Study on initial combustion characteristics of kerosene based on inductive charging ignition system

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Abstract. Spark ignition is an important method to achieve combustion of in-cylinder mixture. The inductive charging ignition is considered to be a simple and effective ignition method. This study presents a circuit simulation model of this ignition system in MATLAB/Simulink and the effects of charging voltage, charging time and multi-pulse charging interval on ignition energy were calculated and the ignition energy value was obtained. The experimental study of the ignition system in a constant volume vessel was carried out to explore the influence of ignition energy on the initial combustion of kerosene. The results show that the simulation results match well with the experimental results. With the increase of ignition energy, the initial flame propagation of kerosene shows speed fluctuations and the higher ignition energy makes the propagation speed of flame fluctuate more obviously.

1. Introduction

As a forced ignition method, spark ignition can accurately control the ignition timing to meet the ignition requirements of the engine under different working conditions [1]. In addition, changing the ignition energy can also meet the ignition requirements of different fuels. Nowadays, the gasoline engine ignition system and technology for vehicle engines have been perfected. However, in the aviation piston engine with kerosene, the development of the ignition system still faces many difficulties. Compared with gasoline, the poor volatility and high viscosity of kerosene are not conducive to the formation of combustible mixture and the propagation of flame [2]. Under the same conditions, the requirements for ignition energy are higher, especially in cold start condition. Besides, lower auto-ignition temperatures and octane values make kerosene more susceptible to knocking than gasoline [3-5], so it is a big challenge for the ignition system to avoid engine knock.

In recent years, Scholars from all over the world have made great efforts in the design and development of ignition systems. Research and optimization design based on capacitor discharge ignition system were conducted, which improved the ignition energy [6, 7]. Some scholars studied the fast and efficient charging and testing of ignition systems [8]. Some scholars proposed a single-capacitor multiple discharge method on a two-stroke engine to improve in-cylinder combustion [9]. Besides, some scholars analyzed the effect of spark ignition on HCCI combustion characteristics on a direct-injection gasoline engine, and calculated the minimum ignition energy of spark-assisted HCCI [10, 11]. By combining spark ignition with HCCI in homogeneous mixed gas mode and high load, a spark induced compression ignition (SICI) combined combustion method was proposed [12]. In
addition, a method for calculating the minimum ignition energy was proposed for different fuels [13-15]. For the ignition system of aviation piston kerosene engine, the ignition characteristics and deflagration characteristics were studied, and a special control system was developed before the calculation and experimental study of ignition energy were carried out [16, 17].

In this paper, the inductive discharge ignition (IDI) system is the main research subject. The spark discharge process is studied and the simulation study is carried out for this type of ignition system by using MATLAB/Simulink. An optical experiment was performed in a constant volume vessel to verify the results of the simulation model. The initial combustion characteristics of kerosene was analyzed. The influence of ignition energy on the initial stage of kerosene combustion was explored. The results show that the charging time and charging voltage have a significant impact on ignition energy; multi-pulse ignition can effectively accumulate ignition energy and is an ideal high-energy ignition method. Higher ignition energy can significantly accelerate the flame propagation of kerosene. It is also found that ignition energy affects combustion schlieren of kerosene considerably which can be useful to improve combustion on future studies.

2. Methodology

2.1. Inductive discharge ignition system

IDI system stores magnetic energy by the inductor and converts magnetic energy into high-voltage electric energy to act on the spark plug [18]. The fire core formed between the spark plug electrodes is used to ignite the mixture to achieve combustion of the combustible mixture so as to keep stable operation of the engine. The IDI system is shown in Figure 1.

![IDI System Diagram](image)

**Figure 1.** Schematic diagram of inductive discharge ignition system.

The circuit of the primary coil can be viewed as a *RL* circuit with zero state response, where *R* is the primary coil resistance and *L* is the primary coil inductance. According to Kirchhoff’s voltage law (KVL), the differential equation of the circuit can be obtained as

$$L \frac{di_L}{dt} + Ri_L = U_s$$

(1)

