Detonability enhancement by use of a nanosecond plasma

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1 Introduction

Detonability is described as the efficiency of ignition or propagation of detonation, although a choice of the most relevant definition is still under debate. Each of these phenomena is represented by its characteristic length, that is, the transition distance from deflagration to detonation (DDT) and the mean width of the cells resulting from the intrinsic instability of the detonation reaction zone. The DDT distance and time represent the rapidity to obtain detonation from a flame generated with a low-energy device, and the cell width represents the capacity for detonation to propagate in a channel of finite transverse dimension. Thus, the smaller the DDT length or the cell width, the greater the detonability. Interest of detonation as a substitute to the usual isobaric combustion process is explained by its high characteristic pressure and short reaction times and lengths. For example, scientific research related to pulsed or rotating detonation engines is very important over the past decades. One of the main issues is to ensure detonation ignition and propagation in a large range of initial conditions because imperfect mixing of fuel and oxidizer, specific initial conditions such as low initial temperatures decrease detonability [1–7]. This paper presents the results of experiments and calculations that demonstrate that plasma enhances detonability, that is, decreases the DDT length and the cell width. Our work investigates (i) the links between the pre-dissociation of a gas mixture by plasma action and (ii) the decrease of the characteristic times and lengths of the combustion reactions. For the DDT experiments, a nanosecond multichannel capillary discharge was used to ignite the flame. For the experiments on the cellular detonation regime, a nanosecond discharge homogenously distributed was used to pre-dissociate the mixture at the moment of arriving of the detonation wave front.

2 Experimental setup

For the DDT experiments, the tube was 3.5-m long with cross-section 4x4 cm^2, and the studied gas was the stoichiometric H_2:O_2 mixture at 600 - 800 mbar. We estimate a specific delivered energy in the capillaries to be as high as about 1 ev/particule. Flame ignition, evolution and transition to detonation were recorded using schlieren imaging. The results were compared to the ignition by a classical automotive spark. For the cellular detonation experiments, the tube was 3.5-m long with cross-section 5x5 cm^2 and the studied gas was the stoichiometric H_2:O_2 mixture diluted with 40 % of argon. The specific delivered energy in the discharge was about 10^{-3} eV/particule in the whole volume defined by the tube cross section and the length of the high-voltage electrode, 20 cm. The plasma effect was analysed from the recordings of the tracks left by the detonation cellular structure on soot-coated plates positioned opposite to the high-voltage electrode, and the electrical parameters of the discharge were recorded using the back current shunt technique.

