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The Effects of Ignition Delay and Fuel Injection Duration on Sparked-Spray Combustion Using Gasoline and Methanol in the Atmospheric Environment

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Abstract: The sparked-spray method represents a novel combustion approach that employs an electrical spark to directly ignite fuel spray through cooperative control of fuel injection and spark ignition timing, forming an intense flame kernel for enhanced combustion performance. This method offers potential advantages in combustion efficiency and flame propagation characteristics compared to conventional ignition strategies. This paper investigated the effects of ignition delay and fuel injection duration on sparked-spray combustion characteristics using gasoline and methanol as test fuels in an atmospheric environment through high-speed photography. The study systematically examined the relationship between ignition timing parameters and combustion performance by analyzing projected flame area as a quantitative measure of flame intensity. Experimental results demonstrate that optimal ignition occurs when the ignition delay is 1.2 ms or 1.5 ms, where the spray is more readily ignited and produces larger projected flame areas under identical injection duration conditions. Furthermore, regardless of injection duration variations, methanol spray consistently exhibits superior combustion characteristics, generating larger projected flame areas and longer flame survival duration compared to gasoline spray.

Keywords: methanol spray; gasoline spray; fuel injection duration; ignition delay; projected flame area

1. Introduction

The global pursuit of carbon neutrality has intensified research into zero-carbon and low-carbon fuels. While hydrogen represents an ideal zero-carbon fuel, widespread adoption faces significant challenges due to high transportation and storage costs [1]. Ammonia has emerged as a promising alternative, offering dual functionality as both a zero-carbon fuel and a hydrogen carrier [2].

Compared to hydrogen, ammonia presents several practical advantages. It can be liquefied at 20° C under relatively modest pressure (less than 10 bar), making transportation and storage significantly more cost-effective [3]. Additionally, ammonia can be produced more easily and economically than hydrogen, ensuring a reliable supply at scale [1]. These characteristics have positioned ammonia engines as a focal point of current research efforts.

However, the primary challenge in ammonia internal combustion engines lies in overcoming ammonia's inherently poor combustion characteristics [4]. This challenge parallels the ignition difficulties and slow combustion rates observed in ultra-lean gasoline combustion [5]. Consequently, advances in ultra-lean gasoline combustion research provide valuable insights for developing ammonia engine technology. Mazda Corporation [6] pioneered breakthrough work in this field in 2019 with their Spark Controlled Compression Ignition (SPCCI) technology for ultra-lean combustion. This innovative system employs multiple fuel injections combined with high swirl ratios to create richer mixtures around the spark plug, ensuring reliable ignition. The rapid combustion of this enriched region acts as an "air piston", compressing the surrounding ultra-lean mixture and triggering compression ignition, thereby shortening combustion duration and enhancing thermal efficiency. Building upon this concept, Hu et al. [7] introduced an innovative approach in 2020 using gasoline and ethanol-gasoline blends in an optical single-cylinder engine. Their strategy involved creating a homogeneous ultra-lean pre-mixture through multiple early injections, followed by a brief final fuel injection (termed 'tail injection') immediately before spark timing. The spark directly ignites this tail injection spray, forming a 'moving ultra-high-energy ignition source' that reliably ignites low-reactivity lean mixtures. They designated this technique sparked-spray induced combustion (SSIC) [8]. Toyota Corporation [9] further validated the potential of sparked-spray ignition in 2023. Their experiments with direct-injection gasoline engines under ultra-lean conditions (excess air ratio of 2.5) demonstrated that the ignited tail injection spray effectively extended the lean burn limit while significantly improving thermal efficiency and reducing nitrogen oxide emissions. The study indicated that future engines incorporating sparked-spray ignition could potentially achieve thermal efficiencies exceeding 50%. Given the demonstrated success of SSIC in gasoline engine lean combustion, researchers have begun exploring its application for ammonia combustion enhancement. Yu et al. [10] investigated this concept in a constant volume combustor, using a spark-ignited micro gasoline injector to ignite premixed ammonia-air mixtures. Their findings revealed that igniting small quantities of gasoline dramatically increased both combustion intensity and rate compared to direct ammonia-air ignition.

However, existing ammonia combustion studies have relied on high-carbon fuels, creating an urgent need to identify low-carbon or zero-carbon alternatives for tail injection. This requirement has sparked interest in more environmentally sustainable fuel options. Methanol has emerged as particularly attractive among alternative fuels for ammonia combustion enhancement [11]. As a 'carbon-neutral' fuel, methanol offers high oxygen content, excellent combustion properties [12], and remains liquid under atmospheric conditions [13]. Recent investigations of synthetic gasoline-like fuels have revealed distinct physical and chemical properties compared to conventional gasoline, significantly affecting spray atomization and combustion behavior in advanced engine systems [14, 15]. Methanol exhibits unique spray characteristics under various injection conditions, which proves critical for optimizing fuel injection strategies in advanced combustion systems. Research has consistently demonstrated methanol's effectiveness in enhancing ammonia combustion. Wang et al. [16] investigated methanol's promotional effects through simulations of ammonia/methanol engine combustion with pilot diesel injection. Their results revealed substantial engine power increases when methanol content increased from 0% to 20%. Xu et al. [17] conducted numerical studies of ammonia/methanol blend combustion, finding that 20% methanol addition increased peak laminar burning velocity by 60%.

