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Characterization of gasoline combustion with laser and spark ignition*

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Abstract: The combustion of gasoline-air mixtures in a constant-volume combustion chamber with an initial condition of 0.1 MPa pressure and 363 K temperature is experimentally investigated with laser ignition generated by a Q-switched Nd:YAG laser (wavelengths of 532 and 1064 nm). Spark ignition is also tested, and the results are used as the benchmark. Combustion chamber pressure is measured by a piezoelectric pressure transducer, and recorded using a digital oscilloscope. When the equivalence ratio is swept from 1.2 to 1.8, laser and spark ignition show marginal differences in pressure rise rate and peak pressure. The maximum pressure rise rate and the maximum peak pressure are obtained at equivalence ratios of 1.6 and 1.8 for laser ignition and spark ignition, which are 39.4 MPa/μs and 0.68 MPa for the laser wavelength of 532 nm, 38.8 MPa/μs and 0.67 MPa for the laser wavelength of 1064 nm, and 38.1 MPa/μs and 0.67 MPa for spark ignition, respectively. When the equivalence ratio is reduced below 1.2, the pressure rise rate and peak pressure of the laser ignition are significantly higher than those of spark ignition, and the lean limit for laser ignition is also wider than that of spark ignition; therefore, laser ignition is more favorable for lean combustion. For both the laser and spark ignitions, the ignition energy demonstrated a limited impact on both the pressure rise rate and peak pressure. Heat release rate in the combustion chamber is calculated, and the results show that variations of heat release are in accordance with variations of the pressure history.

Key words: Laser ignition, Spark ignition, Pressure rise rate, Peak pressure, Heat release rate
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1 Introduction

With increased environmental awareness, more stringent emission regulations, and the challenges of sustainable energy supply, development of internal combustion engines with high efficiencies and low emissions has become the focus of engine researchers. Lean combustion in gasoline engines has the potential of improving fuel economy while reducing emissions. However, there are many challenges in applying lean combustion technology. Ignition related problems, such as the sluggish flame initiation and propagation, can lead to instable combustion, and even to some extent engine misfiring (Morsy, 2012). High-energy ignition is one solution, however, it increases the voltage and energy demands for the conventional ignition system. Additionally, increasing the voltage and energy does not always improve ignitability, and in some cases, it even causes reliability problems. Typical problems include secondary high voltage breakdown, poor timing sensor reliability, and electrode degradation and erosion, which lead to spark plug failure (Phuoc, 2006). Thus, a new ignition technology is crucial to the successful implementation of lean combustion technology.

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Recently, many investigations have been carried out on new ignition systems, such as plasma jet igniters (Chintala *et al*., 2006), laser-induced spark ignition (Richardson *et al*., 2004), and rail-plugs ignition (Gao *et al*., 2004). Most of the challenges listed above could potentially be solved by the use of laser-induced spark ignition because it has many potential benefits including better control over the timing and locations of ignition. Laser-induced spark ignition systems do not have electrodes, which potentially leads to a longer lifetime. More importantly, laser-induced spark ignition would allow ignition in multiple locations inside the chamber, shortening the combustion duration of the lean mixtures.

In recent years, laser ignition has become a well-researched topic because of its many potential benefits over conventional electric spark ignition. Laser ignition can be divided into four categories: laser thermal ignition, laser-induced photochemical ignition, laser-induced resonant breakdown ignition, and laser-induced spark ignition (Bradley *et al*., 2004). Currently, laser-induced spark ignition, which is also called non-resonant breakdown, is the most frequently adopted ignition mode to initiate combustion, primarily because of its flexibility in the requirements of laser wavelength and the high feasibility of implementation (Morsy, 2012). Laser-induced spark ignition begins with the initial seed electrons produced from impurities in the gas mixture (e.g., dust, aerosol, or soot particles). It is very unlikely that the initial electrons are produced by multiphoton ionization because the intensity of the focus (1012 W/cm^2) is lower than the intensity required for ionizing gas molecules (>1014 W/cm^2) (Srivastava *et al*., 2009; Tihay *et al*., 2012). This process releases electrons, which absorb more photons via the inverse Bremsstrahlung process, and increase their kinetic energy. The liberated electrons collide with other molecules and ionize them, leading to an electron avalanche and breakdown of the gas. As a result, spark plasma with high temperature and high pressure is created. This extreme condition relative to the ambient gas leads to the development of a rapidly expanding shock wave that has sufficient energy to ignite fuel-air mixtures (Bradley *et al*., 2004).

