Investigation of flame propagation enhancement by a ultrashort nanosecond discharge pulse using the Rayleigh scattering thermometry

C. Kong[1], Y. Bao[1], T. Hurtig[2], M. Aldén[1] and A. Ehn[1]

[1]*Division of Combustion Physics, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden*
[2]*Swedish Defense Research Agency, SE-164 90 Stockholm, Sweden*

Abstract: This work aims at investigating the direct impacts of a single-pulse nanosecond (NS) discharge on a lifted methane-air flame by using Rayleigh scattering thermometry. It is found that the propagation speed of flame front is enhanced 55% of the local flame speed after the discharge pulse even though the gas temperature increment is less than 30 K. This flame propagation enhancement is speculated to be a result of the discharge-induced long-lived radicals, besides the thermal effect.

Keywords: nanosecond pulsed discharge, plasma assisted combustion, flame propagation enhancement, Rayleigh scattering thermometry.

1. Introduction

Non-thermal plasma has short response time and high efficiency for radical productions and thus it is a very promising technique for combustion enhancement [1-3]. Such a scheme would allow for combustion control and assistance to (1) increase fuel flexibility and (2) enable combustion of leaner gas mixtures. However, the direct kinetic effect of plasma on combustion is still ambiguous due to the thermal-chemical coupling [4]. The electric discharge is essentially an energy deposition way to convert the electrical energy to other energy forms such as chemical energy in the radical species and thermal energy. According to the second law of thermodynamics, the input energy finally converts to thermal energy, but from the kinetic viewpoint, the plasma energy conversion depends on time scales [5]. Therefore, one possible way to decouple the thermal and kinetic effects is using a single-pulse nanosecond (NS) discharge, which can directly affect the flame without any delay time, and thus the effects of radicals and heat can be separated according to their different accumulation time scales. Another more direct way is to measure the temperature and radical species around the flame under the impacts of discharge. Based on these two ideas, an experimental setup was designed to investigate the direct interactions between non-thermal plasma and flame. In this work, we report the recent progress on the NS-discharge actuated combustion. The flame propagation enhancement by NS-discharge is confirmed and the kinetic and thermal effects are discussed based on the instantaneous temperature measurement.

2. Experimental setup

Fig. 1 shows a schematic of the experimental setup. A McKenna burner together with a round brass stabilizing plate is used to produce and sustain a lifted flat methane-air flame. The distance between the burner and the stabilizing plate is 2.1 cm. The gas flow rates of methane and air for combustion are 0.84 standard liter per minute (SLPM) and 13.34 SLPM, respectively and thus the equivalence ratio is equal to 0.6. The corresponding flame speed is around 9 cm/s [6]. The mean flow speed is calculated to be 9.1 cm/s and thus the flame can be lifted up and stabilized. Meanwhile, a coflow air is fed with a flow rate of 5.2 SLPM to lift the flame rim up, thus to prevent breakdown near the flame rim.

An ultrashort nanosecond high voltage (HV) pulse generator with a pulse duration of 3 ns (FID GmbH FPG 200-1NM1) was used to prevent the plasma contraction at atmospheric pressure and thus to generate a diffusive plasma discharge, which directly goes through the lifted flame front. In order to fix the position of the discharge volume, a small tip was installed on the center of the top brass plate. The maximum pulse repetition frequency (PRF) of the HV pulser is 1 kHz. However, it was found that the NS-discharge has poor repeatability due to the memory effect of discharge when the PRF is high. Therefore, the PRF was set to 1 Hz in this work to guarantee the repeatability from pulse to pulse. The voltage amplitude is fixed at 30kV.

The spontaneous emissions from the discharge volume and the flame were imaged using an intensified charge-coupled device (ICCD, iStar Andor) mounted with a UV lens (Nikon, 105mm, f/4.5) and a bandpass interference filter (320nm±20nm, Semrock). Furthermore, the translational temperature around the flame front was measured using the Rayleigh scattering thermometry. A brilliant B laser (Quantel) with second harmonics was employed to produce the 532 nm laser pulse, which was focused by a two-faceted glass component (FC) and a positive cylindrical lens with a focus lens of 475 mm to form a laser sheet with a width of 3 mm. A half-wave plate (HW) was also inserted to change the polarization of laser beam for maximum of Rayleigh scattering signal. The Andor ICCD camera mounted with a visible light Nikon lens (135mm, f/2) was used to acquire the Rayleigh scattering signal. In order to synchronize the NS-discharge and the laser, a pulse generator (BNC575, Berkeley Nucleonics) was utilized to externally trigger the flash lamp and the Q-Switching of the laser, the nanosecond high voltage pulse generator and the ICCD camera.

