Large Eddy Simulations of turbulent premixed flame ignition and stabilization by pulsed plasma discharges

Yacine Bechane[1], Nasser Darabiha[1], Vincent Moureau[2], Christophe Laux[1] and Benoît Fiorina[1]
[1] Laboratoire EM2C, CNRS, CentraleSupélec, Université Paris-Saclay,
3 Rue Joliot Curie, 91190 Gif-sur-Yvette cedex, France
[2] Normandie Univ, INSA Rouen, UNIROUEN, CNRS, CORIA, 76000 Rouen, France

1 Introduction

The reduction of pollutant emissions in aircraft engines and power plant is a major issue for gas turbine manufacturers. An efficient solution to reduce pollutant formation is to maintain a relatively low temperature in the combustor primary zone, by decreasing for instance the mixture equivalence ratio. However, low flame temperature induces slower chemical reaction rates, which often result in an increase of flame instabilities and extinctions.

An emerging solution to enforce flame stabilization in lean regimes, suitable to a wide range of combustion applications, is to generate electrical discharges at the flame basis [1, 2]. Among these various types of discharges, the Nanosecond Repetitively Pulsed (NRP) discharges [3, 4] have shown to be particularly efficient. Beneficial effects of plasma-assisted combustion have been recently observed in large scale burners, allowing reductions from 50 to 70% of the lean extinction limit of a 75 kW premixed propane-air flame at atmospheric pressure [5], and of a 200 kW kerosene-air turbojet aerodynamic injector operating at 3 bar [6]. In most cases reported in the literature, plasma-assisted stabilization of lean flames is typically obtained with plasma powers less than 1% of the power released by the flame. The good efficiency of such process is due to the fact that the energy of the electric discharge is spent on ionization, excitation and dissociation of molecules rather than just increasing the gas temperature [7]. The relaxation of excited molecules by collisional quenching reactions with molecules results in an ultra-fast (few nanoseconds) increase of radicals and gas temperature inside the discharge channel. In typical conditions, up to 50% of molecular oxygen can be dissociated in the inter-electrode region [7]. Such high concentration of radicals has a positive effect on the flame stabilization [4, 8].

Despite this proven efficiency, the fundamental mechanisms of plasma-assisted combustion are not well understood. Also, the numerical tools needed by engineers to assess the performances of NRP discharges in practical configurations and optimize their design do not exist. The objective of the present work is to elaborate and validate against experimental data a modelling route suitable to perform Large Eddy Simulations (LES) of turbulent premixed flames stabilized by plasma.The MiniPAC configuration [4] is retained as test case to validate the model taken into account to model the plasma-assisted combustion.

Correspondence to: yacine.bechane@centralesupelec.fr

2 Phenomenological NRP discharges model

NRP discharges are characterized by high voltage pulses (5 to 20 kV) that last few nanoseconds and are repeated at frequencies of the order of tens of kHz. Each pulse causes an increase in the kinetic energy of the electrons. The kinetic energy of electrons is then transferred to the surrounding heavy particles through collisional processes. The rate at which these collisional processes occur depends on the reduced electric field E/N defined as the ratio of the electric field magnitude E to the gas number density N. Several detailed plasma kinetic mechanisms have been proposed in the literature [9] to model non-equilibrium plasma effects on combustion processes. The methods include solving the governing equations for the electric field and the electron energy, as well as the continuity equations for neutral and excited species, and the energy, mass and momentum balance equations for the gas mixture. However, these strategies require prohibitive computational resources for 3-D combustion simulations. The plasma model developed by Castela [8], which significantly reduces the computational costs, is therefore retained here to enable 3-D simulations of plasma-assisted ignition and combustion. Instead of solving a continuity equation for each additional excited states of molecules, the model captures non-equilibrium plasma effects by including only source terms in energy and species balance equations and adding a balance equation for vibrational energy.

The model is based on the observation that for NRP discharges, characterized by E/N in the range of $100 - 400$ Td (1Td = $10^{-17}\ Vcm^2$), the pulse energy translates into ultra-fast heating and ultra-fast dissociation of O_2 molecules as well as slow gas heating [7, 11]. Thus, the model considers that the discharge power $\dot{E}^p$ is split into three contributions:

$$\dot{E}^p = \dot{E}^p_{chem} + \dot{E}^p_{heat} + \dot{E}^p_{vib} \tag{1}$$

The chemical $\dot{E}^p_{chem}$ and thermal $\dot{E}^p_{heat}$ terms refer to the ultra-fast dissociation of O_2 molecules and gas heating, respectively. The vibrational contribution $\dot{E}^p_{vib}$ refers to the energy transferred into the vibrational states of N_2. The equations governing the reacting flow and accounting for the impact of NRP discharges read:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} \tag{3}$$