Equation (1) is a first-order linear non-homogeneous differential equation. *U*<sub>s</sub> represents the supply voltage and the complete solution is composed of two parts: the special solution (*i*<sub>L</sub> = *i*<sub>L</sub>(*)t* → *U*<sub>s</sub> / *R*) and the corresponding homogeneous solution of the homogeneous differential equation (*i*<sub>L</sub> = *Ae*<sup>-t/τ</sup>). *τ* = *L*/ *R* is the time constant. According to the commutation law *i*<sub>L</sub>(0<sup>-</sup>) = *i*<sub>L</sub>(0<sup>+</sup>) = 0, the induced current is

$$i_L = \frac{U_s}{R} \left(1 - e^{-\frac{t}{\tau}}\right)$$

(2)

In the IDI system, the energy stored in the primary coil can be expressed by
In Equation (3), $E_t$ represents the energy stored in the primary coil, $L$ is the primary inductance value of the ignition coil and $I$ is the maximum current value when the primary loop of the ignition coil is turned off.

2.2. Spark ignition analysis

Ignition energy refers to the energy released at the moment of discharging between the positive and negative electrodes of the spark plug. During ignition, the high voltage generated between the electrodes of the spark plug will ionize nearby combustible mixture molecules and form a voltaic arc. Around the generated arc, the electric energy is converted into heat energy intensively. The nearby free fuel molecules and oxygen molecules tend to react under the action of high temperature, and the combustion occur consequently; the heat released by the reaction continues to heat the surrounding mixture. This process thus produce a chain reaction, and the burning flame spreads from a tiny core to the peripheral region. Establish mathematical model of ignition and flame core propagation and make the following assumptions:

- (1) The system is always in a thermodynamic equilibrium state;
- (2) The pressure in the burned zone and the unburned zone remains uniform;
- (3) Ideal gas law apply;
- (4) The size of the flame core is much smaller than the cylinder size;
- (5) The combustion mixture is in a chemical equilibrium state at all times;
- (6) The temperature of the flame core is sufficiently low, and the combustion dominates the expansion of the flame core. The effects of the heat conduction and thermal diffusion between the burned and unburned area are neglected.

Figure 2. Thermodynamic model of flame core in the early stage of combustion.

The mathematical model satisfies the conservation of mass, the first law of thermodynamics, and the law of conservation of energy. The model is shown in Figure 2. The relationship between the size of the flame core and the ignition energy in the initial stage of combustion can be calculated theoretically. Since the spark plug ignition process is very short, it is assumed that the combustible mixture between the positive and negative electrodes of the spark plug does not react chemically. In this process, the ignition energy $E_t$ can be expressed as
\[ E_2 = m_0 c_v \left( T_2 - T_1 \right) \]  

(4)

where \( m_0 \) is the mass of the mixture between the electrodes; \( c_v \) is the specific heat capacity; \( T_1 \) is the temperature of the mixture before electrode discharge; \( T_2 \) is the discharge temperature. When the discharge finish, the volume of high temperature mixture expands from \( V_1 \) to \( V_2 \), the temperature rises to \( T_3 \), and the pressure remains constant. According to the energy equation

\[ m_0 c_v \left( T_2 - T_1 \right) - m_0 c_v \left( T_3 - T_1 \right) = P \left( V_2 - V_1 \right) \]  

(5)

According to ideal gas law, it can be concluded that the flame core temperature \( T_3 \) is

\[ T_3 = \left[ \frac{1}{k} \left( \frac{T_2}{T_1} - 1 \right) + 1 \right] T_1 \]  

(6)

In the Formula (6), \( k \) is a specific heat ratio. According to the ball volume formula \( V = \frac{4}{3} \pi r^3 \), the initial radius \( r \) of the flame core can be calculated

\[ r = \left[ \frac{k - 1}{k} \cdot \frac{3E_2}{4P \pi \left( 1 - \frac{T_1}{T_3} \right)} \right]^{\frac{1}{3}} \]  

(7)

### 2.3. Simulation model

The circuit simulation model of the IDI system based on MATLAB/Simulink is shown in Figure 3. The value of the ignition energy can be calculated by the simulation. The meanings and values of the parameter symbols in the circuit are shown in Table 1. The simulation model includes a primary loop and a secondary loop. 12VDC is used as the power supply in the primary circuit. The switch controlled by the PWM signal in the circuit controls on and off. When the Switch is turned on, the power supply charges the coil inductor; when the Switch is turned off, the primary coil begins to discharge gradually, and a mutual inductance electromotive force is generated in the secondary coil.