Previous studies have suggested that the laser spark is produced by a non-resonant breakdown (Ronney, 1994; Phuoc and White, 1999; Kopecek *et al*., 2003). Srivastava *et al*. (2009) studied laser-induced spark ignition of lean hydrogen-air mixtures at an initial pressure of 3 MPa and an initial temperature of 323 K in a constant volume combustion chamber. They found that, compared with spark plug ignition, laser-induced spark ignition led to a higher pressure rise rate inside the combustion chamber, which was caused by the absence of a plasma quenching effect with laser ignition. In the research conducted by Weinrotter *et al*. (2005a) on hydrogen-air mixtures, it was found that the combustion process for hydrogen-air mixtures shows no significant dependence on laser pulse energies (3–50 mJ), and longer combustion durations with leaner mixtures could be observed, which was explained by the slower flame velocity of leaner gas mixtures (Qin *et al*., 2000; Lamoureux *et al*., 2003). However, Kopecek *et al*. (2003) investigated the effect of laser pulse energy in methane-air mixtures and concluded that shorter combustion durations and higher peak pressures can be achieved with increased laser pulse energy, which was also observed by Morsy and Chung (2003). Fuel-air mixtures were also ignited using a spark plug under identical experimental conditions, and results were compared with those of laser ignition by several researchers; they found that laser ignition led to shorter ignition delay and shorter combustion duration compared with conventional spark ignition (Ma *et al*., 1998; Kopecek *et al*., 2005). Pressure history of hydrogen-air mixtures in the combustion chamber for single, two, and three point ignition was experimentally investigated by Morsy and Chung (2003) and Morsy (2012), and it was concluded that significant enhancement of the combustion process, especially in lean mixtures, could be achieved through the use of the most incident laser energy achieved by laser-induced cavity ignition, by simultaneous initiation of combustion at multiple locations, or through increasing the turbulence caused by ignition.

Despite the research that has been conducted by others, there are limited data or publications available for the combustion of liquid fuel using laser-induced spark ignition. Thus, the research objective of this study is to investigate the combustion process of gasoline-air mixtures with laser-induced spark ignition. This study focuses on the impact of equivalence ratios (Φ) and ignition energies on pressure histories. Gasoline-air mixtures were also ignited using a spark plug under identical experimental conditions, and results were compared with those of laser-induced spark ignition.

2 Experimental setup

Fig. 1 shows a schematic of the experimental setup for laser-induced spark ignition. It consists of five main parts: the laser, the combustion chamber, the temperature and pressure measuring systems, the heating system (temperature was controlled by six resistance heaters in each wall of the chamber), and the intake and exhaust system; the details of which were described by Xu *et al*. (2014). If not otherwise stated in the following text, laser ignition means laser-induced spark ignition.

The optical scheme of the igniting beam is depicted in Fig. 2. The laser beam is focused in the chamber by a spherically corrected convex lens with focal length of 500 mm, and the absorbed energy deposited in the plasma is calculated by integrating the measured values of the energy meters Ea and Eb. More details about the parameters of the focused laser and the mathematic formula of laser ignition energy can be found in (Xu *et al*., 2014).

