Research of Measure and Control System for Laminar Burning Velocity in Constant Volume Combustion Chamber

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Abstract. The synchronization among the central electrode ignition control system, high-speed schlieren imaging system and pressure data acquisition system inside a constant volume combustion chamber (CVCC) should be accurately controlled in the study of the laminar burning velocity of fuel by spherical expansion flame method in a CVCC. In this paper, the digital delay pulse generator and the high-speed data acquisition card are used to control the synchronization among the abovementioned three systems with the control error in 30 μs, and then the schlieren image of the flame front and the pressure inside a CVCC are captured successfully. These lay a solid foundation for the measurement of laminar burning velocity by constant pressure method (CPM) and constant volume method (CVM).

1. Introduction

In order to alleviate the huge pressure on petroleum resources and the environment caused by the development of the national economy, it’s essential to find and develop stable clean, renewable energy for us. The development of renewable biomass fuel is one of the important technologies to reduce the dependence on non-renewable fossil fuels and achieve the goal of energy saving and emission reduction [1].

Rapid thermal cracking is a method of converting biomass into effective energy. Its basic principle is in anaerobic conditions, thermal decomposition of biomass which occurs by heating and then converted to coke, liquid and gas products by adjusting the appropriate temperature and steam residence time. The production conditions of the highest liquid yield are at a moderate temperature (about 600 ℃) and very short steam residence time (2-3s), and the highest liquid yield can reach 75% [2].

In the book “Biomass Pyrolysis” [3], supercritical ethanol is used to improve the quality of biomass oil from rice husk, and the physical and chemical properties of the refined fuel oil are analyzed. The results showed that the refined fuel oil is an ideal engine fuel which mainly comprises of ethanol, ethyl acetate, ether, acetone and butanone [4].

In the operation of the ignition engine, the combustion of the fuel-air mixture is mainly premixed turbulent combustion. Laminar combustion is the basis of turbulent combustion. Laminar burning velocity is an important physical and chemical parameter of combustible mixtures, and it describes the
diffusivity, reactivity and exothermicity of combustible mixtures. A profound knowledge of laminar burning velocity is essential to verify kinetic models and constrain uncertainties of rate constants. Besides, it is used as a scaling parameter for turbulent flame speed for turbulent premixed combustion modelling [5]. Furthermore, the laminar burning velocity is used to estimate the time between the formation of the flame inside the engine and its propagation to the cylinder wall and it is significant for the optimization of engine structure size design [6]. Therefore, the laminar burning velocity of pyrolytic biomass oil must be studied [7].

2. Experimental setup and control process

The experimental setup for measuring laminar burning velocity is shown in Fig. 1 [8]. It consists of a constant volume combustion bomb, a temperature-controlled heating system, a fuel injection and exhaust system, an ignition system, a timing control system, and a high-speed schlieren photography system as well as a pressure data acquisition system [9].

![Figure 1. Experimental system of CVCC](image)

The system can be used to study the premixed combustion process of conventional fuel, alternative fuel and mixed fuel under different equivalent ratios, initial temperature, initial pressure and ignition modes (spark ignition and laser-induced spark ignition). If the fuel injection system is slightly modified, the combustion characteristics of the fuel under high pressure can be studied by using the gas distribution system controlled by high-pressure gas cylinders and electromagnetic valves.

In the experiment, the synchronization among the ignition system, the high-speed schlieren photography system and the acquisition system of the pressure data in the combustion process should be precisely controlled. While the combustible mixture is burning in the CVCC, the schlieren image of the flame front and the pressure rise inside the CVCC is recorded. The control measurement system is shown in Fig 2.

The synchronous control process is as follows: when the homogeneous mixture is ready, press the start button and input a 10 μs of TTL high-level trigger signal in the digital delay pulse generator DG645 (SRS Company of USA). DGS outputs three channel of synchronous control signals according to the equipment needs. One channel of signal control the central electrode ignition control system, input 300,000 V high voltage to the central electrode and electric charge is produced to ignite the homogeneous mixtures in the central electrode gap. Another channel of the signal controls the high-speed CCD (Phtron SA4) with 6000fps at 512 x 512 pixels to record the schlieren image of the flame front. The last channel of signal triggers a high-speed data acquisition card MP4623 to collect the pressure rise data in the CVCC. The data acquisition card records the pressure value in the CVCC at 500kHz /12bit AD conversion speed and transmits it to the computer via USB. The pressure sensor is
Kistler 6115A and the pressure signal is amplified by the charge amplifier 5018A. The time difference of the three channels of the synchronous control signal is within $30 \mu s$, and the high-speed synchronization control is realized.

