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Experimental study of microwave resonance plasma ignition of methane–air mixture in a constant volume cylinder

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ABSTRACT

Application of microwave induced plasma to ignition and combustion offer potential for energy saving and emission reduction in internal combustion engines (ICEs). In this paper, the concept of microwave resonance plasma ignition (MRPI) is proposed and investigated. Experiments were carried out in a cylindrical constant volume combustion chamber, which was designed not only to simulate the size and configuration of the real engine combustion chamber at the top dead center (TDC), but it also enables the generation of resonance to obtain strong electric field in the large space. The ignition source consumes low ignition energy similar to that of the traditional spark plug, yet offers the advantages of extending the ignition limit, enhancing the combustion stability and improving the energy conversion efficiency. Results showed that the ignition limit was expanded to equivalence ratio (ϕ) of 0.55 and 3.0 for the lean and rich mixtures, respectively. For $\phi = 0.70$, due to the more complete combustion for the MRPI mode, the energy conversion efficiency was 13.4% higher than the SI mode. Initial ignition stage was captured by using a high speed camera.

1. Introduction

Spark ignition (SI) gasoline engines are widely used in land-based transportation. Compared to diesel engines, they require 20–30% higher fuel consumption due to the lower compression ratio, lower specific heat ratio, lower burning speed, higher pumping loss, higher heat transfer and higher cycle-to-cycle variation [1]. These six disadvantages leading to low thermal efficiency can be traced to the traditional single-point spark ignition and the subsequent flame propagation limit, in that the ignition generates the equilibrium thermal plasma only between the electrodes. Hence, using traditional spark ignition, even with a high ignition energy, it is difficult to ignite ultra-lean mixtures.

To achieve stable ultra-lean combustion with high thermal efficiency and low NO_x emissions, multiple-point ignition or even space ignition are viable options. Microwave induced plasma is a promising approach in this direction.

The interaction of plasma with flames has been widely investigated [2–6]. Plasmas are generally classified as thermal plasma and non-thermal plasma, and can be generated by microwave [7–9], radio frequency wave, dielectric barrier discharge, nanosecond discharge and other electric discharges. Thermal plasma follows the major laws of equilibrium thermodynamics and can be characterized by a single temperature at each point of space, i.e. the electron energy is equilibrium with the energy of the bulk gas. The feature of non-thermal plasma is that the temperature related to different plasma particles and different degrees of freedom is multiple. Generally, the energy is transferred to the electrons without causing large increases in the temperature of heavy particles, thus leading to the electron temperature often significantly exceeds the gas temperature [3]. Studies have found that non-thermal plasma has a remarkable effect on the combustion performance including accelerated reaction rates and enhanced flame stability [10].

Microwave ignition for IC engines can be divided into two categories: (1) Microwave Torch Ignition (MTI) [11–17] and (2) Microwave Assisted Ignition (MAI) [18–23]. A typical MTI application is the Quarter Wave Coaxial Cavity Resonator (QWCCR), which creates plasma by inducing electrical breakdown of a gas mixture surrounding the tip of the electrode by using a microwave electric field [14]. The QWCCR is made up of a specially designed cavity in which the microwave energy is coupled through the electrode terminal such that through resonance, a strong electromagnetic field is formed such that breakdown in the combustible mixture occurs near the electrode tip from which the plasma is created to initiate combustion. Extensive experimental and theoretical

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analyses have shown that the ignition energy of the QWCCR is close to that of the spark plug, and that while the lean ignitability limit can be extended (to equivalence ratio, $\phi = 0.80$), the result is not satisfactory [17] because microwave resonance only focuses at one point instead of the entire combustion chamber. Regarding MAI in a system developed by Ikeda et al. [18,19], a locally intensified microwave field was formed by a microwave antenna. Plasma was initiated by spark discharge, and then expanded and sustained by microwave. The plasma provided higher radical concentrations and enhanced combustion. In particular, Wolk et al. [22] demonstrated that the equivalence ratio for lean and rich ignition limits of methane–air mixtures at 0.1 MPa could be respectively extended to 0.5 and 1.3 through MAI.

Recognizing the potential of microwave assisted ignition, particularly that of MAI, and that the above methods involve single-point ignition, we present here in an alternative method, namely Micro-wave Resonance Plasma Ignition (MRPI), in which the resonance field is substantially expanded by utilizing the entire combustion chamber as a cavity resonator. Specifically, compared with microwave-assisted spark plug, plasma is directly generated by the microwave resonance. Microwave radiates in all directions and excites the plasma instead of playing an assisting role to expand the plasma as for the MAI. Consequently, the lean and rich limits can be substantially extended by employing the MRPI, as will be shown in due course.

2. Experimental setup and methodology

The series of experiments of microwave ignition with a coupling antenna and spark ignition with a traditional spark plug were performed in a constant volume cylindrical combustion chamber, as schematized in Fig. 1.

