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Laser-Induced Particle Jet and Its Ignition Application in Premixed Combustible Gases [*]

YANG Qian-Suo(杨乾锁)[**], LIU Chun(刘春), PENG Zhi-Min(彭志敏), ZHU Nai-Yi(竺乃宜)
Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190

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A hot particle jet is induced as a laser pulse from a free oscillated Nd:YAG laser focused on a coal target. The particle jet successfully initiates combustion in a premixed combustible gas consisting of hydrogen, oxygen, and air. The experiment reveals that the ionization of the particle jet is enhanced during the laser pulse. This characteristic is attributed to the electron cascade process and the ionization of the particles or molecules of the target. The initial free electrons, which are ablated from the coal target, are accelerated by the laser pulse through the inverse Bremsstrahlung process and then collide with the neutrals in the jet, causing the latter to be ionized.

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A laser-induced spark or breakdown results from the electron cascade effect, where the laser photons are absorbed by the electrons in the inverse Bremsstrahlung process (IBP), and the neutrals are ionized through their collision with these accelerated electrons.[1−4] A few free electrons are required as the seed electrons for the initiation of the process. In the laser-induced breakdown of the molecular gases, these free electrons are produced by the multi-photon ionization of the interaction between the target molecule and the laser photon. The laser photon energy in near infrared or visible wavelength is smaller than the ionization potential of most gases; hence the initial free electron is only produced by the multi-photon ionization.[2] Theoretical analyses and experimental results reveal that when a laser beam in the order higher than 10^{10} W/cm^2 interacts with a gas, multi-photon ionization occurs, and these initial free electrons are produced for the IBP.[2−4]

For a conventional Q-switched laser pulse, the laser beam's power is from 10^7 W to 10^9 W, and the radius of the focal spot can be smaller than 0.5 mm after the beam is focused. This irradiance is strong enough to lead the multi-photon ionization and to produce the free electron.[1,2] This type of laser is therefore usually used as the laser source for laser ignition experiments, and theoretical research is also commonly focused on the kinetic and dynamic mechanism of this ignition process.[4] However, it is impossible that the seed electrons cannot be produced by a continuum wave or a free oscillated laser beam through multi-photon ionization because the power level is much lower than the threshold of multi-photon ionization.[2−4] However, a laser beam with a lower power than the breakdown threshold can be utilized to produce plasma and spark through the IBP and the collision mentioned above because the initial free electrons are provided by another process, such as laser ablation.[5−7]

It is well known that when a powerful laser beam heats a solid target, surface vaporization at the heated area takes place and some hot particles, which contain neutrals, ions, and free electrons, are ablated from the target.[5] These free electrons are also the initial electrons for the IBP. In this Letter, we report on the experimental research for a laser-induced particle jet through the interaction between a coal target and a laser pulse. As the laser beam is focused onto a coal target, the particle jet is immediately produced. The jet contains some free electrons which will be then become seed electrons for the IBP. The experimental result reveals that the electron density in the particle jet increases, and a flame kernel finally forms as the jet expands during the laser pulse. Such a hot particle jet can successfully ignite the premixed combustible gas comprising hydrogen, oxygen, and air.

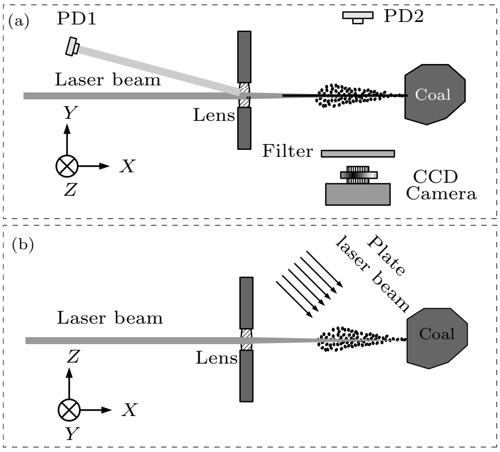

Fig. 1. Experimental setup for the laser-induced particle jet on (a) $X-Y$ plane and (b) $X-Z$ plane.

