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Pressure Oscillations Generated by Knocking Combustion of C_2H_2 in a Constant Volume Vessel

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Abstract. Onset of super-knock in highly intensified spark ignition engines poses a great threat to the reliability. In this context, An approaching attempt was exerted on the initial condition of C_2H_2-O_2-N_2 mixtures ignited within a constant volume vessel, in order to determine the critical condition of knock and response to oxygen ratio, acetylene ratio and mixture density. Results show that with a low acetylene content, sole elevation of oxygen doesn't necessarily lead to knock onset. On the other hand, with oxygen content fixed to a sufficient value, elevation of acetylene content results in louder combustion noise and when it approaches the stoichiometry ratio, auto-ignition happens in the unburnt far end and strong oscillation appears on the combustion pressure curve. Surprisingly, elevation of mixture density has no significant effect on knock propensity.

Introduction

Downsizing is an effective strategy for gasoline engines to reduce fuel consumption and CO_2 emission. In the approach to downsizing, turbocharge and direct injection are commonly reckoned to be the most important techniques. However, application of them exerts a greater knock risk on the engines and moreover a new abnormal combustion phenomenon, namely super knock, which is even more devastating, stochastically occurs. Super knock usually happens before the spark ignition, which drives researchers to relate it to pre-ignition. Therefore, endeavors were made to dig the cause of pre-ignition[1-4]. On the other hand, although preignition is reckoned to be the indicator, it actually doesn't necessarily result in super knock. Regarding this, the transformation of deflagration to detonation is speculated by many researchers to be the key point.

In this context, acetylene was ignited within a constant volume vessel for knock research due to its high knock tendency and gaseous nature convenient for mixture preparation. An approaching attempt was exerted on the initial condition of C_2H_2-O_2-N_2 mixtures in order to determine the critical condition of knock and response to oxygen ratio, acetylene ratio and mixture density. During the experiment, pressure profile and combustion images were simultaneously recorded to observe pressure waves generated in the vessel.

Experimental setup and conditions

Experiments were performed in a constant volume vessel with gas pressure and vessel temperature accurately controlled. The inner chamber is generally a 136*136*136 mm^3 cubic structure with two opposite mounted 130mm diameter quartz windows to enable optical access for shadowgraph imaging. Schematic of the vessel and its affiliated devices is shown in Figure 1. Principles of the experimental setup has been described in detail by Huang in [5]. In this experiment, temperature of the vessel body was kept 383K to prevent vapor condensation. Flame images were captured by the CCD camera (model MotionPro Y4-S1) with a resolution of 608*592@10000fps which resulted in a ratio scale of 0.204mm/pixel. Moreover, the image recording was synchronized with the measurement of pressure history in the chamber by a piezocrystal sensor (model Kistler 6052C). The sampling frequency was kept at 100 kHz to capture pressure oscillations.

