame lift-off length. And then the more quantity of the air entrainment which accelerated the fuel–air mixing rate decreased the equivalence ratio in the lift-off length. Thus the fuel combustion efficiency was high and the quantity of soot formation was relatively small. On the other hand, with the increase of fuel injection pressure, the length of the flame region at the most upstream location of diesel jet flame which is mostly of the fuel oxidation would barely change. That meant reaction processes of soot formation and oxidation were shorten, which kept soot formation rate low.

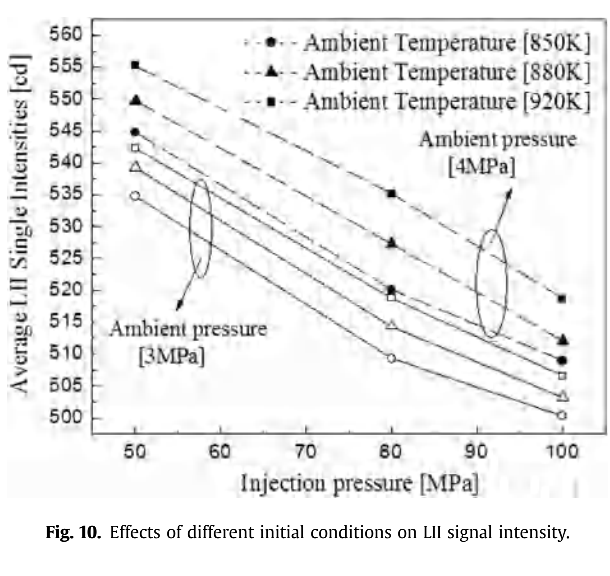

Fig. 10. Effects of different initial conditions on LII signal intensity.

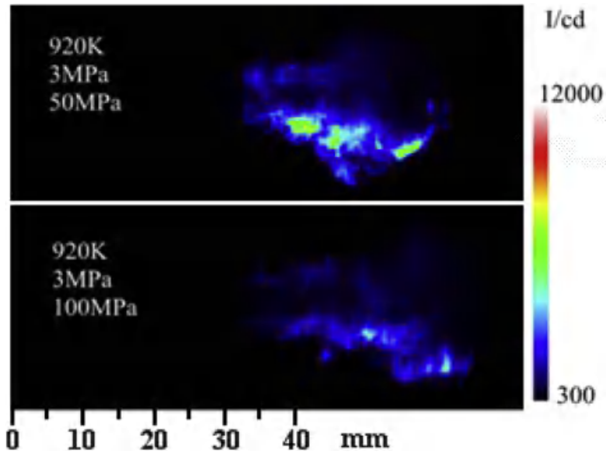

Fig. 11. Two dimensions images of LII signals at different ambient pressure and injection pressure.

With the increase of ambient pressure, the average LII signal intensity is increased, which is proportional to soot concentration produced as shown in Fig. 10. As previously mentioned, the high ambient pressure could result in the decrease of the lift-off length and the quantity of the entrained air in the spray, the increase of the equivalence ratio of fuel–air mixture. And then the quantity of soot formation in the combustion process of diesel fuel was increased at this condition. The effect of ambient pressure on the LII signal was smaller than that of the injection pressure. As could be seen from Equation (3) and Equation (4), the characteristic length γ was related to ambient pressure, thus the equivalence ratio of the entrained air in the spray was determined by the lift-off length H and the characteristic length γ. The quantity of the entrained air was changed as the changes in the ambient density in the lift-off length. All of these factors caused that the effect of ambient pressure on the quantity of the entrained air decreased.

