5 Combustion/Pre-ignition

5.1. Microwave Enhanced Combustion on a Constant Volume Combustion Chamber for Lean Combustion and EGR Dilution

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Abstract

The effect of microwave enhancement on combustion was investigated using a spherical, constant-volume combustion chamber. Microwave energy at 2.45 GHz was coupled into the spherical chamber using a quarter-wavelength dipole antenna. Standing waves of high-strength electrical fields were created to enhance the flames ignited by a spark plug. Pressure traces of combustion with and without microwaves were recorded to compare the combustion improvements. Microwave power levels and discharge durations were also varied to understand their impact on the level of improvement. Results indicated that the microwave system can effectively accelerate combustion and improve cycle stability for dilute combustion, including lean burn at about 0.8 equivalence ratio and stoichiometric operation with 20% exhaust gas recirculation (EGR) dilution.

1 Introduction

In the last decade, stringent emission mandates and a high demand for fuel economy have continuously driven the development of new engine technologies towards cleaner and more efficient combustion applications. Engine efficiency continues to improve with dilution, lean or EGR, through cooler combustion, reduced throttling and improved thermodynamic working fluid properties [1]. The efficiency improvements gradually deteriorate at higher dilution levels due to a reduction in the combustion efficiency and the protracted burn durations in the engine [2]. Excessive combustion durations impose a hard limit to the amount of dilution that can be tolerated due to combustion instability [3].

To overcome these negative effects on engine efficiency, new technologies have been developped to extend the dilution limit. New port and combustion chamber designs have improved charge preparation and turbulence levels, which lead to a faster flame development [4]. However, increasing the turbulence level can have a negative impact on volummetric efficiency and does not couple well with other efficiency improvememnt technologies like Miller cycle operation [5]. Advanced ignition systems, such as micro-pilot [6], multiple spark plugs [7], pre-chamber [8], corona ignition [9] and high energy ignition [10][11] can improve the ignition performance and reduce burn duration by igniting in multiple locations or for longer durations, but at an increased hardware cost and higher in-use costs associated with durability and energy consumption. In addition, while ignition systems have a positive impact on the initial flame kernel propagation rates, they have no influence during the fully turbulent portion of the combustion event.

Microwave enhanced combustion was conceived as a possible solution to the limitations associated with high levels of EGR dilution for positively ignited engines. MEC improves the reaction kinetics alone through the potential to deliver energy directly to the flame front in the form of electromagnetic excitation of reaction species above and beyond what can be accomplished thermally [12]. Becuase it is a field, the MEC solution also has the potential to improve combustion throughtout the entire combustion period, and not only during the inital kernel formation period.

In this study, we developpd a microwave system to conduct MEC experiments on a laminar burning velocity (LBV) vessel. A microwave antenna was designed to effectively couple microwave energy inside the LBV vessel and generate high-intensity standing waves of electromagnetic fields for MEC. Microwave frequency, pulse duration and duty cycle were evaluated and optimized for the MEC performance. Experimental results indicated that the MEC system can effectively accelerate combustion and reduce cyclic varibility for lean and EGR diluted combusion.

2 Experimental Setup

2.1 Microwave Antenna

For the LBV vessel, the inner diameter is very close to the free-space wavelength of the microwave energy produced by the microwave generator at 2.45 GHz. Therefore, to efficiently couple microwaves into the vessel cavity, it is optimal to establish the internal microwave standing waves following electric and magnetic field strength contours for the spherical cavity mode, TM101 [13], as illustrated in Figure 1.