3. Control process software system

The synchronous control software in this paper is based on the Windows7 operating system, and the developed version is in LabVIEW2012. As shown in Fig. 3, the acquisition of combustion pressure needs to cooperate with the implementation of the ignition program. After the pre-trigger button is pressed, the AD configuration and startup functions are called and the corresponding sampling is set. In this paper, the total number of sampling points of combustion pressure is 190,000, the sampling frequency is 500kHz, the total sampling time is 380ms, and the trigger mode is an external descending pulse signal, the polarity of the voltage is a single terminal signal, and the acquisition voltage range is between 0-10V.

When the setup is completed, the data acquisition card is in the state of waiting for the external trigger signal, while the program enters the next sequential branch. The conditional loop structure and the true and false structure are nested in the sequence branch. The program jumps out of the conditional loop to the next sequential branch only after sending a fire command and received a signal response returned from the lower machine. Otherwise, the program is always in the state of waiting for the fire to be lit. In the next sequential branch, the loop calls the sampling read-in function, and determines whether the function return value is "0". If the function return value is "0" it indicates that the sampling has been completed and has been stored in the cache. The function return value of "0" is taken as the condition for jumping out of the loop. After jumping out of the loop, recall the read-in data function to read the specified sample number of voltage value into the computer. The voltage value and the combustion pressure are converted and plotted in a two-dimensional diagram.

4. Experimental result

The initial experimental condition is $P_i = 0.1$ MPa and $T_i = 358$ K, the fuel is ethanol and the equivalence ratio is 1.0. The synchronization among ignition, high-speed schlieren imaging, and pressure data acquisition is realized. The flame front development of the ethanol-air mixture and pressure rise process in the CVCC are shown in Fig. 4. There are three stages of the in-vessel pressure change; constant pressure stage, pressure rise stage and pressure drop stage. The schlieren images of the ethanol-air mixture in the constant pressure stage are exhibited in Fig. 5. The laminar burning velocity at the initial conditions (initial pressure, initial temperature, equivalence ratio) can be obtained using the constant pressure method (CPM). The in-vessel pressure of ethanol-air mixtures with different equivalence ratios is shown in Fig 6. The laminar burning velocity from the initial pressure to 60% of the maximum pressure (corresponding to the different temperature at which the pressure is raised) can be obtained using the Constant Volume Method (CVM).
5. Data processing

5.1. CPM

From the images shown in Fig 5, the flame front radius $r_f$ can be obtained as follows:

\[ r_f = \sqrt{\frac{N_f}{N_w}} R_w \]  

(1)

where $N_f$ is the pixels inside the flame front, $N_w$ is the pixels of the optical window, and $R_w$ is the actual radius of the optical window. The $N_f$ and $N_w$ can be obtained by Photoshop software, as shown in Fig 7.
Figure 4. Flame front development and pressure rise process of the ethanol-air mixture in a CVCC. Initial experimental condition: 0.1MPa, 358K, equivalence ratio of 1.0.

Figure 5. The schlieren images of the ethanol-air mixture in a CVCC. Initial experimental condition: 0.1MPa, 358K, equivalent ratio of 1.0.

Figure 6: The in-vessel pressure of ethanol-air mixture with different equivalence ratios. Initial experimental condition: 0.1MPa, 358K, equivalence ratio of 1.0.

Figure 7. Flame front detection

To avoid the interference of ignition energy and wall confinement on the laminar burning velocities ($S_u$), only the flame image with a radius of 8-25 mm is chosen. Then based on the flame radius and the time after ignition, the stretched laminar burning speed ($S_b$) can be obtained by:

$$S_b = \frac{dr_f}{dt}$$  \hspace{1cm} (2)

For measuring $S_u$ with the CVCC, the stretch effect must be considered. Flame stretch rate is defined as the Lagrangian time derivative of the logarithm of the infinitesimal area $A$ on the flame surface [10]. For spherical propagation flame, the expression is as follows:

$$\kappa = \frac{d \ln A}{dt} = \frac{1}{A} \frac{dA}{dt} = 2 \frac{dr_f}{r_f} = \frac{2}{r_f} \frac{S_b}{r_f}$$  \hspace{1cm} (3)