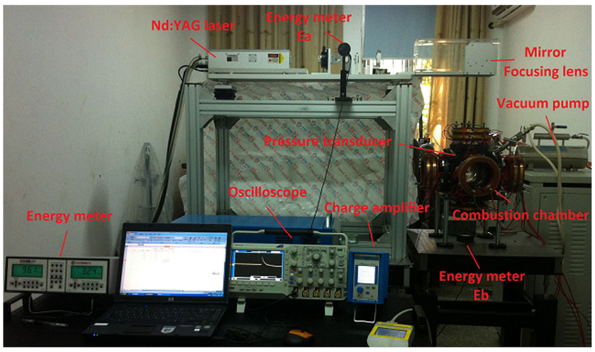

Fig. 1 Sketch of laser ignition experimental setup

The liquid fuel used in the experiments was No. 93 gasoline, supplied by China Petroleum & Chemical Corporation (Sinopec Group). Under a certain volume, pressure, and temperature in the constant-volume combustion chamber, the volume of fuel required for a certain equivalence ratio (Φ) was calculated by

$$m_{\mathrm{air}} = \frac{pV_{\mathrm{c}}}{T}\frac{M_{\mathrm{r}}}{R\times 10^{3}}, \quad (1)$$

$$V_{\mathrm{f}} = \frac{m_{\mathrm{air}}}{\alpha\rho_{\mathrm{f}}}\Phi, \quad (2)$$

where m_{air} is the mass of air, p and T are the initial pressure and temperature (0.1 MPa and 363 K), V_{c} is the volume of the chamber (1.7 L), M_{r} is the relative molecular mass of air (29 g/mol), R is the molar gas constant (8.314 J/(mol·K)), V_{f} is the liquid volume of the gasoline, α is the theoretical air-fuel ratio of gasoline (14.7), and ρ_{f} is the density of gasoline (0.725 g/ml).

It was ensured that the initial experimental conditions were identical for all experiments reported in this study. Different gasoline-air ratio mixtures were investigated at an ambient temperature of 298 K and

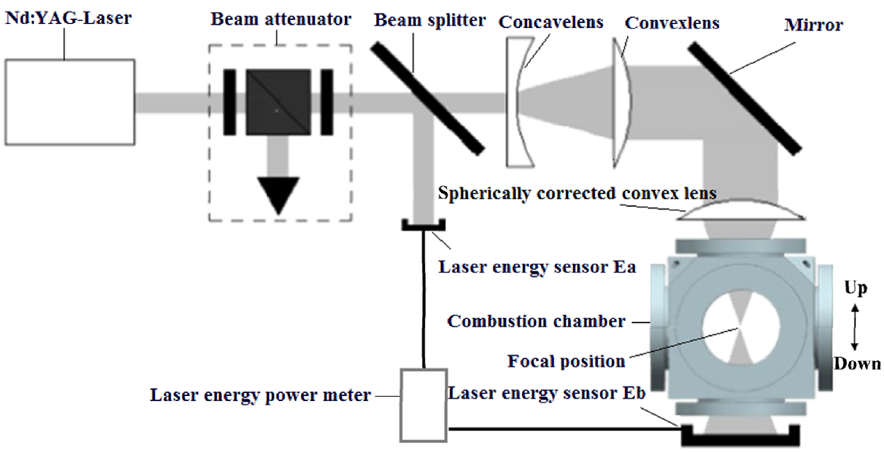

Fig. 2 Laser beam propagation in the laser induced ignition experiment

an air humidity of 56%. Before each experiment, the chamber was initially evacuated by a vacuum pump to remove residual gases and was heated up to the initial temperature of 363 K. Injection occurred at a pressure of approximately 0.05 MPa, and then the air was introduced. Before the ignition was conducted, the chamber was maintained for 5 min to guarantee a homogeneous mixture.

3 Results and discussion

Pressure history is one of the most basic characteristics of combustion in internal combustion engines (Luján *et al.*, 2010), providing quantitative information, such as peak pressure, indicated mean effective pressure (IMEP) and pumping work for mechanical design and engine calibrations (Payri *et al.*, 2011). Therefore, this study of pressure history under various initial conditions (ignition energy and equivalence ratio) provides critical information for practical applications of laser ignition.