$$\frac{\partial (\rho Y_k)}{\partial t} + \frac{\partial (\rho u_i Y_k)}{\partial x_i} = -\frac{\partial (\rho V_{k,i} Y_k)}{\partial x_i} + W_k \dot{\omega}^c_k + W_k \dot{\omega}^p_k \tag{4}$$

$$\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho u_i e)}{\partial x_i} = -\frac{\partial q_i}{\partial x_i} + \frac{\partial (\sigma_{ij} u_i)}{\partial x_i} + \dot{E}^p_{chem} + \dot{E}^p_{heat} + \dot{R}^p_{VT} \tag{5}$$

$$\frac{\partial (\rho e_{vib})}{\partial t} + \frac{\partial (\rho u_i e_{vib})}{\partial x_i} = \frac{\partial}{\partial x_i}(\rho D \frac{\partial e_{vib}}{\partial x_i}) + \dot{E}^p_{vib} - \dot{R}^p_{VT} \tag{6}$$

where W_k and $\dot{\omega}^c_k$ are the k^{th} species molar mass and molar production rate by combustion reactions respectively. $\dot{\omega}^p_k$ is the species molar production rate induced by ultra-fast species dissociation by the plasma discharge. As discussed in [7, 8], the dominant chemical effect of the plasma being the dissociation O_2 into O, the following model for $\dot{\omega}^p_k$ is retained:

$$\dot{\omega}^p_O = \eta \, \frac{Y_{O_2}}{Y^f_{O_2}} \, \frac{\dot{E}^p}{e_O \, W_O} \tag{7}$$

$$\dot{\omega}^p_{O2} = -\frac{W_O}{W_{O2}}\,\dot{\omega}^p_O \tag{8}$$

$$\dot{\omega}^p_k = 0 \quad \text{, for k} \neq O_2, O \tag{9}$$

where e_O is the energy per unit of mass of specie O and $Y^f_{O_2}$ represents the mass fraction of O_2 in the fresh mixture. Parameter η is the normalized amount of energy used to dissociate O_2 molecules.

The energy Eq. (5) incorporates additional source terms from the plasma discharge. Equation (6) is the additional conservation equation for the vibrational energy e_{vib}, carried by N_2 molecules, and D is taken as equivalent to the diffusion coefficient of N_2 . The term $\dot{R}^p_{VT}$ in both Eqs (5) and (6) refers to the relaxation rate of the vibrational energy into gas heating and it is modelled considering the Landau-Teller harmonic oscillator approach [10]. The plasma source terms are modeled as:

$$\dot{E}^p_{chem} = \eta\,\frac{Y_{O_2}}{Y^f_{O_2}}\,(1 - \frac{e_{O_2}}{e_O})\,\dot{E}^p \tag{10}$$

$$\dot{E}^p_{heat} = [\alpha - \eta\,\frac{Y_{O_2}}{Y^f_{O_2}}\,(1 - \frac{e_{O_2}}{e_O})]\,\dot{E}^p \tag{11}$$

$$\dot{E}_{vib} = (1-\alpha)\,\dot{E}^p \tag{12}$$

where α is the normalized amount of energy deposited at ultra-fast scales. Following both experimental [7] and numerical [11] investigations, α and η are set to 55% and 35% in all simulations, respectively.

3 Preliminary Results

The above model has been implemented in the finite-volume low-Mach LES-DNS solver YALES2 [12] . A series of canonical computations have been conducted to validate the numerical implementation. Solutions provided by YALES2 are compared against experimental data and DNS results obtained by Castela [8] using the compressible DNS solver YWC [13]. A selection of the validation cases is presented here.

The first case studied consists in 2-D simulations of a series of 10 plasma discharge pulses applied in air at $300K$ without combustion. The geometry Configuration is shown in Fig.1. As observed by [8], a fraction of the energy deposited by the discharge leaves the domain in the form of acoustic waves causing locally a temperature decay, which cannot be captured by the low-Mach number formulation. To correct this lack, this amount of acoustic discharge energy leaving the domain has been evaluated from the DNS computations [8] and then deducted from the amount of energy deposited in the low-Mach solver YALES2. To validate this procedure, the evolution of the temperature at the center of the discharge computed by [8] using a compressible DNS solver YWC (blue curve) is compared in Fig.2 against low-Mach number YALES2 (red curve) solutions. Even if the temperature is under-estimated by YALES2 at the ultra-fast scale, a fast relaxation towards the DNS solution is observed between two pulses. As this relaxation time is much shorter than chemical time-scales, no influence of this assumption on the combustion process can be expected.

