Proceedings of ASME Turbo Expo 2011
GT2011
June 6-10, 2011, Vancouver, British Columbia, Canada

GT2011-45161

APPLICATION OF DIELECTRIC BARRIER DISCHARGE TO IMPROVE THE FLASHBACK LIMIT OF A LEAN PREMIXED DUMP COMBUSTOR

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ABSTRACT

In recent years, lean-premixed (LP) combustors have been widely studied due to their potential to reduce NO_x emissions in comparison to diffusion type combustors. However, the fact that the fuels and oxidizers are mixed upstream of the combustion zone makes LP type of combustors a candidate for upstream flame propagation (i.e., flashback) in the premixer that is typically not designed to sustain high temperatures. Moreover, there has been a recent demand for fuel-flexible gas turbines that can operate on hydrogen-enriched fuels like Syngas. Combustors originally designed for slower kinetics fuels like natural gas can potentially encounter flashback if operated with faster burning fuels like those containing hydrogen as a constituent. There exists a clear need in fuel-flexible lean-premixed combustors to control flashback that will not only prevent costly component damage but will also enhance the operability margin of engines. A successful attempt has been made to control flashback in an atmospheric LP combustor, burning natural gas-air mixtures, via the application of Dielectric Barrier Discharge (DBD). A low-power DBD actuator was designed, fabricated and integrated into a premixer made out of quartz. The actuator was tuned to produce a low magnitude ionic wind with an intention to modify the velocity profile in the premixer. Flashback conditions were created by decreasing the air flow rate while keeping the fuel flow rate constant. Within this experimental setup, flashback happened in the core flow along the axis of the cylindrical premixer. Results show that the utilization of the DBD delays the occurrence of flashback to higher equivalence ratios. Improvements as high as about 5% of the flashback limit have been obtained without compromising the blowout limit. It is anticipated that this novel application of DBD will lead to future demonstrations of the concept under realistic gas turbine operating conditions.

INTRODUCTION

Diffusion flames are widely used in industrial and transportation combustion systems. The reaction region of such flames is a surface located between the fuel and oxidizer streams where the mixture is in stoichiometric conditions, leading to the highest flame temperatures that favor the formation of nitrous oxides (NO_x) [1]. Hence, to reduce these emissions, lean-premixed-prevaporized and lean-premixed combustion concepts have been widely studied in recent years. Since the fuels and oxidizers are mixed together upstream of the combustion chamber, these types of combustors may suffer from operational issues like auto-ignition and flashback [2]. Recent demand for clean fuel via coal or biomass gasification has increased interest in the development of combustion systems that can operate on synthesized gas having hydrogen content [3, 4]. A combustion system initially designed for slower burning fuels, for example conventional natural gas, may encounter issues like higher NO_x emissions, hot-tone combustion instabilities, auto-ignition and flashback when operated with reactive fuel blends having higher hydrogen or even higher hydrocarbon contents [3].

Flashback is the upstream propagation of the flame from the combustion chamber into the premixer or burner tube causing overheating in this section of the system that is not designed to sustain high temperatures [2,5]. Flashback leads to severe and costly damage to the gas turbine hardware. It is recognized that in practical combustors, flashback can generally occur either in the boundary layer or in the core flow and via mechanisms like combustion instabilities and combustion-induced vortex breakdown [6].

Flashback occurs if the local flow velocity is lower than the flame speed [5]. Due to the shear stress that reduces the velocity down to zero at the wall, there is high propensity for flashback to occur in the boundary layer. Lewis and von Elbe [7] developed a criterion for determining occurrence of flashback in fully developed laminar flows, which involved the concept of a critical velocity gradient, defined as the ratio of the laminar flame speed and the penetration depth where the wall quenching is effective. If the flow velocity gradient at the wall is kept higher than the critical value, flashback through the boundary layer is avoided. In fully developed turbulent flows, the critical velocity gradient is much higher than in laminar flows at a given mixture composition [8].

Flashback may also occur along the axis of burner tubes with large radius [9] and in nozzles with relatively flat velocity profile [10]. In addition, flashback in the core flow can take place in circular premixers with a significantly reduced axial velocity on the axis [2]. For all these cases, the velocity gradient at the wall is sufficiently high to avoid the flame propagation through the boundary layer, while the flame speed exceeds the core flow velocity allowing upstream flame propagation along the center line. It has been mentioned [6] that the main design rule to prevent this type of flashback is to avoid having wake regions in the premixer.

Regardless of the mechanisms, as discussed above, occurrence of flashback depends on the magnitude of the local flow velocity relative to the flame speed. It then seems possible to avoid upstream flame propagation in the premixer by appropriately modifying the flow field.

This paper provides the details of a successful attempt made to control flashback via the novel application of a Dielectric Barrier Discharge (DBD) in a lean-premixed combustor burning natural gas-air mixtures at atmospheric conditions. Some background description of DBD technology and its current applications are presented next, followed by details of the experimental setup, major results and conclusions.

DIELECTRIC BARRIER DISCHARGE FOR FLUID DYNAMICS AND CHEMICAL KINETICS APPLICATIONS

Dielectric barrier discharge actuators, also known as plasma actuators, are electro-fluidic devices comprising two offset electrodes placed on each side of a dielectric (insulating) material as shown on Fig. 1. When a high-frequency AC electric signal of several kilovolts is applied to the electrodes, the gas in the vicinity of the electrodes gets partially ionized generating plasma with a purple glow. Due to the electric field, the charged particles in this thin region are accelerated and they transfer their kinetic energy via collisions to the neutral gas molecules around them causing an ionic wind of a few meters per second. In practice, the ionic jet is generally needed on just one side of the dielectric sheet and therefore one of the electrodes is often embedded under a layer of insulation. This avoids the formation of unexploited plasma and improves the efficiency of the DBD without changing the working principle [11].