The processes of diesel jet flame and the soot concentration were synchronously measured in this paper, as shown in Fig. 12. In the premixing combustion period of diesel spray before being ignited, there was a region with the high fuel–air equivalence ratio in the location close to the injector nozzle, where the evaporation rate was decreased and the fuel–air mixing rate barely changed. And due to the evolution of fuel atomization, the rates of the air entrainment and evaporation were increased. The equivalence ratio of fuel–air mixture was significantly decreased at the outer edge of the spray plume. And at the downstream outer edge of the spray plume where fuel and air began to mix, due to the effect of high ambient temperature, the diesel fuel would be ignited, causing the formation of the flame which encompassed the spray. As the mixing of the fuel at the center of the spray plume and the air around, the fuel concentration could be maintained close to the theoretical value of the fuel–air equivalence ratio [32]. Fig. 12 shows the spray being encompassed by the flame surface front at the downstream region of the fuel spray. As the relative fuel-rich region existed, combustion in the region caused the more quantity of soot formation at the high temperature. Thus, the natural mixture concentration and temperature stratification in the mixing process of fuel spray had impact on not only the ignition and combustion process of fuel spray, but also the soot formation. From the distribution of the LII signal intensity in Fig. 12, we could see that the distribution of soot concentration was uniform from the soot formation to the fully development of soot particles, and the obvious increase of soot concentration had not appeared. So, it proved that the formation and oxidation of soot particles including PAHs had been constantly occurring in the entire combustion process. And the soot particles emissions were determined by the formation and oxidation rate of soot particles jointly.

As the optical depth is the intrinsic characteristic of diesel spray, when laser sheet passed through the spray, laser energy will be absorbed by lots of soot particles produced in the combustion process, and unburned fuel droplets have a strong scattering to laser sheet, which causes the energy dissipation of laser sheet in the optical path, and then the weaker laser energy is absorbed by lots of soot particles in the downstream region of the optical path. Due to that, the measurement error is caused. Thus, from Figs. 11 and 12 we can observe the non-uniformity of measurement results of LII signal intensity. The adjustment of laser wavelength and intensity, the improvement of uniformity of laser sheet power, and other aspects will be further studied in the future.

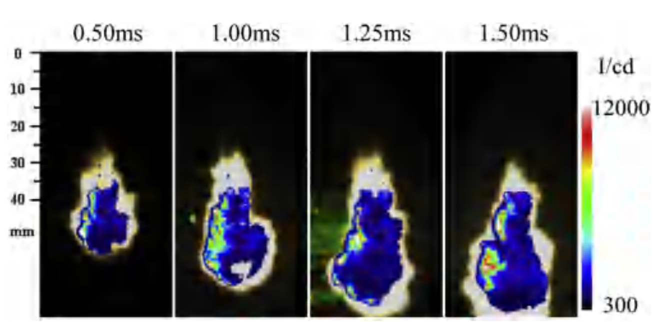

Fig. 12. Distribution of soot concentration in diesel combustion process. The 0.50 ms, 1.00 ms, 1.25 ms and 1.50 ms respectively represent the timing after start of injection of each figure.

5. Conclusions

In this paper, high-speed photograph measurement and LII were applied to measure and analyze two-dimensional distribution images of flame structure and soot formation in the combustion process of diesel spray. The evolution of diesel jet flame, the soot formation and the distribution of soot concentration, and the emission characteristics of soot particles were studied.

1. At the same ambient temperature and diesel fuel injection pressure, the ignition delay of diesel fuel was decreased with the increase of ambient temperature; at the same ambient pressure and diesel fuel injection pressure, the ignition delay was decreased with the increase of ambient pressure.
2. The higher ambient temperature and pressure caused the shorter flame lift-off length; the lift-off length exhibited a non-linear change with a change in temperature and pressure. At the same ambient temperature and pressure, the higher diesel fuel injection pressure resulted in the longer lift-off length.
3. With the increase of ambient temperature and pressure, the average LII signal intensity increased, which is proportional to soot concentration produced in the combustion process. At the same ambient temperature and pressure, the soot formation in the spray decreased about 7% with the increase of diesel fuel injection pressure from 50 MPa to 100 MPa. Soot particles were primarily produced in the relative fuel-rich region, which was encompassed by the flame surface front at the downstream of the diesel spray.

Acknowledgment

This work was supported by the State Nature Science Foundation of China (No. 51176056).