![Figure 3. Ignition system circuit simulation model.](image-url)
Table 1. Ignition system circuit model parameters settings.

| Parameter | Meaning                                           | Value  |
|-----------|---------------------------------------------------|--------|
| $R_1$     | Primary coil equivalent resistance                | 1.5Ω   |
| $C_1$     | Primary coil equivalent capacitance               | 0.3μF  |
| $R_2$     | Secondary coil equivalent resistance              | 10kΩ   |
| $C_2$     | Equivalent capacitance of secondary coil and spark plug | 70pF   |
| $R_g$     | Spark plug equivalent resistance                  | 1MΩ    |
| $L_1$     | Primary coil inductance                            | 4.5mH  |
| $L_2$     | Secondary coil inductance                          | 13H    |
| $\varepsilon$ | Turn ratio                                          | 50     |

2.4. Experimental setup

The experiment was carried out in a constant volume vessel to study the characteristics of flame core and flame propagation during combustion. This experiment can verify the mathematical calculation model and investigate the influence of the ignition characteristics on kerosene combustion characteristics. The test system is shown in Figure 4. It mainly consists of seven subsystems: constant volume vessel, ignition control system, thermal insulation and sealing system, heating control system, intake and exhaust system, optical schlieren system and data acquisition system. The schlieren method is used to detect the flame boundary and a high-speed camera is used to capture and record the flame combustion process. This experiment used TRI's Phantom v7.3 high-speed camera, which used a lens focal length of 105 and an aperture of 2.8. The basic shooting speed is 10000 fps, the exposure time is 20 μs, and the pixel size is 512×512. The photographing process starts with a trigger signal that is synchronously controlled by the ignition signal to implement timing control.

The principle of the schlieren method is to convert invisible density changes into visible amplitude or color changes. In the experiment, there is a large density gradient between the reactants in the unburned zone and the combustion products (water and carbon dioxide) in the burned zone, and the flame boundary can be obtained by the schlieren measurement, so that the burning speed of the flame can be obtained.

![Figure 4. Test system schematic.](image-url)

1-Steady state pressure gauge; 2-Vent; 3-Combustion chamber; 4-Pressure sensor; 5-Electric heating rod; 6-Pedestal; 7-Insulation materials; 8-Spark plug; 9-High pressure gauge; 10-Low pressure gauge; 11-Precision pressure gauge; 12-Temperature Sensor; 13-Fuel inlet; 14-Upper spark plug mounting hole.
3. Results & Discussion

3.1. Simulation study results

As shown in Figure 5, the charging time is 4 ms. As the charging voltage increases, the ignition energy also increases, but the ignition energy does not increase linearly with the charging voltage. This means that the influence of different charging voltage of the primary coil on the ignition energy differs. However, the excessive charging voltage cannot be unified with the power supply of the engine and other electronic devices of the vehicle. The high voltage can easily cause interference to the entire electrical control system; in addition, the excessive charging voltage may cause the coil to overheat which will damage the coil and affect its reliability.

![Figure 5. Effect of charging voltage on ignition energy of PEI.](image)

The charging voltage of the primary coil is set to 18V. Figure 6 demonstrates that when the charging time of the primary coil is gradually increased from 1 ms to 7 ms, the ignition energy grows linearly between 1ms and 4 ms. After 4 ms, the increasing trend of ignition energy gradually slows down; after 7 ms, the ignition energy comes to saturated state and hardly changes with the increase of charging time.

![Figure 6. Effect of charging time on PEI ignition energy.](image)
The multi-pulse ignition method can accumulate the ignition energy, thereby improving the possibility of successful ignition. The charging time corresponding to the single pulse is 4 ms, the pulse number is 3, and the multi-pulse interval is 0.25 ms, 0.50 ms, 0.75 ms, 1.00 ms and 1.25 ms.

The Figure 7 shows that when the multi-pulse interval is 0.25 ms, the first ignition energy is only 124.5 mJ, which is much smaller than the ignition energy at the single pulse ignition. When the time interval of multiple pulses is gradually increased from 0.25 ms to 0.75 ms, the total ignition energy of the three ignitions increases significantly. When the time interval of multiple pulses is greater than 0.75 ms, the ignition energy of the three ignitions does not change too much. The total energy is highest when the multi-pulse interval is 0.75 ms.