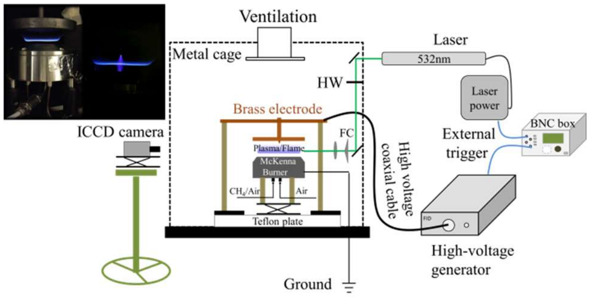

Fig. 1 A schematic of the experimental setup

3. Results and discussion

Fig. 2 shows snapshots of spontaneous emissions during the fast NS breakdown process. With the electrode configuration used in this work, the breakdown initiates near the top tip because of the largest local electric field strength. Later the ionization wave propagates to the flame front. As we know, the flame front can be regarded as weakly-ionized plasma [8]. Under the impact of ionization wave, local strong electric field can build up and cause the nitrogen excitation and emission near the flame front. The ionization occurs earlier in the post flame zone compared to the pre-flame zone between the flame front and the burner surface, due to the high temperature and the large reduced electric field strength (E/N). When the local E/N becomes large enough with time in the cold pre-flame zone, the ionization and breakdown also starts. Since the top surface of the Mckenna burner is made of porous copper plug, it is coarse and thus the E/N over the burner distributes inhomogeneously. Many positive streamers start at spots with high E/N separately and propagate upwards, forming the brush-like discharge morphology close to the surface of burner, as shown in Fig. 2. These streamers can merge together when they are close to the flame front. Therefore, the flame front is basically surrounded by a diffuse plasma volume. The detected strong emission signal in Fig. 2 is mainly due to the N2(C-B) transition and its lifetime is only tens of nanoseconds.

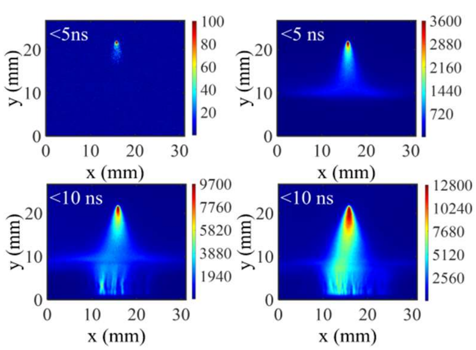

Fig. 2 Snapshots of spontaneous emissions during the fast breakdown process. The interference filter (320±20nm) is mounted to capture these images. The gate of ICCD is 3 ns.

Thermal impacts are always coupled with the chemical impacts in the plasma assisted combustion and thus the temperature is measured using the Rayleigh scattering thermometry to isolate the thermal effect. Fig. 3(A) shows the temperature profiles mainly in the pre-flame zone (T_g<600K). The x axis is parallel to the burner surface and the y axis represents the relative height. Fig. 3(B) indicates that the local temperature increases with the delay time after discharge pulse, but the temperature increment is still less than 30 K. The standard deviation is estimated to be around 10 K, as shown in Fig. 3(C).

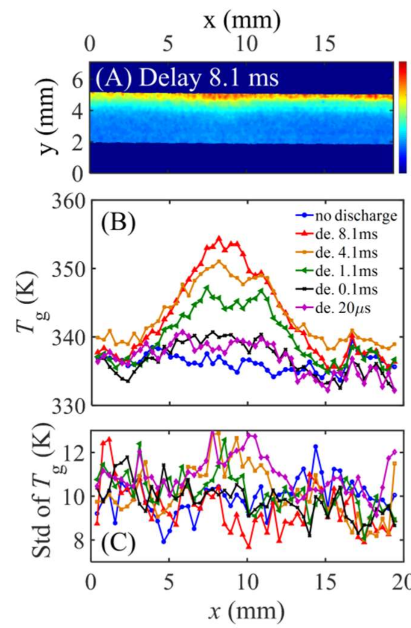

Fig. 3 Temperature profiles in the pre-flame zone with different delay time after discharge. The temperature unit is Kelvin degree (K).

Due to the NS-discharge, the local flame propagation speed is indeed enhanced so that the flame front propagates upstream, as demonstrated in Fig. 4. To quantify the enhanced propagation speed, a shift distance (l_s) of the propagated flame front is defined and plotted with respect to the delay time, as shown in Fig. 5. A shift speed is fitted to be 5 cm/s. By assuming that this shift speed is only because of the discharge and the flame stretch effect is not considered, the flame propagation speed enhancement due to discharge is estimated to be 55% of the local flame speed (9 cm/s).

