Measurement on minimum ignition energy of n-decane with pyrolysis

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Abstract. Measurement on the minimum ignition energy (MIE) of n-decane with pyrolysis is investigated experimentally. Certain decomposition rate n-decane vapor is simulated by blending certain proportion of ethylene into n-decane vapor. Two equivalence ratios (1 and 0.7) and five blending ratios (0, 0.2, 0.4, 0.6, 0.7) of ethylene are, respectively, designed to represent different decomposition rates and equivalence ratios. The effect of different decomposition rates and equivalence ratios on the MIE of n-decane is investigated in following experiments. Two experimental methods are used for measurement. Technique of high-speed schlieren system is adopted to obtain images of the flame kernel by which the relationship between flame kernel radius and flame speed is calculated. An ignition probability model based on the logic regression theory is established to obtain the ignition probability curve. Results indicate that MIE is sensitive to the blending ratio of ethylene when equivalence ratio is 0.7. With elevated blending ratio of ethylene, MIE decreases rapidly firstly and with the continuous increasing of the blending ratio, the decreasing of MIE is lagging which indicates that there is a limit to the effect of the blending ratio of ethylene on the MIE. It is also found that values of MIE are closed when ethylene blending ratio is big enough whatever the equivalence ratio is.

Keywords: MIE; n-decane; flame radius; ignition probability model.

1. Introduction

Ignition is one of the most fundamental and essential problems in combustion researches and plays an important role in the performance of aeroengine combustion chamber [1]. It is well known that successful ignition depends on the energy deposited into the combustible mixture [2]. If the deposited energy is smaller than the so-called minimum ignition energy (MIE), the flame kernel will be extinguished rapidly due to the lack of energy. However, the relationship between MIE and fuel pyrolysis is not examined and there still exist large numbers of problems such as the measurement of MIE to be studied. Thus, MIE is recognized as one of the key parameters in combustion [3, 16, 17]. Chen [4] et al. studied the critical flame size and MIE of the spherical flame, and found that the initial formation process of the flame can be divided into three typical regimes according to Lewis number, and the dependence between MIE and cube of the critical kernel size was proposed. Cui [5] et al. studied MIE of methane at high temperature and high pressure, and found that MIE has a linear
relationship with the reciprocal of the square of pressure, and an approximate linear relationship with the reciprocal of temperature.

The success of ignition can also be affected by the activity of the combustible mixture [6]. In some advanced combustion chambers, engines are cooled with inboard fuel to reduce the weight of cooling system. Temperature in combustion chamber can reach 1050-1450K at which aviation kerosene decomposes into light gaseous species such as hydrogen, methane and ethylene. Zhao[7] et al. studied the effect of pressure on kerosene thermal cracking under supercritical condition, and found that the thermal diffusion effect was enhanced and the kerosene residence time was longer when the pressure was increased; Hou[8] et al. studied the relationship between aviation kerosene thermal cracking reaction and steam reforming reaction, and found that steam reforming reaction could weaken the thermal diffusion deterioration in the thermal cracking reaction and significantly improve the heat sink. Jiao [9] et al. studied thermal cracking and thermal diffusion of aviation kerosene and found that with the increase of heat flow, the thermal conversion and gas production are significantly improved. Since aviation is a mixture of alkanes, olefins and aromatic hydrocarbons, it is difficult to study its properties and combustion process [10]. N-decane is popularly selected as a surrogate fuel because its chemical and physical properties is similar to kerosene. It was found [21, 22] that ethylene is the main product of n-decane after pyrolysis at 1300k. Thus ethylene is blended into n-decane with different proportions to simulate the state of n-decane after pyrolysis. There are few experimental studies in effect of pyrolysis on the MIE.

In this study, the high-speed schlieren technique is used to take the images of ignition and development of flame kernel in the constant volume combustion chamber. The correlation between flame kernel development speed and flame kernel radius was analyzed based on the development of flame kernel. Effect of ethylene blending ratio on the development of flame kernel was also investigated. Furthermore, an ignition probability model was established with logic regression theory and MIE of n-decane with different ethylene blending ratio was measured using the ignition probability model. The effect of ethylene blending ratio and ignition energy on MIE was studied experimentally as well.