Based on the previous study [10], which established that SSIC is an efficient method for mitigating ammonia's combustion challenges, this paper further investigates the effects of ignition delay and fuel injection duration on the ignition of gasoline and methanol sprays in a constant volume vessel (CVV). Additionally, the combustion performance following ignition was compared between gasoline and methanol sprays by measuring the projected flame area. These findings provide a foundation for subsequent research on ammonia ignition using sparked-spray technology.

2. Experimental Setup

2.1. Experimental Facility

Figure 1 shows the experimental platform, which is mainly composed of a CVV, a high-pressure fuel injection system, an ignition system, a control system, and a high-speed photography system. The CVV is equipped with two pieces of quartz glass and equipped with a fuel injector and spark plug on top. The high-pressure fuel injection system mainly consists of a fuel (methanol or gasoline) tank, a fuel pump, and a fuel injector. The ignition system consists of an ignition coil and a spark plug. The high-speed photography system is based on a Phantom VEO 610 (Vision Research, Wayne, NJ, USA) high-speed camera and a computer with camera control software. The camera triggers synchronously with the fuel injector. The control system is based on NI Compact-RIO (National Instruments, Austin, TX, USA) and LabVIEW (National Instruments, Austin, TX, USA), and injection and ignition control programs are integrated into a LabVIEW program. The schematic diagram of the control delay is shown in Figure 2. The injector will start injecting fuel into the CVV, then the spark plug begins to ignite after the set ignition delay, while the camera starts to capture synchronously. Table 1 shows the experimental parameters.

During the injection process, the high-pressure fuel (20 MPa) rapidly atomizes upon entering the atmospheric environment, creating fine droplets that immediately begin to evaporate. This creates a region of fuel vapor-air mixture around the spray periphery, which provides the combustible medium for spark ignition. The timing coordination between injection and ignition is critical to ensure adequate fuel vapor concentration at the spark plug location.

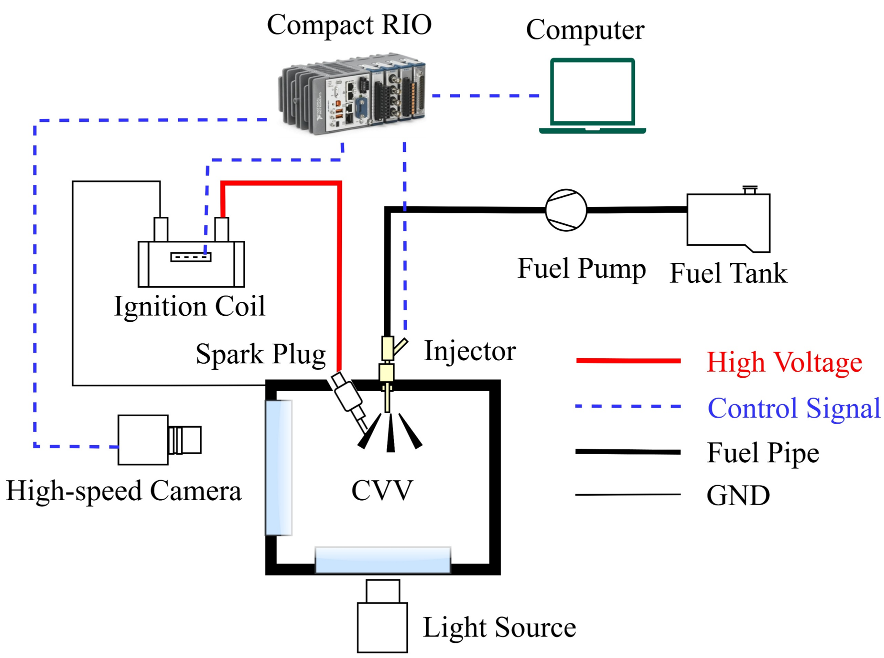

Figure 1. The experiment platform of a constant volume vessel.