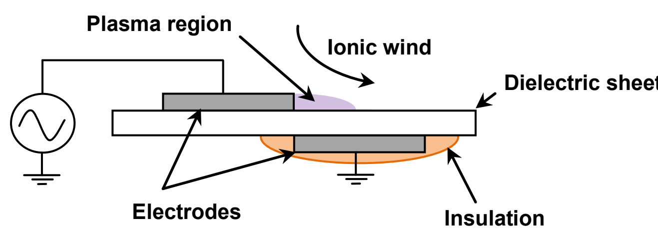

FIGURE 1: Plasma actuator configuration for ionic jet induction.

It is worthwhile to note that in the process of generating the ionic wind the DBD does not involve the introduction of additional fluid flow. The DBD only redirects some part of the gas flow towards where the plasma is located [12], as shown in Fig. 1. Other investigations have shown that at a fixed actuator input frequency, the equivalent body force (actuator strength) inducing flow acceleration generally increases with actuator input voltage [13].

Based on the earlier investigations, it may be inferred that for a tubular flow and fixed mass flow rate, the utilization of DBD accelerates the flow at the wall by directing flow away from the centerline axis towards the surface. This is sketched in Fig. 2, where the tubular flow into a sudden expansion is shown. The bottom and the top parts of the figure depict the flow characteristics without and with DBD application respectively. With DBD actuation, the velocity profile changes from a typical pipe-flow profile to one that shows an increase in flow velocity near the wall and a decrease in velocity at the centerline. The figure also shows the influence of this change in velocity profile in the tube on the flow characteristics after the sudden expansion. In particular, the location of the reattachment point is expected to be closer to the expansion (dump) plane [14], resulting in a stronger recirculation zone.

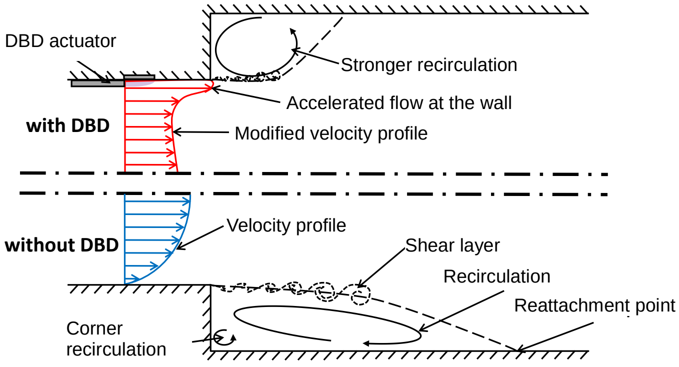

FIGURE 2: Schematic of tubular flow into a sudden expansion (dump plane) with DBD actuation (Top) and without DBD actuation (Bottom).

The advantages of the DBD plasma actuator over other flow control devices are its minimum protrusion, simplicity, robustness and also the fact that it involves no moving parts. In addition the setup needs low-power and low-weight generators for operation. To-date, experimental applications of plasma actuators have been mainly in the area of flow-control. The ionic jet that is generated has been shown to be effective in controlling the stall of stationary airfoils [15], provoking the stall of wind turbine blades [16], damping the vortex shedding induced oscillations of bluff bodies [17], controlling the boundary layer transition [18], etc.

Recently, DBD have also been applied in chemically reacting flows for enhancement of combustion kinetics. In these applications, the plasma is used to crack the fuel and/or air particles into smaller molecules and active radicals, thus assisting in the initiation of chain branching reactions and enhancing flame stability [19]. In these combustion experiments, the reactants were required to flow through the plasma region and thus the DBD setup was configured to cover the complete combustor cross-section. The electric power necessary to obtain a significant effect on combustion kinetics was found to be less than 1% of the combustor thermal power. It was shown that plasma actuation improves the flame blowout limit and reduces ignition delay time by an order of magnitude. Other studies demonstrated that the application of DBD leads to a more complete combustion [20] and helps reducing soot production in diffusion flames [21].

As shown on the generic premixed combustion stability map of Fig. 3, unlike the previous reacting-flow studies where the emphasis of DBD application was on enhancement of chemical kinetics to improve flames lean blowout limit, the focus of the current investigation was to utilize the fluid dynamics (ionic wind) effect of DBD to control flashback and to extend the stable flame limit on the richer side. This was accomplished, as explained later in the paper, by modifying the flow field in the premixer via a novel configuration of the DBD setup.

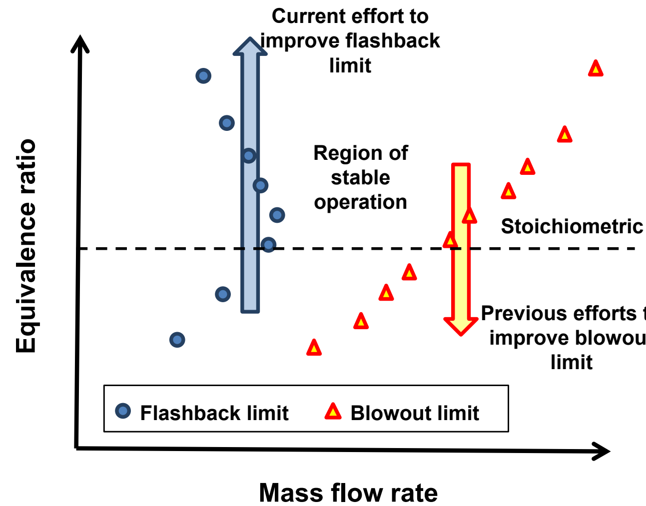

FIGURE 3: Combustor stability diagram showing the stable operation region and the limits of flashback and blowout.

