Investigation of Hythane, LPG and DME Laminar Flame Speed by Ionization Current Method in a Constant Volume Bomb

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Abstract

The centrally ignited, spherically expanding flames for mathane-hydrogen (hythane), liquified petroleum gas (LPG) and dimethyl ether (DME) were recorded by Schlieren photography in a bomb. The ionization current between the electrodes was sampled and characterized correspondingly to the combustion process. The relationship between the laminar flame speed and the current is established by the correlation theory. The results show that the speed and the current in vicinity of first peak have no correlation for hythane and LPG, and have a little correlation for DME fuel. The speed and the current in the vicinity of second peak have good correlation for three fuels. Hythane has a higher correlation and its coefficient is about 0.9, and DME has a middle correlation and its coefficient is about 0.7, while LPG has lower correlation and its coefficient changes from 0.51 to 0.66.

Introduction

With increasing concern about energy shortage and environmental protection, improving engine fuel economy and reducing exhaust emissions have become major research topics in combustion and engine development. Alternative fuels, such as hydrogen, methane, liquified petroleum gas, dimethyl ether, et al, are usually regarded to be clean fuels compared to diesel and gasoline, thus the introduction of these alternative fuels is beneficial to the slowing-down of fuel consumption and the reduction of engine exhaust emissions.

Laminar burning velocities of combustible mixtures are fundamentally important in regard to developing and justifying the chemical kinetics mechanism of the fuels, as well as in regard to predicting the performance and emissions of internal combustion engines. There are many techniques for measuring experimentally the laminar burning velocity of combustible mixtures, such as counterflow double flames [1], flat flame burner [2,3] and spherically expanding flames [4-10]. For a spherically expanding flame in a closed combustion bomb, the stretch imposed on the premixed flame is well defined. The asymptotic theories and experimental measurements have suggested a linear relationship between the flame speeds and flame stretches. Therefore, the fundamental burning velocity of alternative fuel is measured by closed bomb technique. C. Prathap [4], Zuohua, H [5], Khizer, S [6] Haiyan, M [7], Luijten[8] performed the laminar burning velocity of Spherically expanding flames measurement for syngas, natural gas–hydrogen–air mixtures, methanol and hydrogen enriched natural gas. Liao, S[9] and Jerzembeck [10] measurement Laminar burning velocities for mixtures of methanol and gasoline at elevated temperatures and high pressure.

Recently, a great deal of attention has been paid to spark plug detector, some researches concern the relationship among the ionization current and the cylinder pressure[11], air-fuel ratio [12], combustion diagnosis [13,14]. The spark plug detection of ionization current does not require any modification to engine block or cylinder, therefore this technique can simplify the traditional measuring and controlling system, and is considered to be effective approaches in combustion diagnosis, such as misfire, knock and partial-burn [15-17], and engine control, such as homogenous charge compression ignition (HCCI) engine, auto-ignition gasoline engines, spark advance and closed-loop ignition timing control [18-21].

Centrally ignited, spherically expanding flames of mathane-hydrogen (hythane) and liquefied petroleum gas (LPG) and dimethyl ether (DME) were measured, and the correlation theory was used to establish the relationship between the premixed laminar flame propagation speed and the ionization current. The goals of present work are to present a new method to quantify the laminar burning velocity with the ionization current during combustion detected by the spark plug.

2. Experiments and procedures

Figure 1 shows mixture preparing and ionization current detection system. In this system, the gas sources are oxygen (O_2) and nitrogen (N_2) and fuels which are mathane-hydrogen (hythane) and liquefied petroleum gas (LPG) and dimethyl ether (DME), respectively. Those gases were well mixed to become a homogeneous mixture in the mixing chamber. The combustion bomb is a cubic chamber with the inside size $108\times108\times135$ mm and its quartz glass windows are round-shape with the diameter of 80 mm for optical accessible. A 12 bit, 544×544 pixel REDLAKE HG-