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3 Results

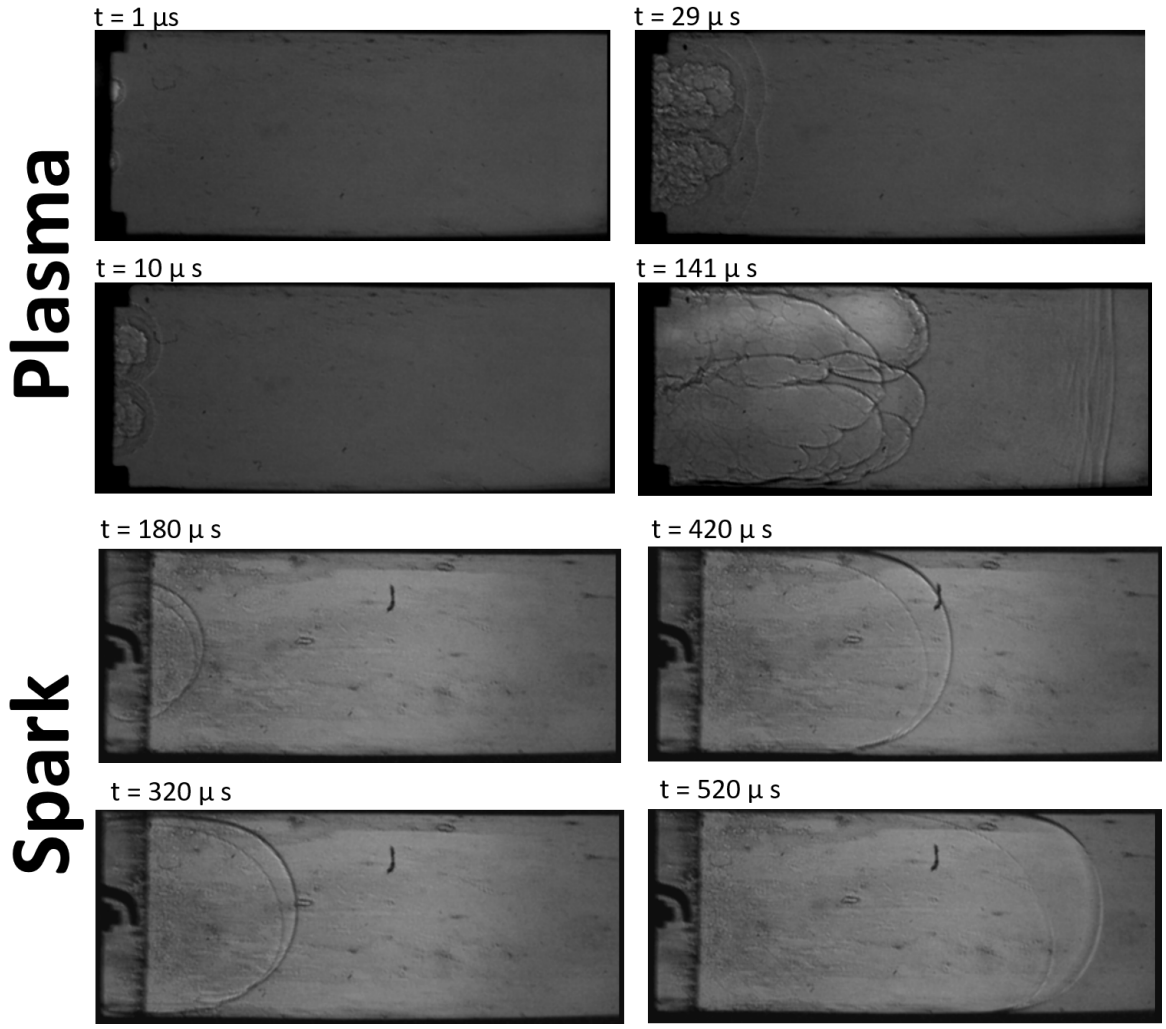

Figure 1: Ignition and evolution of the flame in the stoichiometric H_2:O_2 mixture at 600 mbar (Schlieren). Top: nanosecond discharge with the plasma electrode. Bottom: automotive plug.

Figure 1 shows typical Schlieren pictures of the ignition and evolution of the flame in the stoichiometric H_2:O_2 mixture at 600 mbar. The flame evolution is much faster and its front shows more structures, hence a larger combustion surface, with the nanosecond plasma discharge than with the automotive plug. For example, the fourth picture of the plasma sequence at 141 μs shows that the flame has reached half the field when this position is only reached at 420 μs with the ignition by the automotive plug. As a consequence, the push on the initial mixture is faster and stronger as indicated by the presence of compression waves ahead of the front (the dark vertical lines at the rightmost part of the picture at 141 μs. The flame shows several combustion kernels, generated by the multiple-point electrode, hence a more turbulent front. In contrast, the flame front obtained with the automotive plug always shows a smooth surface in the frame time of the recordings. The plasma ignition thus leads to a faster and more turbulent flame that speeds up the transition to detonation (fig 3, left). Figure 2 shows soot recordings corresponding detonation experiments in the H_2:O_2 mixture at 150 mbar diluted with 40% of argon. The zone over which plasma was triggered is indicated by the "P" for the middle and the right plates in 2. A decrease of the detonation cell width is easily observed by comparison with the cells on the reference

