Laser Diagnostic Imaging of Energetically Enhanced Flames Using Direct Microwave Plasma Coupling

Xing Rao, Stephen Hammack, Campbell Carter, and Tonghun Lee

Abstract—**Quantitative images of temperature and hydroxyl (OH) concentrations are presented in plasma-enhanced flames, where a nonthermal microwave plasma discharge is coupled directly with the reaction zone of the flame. The plasma jet is generated through a novel microwave (2.45 GHz) waveguide based a coaxial reactor system. Planar laser-induced fluorescence is used to generate the OH fields, and planar Rayleigh scattering thermometry is used for the temperature. Plasma-enhanced flames present new possibilities for ignition and flame holding under harsh operating conditions, including stabilization of combustion in hypersonic flame conditions.**

Index Terms—**Laser-induced fluorescence, nonequilibrium microwave plasma, plasma-enhanced combustion, Rayleigh scattering.**

NONEQUILIBRIUM plasmas are of great interest for enhancing chemical energy conversion which can lead to positive effects, such as pollution reduction, fuel reforming, ignition, and flame stabilization under harsh conditions [1]. Of the many types of plasma-generating systems, microwave is particularly enticing due to its high efficiency, ability to operate under high pressures, longer lifetime due to the absence of high-temperature electrodes, etc. We have previously shown that highly efficient plasma enhancement can be achieved when the electric field is directly coupled into the flame reaction zone [2] by using a re-entrant cavity system [3]. This study is an extension of this concept to more realistic flame geometries using both premixed and non-premixed conditions. The goal is to show spatially resolved images of how the flame and plasma energy interact for various plasma-enhanced flame configurations.

The plasma reactor (Amarante Technologies) demonstrated uses a new and proprietary energy delivery system for the generation of the plasma. It is designed to process chemical energy conversion on the order of kilowatts, whereas our previous plasma discharge system was limited to about 30 W. To generate the needed e-field for the plasma discharge to initiate, a waveguide is used to propagate the microwaves from a magnetron power supply to a plasma applicator, where a coaxial electrode in the center of the torch acts as an antenna to transmit the microwaves to the tip of the nozzle. The power supply used here is at 2.45 GHz with 2-kW capacity; however, in all experiments, less than 100 W is needed in order to initiate the plasma discharge in the flame. Microwave power is focused on the tip of the torch, where the flame and reaction zone are located, through adjustments of a three-stub tuner and sliding short. The absorbed microwave power can be determined from the difference of incident and reflected powers. As soon as a microwave power of more than 30 W is applied, a nonequilibrium discharge is established and is coupled into the flame. The system is flexible and can accommodate various flame geometries, both premixed and non-premixed, depending on the nozzle geometry and fuel and air flow.

The images shown were obtained using laser diagnostics around the reactor. For hydroxyl (OH) planar laser-induced fluorescence (PLIF), UV laser radiation at 283 nm was used to excite the $Q_1(8)$ transition in the $A^2\Sigma^+ - X^2\Pi$ (1, 0) band. A 532-nm emission from a frequency doubled Nd:YAG laser

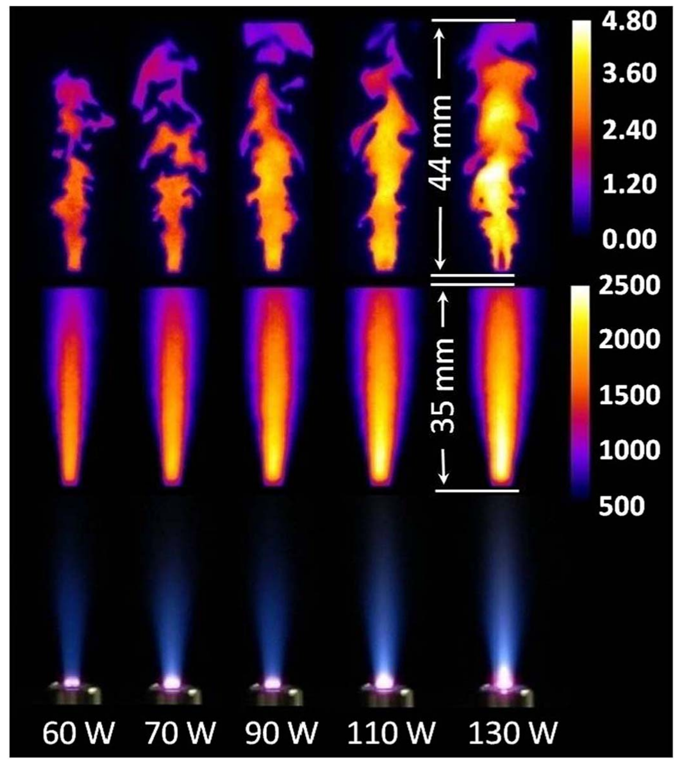

Fig. 1. (Top) Single-shot OH PLIF images, (middle) averaged Rayleigh scattering temperature fields, and (bottom) photographs at a total flow rate of 15 LPM of equivalence ratio of 1.0 for power levels from 60 to 130 W in the premixed mode.