The flame propagation enhancement can be due to local heating and chemical actuation. Using the GRI-Mech 3.0 mechanism, the flame speed increment is calculated to be 23%-40% when the gas temperature increases 30 K-50 K. Since the measured temperature increase after NS-discharge is smaller than 30 K, the thermal effect cannot be the only reason for the found flame speed enhancement. Some kinetic effect should also work and contribute more than 50% to the flame speed increase. Furthermore, the flame propagation enhancement is detectable even 28 ms after the discharge pulse. It infers that the kinetic effect works for a relatively long time because of some long-lived radical species produced by the methane-air reforming in the upstream.

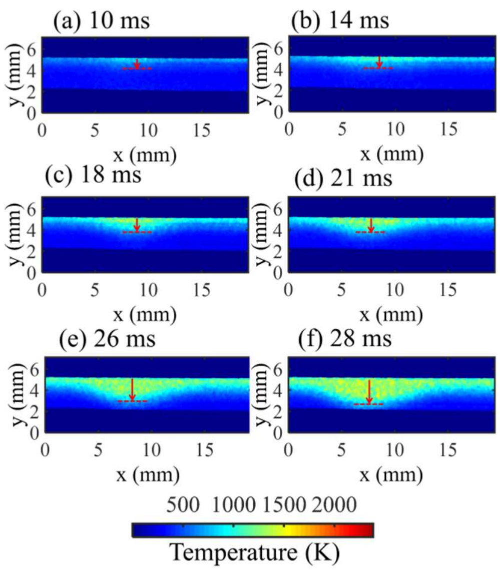

Fig. 4 Snapshots of the temperature profiles around the flame front with different delay time from the discharge. The temperature unit is Kelvin degree (K).

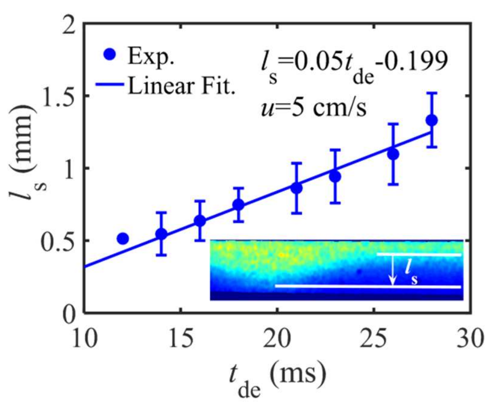

Fig. 5 Shift distance (l_s) of the propagated flame front with respect to the delay time after discharge.

4. Conclusions

By using an ultrashort nanosecond discharge pulse directly going through a lifted flat flame, the flame propagation is definitely enhanced. The local flame speed increment is estimated to be 5 cm/s, which is 55% of the normal flame speed. This flame propagation enhancement is basically due to the thermal and kinetic effects. The temperature increment due to discharge is measured to be less than 30 K, which can only result in a flame speed increase of 23% according to the kinetic simulation with the GRI-Mech 3.0 mechanism. Therefore, the kinetic effect should contribute more than 50% to the flame speed enhancement.

Acknowledgements

The work was financially supported by the Swedish Energy Agency, the Swedish Research Council, the Knut and Alice Wallenberg foundation and the European Research Council. C. Kong also appreciate the travel grant from the Royal Physiographic Society in Lund.

References

[1] S.M. Starikovskaia, Journal of Physics D: Applied Physics, **47**, 353001 (2014).

[2] A. Starikovskiy, N. Aleksandrov, Progress in Energy and Combustion Science, **39**, 61 (2013).

[3] Y.G. Ju, W.T. Sun, Progress in Energy and Combustion Science, **48**, 21 (2015).

[4] D.A. Lacoste, B.J. Lee, A. Satija, S. Krishna, S.A. Steinmetz, I. Alkhesho, O. Hazzaa, R.P. Lucht, M.S. Cha, W.L. Roberts, Combustion Science and Technology, **189**, 2012 (2017).

[5] S. Yang, S. Nagaraja, W.T. Sun, V. Yang, Journal of Physics D: Applied Physics, **50,** 433001 (2017).

[6] Y. Wu, V. Modica, B. Rossow, F. Grisch, Fuel, **185**, 577 (2016).

[7] S.F. Adams, J.E. Caplinger, B.S. Sommers, Plasma Sources Science and Technology, **24**, 025031 (2015).

[8] A.B. Fialkov, Progress in Energy and Combustion Science, **23**, 399 (1997).