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100K high speed CCD camera is used to record the flame development at 5000 pictures per second with a schlieren optical system. A pair of straight threaded stainless steel electrodes are located in the central of the bomb to serve as the spark plug and ionization current detector. The quantity of each gas in the mixing chamber was adjusted according to the partial pressure of each component. A vacuum pump was used to draw out the gases from the chamber. The initial pressure in the combustion bomb was measured by a mercury manometer with the pressures accuracy of 1mmHg. The pressure during the combustion was recorded by a piezoelectric absolute pressure transducer, model Kistler 4075A, with a resolution of 0.01 kPa. The initial condition is at the equivalence fuel-air ratio ϕ_a =1, the pressure p_0 =0.1 MPa and the temperature T_0 =300 K. The initial condition was strictly controlled in the experiments to realize the same initial pressure and temperature. The influence of wall temperature on mixture temperature can be avoided by providing enough time between each experiment. The uncertainty in the experimental determination of the laminar burning velocity is mainly related to the derivation of the flame area from the digital flame images. For the flames to be analyzed (generally 50 to 30 mm), the flame resolution (0.147 mm) is high enough that there is only a small value of the flame size error. The standard error of estimation is generally less than 5% over the measured ranges.

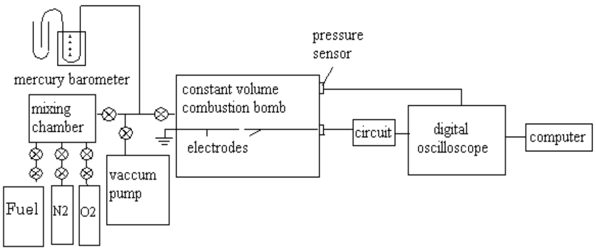


Fig. 1 Mixture preparing and ionization current detection system

The laminar burning velocity can be deduced from the well established expanding flames method as described in Ref. [6]. For a spherical expending flame, the stretched flame velocity, S_n, reflecting the flame propagation speed, is derived from the flame radius, r_u, versus time, t, as

$$S_n = dr_u / dt \qquad (1)$$

where the flame size r_u is defined as the Schlieren flame size, which is derived from the digital Schlieren flame area in advance.

3.Theory of correlation

Supposing that (x, y) are two-dimension random vectors, the samples with n size $(x_1, y_1), (x_2, y_2)\cdots, (x_n, y_n)$ are acquired. The simultaneous change in value of the two numerically random variables may be correlated. Basically, the sample correlation coefficient, ρ, of $(x_1, y_1), (x_2, y_2)\cdots, (x_n, y_n)$ can be express by the following equations [22]:

$$\rho = l_{xy} / \sqrt{l_{xx} \cdot l_{yy}} \qquad (2)$$

and $l_{xy} = \sum_{i=1}^{n} \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)$;

$$l_{xx} = \sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2 ; \quad l_{yy} = \sum_{i=1}^{n} \left(y_i - \bar{y}\right)^2$$

Where $\bar{x}, \bar{y}$ are the average values of x, y, ie,

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i ; \quad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

If $\rho = 0$, the variables of x and y has unrelated;

If $\rho > 0$, the variables of x and y has positive correlation;

If $\rho < 0$, the variables of x and y has negative correlation.

The size of the samples is essential in statistics to make sure the sample correlation coefficient, ρ, in Eq.(2) is true. A notable verity, distribution function of t, is thus calculated by following equation (3) [23].

$$t = \frac{\rho\sqrt{n-2}}{\sqrt{1-\rho^2}} \qquad (3)$$

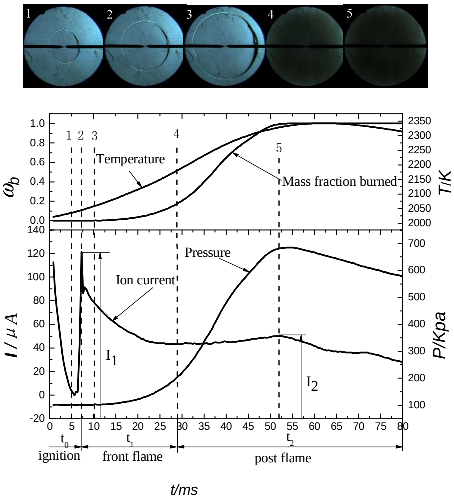
where n is the sample number, n＞2.

