Parametric study of the kinetic and thermal effects of NRP discharges on the flame acceleration process for hydrogen-air deflagration-to-detonation transition

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Abstract: This work is dedicated to the study of NRP discharges to enhance the deflagration-to-detonation process in stoichiometric H2:Air. Two morphologies are investigated, the Glow (G) mode associated with negligible thermal effect and dominant dissociation processes and the Spark and Glow (S&G) mode with fast gas heating and dominant thermal processes. The G mode results in an small increase of early front speed but it is not enough to achieve DDT process, while in the S&G mode, it is systematically achieved.

Keywords: DDT, nanosecond discharge, detonation, glow discharge, spark.

1. Introduction

Detonation is the supersonic propagation mode of combustion waves. It is associated with high pressure and temperature along the propagating shock producing ideal conditions for propulsion (pulsed detonation engines [1] and rotation detonation engines [2]) and power generation [3]. One challenge is to generate a self-sustained detonation (at Chapman-Jouguet CJ conditions) over short distances and for a small amount of input energy. The preferred way is to achieve detonation is by the deflagration-to-detonation transition (DDT) process. The deflagration waves are intrinsically unstable and accelerate to reach the conditions for DDT but can be enhanced to achieve it more efficiently. The preferred way is to use geometrical arreangements, named obstacles, to generate turbulences on the path of the deflagration. However, they increase the complexity of the DDT designs and are damaged over time. Other promising solutions needs to be investigated.

The use of plasma to enhance the properties of combustion has been extensively studied over the last two decades. Energy branching as a function of electron energy in combustible mixtures and changing of the efficient activation energy are discussed in recent reviews [4,5]. In the field of plasma-assisted combustion, decrease of the ignition delay [6], extending the flammability limits, and increasing the combustion stability of lean mixtures [5,7] have been demonstrated both experimentally and numerically. Shock-tube experiments showed 3-4 orders of magnitude reduction in ignition delay for methane-based mixtures [8].

The nanosecond discharges are considered because of their short characteristic time to input energy into the system. It includes high levels of molecule dissociation [5], fast gas heating (FGH) [9] and compression waves [10]. The deflagration enhanced by nanosecond plasmas are transitioning faster and over shorter distances compared to thermal plasmas. Zhukov et al. [11] and Alicherif et al. [12] obtained shorter DDT times for hydrocarbons and hydrogen mixtures, respecticely, when comparing a high-volatge nanoseconde discharges to a spark. A significant decrease of run-up DDT length was obtained by Gray et al. [13] when applying a NRP plasma on the deflagration path. Tropina et al. [14] numerically showed that the oxygen dissociation obtained by a nanosecond discharge is more effective than joule heating by thermal plasma for DDT. Vorenkamp et al. [15] demonstrated a non-linear effect of a nanosecond plasma for DDT in micro-channels showing that longer discharges result in longer transition lenght.

However, it is still not clear, in the case of a nanosecond discharge, how to differentiate the thermal and chemical processes implied in the DDT enhancement. This work aims at investigating the effect on the DDT of two NRP discharges with similar discharge properties but different dominant processes (kinetic and thermal).

2. Experimental setup

A schematic of the experimental setup is shown in Figure 1. The deflagration tube is made of stainless steel, 3350-mm long and with a 39-mm diameters. It is composed of 6 stainless steel independent sections and one glass section that can be moved independently.

The mixture studied is stoichiometric H_2:Air realised by partial pressure method monitored by a static pressure gauge (Keller Leo 3). The experiments are realised for 1000 mbar and ambient temperature. Before each experiment the tube is flushed with compressed air to evacuate all impurities. A vacuum of 10^{-1} mbar is obtained using a vacuum pump (Edward RV8). After injection of the fuel and air, the mixture is recirculated for 3 minutes using a reciculation pump (KNF Laboport N 842.3 FT.18).

The plasma high-voltage electrodes are instaled in the glass section and supplied by a NRP discharge generator (FID FPD 25-100MC2). Both the voltage amplitudes and the repetition rate are varied from 2 kV to 12.5 kV and 5 kHz to 100 kHz respectively to change the discharge morphology. Two types of discharges are obtained, namely the glow (G) and the spark and glow (S&G) modes and will be described further in the next section.

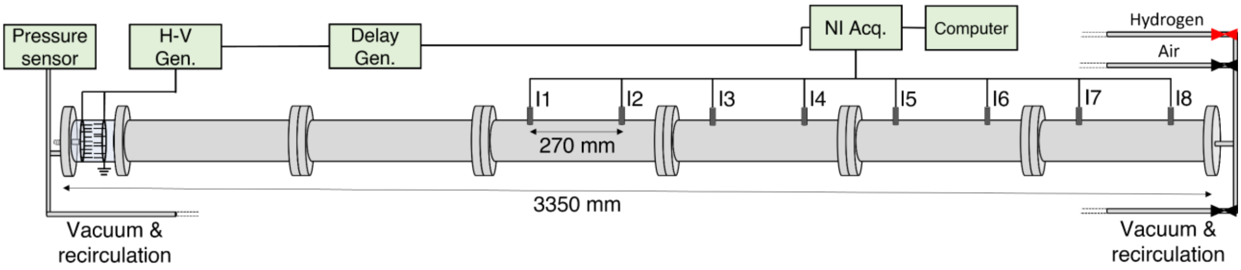

Fig. 1. Schematic of the experimental setup. H-V Gen.= High-Voltage generator; Delay Gen.= Delay Generator; NI Acq= NI Acquisition system.