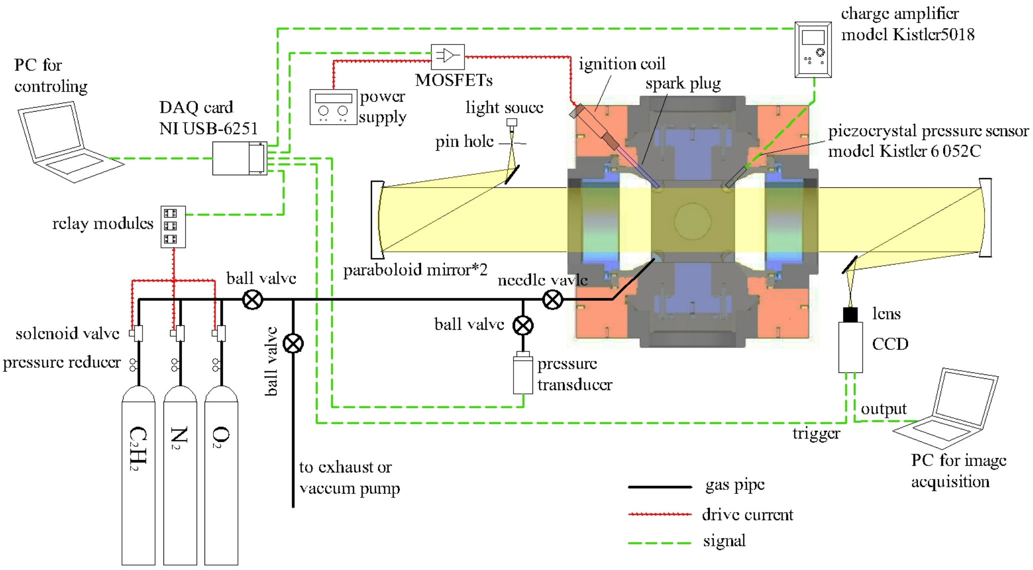

Figure 1. Schematic of the experimental setup

Before each trial, C_2H_2, N2, O2 were charged into the chamber in turn. The pressure transducer mounted next to the chamber monitored the gas pressure during the gas filling process. Coupled with solenoid valves, gas pressure in the chamber could be precisely controlled. In terms of different cases, the overall target charging pressure was calculate on the basis of the ideal gas equation, according to the target charging density and the temperature of the chamber body. Then partial pressures of three gases were determined according to their target concentration. In the end, target charging pressures of component gases could be confirmed according to their filling order.

Onset of knocking is closely related to the structure and size of the combustion chamber. Therefore, before the experiment was conducted, the criteria for knock onset was unknown. In case of danger caused by knocking combustion, tests started from a relatively safe condition (10% O_2, 5% C_2H_2, 7.5kg/m^3 ambient density), then concentration of O_2, C_2H_2 and ambient density were progressively increased in turn with every condition repeated 5 times. Detailed parameters of these tested conditions are shown in table 1.

Table 1. Tested conditions

Parameter	Target Conditions
O_2 Ratio /%	10%，12.5%，15%，*21%*
C_2H_2 Ratio /%	4%，*5%*，5.5%，6%，*6.5%*，7%
Density /(kg/m^3)	*7.5*，10，12.5，15

Results and discussion

In the experiment, the combustion process of C_2H_2 was observed by means of both dynamic pressure acquisition and shadowgraph visualization. Oscillations on the pressure curves directly proves onsets of knocking, while flame images helps to figure out the difference between normal and knocking combustion.

Pressure curves of the combustion process were manipulated as shown in figure 2. The raw pressure curve minus smoothed curve acquired through Savitzky-Golay method equaled to pure oscillation curve. It could be seen that except for dramatic fluctuations caused by knock in a certain period, slight ones (called noise fluctuations) also existed in the rest time. However, these noise fluctuations were in a narrow range within 0.4 bar, which were confirmed to be the system error of the measuring circuit basing on the noise frequency. It is reasonable to set 0.6 bar (1.5 times of 0.4 bar) as the criteria of knocking onset.

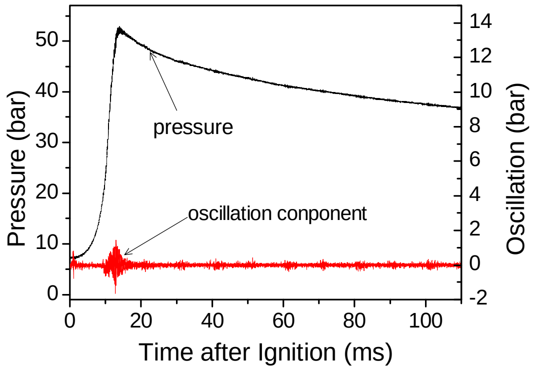

Figure 2. Extraction of pressure oscillations

Knock reponse to O_2 concentration

Experiments with O_2 concentration increased from 10% to 21% under the condition of 7.5 ambient density and 5% C_2H_2 ratio were conducted first. Pressure curves were shown in figure 3.

It could be seen from figure 3 that the peak and the clambing speed of pressure became faster as O_2 proportion increased. What drew attention was that cooling parts of pressure curves under 15% and 21% O_2 conditions almost coincided with each other, while ones under lower O_2 concentrations were quite different. It should be noted that 5% C2H2 needs 12.5% O_2 to complete combustion. Considering the gases seperation effect caused by density difference, more than 12.5% O_2 was necessary for perfect, non-soot combustion. In another word, combustion under conditions with O_2 proportion lower than 12.5% might suffer O_2 insufficiency. Images of these two cases showed that flames developed into anomalous shapes, which were quite diifferent from spherical flames in higher O_2 concentration conditions. Also, residual soot was found in the chamber after the experiment under conditions with O_2 lower than 12.5%.

On the other hand, no knock oscillations were found in any cases of this part, even when O_2/N_2 ratio was higher than that in air. Further increasing O_2 concentration would be meaningless. In cases hereafter, O_2 ratio was fixed on 21%, maintaining the equivalent air/fuel ratio much higher than 1 to minimize the impact of O_2 ratio on knock onset.