The critical value of $t_\alpha(n-2)$ ($\alpha = 0.05$) can be found in the table of distribution function [23]. If $|t| > t_\alpha(n-2)$, the sample correlation coefficient, ρ, in Eq.(2) is accepted; if $|t| \le t_\alpha(n-2)$, the sample correlation coefficient is refused.

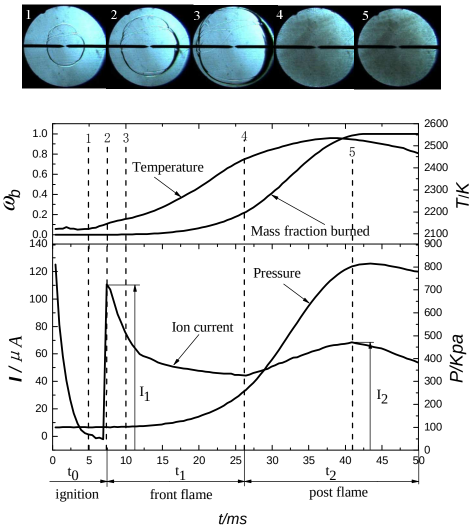
3．Results and discussions

3.1 Combustion and the waveform of ionization current

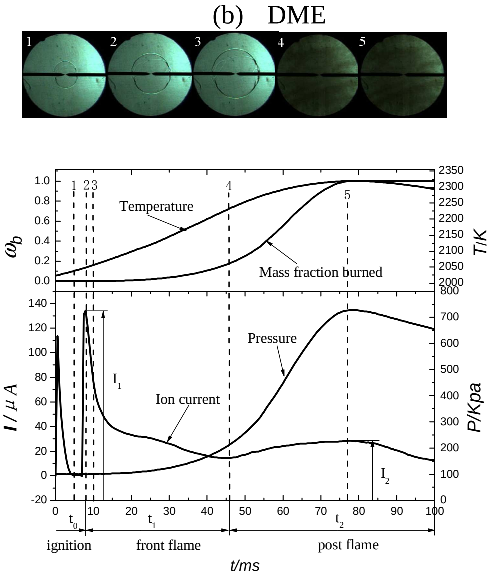
Figure 2a, 2b and 2c are typical instant flame photographs in laminar premixed flames of hythane, DME and LPG, and the measured time histories of the ionization current, pressure, temperature, MFB (mass fraction burned). The detected ionization current is characterized with three stages: ignition, front flame and post flame, which is time scheduled by t_0, t_1 and t_2. There are two peaks of I_1 and I_2 in the curve. The mass fraction burned (MFB) and temperature (T) were calculated based on the sampled pressure data. Rassweiler-Withrow method [9, 24] and two-zone quasi-dimensional model were developed in the computation.



(a) Hythane



(b) DME



(c) LPG

Fig. 2 Time histories of flame photographs, pressure, temperature, MFB and Ionization current

For the three mixtures, the combustion manners are same. After spark occurs, ignition takes place in the center of the chamber, and the flame propagates spherically out to the whole mixture. So the measured ionization current, bomb pressure and temperature are similar. Three stages in the current curves can be defined obviously. During ignition, a sharp and short increase of ionization current is observed. Shortly after the discharge, the current drops to near zero over a period of time t_0. This is called ignition phase. As flame kernel develops and its diameter increases with time, the current increases remarkably and reaches to its first peak (I_1) with a small rise of pressure, temperature and MFB. The spherical flame propagates continuously, the current descents to a lower level during the period of time t_1 (line 4). And then, it is ascent again to the peak two (I_2), where the bomb pressure and temperature reach its maximum and the flame propagates fast to its end out of the visual window (80 mm).

