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Effects of non-thermal plasma on swirled premixed methane/air flames

Gyeong Taek Kim[1], Dong Min Kim[2], Hyun Seok You[2], Chun Sang Yoo[1], Jeong Park[3], Suk Ho Chung[4]

[1]Department of Mechanical Engineering, Ulsan National Institute of Science and Technology (UNIST),
50 UNIST-gil, Ulsan 44919, Republic of Korea
[2]New Energy Technology Center, Korea Gas Corporation (KOGAS)
1248 Suin-ro, Ansan 15328, Republic of Korea
[3]Department of Mechanical Engineering, Pukyong National University (PKNU),
365 Sinsun-ro, Busan 48547, Republic of Korea
[4]Clean Combustion Research Center, King Abdullah University of Science and Technology (KAUST),
Thuwal 23955-6900, Saudi Arabia

Abstract

The effects of non-thermal plasma on swirled premixed methane/air flames have been experimentally studied by adopting a dielectric barrier discharge (DBD) technique. Lean extinction limits were extended by the non-thermal plasma-induced streamer. Flame configuration was significantly changed from regime III to regime II applying voltage and frequency. This is because the streamer interacts with positive or negative ions and electron in flame.

1 Introduction

Lean premixed gas swirl combustors have been successful in meeting present stringent NOx emission regulations because thermal NOx can be considerably reduced at low flame temperatures [1, 2]. However, there still exist several issues to be resolved in the development of lean premixed gas combustors such as combustion instability and much more stringent emission regulations in the foreseeable future. Progressively strict emission regulations are reasonably expected to control the future development of gas combustion systems. As a result, if environmental problems set regulations below 5 ppm NOx in the future, new alternatives will be needed to satisfy the international emission standards without expensive facilities for exhaust gas clean up.

The combustion instability in lean premixed combustion and stringent regulations have posed unprecedented challenges for researchers to find new technologies to stabilize combustion at extreme conditions and significantly reduce exhaust emissions. As one of new technologies, non-thermal plasma has drawn great attention since it can provide an unprecedented opportunity for combustion stabilization and emission control. Especially, dielectric barrier discharge (DBD) technique has been considered as a promising candidate for generating non-thermal plasma. Non-thermal plasma has several advantages of relatively-low cost and much lower power consumption over thermal plasma such as pulsed corona discharges and arc discharges.

Therefore, the objective of the present study is to experimentally investigate the effects of non-thermal plasma on swirled premixed flame. The influences of the dielectric barrier discharge on the overall characteristics of the premixed flames are reported.

2 Experiment

The experimental apparatus is composed of a swirl combustor, a non-thermal plasma-generating system, and a visualization system as shown in Fig. 1. The swirl combustor has a fuel nozzle with ten holes through which methane is supplied and a compressed dry air is also supplied through a ceramic mixing chamber with 11 mm-diameter at the exit. The plasma-generating system has a DBD reactor and a power supply (Trek, 10/10B-HS). The DBD reactor has a ceramic nose cone to control streamers. The stainless steel fuel nozzle serves as a central electrode and the stainless steel mesh surrounding the outer quartz tube, a dielectric barrier, is a cylindrical electrode. The cylindrical electrode is grounded.

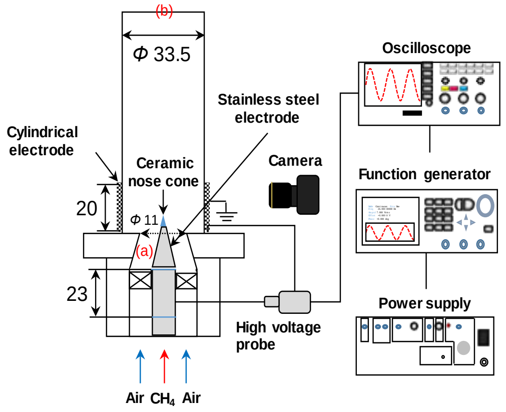

Figure 1: Schematic diagram of the experimental setup.

Corresponding author. Fax: +52-217-2409, +51-629-6126
E-mail address: csyoo@unist.ac.kr, jeongpark@pknu.ac.kr

3 Results and discussion

Figure 2 shows a regime diagram of the premixed flames without plasma in the equivalence ratio (ϕ) and nozzle exit velocity (U_0) space. The premixed flames with a single axial swirler can be classified into three different regimes depending on their flame shapes: an M flame (Regime I), a conical flame (Regime II), and a columnar flame (Regime III). Figure 3 show typical flame shapes in the three different regimes; at a fixed velocity (7 m/s), the flame configuration changes from Regime I (ϕ = 1.0) to Regime II (ϕ = 0.56) to Regime III (ϕ = 0.54) with decreasing ϕ. It is also readily observed from Fig. 3 that the flame length increases with decreasing ϕ. Under relatively-high velocity conditions (7 – 10 m/s), Regime II and III come to exist in a broader area in the ϕ–U_0 space than those under relatively-low velocity conditions (3 – 6 m/s). This is because the recirculation zone moves progressively downstream as the nozzle exit velocity increases.