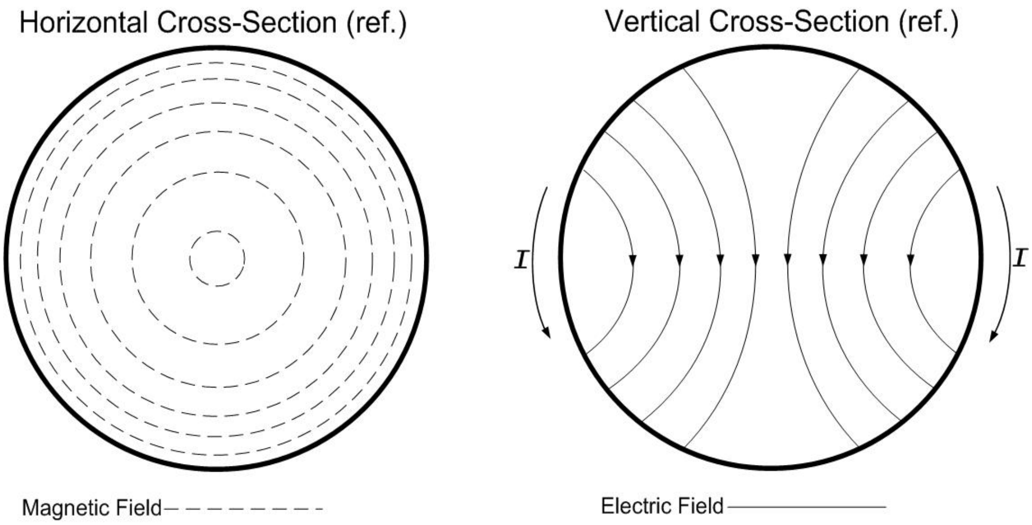

Figure 1: Cross-Section of Spherical Cavity Mode, TM101

MW energy can be coupled into a chamber by many methods. To work in conjunction with the transmission line and the chamber characteristics, a electrical-field coupler type microwave antenna was recommended to generate the TM101 mode fields [14]. Therefore, a micorwave antenna was developped in the form of quarter-wave groundplane dipole as illustrated in Figure 2. The antenna was integrated within a coaxial feed-through to receive microwave power from the amplifier, and ultimately installed in the MEC/LBV test setup. This development facilitated experimental MEC testing with both magnetic and electric field combustion chamber internal coupling methods.

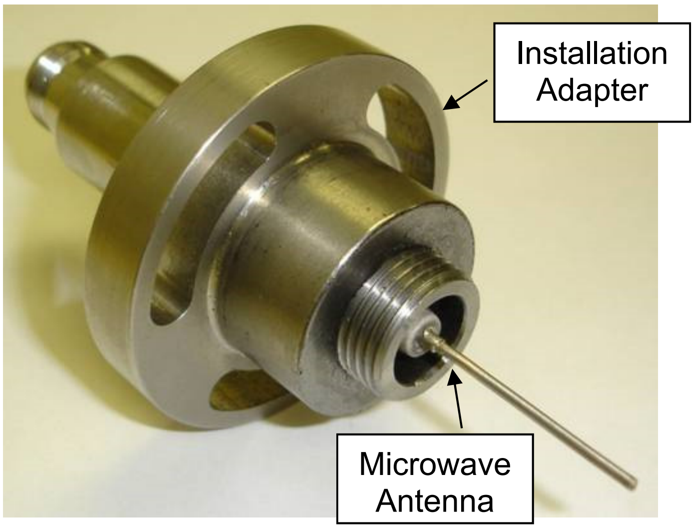

Figure 2: Microwave Quarter-wave Dipole Antenna Installed in the LBV Vessel Adaptor

2.2 Microwave System

The microwave system was integrated with the LBV vessel. A microwave power signal was synthesized by a microwave generator to the desired peak power and pulse duty cycle with a maximum of 2 kW and 100%, respectively. Its forward and reflected power were measured by a directional coupler and power meters. Finally, the microwave signal was transmitted through a coaxial feed-through and coupled into the LBV vessel via a microwave antenna. A circulator was implemented next to the antenna to absorb the reflected energy for power overload protection. Microwave instrumentation components and signals were included as well as interfaces with data acquisition. The system structure of MEC combustion test MW delivery and instrumentation are shown in Figure 3.

