Effect of Microwave Power on Performance of Microwave-Assisted Spark Ignition under CO₂-Diluted Condition

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Abstract. To explore the application potential of microwave assisted ignition under EGR conditions, the effect of microwave peak power on MAI performance under 8% CO₂ and non-diluted condition is investigated in a constant volume combustion chamber with peak power varying in 0–1000W under equivalence 1.0 and ambient pressure 0.2 MPa. Results show that increasing the microwave peak power can strengthen the MAI enhancement, however, increasing peak power presents a linear relation in non-diluted cases indicating the thermal effect of microwave. In 8% CO₂ case, it tends to be a threshold process, indicating that microwave exhibits more in chemical kinetics effect.

1. Introduction
Exhaust Gas Recirculation (EGR) is one of the most representative methods to satisfy the energy need of “high efficiency and low emissions” in automobile and aviation field. Due to the addition of burned gas, the combustion event goes with much lower combustion temperature and slower combustion speed, and thus the nitrogen oxide emission can be significantly reduced [1]. Apart from the potential in reducing nitrogen oxide emission, the EGR method also attracts great attention in suppress knock and super knock which occurs in the spark ignition engines because the pre-ignition of unburned mixture. EGR can obviously decreases the temperature and speed of combustion, so that it is of great potential in suppressing knock phenomenon. Even though EGR exhibits great potential in reducing harmful emission and suppressing knock, a critical issue with this strategy is the difficulty in reliable ignition or re-ignition particularly near extreme conditions. Moreover, the slow combustion speed under over-diluted conditions also decreases thermal efficiency and increasing the cycle to cycle variations of internal combustion engines. Therefore, finding solutions to improve ignition and combustion performance under mentioned conditions has attracted great attention in past decades, such as hydrogen addition [2], laser ignition [3] and plasma-assisted ignition and combustion [4, 5].

Recent years, an advanced Microwave-Assisted spark Ignition (MAI) [6] method has drawn significant attention of researchers, due of its perfect integration with conventional spark plugs and the great application potential in enhancing spark ignition process. MAI process can be devised into several stages: firstly, spark plug discharge breakdowns the mixture and induces initial plasma, and then microwave is emitted which would expand the initial plasma and eventually enhance the ignition.
Previous study [7] has shown MAI great performance in enhancing the lean burn characteristics in internal combustion engines.

To clearly illuminate the coupling mechanism between microwave and spark plasma, Zhang et.al. [8] has designed a specifically small-diameter antenna device to minimize heat loss to spark plug, and explored MAI performance in a 1.6 L Constant Volume Combustion Chamber (CVCC), has results show that microwave increased the development speed of an early flame kernel by 60% with 1 kHz microwave pulse repetition frequency and 1000 W peak power under the condition of equivalence ratio 0.6 and ambient pressure 0.1 MPa. However, as the ambient pressure increased, the enhancement effect of microwaves on flame kernels was found to diminish.

In addition, to further understand the relation between ambient pressure and MAI performance and increase the MAI enhancement under high ambient pressures, Zhang et.al. [9] tests the MAI performance with C 2 H 2 -Air spherical expanding flames in based on same experimental setup under ambient pressures from 0.1 to 0.6 MPa and equivalence ratios from 0.5 to 1.9. Results showed that Normalized Reduced Electric Field (REF) is found to correlate well with the decreasing trend of normalized flame radius enhancement with increasing ambient pressure, indicating that REF is probably one of the key factors affecting MAI performance. The influence of microwave Pulse Repetition Frequency (PRF) on MAI under PRF from 1 to 80 kHz are studied and discussed for both non-combustion discharge and ignition tests.

Although most researches in MAI have exhibited promising property under lean conditions, the characteristic of MAI under EGR diluted condition has never explored before. The main goal of this paper is studying the MAI enhancement on ignition process under CO 2 diluted condition, and testing the effect of microwave power on MAI performance. CO 2 is added into CH 4-air mixture with the equivalence ratio and ambient pressure unchanged. Initial flame kernel development is used to reflected the effect of CO 2 dilution. All experiments are conducted in a constant volume chamber and recorded by the high speed schlieren system.

2. Experiment methods

Figure 1 provides the experimental setup which consists of four main parts, namely, CVCC system, microwave system, ignition system and schlieren system. In microwave system, the solid-state microwave source generates 2.45 GHz microwave with pulse frequency of 1 kHz and duty cycle of 20%, and during each test the microwave energy can be calculated with below equation:

\[ E_{\text{microwave}} = 20\% \times P \times t \times \eta \]  \hspace{1cm} (1)

Where \( P \) is the power of microwave source, \( t \) is the microwave duration time 1ms and \( \eta \) is the transmission efficiency which is referred to 25%. The spark energy is about 45 mJ deduced through voltage and current measured by oscilloscope. More details are referred to [8].

Figure 1. Schematic diagram of experimental setup
The ignition experiments are conducted in the CVCC and each test is repeated for 5 times to ensure the reliability of data. Before charging each component of mixture into the chamber, the chamber is vacuumized. CO₂ dilution ratio is defined as

\[
\text{Ratio}_{CO_2} = \frac{V_{CO_2}}{V_{CO_2} + V_{CH_4} + V_{Air}}
\]  

(2)

Where \( V_{CO_2} \), \( V_{CH_4} \) and \( V_{Air} \) represent the volumes of \( CO_2 \), \( CH_4 \) and air respectively.

