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Experimental Study of Influence on Microwave Plasma Ignition Combustion Performance of Pulse Microwave Signals

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ABSTRACT It has been demonstrated by a large number of studies that microwave ignition can greatly extend the lean-burn limit in the internal combustion engines. This paper investigates the influence of the pulse period and duty cycle of pulsed microwave signals on the combustion performance of CH_4–air mixtures during microwave ignition in a constant-volume combustion chamber for a lean-burn equivalence ratio $\varphi = 0.6$ and the same energy input as for conventional spark ignition. Combustion performance was evaluated with respect to combustion pressure, lean-burn limit, OH concentration, initial flame kernel, and composition of combustion emissions. The results indicate that the duty cycle (i.e. average power) strongly influences the formation and development of the initial microwave discharge, while the pulsewidth influences the generation of non-equilibrium plasma which contributes to sustained combustion. The increasing the duty cycle can improve the ignition success rate, extend the lean-burn limit, and reduce the flame development time. Moderately increasing pulsewidth can further extend the lean-burn limit, particularly for elevated initial pressures.

INDEX TERMS Non-equilibrium plasma, lean-burn, flame kernel, hydroxyl radical.

I. INTRODUCTION

A common consensus regarding environmental protection has generally been agreed upon, which includes the concepts of energy conservation and contaminant emission reduction. As fuel prices continue to rise, the call for energy conservation and emission reduction grows louder. For this reason, automobile manufacturers have applied various technologies, such as gasoline direct injection, turbocharging, exhaust gas recirculation, and variable valve timing and valve lift electronic control systems to reduce fuel consumption via improvements in engine efficiency, resulting in energy conservation and emission reduction [1]–[4]. However, under the condition of dilute combustion mixtures, conventional spark ignition systems are subject to misfire or incomplete combustion [5], making it challenging to keep engines running stably.

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Compared with the conventional spark ignition, plasma ignition features an extended combustion limit and reduced exhaust gas emission. Methods to accomplish this include microwave discharge, radio frequency discharge, laser ignition, dielectric barrier discharge, and nanosecond pulse discharge [6]–[9]. Plasma is a composition of ions, electrons, and non-ionized neutral particles, which, as a whole, is in an electrically neutral state. Depending upon the relationship between electron temperature and ion temperature, plasma can be characterized as equilibrium plasma or non-equilibrium plasma. Equilibrium plasma is a steady-state plasma that satisfies dynamic, chemical, and excitation equilibriums. During the ignition process, equilibrium plasma mainly aims to heat mixed gas for ignition [10]. By comparison, in non-equilibrium plasma the electron temperature is much higher than the heavy particle temperature, and the electron speed is relatively high. The combustion acceleration effect of the non-equilibrium plasma results in the following unique characteristics: the inelastic collision

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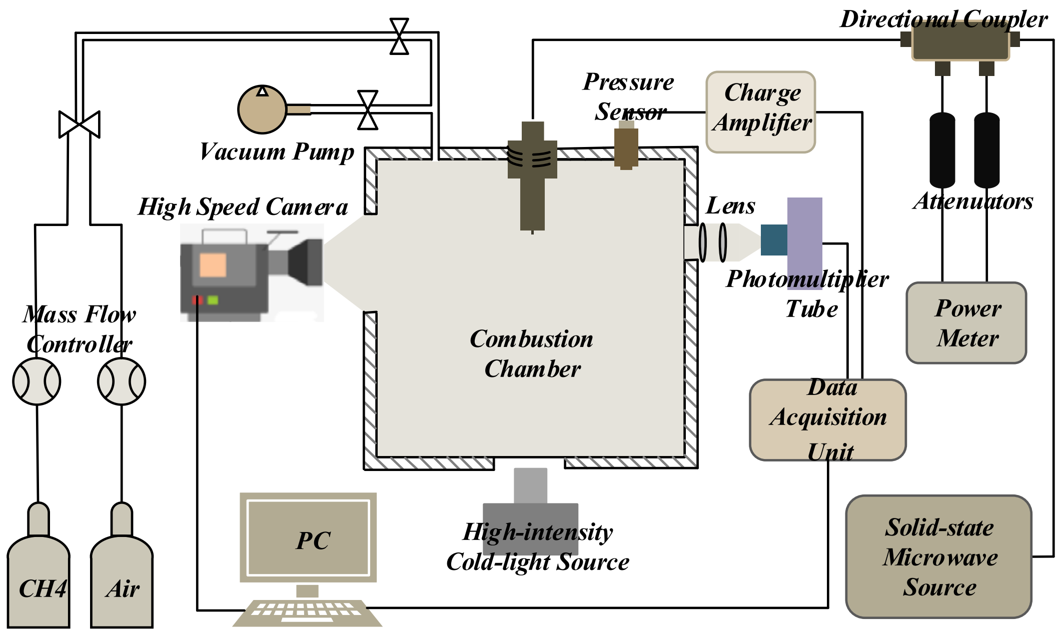