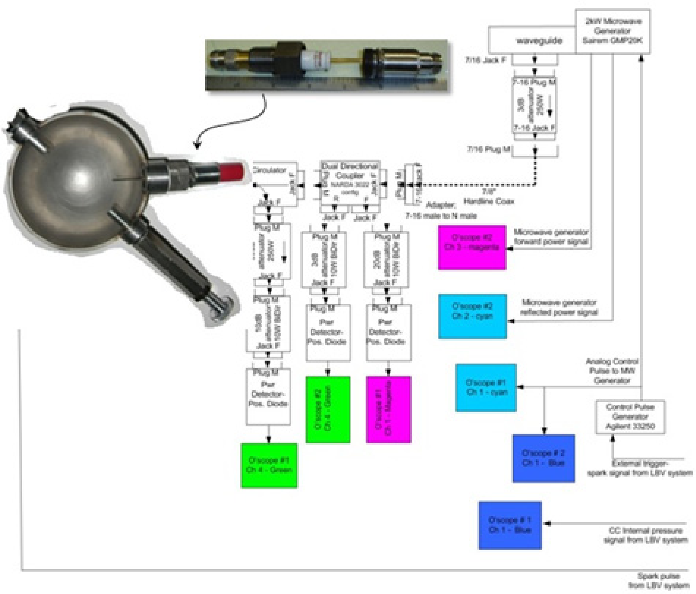

Figure 3: MEC system for Combustion Tests

An LBV internal pressure signal was routed to the MEC instrumentation setup to include measurements of the chamber internal pressure with the other MEC test signal traces and data files. Finally, the spherical LBV combustion chamber and the spark ignition circuit and spark plug are schematically included in the diagram. The physical integrated MEC MW delivery and instrumentation system and the LBV combustion chamber system is shown in Figure 4.

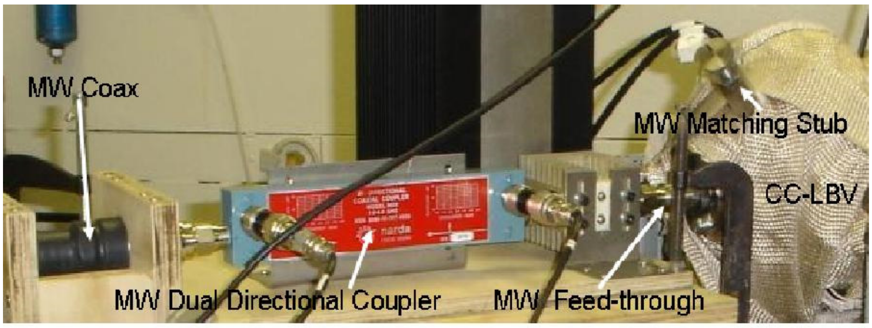

Figure 4: Integrated MEC /LBV Components during Preparation for Combustion Testing

3 Results and Discussions

MEC testing on the LBV vessel investigated the potential for enhanced combustion using standing waves of electromagnetic (MW) fields. The MEC testing was conducted at varying levels of dilution and with variations of MW coupling and configuration. MEC/LBV testing continued to be conducted in an “interleaved” test technique (MW-No MW) in order to limit potential influences on test results by un-related or relatively long-term drift in test conditions.

During the test interval, interactive test/modify/test experiments were conducted to optimize the MEC performance. Testing began with the more familiar MW magnetic loop-in-the-LBV configuration and then migrated to testing with the MW antenna configuration. Different microwave pulse widths and discharge timings were evaluated. By the end of the test interval, refinements in configuration and technique produced significantly accelerated combustion events with MW power applied. These tests were conducted using the e-field coupler microwave antenna configuration and at dilute A/F conditions.