2. Experimental setup
The experimental system is a constant volume combustion bomb, combined with plasma ignition device, gas circulation system, data acquisition system and high-speed schlieren system. The schematic diagram of the experimental system is shown in Figure 1. The constant volume combustion bomb is a stainless steel chamber whose inner diameter is 20cm and length is 25cm. Standard working pressure of the constant volume combustion bomb is from 0.01MPa to 4MPa and overall strength safety factor is 2.0%. The air leakage rate of the inner chamber is below 0.1% within 5 minutes. The temperature control system adopts internal heating method, the range of heating temperature is 20-230℃, and the inner wall of the projectile is resistant to high temperature for 300℃. A pair of quartz glass window is mounted at the ends of the cylindrical chamber and the surface of these two windows is finely ground. The light transmittance is more than 95%.
A low energy ignition system with good performance and repeatability is designed to carry out ignition experiments near MIE. In this experiment, a self-designed capacitor charge discharge ignition system is used. The system diagram is shown in Fig.2, which consists of DC power supply, diode, resistor, capacitor and control module. The DC power supply is 0-20kV continuously adjustable, the resistance is 100MΩ, and range of the capacitance is 200pF-0.1μF. The range of available output energy is 5-500mJ.

To ensure the equivalence ratio of fuel, the experimental platform is equipped with a gas circulation system that can be finely controlled, and a gas premixed tank whose gas intake and gas output can be accurately controlled. The premixed tank is designed with the idea of premixed before injected. A static pressure transmitter Rosemount 3051T is installed in the gas premixed tank and the chamber of constant volume combustion bomb, with a measurement accuracy of 0.02% F.S.

The schlieren system [11] used in the experiment is shown in Fig.3, including a light source, convex lens, a light knife and a high-speed camera. A xenon lamp is used as a continuous light source and parallel light path layout is adopted. The point light source is refracted by a convex lens whose diameter is 10 cm and focal length is 0.5 m to form a directional light. The imaging of the directional light is re-converged by another convex lens and captured by the Phantom-V2512 high-speed camera after being cut by a light knife. The parameters of the high-speed camera are set as resolution 1280×800, frame number 25000Fps, exposure time 1.5μs. The schlieren system uses the rising edge of
the current as the trigger signal triggering the camera to work through the pulse signal generator (DG535).

![Schlieren light path](image1)

![High-speed camera](image2)

**Fig.3** High-speed schlieren system

The electric parameter measurement system in the experiment is shown in Fig.4. The voltage parameters are measured by the high-voltage probe P6015A produced by Tektronix company, with a bandwidth of 75MHz and a measurement range of 0-40kV. The current measurement adopts Pearson 6600 current sensor with a range of 0-500A and a bandwidth of 120MHz. The measured voltage and current signals are collected by a four channel MDO3024 digital oscilloscope of Tektronix company.

![Oscilloscope](image3)

![Voltage probe](image4)

![Current sensor](image5)

**Fig.4** Signal acquisition equipment
3. Results and analysis

3.1. Ignition and development of flame kernel

![High speed schlieren images of ignition success and failure under different working conditions](image)

**Fig.5** High speed schlieren images of ignition success and failure under different working conditions
Fig. 6 Flame propagation speed flame size diagram under different ignition energy conditions under different working conditions.
In previous study [4], radius of flame kernel and flame velocity are key to analyze the development of flame kernel and it is found that there exists a critical length controlling self-sustain flame initiation. Only if radius of flame kernel is larger than the critical length can flame kernel develop into self-sustain flame. In this work, relation between flame velocity and radius of flame kernel is examined by schlieren images of flame kernel. Whether ignition is successful can be judged from relation between flame velocity and radius of flame kernel. Besides, effect of ethylene blending ratio and ignition energy on the development of flame kernel is analyzed.