Two ignitions systems are positioned at the beginning of the tube to independently study the effects of kinetic and thermal process. A standard spark plug is used to ignite the mixtures for the case of the no-plasma and G mode experiments. For the S&G mode, the high-voltage electrodes serve as both ignition and enhancement system.

A total of 8 ionic probes, each separated by 270 mm, are positioned to measure a drop in voltage associated with the ions in the flame front. The signals are sent to a high-speed acquisition system (NI, PXI-5105 Oscilloscope) and are used to characterise the instantaneous speed of the flame front. This is a key parameter to determine if the deflagration has transitioned to a detonation. Figure 2 shows examples of signals obtained. A deflagration is characterize by a slow raise of signal whereas a detonation is characterize by a sharp increase of signal.

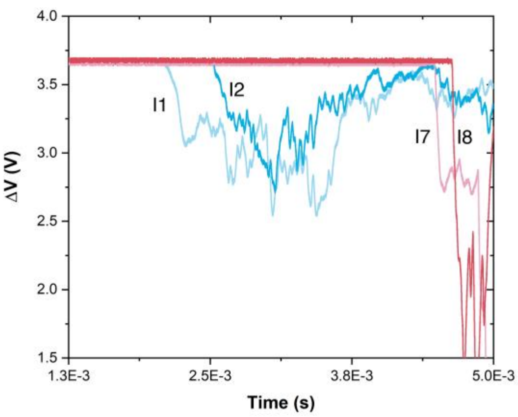

Fig. 2. Typical ionic probe signals obtained for a deflagration (I1 and I2) and a detonation (I7 and I8).

3. Results and Discussions

The properties of the plasma are changed by varying the parameters of the high-voltage generator. The two modes are named according to their apparences. Figure 3 presents the morphologies of the plasmas for the G mode, Fig. 3-a, and the S&G mode, Fig. 3-b.

The G mode (a) is a glow discharge connecting the high-voltage and grounded electrode. It is characterised by a strong visible emission at the vicinity of the electrodes. The resulting current is small and the temperature increase is, therefore, small. The dominant processes are mainly kinetic with high degree of dissociation when the discharge is sustained over long periods of time. The S&G (B) mode is a glow discharge with non-thermal spark events happening, the intensity and the frequency of the sparks is depending upon the voltage amplitude at a given repetition rate. The picture shown in Fig. 3-b is integrated over time. This mode is characterized by a fast and significant heat release (FGH) associated with a current increase. The dominant process is thermal with ignition of the mixture by the discharge due to the sharp temperature increase.

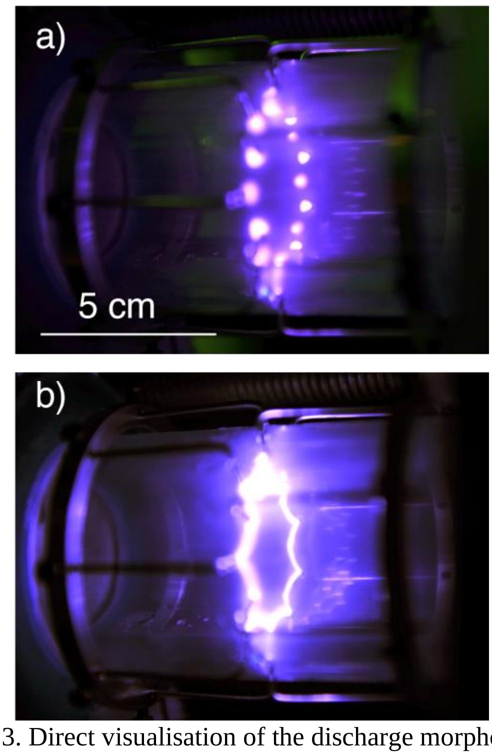

Fig. 3. Direct visualisation of the discharge morphology for G (a) and S&G modes (b). The images are obtained in air at 1000 mbar for 100 KHz, 7.5 kV (a) and 7.7 kV (b).

The transition map for the two modes is shown in figure 4 for 1000 mbar in stoichiometric H_2:Air. As the reptition rate increases, the transition is obtained at lower values of applied voltage. A total of 4 conditions were investigated both in the G and S&G modes by slightly increasing the applied voltage starting from the G mode. This methodology allows to study the effect of kinetic and thermal processes with similar applied voltage and pulse repetition rate. The selected frequencies were 10, 40, 70, and 100 kHz named A, B, C, and D respectively. To differentiate the two modes subscript will be used, for example, A_G and $A_{S\&G}$ represents glow mode and spark and glow mode at 10 kHz respectively. Note that about 0.1 kV of applied voltage separates the two modes.