FIGURE 1. Diagram of apparatus for microwave ignition experiment.

between high-energy electrons and reactants leads to an internal energy increase or energy transfer of combustible mixture molecules, which further results in loosening, or a break or split, of molecular bonds in the combustible mixture into free radicals, whereupon a large number of active radicals, ions, and excited molecules are formed, which promotes a kinetic chemical chain reaction and accelerates the chemical kinetic combustion process, realizing large volume/space ignition and combustion [11]–[13]. Therefore, most plasma ignition systems are based on the use of non-equilibrium plasma.

In contrast with laser ignition which requires special optical accessible engines [7], and in-chamber resonant microwave ignition that is sensitive to piston position in the internal combustion engine [14], microwave plasma igniter (MPI) is an ignition means with the advantages of a simple and compact structure, and convenient and flexible ignition control system. The MPI is based on a $\lambda/4$ coaxial cavity [15]. It resonates at the open end to produce a maximum field strength, which results in a breakdown and ionization of nearby gases. Different microwave signals have different influences on the formation, development, and temperature characteristics of the plasma during the microwave discharge [16]. The MPI is driven by a solid-state microwave source with variable pulsed power, number of pulses (*np*), pulse period (*pp*), and duty cycle (*dc*) to easily and precisely adjust and control the plasma discharge characteristics.

Whether in a constant-volume combustion chamber or in an actual engine cylinder, microwaves may extend the lean-burn limit. Wolk *et al.* [6] found that in a combustion test performed in a constant-volume combustion chamber, adding microwaves may extend the lean-burn limit by 10%, and in a single-cylinder Waukesha ASTM-Cooperative Fuel Research engine, the use of microwave-assisted spark plug may extend the lean-burn limit by 5–15% [17]. This study focuses on the effect of different pulsed microwave signals on the ignition and combustion process. Tests are performed with the microwave ignition system shown in Fig. 1 to study the variation in combustion pressure, OH concentration, ignition success rate and lean-burn limit resulting from different *pp* and *dc* in a constant-volume combustion chamber. The changes in the initial flame kernel during combustion were recorded with a high-speed camera to study variation in the initial flame kernel area. A gas chromatograph (GC) was used for quantitative analysis of CO, CO_2 and CH_4 in combustion products.

II. EXPERIMENT SETUP

A diagram of the experimental apparatus is shown in Fig. 1. Experiments were carried out in an optically accessible cylindrical constant-volume combustion chamber with diameter and height of 80 mm and 50 mm respectively. In other words, total volume of combustion chamber is 251 cm^3. Quartz observation windows were positioned on the wall and the bottom of the combustion chamber. Wherein, observation window on the right wall is used for the collection of OH intensity with a photomultiplier (PMT HAMAMATSU H9306). To eliminate spectrum interference of other wavebands and to avoid PMT over-range due to high light intensity, an optical band-pass filter (Andover 307FS10-25) and a neutral density filter (ND-3.00) were provided at the front end of PMT.

A high-speed camera (pco.dimax S1) was positioned at the left side of the combustion chamber to record the flame kernel change during the combustion process through the observation window. To record the development process of the initial ignition flame kernel in detail, the camera only covered the area around the ignition point of the MPI. To ensure image sharpness, a high-intensity cold light source (Hecho S5000) was provided for supplemental lighting.

