

Numerical simulation of the effect of the ion-driven wind on flame stability

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1 Introduction

When an electric field is applied to a flame, the charged species present in the flame front undergo a volumetric electric force, which changes the flow dynamics in the flame front region. This modification of the flow can contribute to a better stabilization of a diffusion lifted flame. All studies interested in combustion interaction with an electric field have shown improvements in combustion stabilisation. However, because of the disparities among results, it is difficult to draw conclusions on what is the key physical phenomenon responsible for stabilisation improvement. Numerical simulation may be a valuable approach for answering this question. Until now, only few studies have proposed modelling approaches for combustion in the presence of an electric field [1, 4]. In these numerical studies, the negative ions are overlooked, and only the movement of positive ions under the effect of a direct electric field (DC) was examined. In the present paper, the simplified mathematical model [4] is improved in order to include anions. The equations of aerothermochemistry coupled with transport equations for positive ion, negative ion and electron concentrations along with a Poisson equation for the potential electric field are solved. This model does not incorporate possible effects of the electric field on the combustion chemistry and accounts solely for ion-driven wind effects. The objectives of the study are: (1) to assess the ability of the ion-driven wind phenomenon to influence flame stabilisation, when both positive and negative ions are considered. (2) to provide a numerical tool for predicting the behaviour of the flame under the effect of an external electric field. In this context, a generic configuration, already used in [4], representative of a lifted diffusion methane/air laminar flame is used to analyse the mechanism of stabilisation of the flame in the presence of an applied electric field. This configuration is schematised in fig. 1.

2 Model description

2.1 Governing equations

The classical equations for compressible, gaseous multi-component, reacting flows in the presence of electric body forces are solved (see [4]).

The components F_i of the electric body force that is exerted on charge carriers when an electric field is imposed are determined from the components E_i of the electric field intensity and charged species

concentrations n^+ , n^- :

$$F_i = eE_i(n^+ - n^-) \quad (1)$$

where the + and - subscripts denote properties of positive and negative charge carriers, respectively. e is the electron charge. The electric field intensity is related to the electric potential V by the simple differential equation:

$$E_i = -\frac{\partial V}{\partial x_i} \quad (2)$$

Then, the Poisson equation describing the electric potential repartition, which evolves in time with charged species concentrations, must be solved at each time step:

$$\nabla^2 V = -e \frac{(n^+ - n^-)}{\epsilon_0} \quad (3)$$

ϵ_0 represents the permmissivity of free space.

When an electric field is applied, an additional mass flow J_i^k , due to the electric mobility κ , has to be considered in the transport equations of charged species: $J_i^k = C^k \rho \kappa^k Y^k E_i$; The expression of the charged species equations is written as:

$$\frac{\partial \rho Y^k}{\partial t} + \nabla \cdot (\rho \vec{V} Y^k) = \nabla \cdot (D^k \nabla \Phi - C^k \rho \kappa^k Y^k E) + \dot{\omega}^k \quad (4)$$

where C^k is negative if the specie is negatively charged and positive if the specie is positively charged, the term $\dot{\omega}^k$ correspond to the specie source term.

The evolution of electric mobility of ions in air with temperature and electric field intensity is defined by the expression (Private communication 2010 of M. Yousfi A. Besktein, [5]) :

$$\kappa^i(T, E) = -5.5 \times 10^{-6} + 9.2 \times 10^{-7} \times T + 9.5 \times 10^{-11} \times T^2 \quad (E \leq 2 \times 10^5 \frac{V}{m})$$

For a very weakly ionized media such as flame the electron mobility can be approximated by [6]:

$$\kappa^e = \left(\frac{m^i}{m^e}\right)^{0.5} \kappa^i$$

Using the Einstein relationship, the diffusion coefficient is related to the electric mobility: $D^k = k_b \frac{T}{e} \kappa^k$ (k_b is the Boltzmann constant)

Also, the electric field has a contribution in the total energy transport equation, which is given by:

$$f = \sum_j^{j=x,y,z} \sum_{k=1}^{N_c} e n^k C^k E_j (u_j - \frac{D^k}{Y^k} \frac{\partial Y^k}{\partial x_j} + C^k \kappa^k E_j) \quad (5)$$

with N_c the number of charged species.