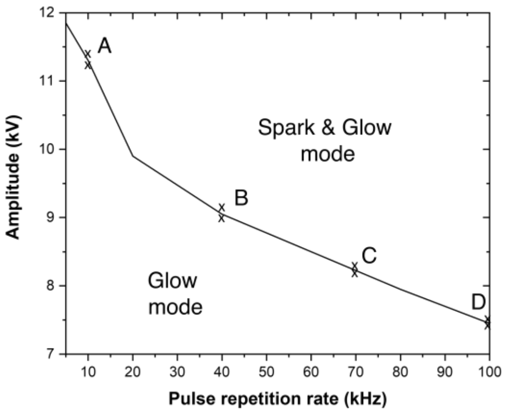

Fig. 4. Transition map from glow to spark and glow modes expressed as voltage amplitude vs pulse repetition rate. The letters A, B, C and D represents the different cases studied in this work.

The flame acceleration results obtained for all the conditions are showed in Figure 5 for the no plasma and the G mode and in Figure 6 for the S&G mode.

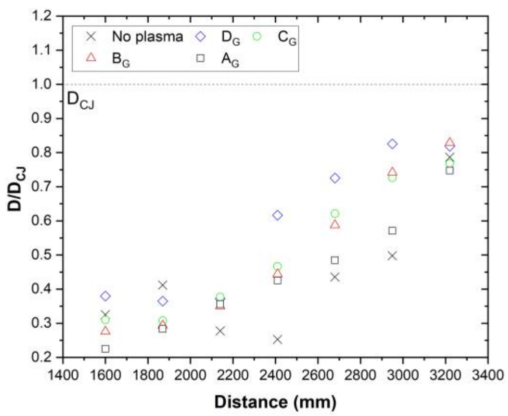

Fig. 5. Flame front speed versus distance for the case of no-plasma and plasma in the G mode.

For the no-plasma case, the mixture is ignited by the spark plug with a pulse duration of 1 ms and 10 kV applied voltage. The deflagration propagation speed is increasing but the transition is never achieved. The same behaviour is observed for the G mode. In this case, the plasma is sustained for 30 secondes before ignition of the mixture by the spark plug with a pulse duration of 1 ms and 10 kV. No significant effect of the plasma is observed but a minor increase of propagation speed can be observed for the highest frequencies. It seems that the effect of the plasma is observed only for the early stages of the flame propagation.

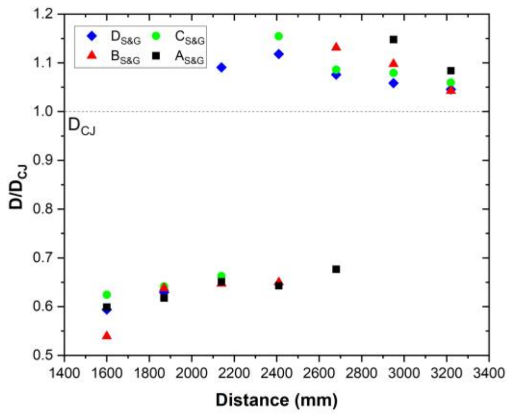

Fig. 6. Flame front speed versus distance for the case of plasma in the S&G mode.

For the S&G mode, the plasma is igniting the mixture via fast thermal heating. A significant increase in the flame speed is observed and the DDT is achieved for all the tested conditions. For the highest frequency, the DDT process is achieved faster, in less than 2 meters for 7.5 kV of applied voltage. For the lowest frequency, the DDT process is achieved in 3 meters for 11.2 kV of applied voltage.

In the case of the G mode, where the dissociation process is dominant, we do not observe a significant increase of the flame front speed. This result can be correlated to the one obtained in [15] where the authors claim that the kinetic effect of the plasma is non-linear on the DDT process. Therefore, it is necessary to vary the application time of the plasma and the time between the plasma and the discharge to find favorable conditions for flame acceleration.

In the case of the S&G mode, where the fast thermal heating is dominant, the DDT process is achieved at various length depending on the pulse repetition rate. The heat release process as well as the formation of the flame kernels must be investigated to further understand the mechanism leading to successful DDT.

4. Conclusions

This work aimed at investigating the effect of two NRP modes where kinetic or thermal processes are dominant on the DDT process of the stoichiometric H_2:Air mixture at 1000 mbar. The findings are :

- The morphology and dominant processes of the discharge can be significantly changed by slightly modifying the applied voltage at a given frequency.

- Two modes are obtained in the combustible mixture, namely the Glow mode characterized by a negligible thermal effect and the Spark and Glow characterized by a fast gas heating.
- For the G mode, no noticeable effect on the flame front speed is observed but the application time of the plasma was not investigated in this work. Futher studies are necessary to better understand the role of dissociation by plasma action on the flame acceleration process.
- For the S&G mode, a significant enhancement is observed. The DDT process is occurring for all the tested conditions with a strong dependency of the applied frequency. For higher frequencies, the DDT is happening faster. More studies on the heat release mecanisms are necessary to better understand how it translate to faster DDT process.

An extensive study of the two modes and their impact on the ignition and DDT process will follow this work.

Acknowledgements

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5. References

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