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The effects of incident electric fields on counterflow diffusion flames

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ABSTRACT

Numerical simulations of counterflow laminar diffusion flames impinged by sub-breakdown DC electric fields are performed in this work using multi-component transport and a detailed chemical mechanism for methane–air combustion that includes elementary steps for the conversion of six electrically charged species. The electric field is induced by two electrodes located on the oxidizer and fuel sides and arranged parallel to the mixing layer in a configuration resembling the one recently studied experimentally by Park et al. (2016) [1], which unveiled significant electric-field effects on the aerodynamics. In these simulations, the electric drift of the charged species leads to a bi-directional ionic wind that is axially directed toward both injectors. The major components of the ionic winds are the H_3O^+ and O_2^- ions, which are steered by the electric field into the fuel and oxidizer streams, respectively. At sufficiently high electric fields of the order of a few kilovolts per centimeter, the ionic wind intricately couples with the aerodynamic field of neutral molecules flowing into the burner, in a manner that ultimately leads to non-negligible disturbances of the velocity field. The overall effect of these interactions consists of a decrease in the local strain rate and in the stoichiometric scalar dissipation rate, which increases the burning rate of the diffusion flame. The functional form of the scalar dissipation rate depends on the applied electric field, which may have consequences for the subgrid-scale modeling of these processes. In contrast to electrified one-dimensional premixed flames, here the current ceases to vary monotonically with the voltage as a result of the coupling with the aerodynamic field. Comparisons between the present numerical simulations and the experiments performed by Park et al. (2016) [1] are made that indicate qualitative agreement. Quantitative disagreements related to the saturation intensities and to the strength of the electric disturbances of the velocity field are discussed, and possible sources of these discrepancies are identified.

1. Introduction

The impingement of electric fields on flames is known to have potential for mitigating combustion instabilities, enhancing flame propagation, and decreasing pollutant emissions [1,2]. Many different technologies have been proposed to accomplish this objective, but the requirements of low complexity and low power consumption have proven to be very stringent constraints. This method takes advantage of the charged species produced by chemi-ionization kinetics in the flame, thereby generating non-electroneutral regions in the flow field. In particular, the imposed electric field steers the charged species, which exchange momentum with the rest of the gas, thereby changing the flow around the flame and creating an ionic wind whereby anions and cations flow towards the corresponding electrodes. The electric field can shift the flame position and, depending on the configuration and operating parameters, may stabilize combustion while reducing the emission of pollutants.

The effects of electric fields on flames have been observed experimentally in a number of studies. Those experiments have provided detailed analyses of ionic chemistry of hydrocarbon flames [3], laminar premixed-flame speed augmentation by electric fields [4], electric extinction of liquid-pool fires and jet diffusion flames [5], electrically induced instabilities in premixed flames [6], and variations of lift-off heights jet diffusion flames with electric fields [7,8]. Similarly, reduction in pollutant emissions by using electric fields have been demonstrated for high-power combustors of industrial relevance [9]. Furthermore, active control of small-scale electrified diffusion flames has been performed in earlier

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experimental works by integrating the burner in an electric circuit to obtain a desired flame response [10]. However, experimental studies tend to be limited to the qualitative characterization of the macroscale dynamics of the flame because of outstanding challenges associated with measuring the distribution of charged species and the hydrodynamic flow field. Numerical simulations can palliate these shortcomings and may serve as a complementary tool to understand the flame response to an applied voltage, as shown in this study.

Counterflow laminar diffusion flames represent a cornerstone in subgrid-scale models for nonpremixed turbulent combustion [11,12]. However, their interactions with electric fields have been the focus of only a very few studies to date. From the computational standpoint, and in contrast to premixed combustion, the effects of electric fields on counterflow diffusion flames have generally received much less attention, although progress has been recently made in simplified models for their interactions with axial electric fields [13]. The early experimental work of Dayal and Pandya [14,15] employed an electric field generated by two electrodes surrounding each orifice exit of the two opposing nozzles, and showed that the electric interaction shifted an ethyl-alcohol/oxygen diffusion-flame position by $\sim$5–6% toward the oxidizer side and increased the flame temperature by about 60 K from the nominal unelectrified values. The results were interpreted on the basis of a prevailing chemical effect induced by the electric field on the flame, in that free electrons, produced by the flame and energized by the electric field, enabled dissociation reactions that would have been impossible otherwise, thereby producing oxygen and hydrogen radicals that imbalanced the unelectrified flame structure.

