The effect of the ignition energy and mixture energy density on the detonation onset in internal combustion engines

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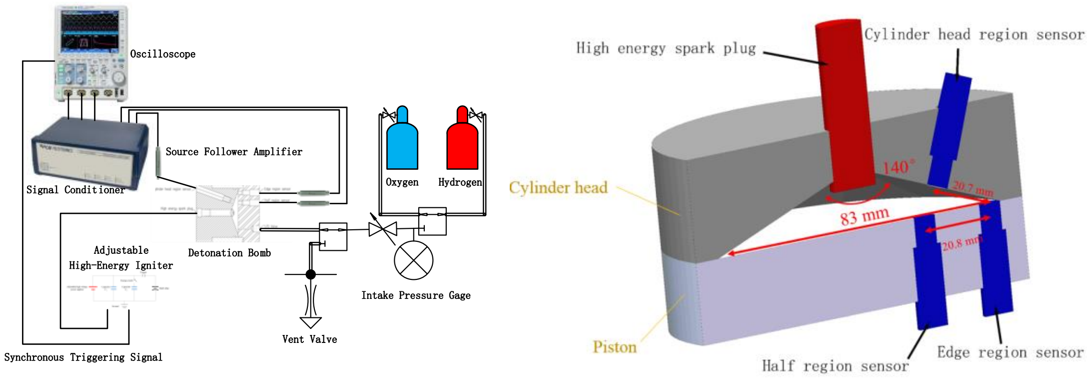
1 Introduction

Based on the thermodynamic principle, increasing the compression ratio is an efficient way to increase the thermal efficiency of IC (internal combustion) engines. However, with the further increase of the compression ratio, super knock would occur that potentially can destroy engines rapidly [1,2]. Based on previous researches, the super knock is usually caused by the onset of a detonation wave [3–6]. In order to suppress the super knock, exploration of the detonation onset in IC engines is significant. Bates et al. [7] found that the hot spot reactivity ε and the temperature gradient near the hot spot ξ could determine the detonation onset in IC engines. Robert et al. [8] considered the shock wave generated by the deflagration as an important factor affecting the detonation onset in IC engines. Bradley et al. [9] found that the increase of the turbulence would strengthen the leading shock wave and thus facilitate the onset of detonation. Pan et al. [10] found that the pressure wave disturbance would affect the end-gas auto-ignition mode and thus determine the formation of a detonation in IC engines. Our recent research [11] found that the interaction between the shock wave and flame front would determine the detonation onset in IC engines. According to these researches, it can be seen that the shock wave and the flame front are two main factors that determine the detonation onset. The present research found that the ignition energy would determine the shock wave intensity and the mixture energy density would determine the heat release of the flame front. Consequently, the ignition energy and the mixture energy density would determine the detonation onset as well as the super knock in IC engines.

2 Experimental Setup

The system of the DBD (detonation bomb device) experimental setup is shown in Figure 1 (a). Briefly, there are four parts in the DBD system: separately the detonation bomb, the intake-outlet system, the variable high-energy ignition system and the signal acquisition/processing system. The detailed information can refer to the previous research [1]. The structure of the detonation bomb is shown in Figure 1 (b). The cylinder bore is 83 mm and the angle of the cylinder head is 140°. The clearance of the chamber is 0 mm, which represents the end of the compression stroke when the piston is at the top dead center. A high-energy spark plug is installed in the center of the chamber. Charging and discharging of the gas is through the I/O valve on the piston side. Three pressure sensors were flushed installed in different positions of the DBD chamber. Two of them were installed on the piston side, separately the edge region and the half region of the piston. One of them was installed in the cylinder head, mimicking the way that pressure sensor installed in real IC engines. The resonant frequency of these pressure sensors is more than 500 kHz and the rise time is shorter than 1 μs. The sample frequency of the acquisition system is as high as 250 MHz for each channel, which could guarantee the capture of the shock wave behavior and the detonation formation process.



(a) The experimental system (b) The Cross-section of the detonation bomb

Figure 1: The system of the detonation bomb device.