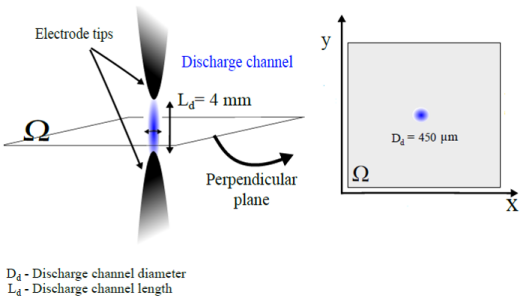

Figure 1: Schematics of a pin to pin configuration of NRP discharges device. The 2-D computational domain is a plane perpendicular to the inter-lectrode axis.

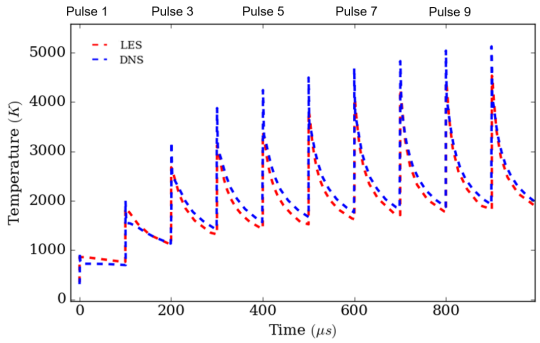

Figure 2: Temporal evolution of the gas temperature at the center of the discharge channel in a sequence of 10 pulses in air. The following parameter values were used: $f = 10kHz$, $E_d = 0.67mJ$, $\alpha = 0.55$ and $\eta = 0$.(Blue) using a compressible solver YWC [8], (red) using a low-Mach LES Solver YALES2 [12].

The same configuration is retained by replacing air by a methane-air mixture of an equivalence ratio of 0.8. Two computations are conducted. In the first simulation $\eta = 0$ (no atomic oxygen is produced by the discharges), whereas $\eta = 0.35$ in the second simulation (35% of the discharge energy is consumed for the dissociation of O_2). The results are shown in Fig. 3(left). When O_2 dissociation by the NRP discharges is neglected ($\eta = 0.0$), four discharges are required to ignite the methane-air mixture. But, when the O_2 chemical effect of the plasma is considered ($\eta = 0.35$), the mixture ignites after only two discharges. These results are consistent with those obtained by Castela [8]shown in Fig.3(right). The production of O radical by plasma discharges significantly accelerates the ignition.

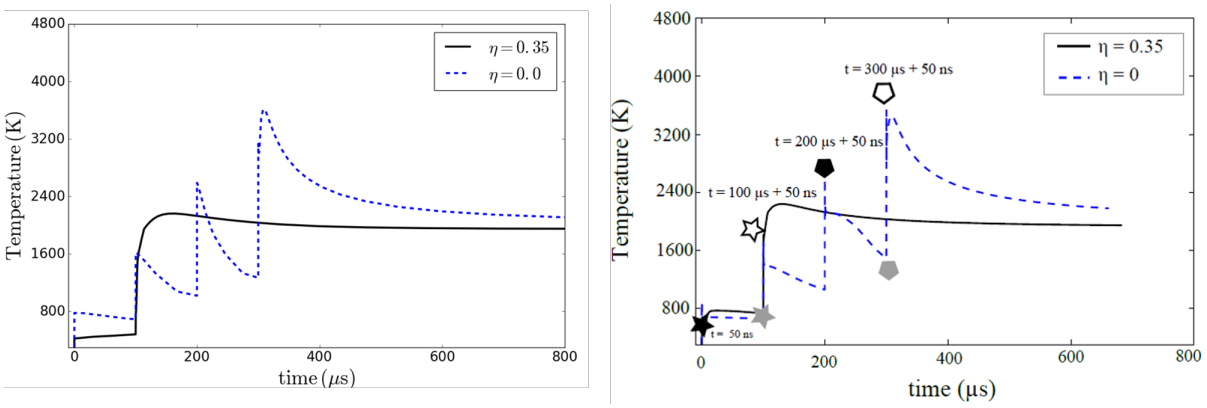

Figure 3: Temporal evolution of the maximum value of gas temperature for a methane-air mixture, $\phi = 0.8$. The mixture ignites after two discharges for $\eta = 0.35$ (solid line) whereas four discharges are needed for $\eta = 0.0$ (dashed line). Left: using LES Solver YALES2 [12] (current work). Right: using DNS compressible solver YWC (M.Castela) [8].

