A STUDY ON THE INFLUENCE OF IGNITION ENERGY ON IGNITION DELAY TIME AND LAMINAR BURNING VELOCITY OF LEAN METHANE/AIR MIXTURE IN A CONSTANT VOLUME COMBUSTION CHAMBER

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Abstract - This study presents the effect of ignition energy (E_{ig}) on ignition delay time (t_{delay}) and uncertainty of laminar burning velocity (S_u^0) measurement of lean methane/air mixture in a constant volume combustion chamber. The mixture at an equivalence ratio of 0.6 is ignited using a pair of electrodes at the 2-mm spark gap. E_{ig} is measured by integrating the product of voltage V(t) and current I(t) signals during a discharge period. The in-chamber pressure profiles are analyzed using the pressure-rise method to obtain t_{delay} and S_u^0. S_u^0 approximates 8.0 cm/s. Furthermore, the increasing E_{ig} could shorten t_{delay}, leading to a faster combustion process. However, when E_{ig} is greater than a critical value, called minimum reliable ignition energy (MRIE), the additional elevating E_{ig} has the marginal effect on t_{delay} and S_u^0. The existence of MRIE supports to optimize the ignition systems and partly explains why extreme-high E_{ig}>> MRIE has less contribution to engine performance.

Key words - Laminar burning velocity; Ignition delay time; Lean methane/air mixture; Minimum reliable ignition energy; Constant volume combustion chamber

1. Introduction

Enhancing the engine thermal efficiency [1-3] is an effective way to improve the vehicle fuel economy and vehicle emissions that have drawn extensive efforts toward achieving a sustainable society. However, the lower thermal efficiency of the stoichiometric concept is one of the challenges to meet the fuel economy and emissions regulations of spark ignition (SI) engines [4]. This is because the required intake throttling results in significant pumping losses [5-7]. Moreover, the high combustion temperature at the stoichiometric operation increases the cooling heat losses [1, 8] and NO_x emission [1]. In addition, the stoichiometric mixture could be incompletely burned near top dead center (TDC) due to dissociation of CO_2 in the hot O_2-depleted gases [9, 10].

Lean burn technology is one of the promising methods for enhancing the thermal efficiency of SI engines by mitigating the aforesaid-disadvantages of stoichiometric concept [1, 2, 7]. By applying the lean combustion concept with cooled exhaust gas recirculation (EGR) to new prototype L4 engine, Nakata et al. [1] achieved the maximum efficiency of 45.7%, more than 9% as compared to the achievement in the stoichiometric condition. However, the fuel-lean combustion also presents challenges to the misfire problem and the slow-burning rate [4-7] that interfere the achievement of optimal combustion phasing and combustion duration. How to secure the ignition and accelerate the flame propagation of such fuel-lean combustion through the fundamental understanding are thus essential for further developing high-thermal efficiency SI engines. This motivates the current study to investigate the effect of ignition energy (E_{ig}) on the flame development of lean methane/air mixture at equivalence ratio $\phi = 0.6$ that is close to the lower flammability limit.

As for successful flame development, many researchers investigated a critical flame radius [11-13] for self-sustained propagation. As long as the heat release from chemical reactions is larger than the heat dissipation rate, the flame kernel could pass its critical radius and propagate steadily. Then ignition delay time (t_{delay}) that is the duration between the start of ignition (SOI) to the critical radius, offers an effective way to characterize the physicochemical property of fuel/air mixture in the successful flame development [14, 15]. In term of in-chamber pressure rise, t_{delay} can be defined as the duration from SOI to the instant of 10% burning point [15, 16].