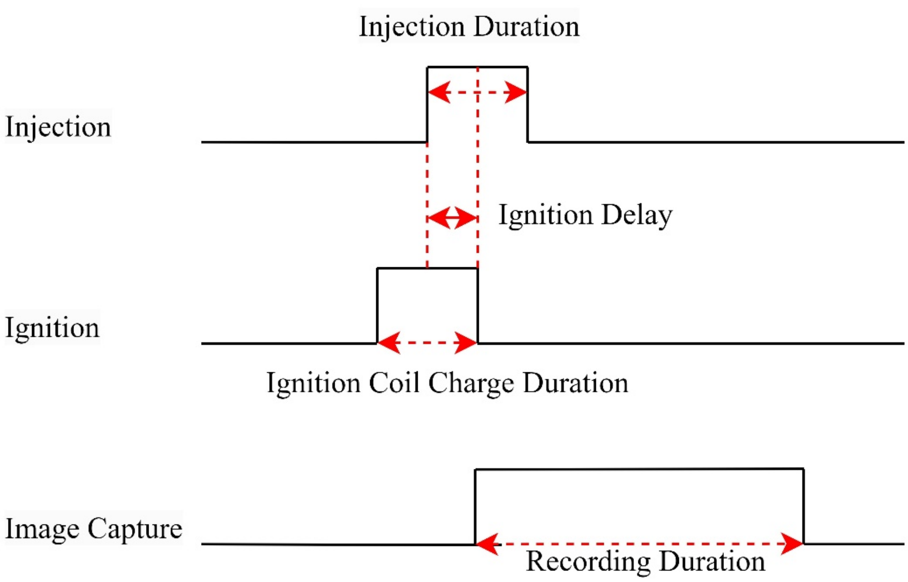

Figure 2. Schematic diagram of control delay.

Table 1. Experiment-related parameter settings.

Parameters	Values
Ambient temperature	298 K
Ambient pressure	0.1 MPa
Fuel injection pressure	20 MPa
Fuel injection duration	0.25 ms/0.30 ms/0.35 ms
Ignition coil charging time	8 ms
Ignition delay	0 ms–2.5 ms
Ignition energy	57.5 mJ
Image capturing pixels	560 × 528
Image capturing frequency	10,000 Hz
Image exposure time	90 μs

2.2. Image Processing

The projected flame area extracted from digital images serves as a critical parameter in this study for quantifying flame intensity. To obtain this parameter, digital image processing techniques are implemented using MATLAB code. The computational methodology employs a pixel-wise analysis approach, whereby each pixel in the image is systematically evaluated based on its green (G) channel intensity value. A threshold-based classification scheme is applied, where pixels exhibiting G channel values greater than 150 are identified and classified as flame regions. The projected flame area is then calculated by summing the total count of pixels that meet this threshold criterion.

2.3. Fuel Comparison Methodology

In this study, gasoline and methanol were compared using equivalent injection durations (i.e., equivalent volumes) rather than equivalent energy content. While methanol and gasoline have different energy densities, the volume-based comparison approach was selected for the following reasons:

First, this research focuses primarily on the ignition characteristics and flame initiation behavior of sparked-spray combustion rather than the overall energy release or combustion efficiency. The key objective is to investigate how ignition delay and injection duration affect the ability to establish and sustain a flame kernel, which is more dependent on fuel volatility, atomization characteristics, and ignitability rather than energy content.

Second, the volume-based approach aligns with practical fuel injection system design, where fuel delivery is typically controlled by injection duration and pressure, making this comparison methodology more relevant to real-world applications.

Third, as this study serves as a foundation for subsequent research on ammonia combustion enhancement using sparked-spray ignition, the focus is on evaluating the ignition promotion capability of different pilot fuels rather than their energy contribution. The superior performance of methanol observed in this study is attributed to its higher volatility and oxygen content, which facilitate vapor formation and flame propagation, rather than its energy density.

While energy-equivalent comparison would provide additional insights into combustion efficiency, the current methodology is appropriate for the specific research objectives of characterizing ignition behavior and establishing optimal sparked-spray parameters for future ammonia combustion applications.

3. Results and Discussions

3.1. Spark Changes at Different Ignition Delays

To enhance the visibility of the spray, spark, and flame within the imagery, the captured images were cropped to establish a proportional representation. Specifically, the aspect ratio allocated to the spray (Figure 3), spark (Figure 4), and flame (Figure 6) images was 4:1:1, respectively.

Figure 3 illustrates the spray development characteristics of gasoline and methanol under the condition of 0.25 ms injection duration (where G denotes gasoline and M denotes methanol). The red circles indicate the sparkplug location within the combustion chamber. Visual analysis reveals that the methanol spray exhibits accelerated propagation, reaching the spark plug region more rapidly compared to the gasoline spray. These observations demonstrate that methanol spray develops at a faster rate than gasoline spray during the same time interval following injection initiation, indicating superior atomization and penetration characteristics of methanol under the tested conditions. The spray development images show the liquid fuel penetration, while combustion occurs at the vapor-air interface where sufficient fuel vapor concentration exists. The faster propagation of methanol spray observed in Figure 3 facilitates more rapid vapor formation due to methanol's higher volatility compared to gasoline, creating more favorable conditions for ignition.

Figure 4 displays combustion images with four ignition delays (0 ms, 0.2 ms,0.5 ms, and 0.8 ms) at 0.35 ms fuel injection duration. The images reveal that at the ignition delays of 0 ms and 0.2 ms, the spark has significant deformation with methanol spray at the time of 0.2 ms and 0.5 ms after ignition. The reason may be that the speed of methanol spray is faster than the gasoline spray, which leads to more spray kinetic and more effect on the spark. When the ignition delays are set to 0.5 ms and 0.8 ms, the injection process has ended at ignition time, the remained spray kinetic is reduced, which decreases the impact on sparks and results in less deformation.