METHODOLOGY

Experimental Setup

The schematic of the atmospheric combustion rig is shown in Fig. 4. The combustible mixture enters the vertical rig through four inlets, equally spaced circumferentially at the bottom of the rig. The flow then passes through a settling/flow-conditioning section comprising a diffuser, a stainless steel honeycomb, a fine-meshed screen and a contraction, before entering the premixer. The first part of the premixer is made from stainless steel and provides for instrumentation ports and acts as an interface between the contraction section and the second part of the premixer, which is made out of quartz to facilitate the integration of the DBD. The two parts of the premixer are separated by a fine stainless steel wire mesh, installed to prevent the flame from travelling upstream in the contraction section. The wire mesh is grounded through the metal section of the premixer as part of the DBD setup requirement (explained in the next section on DBD integration and setup). The quartz premixer section has an inner diameter of 0.050 m and a length of 0.152 m. The flow then enters a quartz combustion chamber that is 0.419 m long and has an inner diameter of 0.103 m. Two type-K thermocouples are installed, one in the stainless steel premixer section and the other at the combustor exit to measure the temperature of the combustible mixture and the exhaust gases respectively.

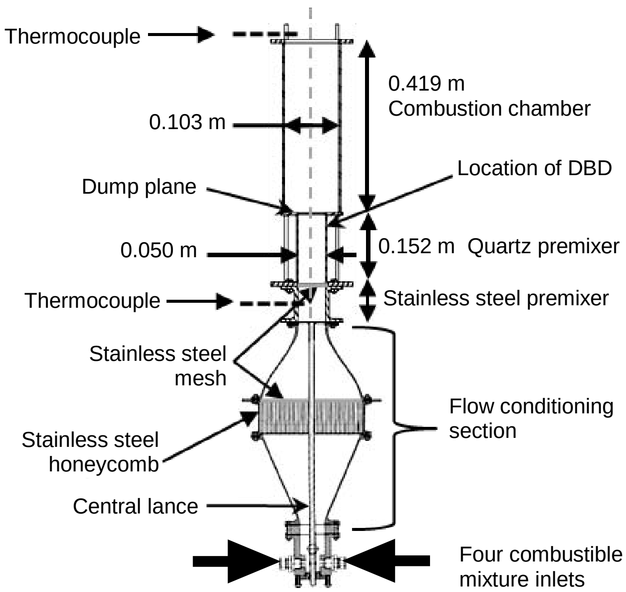

FIGURE 4: Cross section of the flow conditioning section and combustor (not to scale).

The rig is also provided with a tubular central lance through which fuel or fuel-air mixture may be introduced for diffusion and partially-premixed flame studies. For the present work, the central injection was not used and thus the lance was pulled upstream to sit in line with the exit of the contraction section.

TABLE 1 NATURAL GAS COMPOSITION

Constituent	Volume Percent
Methane	96.49
Ethane	1.41
Nitrogen	1.31
Carbon dioxide	0.68
Propane	0.09
Normal-Butane	0.01
Iso-Butane	0.01

The gas supply system comprises five feed lines, one for compressed air and the other four for various fuels and inert gases. The gases are then fed to a static mixer where various fuel compositions and air can be mixed uniformly and online before the introduction of the combustible mixture in the combustion rig. The fuel lines are also provided with solenoid valves and check valves for system safety. For the results reported here, the only fuel used was natural gas which was supplied through the commercial fuel line. Typical composition of the fuel, as provided by the fuel supplier, is given in Table 1, showing that the fuel comprised more than 96% of methane. The air flow rate was metered via an electronic flow controller. On the other hand, fuel was controlled using a manual needle valve, but monitored using an electronic flow meter. The controller and the flow meter were calibrated for the correct range of supply with full scale accuracy of ±1%. The data acquisition system was composed of a National Instruments SCB-68 connector block and a DAQ card (model PCI-MIO-16XE-10, 100 ks/s, 16-bit) connected to a desktop computer.

Digital images and videos of the flame were captured using a 12.3 megapixels Nikon D300 camera with a shutter speed of 1/8000s-30s and a repetition rate of 8 frames per second. Two different camera lenses were used, a 50mm one and an 85mm one. The camera was mounted with its image plane parallel to the combustion chamber centerline axis.

To characterize the flow velocity profiles, with and without DBD application, a Constant Temperature Anemometer (CTA) from Dantec Dynamics was used. The measurements were made under non-reacting iso-thermal conditions, approximately 1 mm downstream of the combustor dump plane along two orthogonal axes. The mass flow rate of air through the combustor during these measurements was set to match the average flow velocity under combustion experiments. For each measured point, 10 000 samples were recorded at a rate of 3 kHz. To avoid electromagnetic interference from the DBD actuator (operated at 4 kHz, as explained later) on the velocity measurements, the low-pass filter of the CTA system was set at 3 kHz. For these measurements, the combustion chamber length was shortened to allow the introduction of the CTA probe.

Integration and Setup of DBD

In addition to the unique application of DBD in flashback control, another novelty of the reported work is in the configuration of the DBD setup, as pointed out earlier. A photograph of the rig setup is given in Fig. 5, which shows the location of the DBD actuator with respect to the combustor inlet (dump plane). For the purpose of the experiments, the DBD was installed on the 0.0025 m thick wall of the quartz premixer, as shown in the schematic of Fig. 5. A thin stainless steel sleeve was inserted concentric to the inner diameter of the quartz premixer and attached to the grounded stainless steel mesh (which primarily served as flame arrestor, as explain earlier). The stainless steel sleeve thus served as the grounded electrode for the DBD actuator setup. The length of the sleeve was adjusted to end 0.044 m short of the combustor dump plane. This length was chosen to optimize the influence of the ionic wind from the DBD on the flow/flame dynamics and to prevent electric arcing with the stainless steel dump plane. A 0.013 m wide, 0.074 mm thick (0.038 mm of adhesive and 0.036 mm of metal) copper foil tape was pasted on the outer wall of the premixer and covered with insulation material. The copper foil, which served as the encapsulated electrode was connected to a high-voltage generator from Electrofluids Systems (Minipuls 6). When supplied with the required voltage, this DBD actuator configuration provided its ionic wind in the downstream flow direction.