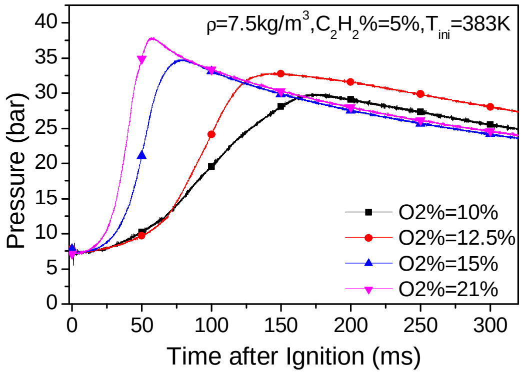

Figure 3. Combustion pressure at different O_2 concentreations

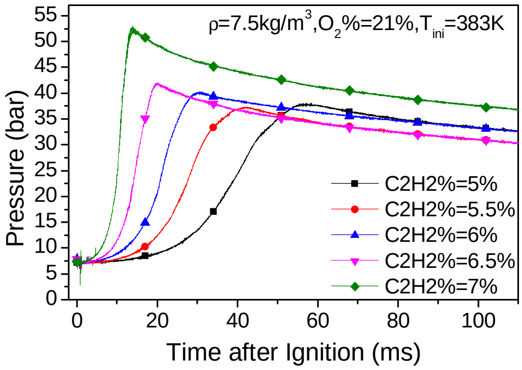

Figure 4. Combustion pressure at different C_2H_2 concentreations

Knock response to C_2H_2 concentration

Figure 4 shows pressure curves of cases in which concentration of C_2H_2 ranges between 5%~7% with 7.5 kg/m^3 mixture density and 21% O_2 concentration. In the experiment, the filling ratio of C_2H_2

increased from 5% to 7% with steps of 0.5%. However, pressure oscillation didn't happen until C2H2 ratio reached 7% when obvious fluctuations and a much greater pressure rise were observed on the pressure curve. Besides, combustion noise by ear definitely augmented with the increasing of C_2H_2 ratio.

Figure 5 compares combustion images of 5% C_2H_2 (A~E) and 7% C_2H_2 (F~J) concentrations in the same time series. Auto-ignition could be observed in image I, when the flame front stood still and became thicker. Image in the end gas region became fuzzy, implying the photography tailing effect caused by quick movements of the pressure wave front. At the meantime, pixel overexposure happened in the burnt region.

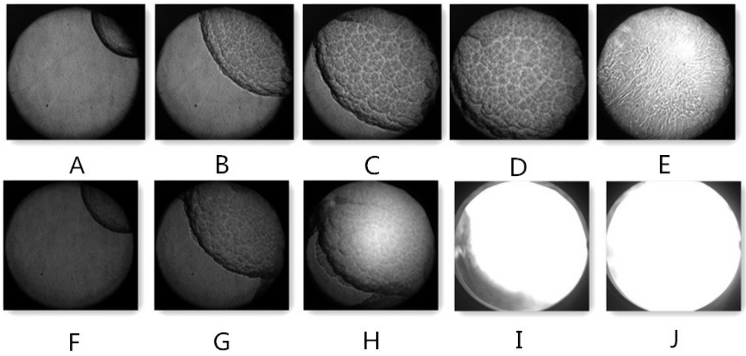

Figure 5. Flame images of normal and knock combustion

Knock response to mixture density

It has been stated before that, when O_2 is excessive, further increasing its concentration wouldn't lead to knocking onset, while raising C_2H_2 concentration would significantly augment combustion noise and when to an extent finally lead to knock. In order to evaluate the influence of mixture density on knocking, the minimum C_2H_2 concentration for knocking onset was determined by means of sweep tests. In terms of each mixture density, O_2 concentraion was fixed at 21%, and C_2H_2 concentration was elevated 0.5% every test from 5% on until pressure oscillations was observed on the combustion pressure curve.

Results showed that, when the mixture density was between 7.5~12.5 kg/m^3, no obvious pressure oscillation was observed until C_2H_2 concentration reached 7%. Even in 15 kg/m3 density conditions, the minimum C_2H_2 concentration for knock onset was found to be 6.5%. Therefore it is reasonable to reckon that elevation of mixture density doesn't necessarily increase knock tendency.