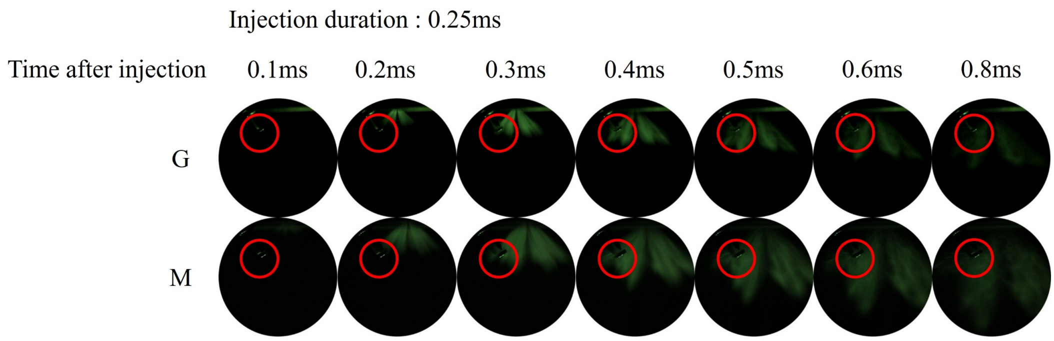

Figure 3. Gasoline and methanol spray injection process.

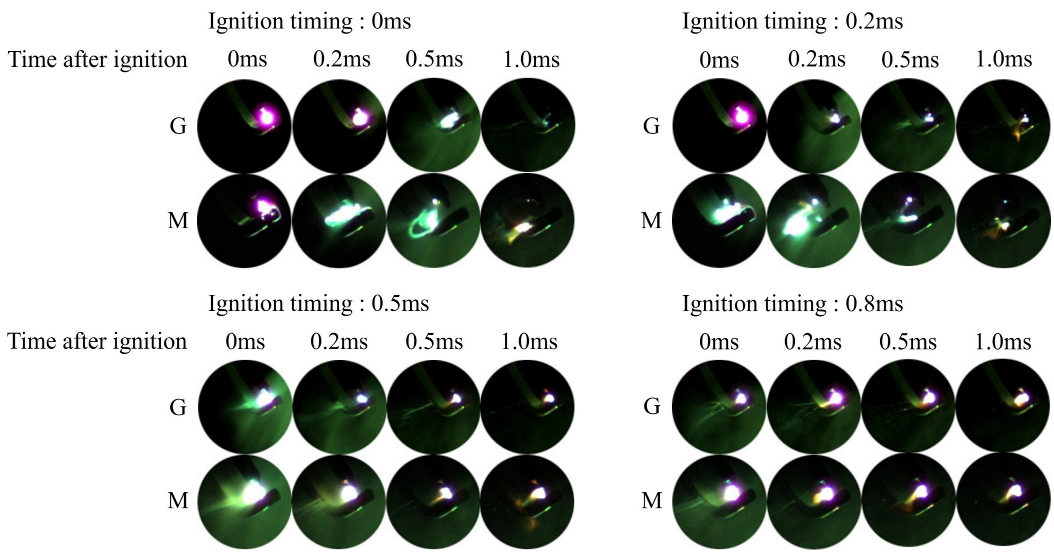

Figure 4. Spark changes at different ignition delays.

Figure 5 displays the relative projected flame area of the ignited spray with different injection durations and ignition delays. The *RPFA* represents the intensity of combustion, which is a dimensionless number. The formula of *RPFA* is (1).

$$RPFA = \frac{PFA}{PFA_{\min}} \tag{1}$$

PFA represents the number of pixels representing flames in the image, $PFA_{\min}$ represents the number of flame pixels in the image representing the minimum flame area.

Compared with the gasoline spray curves, it is observed that there is a sharp peak when the ignition delay is 0.5 ms because of the spark deformation.

Compared with the methanol spray curves, it demonstrates that the sharp peaks of the curves appear at ignition delays of 0 ms and 0.2 ms, it is because the faster speed of the methanol spray causes significant deformation of the spark. When the ignition delay is set to 0.5 ms, two peaks can be observed in a curve; the first peak contributes to the spark deformation, and the second peak represents the continued development of the *RPFA*. When the ignition delay is adjusted to 0.8 ms, the first sharp peak, which resulted from the spark deformation in Figure 5a–c almost disappears. This is because the injection process has already ended at ignition time. As a result, the change of the *RPFA* is insignificant, with a slight peak only appearing at the methanol injection duration setting of 0.35 ms. This may be due to the slightly later end of injection caused by the longer injection duration, and hence causes spark deformation.