Pressure histories were measured by a piezoelectric pressure transducer, and recorded using a digital oscilloscope. Fig. 3 shows the pressure histories of gasoline-air mixtures with various equivalence ratios ignited by laser ignition with two laser wavelengths (Figs. 3a and 3b) and ignited by spark ignition (Fig. 3c). For laser ignition, the incident laser energy has to be discerned from the absorbed laser energy; the absorbed energy is exactly the energy necessary to yield ignition inside the combustion chamber, and incident energy determined by working voltage is the total pulse energy needed to generate ignition. In this study, laser ignition energy means the absorbed laser energy.

3.1 Pressure rise rate

The burning rate and flame velocity have been correlated with the pressure rise rate. A higher pressure rise rate reflects a faster burning rate and a faster flame velocity. In this study, pressure rise rate is the mean value of the range of peak pressure between 20% and 80%.

3.1.1 Impact of equivalence ratios on pressure rise rate

Fig. 4 illustrates the pressure rise rate for laser ignition and spark ignition under various equivalence

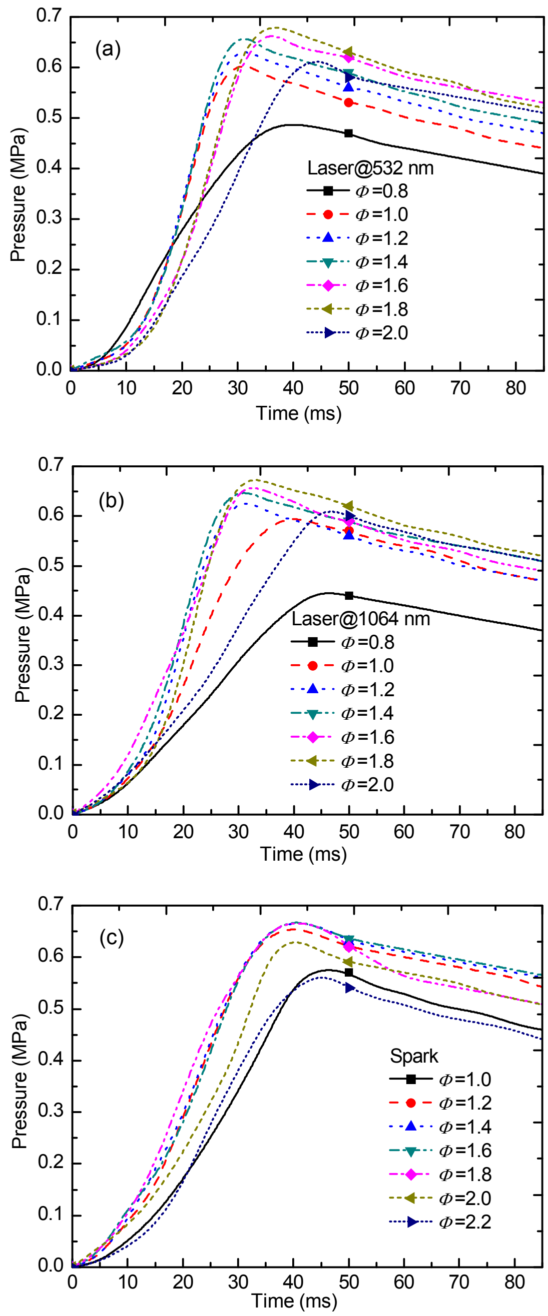

Fig. 3 Pressure vs. time for gasoline-air mixtures with various equivalence ratios
(a) Laser wavelength of 532 nm; (b) Laser wavelength of 1064 nm; (c) Spark ignition (ignition energy of 11–13 mJ)

ratios. At the equivalence ratio of 1.8, the pressure rise rates for laser ignition with wavelengths of 532 and 1064 nm were 39.4 and 38.8 MPa/μs, respectively. When the equivalence ratio was changed from 1.8, the pressure rise rates were reduced. For the gasoline-air mixtures with the same equivalence ratio, the pressure rise rate of the laser ignition with a wavelength of 532 nm was slightly higher than that of 1064 nm, resulting from the higher focal intensity of the laser wavelength of 532 nm compared with that of 1064 nm. The maximum pressure rise rate for spark ignition was 38.1 MPa/μs, achieved at an equivalence ratio of 1.6. Compared with laser ignition, the pressure rise rate showed little change for the equivalence ratios between 1.2 and 1.8.

