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Application of a novel microwave-assisted plasma ignition system in a direct injection gasoline engine

Joonsik Hwang[a], Wooyeong Kim[a], Choongsik Bae[a,*], 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

HIGHLIGHTS

- Combustion phase was advanced by applying microwave on flame.
- On average, OH intensity with microwave ejection was 3.5 times larger than that of conventional spark.
- Fuel efficiency was improved up to 7.8% with microwave ejection.
- Microwave ejection was advantageous in reduction of CO and HC.

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ABSTRACT

An experimental study was carried out to investigate the effect of microwave-assisted plasma ignition on the combustion and emission characteristics in a 500 cm^3 single cylinder direct injection gasoline engine. The microwave-assisted plasma ignition system consisted of a 2.45 GHz magnetron (3 kW), a waveguide, a mixer and a non-resistor spark plug. The first experiments were performed in a 1400 cm^3 constant volume combustion chamber (CVCC) to clarify the mechanism of combustion enhancement by microwave ejection. The combustion tests were performed using an acetylene-air mixture at a range of relative air/fuel ratios (λ) under initial ambient pressures of 0.3 MPa and 0.5 MPa. The microwave-assisted plasma ignition has more advanced combustion phase than the conventional spark ignition showing larger initial flame kernel size and faster flame speed. The imaging results of the hydroxyl (OH) radical in ignition and flame demonstrated the potential of a faster chemical reaction by applying microwave on combustion. The microwave-assisted plasma ignition had a higher spark intensity and larger covering area than the conventional spark plug. The distribution and intensity of OH radicals on the surface of the flame were also higher with microwave ejection. In terms of engine test, lean limit was extended up to lambda 1.55 and the fuel efficiency was improved by 6% by microwave-assisted plasma ignition. The combustion phase was advanced so the peak of in-cylinder pressure and heat release rate increased more than those of conventional spark ignition. Based on the faster combustion, the combustion stability was enhanced so the lean limit was extended to lambda of 1.57. The microwave-assisted plasma ignition system was advantageous in the reduction of carbon monoxide and unburned hydrocarbon emissions, whereas nitrogen oxide emissions increased due to the higher temperatures in the combustion chamber. The engine test results finally demonstrated that the certain level of microwave ejection energy could improve all of engine performance and emission characteristics than conventional spark ignition system.

1. Introduction

Increasing concerns about the environment and petroleum resources have forced the automobile industry to develop high efficiency clean vehicles. Among many automotive technologies, charge dilution and lean air-fuel mixtures have been adopted as a key technology to improve fuel efficiency and exhaust emissions [1–3]. The lean burn concept has several clear advantages, including (1) high thermal efficiency because of less heat losses to surroundings, (2) low level of nitrogen oxides (NO_x) emissions in exhaust gas; and (3) low energy losses by

* Corresponding author.
E-mail address: csbae@kaist.ac.kr (C. Bae).

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Nomenclature

CA_{10}	crank angle degree at 10% of total heat release rate [CAD]
CA_{90}	crank angle degree at 90% of total heat release rate [CAD]
E	electric field [V/m]
N	gas density [m^{-3}]
σ_{imep}	standard deviation of IMEP
P	in-cylinder pressure [MPa]
Q	heat from the system [J]
γ	ratio of specific heat [a.u.]
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]
V	in-cylinder volume [m^3]

Abbreviations

bTDC	before top dead center
CAD	crank angle degree
CCD	charge coupled device
CVCC	constant volume combustion chamber
CO	carbon monoxide
COV	coefficient of variation
DC	direct current
EGR	exhaust gas recirculation
FDT	flame development time
FWHM	full width at half maximum
PLIF	planar laser induced fluorescence
RF	radio frequency
SI	spark ignition
SCR	selective catalytic reduction
TWC	three-way catalyst
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
SCR	selective catalytic reduction
TWC	three-way catalyst
NO_x	nitrogen oxide
LNT	lean-NO_x trap