2.2 Chemical kinetics mechanism

The combustion of neutral species is described with a tabulated chemistry accessed with two control parameters: the mixture fraction Z and a progress variable $Y_c = Y_{CO_2} + Y_{CO}$, which are transported [4, 7, 8]. Concentrations of the neutral species, the heat release source term and the progress variable source term are directly extracted from the chemical table. To construct the tabulation, a library of

methane/air premixed flames with varying equivalence ratio generated with the program Chemkin is created. The very detailed GRI 3.0 chemical mechanism [9], which contains 325 reactions and 53 neutral species, is employed.

For the kinetics of charged species, a mechanism featuring 40 ionic reactions and 6 charged species (H_3O^+ , CHO^+ , e^- , O_2^- , O^- and OH^-) is adopted. The source terms of charged species (eq. 4) are determined via an Arrhenius law; the rate coefficients are calculated using the data of Prager et al. [11]. Since the concentration of any neutral specie present in the mechanism is always much larger than the concentration of any charged specie; The production/disparition of charged species is suppose to have no impact on neutral species concentrations.

This retained approach to handle the kinetics of charged species is evaluated by computing the experience of Goodings et al. [10], which concerns a lean methane-oxygen flame. Fig. 2 compares our simulation results for the total positive and negative ion concentrations to the experimental data [10] and to numerical results from Prager et al. [11]. The general shape of the profiles as well as the maximum ion concentrations and the ion profiles width are consistent with the experiment, and they are closed to the results from Prager and al. [11] obtained with a mechanism including 11 charged species and 38 neutrals (273 recations).

3 Results

The studied configuration is a two-dimensional laminar diffusion methane/air flame, which is subjected to a positive or negative DC electric field (fig. 1). The electric voltage is applied to the electrode situated at the end of the solution domain, once the flame is located at its natural height of stabilization.

The figure 3 compares the iso-progress variable profiles before and after applying the electric field. The flame, after applying an electric field of 0.6kV (positive polarity) or -0.6kV (negative polarity), is moved to the injector and its stabilization height decreased significantly. The electric field produces a translation of the flame toward the burner. These results reproduce qualitative observations in similar experimental configurations [12] where stability improvement is shown for both polarities (positive and negative). Since the possible effects of the electric field on the combustion chemistry are not modeled, the observed effects visualize the responsibility of the ion-driven wind.

The generally proposed explanation [13] for the flame displacement is that the charged species, produced naturally in the flames by a mechanism of chemi-ionization, undergo a volumetric electric force. This force, according to the electric field polarity, generates a mass transfer of positive or negative ions toward the electrode positioned at the burner level. Then, the molecules coming from the injector undergo collisions with these ions and reduce their velocity. Due to the local decrease of the flow velocity, the flame encounters favorable local conditions to propagate further downstream reducing in the process its stabilization height (fig. 3).

The electric field distribution in the flame, for the applied electric voltages of 0.6kV and -0.6kV, is described by the figures 4, 5 and 6. These figures show, respectively, the repartition of: electric potential, electric intensity and electric force vectors close to the flame tip.

As shown in Fig. 4, whatever the polarity of the applied voltage, two main zones compose the electric potential distribution: (1): Downstream of the flame tip. This zone is nearly equi-potential with an electric potential close to that of the electrode V_0 .(2): Upstream of the flame tip, in the space situated between the flame base and the bottom electrode. this zone is characterized by a sharp drop of the electric potential. Then, the flame base behaves as an additional electrode of a tension of the same order as the applied voltage. These trends are found in close agreement with the experimental observations of Criner et al. [12].