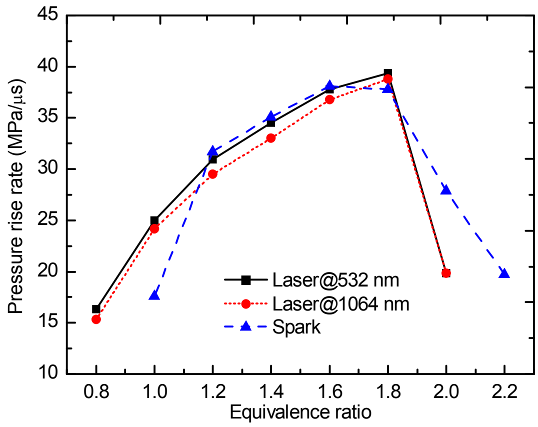

Fig. 4 Pressure rise rate vs. equivalence ratio for laser ignition and spark ignition (ignition energy of 11–13 mJ)

The decline of the pressure rise rate with lean mixtures is due to the lower energy content, lower burning temperature, and slower flame velocity. With leaner mixtures, it was also found that the combustion pressure for laser ignition increased more rapidly compared with spark ignition, as indicated by a higher pressure rise rate. As a result, the combustion duration for laser ignition decreased relative to the conventional spark ignition. With laser ignition, the distance over which the flame must travel to complete the combustion process is shortened.

Further increase of the equivalence ratio from 1.8 to 2.0 led to a rapid decrease in the pressure rise rate for both laser and spark ignition. For rich mixtures, it is caused by the low content of oxygen and slow chemical reaction rate.

3.1.2 Impact of ignition energies on the pressure rise rate

The ignition energy of spark ignition can be calculated from voltage, current, and the duration of the ignition process. In this study, the energy consumption of the resistance was also considered. Fig. 5 shows the pressure rise rate for laser ignition and spark ignition at an equivalence ratio of 1.2 under various ignition energies. There was no significant effect of ignition energies on the pressure rise rate for laser wavelengths of 532 and 1064 nm, which has also been reported by Weinrotter *et al.* (2005a) and Dharamshi *et al.* (2014). Weinrotter *et al.* (2005a) investigated the effect of laser pulse energies on the combustion of hydrogen-air mixtures, and concluded that laser ignition energy had a limited impact on the pressure rise rate. Similar experiments on hydrogen-air mixture combustions in the combustion chamber were also conducted by Dharamshi *et al.* (2014). They compared the pressure-time history by using standard laser pulse energy and the minimum ignition energy, and it was observed that the difference in the pressure rise rate was less than 5%. An explanation for this is that increasing the energy had a limited effect on the beam pulse duration. Furthermore, since the breakdown threshold intensity for a given gas is constant, the effect of increasing laser energy acts only to achieve this breakdown prior to the desired focal position (minimum beam waist) (Dearden and Shenton, 2013). Thus, increasing the laser energy may have an adverse effect of bringing the plasma location closer to the cylinder wall (Dearden and Shenton, 2013). Similarly, it was found that the spark ignition energy also had a limited effect on the pressure rise rate.