3.1 MEC performance on Lean Combusiton

In this test, MEC was evaluated at a constant lean A/F ratio, 0.8, diluted by dry lab-grade air. The microwave power levels in the LBV vessel were from 0.7 kW to 1.6 kW. Room temperature iso-octane fuel was used and, the normal combustion time interval (time between ignition and maximum internal pressure) was 160 ms. Continuous microwave power was applied for a period of 160 milliseconds, starting one millisecond prior to ignition. Increasing levels of continuous microwave power were applied within the LBV during the MEC tests. Several series of multiple interleaved MW-No MW tests were performed at each MW power level to acquire relevant combustion data.

For these tests, it was found that microwave power levels above a threshold of 1kW consistently yielded larger than 10% reduction in the time required to reach peak pressure and also significantly improved combustion data variability, compared to combustion tests without microwave. Figure 5 illustraed results from a series of interleaved (MW-No MW) combustion tests using 1.6 kW of continuous MW power. Tests using pulsed microwave around 50% duty cycle resulted in 80%-90% of the pressure rise acceleration achieved with continuous microwave (Figure 6).

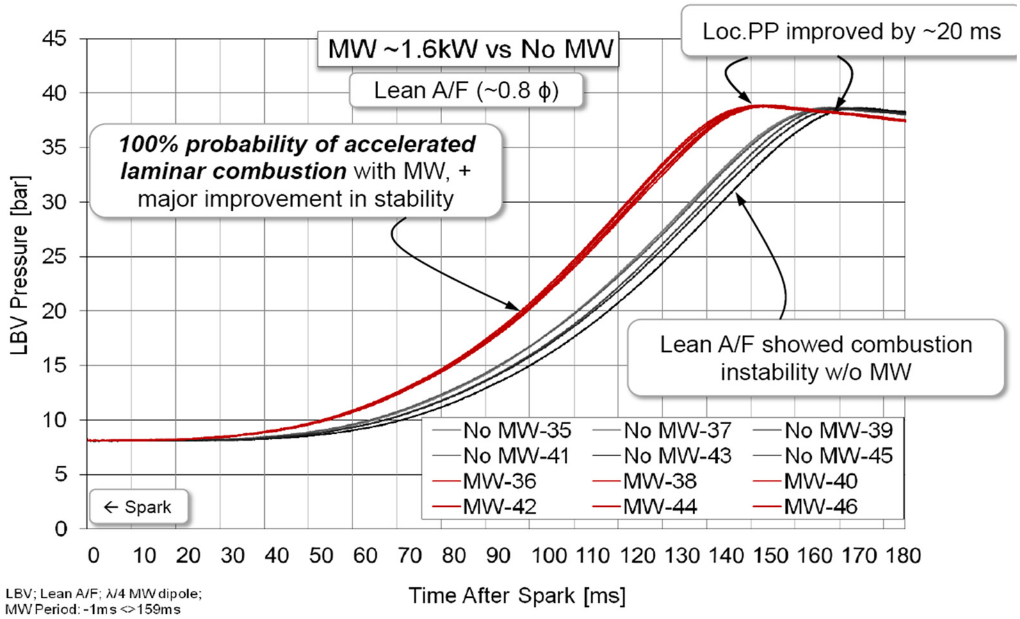

Figure 5. MEC Lean Combustion Results by Continuous Microwave at 1.6kW

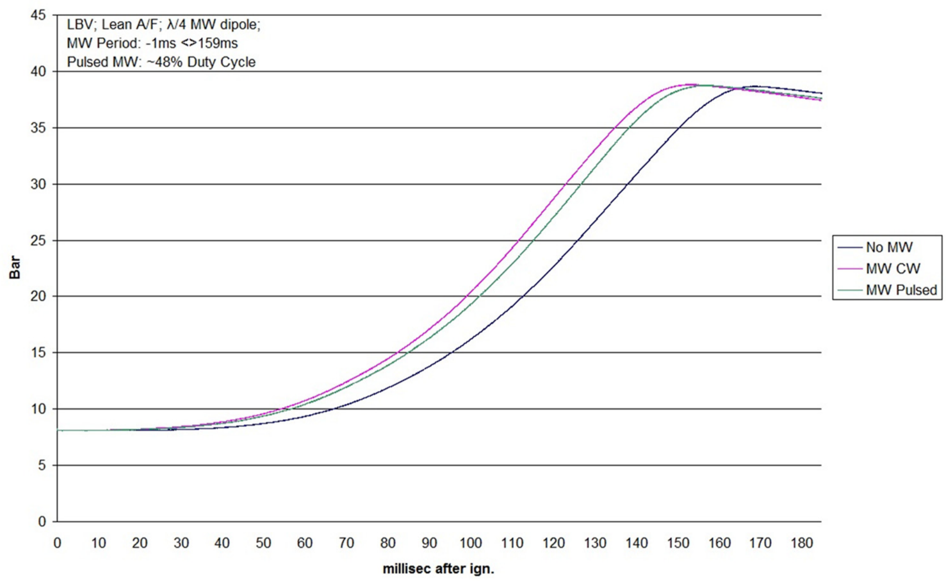

Figure 6. MEC Lean Combustion Results by Continuous and Pulsed Microwave at 1.4kW

