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# Microwave-assisted plasma ignition in a constant volume combustion chamber

Joonsik Hwang[a], Choongsik Bae[a,*], Jooyoung Park[b], Wonho Choe[b], Jeonghwa Cha[c], Soohyung Woo[c]

[a] *Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Republic of Korea*
[b] *Department of Physics, Korea Advanced Institute of Science and Technology, Republic of Korea*
[c] *Hyundai Motors Co., Republic of Korea*

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## ABSTRACT

An experimental study was carried out to investigate the effect of microwave-assisted plasma ignition on laminar flame development in a 1.4 l constant volume combustion chamber (CVCC). The microwave-assisted plasma ignition system consisted of a commercially available 2.45 GHz magnetron (700 W), a waveguide, a 3-stub tuner, a mixer and a non-resistor spark plug. The combustion tests were performed using an acetylene–air mixture at a range of equivalence ratios and initial ambient pressures. The ejection timing of the microwave also varied based on the spark event. In-chamber pressure analysis and high speed imaging were combined in a CVCC to compare the results between the microwave-assisted ignition and the conventional spark ignition. The enhancement was evaluated from the combustion phase, combustion index, and the flame kernel size based on the in-chamber pressure results and shadowgraph images. Compared to the conventional spark ignition condition, the microwave-assisted plasma ignition showed an extended lean limit with the advanced combustion phase. The conventional spark ignition had a lean limit at the equivalence ratio of 0.6, while it was extended to 0.5 by the microwave-assisted plasma ignition under the initial ambient pressure of 0.1 MPa. The flame development time (time for 0–10% of total net heat release) for the microwave-assisted plasma ignition showed significant advancement especially in the lean mixture condition. The shadowgraph images indicated that the flame speed increased up to 20% with the microwave-assisted plasma ignition. In terms of equivalence ratios and initial ambient pressures, the enhancement was decreased with rich mixture and high initial ambient pressure conditions. In this situation, however, an early microwave ejection strategy was found to be beneficial to combustion showing a higher combustion index than the conventional spark ignition condition.

## Abbreviations

| | |
|---|---|
| CVCC | constant volume combustion chamber |
| CO | carbon monoxide |
| COV | coefficient of variation |
| DC | direct current |
| EGR | exhaust gas recirculation |
| FDT | flame development time |
| FRS | filtered Rayleigh scattering |
| FRT | flame rise time |
| GDI | gasoline direct injection |
| HC | hydrocarbon |
| HSP | high speed plasma |
| IGBT | insulated gate bipolar transistor |
| IMEP | indicated mean effective pressure |
| NCHR | normalized cumulative net heat release |
| $NO_x$ | nitrogen oxide |
| PIV | particle image velocimetry |
| PLIF | planar laser induced fluorescence |
| PWM | pulse width modulation |
| QWCCR | quarter wave coaxial cavity resonator |
| REMPI | radar resonance-enhanced multi photon ionization |
| RF | radio frequency |
| RHRR | representative heat release rate |
| RT | rotational-translational |
| SI | spark ignition |
| UV | ultraviolet |
| VT | vibrational-translational |

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[*] Corresponding author. Fax: +82 42 350 5023.
*E-mail address:* csbae@kaist.ac.kr (C. Bae).

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## Nomenclature

| | |
|---|---|
| $E$ | electric field [V/m] |
| $I_c$ | index of combustion [a.u.] |
| $n$ | gas density [$m^{-3}$] |
| $P_{in-chamber}$ | in-chamber pressure [Pa] |
| $P_{max,\ con}$ | maximum in-chamber pressure with conventional spark ignition [Pa] |
| $P_{max,p}$ | maximum in-chamber pressure with microwave-assisted plasma ignition [Pa] |
| $T_{10}$ | duration from start of ignition command to 10% of total cumulative heat release [s] |
| $T_{50}$ | duration from start of ignition command to 50% of total cumulative heat release [s] |
| $T_{90}$ | duration from start of ignition command to 90% of total cumulative heat release [s] |
| $t$ | time [s] |
| $t_{con}$ | time of the peak pressure with conventional spark ignition [s] |
| $t_p$ | time of the peak pressure with microwave-assisted plasma ignition [s] |