Figure 4 shows a regime diagram of the premixed flames with plasma. It demonstrates that plasma can considerably extend the lean extinction limits for all the velocity range compared to those without plasma in Fig. 2. Overall, stable premixed flames can exist over a much wider range of equivalence ratios and velocities with plasma than without plasma. When AC voltage is applied to the fuel nozzle, the electric discharge can be observed in the premixed flames. This indicates that streamers and ozone can be induced by the discharge, which significantly enhance the flames [3, 4]. Under relatively-high velocity conditions, however, the effect of plasma on the extension of extinction limits is more significant than that under relatively-low velocity conditions.

To identify the effects of streamers on the methane/air premixed flames, the characteristics of streamer generation in the flames were investigated. Time-averaged spatial distributions of streamers for Regimes II and III are shown in Fig. 5. The images in the figure represent snap shots with short-time exposure (100 ms) through the 330-nm band-pass filter, where the bright lines indicate the paths of streamers. Most of the streamers develop from the fuel nozzle electrode below the ceramic nose cone and propagate radially toward the mesh electrode. The initial points of streamers are concentrated on the fuel nozzle electrode which coincides with the flame front location. Since abundant positive ions exist in high temperature flame zone [5], the coincidence of streamer and flame locations indicates that a flame can serve as an extended electrode by reducing the effective distance between electrodes. It is also observed from the figure that in Regime II (ϕ = 0.55), the intensity and distribution of streamers are stronger and wider than those in Regime III (ϕ = 0.50). The effects of the streamers on the premixed flames will be further investigated.

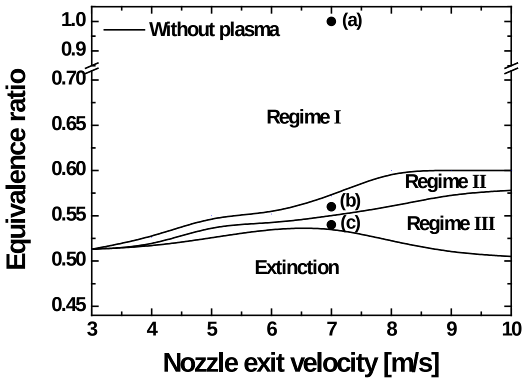

Figure 2: Flame stability map without plasma.

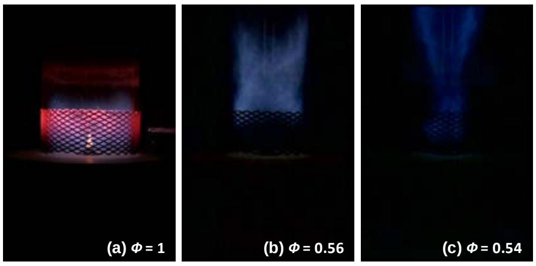

Figure 3: Flame images for ϕ = 1, 0.56, and 0.54 at 7 m/s.

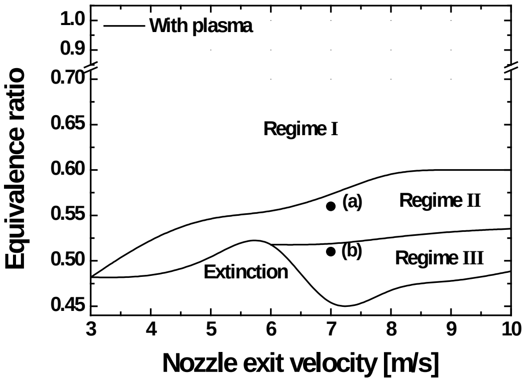

Figure 4: Flame stability map with plasma (7 kV and 4 kHz).

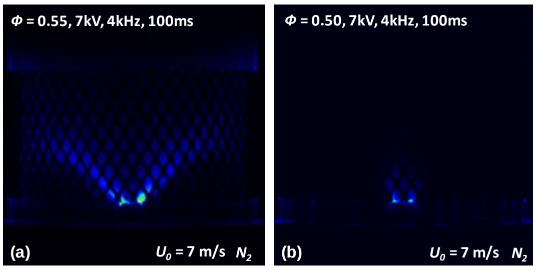

Figure 5: Streamers and flame images with plasma taken by an ICCD camera through a 330-nm filter for (a) ϕ = 0.55, and (b) ϕ = 0.50 at 7 m/s.

4 Conclusions

The characteristics of non-thermal plasma-assisted lean premixed flames were investigated experimentally. The flame premixed flames can be classified into three different regimes depending on its shape; it changes from an M flame (Regime I) to a conical flame (Regime II) to a columnar flame (Regime III). A flame in Regime III without plasma drastically changes to a flame in Regime II with plasma when strong streamers are developed by plasma. It is also found that the streamers extend lean extinction limits and enhance flame stabilization.

5 Acknowledgment

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