To the first peak of I_1, the ions are produced by the chemical reactions in the propagating flame zone; thus, the chemi-ionization is the predominant ionization in the first stage. The flame front remains only for a limited time in the region where the current could be detected. Because of the thickness of laminar flame is less than 0.1 mm [24], the flame front leaves for the gap of the electrodes and the current decreases quickly.

At the end of combustion, most fuel is burned and the temperature is over 2200 K. The current reaches to its second peak I_2. However, the rise of the current is rather slower. During this post flame stage, the ionization process is governed by the thermal ionization. The major contributor is NO^+ ions, because NO molecules are easily to be ionized for its lower ionization energy (9.26405 eV) [16,18,19,21]. Therefore, the current is due to the excited NO at the elevated high temperature (about 2200 K in this study). It disappears when the temperature is a little lower.

3.1 Correlation of laminar burning velocity and ionization current

Laminar burning velocities can be obtained from the Schlieren image analysis during the early combustion period (Eq.1). The flame speed was calculated from 6 to 26 mm to avoid large errors. The flame radius r_u and the flame speed S_n of three fuels measured are drawn in figure 3 and figure 4. It is obvious that DME mixture has the highest flame speed and it decreases with the flame radius, LPG has the lowest speed and its speed is slightly decreased with the radius, hythane has a middle flame speed and its speed gives an increase at the initial stage and then almost keeps its speed.

To obtain the correlation between the laminar burning velocity and the ionization current, the first peak current I_1 and the second I_2 are focused and their correlations are studied according to equations 3 and 4 for the three fuels as table 1-4.

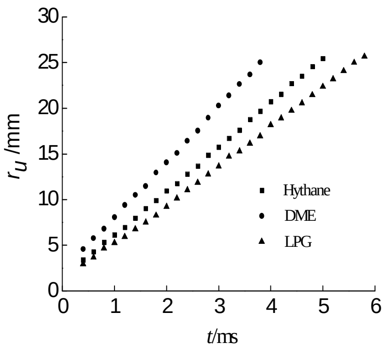


Fig.3 Flame radius versus time

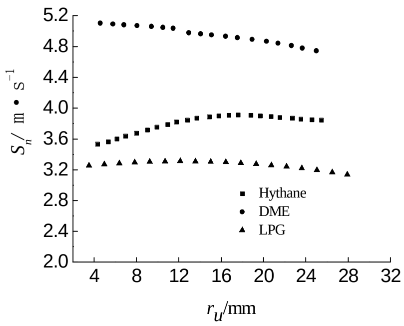


Fig.4 Flame speed versus radius

Table 1 Correlations between S_n and I_1

fuels	Sampling frequency/ms	Sampling number/n	Coefficient of correlation ρ	t	$t_\alpha(n-2)$ ($\alpha=0.05$)	result
DME	0.2	34	0.342	2.093	1.946	correlation
Hythane	0.4	21	-0.213	2.037	2.043	irrelevance
LPG	1	30	0.241	2.048	2.327	irrelevance

Table 2 Correlations between S_n and I_2 for hythane

Sampling frequency/ms	Sampling number/n	Coefficient of correlation ρ	t	$t_\alpha(n-2)$ ($\alpha=0.05$)	result
0.2	34	0.939	15.543	2.037	correlation
0.4	34	0.952	17.633	2.037	correlation
1	34	0.893	11.212	2.037	correlation

Table 3 Correlations between S_n and I_2 for DME

Sampling frequency/ms	Sampling number/n	Coefficient of correlation ρ	t	$t_\alpha(n-2)$ ($\alpha=0.05$)	result
0.2	21	0.762	5.118	2.093	correlation
0.5	21	-0.702	-4.298	2.093	correlation

Table 4 Correlations between S_n and I_2 for LPG

Sampling frequency/ms	Sampling number/n	Coefficient of correlation ρ	t	$t_\alpha(n-2)$ ($\alpha=0.05$)	result
0.1	30	0.507	3.109	2.048	correlation
0.5	30	0.663	4.328	2.048	correlation
1	30	0.659	4.640	2.048	correlation

There are no correlations between S_n and I_1 for hythane and LPG, and there is a week correlation for DME, for the correlation coefficient is only about 0.3. However, there are strong correlations between S_n and I_2 for three fuels and significant affected by sampling frequanencies. Hythane has a higher correlation and its coefficient is about 0.9 for three sampling frequency, and DME has a middle correlation and its coefficient is about 0.7 for two sampling frequency, while LPG has lower correlation and its coefficient changes from 0.51 to 0.66.