A typical AC signal generated by the high-voltage (HV) generator and applied across the electrodes for all the experiments reported here, unless otherwise explicitly stated, is shown in Fig. 6. It consists of a 4 kHz triangular wave, with a peak-to-peak voltage of 19.2 kV. The signal was continuously monitored via a probe mounted on the HV generator and connected to an oscilloscope.

Fig. 6 also shows the time resolved current consumption of the system measured with a PEARSON model 4100 current monitor connected to the oscilloscope. The current curve shows streaks during the rise and fall of the voltage in the cycle. These streaks indicate the generation of plasma and thus plasma was only produced for a fraction of the global cycle period. However, since the period of the AC signal is generally much smaller that the response time of the flow, it is common to consider the plasma generation and the associated induced (ionic wind) velocity as continuous processes.

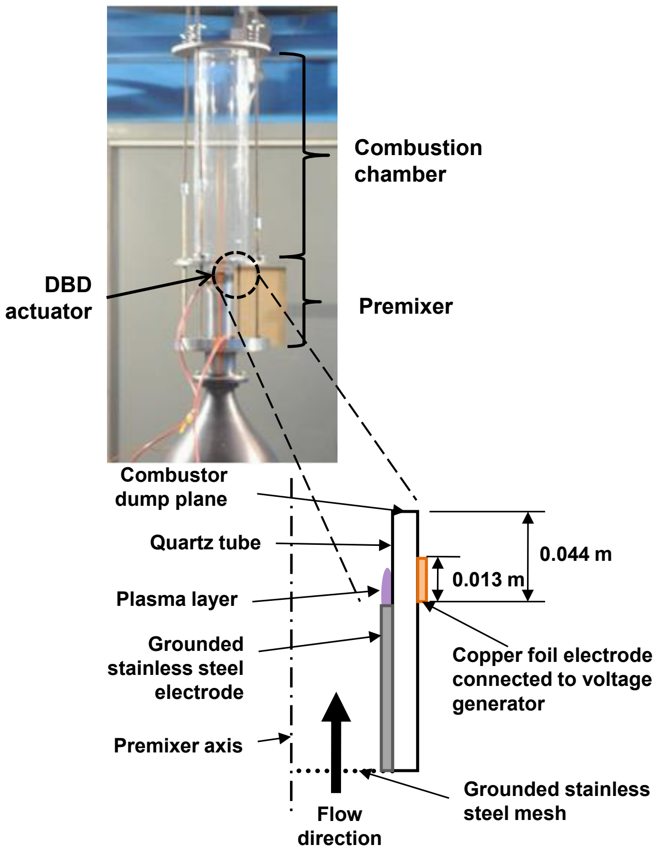

FIGURE 5: Dielectric Barrier Discharge integration in the premixer (schematic not to scale).

From the typical voltage and current signatures shown in Fig. 6, one may calculate the total power consumption of the DBD to be 156.6 W, which corresponds to 2.4 ~ 4.4 % of the thermal power of the combustion system used in the present investigation. However, it may be noted that all of this electrical power was not solely consumed by the DBD actuator because of the losses in the system [15]. For example, in the present experiment, large amounts of unused plasma were generated all along the wires in comparison with the plasma produced in the test section. It may be pointed out that the relative power requirement of the DBD setup may be minimized if dedicated efforts are made to reduce these losses, which was not the objective of the present work.

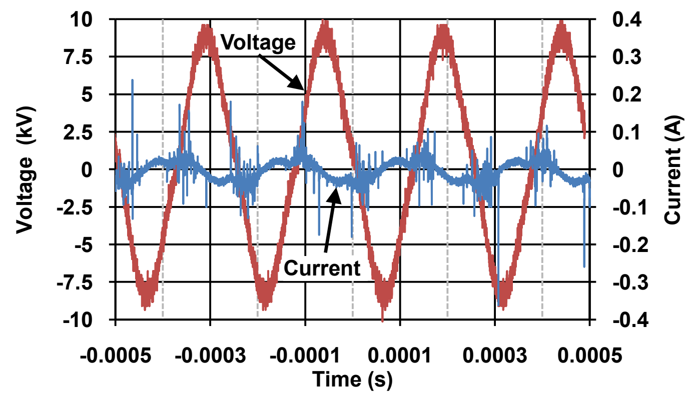

FIGURE 6: Voltage and current signals for the Dielectric Barrier Discharge actuator.

Experimental Procedure

During the experiments, the combustor was ignited at a given fuel flow rate using a spark igniter and the flame was stabilized at the dump plane by adjusting the air flow rate. Thereafter, the fuel flow rate was held constant while the air flow rate was metered via the DAQ system in predetermined steps towards either the rich (flashback) or lean (blowout) conditions. For every measurement point, the flame was first stabilized at the dump plane for two minutes to allow for the combustion chamber and the premixer to achieve thermal equilibrium. For the flashback points, seven flashbacks were induced. The measured fuel and air flow rates for the last five were averaged and used to produce the data, while the first two flashbacks were not considered and were aimed mainly at heating up the premixing section. To ensure repetitiveness of the data, the experiments were conducted at an almost constant pace such that the time between every flashback occurrence was nearly constant (~4 minutes). Hence, around 30 minutes were necessary to record a single data point. A similar procedure was adopted to produce the other data points corresponding to flame liftoff and blowout.

To further verify the repetitiveness of the results, the flame flashback and liftoff limits at a fixed fuel flow rate of 0.102 g/s and both with and without DBD actuation were measured twice on two consecutive days. The variations were found to be less than 0.65%, thus giving confidence in the data accuracy. In addition, the precision (repeatability) of the measurements was assessed using the Student's t-distribution.