![Figure 7. Effect of Multi-pulse Interval on PEI Ignition Energy.](image)

3.2. Effect of ignition energy on initial combustion characteristics of kerosene

Based on above experiment system, an experimental study of kerosene combustion was carried out and the ignitability of kerosene was analysed. Ignition is performed by IDI which is powered by a 12VDC power supply. The ignition energy is varied by adjusting the coil charging time. From the previous ignition energy simulation study, the ignition energy value can be obtained when the coil charging time is 1~4ms, as shown in Table 2.

Table 2. Ignition energy values for different coil charging times.

| Primary coil charging time | Ignition energy $E_2$ |
|---------------------------|-----------------------|
| 1 ms                      | 4.5 mJ                |
| 2 ms                      | 25.7 mJ               |
| 3 ms                      | 47.2 mJ               |
| 4 ms                      | 64.9 mJ               |

Figure 8 shows the variation of the initial flame core radius of kerosene combustion at different charging times. The ambient temperature was $T = 500$ K, the ambient pressure was $P = 0.10$ MPa, and the equivalent ratio is $\phi = 1.0$. The figure demonstrates that the measured $r$ increases with the increase of the ignition energy $E_2$ and the trend is consistent with the theoretical value. The Equation (7) illustrates that there is a theoretical cubic relationship between $r$ and $E_2$, that is $r^3 \propto E_2$. By calculation, the test actual value also satisfies the relationship in the Equation (7), thereby verifying the reliability of the test data. Therefore, it is known from the test results that the initial flame core radius $r$ is effectively increased by increasing the ignition energy $E_2$. 

![Figure 8. Variation of initial flame core radius.]
Boundary conditions:
kerosene
$T = 500K$
$P = 0.10MPa$
$\phi = 1.0$

| $E_2$ (mJ) | $r$ (mm) |
|------------|----------|
| 4.5        | 3.91     |
| 25.7       | 6.99     |
| 47.2       | 6.52     |
| 64.9       | 8.04     |

Initial flame core radius $r$ (mm)

Ignition energy $E_2$ (mJ)

Actual $r$
Theoretical $r$

Figure 8. The initial flame core radius of kerosene combustion under different ignition energies.

Figure 9 shows the contrast of the kerosene combustion flame developed under different ignition energies. The ambient temperature of the test was $T = 500$ K, the ambient pressure was $P = 0.10$ MPa, and the equivalent ratio is $\phi = 1.0$.

Figure 9. Combustion schlieren of kerosene under different ignition energies.

As shown in Figure 10, it can be seen that the initial radius of the flame is different under different ignition energies at 3 ms. The larger the ignition energy, the larger the flame radius at this moment. With the increase of time, for the ignition energy of 4.5 mJ, the flame grows steadily and linearly during the whole process. This implies that since the ignition energy is too small, the combustible mixture around the spark plug is difficult to be completely ignited. As a result, the propagation power of flame is never greater than the propagation resistance of unburned zone during the propagation. The
flame propagation radius at the same time is smaller than the other three sets of ignition energy, which indicates that the flame propagation speed is always smaller than the other three groups. For the ignition energy of 25.7 mJ, 47.2 mJ and 64.9 mJ, the larger ignition energy can achieve the larger flame radius at the same time. From the change in slope of flame radius of these three sets of ignition energy, obvious acceleration process, constant speed section and deceleration section occur during the flame propagation. This implies that during the initial combustion of kerosene, the flame propagation speed fluctuates significantly. In addition, comparing flame propagation radius of different ignition energies, the result shows that as the ignition energy increases, the difference gradually decreases. It is inferred that when the ignition energy is greater than a certain value, its effect on flame propagation is significantly reduced. It can be concluded that an appropriate increase in ignition energy helps to accelerate flame propagation.

![Flame propagation radius and time](image)

**Figure 10.** Development of kerosene combustion flame under different ignition energies.

4. Conclusions
The working principle of the IDI system and the discharge process of spark ignition are analysed. The simulation study is carried out with MATLAB/Simulink. Through the experimental study, the initial development of the flame core of kerosene was obtained. The influence of different ignition energy on the kerosene flame core was explored. The results of this study can provide recommendations for the design of the ignition system. The optimum ignition energy can be calculated by coordinating the charging voltage and charging time. The experimental study on initial combustion experiment characteristics of kerosene can also provide reference for further research.