Schlieren images of successful ignition and failure ignition are shown in Fig.5. The interval of each picture is 1ms in stoichiometric conditions ($\phi=1$) and 5ms in fuel-lean condition ($\phi=0.7$). It can be seen that in stoichiometric conditions, the change of the ethylene blending ratio has little effect on the development process of the flame kernel. When equivalence ratio is 0.7, it can be observed from the development process of the flame kernel that with the increase of blending ratio of ethylene, the development speed of flame kernel is obviously accelerated. The reason is that under the same fuel atomization conditions, the fuel and air are fully mixed when the equivalence ratio is 1, and the particle distribution of combustible mixture is relatively uniform, which is more favorable for the flame propagation. In fuel-lean condition, the mixing of fuel and air is not sufficient and the mixture is not uniform, blending of ethylene greatly improves the reactant activity of combustible mixture and shortens the time required for flame propagation, which improves the success rate of ignition. From the schlieren images, it can also be observed that there is a great difference in the boundary position in different ethylene blending ratio case, and this change gradually weakens with the increase of the blending ratio.

The relationship between flame propagation speed and flame size with different ignition energy can be obtained based on the schlieren images, as shown in Fig.6 (a)-(h). The development of flame kernel under the case of successful ignition is defined as two regimes [13], as shown in Fig. 6 (a). It can be seen that in regime $I$ the flame propagation velocity decreases with flame size and in regime $II$ increases for different values of ignition energy. There is an inflection point between two regimes. The reason for the two regimes and inflection point is that the magnitude of the initial energy is much larger than that of the combustion chemical reaction, the initial chemical reaction is very fast, thus, the initial development speed of the flame kernel is fast. However, for the combustible mixture whose Lewis number is larger than the critical Lewis number, due to the effect of heat diffusion and heat conduction, the ignition energy dissipates rapidly, so the combustion chemical reaction speed decreases afterward, correspondingly, the development speed of the flame kernel also decreases. It is also found that although the value of ignition energy is large enough, the initial development speed of the flame kernel in fuel-lean condition is smaller than that in stoichiometric condition. Because combustion chemical reaction is sensitive to reactant concentration and activity, and the reactant concentration of combustible mixture is small in fuel-lean condition, the initial speed of flame kernel development in stoichiometric condition is larger than that in fuel-lean condition. With the increase of the ignition energy, the final size of the flame kernel is also increasing. However, with the increase of ethylene blending ratio, the effect of ignition energy on the final size of the flame kernel is weakened. The reason is that larger the initial energy injected into the reactant is, shorter the time for regime $I$ is, thus the flame kernel can develop sufficiently in regime $II$ and the final size of the flame kernel is larger. When ethylene is blended into the fuel, the reactant concentration and reactant activity of the combustible mixture become higher, and the combustion chemical reaction intensifies. However, with the increase of the mixing ratio, the change of reactant concentration and activity is close to saturation, so the effect of blending ethylene weakens.

3.2. Measurement of MIE
Ignition is essentially a statistical phenomenon in engineering experiments [2,23]. In addition to the ignition process itself, numbers of uncontrolled variables such as the uncertainty of combustible mixture composition, discharge instability and discharge energy non-uniformity will affect the success
of ignition. Therefore, exploring the statistical nature of the ignition is of great significance to the understanding of the ignition process.

An ignition probability model is established with the logic regression theory, which is a simple method of binary response modeling. Based on the logistic regression model [14], the functional relationship between ignition probability \( P \) and energy \( E \) is obtained

\[
P(E) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 E)}}
\]

Where \( \beta_0 \) and \( \beta_1 \) are fitting parameters.

According to the above equation, the corresponding regression curve is obtained. Ko [15] defined MIE as the ignition energy with 50% ignition probability \( (P = 50\%) \), and obtained MIE as follows:

\[
MIE = (\ln \frac{50\%}{1 - 50\%} - \beta_0) / \beta_1 = -\frac{\beta_0}{\beta_1}
\]

Ignition probability is a parameter to characterize the ignition ability, which is used to compare the ignition ability of different discharge modes. Ignition probability \( P \) is defined as the ratio of successful ignition events \( m \) to total ignition attempts \( n \)

\[
P = \frac{m}{n}
\]

The ignition test is conducted using the ignition circuit and experimental equipment introduced above, and the energy stored in the discharge circuit is varied by changing the capacitance. If the ignition occurs at a given ignition energy, the result of the test is specified as "1" ("Ignition successful"), and if no ignition occurs, the result is "0" ("Ignition failure"). The established ignition probability model is used to evaluate the test data, and the probability distribution of ignition probability and ignition energy in different conditions is obtained, as shown in Fig.7. Judging from the probability distribution, a considerable part of the test data of ignition success and ignition failure overlap, which fully shows the uncertainty of the ignition process and shows that the ignition process is essentially a statistical phenomenon.