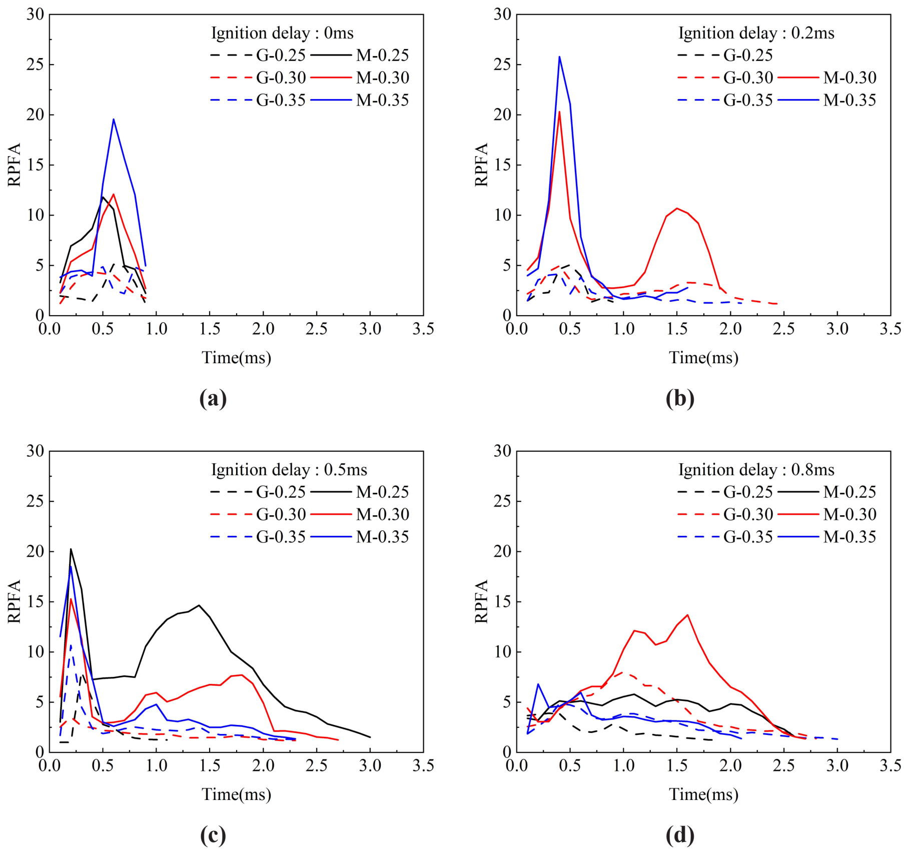

Figure 5. *RPFA* curves at different ignition delays, the ignition delay of (**a**) is 0 ms, the ignition delay of (**b**) is 0.2 ms, the ignition delay of (**c**) is 0.5 ms, and the ignition delay of (**d**) is 0.8 ms.

In Figure 5b, when the ignition delay is 0.2 ms and the injection duration is 0.3 ms, the ignition of the methanol spray will form a flame that continues to develop, which is manifested as the second peak. Conversely, when the injection duration is increased to 0.35 ms, no secondary peak can be observed. This phenomenon may be attributed to the larger spray kinetic associated with a longer injection duration. Under the condition of a 0.2 ms ignition delay, the spray concentration near the spark plug may be insufficient to sustain the flame, resulting in a weak flame that can be extinguished by the larger kinetic energy. On the other hand, the kinetic energy produced by a 0.3 ms injection duration is not enough to extinguish the flame, allowing the flame kernel to continue developing. This phenomenon can be further confirmed by combining the analysis of Figure 5a, c. In Figure 5a, due to the ignition delay is 0 ms, the fuel concentration near the spark plug is insufficient for the flame to develop fully, hence no second peak is formed. In Figure 5c, a 0.5 ms ignition delay increases the spray concentration around the spark plug, allowing the ignited flame to resist the impact of spray kinetic without being extinguished. Even so, the size of the flame is still affected by the spray kinetic, and a longer injection duration carrying greater spray kinetic may lead to a reduction in the *PFA* of the newly ignited flame. Therefore, to ensure the successful development of the flame, it is crucial that the spark plug is surrounded by an appropriate concentration of spray at the time of discharge, and at the initial stage of fire kernel formation, the kinetic of the fuel spray must be moderate to avoid extinguishing the nascent fire kernel.

3.2. Ignition Characteristics of Gasoline and Methanol Sprays

Figure 6 demonstrates the combustion process at four different ignition delays (0.5 ms, 1.5 ms, 2.0 ms, 2.5 ms). Comparing the combustion images of the gasoline and methanol sprays at the four different ignition delays, it is evident that the *PFA* formed by the methanol spray is significantly larger than that of the gasoline spray. This phenomenon indicates that methanol is easier to ignite and the methanol flame is more intense than the gasoline flame. This may be due to the oxygen content of methanol.

Figure 7 shows the *RPFA* change with different injection durations and ignition delays. For methanol, when the ignition delay is 0.5 ms and 1.5 ms, the *RPFA* decreases with the increase in the injection duration. When the ignition delay is 2.0 ms, the *RPFA* for sprays ignited with 0.25 ms and 0.30 ms injection durations were similar. However, when the injection duration was increased to 0.35 ms, the *RPFA* decreased significantly. This is because of the fuel kinetic. When the ignition delay is set to 2.0 ms, the earlier end of injection for the 0.25 ms and 0.30 ms injection durations, along with the decrease in methanol concentration around the spark plug, results in a similar size of the *RPFA* after ignition. For the condition with an injection duration of 0.35 ms, remained fuel kinetic persist due to the delayed end of injection.