A deflagration is produced by a high-energy spark ignition. With the ignition of the high-energy spark plug, a rapid chemical reaction would occur which results in a high-speed combustion. Besides, the instantaneous large energy release of the ignition would produce a shock wave as a leading shock wave of the high-speed combustion. Therefore, the high-speed combustion and the leading shock wave together constitute a deflagration. With the increase of the spark ignition energy, the shock wave intensity would be increased and the leading shock wave would be stronger [12]. In this research, the leading shock wave is the main factor affecting the detonation onset. The method to change the spark ignition energy is to change the number of the capacitors in the high-energy spark ignition system. The energy switch would determine the number of the capacitor in the system. The system with two capacitors would contain more energy than that with only one capacitor ($E=1/2CV^2$). The voltage of the power supply is fixed to 5 kV and each capacitor has a capacitance of 2 μF. Two capacitors are used in the high-intensity spark ignition and thus 4 μF capacitance is contained in the ignition system to store the total energy of 50 J; one capacitor is used in the low-intensity spark ignition and thus 2 μF capacitance is contained in the ignition system to store the total energy of 25 J. Thus, according to the above theory, the effect of the ignition energy on the detonation formation can be explored.

One thing needs to be emphasized is that different ignition energies would result in the leading shock wave with different intensities, and the initial leading shock wave is an essential condition for the occurrence of the engine knock. In this experiment, the knock is induced by the spark ignition. However, the engine knock could also be caused by other different reasons. For instance, the pre-ignition of the hot spots, the auto-ignition of the end gas, the flame accelerated to the deflagration and so on can all cause the engine knock. Frankly speaking, it is hard to mimic all the situations mentioned above. Among these causes of formation, the initial leading shock wave caused by the auto-ignition, flame acceleration or the deflagration is the essential factor for the occurrence of the engine knock. Therefore, in this research, the initial leading shock wave caused by the above diverse factors is represented by the shock wave caused by a high-energy spark ignition. Furthermore, different intensities of the auto-ignition, flame acceleration or deflagration would result in the initial shock wave with different intensities. Such shock wave with different intensities is realized by the high-energy spark ignition with different energies in this research, which may result in a super knock, heavy knock, mild knock or non-knock. It depends on the interactions between the shock wave and the flame front, which may intensify the initial shock wave to a high level to form a knock or even a high-intensity knock as researched below.

The mixture of hydrogen and oxygen was used in the DBD experiments. There are two reasons why the hydrogen was used in the experiments as the fuel. The first reason is that the hydrogen is a widely used alternative fuel in IC engines, which also involves the heavy knock problem when it works in a high load operation condition [13]. The other reason is that the detailed chemical reaction mechanism for H_2/O_2 has been thoroughly revealed, while the size of the reaction mechanism is also acceptable for numerical simulations. The reason for the use of oxygen instead of air is listed as below. Air can be regarded as the nitrogen diluted oxygen. Based on previous researches, fuel with diluted oxygen needs a higher pressure for the detonation initiation [14]. In other words, the mixture of hydrogen and nitrogen diluted oxygen (air) needs a higher in-cylinder pressure for the detonation onset than the mixture of hydrogen and pure oxygen [15]. In order to obtain the detonation onset phenomenon, the in-cylinder pressure of H_2/Air should be increased to a higher level than that of H_2/O_2. It is dangerous to conduct DBD experiments at such a high pressure. Therefore, the stoichiometric mixture of H_2/O_2 was used in the DBD experiments. However, the mechanism that the ignition energy and in-cylinder pressure affect the detonation onset would be the same by using H_2/O_2 or H_2/Air. The difference would be that the critical pressure of H_2/Air is higher than that of H_2/O_2. Therefore, the critical pressure obtained in this DBD experiment cannot be directly applied in IC engines that use the mixture of H_2/Air. The critical in-cylinder pressure of the H_2/Air used in IC engines should be higher. However, the effect mechanism obtained from this research could be applied in the knock of IC engines.

