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Plasma-combustion coupling in a dielectric-barrier discharge actuated fuel jet

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ABSTRACT

A plasma-combustion coupling mechanism is proposed and applied to the laser-induced atmospheric-pressure ignition and combustion of a hydrogen jet as assisted by a dielectric-barrier discharge (DBD). The specific configuration matches corresponding experiments, and the proposed coupling mechanism leads to an improvement of the prediction for ignition probability and explains the observed electrical power increase during burning conditions. To realize this, the model includes the key effects of the fast DBD microflimentary plasma structure on combustion time scales, which would not be included in a simpler quasi-steady approximation. It also explains observed plasma emission patterns and the dependence of the DBD power absorbed on the cross-flow velocity. The main conclusion of the present computational analysis is that the interaction of plasma and combustion supports a two-way coupling rooted in the electron and neutral energy equations. The coupling selectively amplifies the energy and radical contributions by the discharge at the ignition hot spot. These contributions dominate the evolution of hot spots interacting with the local electric field over dielectric surfaces and are a key ingredient of predictive ignition models. Results are discussed in the context of the lower pressure, lower equivalence ratio and lower dimensional (often premixed and quasi-one-dimensional) studies that provide insights for developing this integrated model while illuminating the important differences of the coupling in non-premixed conditions at atmospheric pressure.

1. Introduction

It is well-understood that plasma can accelerate combustion rates [1–6]. While most of this work has focused on how the electrical discharg e can affect chemical kinetics, Savelkin et al. [7] have recently shown a strong reverse coupling effect: combustion and mixing can affect the discharge leading to an increase of the electrical power absorbed and a broadening of the plasma's extent. Yet the mechanisms of this two-way coupling are not fully understood, and it remains uncertain what factors are important in any particular configuration. We develop a model to analyze the mechanisms that are active in the laser-induced ignition of a round fuel jet in a turbulent cross-flow in the presence of a dielectric-barrier discharge (DBD) plasma. Our goal is to identify and represent in a simulation how the plasma-combustion interaction affects the ignition probability. Experimental observations for this same configuration are recently reported [8,9]; observations of particular interest are summarized here:

- The DBD plasma enhances ignition above a threshold, although it also slightly hinders is probability for low applied voltages. A two-stage ignition and associated blow-off process has been identified in the regime when the DBD supports ignition.
- Although the actuator is axisymmetric, the plasma light emission is not once the jet is burning. The absorbed electrical power is significantly increased by the flame, and, more interestingly, decreases when the flame is in a cross-flow. Both of these observations indicate coupling between the flow, plasma, and flame.
- Light emissions at 720 nm (near the water vapor infrared band) are more intense and more spatially distributed with DBD-actuation, pointing to additional coupling.

To explain these observations we develop a model for the interaction of plasma and combustion on the time scales of turbulent combustion ($\sim 10^{-2}$ s). These are fast relative to the flow, yet around 10^6 times slower than the characteristic time for electron transport and ionization in atmospheric air ($\sim 10^{-8}$ s),

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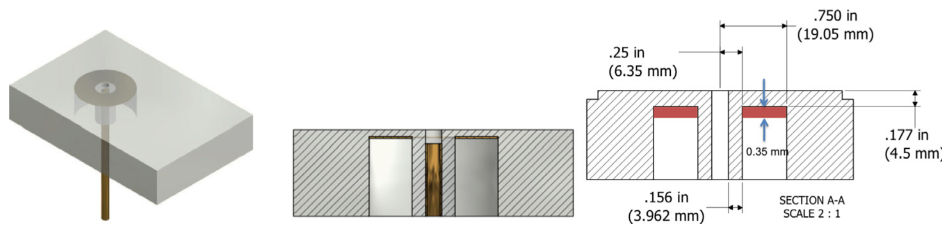

Fig. 1. DBD setup with the electrodes drawn in brown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which occurs for reduced electric field strength $E/N \gtrsim 100\,\mathrm{Td}$. Therefore, we anticipate at the outset that a detailed resolution of the electron transport is unneeded and would likely be computationally infeasible. However, despite this time-scale difference, we can also anticipate that an only weak coupling of fluid and plasma dynamics [10], whereby the fluid would be approximated as unchanging on the plasma time scale, would miss essential interactions that are tightly coupled at atmospheric pressure [11, ch. 9]. The primary two-way coupling can be anticipated to arise from a decrease in specific collisional loss with increasing temperature and Joule heating [11, p. 223]. Because the ratio between electron drift is expected to far exceed fluid velocity for our conditions ($v_d/U_\infty \gtrsim 10^4$), the avenue of such a coupling is anticipated to be through the relatively slow change of the target state that the electrons impact in the their drift.