For a confidence level of 95%, the random uncertainty ($\delta\bar{m}$) of the average value ($\bar{m}$) calculated from "n" number of measurements at the same operating condition was calculated using the standard deviation (σ_m):

$$\delta\bar{m} = \pm 2.776 \cdot \frac{\sigma_m}{\sqrt{n}} \quad (1)$$

The random uncertainty was calculated for all data points and for most of these points, $\delta\bar{m}$ was found to be too small to be displayed with error bars on the stability diagram presented in Fig.11. For the fuel flow rate, the normalized maximum uncertainty ($\delta\bar{m}_{max}/\bar{m}$), was 0.65%, while $\delta\bar{m}_{max}/\bar{m}$ for the equivalence ratio at flashback, liftoff and blowout conditions was found to be 0.74%, 0.51% and 1.42% respectively.

RESULTS AND DISCUSSION

Flame and Flow Characteristics

Figures 7 and 8 show images of the flame, without and with the application of DBD respectively. For the frames (a) to (d) of each figure, the 85mm lens was used, while the 50mm lens was used for the rest. These images were recorded at a fuel flow rate of 0.102 g/s and various air flow rates i.e., various equivalence ratios. On both figures, the bold lines represent the position of the dump plane, and the walls of the premixer and combustor sections.

Image (a) in both figures represents a stable flame at the same fuel and air flow rate conditions. A comparison between these images shows that the flame stabilization mechanisms encountered without and with DBD application are quite different. Without DBD actuation, the flame stabilizes on the rim of the premixer, while with DBD actuation i.e., under the influence of the ionic wind generated by the DBD, the flame anchoring is provided by the outer recirculation zone. This behavior is supported by the observations available in the literature and as discussed earlier in the paper (refers Fig. 2). The flow acceleration in the vicinity of the premixer wall by the application of DBD helps in strengthening the outer recirculation zone in the combustor, which in turn helps in anchoring the flame at the dump plane.

Comparison between the images of Figures 7 and 8 further shows that the application of DBD modifies the flame characteristics at any given operating condition. This is true both for increase in equivalence ratio (leading to flame flashback) as well as for decrease in equivalence ratio (leading to flame liftoff and blowout). Also, when comparing Fig. 7 with Fig. 8, it may be noted that at an equivalence ratio of 0.70 (Image (e) on both figures), the flame is attached to the dump plane for the case without actuation, while it is lifted-off for the actuated case. Hence, the flame detaches at a lower air mass flow rate with DBD actuation.

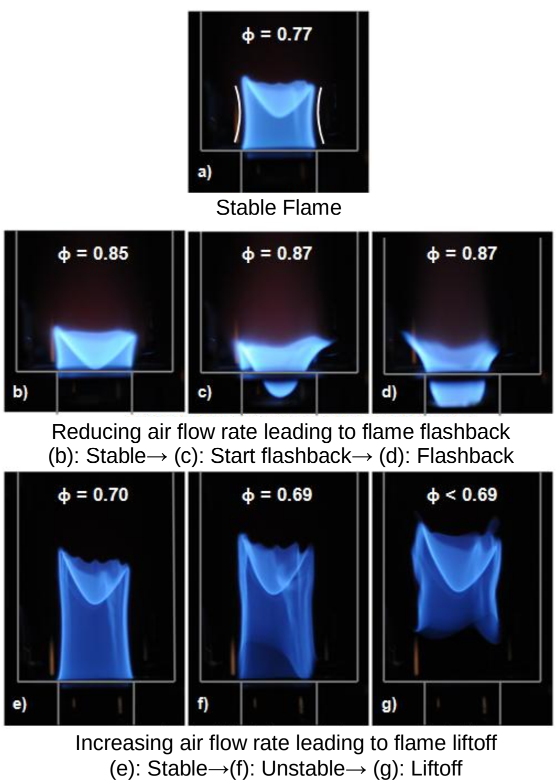

FIGURE 7: Flame characteristics without DBD actuation at a fuel flow rate of 0.102 g/s and varying equivalence ratios.

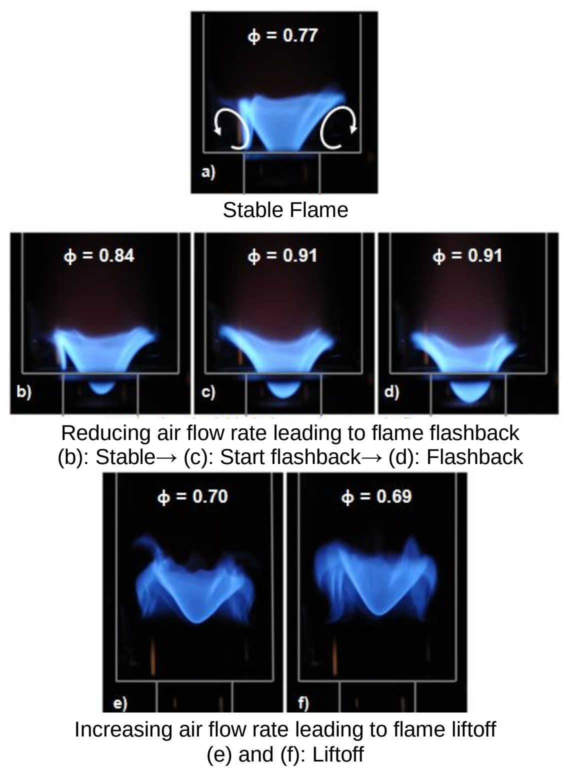

FIGURE 8: Flame characteristics with DBD actuation at a fuel flow rate of 0.102 g/s and varying equivalence ratios.