![Fig.7 Probability distribution of ignition probability and ignition energy](image-url)
The relationship between the ignition probability of conventional spark discharge and the number of ignition attempts is shown in Fig.8. It can be seen from Fig.8 that the sample size should not be less than 30 times for the ignition probability to reach a stable state. In order to obtain the accurate ignition probability under different working conditions, 40 ignition attempts were made under each working condition in this experiment.

The ignition probability regression curve can be obtained by substituting the ignition data of all working cases into the ignition probability model, as shown in the Fig.9.

![Fig.8 Ignition probability distribution curve](image1)

![Fig.9 Ignition regression curve](image2)

![Fig.10 Change of MIE with ethylene blending ratio](image3)

The spark energy with a 50% probability of ignition is defined as MIE. The results demonstrate that MIE of n-decane decreases with the increase of ethylene blending ratio in fuel-lean condition. However, the effect of ethylene blending ratio on MIE is weakening. As shown in the Fig.10, with the increase of ethylene blending ratio, MIE in condition decreases gradually, while in stoichiometric condition ethylene blending ratio impacts little effect on MIE of n-decane. The reason is that MIE is sensitive to the concentration and activity of reactants. When the ethylene blending ratio is 0.7, the value of MIE in fuel-lean condition is close to that in stoichiometric condition with no ethylene blending. The reason is that reactant concentration and activity is close to saturation with the increase of ethylene blending ratio.

4. Conclusion
In this study, relation between flame kernel radius and flame development velocity is investigated by schlieren images of flame kernel. Effect of ethylene blending ratio and ignition energy on
Development of flame kernel is analyzed. Measurement on MIE of n-decane is based on the ignition probability model. It can be found that MIE of n-decane is more sensitive to high active small molecule combustible gas such as ethylene in fuel-lean condition. In stoichiometric conditions ($\phi=1$), the blending of ethylene has little effect on MIE of n-decane. Based on the above analysis, the following conclusions can be drawn:

1. The development process of the flame kernel can be divided into two regimes when ignition is successful, and there is an inflection point between the two regimes. The flame kernel develops slowly in regime I and accelerate in regime II. If the development speed and size of the flame kernel reach a certain critical value, the development of flame will accelerate and self-sustaining combustion will come into being. Otherwise, the flame kernel will decay and the ignition will fail;

2. MIE of n-decane is sensitive to the blending ratio of ethylene in lean-fuel condition. With the increase of blending ratio of ethylene, MIE of n-decane decreases continuously, and the decrease range of MIE decreases gradually with the increase of blending ratio, indicating that there is a limit for the influence of blending ratio of ethylene on MIE of n-decane;

3. When the equivalence ratio is 1, the influence of ethylene blending ratio on MIE of n-decane is not significant, and it is found that MIE of n-decane decreases with ethylene blending ratio in lean mixture is similar to MIE when the equivalence ratio is 1.