One effective way to shorten t_{delay} for successful inflammation under lean conditions is to generate the robust and healthy embryonic kernel by effective and reliable ignition energy (E_{ig}). Chen et al. [11, 13] and Kelley et al. [12] indicated that increasing E_{ig} could enhance the minimum flame propagation rate $(dR/dt)_{min}$ shortly after SOI. In addition, Lawes et al. [17] found that the low E_{ig} induces a non-spherically propagating flame, while the high E_{ig} could initiate a more stable spherical flame kernel. Recently, Zhou et al. [18] found that $(dR/dt)_{min}$ particularly increases with a specific range of E_{ig}; beyond this range $(dR/dt)_{min}$ is virtually independent of additional increasing E_{ig}. Unfortunately, these studies mainly focused on the flame speed rather than t_{delay}.

In this study, the lean methane/air mixture at the equivalence ratio (ϕ) of 0.6 is used to investigate the effect of ignition energy on ignition delay time and uncertainty of flame speed measurement in a constant-volume combustion chamber (CVCC).

2. Experimental Method

Experiments of lean methane/air mixture at equivalence ratio $\phi = 0.6$ are conducted in a cylindrical constant-volume combustion chamber (CVCC), as shown in Figure 1, at the room temperature and atmospheric condition. The stainless-steel vessel with an inner diameter of 160 mm is equipped with intake and exhaust ports, electrodes, and pressure transducers. The pin-to-pin electrodes having spark gap d_{gap} = 2 mm are connected to a car ignition coil.

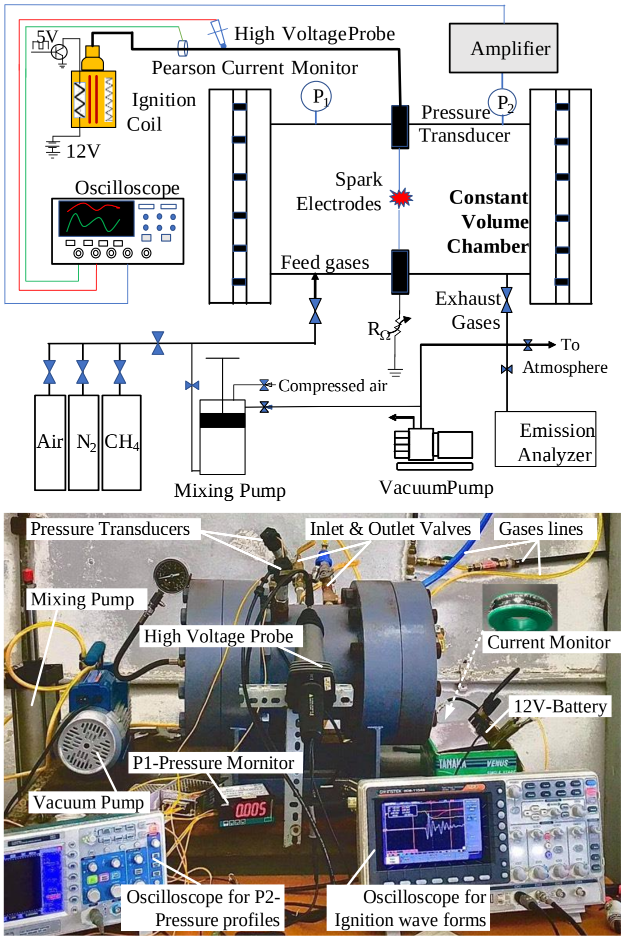

Figure 1. *The top is a schematic diagram of the experimental setup. The bottom is our experimental facilities alongside measurement equipment*

We first vacuum the combustion chamber before injecting the appropriate mole fraction of methane and air to the desired initial pressure p_i = 1 bar using the partial pressure method. The pressure transducer P_1 (CSR1 model) having a range of (-1 to 3 bar) is connected a digital monitor to control the partial pressure of fuel and air sequentially, so does the initial pressure (pi = 1 bar) during the mixture preparation before igniting. After mixing, the valve located between P1 and the combustion chamber is closed to ensure no overloaded effect on P1. It notes that the nominal purity of methane is 99.9%. The methane/air mixture is then mixed well by the mixing pump before discharging a spark. The pressure transducer P_2 (ST18 model) having a range of (0 - 6 bar) is connected to 100MHz-Oscilloscope to detect the in-chamber pressure rise during the combustion processes.