Concerning the flashback process, images (b) through (d) of Fig. 7 show that for the non-actuated case, as the equivalence ratio is increased through reduction in air mass flow rate, the stabilization location of the flame front gradually moves upstream along the axis of the combustor until it fully detaches from the rim. Immediately thereafter, the flame starts to propagate in the premixer. However, for the actuated case of Fig. 8, it may be noted that although the flame protrudes upstream of the dump plane with the increase in equivalence ratio, it stays stabilized until a much higher equivalence ratio. Then the flame flashes back in the premixer.

In order to verify that the observed differences in the flame characteristics were indeed due to the modification of flow field caused by DBD actuation, flow velocity measurements were made using the CTA system. They were conducted at 1-mm downstream of the dump plane and across the combustor cross section under non-reacting flow conditions at various flow rates. Sample results are shown in Fig. 9, where the operating conditions correspond to those of stable flames of Figures 7 and 8. The mean velocity profiles show a dip at the centerline axis of the combustor. This is expected for flows exiting a contraction section and not having enough length to adopt a fully developed tubular flow, which was the scenario in the current work. The figure also shows that the velocity gradient in the near wall region increases with the application of DBD. Because the mass flow rates are held constant, the increase in velocity close to the wall is compensated by the decrease in velocity magnitude at the axis.

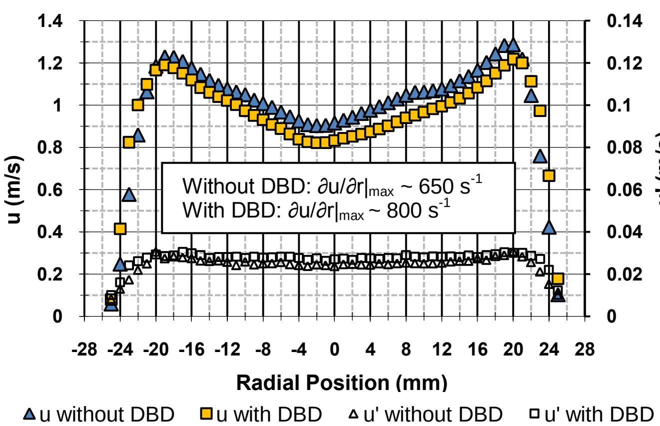

FIGURE 9: Mean and RMS velocity profiles with and without DBD. Operating conditions are corresponding to stable flame flow rates.

Fig. 10 shows mean velocity profiles for operating conditions where the average flow velocity was matched to that at flashback condition (Image (c) of Figures 7 and 8). It may be noted that because the equivalence ratio under the DBD case is significantly higher compared to that of no-DBD case, the total flow rate for the DBD case is thus lower. Nevertheless, comparison of velocity profiles shows that one of the effects of DBD actuation is to increase the velocity gradient at the wall. For the conditions of Fig. 10, this increase is from 250 s^{-1} (as measured from without-DBD profile) to 346 s^{-1}. The increase in velocity gradient, as seen in both Fig. 9 and Fig.10, provides the explanation for flame liftoff with DBD actuation (for example, compare Image (e) of Fig. 7 with Image (e) of Fig. 8, recorded under the same flow rate and equivalence ratio).

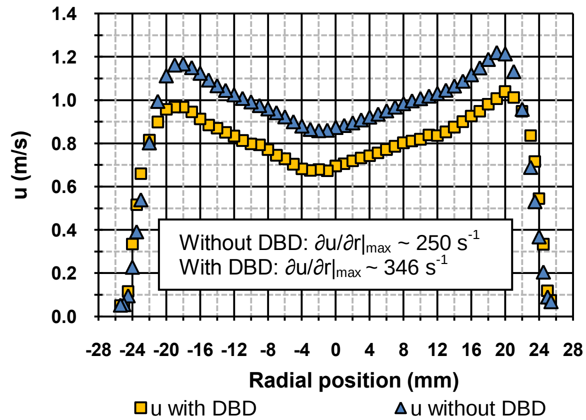

FIGURE 10: Mean velocity profiles with and without DBD. Operating conditions corresponding to flame flashback at a fuel flow rate of 0.102 g/s.

Stability Mapping

The combustor performance as encountered during the present work is mapped on the stability diagram of Fig. 11. The flashback, liftoff and blowout limits separate combustor operation in four different zones. The mapping was conducted by keeping the fuel mass flow rate constant and varying the air flow rate in discrete steps either towards flame flashback or flame liftoff and subsequent blowout. From the flashback point of view, which was the focus of the current effort, decreases in air mass flow rate translate into lower flow velocities as well as higher equivalence ratios, which in lean conditions leads to higher flame speeds [22]. Hence, in the present work, reduction of air flow rate promotes flame flashback in two different ways. This behavior corresponds to the upper region of the stability diagram. On the other hand, as the air flow rate is increased, the flow velocity rises, the equivalence ratio reduces and so does the flame speed. At a sufficiently high air flow rate, the flame starts to liftoff. This point corresponds to the liftoff limit defined by the triangles on the stability diagram. Ultimately, the flame is completely lifted off and the combustor operation is characterized by an unstable and lifted flame. This behavior is observed for operating conditions in the detached flame region of the stability diagram. When the air flow rate is increased further, the flame is pushed out of the combustion chamber and extinguishes. This condition is indicated by the blowout points (circles) on the stability diagram of Fig. 11.

The aim of the present study was to enhance the stable operation regime of the combustor by delaying the flashback limit to higher equivalence ratios through the application of DBD actuation. As shown in Fig. 11, this was accomplished for the three highest fuel flow rates. In terms of equivalence ratio, a maximum improvement of 4.6% was achieved at a fuel flow rate around 0.102 g/s and with a 19.2 kV peak-to-peak voltage at 4 kHz frequency applied to the DBD actuator. The fact that the equivalence ratio at which flashback occurs increases with the application of DBD does not only mean that it takes place at a lower air flow rate (lower by 4.2% at this fuel flow rate), it also signifies that flashback happens at a much higher flame speed. Flame speeds (S_L) calculated using data from [22] for methane are shown in Fig. 11 for some selected flashback points. For the operating point where maximum control is achieved through DBD use, the flashback occurs at a flame speed 10 % higher compared to a flame speed of 0.30 m/s under no actuation case. This implies that if the experiments were to be conducted at fixed equivalence ratio (thus at fixed flame speed) by varying the air and fuel flow rates simultaneously, the improvement of the flashback limit via DBD application in terms of total flow rate would have been even higher.