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[**] Email: qsyang@imech.ac.cn

Figure 1 shows the experimental setup of a laser-induced particle jet in the atmosphere environment where a cylinder coal block 1 cm in diameter and 1 cm long is the target. The laser pulses come from a free oscillated Nd:YAG laser, with each pulse having a maximum energy of about 300 mJ and a pulse duration of about 200 µs. The laser beam, which has a diameter of 6 mm, passes through the lens with a focus length of 100 mm. The beam is focused on the coal target and its surface has a focus spot approximately 0.5 mm or less in diameter. It can be calculated that the irradiance at the focal spot is much lower than the breakdown threshold of the air (about 10^{10} W/cm^2) for such a laser pulse. Therefore, actual breakdown in air does not occur for this device.[4]

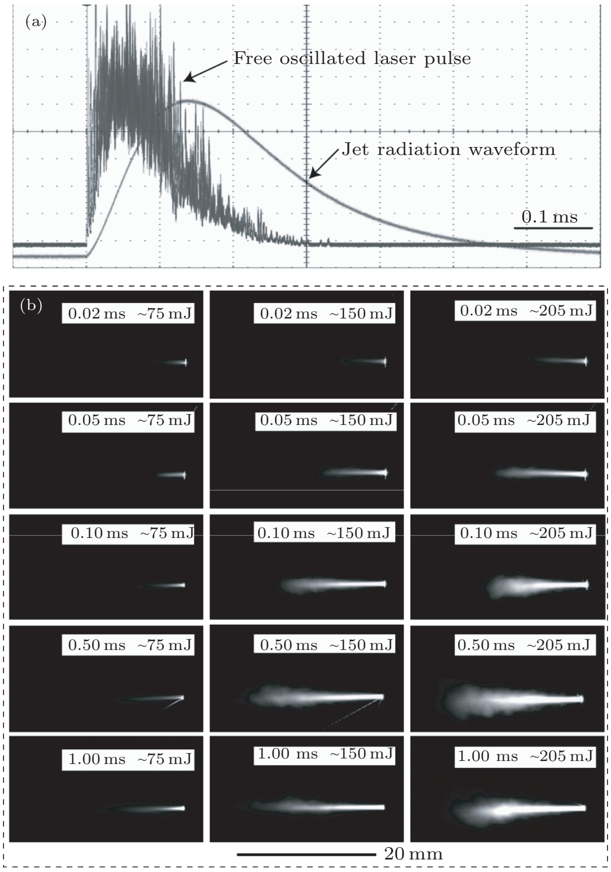

Fig. 2. (a) Waveforms of the laser pulse and radiation from the particle jet. (b) Images of the particle jet by planar laser beam scattering where the laser pulse energy is at 75 mJ, 150 mJ, and 205 mJ, and the exposure time is at 0.02 ms, 0.05 ms, 0.10 ms, 0.50 ms, and 1.00 ms, respectively.

Two photodiodes are used for the traces of the oscillated pulse and radiation from the particle jet shown in Fig. 1. The corresponding waveforms are recorded by a 200 MHz digital storage oscilloscope (Tektronix TDS 2024B), where the light entering one of the photodiodes comes from the reflection of the laser beam on the surface of the lens. The detection direction of the other photodiode for the radiation of the hot particle jet is perpendicular to the laser beam, as shown in Fig. 1. A planar laser beam with a wavelength of 532 nm passes through the jet's axis to irradiate the particles in the jet. The scattering light of the particles on the beam plane is recorded by a CCD camera, the front of which is covered by a narrow-band filter with a center-wavelength of 532 nm. The camera forms two-dimensional distribution images of the particles.

The waveforms of the free oscillation laser pulse and the particle jet radiation are displayed in Fig. 2(a). For the laser pulse, the waveforms consist of many relaxation oscillated pulses with a duration of about 1 µs and a rising time shorter than that of the jet radiation. Moreover, the duration of the latter is longer than that of the former, although they appear almost simultaneously. The experimental result also reveals that the trace profile and the strength of the jet radiation do not depend on the ambient pressure around the laser-induced particle jet above. Since this experiment is set up in a closed device, the radiation's waveform and the strength of the jet do not change, when the pressure of the device is gradually reduced from the atmosphere to 100 Pa. This means that the radiation comes only from the interaction of the laser light with the coal target and, therefore it is the coal molecules that dominate the collision between the accelerated electron by the laser photon and the neutrals, not the air molecules.