More recently, Park et al. [1] studied a similar experimental configuration based on an electrified nonpremixed counterflow burner and included Particle Image Velocimetry (PIV) visualizations of the flow, which is a technique that has been early recognized as challenging to deploy in electrified flames due to potential self-charging of the tracers (e.g., see discussion in Ch. 7 in Ref. [2]). They used two mesh electrodes, which produced an electric field aligned with the axis of the burner that traversed the diffusion flame. The results included electric intensity/voltage curves revealing differences with respect to previously reported electric responses of premixed flames, such as the emergence of an overcurrent at intermediate voltages. Additionally, the PIV measurements suggested that the dominant electric effect pertained to the momentum coupling with the neutral particles in the form of an ionic wind, which appeared to vastly modify the flow structure to the extent that an extra stagnation plane induced by the electric interactions was observed in some cases. The numerical simulation of the experimental configuration employed by Park et al. [1] is the focus of the present study with the goal of elucidating the nature of these flow modifications.

Numerical simulations involving electric-field effects on combustion, subject to detailed chemistry and complex transport, are scarce in the literature and have been mostly limited to one-dimensional (1D) premixed flames[1] [17–22]. In these, the electric force induced by the motion of ions solely acts to readjust the hydrodynamic pressure gradient to satisfy mass conservation. Other problems such as two-dimensional laminar jet flames, where the interactions with the underlying flow field are more complex, have been simulated using skeletal mechanisms [23–25] and flamelet-based models to reduce the computational cost of resolving the reacting layers [26–28]. In most cases, numerical predictions tend to disagree with experimental measurements of electric intensities and charged-species profiles by factors of 2–3, indicating the relatively early stage at which the predictive capabilities in this research discipline are to date.

A number of important barriers, which are clearly manifested also in the present study, hinder the development of theoretical and computational studies of electrified flames. These are related to: (a) the multi-scale nature of the electric/aerothermochemical coupling phenomena, including the existence of a large disparity in time scales of the motion of electrons and neutrals; (b) the complexities associated with the description of the molecular transport of charged species; and (c) the absence of accurate descriptions of ionic chemistry and the overreliance of ionic chemical pathways on the prediction of sub-ppm concentrations of radical precursors.

Each of the barriers outlined above has a corresponding effect on the calculations. Firstly, the wide range of time scales typically leads to an exceedingly high computational cost, particularly in configurations such as the one treated here where the fluid mechanics of the bulk gas plays an important role. Specifically, the chemical kinetics of charged species and the motion of the electrons occur in characteristic time scales that are much shorter than those of convection and diffusion of the bulk gas, thereby causing severe numerical stiffness in the integration of the conservation equations. In the present investigation, a pseudo-time stepping algorithm is developed for a fast approach to a steady solution. Secondly, the molecular transport of charged species requires consideration of electric drift velocities, whose intensities are characterized by electric mobility coefficients that remain largely uncertain in the available literature and therefore lead to potentially different results. The present study employs values of the electron mobility recently updated by Bisetti and El Morsli [18] albeit for planar premixed flames, since studies related to this quantity are even more scarce for counterflow diffusion flames. Lastly, the ionization chemistry of electrified flames relies on the correct prediction of minor neutral intermediates and on the accurate representation of reaction rates for the chemical conversion of charged species. The former requires appropriate mechanisms for the neutrals that can predict minute quantities of radicals such as CH and O, which, in the methane flames addressed here, are believed to be responsible for initiating the ionic radical chains. This is typically attempted by using detailed mechanisms such as the GRIMech 3.0 [29] employed in this study, although it appears to be insufficient as suggested by the results presented below. The detailed mechanism for the neutrals requires coupling with a submechanism for ionized species, such as the relatively complex one provided by Belhi et al. [27] for lifted jet diffusion flames that is used in the present work.

In this investigation, numerical simulation results are presented for electric-field interactions with counterflow laminar diffusion flames in the configuration depicted in Fig. 1, which is similar to that studied experimentally by Park et al. [1] and is described later in the text in Section 2. The involved velocities are much smaller than the speed of sound and warrant moderately large Reynolds numbers within the laminar regime, in such a way that the flow remains axisymmetric and mostly steady with some exceptions in particular cases which are outlined below. The analytical formulation of the problem includes a two-way coupled system of conservation equations describing the aerothermochemical and electric fields, multi-component transport coefficients for the involved species, and a detailed chemical mechanism for $CH_4/O_2/N_2$ combustion that accounts for ionic chemistry, as mentioned above. The simulations focus on a set of operating parameters involving a wide range of electric voltages and two different injection mixture compositions. The results include comparisons against experimental velocity fields, quantitative descriptions of the electric effects on the diffusion-flame structure, translations of the results into mixture-fraction space to assess electric effects on the scalar

[1] A recent publication by Belhi et al. [16], which addresses numerically a nonpremixed counterflow configuration similar to the one presented in this study, was brought to the attention of the authors during the revision of this manuscript.