As a result of this potential repartition, The electric field is negligible downstream the flame base because of the quasi-potentiality of this zone. Thus, as the electric potential drops sharply in the space situated between the flame base and the inlet plan, a strong axial electric field is induced (fig.5). While this axial component of the electric field points in a direction opposed to the main direction of the flow for a positive applied voltage ($V_0=0.6$ kV) (fig.5-left), it takes the same direction as the fresh gases coming from the injector for a negative applied voltage ($V_0=-0.6$ kV) (fig.5-right). Hence the negative sign of the axial component for a positive applied electric field and the positive sign for the negative polarity.

Close to the flame tip, the difference between positive ion and negative charged species concentrations is significant and positive for $V_0>0$ or negative for $V_0<0$; the resultant electric force in the axial direction is then, whatever the polarity of the applied electric field, opposed to the main direction of the flow (Fig. 6). The electric force obliges the flow field to slow down ahead of the flame then favoring its upstream propagation and finally its anchoring.

According to the figures 3 et 6, it is clear that the improvement of the stability is better in the positive case than in the negative case. It can be simply explained by the fact that the total charge, close to the flame base, of the positive ions responsible for the flame displacement in the positive case is bigger than that of the negative ions responsible for the improvement of the stability in the negative case. To the following this, the electric force is greater in the positive case and it causes a more important displacement of the flame.

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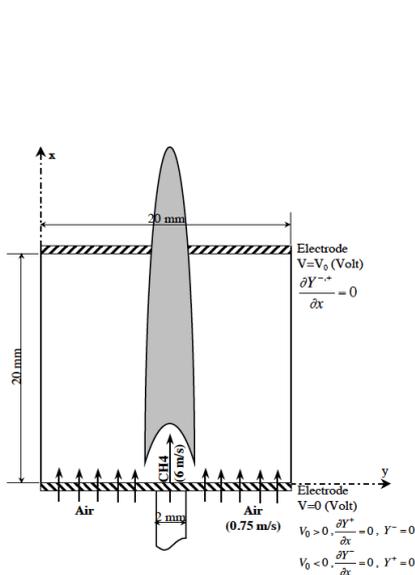


Figure 1: Studied configuration.

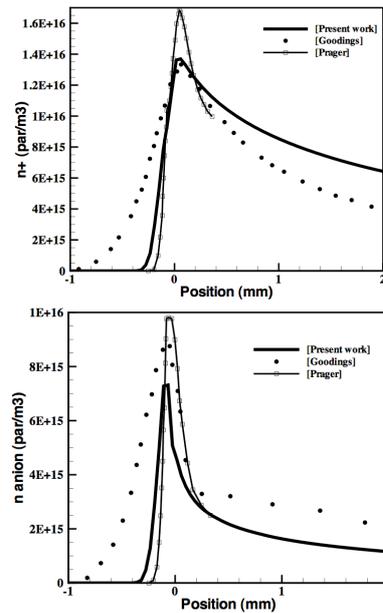


Figure 2: Concentrations of positive (top) and negative (bottom) ions in comparison to the experiment of [10] (symbols) and to the simulation of [11] (line with symbols).

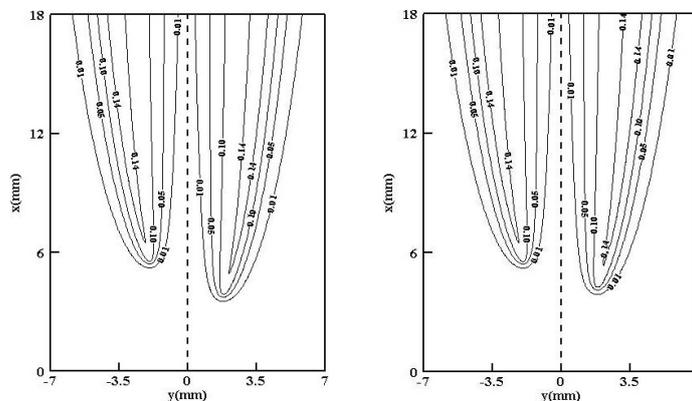


Figure 3: Iso-progress variable before and after applying the electric field, $V_0 =$: (left) 0.6 kV and (right) -0.6 kV.