Relatively high, time-varying reflected microwave energy was observed to be associated with the microwave combustion acceleration process (Figure 7), and the indicated acceleration process appeared to be continuous under steady and pulsed microwave conditions. Microwave instrumentation signals showed continuous growth of the indicated (by the reflected power signal) acceleration process during intervals between MW pulses when the MW power was off. When MEC tests with microwave power applied but without ignition were conducted, combustion did not occur.

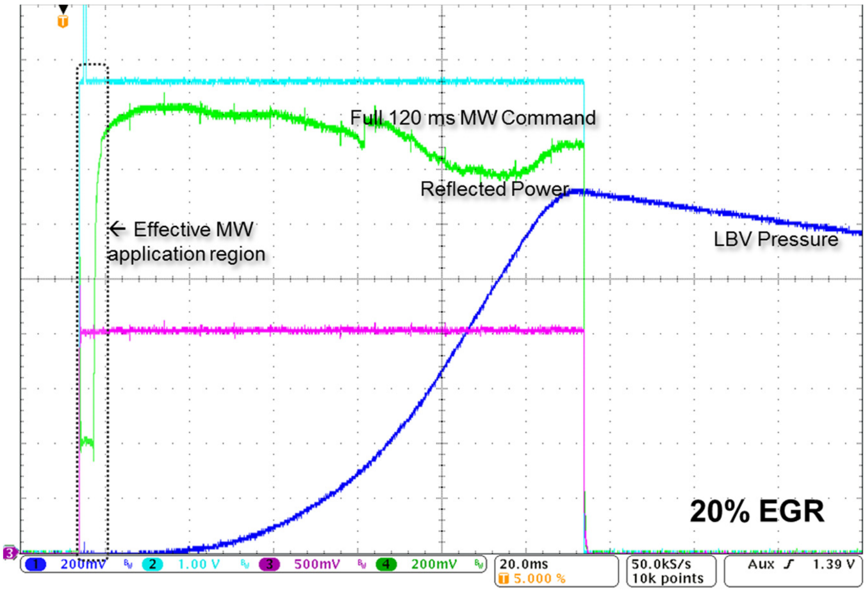

Figure 7. Example MEC MW Instrumentation Signal Traces - Accelerated Combustion Test

3.2 MEC performance on EGR Combusiton

The MEC performance was evaluated in the LBV at stoichiometric A/F ratios and 20% EGR dilution. For these tests, EGR was simulated through additional N_2 dilution. The normal combustion time interval (time between ignition and maximum internal pressure) was 120 ms. The MEC/LBV physical setup was the same as used in the lean MEC experiment to facilitate direct result comparisons. The MW power start timing was swept between -1ms and +4ms relative to ignition, in 1 ms steps. Continuous microwave power levels of about 1.3 kW were applied for durations of 120 ms for tests with microwave. All MEC testing was conducted using the previously described interleaved (MW- no MW) procedures to limit potential influences on test results by un-related or relatively long-term drifts in test conditions. Emissions were continuously sampled and evaluated to assure maintenance of the target conditions. Comparative analysis was conducted on emissions collected during special sequences of consecutive MW combustion tests and consecutive No MW tests.