## 1. Introduction

The automotive industry is pursuing high efficiency clean vehicles due to increasing environmental concerns and the depletion of petroleum resources. Several technologies such as lean-burn, exhaust gas recirculation (EGR), turbocharger, and gasoline direct injection (GDI) have been applied in a spark ignition (SI) engine to improve efficiency [1–4]. However, these methods limit the engine operating conditions due to the deteriorated combustion stability, especially during ignition and the initial flame development [5]. Innovative approaches including new ignition and combustion concepts are needed to enhance the combustion. At this stage, the application of plasma to ignition and combustion is considered as a promising way to achieve high efficiency and low emission vehicles. Plasma is a form of matter in which many of the electrons wander around freely among the nuclei of the atoms. It has been called the fourth state of matter, the others being solid, liquid, and gas. Plasmas can be classified as “thermal” or “non-thermal” based on the relative temperatures of electrons, ions, and neutrals. In thermal plasma, the temperatures are in a thermal equilibrium state by the sufficient kinetic energy exchanges between electrons, ions, and neutrals. Thermal plasma is characterized by the high gas temperature and the high level of ionization. Thus, enormous heat losses to the surroundings and thermal damages to the electrodes are inevitable. The ions and neutrals of non-thermal plasma on the other hand are at a lower temperature, while the electrons are much hotter. Reaction kinetics can be enhanced in the non-thermal plasma because the energy transfer from electromagnetic waves to free electrons in gases results in inelastic electron collisions with ions and neutrals having sufficient energy for initiating the electronic and vibrational activation, the molecular dissociation and the ionization reactions [6]. The plasma generation requires lower input energy and thermal damage in the ignition system is reduced. Therefore, many research groups are now attempting to replace the conventional spark ignition system with the non-thermal plasma ignition system for ignition and combustion control [7–13].

Mariani et al. applied a radio frequency sustained plasma ignition system in a 1.6 l turbocharged spark ignition engine [14]. The system was composed of an igniter with a star shaped electrode and a resonant transformer circuit, which amplified the input voltage delivered by an external power supply unit. The 100 V input voltage was amplified up to 6 kV with the frequency of 4.967 MHz. Corona discharge occurred at the end of sharp electrodes. The experimental results showed that the new ignition system improved the engine efficiency, extended the lean limit of combustion, and reduced the cycle-by-cycle variation compared to the conventional spark plug system. The system also had advantages in the reduction of carbon monoxide (CO) and unburned hydrocarbon (HC) emissions. However, the nitrogen oxide ($NO_x$) emissions were slightly increased compared to the conventional spark plug system. Shiraishi et al. devised a high speed plasma (HSP) igniter using a nanosecond pulse between coaxial cylindrical electrodes [15]. The pulse had a full width at half maximum (FWHM) of approximately 80 ns. A voltage range of 10–50 kV was used for the ignition. The effects of the HSP system on the combustion phase and the instability were investigated in a 0.5 l single cylinder spark ignition engine. In-cylinder pressure analysis and high speed imaging were performed to compare the combustion characteristics between the HSP and the conventional spark ignition system. It was found that the start of combustion was advanced with the HSP system despite the identical ignition command. The coefficient of variation (COV) of the indicated mean effective pressure (IMEP) was maintained at less than 5% with the HSP, while it reached up to 20% with the conventional spark ignition system at the air–fuel ratio of 22. From flame imaging, the HSP system formed a ring shape flame kernel by dispersing into the space around the central electrode. The flame development was much faster than that with the conventional spark plug system.

Meanwhile, the application of microwave also offered similar advantages in ignition and combustion. Stockman et al. investigated the combustion enhancement of a laminar, premixed $CH_4$/air wall stagnation flat flame in a cavity resonator [16]. They measured the flame temperature, the laminar flame speed, and the hydroxyl radical (OH) concentration through filtered Rayleigh scattering (FRS), particle image velocimetry (PIV), and planar laser induced fluorescence (PLIF), respectively. The microwave was generated by a 1.3 kW, 2.45 GHz continuous wave magnetron. The result from the FRS revealed that the temperature was increased by 100–200 K in the post-flame zone with the microwave ejection. The flame speed enhancement measured by the PIV demonstrated that the restabilization of the flame with the application of microwave radiation led to an increase in the laminar flame speed by up to 20%. At the same time, diagnostics with the PLIF showed that the peak OH-number density increased by 6.5% with the microwave application. Michael et al. studied the effects of the pulsed microwave addition to laminar $CH_4$/air flame [17]. The microwave source utilized was a 3 GHz pulsed magnetron capable of 30 kW peak power pulses varying in length from 1 to 3 $\mu$s. The relative increase in $NO_x$ concentration was measured using a selective radar resonance-enhanced multi photon ionization (REMPI) technique. A laser shadowgraph with a Nd:YAG laser pulse was also performed to assess the presence of a flame kernel. The REMPI result indicated that the $NO_x$ emissions were increased as the microwave power was increased due to the elevated flame temperature in the post-flame zone as shown by the previous research group. From the shadowgraph imaging, the microwave-assisted flame showed the ability to sustain deflagration fronts at the ultra-lean equivalence ratio of 0.3, while it was limited at 0.6 without microwave. The flame enhancement of the microwave-assisted plasma ignition can be explained based on the two main mechanisms. The first mechanism is the relaxation of rotational and vibrational states (the molecule’s internal degrees of freedom). The conversion of the electron energy to the translational degrees of freedom in the molecules is insignificant due to the large differences in mass between electrons and molecules [18]. Thus, only internal degrees of freedom of the molecules can be increased by the electron impact under the oscillating electric field. The rotational states of the

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