3.2 Peak pressure

As shown in Fig. 3, the time needed to reach peak chamber pressure was 30–50 ms and 30–45 ms for laser ignition with a wavelength of 532 and 1064 nm, respectively. In spark ignition, the time needed to reach peak pressure was 30–45 ms. The results presented in this study are comparable to those from Srivastava *et al.* (2009), where 50 ms was needed to reach peak pressure for a hydrogen-air mixture at an air/fuel equivalence ratio of 2.4. However, Weinrotter *et al.* (2005b) investigated methane-hydrogen-air mixtures at an initial temperature of 473 K and initial pressures up to 3 MPa, and the time needed to reach peak pressure was about 400 ms. It is proposed that the differences can be explained by the different fuel types and different initial conditions.

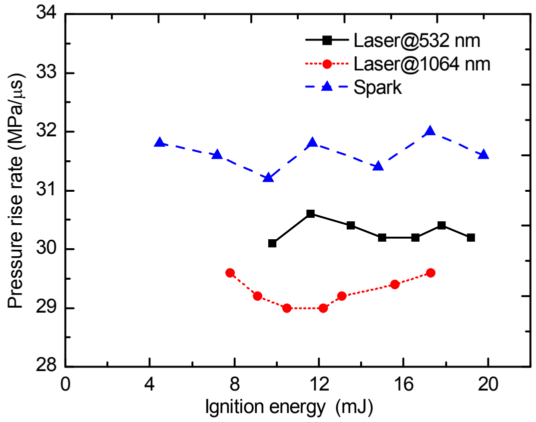

Fig. 5 Pressure rise rate verses ignition energy for laser ignition and spark ignition (equivalence ratio of 1.2)

3.2.1 Impact of equivalence ratios on peak pressure

Fig. 6 shows the peak pressure at various equivalence ratios. With laser ignition the peak pressure increased at first, and then was reduced later when the equivalence ratio was increased for both wavelengths of 532 and 1064 nm. The maximum peak pressures for both wavelengths of 532 and 1064 nm were obtained at an equivalence ratio of 1.8, which were 0.68 and 0.67 MPa, respectively. When equivalence ratios were changed from 1.8, the peak pressure decreased. The results show that the variations in the trends for spark ignition are similar to those of laser ignition. The maximum peak pressure (0.67 MPa) was obtained at an equivalence ratio of 1.6. According to these results, lean mixtures with low energy content experienced clearly a longer combustion duration and thus more heat loss. Because of these disadvantages, the peak pressure for the leaner mixtures is lower. The decline of peak pressure for the rich mixtures is caused by a low oxygen concentration, incomplete combustion, and long combustion duration. In addition, the increased specific heat ratio of rich mixtures also led to a low peak pressure. Compared with spark ignition, the peak pressure observed with laser ignition is approximately 12% higher at the equivalence ratio of 1.0, indicating that laser ignition could be more favorable for igniting a lean mixture. The differences in peak pressure reduced with increases of the equivalence ratio.

3.2.2 Impact of ignition energies on peak pressure

The peak pressures of gasoline-air mixtures at an equivalence ratio of 1.2 for laser ignition and spark under various ignition energies are shown in Fig. 7. The peak pressure remained almost unchanged with different ignition energies for both laser and spark ignition. These results are in good agreement with recent studies (Qin *et al.*, 2000; Weinrotter *et al.*, 2005b). Weinrotter *et al.* (2005a) studied hydrogen-air mixtures and concluded that there was no significant effect of laser pulse energies on the peak chamber pressure. Dharamshi *et al.* (2014) also observed that with the laser pulse energy increasing, the peak cylinder pressure remained almost the same.

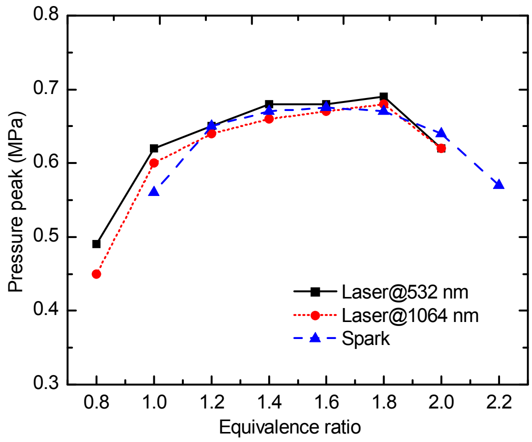

Fig. 6 Peak pressures for laser ignition and spark ignition under various equivalence ratios (ignition energy of 11–13 mJ)