The combustion chamber was evacuated to an absolute pressure of 2 kPa prior to the experiment. A mass flow controller (Sevenstar CS200, with an accuracy of 0.35% FS) is used to measure partial pressure to precisely control the mixing ratio of the gases. During the experiment, the pressure sensor (Kistler 6125C) sends the pressure signals to the data acquisition unit (Kistler 5165A) via the charge amplifier (Kistler 5018A). The data acquisition unit dynamically acquires the signals sent by the PMT and the charge amplifier at 10 ks/s. To detect the composition of combustion emissions, GC (Zhejiang Fuli 9790II) with flame ionization detector was used for quantitative analysis of CO, CO_2 and CH_4 in emissions collected by gas sampling pump (Chengdu Xin Weicheng VMC8001, with a 1 L/min sample rate).

The microwave ignition system consisted of the MPI, transmission measurement system, and the pulsed microwave source (Ampleon XCtrl4). The structure and working principles of the MPI have been previously been described in detail [18]. A 2.45 GHz MPI is installed at the top center of the combustion chamber. It has the same thread size as that of a conventional spark plug, M14 × 1.25, which facilitates practical application. The maximum pulse power of the solid-state microwave source is 1.2 kW, the minimum *pp* is 0.2 μs, with adjustable *np*and*pw*, and its frequency is adjustable from 2.4–2.5 GHz. These parameters can be changed quickly and precisely, allowing the microwave source to enhance and maintain the discharge from the MPI. This study aims to study combustion characteristics of microwave ignition with signals having constant peak pulse power (1 kW) and energy, but varying pulse characteristics, for $pp = 5$ μs and $dc = 0.5$. Specific pulse parameter meanings and settings are presented in Fig.2 and Table 1 respectively. According to the incident and reflected power measured by the power meter (CETC41 AV2436A), the microwave power delivered to the discharge is approximately 50% of the source's output power. The net microwave energy delivered to the discharge for all conditions of pulse parameter settings is approximately 68 mJ, the same as the ignition energy of a conventional spark plug [19].

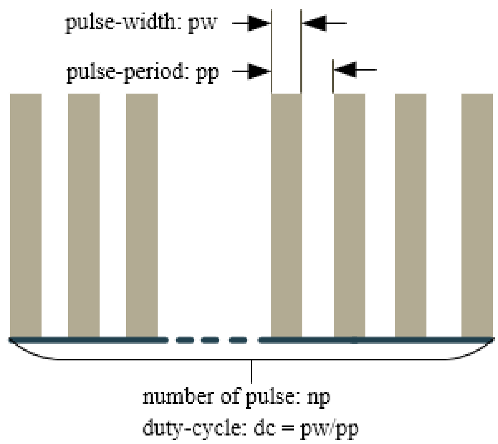


FIGURE 2. Diagram for microwave mode and controllable parameters of pulse microwave source.

TABLE 1. Microwave control signal parameters for each experiment case.

Equivalence ratio φ = *0.6* Peak pulse power = 1 kW			
Parameter 1	*Parameter 2*	*np*	*pw*[a]
pp = 5 μs	*dc* = 0.1	272	0.5 μs
	dc = 0.3	90	1.5 μs
	dc = 0.5	54	2.5 μs
dc = 0.5	*pp* = 2 μs	136	1.0 μs
	pp = 4 μs	68	2.0 μs
	pp = 6 μs	45	3.0 μs

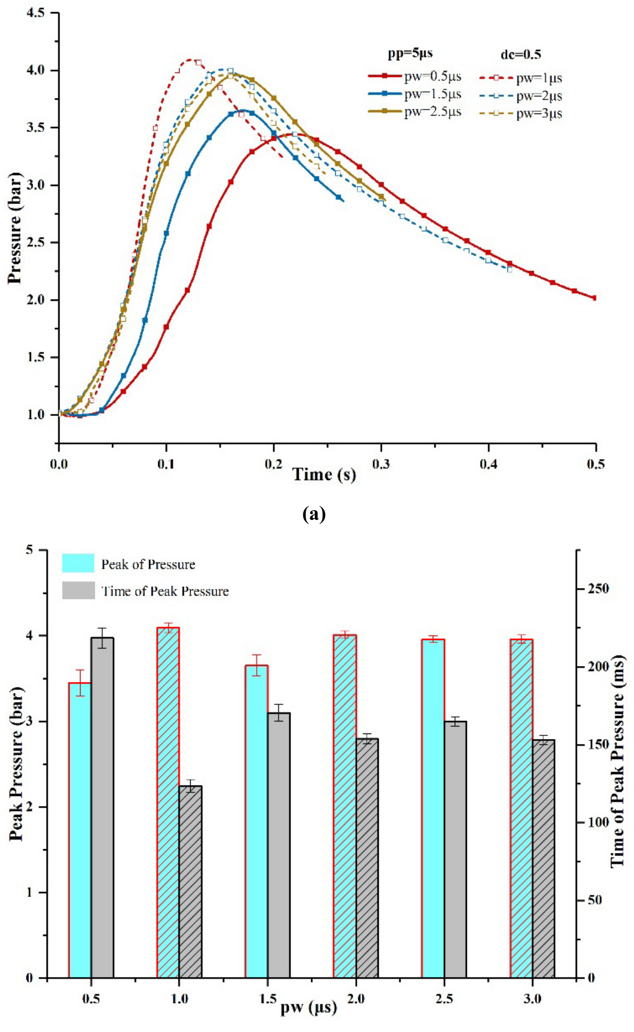
[a]Table 1 lists the pulse parameters corresponding to *pw* values referenced by the experiments described in this study