The fuel kinetic affects the newly ignited flame, resulting in a decrease in the *RPFA*. Further, when the ignition delay is 2.5 ms, the remained fuel kinetic for all three different injection durations is not sufficient to significantly affect the flame, which may lead to some fluctuations in the *RPFA* as the concentration of methanol in the vicinity of the spark plug continues to decrease. The gasoline case is slightly different. Figure 7b–d all show that the peak of the *RPFA* occurs between 0.5–1.0 ms after ignition, and their values are similar. This is because the flame produced by igniting the gasoline spray is relatively small and unstable, so the spark area is the main part of the gasoline flame area in all three cases.

Figure 7 indicates that, regardless of the injection duration conditions, the *RPFA* resulting from the ignition of methanol spray is generally larger than that of gasoline spray at the same ignition delay. Furthermore, the survival duration of the flame resulting from the ignition of the methanol spray is generally longer than that of the gasoline spray. This suggests that the methanol spray can contribute to a more intense and prolonged combustion process compared to the gasoline spray.

3.3. Optimal Ignition Delay for Methanol Spray Ignition

Figure 8a – c depicts the variations in the *RPFA* obtained from igniting methanol spray at different ignition delays in three injection duration conditions. Figure 8d depicts the ignition delay corresponding to the maximum *RPFA* obtained under the three fuel injection duration conditions.

Despite the presence of unstable conditions, the *RPFA* shows a trend of first increasing and then decreasing with the increase of ignition delay. The maximum *RPFA* resulting from the ignition of the methanol spray occurs at the ignition delay of 1.5 ms when the injection duration is 0.25 ms. When the injection duration is 0.30 ms and 0.35 ms, the maximum *RPFA* occurs at the ignition delay of 1.2 ms and 1.5 ms, respectively. Referring to the three curves in Figure 8d, it shows that the *RPFA* obtained by igniting the methanol spray decreases as the prolongation of injection duration is prolonged.