3. Results and discussion

Fig. 2 shows the image sequences of flame kernel development in both microwave-assisted ignition (MAI) mode and spark ignition (SI) mode with equivalence ratio (\( \phi \)) 1.0 and ambient pressure 0.2MPa. In SI case, spark discharge initiates a flame kernel which then expands quickly, with the flame surface gradually becoming smooth. A few wrinkles are generated after spark breakdown, which may be induced by the randomness of discharge channel. However, these wrinkles gradually disappear in following expanding.

![Figure 2](image)

\( 0.033 \text{ms} \quad 0.533 \text{ms} \quad 1.033 \text{ms} \quad 1.533 \text{ms} \quad 2.033 \text{ms} \)

Figure 2. Comparison of initial flame development in MAI and SI mode with equivalence ratio 1.0 and ambient pressure 0.2MPa.

Differently, in MAI mode, addition of microwave generates a bright spot near the initial flame kernel, and this microwave pulse also significantly deforms the flame surface make the flame surface area increase a lot. The deformation of flame is retained as the flame expands further. The deformed part increases the flame area and thus it increases the burning rate.

The formation regime for the sustained wrinkles may be that when microwave pulse is emitted in, it generates an intensified electric field near the gap zone between the two electrodes. This intensified field mostly accelerates electrons around the intensified-zone, however, electrons far away from the zone will not be so strongly enhanced. Then collisions between electrons and bulk particles will occur and then the local temperature will increase accordingly. Since the electrons located at different zones are of different kinetic energy, there will be a temperature gradient arising between intensified zone and weak zone. Then, the temperature gradient will induce the pressure gradient and the latter will drive the ions or other particles of majority of mass away. This impulsive force induced by microwave pulses seems to be directional in each case which then promotes the wrinkles developing into flame deformation and that is retained in following propagation.
Figure 3. Flame kernel radii development vs. time in MAI mode and SI mode with 0.75 equivalence ratio and 0.2MPa ambient pressure.

To further analyze the effect of microwave peak power on MAI performance, the variation of flame kernel radius is selected for comparison. The flame kernel radius is obtained by identifying the flame boundary and calculated the 2-D flame area with MATLAB program of image processing. Each case is repeated for 5 times and the mean value is adopted as the flame radius. Figure 3 shows the variation of flame kernel radius with time in both two modes with different microwave peak power. In 200 W case, the flame radius development shows non-obvious difference with that in SI case. Increasing the microwave peak power to 400 W, there is a soar in the flame radius curve compared with that in SI case. However, further increases in microwave peak power show limited enhancement on flame radius. The tendency of flame radius curve varying with time may be because that there is a threshold valve of microwave electric field, beyond which the chemical kinetics will be greatly enhanced. Increasing the microwave peak power, the microwave electric field intensity increases accordingly. When the peak power reaches 400W, the chemical kinetics is enhanced so that the enhancement is obvious. Further increases in peak power the enhancement levels off indicating that in that situation the flame front may have already leave away from the zone of strong electric filed.

Figure 4. Variation of flame kernel radius of MAI with microwave peak power varying from 0~200W under 8% CO₂ diluted condition and equivalence ratio is 1.0 and ambient pressure is 0.2MPa.
Figure 5. Microwave of different peak power induced bright spots under 8% CO₂ condition and non-diluted condition.

Figure 4 shows the variation of flame kernel radius with time under 8% CO₂ diluted condition. Different from that shown in Fig. 3, there is significant variation in the SI flame radius development, indicating that the ignition is instable. As 200W microwave pulse added, this variation in flame development is greatly improved, even if it has no obvious effect on the propagating flame. Increasing the microwave peak power, the flame radius shows stable increment. It is believed that microwave most probably shows thermal effect in CO₂ diluted situation, so the enhancement is directly related to microwave peak power.

Besides, both in Fig.3 and Fig.4 the flame radius curves under different conditions are identical with each other after the flame reaches self-sustained stage, implying that the microwave emitted in the early stage will not affect the flame speed.

Fig. 5 gives information about the bright spots induced by microwave with different peak powers. Apart from the 200W case in which the bright spot is brighter under non-diluted condition, there is no obvious brightness difference between two conditions, indicating that in both two conditions the energy absorption is the same.

4. Conclusion
The effect of microwave peak power on MAI performance under 8% CO₂ and non-diluted condition is investigated in a constant volume combustion chamber with peak power varying in 0~1000W under equivalence 1.0 and ambient pressure 0.2 MPa. Based on the observation, it can be concluded that increasing the microwave peak power can strengthen the MAI enhancement, however, increasing peak power presents a linear relation in non-diluted cases indicating the thermal effect of microwave. In 8% CO₂ case, it tends to be a threshold process, indicating that microwave exhibits more in chemical kinetics effect.

Acknowledgments
This work was financially supported by the State Key Laboratory of Automotive Safety and Energy (KF2028) and the National Natural Science Foundation of China (Grants 51576083).

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