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Reference
[1] Lindl, J. D., Amendt, P., Berger, R. L., Glendinning, S. G., Glenzer, S. H., Haan, S. W., & Suter, L. J. (2004). The physics basis for ignition using indirect-drive targets on the National Ignition Facility. Physics of Plasmas, 11(2), 339-491.
[2] Bane, S. P., Ziegler, J., Boettcher, P., Coronel, S., & Shepherd, J. E. (2013). Experimental Investigation of Spark Ignition Energy in Kerosene, Hexane, and Hydrogen. Journal of Loss Prevention in The Process Industries, 26(2), 290-294.
[3] Beduneau, J., Kim, B., Zimmer, L., & Ikeda, Y. (2003). Measurements of minimum ignition energy in premixed laminar methane/air flow by using laser induced spark. Combustion and Flame, 132(4), 653-665.
[4] Chen, Z., Burke, M. P. & Ju, Y. (2011). On the critical flame radius and minimum ignition energy for spherical flame initiation. Proceedings of the Combustion Institute, 33(1), 1219-1226.
[5] Cui, G., Zeng, W., Li, Z., Fu, Y., Li, H., & Chen, J. (2016). Experimental study of minimum ignition energy of methane/air mixtures at elevated temperatures and pressures. Fuel, 257-263.
[6] Oberlin, A., Villey, M., & Combaz, A. (1980). Influence of elemental composition on carbonization: Pyrolysis of kerosene shale and kuckersite. Carbon, 18(5), 347-353.
[7] Zhao, G., Song, W., & Zhang, R. (2015). Effect of pressure on thermal cracking of china rp-3 aviation kerosene under supercritical conditions. International Journal of Heat & Mass Transfer, 84, 625-632.
[8] Hou, L., Zhang, D., & Zhang, X. (2017). Interaction between thermal cracking and steam reforming reactions of aviation kerosene. Fuel Processing Technology, 655-662.
[9] Jiao, S., Li, S., Pu, H., Dong, M., & Shang, Y. (2019). Experimental investigation on thermal cracking and convective heat transfer characteristics of aviation kerosene RP-3 in a vertical tube under supercritical pressures. International Journal of Thermal Sciences,.
[10] Gang, Y. (2006). Analysis of thermophysical properties of Daqing RP-3 aviation kerosene. Journal of Propulsion Technology,.
[11] C. B. Wells. (1965). Knife-edge controller for a schlieren system. Applied Optics, 4(7), 815-818.
[12] Padala, S., Nishiyama, A., & Ikeda, Y. (2016). Flame size measurements of premixed propane-air mixtures ignited by microwave-enhanced plasma. Proceedings of the Combustion Institute, S1540748916302309.

[13] Beduneau, J. L., Kim, B., Zimmer, L., & Ikeda, Y. (2003). Measurements of minimum ignition energy in premixed laminar methane/air flow by using laser induced spark. Combustion and Flame, 132(4), p.653-665.

[14] Nick, T. G., & Campbell, K. M. (2007). Logistic regression. Methods in Molecular Biology, 404(404), 273.

[15] Ko, Y., Anderson, R. W., & Arpaci, V. S. (1991). Spark ignition of propane-air mixtures near the minimum ignition energy: Part I. An experimental study. Combustion and Flame, 75-87.

[16] Gillard P., Strozzi, C., Chehouna, & K. (2014). Minimum ignition energy measurements for alpha-pinene/air mixtures. Combustion Science & Technology.

[17] Lin, B., Wu, Y., Zhang, Z., & Chen, Z. (2017). Multi-channel nanosecond discharge plasma ignition of premixed propane/air under normal and sub-atmospheric pressures. Combustion and Flame, 102-113.

[18] Zhong, F., Fan, X., Yu, G., Li, J., & Sung, C. (2009). Thermal Cracking and Heat Sink Capacity of Aviation Kerosene Under Supercritical Conditions. Journal of Propulsion and Power, 25(6), 1226-1232.

[19] I. Sochet, & P. Gillard. (2002). Flammability of kerosene in civil and military aviation. Journal of Loss Prevention in the Process Industries, 15(5), 335-345.

[20] Kurdyumov, V. N., Blasco, J., Sanchez, A. L., & Linan, A. (2004). On the calculation of the minimum ignition energy. Combustion and Flame, 136(3), 394-397.

[21] J. Smolke, F. Carbone, F.N. Egolfopoulos, H. Wang (2018). Effect of n-dodecane decomposition on its fundamental flame properties. Combust. Flame. 190: 65.

[22] S.M. Sarathy, C.K. Westbrook, M. Mehl, W.J. Pitz, C. Togbe, P. Dagaut, H. Wang, M.A. Oehlschlaeger, U. Niemann, K. Seshadri (2011). Comprehensive chemical kinetic modeling of the oxidation of 2-methylalkanes from C7 to C20. Combust. Flame. 158: 2338.

[23] Bane, S. P., Shepherd, J. E., Kwon, E., & Day, A. C. (2011). Statistical analysis of electrostatic spark ignition of lean H2/O2/Ar mixtures. International Journal of Hydrogen Energy, 36(3), 2344-2350.