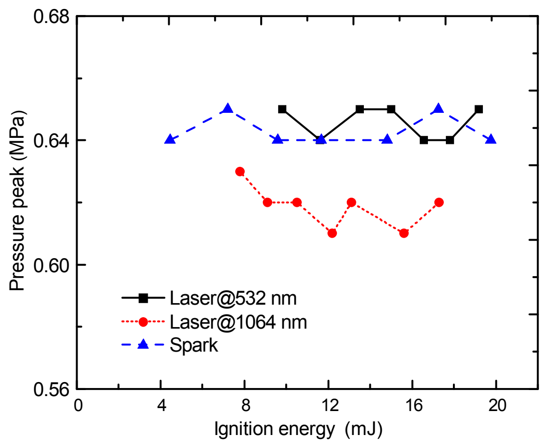

Fig. 7 Peak pressures vs. ignition energy for laser ignition and spark ignition (equivalence ratio of 1.2)

3.3 Heat release analysis

The heat release calculations of the gasoline-air mixture combustion in the chamber are based on laws of thermodynamics and in order to simplify the analysis, the following assumptions have to be made (Dharamshi *et al*., 2014):

1. The cylinder charge was considered an ideal gas;
2. Thermodynamic properties of combustible mixtures inside the combustion chamber were assumed to be uniform;
3. Dissociation of combustion products was neglected;
4. Heat transfer between the combustion chamber walls and mixtures during the combustion, which was less than 100 ms, was neglected;
5. It is assumed that the value of heat capacity ratio (γ) remains constant.

The heat release rate in the combustion chamber was calculated by (Dharamshi *et al*., 2014)

$$\frac{\mathrm{d}Q}{\mathrm{d}t}=\frac{1}{\gamma-1}V\frac{\mathrm{d}p}{\mathrm{d}t}+\frac{\gamma}{\gamma-1}p\frac{\mathrm{d}V}{\mathrm{d}t}, \tag{3}$$

where Q is the net heat release, t is the time, V is the volume of the combustion chamber, and p is the pressure. In this study, experiments were performed in a constant-volume combustion chamber; therefore the second term in Eq. (3) equals zero:

$$\frac{\mathrm{d}Q}{\mathrm{d}t}=\frac{1}{\gamma-1}V\frac{\mathrm{d}p}{\mathrm{d}t}. \tag{4}$$

The final equation for calculating net heat release is presented as

$$Q=\int_0^t\left(\frac{\mathrm{d}Q}{\mathrm{d}t}\right)\mathrm{d}t. \tag{5}$$

Fig. 8 shows net heat release vs. time for gasoline-air mixtures at the equivalence ratios of 1.0 and 2.0, and an ignition energy of 11–13 mJ.

As the volume of the combustion chamber is constant, the heat release depends on the pressure history. Consequently, the variation of heat release was in accordance with the variation of pressure history. Significant differences in slope of heat release indicate the variations in combustion duration (Srivastava *et al*., 2011). For lean mixtures, at an equivalence ratio of 1.0, the combustion duration in laser ignition was shorter than that in spark ignition.

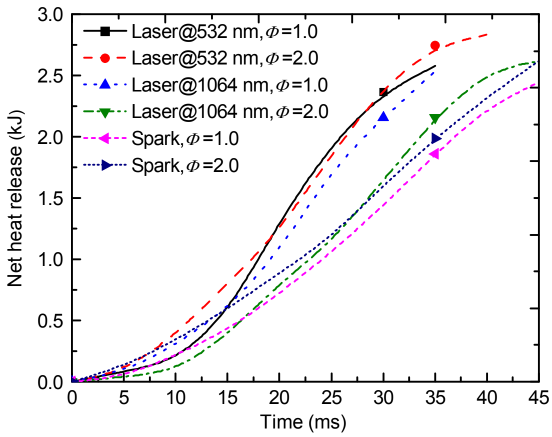

Fig. 8 Net heat release vs. time for gasoline-air mixtures ignited by laser and spark ignition (equivalence ratios of 1.0 and 2.0, and ignition energy of 11–13 mJ)