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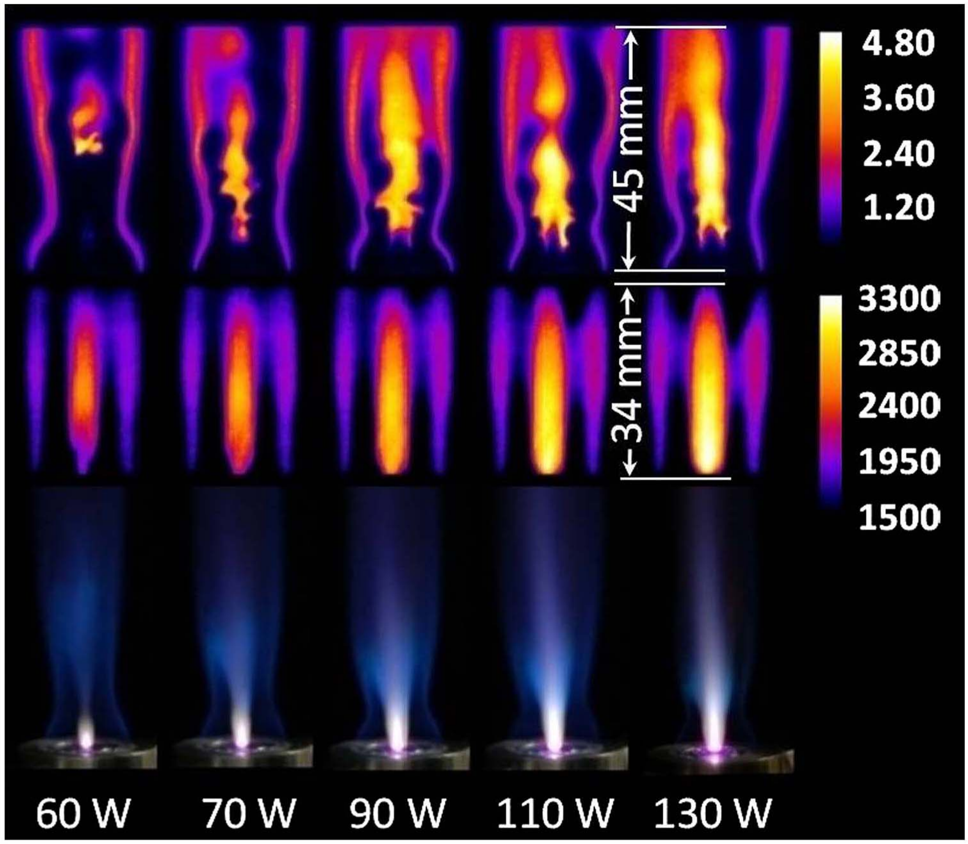

Fig. 2. (Top) Single-shot OH PLIF images, (middle) averaged Rayleigh scattering temperature fields, and (bottom) photographs at total flow rate of 1 LPM of methane and 5 LPM of air for power levels from 60 to 130 W in the non-premixed mode.

was used for the Rayleigh scattering temperature measurement, in which scattering light signal is related to the density of the gas and, thus, the temperature.

Figs. 1 and 2 show the OH concentrations and temperature fields for both premixed and non-premixed cases, respectively, where the plasma power is varied from 60 to 130 W. All conditions shown here are cases where the flow speed is too fast for stabilization of the flame to occur without a plasma discharge. As can be seen in the third row, a purple and white discharge from the plasma can be seen to anchor the flame to the tip of the torch, followed by the blue emission from the oxidation of methane. As the plasma power is increased, the temperature of the discharge varies over a wide range from under 1000 K to well over 2000 K. The mechanism of the flame enhancement is also expected to drastically vary over this range, as can be seen from the OH concentrations, which increase more than 300% over this wavelength range. For the non-premixed case, a central air discharge results in the plasma discharge and fuel injected around the edge. Two distinct reaction zones from the interaction with the plasma and diffusion with the surrounding air can be observed.

In conclusion, photographs of a directly coupled plasma-enhanced flame at atmospheric pressures, single-shot OH PLIF images, and averaged planar Rayleigh scattering thermometry images of methane/air flame have been presented for two different flame geometries. The concept of enhancing the chemical energy conversion of flames by coupling the plasma energy into the reaction zone could potentially present new opportunities for advanced combustion and propulsion systems in the future.

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