For the two lowest fuel flow rates of Fig. 11, it may be noted that the application of DBD at a voltage of 19.2 kV favors the occurrence of flashback, thus causing a shrinkage in the stable operation regime. This is due to the reduction of the axial velocity in the core flow that occurs to compensate the velocity rise near the wall when the DBD is turned on. This velocity reduction at the axis supports the core flashback under these flow conditions. However, it was found that it is very much possible to improve the flashback limit not only back to the non-actuated limit, but even beyond by tuning the strength of the induced ionic wind through the adjustment of the voltage applied to the DBD actuator. As shown in Fig. 11, reducing the excitation voltage from 19.2 kV_{p-p} to 13.2 kV_{p-p}, increased the equivalence ratio at which flashback occurs by 3.9%.

To further verify that DBD actuation was indeed preventing flashback, a flame was stabilized at a fuel flow rate of 0.102 g/s and the DBD actuator was turned on. The air flow rate was then reduced to attain an equivalence ratio mid-way between the actuated and non-actuated flashback limits on the stability diagram of Fig. 11. When the DBD actuator was turned off at this condition, the flame immediately started to propagate upstream in the premixer. The process was repeated a few times and the same result was obtained every time.

It may also be noted in Fig. 11 that DBD actuation causes flame liftoff at a much higher equivalence ratio as compared to the no-actuation case as shown for the three highest fuel flow rates. As pointed out earlier, this is due to the rise in the velocity gradient at the wall induced by the DBD. However, it was found that DBD actuation does not affect the blowout limit, as shown in Fig. 11.

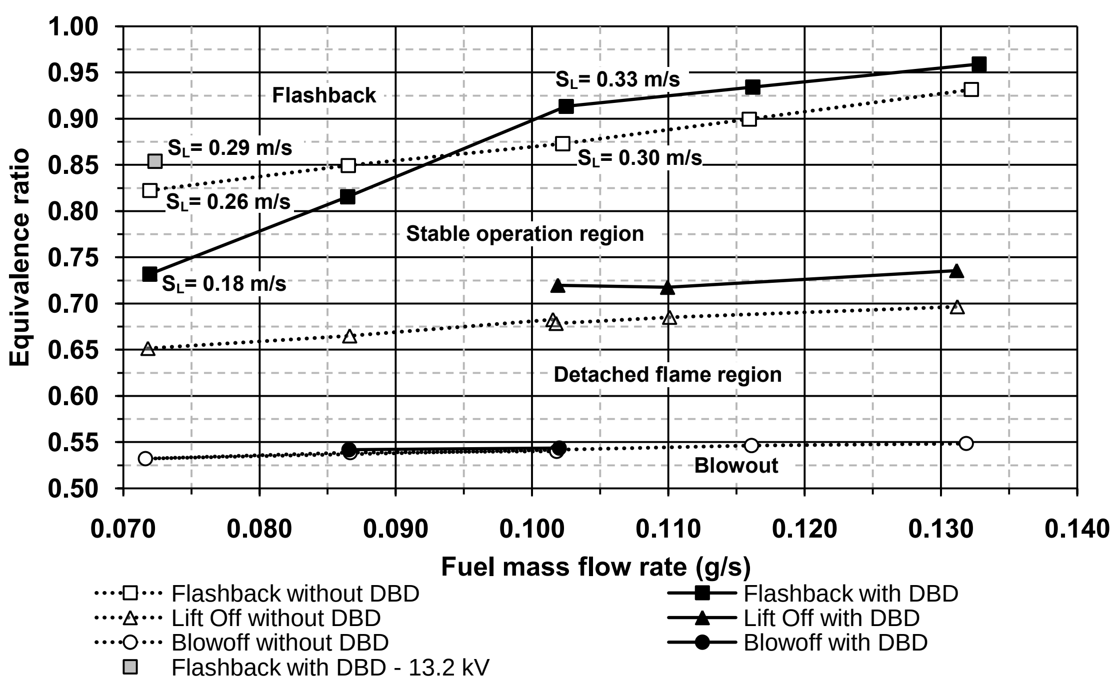

FIGURE 11: Combustor stability diagram, with and without DBD actuation. Flame speeds are also shown at a few selected data points

CONCLUSION

Details of a unique application, involving Dielectric Barrier Discharge to control flame flashback in lean-premixed combustors, have been reported in the paper. The concept was successfully demonstrated, over a range of operating conditions in a premixed atmospheric dump combustor, through a novel integration of a DBD actuator on the wall of the premixer.

Controlled flashback occurrences were generated by metering the air flow rate at a fixed fuel flow rate. It was found that in the experimental combustor, flashback happens through the core flow.

Velocity measurements conducted under non-reacting flow conditions verified that application of DBD modifies the velocity profile by displacing flow from the centerline axis towards the wall of the premixer, thus accelerating the flow near the surface. It was also found that utilization of DBD causes an increase in the velocity gradient at the premixer wall.

The present application of DBD actuation has a profound effect on the flame characteristics including the flame anchoring mechanism in the combustor, and flashback and liftoff limits.

It was found that through effective tuning of DBD operating parameters, the combustor stable operation regime may be stretched as much as 4.6% by delaying flame flashback to occur at higher equivalence ratios.