4 Conclusions

In this paper, the combustion of gasoline-air mixtures in a constant-volume combustion chamber with an initial condition of 0.1 MPa pressure and 363 K temperature was experimentally investigated with laser ignition generated by a Q-switched Nd:YAG laser (wavelengths of 532 and 1064 nm). The same experiments were also conducted with spark ignition, and the results were compared with those from laser ignition. The following conclusions can be drawn:

It was observed that the maximum pressure rise rate for laser ignition, at both wavelengths of 532 and 1064 nm, was obtained at an equivalence ratio of 1.8 and they were 39.4 and 38.8 MPa/μs, respectively. The maximum pressure rise rate for spark ignition was observed at an equivalence ratio of 1.6 and it was 38.1 MPa/μs. It was found that with leaner mixtures, such as the equivalence ratio of 1.2, combustion pressure for laser ignition also increased more rapidly compared with spark ignition. With laser ignition, the peak pressure rises at first and then decreases later with the increasing of the equivalence ratio for both the wavelengths of 532 and 1064 nm. The maximum peak pressure of both wavelengths was obtained at an equivalence ratio of 1.8; they were 0.68 and 0.67 MPa, respectively. The maximum peak pressure for spark ignition was obtained at an equivalence ratio of 1.6 and it was 0.67 MPa. Compared with spark ignition, the peak pressure generated by laser ignition increased by approximately 12% at the equivalence ratio of 1.0, and the differences in peak pressure reduced when the equivalence ratio was increased.

For laser and spark ignition, there was no significant effect of ignition energy on both peak pressure and pressure rise rate. The heat release rate in the combustion chamber was calculated, and the results show that the variation of heat release was in accordance with the variation of pressure history. For the leaner mixtures, at an equivalence ratio of 1.0, the combustion duration was shortened by laser ignition, which can lead to higher power output.

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中文概要

题 目：汽油激光诱导火花点火与电火花点火燃烧过程对比研究

目 的：激光诱导火花点火（简称激光点火）是取代传统的靠近缸壁的单点电火花点火以实现稀薄燃烧、提高热效率和改善排放的新型点火方式之一。本文通过对比分析两种点火方式在定容弹中的点火及燃烧过程的压力上升率、最大爆发压力及放热率为激光点火技术在内燃机中的应用提供设计过程的参考依据。

创新点：1. 同时进行两种点火方式的试验，保证对比研究的准确性；2. 激光点火采用 532 nm 和 1064 nm 波长的两种激光进行对比；3. 直接采用汽油进行研究。

方 法：通过记录不同当量比的汽油空气混合气在定容燃烧弹内激光点火（532 nm 和 1064 nm 波长）及电火花点火的燃烧过程压力变化：1. 对比分析三种点火情况的压力上升率和最大爆发压力；2. 通过公式计算，对比分析三种点火情况的放热率。

结 论：1. 532 nm 与 1064 nm 波长激光点火的压力上升率和最大爆发压力都在当量比为 1.8 时出现最大值，其中 532 nm 波长激光为 39.4 MPa/μs 和 0.68 MPa，1064 nm 波长激光为 38.8 MPa/μs 和 0.67 MPa；而电火花点火的压力上升率和最大爆发压力则在当量比为 1.6 时出现最大值，分别为 38.1 MPa/μs 和 0.67 MPa；2. 激光点火的稀燃极限相对电火花点火对应的当量比更小；3. 三种点火类型的放热率规律与压力上升率变化规律一致。

关键词：激光点火；电火花点火；压力上升率；最大爆发压力；放热率