III. RESULTS AND DISCUSSION

A. COMBUTION PRESSURE CHANGE

Fig. 3 shows the pressure inside the constant-volume combustion chamber change during the MPI ignition. As shown by pressure change curve, different microwave pulse characteristics do influence combustion, despite a constant total input energy. It is clear that under lean-burn conditions, *dc*has a greater influence on combustion performance. As *dc* is increased (for constant *pp*), pressure increase is accelerated and ignition delay is reduced (Fig. 3a). Increasing *dc* also results in higher maximum combustion pressure (Fig. 3b). As indicated by error bars, fluctuations in the maximum pressure and occurrence time are reduced (*i.e.* combustion stability is improved) by increased *dc*. These effects are attributed to the fact that average applied power is directly proportional to *dc*. The microwave signal is used for both the resonant breakdown of MPI and generation of plasma during combustion. Active radicals required for microwave resonance ignition are produced by gas discharge other than accumulation through chemical reaction [20]. When *dc* is relatively low, relatively low initial ionization energy may result in less ionization of mixed gas on one hand. Since a delayed energy supply will make it impossible to maintain the initial plasma discharge, adding energy to the plasma more rapidly with increased *dc* at the outset serves to increase combustion efficiency.

When *dc* is held constant (0.5), changes in pulse width *pw* have less effect on combustion performance. However, long pulses may hinder the formation of non-equilibrium plasma due to overheating the gases, as we can see that a short *pw* (1 μs) results in a higher peak pressure at an earlier time than longer pulses, even though the average power remains the same. Beyond a certain point (1.5 μs for this initial pressure), increasing *pw* has negligible effect on combustion. Plasma generated by of short *pw* and high electric field strength



(a)

(b)

FIGURE 3. Pressure change in the microwave ignition process for different microwave signals with an initial pressure of 1 bar and equivalence ratio of 0.6. (a) Pressure changes with time during combustion. (b) Peak pressure variation and corresponding time for different microwave signals.

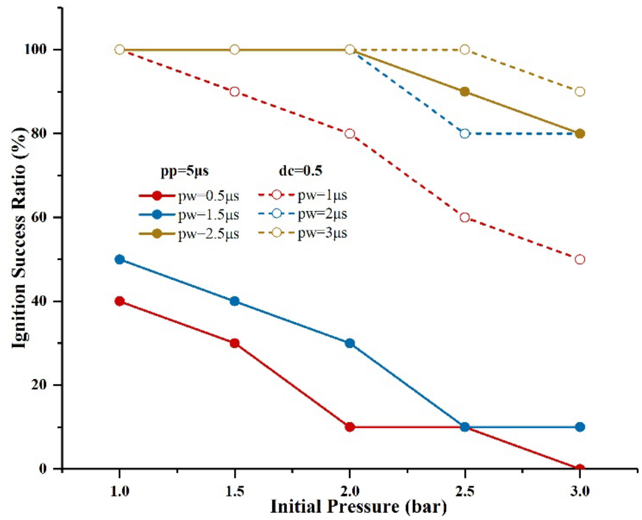


FIGURE 4. Variation to ignition success rate for different initial pressure.

may be more favorable in generating efficient active combustion radicals [21]. Therefore, while the total applied power remains unchanged, shorter microwave pulses prevent the generation of non-equilibrium plasma caused by prolonged heating time, effectively improving microwave assisted combustion effects.