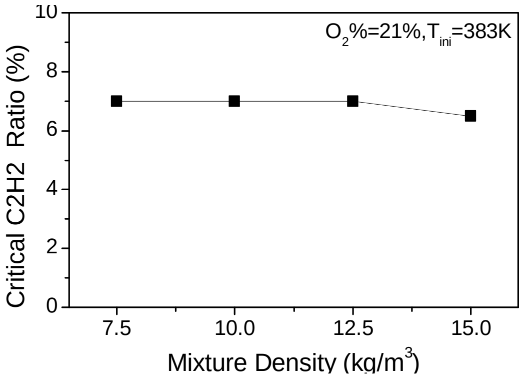

Figure 6. Critial C_2H_2 ratio for knock onset at different mixture densities

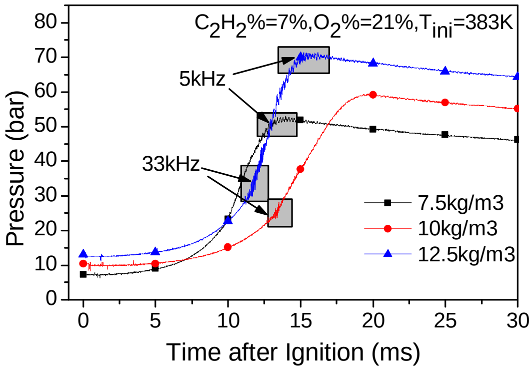

Figure 7. Oscillating pressure profile at different mixture densities

Although the minimum C_2H_2 concentration for knock onset was always 7% in different density conditions, phenomena of these knock cases were different. To demonstrate the difference, pressure profiles of knock cases with different mixture densities are put together in figure 7. While at all three densities oscillations occur, the occurrence time are distinct. At 7.5kg/m^3, oscillation occurs near the pressure peak, while at higher densities, it occurs in the pressure rising stage. Particularly, at 12.5kg/m^3, oscillations occurs in both the former two stages. In partially enlarged view, frequency of the oscillation at the rising stage is figured out to be 33 kHz and one at the peak stage 5 kHz. To analyze the difference between the two frequencies, knock images of 7.5kg/m^3 and 12.5kg/m^3 are put together in figure 8.

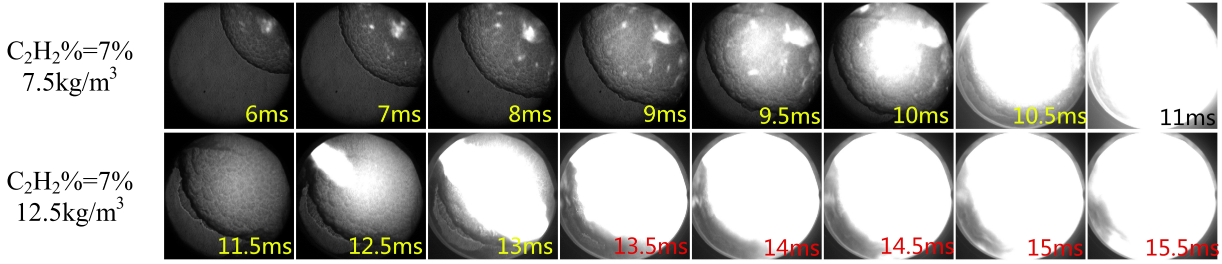

Figure 8. Flame images of knocking onset at 7.5kg/m^3 and 12.5kg/m^3

In figure 8, at both two densities, auto-ignition happens when the flame front approaches the far end, which corresponds to pressure oscillations in the peak stage. Other than this, in images of 12.5kg/m^3, when the flame front reaches the up left corner of the chamber, glowing flame gushes out from the corner at right the same time with the earlier pressure oscillation (at about 12.5ms after ignition). Thus it can be deduced as the cause for the earlier pressure oscillation. Actually, the gas inlet port is located at the up left corner of the chamber, which forms a long thin pipe structure (with 5~8 mm diameter and about 80 mm length) in the chamber. Once auto-ignition happens in this structure, burnt gas would gush out. Noting that this phenomenon doesn't happen at 7.5kg/m^3, it is deduced that the knock criteria for different spatial structure is distinct. Besides, relating the spatial size and oscillation frequency reveals that the oscillation caused by autoignition at locations with smaller spatial size exhibits a higher frequency.

Conclusions

Visualization study of C_2H_2 flames within a constant volume vessel was conducted with emphasis on the response of knock onset to oxygen ratio, acetylene ratio and mixture density. Conclusions are drawn as follows.

(1) When oxygen is excess, solely elevation of oxygen concentration doesn't necessarily lead to knock, while gradual elevation of acetylene concentration significantly amplifies the combustion noise and at 7% C_2H_2 mole ratio knock happens.

(2) Solely elevation of mixture density won't significantly increases knock tendency, while the spatial structure intimately impacts the knock criteria. Oscillations caused by autoignition at locations with smaller spatial size exhibits a higher frequency.

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