The test rig consists of a microwave ignition system, a combustible mixture distributing system, a visualization system and a data acquisition system. The microwave ignition system is composed of a solid state microwave generator, a transmission system and a coupling antenna. The solid state microwave generator is used to deliver microwave pulse with maximum power up to 3 kW, pulse duration ranging from 10 to 2000 μs, and frequency from 2.4 GHz to 2.5 GHz. Once the microwave pulse is delivered by the generator, it can be transmitted to the constant volume combustion chamber though the transmission system which includes a circulator, a dummy load, a directional coupler and auxiliary devices. The circulator and dummy load function as the protective devices to avoid damaging the microwave generator by the reflected wave. The directional coupler measures the incident power and reflected power of the microwave pulse, and the difference of the two powers is considered as the consumed power which is delivered into the combustion chamber. In fact, taking the microwave reflection and the transmission losses into consideration, the consumption power delivered is about 60% of the power consumed by the microwave generator.

In order to achieve the required electric field strength in the large space of the combustion chamber, the size of the combustion chamber and the coupling antenna were specifically designed. According to the microwave resonator theory [24], the combustion chamber was designed as a cylindrical cavity resonator to generate the electric field in the large space. Studies [25] have indicated that the intrinsic resonance frequency f_0 of the cylindrical resonator mainly depends on its diameter and the permeability and permittivity of the mixture. In particular, for methane–air mixtures, and the microwave frequency is 2.45 GHz and the cavity resonant diameter is 93 mm for methane–air mixtures. Therefore, the diameter and height of the cylindrical resonator cavity was designed as 93 mm and 10 mm, respectively, which is similar to the size of a real engine combustion chamber at TDC. The theoretical quality factor of the resonator was 5139. However, because of machining errors, material properties and other unpredicted losses, the practical quality factor of our resonator was 1121 [25]. A needle-shaped coupling antenna, consisting of three layers from inside to outside: a center copper electrode, a dielectric material made of polytetrafluoroethylene and a shell copper conductor, was used to further enhance the electric field strength in the cavity. One end of the coupling antenna was connected to the coaxial transmission line and the other end, like a needle whose length is 6 mm and the tip radius is 0.1 mm, was mounted in the resonator, shown in Fig. 1. The maximum electric field strength could be improved tenfold with the needle-shape coupling antenna [25].

The resonator was filled with a mixture of methane and air. In order to investigate the combustion characteristics of the mixture at different equivalence ratios, two mass flow meters with a timing circuit (Alicat MCQ-50sccm-D and Alicat MCQ-500sccm-D, ±0.2% of full scale) were used to precisely control the required ϕ of the mixture.

A gas chromatography (the Autosystem XL GC, Ar carrier gas), equipped with a thermal conductivity detector (TCD), was used to analyze the stable product gases, such as H_2, O_2, N_2, CO, CH_4 and CO_2. The GC was quantitatively calibrated by using reference

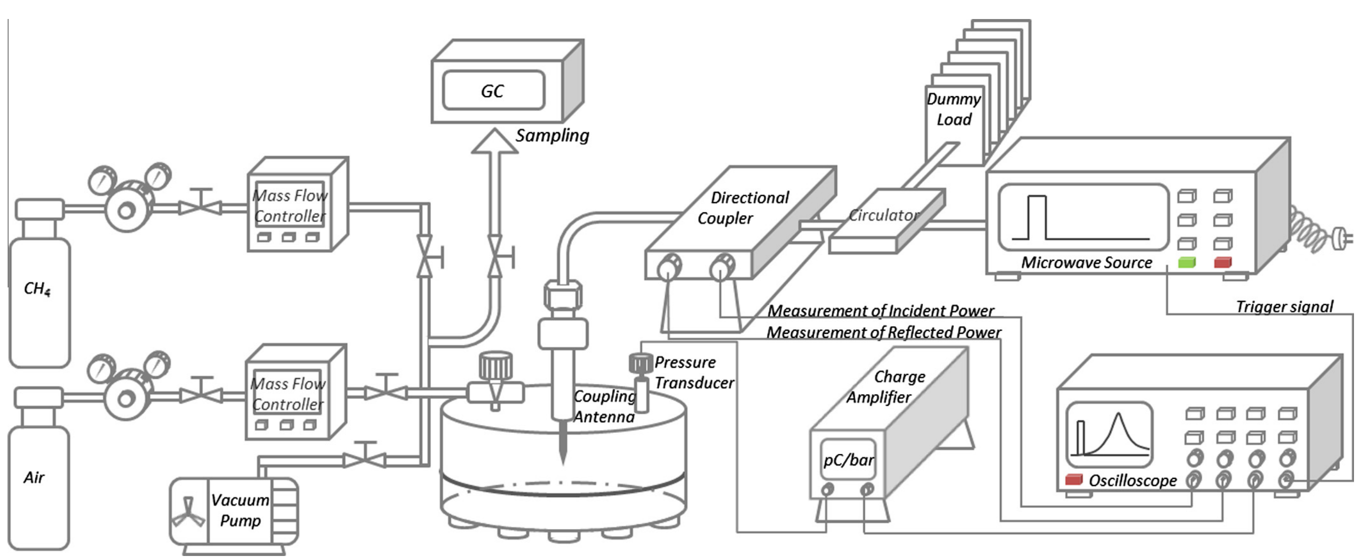

Fig. 1. Schematic of the microwave ignition experiment setup.