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Direct numerical simulation of the effect of an electric field on flame stability

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ABSTRACT

The role of electric fields in stabilising combustion is a well-known phenomenon. Among the possible mechanisms favouring the anchorage of the flame base, the ion-driven wind acting directly on flow momentum ahead of the flame base could be the leading one. Direct numerical simulation has been used to verify this hypothesis and lead to a better understanding of diffusion flame base anchoring in the presence of an externally applied voltage. In this context, a simplified modelling approach is proposed to describe combustion in the presence of electric body forces. The model reproduces the tendencies of experimental observations found in the literature. The sensitivity of the flame lift-off height to the applied voltage is studied and the modification of the velocity field ahead of the flame base induced by the electric volume forces is highlighted.

1. Introduction

Combustion in the lean regime is an efficient way to minimize the emission of pollutants and fuel consumption. The drawback is that instabilities appear which may lead to extinction of the flame or blow-out. Several technical solutions have been proposed to counteract these inconveniences such as modifying the geometry of the burner, introducing swirl or a bluff-body to stabilise the flame by increasing mixing, or adding energy at the flame base with a pilot flame. Active control of flame stability may also be envisaged based on acoustic excitation or application of an electric field.

The impact of the electric field on flames has been evidenced since decennia [1,2]. More recently, in the context of improving the control of combustion, its effect on flame stabilisation has been studied extensively from the experimental point of view. Different kinds of configurations have been addressed: laminar [3] and turbulent [4] combustion, premixed [5] and diffusion [6] flames, in interaction with AC or DC [7,8] electric fields. All studies show improvements in combustion with a negligible energy consumption compared to the thermal power of flames. However, because of the disparities among results, it is difficult to draw conclusions on what is the key physical phenomenon responsible for stabilisation improvement. To answer this question, it is necessary to gain understanding of the mechanisms of the electric field interaction with the flame. Numerical simulation of a flame submitted to an electric field is a valuable approach for achieving this goal.

Complete modelling of electric field interaction with the flame is a very challenging subject which is seldom addressed in the literature. Modelling approaches for combustion in the presence of an external electric field have been developed in the papers from Hu et al. [9] and Ulybyshev [10]. Some assumptions have been made in these models such as supposing a constant electric field intensity in all the computational domain [9] or considering only a transport equation for ions and not for electrons [10]. While Hu et al. address directly the problem of flame stabilisation, Ulybyshev focuses on the reduction of the nitrogen oxide emission by applying an electric field. Papac and Dunn-Rankin [11] have also recently developed a simplified approach for a flame stabilized at the exit of a fuel feed tube, the respective impacts of ion mobility and diffusion on the ion-driven wind are emphasized in this work. Also, Yamashita et al. [12] have proposed a model to describe the underlying mechanisms responsible for the voltage-current characteristic response of a capillary-fed methane diffusion flame in an electric field. In their modelling of the problem, the electric field spatial variation is computed by solving a Poisson equation.

The confirmation of all mechanisms producing improvement in flame stability by applying electric fields is still an open issue. Some authors, as Jaggers and Von Engel [13], have concluded that the change of flame behaviour under electric field action is related to chemical effects via activation of reactions due to collisions with electrons and ions. However, for most authors [4,8–10,14], the field-induced body forces, known as ion-driven wind, which may affect the flame dynamics, is mainly responsible for the observed effects. To examine this last assumption, a model presented in the next section of the paper, has been developed. This model does not incorporate possible effects of the electric field on the combustion chemistry and accounts solely for ion-driven wind. The objective

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of the paper is to assess the ability of that phenomenon to influence flame stabilization. The retained approach to handle the kinetics of charged species in the flame is then presented and validated. A generic configuration representative of a lifted diffusion methane/air laminar flame is then used to analyse the dynamics of stabilisation of the flame extremity in the presence of an applied electric field.

2. Model description

The problem is governed by the classical transport equations for compressible, gaseous multi-component, reacting flows in the presence of electric body forces.

For a gas of density ρ and flow velocity components u_i, the mass continuity and momentum equations read:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_i}=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_i}+F_i \qquad (2)$$

where t and x_i are, respectively, the time and space coordinates. p designates static pressure calculated by the classic perfect gas law and τ_{ij} is the viscous tensor defined as:

$$\tau_{ij}=-\frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij}+\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$

with μ the dynamic viscosity and $\delta_{i,j}$ the Kronecker symbol.