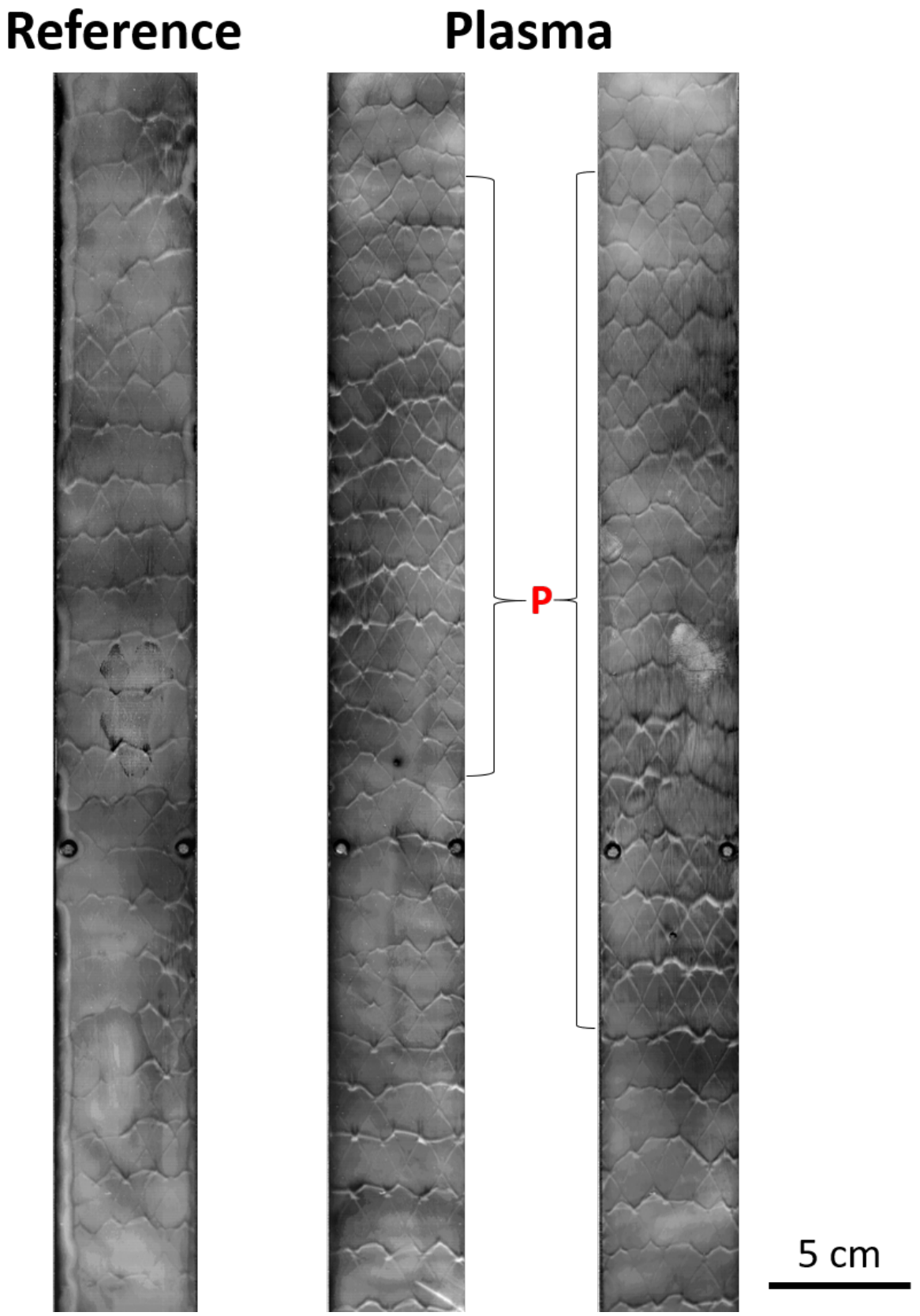

Figure 2: Soot recordings of the detonation cellular structure without (left) and with (middle and right) plasma pre-dissociation for the stoichiometric H_2:O_2 mixture at 150 mbar diluted with 40% of argon.

recording (left), without plasma. The experiments were carried out for initial pressures ranging from 120 mbar to 200 mbar (fig 3).

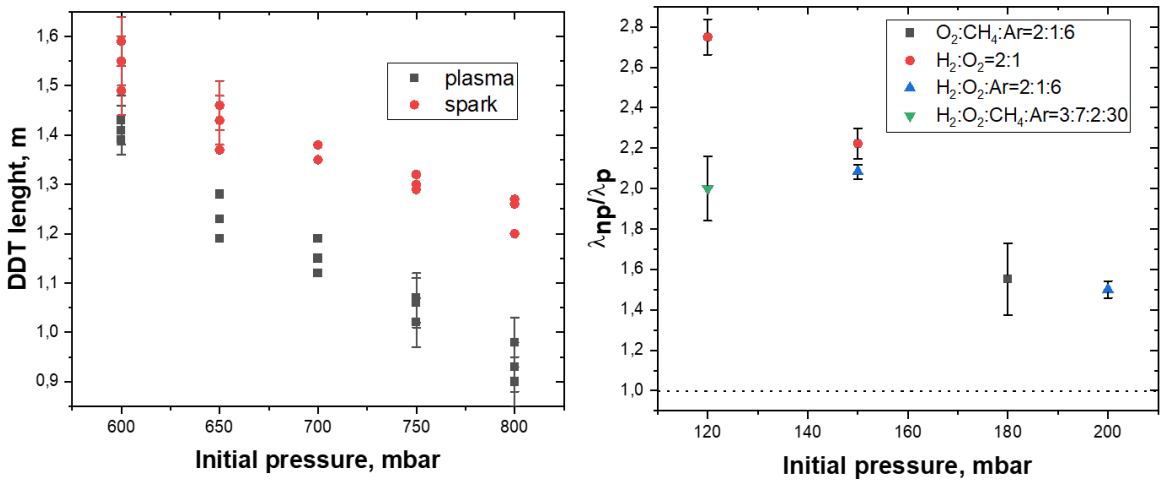

Figure 3: Measured DDT distances (left) and detonation cell widths (right) without and with plasma pre-dissociation for the stoichiometric H_2:O_2 mixture at 150 mbar diluted with 40% of argon