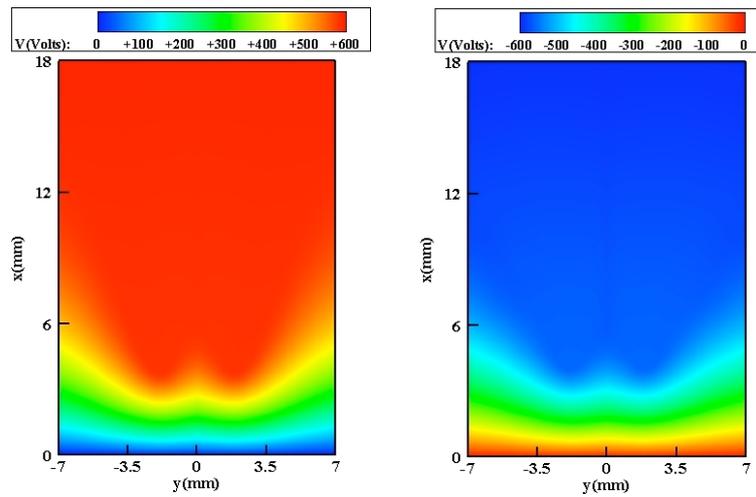


Figure 4: Electric potential distribution for $V_0 =$: (left) 0.6 kV and (right) -0.6 kV.

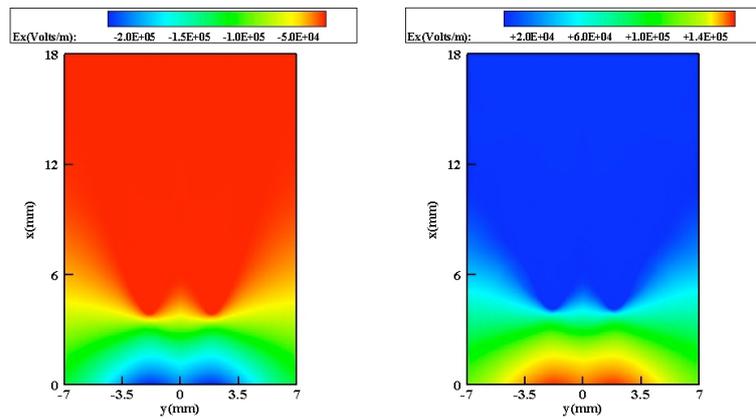


Figure 5: distribution of the axial component of the electric field for $V_0 =$: (left) 0.6 kV and (right) -0.6 kV.

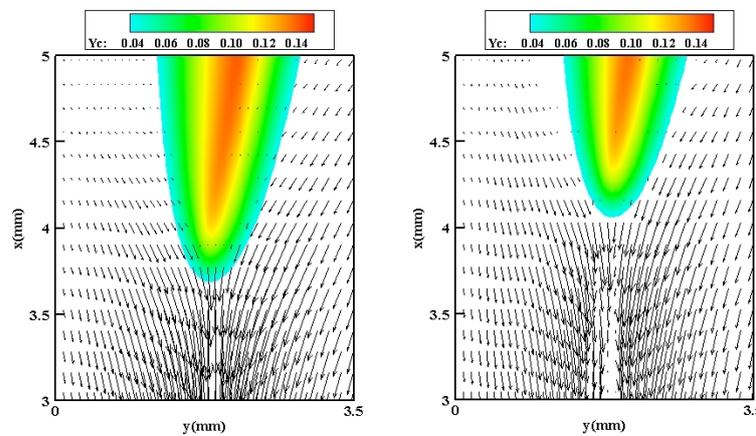


Figure 6: Electric force vectors for $V_0 =$: (left) 0.6 kV and (right) -0.6 kV, close to the flame tip. Same scale on both figures.