References

[1] H. James, S. Makiko, R. Reto, L. Andrew, O. Valdar, Proc. Natl. Acad. Sci. 97 (18) (2000) 9875–9880.
[2] M.Z. Jacobson, Nature 409 (2001) 695–697.
[3] B.S. Haynes, H.G. Wagner, Prog. Energy Combust. 7 (4) (1981) 229–273.
[4] T. Feng, R.D. Reitz, D.E. Foster, Y. Liu, Int. J. Therm. Sci. 48 (2009) 1223–1234.
[5] G. Oberdörster, E. Oberdörster, J. Oberdörster, Environ. Health Perspect. 113 (7) (2005) 823–839.
[6] R. Wilson, J.D. Spengler, Particles in Our Air: Concentrations and Health Effects, Harvard University Press, Cambridge, MA, 1996.
[7] R.J. Santoro, H.G. Semerjian, R.A. Dobbins, Combust. Flame 51 (1983) 203–218.
[8] R.A. Dobbins, C.M. Megaridis, Langmuir 3 (1987) 254–259.
[9] R.A. Dobbins, C.M. Megaridis, Appl. Opt. 30 (1991) 4747–4754.
[10] A. Wiartalla, H. Böcker, M. Durnholz, SAE Tech. Pap. (1995), 950233.
[11] F. Corcione, S. Merola, B. Vaglieco, SAE Tech. Pap. (2001), 2001-01-1258.
[12] Q. Zhang, P.A. Rubini, Fire Saf. J. 46 (2011) 96–103.
[13] N. Kiyomi, N. Makoto, F. Taketoshi, SAE Tech. Pap. (1990), 902081.
[14] H. Redjem, K.P. Geigle, M. Wolfgang, A. Manfred, Int. J. Therm. 49 (2010) 1457–1467.
[15] M. Yukio, K. Takeyuki, M. Shin, SAE Tech. Pap. (1979), 790491.
[16] H. Ishii, Y. Goto, M. Odaka, SAE Tech. Pap. (2001), 2001-01-0656.
[17] K. Yamamoto, M. Takemoto, Fuel Process. Technol. 107 (2013) 99–106.
[18] C. Schulz, B.F. Kock, M. Hofmann, H. Michelsen, S. Will, B. Bougie, R. Suntz, G.J. Smallwood, Appl. Phys. B: Lasers Opt. 83 (3) (2006) 333–354.
[19] V. Narayanaswamy, N.T. Clemens, Proc. Combust. Inst. 34 (1) (2013) 1455–1463.
[20] A.C. Eckbreth, Appl. Opt. 48 (11) (1977) 4473–4479.
[21] A.M. Lynn, Appl. Opt. 23 (1984) 2201–2207.
[22] I. Takayuki, H. Tomofumi, U. Masato, S. Jiro, F. Hajime, SAE Tech. Pap. (2004), 2004-01-1398.
[23] P. Desgroux, X. Mercier, B. Lefort, R. Lemaire, E. Therssen, J.F. Pauwels, Combust. Flame 155 (2008) 289–301.
[24] H. Bladh, J. Johnsson, N.E. Olofsson, A. Bohlin, P.E. Bengtsson, Proc. Combust. Inst. 33 (2011) 641–648.
[25] A.Z. Tahiri, H. Anyoji, H. Yasuda, Agric. Water Manag. 84 (1–2) (2006) 186–192.
[26] G.J. Smallwood, D. Clavel, D. Gareau, SAE Tech. Pap. (2002), 2002-01-2715.
[27] R.L. Vander, M.Y. Choi, Carbon 37 (1999) 231–239.
[28] D.L. Siebers, H. Brian, SAE Tech. Pap. (2001), 2001-01-0530.
[29] M.L. Pichett, D.L. Siebers, Combust. Flame 138 (1–2) (2004) 114–135.
[30] J.D. Naber, D.L. Siebers, SAE Trans. Pap. 105 (3) (1996) 82–111.
[31] D.L. Siebers, SAE Trans. Pap. (1999), 1999-01-0528.
[32] J.E. Dec, SAE Trans. Pap. 106 (3) (1997) 1319–1348.