To get the unstretched flame speed ($S_{b0}$), extrapolation methods should be adopted to eliminate the influence of stretched rate to the flame propagation. Linear extrapolation and nonlinear extrapolation are the most representative methods, there are four main types:
\[ S_b = S_{b0} - L_{b0} \kappa \]  
\[ S_b = S_{b0} - L_{b0} \frac{2S_{b0}}{r_f} \]  
\[ \left( \frac{S_b}{S_{b0}} \right)^2 \ln \left( \frac{S_b}{S_{b0}} \right) = - \frac{2L_{b0} \kappa}{S_{b0}} \]  
\[ \left( \frac{S_b}{S_{b0}} \right)^2 \ln \left( \frac{S_b}{S_{b0}} \right) = - \frac{1}{S_{b0}} \frac{dS_b}{dr_f} - 2L_{b0} \kappa \]  

where \( L_{b0} \) is the Markstein length relative to the burned mixture.

Based on the quasi-steady state and mass conservation law of the flame front, the laminar burning velocity \( S_{u0} \) can be deduced with density ratio and unstretched flame speed:

\[ S_{u0} = \frac{\rho_b}{\rho_u} \frac{S_{b0}}{r_f} \]  

where \( \rho_b \) is the density of burned gases and \( \rho_u \) is the density of burned gases, calculated by the Equilibrium model in CHEMKIN.

To get more accurate results, the radiative correction can be considered as well. Yu et al. [11] propose a correction formula:

\[ s_{u0,BCFS} = s_{u0,Exp} + 0.82s_{u0,Exp} \left( \frac{s_{0,Exp}}{s_0} \right)^{1.74} \left( \frac{T_u}{T_0} \right) \left( \frac{P_u}{P_0} \right)^{-0.3} \]  

where \( s_0 \) is 1cm/s, \( T_0 \) is 298K and \( P_0 \) is 1atm. \( s_{u0,Exp} \) and \( s_{u0,BCFS} \) are the laminar burning velocity obtained in equation (8) and the laminar burning velocity corrected by radiation, respectively. Since the effect of radiation is not very large, this step is sometimes omitted in the calculation process.

### 5.2. CVM

There are some assumptions in calculating the laminar burning velocity with CVM: (1) the unburned gas is uniformly distributed and compressed adiabatically; (2) the internal pressure of the whole combustion bomb is the same; (3) both the burned and unburned gas are ideal gas; the influence of heat loss, radiation and buoyancy is not taken into account; (4) since the flame radius is large in selected region, the effect of the flame stretch is negligible.

Based on the above assumptions, the temperature (\( T_u \)) and the density (\( \rho_u \)) of the unburned gas can be obtained by the ideal gas state equation and the adiabatic isentropic compression equation:

\[ \frac{T_u}{T_i} = \left( \frac{P}{P_i} \right)^{\gamma_u/\gamma_i} \]  
\[ \frac{\rho_u}{\rho_i} = \left( \frac{P}{P_i} \right)^{1/\gamma_i} \]  

where \( P \) is the internal pressure of the bomb, \( T_i, P_i \) and \( \rho_i \) are the initial temperature, pressure and density of the mixture gas, respectively, and \( \gamma_i \) is the specific heat ratio.

Then we introduce the burned mass fraction \( x \) defined as the mass ratio of the burned gas to the initial gas:

\[ x = m_b/m_i \]  

according to the law of mass conservation, Eq. (12) can be converted to:

\[ m_u = m_i - m_b = (1-x)m_i \]  

which indicates that
\[
\frac{4}{3} \pi (r_u^3 - r_f^3) \rho_u = (1 - x) \frac{4}{3} \pi r_u^3 \rho_i \]

(14)

where \(m_u, m_i\) and \(m_b\) are the mass of the unburned, initial and burned gas, respectively. \(r_w\) is the radius of the CVCC.