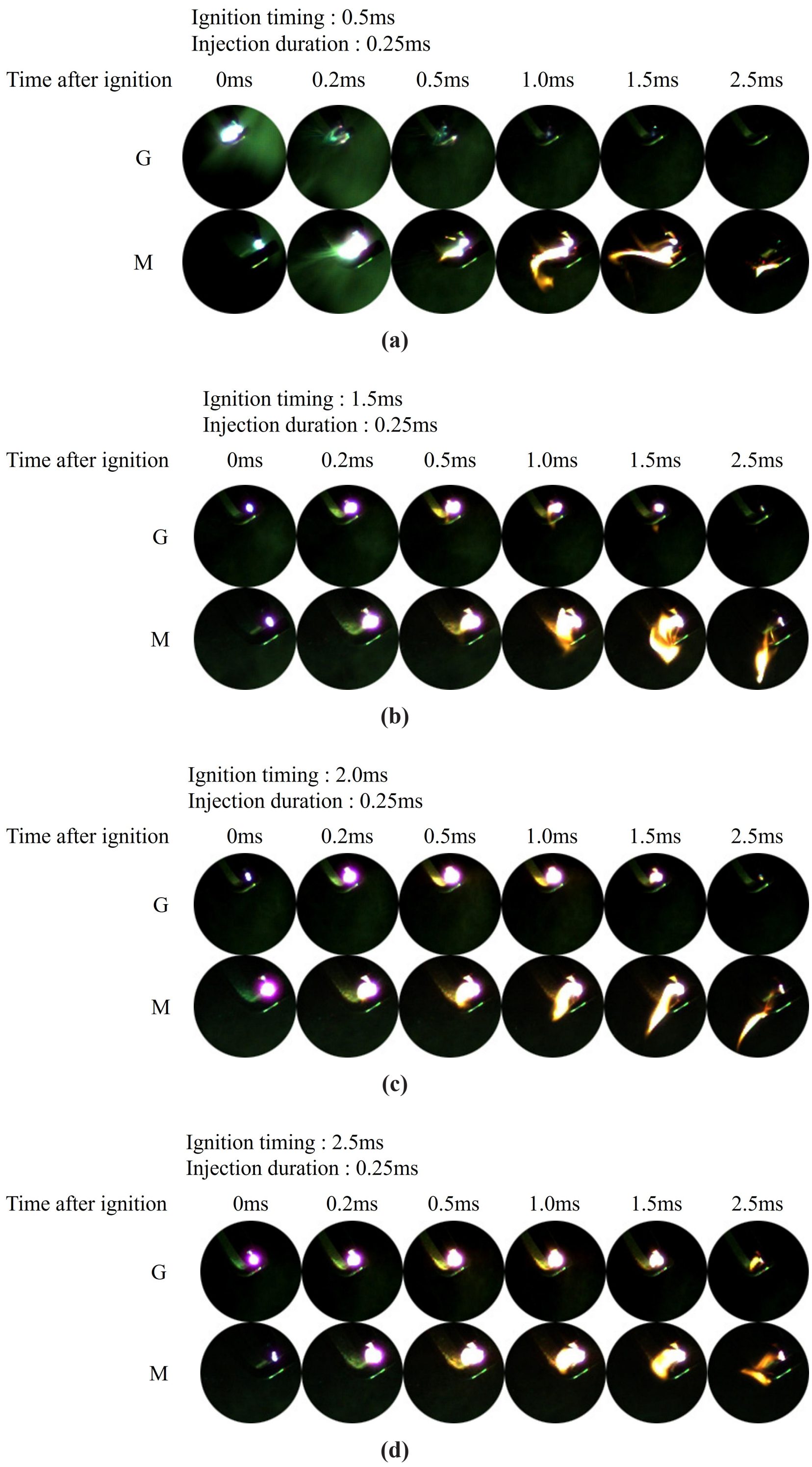

Figure 6. Flame images of ignited gasoline and methanol sprays at different ignition delays, the ignition delay of (**a**) is 0.5 ms, the ignition delay of (**b**) is 1.5 ms, the ignition delay of (**c**) is 2.0 ms, and the ignition delay of (**d**) is 2.5 ms.

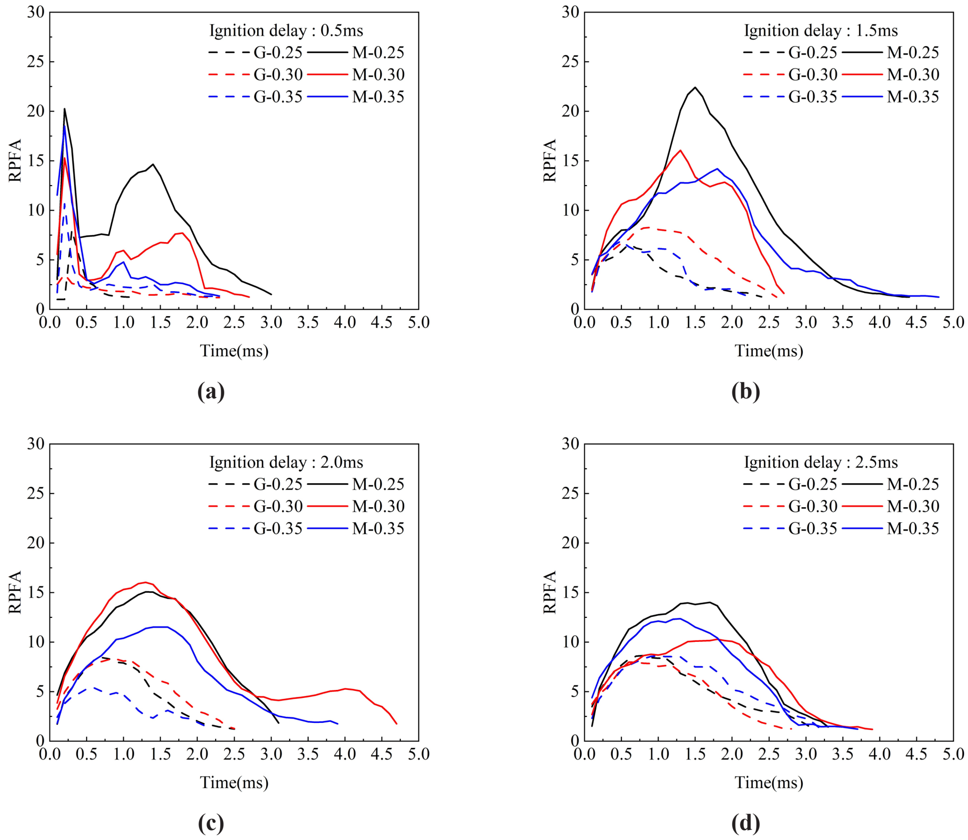

Figure 7. *RPFA* curves at different ignition delays, the ignition delay of (**a**) is 0.5 ms, the ignition delay of (**b**) is 1.5 ms, the ignition delay of (**c**) is 2.0 ms, and the ignition delay of (**d**) is 2.5 ms.

3.4. Experimental Repeatability and Data Interpretation

The experimental results presented in Figures 5–8 exhibit some degree of variability, which can be attributed to several factors inherent to sparked-spray combustion: (1) the stochastic nature of spray atomization and vapor distribution, (2) turbulent mixing effects within the constant volume vessel, (3) spark discharge variability, and (4) the sensitivity of flame initiation to local fuel-air equivalence ratios.

While individual data points show scatter, the overall trends remain consistent across different conditions. The analysis focuses on identifying general tendencies rather than precise quantitative predictions. Each data point represents a single experimental run, and the observed variability reflects the inherent complexity of the combustion process rather than poor experimental control. Future studies would benefit from statistical analysis of multiple repeated measurements to establish confidence intervals and improve quantitative accuracy. Despite these limitations, several reliable trends emerge: (1) methanol consistently outperforms gasoline in terms of flame area and duration, (2) optimal ignition delays fall within the 1.2–1.5 ms range for methanol, and (3) injection duration affects flame characteristics in a predictable manner. These qualitative findings provide valuable guidance for ammonia combustion applications, where relative performance comparisons are more important than absolute quantitative values.