3.3 Correlation between S_n and temperatures

To survey the correlationship between S_n and the temperatures corresponding to the first peak and second peak of the current, the theory of Mallard-Le Chatelier [25] is introduced, which denotes the laminar burning velocity S_n and temperature as following,

$$S_n \propto \left(e^{-T_A/T}\right)^{1/2} \quad (4)$$

where T_A is activation flame temperature in K; T is the flame temperature in K.

T_A is between 10000~25000 K. To a given T_A, the flame velocity S_n varies inversely with the flame temperature T. So, If the flame temperature is replaced by the maximum bomb temperature T_b, the temperatures T_1 and T_2 corresponding to the first and the second current peak, respectively, Eq.4 can be re-expressed by,

$$S_b = \left(e^{-T_A/T_b}\right)^{1/2} \quad (5)$$

$$S_1 = \left(e^{-T_A/T_1}\right)^{1/2} \quad (6)$$

$$S_2 = \left(e^{-T_A/T_2}\right)^{1/2} \quad (7)$$

Where S_b, S_1 and S_2 are the laminar burning velocity calculated by the maximum temperature T_b, the characteristic temperature T_1 and T_2.

Table 5 lists the data of current at first peak (I_1) and second peak (I_2), and the temperatures T_b, T_1 and T_2 for the three fuels. The T_b and T_2 are nearly same because the second peak of current occurs at the end of combustion, which is shown in figure 2. T_b is much higher than T_1 for three fuels because T_1 occurs at the beginning of flame development. At that time, a few fuels are burned.

In this paper, T_A is supposed to be 20000 K. On the basis of Eq.5-7, S_b, S_1 and S_2 can be calculated. The velocity ratios of S_b/S_1, S_b/S_2 and S_2/S_1 have been shown in table 6. There are obvious differences among them. The velocity ratio of S_b/S_2 is nearly 1, S_b/S_1 is about 2.4~4.5, and S_2/S_1 is also about 2.3~4.3. Therefore, the burning velocity has close correlation with the current value in vicinity of second peak, but has a little correlation with the current value in vicinity of first peak. The second peak is an important parameter which can be correlated to the burning velocity.

Table 5 Data of I_1 and I_2 and the temperatures of T_b and T_1 and T_2

fuels	I_1/μA	T_1/k	I_2/μA	T_2/k	T_b/k
LPG	132.89	2020.578	28.35	2198.607	2219.799
hythane	110.57	2024.592	50.25	2334.018	2352.351
DME	121.47	2121.932	67.39	2511.231	2530.502

Table 6 Velocity ratio S_b/S_1 and S_b/S_2 and S_2/S_1

fuels	S_b/S_1	S_b/S_2	S_2/S_1
LPG	2.43	1.09	2.23
hythane	3.96	1.07	3.71
DME	4.58	1.06	4.31

5. Conclusions

(1) DME mixture has a higher flame speed and its speed decrease with the flame radius, while LPG has a lower speed and its speed is nearly unchanged with the radius. The speed of Hythane is in the middle, its speed gives an increase at the initial stage and then decreases gradually with the radius.

(2) The burning velocity and the ionization current in vicinity of first peak have no correlation for hythane and LPG, but has a little correlation for DME and its correlation coefficient is about 0.3. There is a good correlation to the second peak. Hythane has the highest correlation and the coefficient is about 0.9. DME has a middle one and it is about 0.7. LPG has the lowest correlation and it changes from 0.51 to 0.66.

Acknowledgements

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