The mole fraction of fuel and air is calculated by Eq. (1), as below.

$$CH_4+\frac{2}{\phi}(O_2+3.76N_2)\rightarrow CO_2+2H_2O+\frac{7.52}{\phi}N_2 \quad (1)$$

where, mole fraction $\lambda_{CH4} = 1/(1+2\times4.76/\phi)$, $\lambda_{air} = 1- \lambda_{CH4}$; and partial pressure $p_{CH4} = \lambda_{CH4}\times p_i$, $p_{air} = p_i - p_{CH4}$.

A pair of pin-to-pin electrodes at d_{gap} = 2 mm centrally ignites the premixed mixture with a given E_{ig}. In order to measure E_{ig}, an ignition circuit is employed in which the positive side is connected to a high-voltage ignition coil, and the negative side is connected to the ground via a series of loading resistor R_Ω. The higher value of R_Ω is, the smaller value of E_{ig} is. E_{ig} is directly calculated by integration of the product of the discharge current $I(t)$ and the voltage $V(t)$ across the spark gap, where $I(t)$ and $V(t)$ signals obtained by Pearson current monitor 8122 and Pintek high-voltage probe HVP-28HF, respectively, are recorded by a 100MHz-Oscilloscope (Gwinstek GDS-1104B). A typical voltage and current waveform are presented in Figure 2, in which $E_{ig} \approx 1.36$ mJ.

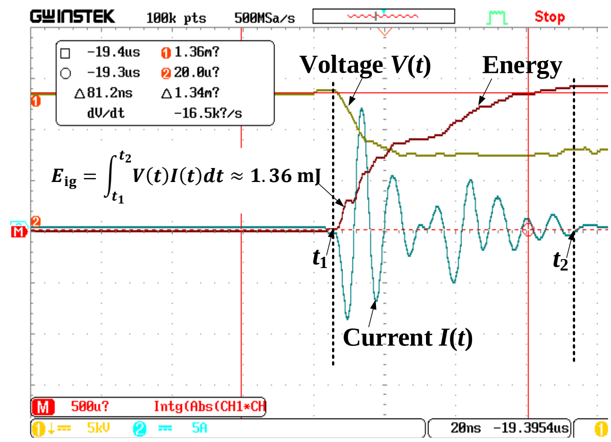

Figure 2. *A typical voltage V(t) and current I(t) waveform, Ignition energy $E_{ig} = \int_{t1}^{t2} V(t)I(t)dt \approx 1.36\ mJ$, and pulse duration $\Delta t \approx 70$ ns*

3. Results and discussion

3.1. In-chamber pressure rise and laminar flame speed

In order to determine laminar burning velocity S_u^0, the pressure history inside the combustion chamber is recorded as indicated in Figure 3. According to Matsugi et al. [19], the in-chamber pressure profile relates to S_u^0 by Eq. (2).

$$p=p_{t=t0}+\int_{t0}^{t}\frac{3S_u^0(p_e-p_0)}{R}\left[1-\frac{p_e-p}{p_e-p_0}\left(\frac{p_0}{p}\right)^{1/\gamma}\right]^{2/3}\left(\frac{p}{p_0}\right)^{c}dt \quad (2)$$

where,

p – instantaneous pressure in the CVCC (bar);

p_e – maximum pressure (bar) [20];

p_0 – initial pressure (bar);

$\gamma = (C_p/C_v)$ –specific heat ratio of the unburned gas;

R – inner radius of the CVCC (cm).