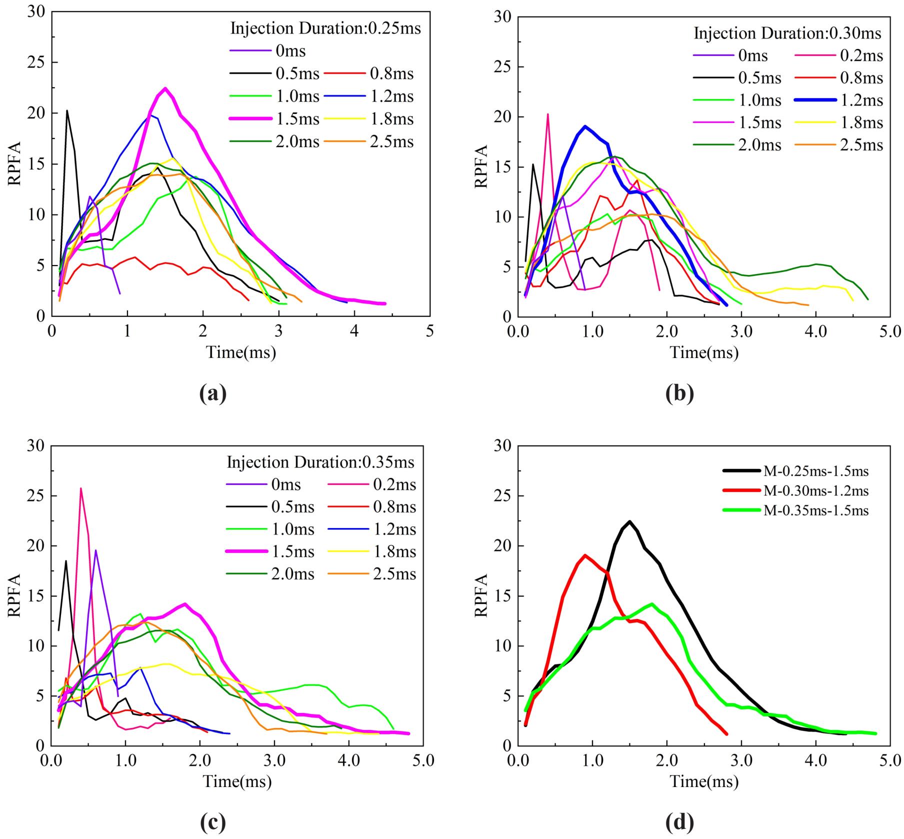

Figure 8. curves at different injection durations, the injection duration of (**a**) is 0.25 ms, the injection duration of (**b**) is 0.30 ms, the injection duration of (**c**) is 0.35 ms, (**d**) depicts the ignition delay corresponding to the maximum *RPFA* obtained under the three fuel injection duration conditions.

4. Conclusions

This study provides an in-depth investigation of the ignition performance and flame behaviour using methanol and gasoline as pilot fuels of sparked-spray. The effects of key parameters of sparked-spray, such as ignition delays (later than injection time) and injection duration, on the ignition were investigated to lay the foundation for the subsequent application of sparked-methanol-spray to induce ammonia combustion. The main conclusions are as follows:

(1) At the same ignition delay, no matter how the injection duration varies, the *RPFA* and survival duration of the flame generated by the ignition of methanol spray are larger and longer than those generated by the ignition of gasoline spray.

(2) For the flame obtained from the ignition of methanol spray, the maximum area of the flame decreases with the increase of the injection duration at the 0.5 ms ignition delay.

(3) Under the same conditions of injection duration, the *RPFA* of the methanol spray shows a tendency to increase and then decrease with the prolongation of the ignition delay. At the injection durations of 0.25 ms, 0.30 ms, and 0.35 ms, the maximum *RPFA* obtained from the ignited spray appeared at the ignition delays of 1.5 ms, 1.2 ms, and 1.5 ms, respectively.

(4) The quantitative performance indicators established in this study—including optimal ignition timing (1.2–1.5 ms), enhanced flame survival duration (3.5 ms for methanol vs. 2.5 ms for gasoline), and superior flame intensity (*RPFA* > 15 for methanol)—provide design criteria for ammonia combustion systems. These parameters suggest that sparked-methanol spray can deliver more effective ignition energy compared to gasoline, making it a promising pilot ignition strategy for overcoming ammonia's inherently poor combustion characteristics.

Limitations and future work: This study has many limitations, including the *RPFA* normalization approach and single-run experimental design, which contribute to data variability. Future research should incorporate multiple repeated measurements, statistical analysis, and more rigorous flame quantification methods to enhance the reliability of quantitative conclusions. Nevertheless, the consistent trends observed across different conditions provide reliable qualitative guidance for sparked-spray ignition system design.

Author Contributions: Z.W.: software, methodology, validation, investigation, formal analysis, visualization, writing—original draft, writing—review & editing; M.L.: software, methodology, validation, investigation, formal analysis, writing—review & editing; W. Y.: investigation, writing—review & editing; Z. H.: conceptualization, supervision, funding acquisition, writing—review & editing; L.L.: project administration, resources, funding acquisition, writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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