The principle of the numerical analysis of the detonation experiments was (i) to carry out a 0D calculation of the pre-dissociated initial state using a plasma kinetic scheme; (ii) to use the results of the calculations as input for a ZND code implementing a detailed chemistry of H_2-based mixtures [8]; (iii) to obtain the temperature profiles in the detonation reaction zone. Indeed, as a first approximation, the ZND induction distance is proportional to the mean cell width. Figure 4 shows the temperature profiles at 150 mbar for the stoichiometric H_2:O_2 mixture diluted with 40% of argon, without (left) and with (right) plasma pre-dissociation. The plasma-case profile was calculated with 2% atomic oxygen added to the initial composition, a number given by the 0D calculations. We observe a reduction of the induction time by a factor of 2, a ratio that agrees with the experimental reduction of the detonation cell size.

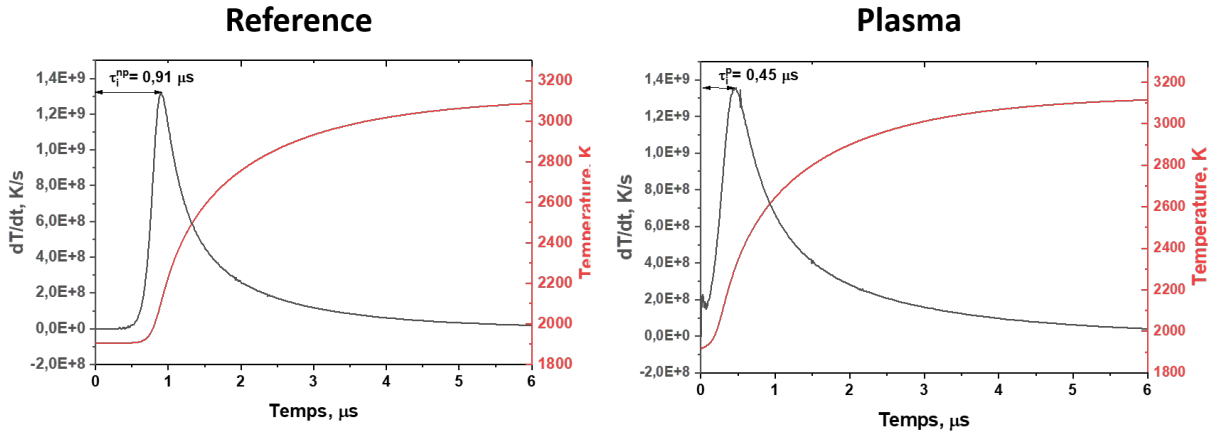

Figure 4: Calculated ZND profiles without (left) and with (right) plasma pre-dissociation for the stoichiometric H_2:O_2 mixture at 150 mbar diluted with 40% of argon

4 Discussion and conclusion

We found that the ignition of a flame with a multichannel plasma nanosecond discharge produces a stronger and more turbulent flame that evolves faster into detonation than a flame obtained with an automotive plug. We also found that the pre-dissociation of the initial composition by application of a plasma nanosecond discharge ahead of a detonation front immediately modifies the wave structure by reducing the size of the detonation cells. This demonstrates experimentally that plasma can enhance detonability defined as either the DDT distance or the cell width. The calculated effect of plasma pre-dissociation on the induction time in the ZND detonation agrees with the measured decrease of the detonation cell width. The DDT distances are known to be very sensitive to the tube length, roughness and constitutive material. To a lesser extent, this also applies to the detonation cellular structure if the transverse dimension of the tubes is too small because the detonation combustion time is much smaller than that of the DDT development. The results obtained in our study should thus be considered as restricted to our conditions. However, because our experimental design and configurations are fundamentally simple, our conclusion is that specific devices implementing detonation as a combustion process could be more efficient and compact by using plasma actions.

5 Acknowledgement

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