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Investigations of microwave stimulation of a turbulent low-swirl flame

A. Ehn^{a,*}, P. Petersson^a, J.J. Zhu^a, Z.S. Li^a, M. Aldén^a, E.J.K. Nilsson^a,
J. Larfeldt^b, A. Larsson^c, T. Hurtig^c, N. Zettervall^c, C. Fureby^c

^a Division of Combustion Physics, Lund University, PO Box 118, SE-221 00 Lund, Sweden

^b Siemens Industrial Turbomachinery AB, SE-612 83 Finspång, Sweden

^c Defence Security Systems Technology, The Swedish Defence Research Agency – FOI, SE 147 25 Tumba, Stockholm, Sweden

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Abstract

Irradiating a flame by microwave radiation is one of several plasma-assisted combustion (PAC) technologies that can be used to modify the combustion chemical kinetics in order to improve flame-stability and to delay lean blow-out. One practical implication is that engines may be able to operate with leaner fuel mixtures and have an improved fuel flexibility capability including biofuels. In addition, this technology may assist in reducing thermoacoustic instabilities that may severely damage the engine and increase emission production. To examine microwave-assisted combustion a combined experimental and computational study of microwave-assisted combustion is performed for a lean, turbulent, swirl-stabilized, stratified flame at atmospheric conditions. The objectives are to demonstrate that the technology increases both the laminar and turbulent flame speeds, and modifies the chemical kinetics, enhancing the flame-stability at lean mixtures. The study combines experimental investigations using hydroxyl (OH) and formaldehyde (CH₂O) Planar Laser-Induced Fluorescence (PLIF) and numerical simulations using finite rate chemistry Large Eddy Simulations (LES). The reaction mechanism is based on a methane (CH₄)–air skeletal mechanism expanded with sub-mechanisms for ozone, singlet oxygen, chemionization, electron impact dissociation, ionization and attachment. The experimental and computational results show similar trends, and are used to demonstrate and explain some significant aspects of microwave-enhanced combustion. Both simulation and experimental studies are performed close to lean blow off conditions. In the simulations, the flame is gradually subjected to increasing reduced electric field strengths, resulting in a wider flame that stabilizes nearer to the burner nozzle. Experiments are performed at two equivalence ratios, where the leaner case absorbs up to more than 5% of the total flame power. Data from experiments reveal trends similar to simulated results with increased microwave absorption.

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* Corresponding author. Fax: +46 46 222 45 42.

E-mail address: andreas.ehn@forbrf.lth.se (A. Ehn).

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1. Introduction and background

Plasma-assisted combustion (PAC) has potential for combustion control and for reducing emissions to meet the globally growing demands on flexible power generation [1]. Plasma, the fourth state-of-matter, can be used for fuel-reforming and flue-gas treatment [2,3], but the focus of the present work is on applying the electric energy directly to the flame. PAC offers a method to modify the thermal and kinetic properties of the reactants, intermediates, radicals and products [4]. Due to fast electron impact excitation and dissociation of molecules at low temperatures, plasma introduces new reaction pathways, modified chemical time-scales, and may significantly change the combustion process [4,5]. Employing PAC improves flame stability and delays lean blow-out, allowing stable combustion with leaner, low-emission fuel-mixtures. PAC may extend the fuel compatibility to open up for using e.g. bio-fuels with minimal hardware modification.

Different technologies may be used to supply electrical energy to the flame including Dielectric Barrier Discharges (DBD) [6], Gliding Arc Discharges (GAD) [7], Microwave Discharges (MD) [8], and Radio-Frequency Discharge (RFD) [9], as described in [4,5]. Adding electric energy through microwave radiation is advantageous for direct stimulation of a flame since there is no need for electrodes (surviving in the harsh environment in a flame). In addition, microwave irradiation will be most efficiently absorbed in the flame-front, where both the electron density and the reduced electric field, E/N , are high. Creating a microwave-plasma is energy-costly, and here we instead endeavor to use microwave irradiation to generate a plasma-like state below dielectric breakdown. This allows us to influence the flame chemistry mainly by increasing the energy of the electrons already produced by chemiionization, a technology previously explored by Ward [10]. Several experimental and computational investigations have been performed for microwave-stimulated laminar flames below dielectric breakdown [11–13], but no previous experimental or computational studies of microwave-stimulation on turbulent swirl-stabilized flames in industrially relevant burners have been found by the authors.

This investigation concerns microwave-stimulated combustion in a lean swirling stratified turbulent flame at atmospheric conditions. The objectives are to demonstrate that the technology

increases both the laminar and turbulent flame speeds and modifies the chemical kinetics so as to enhance flame stability at lean mixtures. A skeletal reaction mechanism for methane (CH_4)–air combustion, expanded with sub-mechanisms for singlet oxygen, ozone, chemionization, electron impact dissociation, ionization and attachment is developed and as a first step applied to laminar flame simulations. The low-swirl flame is studied in an experimental investigations using hydroxyl (OH) and formaldehyde (CH_2O) Planar Laser-Induced Fluorescence (PLIF) and numerical simulations using finite rate chemistry Large Eddy Simulations (LES) [14]. Common trends in experiments and simulations results are used to demonstrate and explain some aspects of microwave-stimulated combustion.

2. Experimental set-up and measuring technique

This investigation of microwave assisted turbulent combustion is performed for flames stabilized by a low-swirl burner [15], offering a good compromise between simplicity and flow complexity. The low-swirl flow is created by an outer annular swirler, with eight swirl-vanes, in combination with an inner perforated plate, Fig. 1a. With this design the swirl and the highest velocities are found in the outer part of the flow discharging from the nozzle [16]. The diverging turbulent flow creates an inner low-velocity region in which the flame is stabilized. The study is performed with the low-swirl burner discharging into a purposely-designed microwave cavity, Fig. 1b, enclosing an air-co-flow of 0.4 m/s. The setup is similar to that used by Ehn et al. [17,18], and includes calibrated mass-flow controllers for CH_4 and air (Bronckhorst Hi-Tec, EL-Flow) and a flow-meter for the co-flow (Fox, Thermal Instruments). Equivalence ratios of $\phi = 0.58$ and 0.62, with theoretical powers of ~ 24 and ~ 27 kW, respectively, were studied.

The microwave system includes a magnetron (National Electronics GA15MP) operating at a frequency of 2.45 GHz, a circulator and a load, sensors for incident and reflected power and a three-stub tuner. The flame is kept in a ($D = 300$ mm) metallic cavity to achieve the mode-pattern that balances the position of the flame, and to obtain proper microwave coupling, Fig. 1c. Microwave coupling to the flame is achieved by tuning the location of the upper metallic grid at the upper end of the cavity, Fig. 1b. The lower metallic

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