The laminar burning velocity S_u^0, $p_{t=t0}$, and the coefficient c are obtained by a least-square fit of the observed pressure-time profile to Eq. (2) as indicated by the solid curve in Figure 3. The pressure data in a range of $(0.25 – 0.9)p_e$ are typically used for the fitting curve to reduce the ignition energy and chamber wall effect on S_u^0 determination. Moreover, the experiment is conducted at least three times for each condition, and the averaged values are used in this analysis to mitigate the uncertainty of S_u^0. By doing so, the averaged laminar burning velocity of lean CH_4/air mixture at ϕ = 0.6 approximates 8.0 cm/s. This result is in reasonably good agreement with available literature obtained by flame imaging technique [21, 22], revealing that our experimental system and the calculation method are reliable.

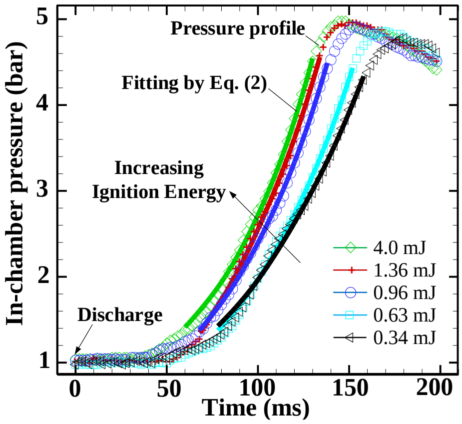

Figure 3. *In-chamber pressure profiles (symbols) and their fitting curves using Eq. (2) (solid curves)*

3.2. Effect of ignition energy on flame development

The effect of E_{ig} on flame development is examined in this subsection. Based on the recorded in-chamber pressure profile (as can be seen from Figure 3), we calculate the representative heat release rate (RHRR) and the normalized cumulative heat release (NCHR) using the expressions proposed by Hwang et al. [16].

$$\text{RHRR}=\frac{dp_{\text{in-chamber}}}{dt} \tag{3}$$

$$\text{NCHR}=\frac{\int_{t_0}^{t}\text{RHRR}\,dt}{\int_{t_0}^{t_{end}}\text{RHRR}\,dt} \tag{4}$$

Where, t_0 is the time of discharge, and t_{end} is at $p = p_e$.

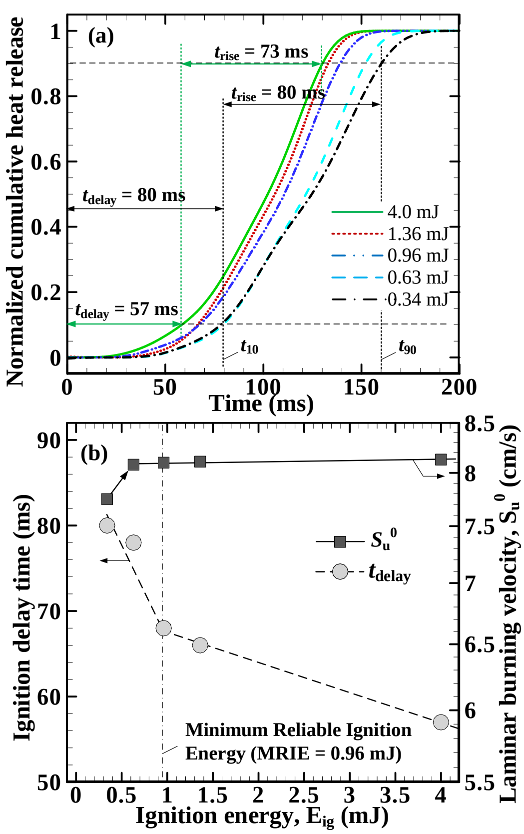

Figure 4. *(a) Effect of ignition energy on the pressure rise inside the constant volume combustion chamber. (b) Effect of ignition energy on ignition delay time (t_{10}) and on S_u^0*