B. LEAN-BURN LIMIT

Microwave ignition can significantly improve ignition performance of lean-burn mixed gas [22]. To study the influence of different microwave signals on lean-burn limit, 10 independent ignition experiments were carried out with CH_4-air mixed gas. One metric for characterizing the lean-burn limit (or ignition stability) is *ignition success rate*, the number of successful ignitions divided by total ignition attempts. A conventional spark plug cannot achieve successful ignition and combustion with mixed gas of the equivalence ratio used in this study, so its ignition success rate is 0. Fig. 4 shows the variation in ignition success rate for different microwave pulse conditions for equivalence ratio $\varphi = 0.6$. It can be seen that improved ignition success rates are directly correlated with increased *dc*. It can also be seen that ignition success rate is also improved by a decrease in initial pressure. Fig. 5 shows the increase in the lean-burn limit resulting from increased initial pressure. Increased *dc* extends the lean-burn limit, which is also improved by decreased pressure. Pulse *dc* mainly influences the formation and development of the initial microwave discharge. The electric field required for gas breakdown is increased with increased atmospheric pressure [23], and the effect of non-equilibrium plasma is weakened by reduced applied electric energy [6]. Therefore, the microwave power required for the MPI to break down the gas will increase with an increase in initial pressure. Increasing *dc* provides adequate power to allow the MPI to break down inflammable gas via ionization at an early stage. Furthermore, as initial pressure is increased, increased *pw* is required for stable ignition. Looking at lean-burn limit as a function of pressure variation, we can infer that ignition success rate will witness a continuous decrease as initial pressure increases, for a given equivalence ratio.

C. OH INTENSITY

The hydroxyl radical (OH) is an important radical during combustion. Additional OH produced by plasma may trigger high-temperature chemical reactions that determine successful combustion, and accelerate chemical reaction to promote combustion [24]. OH plays an important role in maintaining flame stability [25]. Under lean-burn conditions, OH concentration will increase accompanied by an increase in equivalence ratio [26]. This study aims to study variation to maximum OH intensity in constant-volume combustion chamber during experiment at the specific equivalence ratio of $\varphi = 0.6$ when initial pressure is 1 bar and initial

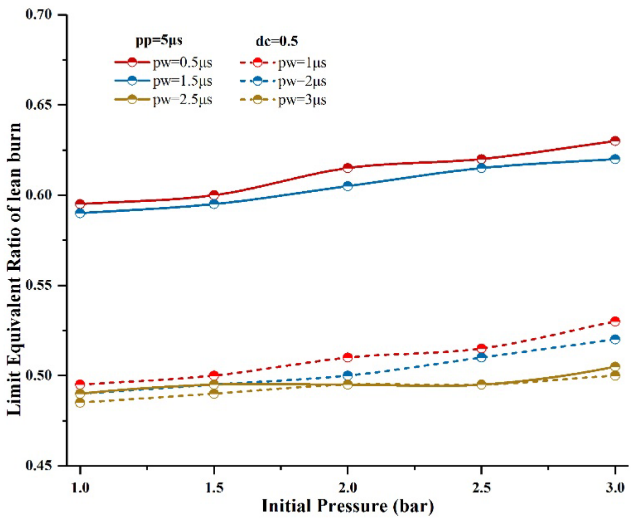


FIGURE 5. Variation to lean-burn limit for different initial pressure.

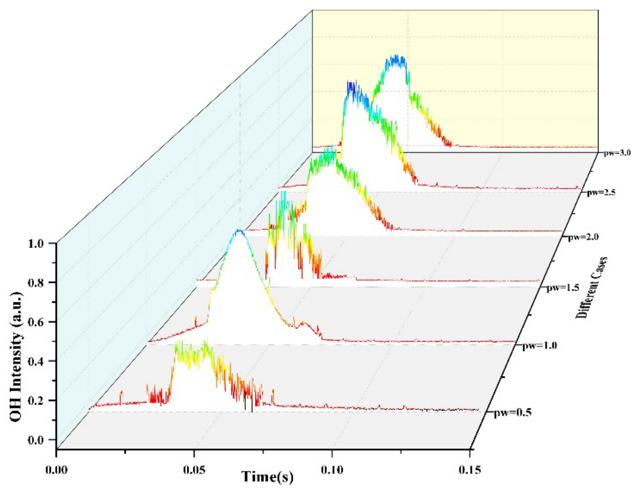


FIGURE 6. Change in peak OH intensity in combustion chamber during microwave ignition process.