MEC testing with under stoichiometric A/F ratios with 20% EGR dilution yielded essentially the same MEC combustion acceleration results. Microwave accelerated time to peak pressure by 10% for the stoich EGR case (Figure 8). The cycle stability was improved as well. Also, as found in the lean MEC testing, relatively high and time-varying reflected microwave energy was observed to be associated with the microwave combustion acceleration process, and the indicated acceleration process appeared to be continuous under steady and pulsed microwave conditions.

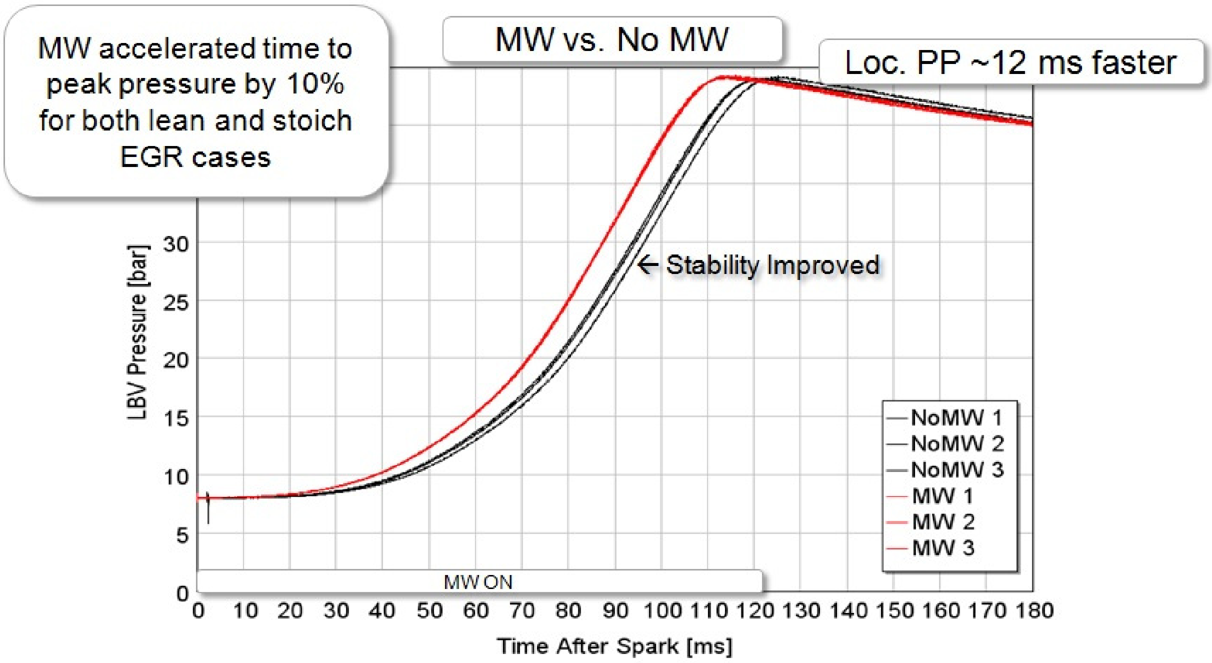

Figure 8. MW Can Accelerate Stoichiometric EGR Combustion

4 Conclusion

In summary, the MEC system established a high intensity field inside a conducting vessel and enhanced the combustion rates for a LBV vessel. Experimental results indicated that at a power level higher than 1 kW, the MEC using a electrical field coupler antenna can effectively improve flame development and cycle stability for dilute combustion – either at lean conditions (0.8 equivalence ratio) or stoichiometric operation with 20% EGR. This proved that fundamental resonance of MW radiation could positively impact dilute combustion on time-scales appropriate for internal combustion engines.

Literature

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