Combining the above Eq. (11) and (14), the relation between \(r_w\) and \(r_f\) can be shown by the following equation:

\[
\frac{r_f}{r_w} = \left[1 - (1 - x) \left(\frac{P_f}{P_i}\right)^{\frac{1}{\gamma_u}}\right] \gamma^0
\]

(15)

The laminar burning velocity is defined as [12]:

\[
S_u = \frac{1}{4 \pi r_f^2 \rho_u} \frac{dm}{dt}
\]

(16)

Combining the Eq. (13), (15) and (16) together, \(S_u\) can be expressed as [13]:

\[
S_u = \frac{r_u}{3} (1 - (1 - x) \left(\frac{P_f}{P_i}\right)^{\frac{1}{\gamma_u}}) \left(\frac{P_f}{P_i}\right)^{\gamma^0} \frac{dx}{dt}
\]

(17)

As for the burned mass fraction, the simplest and most popular method is proposed by Lewis and von Elbe [14], they use a linear relation between \(x\) and \(P\) to estimate:

\[
x = \frac{P - P_e}{P_e - P_f}
\]

(18)

where \(P_e\) is the peak pressure during the combustion. In this relation, \(x\) is considered to be the same as the pressure rise fraction \(p_r\).

Based on above equations, the burned mass fraction can be calculated after obtaining the pressure data from the data acquisition card, and then a wide range of laminar burning velocity during the combustion can be obtained. To get the laminar burning velocity in the initial condition, an extrapolation formula should be used to fit the relationship among the laminar burning velocity, temperature and pressure [13]:

\[
S_u = S^{0} \left(\frac{T_u}{T_i}\right)^{\gamma} \left(\frac{P}{P_i}\right)^{\gamma}\n\]

(19)

where \(\alpha\) and \(\beta\) are exponents of temperature and pressure, respectively. \(S_u^{0}\) is the laminar burning velocity in the initial condition.

For the combustion in the CVCC is assumed to be adiabatic and isentropic, Eq. (19) can be simplified as:

\[
\frac{S_u}{S_u^{0}} = \left(\frac{P}{P_i}\right)^{\gamma}
\]

(20)

where \(c = \alpha (\gamma_u - 1) + \beta\).

Practically, the whole data processing is to get \(S_u\) as a function of the pressure based on the acquired data, then select an appropriate fitting zone to fit the \(S_u(p)\) curve to an exponential form and extrapolate it with the initial condition \((p/p_i = 1)\) to obtain \(S_u^{0}\), as shown in Fig 8.

Fig 8 exhibits the laminar burning velocity as a function of relative pressure. The blue line is the result calculated from the experimental data with CVM, while the red line represents the fitting result obtained by Eq. (20). It can be seen that \(S_u\) increases first and then decreases with the increase of relative pressure, and it changes sharply at the beginning, but only the zone from \(p_r = 0.05\) to \(p_r = 0.2\) is chosen as the fitting zone. There are several reasons. First, Eq. (20) is very sensitive to the undulation of internal pressure and the ignition energy will generate an interference signal at the beginning. Second, when \(p_r > 0.05\), stretch effects can be regarded negligible. Third, when the
pressure exceeds a certain value, the heat loss from the gas to the chamber wall becomes large, which cannot be ignored, resulting in a decrease in $S_u$. Since $p_r = 0.2$ is exactly the critical point where the heat loss can be neglected, so it is more accurate to fit the $S_u$ curve based on the zone from $p_r = 0.05$ to $p_r = 0.2$.

5.3. Comparison of $S_u$ obtained from CPM and CVM

Fig. 9 shows the comparison of $S_u$ obtained from CPM and CVM at 358 K and 0.1 MPa. In CPM, one linear and two nonlinear extrapolation methods are considered. It can be found that the result of the linear method is slightly higher and the deviations of two nonlinear methods are really small. Compared with CPM, CVM has a little higher $S_u$ value, especially at $\Phi = 0.9$. Literature [13] suggested that results using the linear $x-p$ relation led to 20% higher $S_u$ than those from CPM.

6. Conclusion

In this paper, the digital delay pulse generator and the high-speed data acquisition card are used to control the synchronization among the central electrode ignition control system, high-speed schlieren imaging system and pressure data acquisition system in a CVCC. The schlieren image of the flame front and the pressure inside the CVCC at the corresponding time are captured successfully. These lay a solid foundation for CPM and CVM measurement of laminar burning velocity. The laminar burning velocity under the initial conditions (initial pressure, initial temperature, equivalence ratio) can be obtained by CPM using the schlieren images. The laminar burning velocity from an initial pressure to 60% of the maximum pressure (corresponding to the different temperature at which the pressure is raised) can be obtained through CVM according to the pressure date. The data processing of CVM and CPM is introduced, and the results show that the $S_u$ obtained from the CVM and CPM are similar, both two methods can be used to calculate the laminar burning velocity.

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