temperature is 300K (Fig. 6). When *dc* is relatively low, increase in OH intensity is relatively slow due to an unstable initial discharge. As *dc* increases, a significant increase in OH intensity is exhibited. The effect of *pw* and *dc* on OH concentration are similar to that on pressure intensity in combustion chamber. We note that OH duration is only about 50 ms, which suggests OH only exists in the initial phase of ignition.

D. DEVELOPMEN OF FLAME KERNEL

To further understand the differences in ignition performance between different microwave pulse settings, the high-speed camera was used to take photos of variations in the initial flame kernel during combustion. Fig. 7 shows the evolution process of initial flame during MPI ignition when *pw* is 0.5 μs, 1 μs and 2.5 μs respectively. Flame kernel reaches the minimum size during initial discharge ignition development. Successful combustion cannot be maintained when flame is below this size. Furthermore, the minimum flame size may witness a decrease accompanied by increase in equivalence ratio [27]. For successful combustion, it is necessary to enhance the flame kernel at initial stage [16]. Therefore, flame kernel development directly determines ignition success rate.

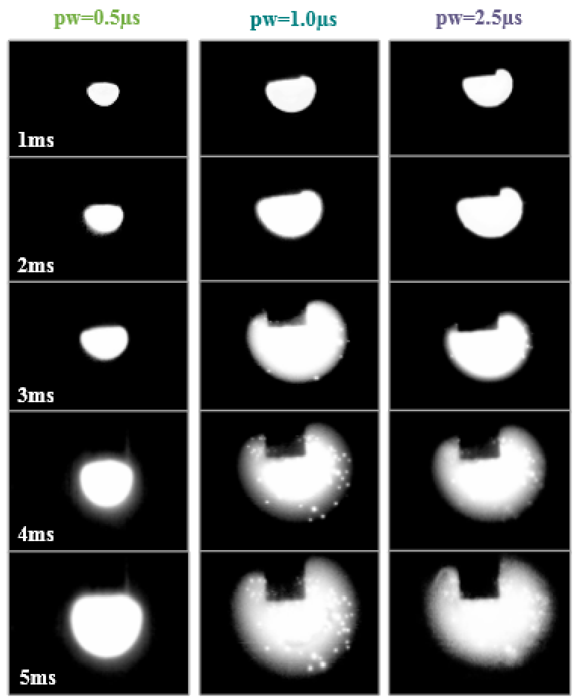


FIGURE 7. Initial flame kernel development for microwave inputs *pw* = 0.5 μs, 1.0 μs and 2.5 μs, under an initial pressure of 1 bar and equivalence ratio of 0.6.

Due to uneven heat transfer in different directions, the flame kernel takes the form of an incomplete sphere [19]. Wolk *et al.* [6] define transverse size of flame kernel as flame size, whereas Padala *et al.* [27] define longitudinal size of flame kernel as flame size. To solve the problem with uneven variation to flame kernel in different directions, this study aims to study variation to initial flame kernel area. Fig. 8 shows variation to initial flame kernel area for different *pp* and *dc*. Its flame kernel area is obviously small when *dc* is low (0.1 and 0.3). Its average flame kernel area seems to be different in case of four different microwave pulse conditions. However, in view of error range, aforesaid four cases are interlaced. Therefore, it is impossible to arrive at a conclusion through comparison of these cases.

When *pw* is as low as 0.5 μs, it is clear that its flame kernel size is relatively small, and variation is also relatively slow. This is the main cause for its relatively low ignition success rate.