To quantify the time duration for the flame development after discharging, we use ignition delay time (t_{delay}) and flame rising time (t_{rising}) introduced by Hwang et al. [16]. The ignition delay time is defined as a time duration from the spark discharge to t_{10}; And the flame rising time is defined as the time duration from t_{10} to t_{90}, where t_{10} and t_{90} are the time at 10% and 90% of the maximum NCHR, respectively. The schematic of NCHR calculated from Eq. 4 is revealed in Figure 4(a), which indicates that the larger E_{ig} is, the shorter values of t_{delay} and t_{rising} are. It is noted that the slope of NCHR curves in Figure 4(a) are quite similar, indicating weakness influence of E_{ig} on t_{rising} and S_u^0. For example, we increase E_{ig} from 0.34 mJ to 4 mJ, increasing about 12-fold, t_{rising} only decreases 9.5% (7 ms); And S_u^0 increases 5% (as shown in Figure 4b). Moreover, when E_{ig} = (0.63 – 4) mJ are employed, the uncertainty of S_u^0 is significantly reduced. For instance, the uncertainty approximates 14% at E_{ig} = 0.34 mJ, but it is about 5% when E_{ig} = (0.63 – 4) mJ. Here the uncertainty is determined as the square root of variance by determining each data point's deviation relative to the mean (standard deviation formula).

As the most important result in this work, we obtain that t_{delay} is strongly dependent on the applied E_{ig} as shown in Figure 4(b). The ignition delay time first decreases drastically with increasing E_{ig} from 0.34 mJ to 0.96 mJ, and then gradually decreases when increasing E_{ig} from 0.96 mJ to 4.0 mJ. The efficiency ratio defined as a ratio of time difference and energy difference in the former approximates 5-fold higher than that of the latter. The result indicates that when E_{ig} is greater than a critical value of 0.96 mJ, the additional increase of E_{ig} has a marginal effect on t_{delay} and S_u^0. The decrease of τ_{delay} with increasing E_{ig} could be attributed to the high concentration of active radical species [23] and/or the growth in the chemical reaction rates [24]. The marginal effect of high E_{ig} is probably because the fresh gas, which is drawn into the inter-electrode gap by vortices and a recirculation zone induced by the shock wave [25, 26] is less or no longer refreshed. Therefore, there are fewer or no more active radicals generated by the additional E_{ig} that is not beneficial for combustion enhancement. The other possibility is the increasing energy losses to the electrodes by heat conduction with increasing E_{ig} [24]. Consequently, the energy deposition rate insignificantly increases even at very high E_{ig} sources. According to the influence of E_{ig} on S_u^0 and t_{delay}, E_{ig} = 0.96 mJ is then defined as the minimum reliable ignition energy (MRIE) in this study.

For practical SI engines, the existence of MRIE could partly explain why very high E_{ig} has less contribution to the improvement of engine performance and emissions. The value of MRIE may also support the optimization and design of an effective and reliable ignition system.

4. Conclusion

The lean methane/air mixture (ϕ = 0.6) is ignited in the constant volume combustion chamber at room temperature and atmosphere under quiescence condition by a pair of pin-to-pin electrodes. The value of ignition energies is also calculated via the voltage and current waveforms. This work reveals the following points:

(1) The laminar burning velocity approximates 8.0 cm/s, which is obtained by the pressure rise method. The result is in reasonably good agreement with previous data in the literature.

(2) The uncertainty of S_u^0 is quite low (~5%) when changing E_{ig} from 0.34 mJ to 4 mJ. S_u^0 becomes virtually independent E_{ig} as $E_{ig} \geq$ MRIE = 0.96 mJ.

(3) Increasing E_{ig} could shorten the ignition delay time or enhance the initial flame propagation speed of the mixture around the electrodes. However, when $E_{ig} \geq$ MRIE, the additional increase of E_{ig} has a marginal effect on $t_{delay.}$

(4) The existence of MRIE suggests that the required $E_{ig} \geq$ MRIE should be employed to obtain an accurate S_u^0 value.

For practical SI engines, MRIE may support the optimization and design of an effective-reliable ignition system.

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