1) Establish a mathematical model of spark ignition and conclude that the ignition energy is proportional to the cube of the radius of the flame core.

2) The simulation results show that the ignition energy increases with the increase of charging voltage and the growth trend is obvious. With the increase of charging time, the ignition energy gradually increases but tends to be saturated. Multi-pulse ignition can effectively accumulate ignition energy and the total ignition comes to highest when the interval of multi-pulse ignition is 0.75ms.

3) With the increase of ignition energy, the flame propagation speed of kerosene gradually increases and shows a significant speed fluctuation. Higher ignition energy makes the flame propagation speed fluctuate more obvious.
References

[1] Dale J D, Checkel M D and Smy P R 1997 Application of high energy ignition systems to engines Progress in Energy and Combustion Science 23(5-6) 379-398

[2] Hu J C, Liu B L, Zhang C, Gao H L, et al. 2019 Experimental study on the spray characteristics of an air-assisted fuel injection system using kerosene and gasoline Fuel 235(2019) 782-794

[3] Hu C M, Wang S D, Bi Y F and Zhong W J 2017 Combustion characteristics of direct injection piston aviation kerosene engine Journal of Aerospace Power 32(05) 1035-1042

[4] Ma H G, Xie M Z, Zeng W and Chen B D 2016 Experimental study on combustion characteristics of Chinese RP-3 kerosene Chinese Journal of Aeronautics 29(02) 375-385

[5] Li J, Zhou L, Zhao Z F, Wang X L and Zhang F J 2019 Research on knocking characteristics of kerosene spark-ignition engine for unmanned aerial vehicle (UAV) by numerical simulation Thermal Science and Engineering Progress 9(2019) 1-10

[6] Liu N, Hu C M and Zhou N H 2006 Research and improvement of digital ignition system for small gasoline engine Small Internal Combustion Engine and Vehicle Technique 35(5) 33-35

[7] Zhou K F, Li X Q and Yin H X 2007 A study on selection of parameters for capacitor discharge ignition device Automotive Engineering 29(5)

[8] Zhang Q, Xu G Q and Du F R 2012 Aero piston engine capacitor discharge ignition system optimization research and design Journal of Aerospace Power 27(2)

[9] Liu R, Wei M X, Bei T X, Ji H C and Chang C 2017 Design and experiment of multi capacitor discharge ignition system Journal of Aerospace Power 32(2)

[10] Wang Y, Shi J T, Wang J, Wang X Y and Liu G 2007 Study on the minimum ignition energy of spark-assisted HCCI combustion Vehicle Engine 2007(3)

[11] Wang Z, Wang J X, Shuai S J and Ma Q J 2005 Effect of spark ignition on HCCI combustion in a gasoline direct injection engine Transactions of CSICE 23(2) 105-112

[12] Wang Z, Xu F, Yang D B and Wang J X 2009 Experimental research of spark induced compression ignition (SICI) combustion Transactions of CSICE 27(1) 11-17

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

[14] W Hner A, Gramse G and Langer T 2013 Determination of the minimum ignition energy on the basis of a statistical approach Journal of Loss Prevention in the Process Industries 26(6) 1655-1660

[15] Kondo S, Takahashi A and Tokuhashi K 2003 Calculation of minimum ignition energy of premixed gases Journal of Hazardous Materials 103(1-2) 11-23

[16] Yang G, Wei M X and Hou X L 2013 Development of ignition control system for electronic controlled kerosene piston engines Agricultural Equipment & Vehicle Engineering 51(3) 26-29

[17] Wolk, Benjamin, Defilippo Anthony, Chen Jyh-Yuan and Dibble Robert 2013 Enhancement of flame development by microwave-assisted spark ignition in constant volume combustion chamber Combustion & Flame 160(7) 1225-1234

[18] Pugi L, Reatti A, Mastromauro R A and Corti F 2018 Modelling of inductive resonant transfer for electric vehicles International Journal of Electric and Hybrid Vehicles 10(2) 131-160