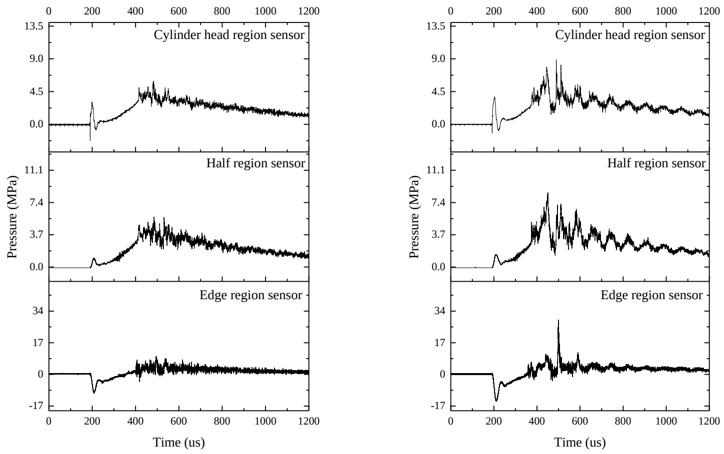
Both the hydrogen and oxygen used are in the ultra-high purity grade (>99.999%) and they were charged into the DBD by the method of partial pressures to realize the stoichiometric equivalence ratio. The experiments were conducted at the in-cylinder temperature of 298 K and the in-cylinder pressure of 0.18 MPa, 0.54 MPa and 0.9 MPa separately to represent different mixture energy densities. The mixture energy density can be defined as the amount of chemical energy released per unit volume: $E_s = H_{low} \cdot n/V$, where the E_s is the mixture energy density (kJ/m^3); H_{low} is the lower heat value of the fuel (kJ/mole); n is the mole number of the fuel (mole); V is the volume of the chamber (m^3) [16]. Based on this equation, the mixture energy density is separately 11647 kJ/m^3, 34927 kJ/m^3, 58167 kJ/m^3 corresponding to the in-cylinder pressure of 0.18 MPa, 0.54 MPa and 0.9 MPa.

3 Results and Discussion

In this section, the DBD experimental results would be presented. Firstly, the results obtained from the critical pressure 0.54 MPa would be presented, in which the ignition energy would determine the detonation onset of the end gas. Then the results obtained from the subcritical (0.18 MPa) and supercritical pressure (0.9 MPa) would be presented separately, in which the detonation onset of the end gas would not be affected by the ignition energy but determined by the mixture energy density.

3.1 Results obtained at the critical pressure

The experimental results for low and high ignition energy are separately presented in Figure 2. There are some characteristics and rules that can be obtained from Figure 2, which are listed as below. Firstly, as shown in Figure 2 (a) and (b), there is always a pressure peak at 200 μs in experiments, which is caused by the electromagnetic interference of a high-energy spark discharge. Such pressure peak could represent the beginning of the deflagration. Secondly, there would always be a huge pressure peak in the edge region in the high ignition energy case (Figure 2 (b)), while no such huge pressure peak would occur in the edge region in the low ignition energy case (Figure 2 (a)). Such huge pressure peak is caused by the detonation onset in the end gas. Finally, the pressure oscillating amplitudes in the high ignition energy case (approximately with Δp of 7 MPa in the cylinder head region and the half region as shown in Figure 2 (b)) are always higher than that in the low ignition energy case (approximately with Δp of 3 MPa in the cylinder head region and the half region as shown in Figure 2 (a)).

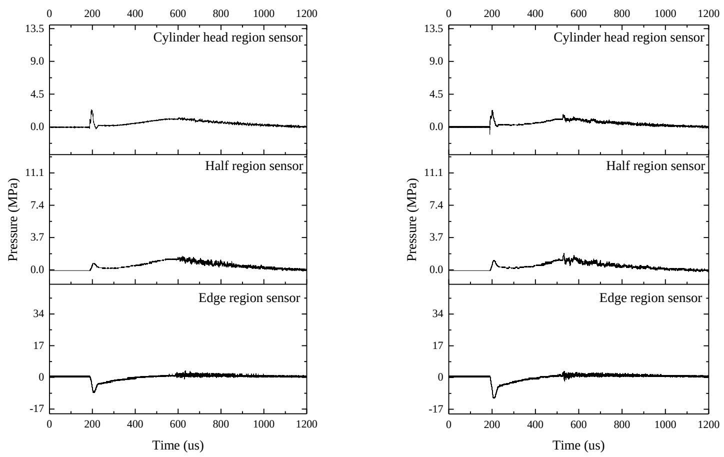


(a) Low ignition energy experimental results (b) High ignition energy experimental results

Figure 2: Pressure profiles obtained from the critical pressure 0.54 MPa (mixture energy density is 34927 kJ/m^3).