The quantitative description of the coupling mechanism we develop is based on the microstructure of DBD plasma, particularly that it is supported by many quasi-periodic microstreamers, each occurring on a $\sim 10^{-9}$ s time scale. Surface charging provides these with an effective memory, so that they recur in the same locations at each change of the voltage polarity [12]. Our specific model is motivated by the observed intensification in the presence of the flame as well as the corresponding electric power absorption changes.

At low gas temperature and large electric frequencies, microstreamers are inefficient and Joule heating is negligible [10]. However recent measurements show a dramatic change when there is a sustained flame, presumably due to the high temperatures supported by turbulent combustion. In this case it is seen that the filament coverage of the dielectric surface increases, has low intermittency, and tracks the flame location [8]. We propose that this coupling is due to the linear decrease in three-body attachment to oxygen with increasing temperature. Our analysis results in a criterion for the formation of self-sustained plasma filaments, which bypass the random avalanche phase [11, p. 328] and form in the pre-ionized gas of previous microstreamers. This is developed to explain these observations and plasma–flame interactions primarily in Section 4.4.3.

Recent analysis of the effect of plasma and combustion in low-dimensional configurations has led to the improvement of kinetic models and the coupling between the Boltzmann equation with trusted models for neutral chemistry [13,14]. Yet studying plasma-combustion coupling in one-dimension is difficult. Thermal coupling between the discharge and the fluid enthalpy contracts the plasma column [11] and selectively amplifies the energy and radical production at distinct locations [8]. Experiments demonstrate the difficulty in obtaining a one-dimensional ignition front, even at very low pressure [14]. Realistic, higher-pressure conditions accentuate this [7,8]. Our current target is thus intrinsically three-dimensional, and mechanism are integrated into a model of a genuinely three-dimensional configuration with corresponding experimental observations. Because the time scales of the electron drift are small and thus neglected, this comparison depends foremost upon the coupling model. Lower-dimensional simulations have been used to determine some model parameters, though in a way such that the three-dimensional results are true predictions.

The following Section 2 provides a description of the target configuration and measurements. Then, Section 3 provides additional detailed motivation and reviews the specific assumptions invoked in crafting the integrated model. Section 4 describes the ion-chemistry model, Section 5 the practical tabulation strategy to include the plasma sources in the governing equations, Section 6 the governing equations, Section 7 the simulation strategy, and Section 8 the results. Conclusions are revisited with additional discussion in Section 9.

2. Experiments

2.1. Apparatus

The experiments were conducted in a subsonic windtunnel with a test section of 0.4 m × 0.4 m cross section and 1.19 m long. A 40-grit sandpaper roughness strip of total height 1.64 and 50.8 mm width trips the boundary layer turbulent 333 mm upstream of the center of the fuel port. PIV measurements confirm that a fully-developed turbulent boundary layer was obtained [9].

The hydrogen fuel enters vertically through the windtunnel floor through a port with diameter $D_H = 4.83$ mm at flow rate $\mathbf{Q} = 17.83\,\mathrm{cm}^3/\mathrm{s}$. The Reynolds number in the tube is $\mathrm{Re}_D = 4\mathbf{Q}/\nu D_H^2 = 44.5$, so the fuel flow is laminar. A laser-induced optical breakdown with measured power $P_{\mathrm{int}} = 17.64 \pm 6.12$ mJ was used to ignite the fuel.

The DBD actuator shown in Fig. 1 was operated with a 12 kV, 30 kHz sine-wave. The dielectric material is quartz; the exposed electrode is a coaxially aligned copper tube with wall thickness 0.51 mm and is recessed 4.8 mm from the top surface of the quartz, which in turn is flush with the windtunnel floor. The other electrode is buried 4.425 mm below the exposed quartz surface. It is a ring of thickness 0.4 mm that extends radially from $r_i = 6.375$ mm $r_e = 19.05$ mm.

2.2. Measurements

A complete description the measurements used to support the analysis in the present study is reported elsewhere [8,9]. The probability of igniting the H_2 jet was measured as the position of a laser spark varied. For each breakdown position, 50 independent experiments were conducted, in which the laser energy and flame ignition status were determined. Ignition was determined based on both schlieren imaging and water emission spectra from the rotovibrational bands at 717 nm [15,16] using a lens with a 720 nm (10 nm FWHM) bandpass filter. The discharges were analyzed with light emission and power measurements to ascertain their contribution of streamers to the current and electric power coupled into the fluid.