Next, the previous methodology is applied to the MiniPAC configuration [4], an experiment specially designed by the CORIA and EM2C laboratories to study the impact of plasma discharges on flame ignition

and stabilization. It's a premixed methane-air burner with a bluff body at the injector outlet to stabilize the flame. In order to apply plasma discharges, two electrodes are added. The anode is attached to the bluff body whereas the cathode is placed above the bluff body. The two electrodes are connected to a Marx type pulse discharge generator that produces high frequency nanosecond pulses.

Two simulations of the MiniPAC ignition are performed, considering:

- only thermal effects, $\eta = 0.0$, with no O_2 dissociation, 55% of the energy goes into the ultra-fast heating and 45% into the vibrational energy ($\alpha = 0.55$).
- both the thermal effects, ultra-fast heating and vibrational energy relaxation, and the chemical dissociation of O_2 into O ($\alpha = 0.55$ and $\eta = 0.35$).

The methane-air mixture equivalence ratio ϕ is 0.95, which corresponds to a stable flame regime. The flow velocity at the inlet is $U = 37.6m.s^{-1}$. The simulation is performed using YALES2 employing a fourth order spatial and temporal scheme and including a Dynamic Smagorinsky model for turbulence and a TFLES model for combustion [14].

Figure.4 presents time evolution of maximum temperature during the plasma discharge. It shows that in the case where only the thermal effects are considered, the ignition does not occur even after 90 pulses. The cumulative effect of the NRP discharges is affected by the turbulence and the hydrodynamic affects of the discharge. The temperature does not reach a sufficiently high value to allow ignition. But the case where both the thermal and chemical affects are considered, the ignition occurs after 10 pulses. Even though the temperature does not reach a high value, the presence of the radical O produced by the discharges allows the oxidation of the methane and consequently the ignition of the flame. This shows the major interest of non-equilibrium plasma discharges which resides in the production of radical species such as O which allows the initiation and the sustainment of combustion at very low temperatures. The impact of NRP discharges on very lean flame stabilization is currently investigated. Corresponding results will be presented at the 27^{th} ICDERS conference.

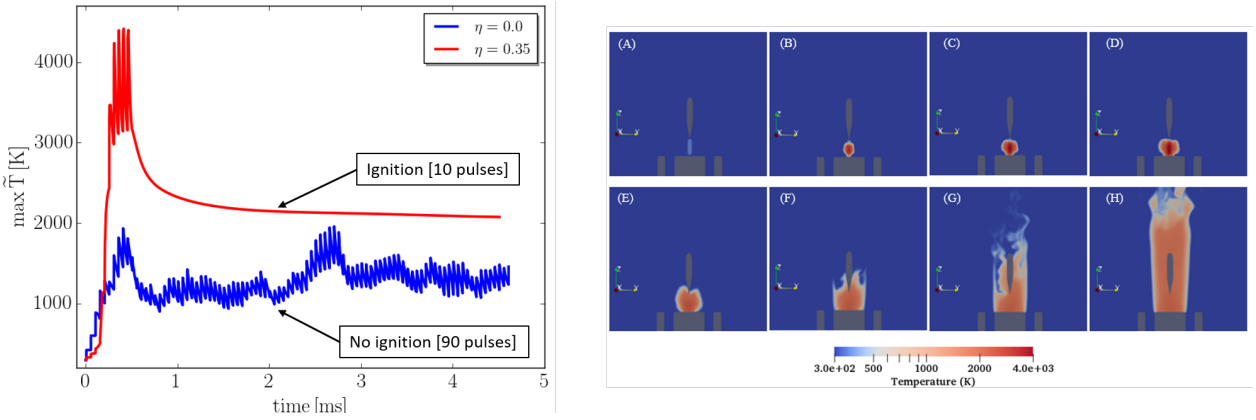

Figure 4: Left: temporal evolution of the maximum value of gas temperature for a methane-air mixture, $\phi = 0.95$ and $U = 37.6m.s^{-1}$. The mixture ignites after 10 pulses for $\eta = 0.35$ (red line). No ignition after 90 pulses for $\eta = 0.0$ (blue line). Right: 2-D temperature fields after the 2^{nd}, 6^{th}, 8^{th} and 10^{th} pulse [A-D] and propagation [E-H] for $\eta = 0.35$.

Acknowledgments

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