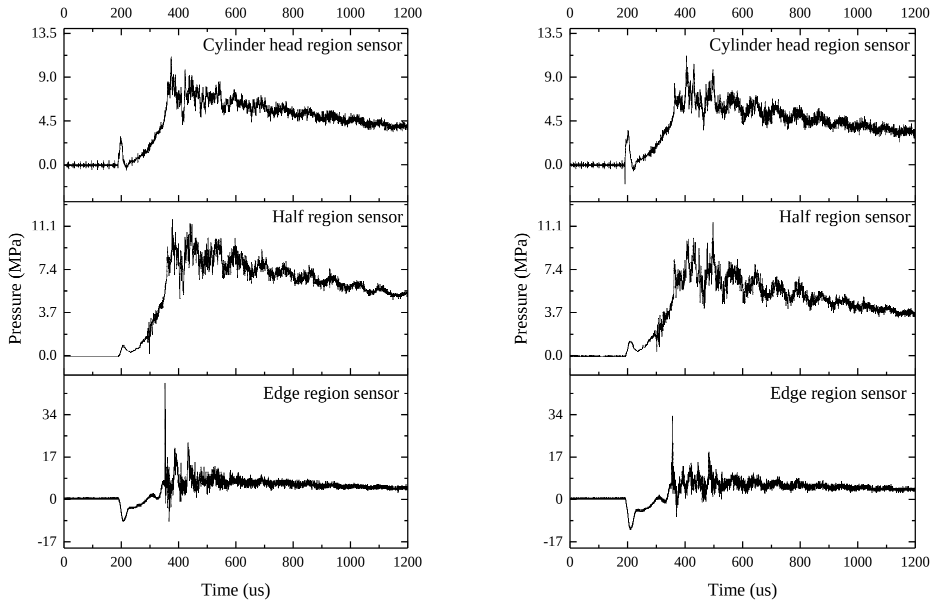
3.2 Results obtained at the subcritical and supercritical pressures

Figure 3 and Figure 4 are the experimental pressure profiles separately obtained at the subcritical and supercritical pressures. It can be seen that, despite the energy of the ignition, the detonation always occurs at the supercritical pressure cases, while it does not occur at the subcritical pressure cases. Therefore, only mild pressure oscillations occur in the subcritical case, while severe pressure oscillations are formed in the supercritical case, which also indicates that only mild knock would occur in the subcritical case while super knock would be formed in the supercritical case once the deflagration occurs. Such finding also explains the phenomenon that the super knock frequently occurs in the situation that IC engines are further downsized, while only the conventional mild knock would occur in traditional IC engines. Further downsizing of IC engines would result in a higher compression ratio and a higher boost pressure, which would lead to a higher in-cylinder pressure as well as a higher mixture energy density on top dead center. Once the in-cylinder pressure before the ignition exceeds the critical pressure, detonation as well as the super knock would easily occur once a deflagration is formed.



(a) Low ignition energy experimental results (b) High ignition energy experimental results

Figure 3: Pressure profiles obtained at the subcritical pressure 0.18 MPa (mixture energy density is 11647 kJ/m^3).



(a) Low ignition energy experimental results (b) High ignition energy experimental results

Figure 4: Pressure profiles obtained at the supercritical pressure 0.9 Mpa (mixture energy density is 58167 kJ/m^3).

4 Conclusion

Self-designed detonation bomb experiments were conducted to explore the effect of the ignition energy and mixture energy density on the detonation onset problem in IC engines. It is found that irrespective of the low or high ignition energy, the super knock as well as the detonation would not occur at the lower pressure (lower mixture energy density), and only mild knock occurs. At the medium pressure (medium mixture energy density), the high ignition energy would result in a detonation wave, while the low ignition energy would not. At the higher pressure (higher mixture energy density), despite the energy of ignition, a detonation wave as well as a super knock would always occur. Therefore, the ignition energy and the mixture energy density are two essential factors that affect the detonation onset and the knock intensity of engines.

5 Acknowledgement

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