cooling system due to the reduced combustion temperature [4]. On the other hand, the disadvantage of the lean burn concept is the reduced combustion rate for homogeneous charge compared to stoichiometric conditions. The most challenging problem with lean burn engines is flame instability. To meet the requirements, completely different technologies such as dual fuel combustion, and high pressure injection strategy are needed. Dual fuel concept can bring fuel flexibility and achieve lean burn by fuel stratification in the combustion chamber. However, these options pose immense technical challenges due to the diversity of modern fuels with varying physical/chemical properties and tremendous optimization process for combustion system. Thus, the development of a novel ignition system for stable combustion in lean burn engines is needed [5]. In order to overcome the combustion instability, various alternative ignition systems have been tested to replace conventional spark ignition system. Among many systems, plasma ignition system is considered as a promising way to achieve high efficiency lean burn combustion. Plasmas can be classified into two groups, “thermal plasma” or “non-thermal plasma” depending on the relative temperatures of the electrons, ions, and neutrals. The temperatures of electrons, ions, and neutrals are in a thermal equilibrium caused by vigorous energy exchanges under thermal plasma regime. The traditional spark ignition and plasma jet ignition are representative examples of thermal plasma. In thermal plasma, both the neutrals and the electrons have extremely high temperatures. Therefore, tremendous amount of thermal heat losses to the surroundings and thermal damages to the electrodes are inevitable. On the other hand, in non-thermal plasma region, the temperatures of the ions and neutrals are much lower than the electron temperature. Plasmas such as microwave discharge and corona ignition are types of non-thermal plasma ignition. The mechanism of non-thermal enhancement includes (1) excitation, dissociation, and ionization of the gas to produce reactive chemical radicals; (2) additional reactive radicals in the spark zone; and (3) effect of ionic wind induced by a momentum transfer from an electric field to the gas due to space charge [6]. Furthermore, the non-thermal plasma can be achieved with much lower input energy than thermal plasma system. The thermal losses and damages to surroundings also can be evitable. Therefore, recent research groups are trying to replace conventional spark ignition system with non-thermal plasma system to achieve high efficiency clean vehicles [7,8].

Mariani et al. tested high frequency sustained plasma ignition system in a 1.6 l multi-cylinder gasoline engine [9]. The system was composed of a 5-star shaped electrode ignitor and a resonant transformer circuit. The input voltage of 100 V was amplified up to 6 kV with a frequency of 4.697 MHz. The ignition was occurred by corona discharge at the end of each sharp electrode. The engine test results showed that the fuel efficiency and combustion stability were improved as compared to conventional spark plug system. The system also reduced carbon monoxide (CO) and unburned hydrocarbon (HC) emissions. However, the nitrogen oxide (NO_x) emissions were slightly increased due to the higher in-cylinder temperature. Wang et al., applied microwave resonance plasma ignition system in a constant volume cylinder [10]. The new ignition system was consisted of a solid state microwave generator, a circulator, a directional coupler and a coupling antenna. The microwave generator had a power of 3 kW and wave frequency of 2.4–2.5 GHz. The combustion tests were performed with methane and air mixture in a constant volume chamber. The exhaust emissions were analyzed by a gas chromatography equipment. It was confirmed that the maximum pressure in the chamber was elevated with microwave resonance plasma ignition. At the same time, both lean and rich limits of methane-air mixture were extended to of 1.82 and 0.33, respectively. The emission analysis also showed that the resultants from incomplete combustion such as carbon monoxide (CO) and hydrocarbon (HC) were significantly lowered with microwave resonance plasma ignition. The energy conversion efficiency could be improved by 13.4% than conventional spark ignition due to enhanced complete combustion. The enhancement of flame formation and development with microwave ejection has been reported from previous research of Hwang et al. [11]. A new microwave-assisted plasma ignition system was developed with a magnetron (2.45 GHz, 700 W), waveguide, a mixing unit, and an igniter. The ignition itself was triggered by conventional spark system, however, the microwave energy was ejected near the spark zone. The experimental result showed that the flame speed was increased up to 20% compared to spark-only operation. The initial flame kernel was enlarged by microwave energy deposition on the flame surface. In terms of microwave ejection timing, it was beneficial to have earlier microwave ejection timing than spark ignition timing.

The early stage of flame kernel development has a dominant impact