To further study the effect of different microwave pulse characteristics on combustion, *flame development time* (FDT) and *flame rise time* (FRT) are introduced. FDT is defined as the duration from the moment of ignition to the time when total net heat release is reduced to 10%. FRT is defined as the

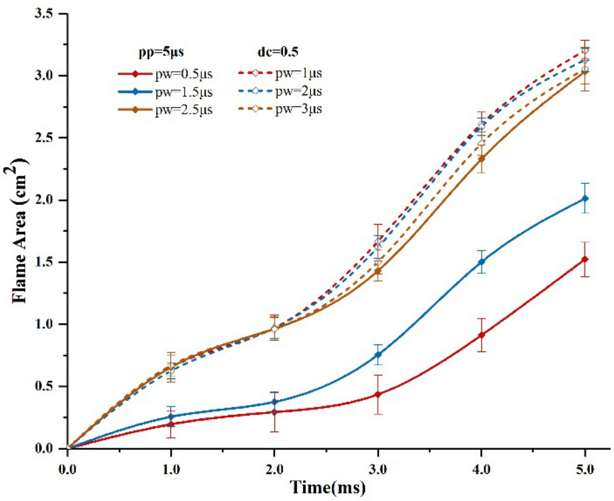


FIGURE 8. Flame area with different times after triggering for all microwave signals tested.

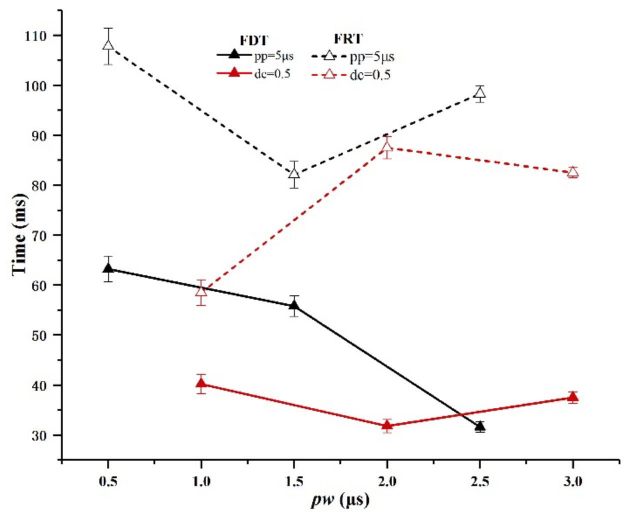


FIGURE 9. Variation to FDT and FRT in case of different microwave signals.

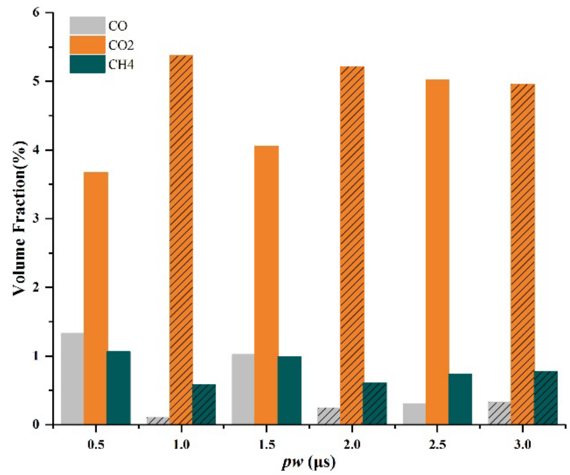


FIGURE 10. Content of CO, CO2 and CH4 in combustion gas corresponding to different microwave signals.

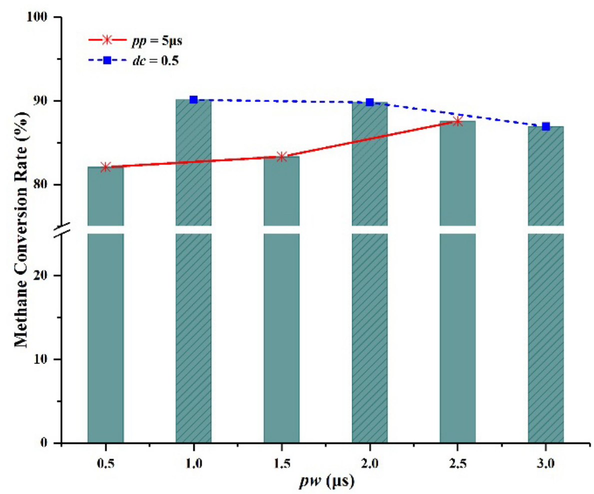


FIGURE 11. CH4 conversion ration corresponding to different microwave signals.

time interval for total heat release from 10% to 90% [28]. As seen in Fig. 9, *pp* and *dc* have a clear influence on FDT and FRT. Increased *dc* can significantly shorten FDT and FRT, and improve combustion performance. *pp* has less influence on FDT and obvious influence on FRT. This is due to the fact that increased *pw* produces increased heating of the plasma, which is unfavorable for generation of non-equilibrium plasma, and affects flame rise time. The main influence of *pw* is on generation of non-equilibrium plasma.