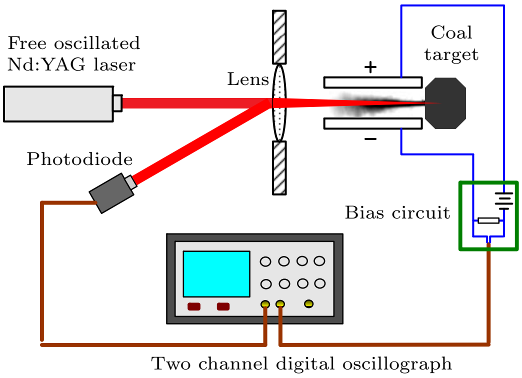

Fig. 3. Experimental setup of the ionization of a laser-induced particle jet.

Figure 2(b) shows images of the particle distribution of the jets obtained by the CCD camera as a result of the particle scattering light on the light beam plane. The energy of the laser pulse and the exposure time of the CCD camera are taken as 75 mJ, 150 mJ, and 205 mJ; and 0.02 ms, 0.05 ms, 0.1 ms, 0.5 ms, and 1 ms, respectively. From the images shown in Fig. 2(b), it can be found that the sizes of the particle jet are directly proportional to the laser energy. Moreover, the velocities of the particle rapidly decrease as they move away from the target. From the image with an exposure of 0.02 ms and a laser energy of 205 mJ in Fig. 2(b), it is calculated that the average velocity of the particle jet is about 450 m/s. In the following images with exposures of 0.05 ms and 0.1 ms, the average velocity decreases to 327 m/s and 182 m/s, respectively. The image with an exposure of 0.1 ms is slightly larger than the one with an exposure of 0.5 ms. For the same laser energy, in Fig. 2(b), the image with an exposure of 0.5 ms has almost the same length as that with an exposure of 1 ms. On the other hand, the transverse size of the particle jet gradually increases with the decrease in particle velocity, which is attributed to the diffusion of the particles.

For the sake of the particle jet's ionization, another experiment is designed as shown in Fig. 3. In front of the coal target, two pieces of aluminum foils are placed 2 mm apart and are utilized as the anode and the electrode for the detection of jet ionization. In the bias circuit for the detection, a 9 V battery and a 1 kΩ resistance are used as the electric source and the load resistance, respectively, as shown in Fig. 3. Like the experimental device shown in Fig. 1, the traces of jet ionization and the laser pulse are simultaneously recorded by a 200 MHz digital storage oscilloscope (Tektronix TDS 2024B). From the bias circuit, it is seen that the signal of the ionization detection is directly proportional to the electron density in the particle jet.

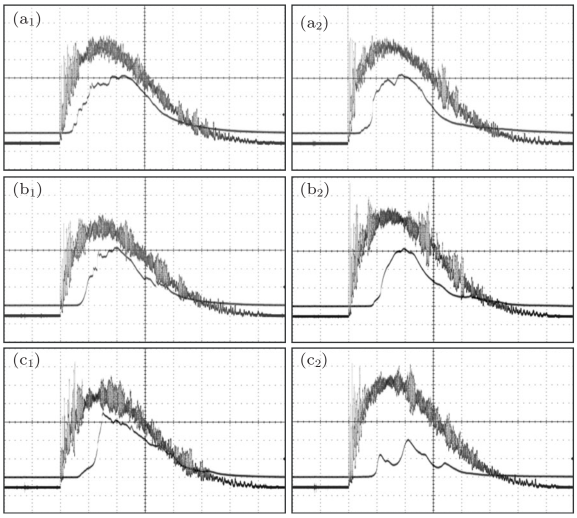

Fig. 4. Traces of the laser pulse and the ionization signal of the particle jet where (a_1) and (a_2) are the first time for the laser-induced particle jet at a position on the surface of the coal target; (b_1) and (b_2) are the second time; and (c_1) and (c_2) are the third.