It was established that at lower flow rates a reduced excitation voltage is required to achieve the benefit of applying DBD. Otherwise the DBD favors the occurrence of flashback at much lower equivalence ratios. Also, DBD application was shown to favor the detachment of the flame from the dump plane at much lower flow rates and much higher equivalence ratios. However, the application of DBD in the present configuration does not affect the blowout limit of the combustor.

Moving forward, the proof-of-concept attempt presented here will be demonstrated on other, and more practical, combustor configurations under representative gas turbine operating conditions.

ACKNOWLEDGMENTS

This work was sponsored by the National Research Council (NRC) Canada and by the Natural Sciences and Engineering Research Council of Canada (NSERC) through a Postgraduate Scholarship. Contributions from these institutions are gratefully acknowledged.

The authors also want to express their gratitude to the NRC staff for providing support during the project. In particular, special thanks go to Michael Player for his daily devotion to the research, to Derek Winfield, David Carey and Wayne Boland for assistance in rig fabrication, and to Dr. Ian Campbell for his valuable advice.

REFERENCES

[1] Kuo, K. K., 2005, *Principles of Combustion. 2nd edition*, John Wiley & Sons, Hoboken, Chap, 1, 3 & 6.

[2] Schäfer, O., Koch, R. and Wittig, S., 2003, "Flashback in Lean Prevaporized Premixed Combustion: Non-swirling Turbulent Pipe Flow Study", Journal of Engineering for Gas Turbines and Power, **125**(3), pp. 670-676.

[3] Davu, D., Franco, R. and Choudhuri, A., 2005, "Investigation on Flashback propensity of Syngas Premixed", AIAA 2005-3585, *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, Tucson, Arizona, pp. 1-11.

[4] Lieuwen, T., 2008, "Flashback Characteristics of Syngas-Type Fuels Under Steady and Pulsating Conditions", DE-FG26-04NT42176, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, pp. 1-41.

[5] Lefebvre, A. H. and Ballal, D. R., 2010, *Gas Turbine Combustion: Alternative Fuels and Emissions*, CRC Press, Boca Raton, Chap.2.

[6] Lieuwen, T., McDonell, V., Santavicca, D., and Sattelmayer, T., 2008, "Burner Development and Operability Issues Associated with Steady Flowing Syngas Fired Combustors", Combustion Science and Technology, **180**(6), pp. 1169-1192.

[7] Lewis, B. and von Elbe, G., 1961, *Combustion, Flames and Explosions of Gases*, Academic Press, New York.

[8] Burton, F., 1959, "Effect of Initial Temperature on Flash Back of Laminar and Turbulent Burner Flames", Industrial & Engineering Chemistry, **51**(4), pp. 564-566.

[9] Plee, S. L. and Mellor, A. M., 1978, "Review of Flashback Reported in Prevaporizing/Premixing Combustors", Combustion and Flame, **32**, pp. 193-203.

[10] Wohl, K., 1952, "Quenching, Flash-back, Blow-off - Theory and Experiments", *4th International Symposium on Combustion*, Pittsburgh, Pennsylvania, pp. 69-89.

[11] Laurentie, J.-C., Jolibois, J. and Moreau, E., 2009, "Surface dielectric barrier discharge: Effect of encapsulation of the grounded electrode on the electromechanical characteristics of the plasma actuator", Journal of

Electrostatics, **67**, pp. 93-98.

[12] Jacob, J., Rivir, R., Carter, C., and Estevadeordal, J., 2004, "Boundary Layer Flow Control Using AC Discharge Plasma Actuators", AIAA 2004-2128, *AIAA 2nd Flow Control Meeting*, Portland, Oregon.

[13] Thomas, F. O., Corke, T. C., Iqbal, M., Kozlov, A., and Schatzman, D., 2009, "Optimization of Dielectric Barrier Discharge Plasma Actuators for Active Aerodynamic Flow Control", AIAA Journal, **47**(9), pp. 2169-2178.

[14] De Zilwaa, S. R. N., Khezzarb, L. and Whitelaw, J.H., 2000, "Flows through plane sudden-expansions", International Journal for Numerical Methods in Fluids, **32**, pp. 313–329.

[15] Roth, J. R. and Dai, X., 2006, "Optimization of the Aerodynamic Plasma Actuator as a Electrohydrodynamic (EHD) Electrical Device", *44th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, pp. 1-28.

[16] Versailles, P., Ghosh, S., Vo, H. D., and Masson, C., 2010, "Preliminary Assessment of Wind Turbine Blade Lift Control via Plasma Actuation", Submitted for publication in Wind Engineering.

[17] Mureithi, N.W., Rodriguez, M., Versailles, P., Pham, A., and Vo, H. D., 2008, "A POD based analysis of the 2D cylinder wake mode interactions", *9th Internal Conference on FIV*, Prague, Czech Republic, pp. 1-6.

[18] Grundmann, S. and Tropea, C., 2007, "Experimental transition delay using glow-discharge plasma actuators", Experiments in Fluids, **42**(4), pp. 653-657.

[19] Starikovskii, A. Y., 2005, "Plasma Supported Combustion", Proceedings of the Combustion Institute, **30**(2), pp. 2405-2417.

[20] Rosocha, L. A., Coates, D. M., Platts, D., and Stange, S., 2004, "Plasma-enhanced combustion of propane using a silent discharge", Physics of Plasma, **11,** 7 pages.

[21] Cha, M.S., Lee, S.M., Kim, K.T., and Chung, S.H., 2005, "Soot suppression by nonthermal plasma in coflow jet diffusion flames using a dielectric barrier discharge", Combustion and Flame , **141**, pp. 438–447.

[22] Vagelopoulos, C.M. and Egolfopoulos, F.N., 1998, "Direct Experimental Determination of Laminar Flame Speeds", *Twenty-Seventh Symposium (International) on Combustion*, **27**(1), pp. 513-519.