E. COMBUSTION PRODUCTS

A large number of plasmas are produced during microwave discharge combustion. Normally, high-energy electrons in plasma may react with methane molecules to generate such radicals as CH_X(= 1-3) and hydrogen via reaction. CH_X may be subject to coupling reaction to convert methane into H_2 and C_2 hydrocarbons, such as ethane, ethylene and acetylene [29]. Combustion gas was sampled for different microwave pulse settings, and the GC was used to analyze such constituents as CH_4, CO and CO_2 in the exhaust gas (Fig. 10). CO content in the exhaust gas is reduced with increased *dc*. Meanwhile, CO_2 content witnesses an increase. This indicates that the combustion intermediate product of CO is reduced, so the combustion is more complete.

Methane conversion rate (MCR) can be indicated as [30]:

$$\frac{\mathrm{C_{out}}}{\mathrm{C_{in}}} MCR = \left(1 - \frac{C_{out}}{C_{in}}\right) \times 100\%$$

where C_{in} refers to volume concentration of methane in the mixed gas before experiment, and C_{out} refers to volume concentration of methane in combustion gas. Fig. 11 shows MCR when different microwave signals are used. When *dc* is increased from 0.1 to 0.5, MCR increases from 82.7% to 87.56%. When *dc* remains constant (0.5), and *pw* is reduced from 3 μs to 1 μs, MCR increases from 86.93% to 90.12%.

These results indicate that MCR may be improved for more complete combustion by increasing *dc* and shortening *pw*.

IV. CONCLUSIONS

This study examined the effect of microwave pulse duty cycle *dc* and pulse width *pw* on lean-burn performance of CH_4-air mixed gas in a combustion chamber, with MDI discharge controlled via precise control of various parameters of microwave signals by a solid-state microwave source. To evaluate resulting combustion characteristics, pressure, OH intensity and flame kernel development during combustion are analyzed. Additionally, variation in lean-burn limit, ignition stability and constituents of combustion gas were studied. Results support the following conclusions:

a) Under lean-burn conditions, increased *dc* can improve the energy supply needed for initial ignition, accelerate combustion, enhance initial flame kernel development, reduce FDT and FRT, enhance pressure inside the combustion chamber, and minimize ignition delay. Meanwhile, it can increase OH intensity produced during combustion, and improve MCR to make combustion more complete.
b) Since *dc* controls average applied power, it directly affects the MPI energy supply, *i.e.* formation and development of initial microwave discharge. *pw* mainly affects the generation of non-equilibrium plasma. When adequate energy is available for initial discharge (sufficiently high *dc*), increased *pw* is unfavorable for generation of non-equilibrium plasma. Increased *pw* may result in nonobvious variations in initial flame kernel development, increased CO content in combustion products, reduced CH_4 conversion rate and poor combustion performance.
c) Increasing *pw* and *dc* can improve ignition success rate, especially as initial pressure is increased. Proper choices of *pw* and *dc* can realize stable ignition under lean-burn condition when equivalence ratio is 0.6, while conventional spark plug cannot achieve successful ignition in this environment.
d) At increased initial pressure, the equivalence ratio of the lean-burn limit is increased, restricting extension of the lean-burn limit. Increased *pw* is effective in extending the lean-burn limit at elevated initial pressures.
e) Short *pw* is more favorable for generation of OH radicals. OH is only in existence at the initial stage of ignition. OH intensity can be taken as an important indicator reflecting combustion performance.

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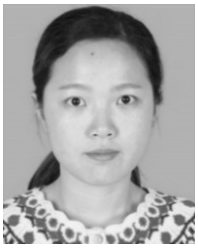

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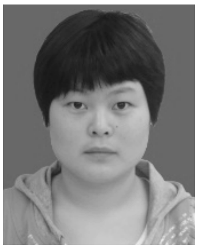

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