Figure 4 shows the waveforms of the jet ionization as well as the laser pulses, where the energy for a laser pulse is about 200 mJ. The experiment indicates that ionization phenomena are gradually observed after the laser pulse heats the coal target. Furthermore, it is shown that the ionization signal decreases as the laser pulse gradually disappears. Therefore, the duration of the ionization signal is shorter than that of the pulse. On the other hand, ionization for the first irradiance is strongest at a fixed position on the target surface. As illustrated in Fig. 4, the peak of the ionization signal gradually decreases as the time of the laser irradiance on the same position increases. After several instances of laser irradiance on the target, a cavity gradually forms on the focal spot due to ablation. The experiments also reveal that the cavity restrains the ablation of the particles at the beginning, but the particles from the target finally tend toward a constant density after many laser-induced particle jets are focused on a fixed position.

From the experimental results in Figs. 2 and 4, it is obvious that the expansion of the particle jet and the ionization process all depend on the laser pulse because the two processes disappear as the laser pulse ceases. Based on the results above, a mechanism is introduced for the interaction of the free oscillated laser pulse with the coal target. After a point on the target is rapidly heated by the focused laser pulse, surface vaporization takes place, some particles are ablated from the target, and a particle jet forms. There are a few free electrons in the jet due to its high temperature ($> 10^3$ K).[5−7] However, the electron density is much lower than 10^7–10^8 cm^{-3} and also lower than the detection level in our device. These electrons absorb the laser photons through the IBP and are accelerated. The collision between them and the particles results in the ionization of these target neutrals, the occurrence of an electron cascade, and, finally the appearance of a flame kernel. Therefore, the ionization of the jet gradually increases after the particle jet forms. However, after the laser power decreases to a certain level, the increasing electron density due to the electron cascade process no longer compensates for the recombination of the free electron with the ions or the positive particle. Therefore, in the experiments shown in Figs. 2 and 3, it is seen that the ionization signal ends earlier than the laser pulse.

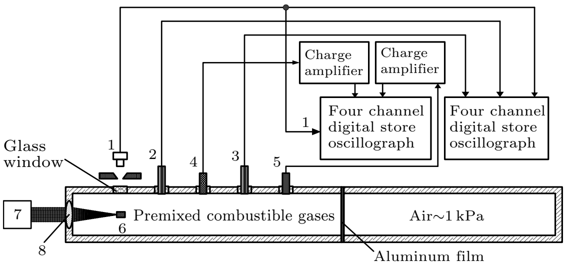

Fig. 5. Experimental setup of the initiation of the premixed combustible gas with a laser-induced particle jet: (1) photodiode, (2,3) ion probes, (4,5) pressure transducers, (6) coal target, (7) free oscillated Nd:YAG laser, (8) focal lens.

As is carried out by a spark induced using a conventional Q-switched laser pulse, the particle jet is able to initiate the combustion of some premixed combustible gases. The experiment points out that a premixed gas consisting of hydrogen, oxygen, and air can be ignited by such a laser-induced particle jet. Under a certain condition, the combustion wave evolves into the detonation wave after it propagates a certain distance. The experimental setup for this is shown in Fig. 5.