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^-:

$$F_i=eE_i(n^+-n^-) \qquad (3)$$

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:

$$E_i=-\frac{\partial V}{\partial x_i} \qquad (4)$$

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

$$\nabla^2 V=-e\frac{(n^+-n^-)}{\epsilon_0} \qquad (5)$$

ϵ_0 represents the permittivity of free space. The momentum transfer from the charged particles to the neutral gas is due to collisions between charged particles and neutral particles. In this approach, it is assumed that the momentum gained by the ions from the electric field is totally and instantaneously transferred into the neutral gas.

Transport equations for the chemical species (neutral or charged) present in the flow have to be solved:

$$\frac{\partial \rho Y^k}{\partial t}+\frac{\partial \rho u_j Y^k}{\partial x_j}=-\frac{\partial \rho Y^k V_j^k}{\partial x_j}+\dot{\omega}^k \qquad (6)$$

The expression of the diffusion velocity, V^k, depends on k representing a neutral species, an ion or an electron. For neutral species, the diffusion flux is simply represented by Fick's law with a constant Schmidt number of 0.7. For charged species, the following relation is used [15]:

$$\rho Y^k V_j^k=-\rho D^k\frac{\partial Y^k}{\partial x_j}+S^k\rho\mu^k Y^k E_j \qquad (7)$$

where S^k is negative if the species is negatively charged and positive if the species is positively charged. The diffusion coefficient of the ions is approximated by the diffusion coefficient D of the corresponding neutrals [16]:

$$D^k=D=\frac{\mu}{\rho Sc}$$

For a very weakly ionized media such as flames, the electron diffusion coefficient is approximated by Delcroix [17]:

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

m^e represents the electron mass and m^i is the averaged mass of ions. The value of the mobilities, $\mu^{i,e}$, directly impact on the body forces and then on the intensity of the ion-driven wind. Mobility evolves with temperature and also mixture composition as observed by Papac and Rankin [18]. Nevertheless, the complex determination of the expression of ion or electron mobility is out of the scope of this paper and tests of the sensitivity of the results to the choice of the expression of mobility have not been performed even if dependence may be expected. No definitive expression for the mobility exists yet in the literature and the value recommended by Fialkov [2] for ion, $\mu^i \sim 1\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ has been retained in this study. Using the Einstein relationship, the electron mobility, μ^e, is related to μ^i:

$$\mu^e=\left(\frac{D^e}{D^i}\right)\mu^i$$

The expressions of the source terms, $\dot{\omega}^k$, are given in the next section.

The total energy equation reads:

$$\frac{\partial \rho E}{\partial t}+\frac{\partial \rho u_i E}{\partial x_i}=-\frac{\partial q_i}{\partial x_i}+\frac{\partial(\tau_{ij}-p\delta_{i,j})u_i}{\partial x_j}+\dot{Q}+f \qquad (8)$$

q_i is the heat flux calculated from Fourier's law. The source term $\dot{Q}$ corresponds to the heat release due to combustion. The electric force contribution in total energy transport equation is given by:

$$f=\sum_{k=1}^{N_c} en^k S^k E_j(u_j+V_j^k)$$

With N_c the number of charged species and n^k the concentration in part/m^3. The impact of this contribution is not significant since the applied electric field is very weak compared to the total energy variation. Joule heating is absent from Eq. (8) since the applied voltages used in this work are quite small (below 12 kV) and the induced electric current resistive losses can then be neglected.

The approach which is retained is very similar to the one recommended by Hu et al. [9] or Yamashita et al. [12]. These latter authors resolve the Poisson equation to get the local electric field while the first suppose a constant electric field.

2.1. Kinetics for CH4/air combustion including charged species

Different approaches to tackle the chemistry of ions in flames can be found in the literature. Starik and Titova [19] describe a detailed mechanism for the kinetics of ions during combustion of a methane/air mixture. This mechanism includes around 208 reactions including positive and negative ions. Prager et al. [20] propose a kinetics accounting for 67 different reactions, where positive and negative ions are included and 200 reactions for neutrals. Hu et al. [9] and Yamashita et al. [12] employed reaction mechanisms with less reactions respectively 31 (28 for neutrals and 3 for ions) and 39 (28 for neutral and 11 for ions) and neglected negative ions. Pedersen and Brown [15] still exclude anions from their mechanism which includes 86 reactions. These authors compare the performance of their mechanism to experimental measurements for four different one-dimensional, laminar premixed flames. The neutral major species are fairly well predicted