The interior diameter and the length of the combustion tube are 5 cm and 71 cm, respectively. The left end is closed and a lens with a focus length of 100 mm is inserted into the wall. As the target, a cylinder coal block 1 cm in diameter and 1 cm in length is fixed at the focus point of the lens in the combustion tube. The right end is also closed by an aluminum film 0.2 mm in thickness. On the right side of the film, a tube of 5 cm in diameter and 1.5 m in length is used as a buffer for the high pressure caused by the reflection of the pressure wave, where the buffer is vacuumed to about 1 kPa in advance. The film will be broken as the pressure wave acts on it. The radiation of the focus point (i.e., the ignition point) is monitored by a photodiode with a response wavelength range of 0.3–1.8 μm. Two pressure transducers are used to record the pressure traces at two points with a distance of 30 mm, and the ionization levels are also recorded by two ion probes with a distance of 30 cm. The distances from the ignition point to the first ion probe and the first transducer are 8 cm and 18 cm, respectively, as shown in Fig. 5. Two four-channel digital storage oscilloscopes (Tektronix TDS 2024B, 200 MHz) are used to record the signals from the ion probes, the transducers, and the radiation at the ignition point. The signals from the transducers enter two charge amplifiers and are then recorded by one of the oscilloscopes. Another channel is used for the radiation's waveform at the ignition point. The other oscilloscope is for the waveforms of the ionization and the radiation at the ignition point. The laser pulse is from the same free oscillated Nd:YAG laser used in the experiments shown in Figs. 1 and 3.

Figure 6(a) shows the waveforms of the two pressure signals where the combustible gases are premixed using 60 kPa hydrogen, 30 kPa oxygen, and 40 kPa air. From the pressure traces, it can be deduced that the reaction in the positions at the two transducers is a combustion process.[8] As the ratio of air in the premixed gases is decreased, the reaction processes at the second ion probe and pressure transducer transit into the detonation, although the processes at the first ion probe and pressure transducer are still conventional combustion. Figure 6(b) shows the waveforms of the pressure transducer, the ion probes, and the radiation at the ignition point where the combustible gas is premixed using 70 kPa hydrogen, 35 kPa oxygen, and 10 kPa air. It is obvious that the waveform of the second transducer is a typical detonation trace.[8] Therefore, as shown in the inset in Fig. 6(b), the rising time of the corresponding ionization signal for detonation is shorter than that of combustion, while its amplitude is higher than that of combustion. The experiments also reveal that the pulse energy for a successful ignition by this type of laser-induced particle jet is as low as 35 mJ. In addition, the ignition delay time only decreases as the pulse energy increases, and the longest one for the lowest ignition energy almost equals the pulse duration, which means that ignition occurs as the laser pulse ends.

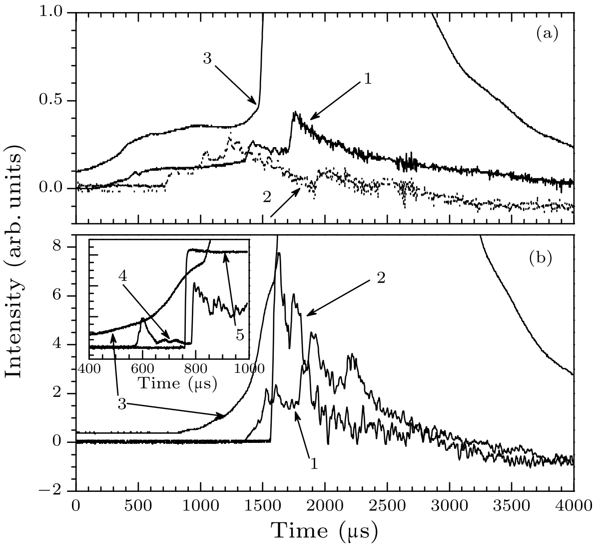

Fig. 6. Pressure evolution of the combustion of the premixed gas in which the pressures of hydrogen, oxygen, and air are (a) 60 kPa, 30 kPa, and 40 kPa; and (b) 70 kPa, 35 kPa, and 10 kPa, respectively. The inset in (b) shows the ionization signals. Curves 1 and 2 are the waveforms of the two pressure transducers; curve 3 is the radiation from the ignition point; and curves 4 and 5 are the ionization signals from the two ionization detectors, respectively.

In summary, a hot particle jet can be induced from a target by a free oscillated laser pulse and free electrons in the jet, which act as seed electrons for the IBP. Having absorbed the laser photons in the IBP, these electrons are accelerated. The collisions between the electrons and the target neutrals result in an electron cascade and an enhanced ionization level of the jet. Such a hot and ionized particle jet can ignite some premixed combustible gases.

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