

Role of Swirl in Flame Stabilization

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Abstract This paper first reviews recent ideas that explain why swirl has a strong stabilizing effect on a flame. Then some measurements are discussed that were obtained using a complex gas turbine fuel injector/mixer operated at realistic levels of swirl and multiple recirculation zones. While swirl is known to have several beneficial effects that improve the mixing and flame stabilization within a gas turbine combustor, swirl also can lead to some undesirable effects. A precessing vortex core can be a source that drives a combustion instability. In addition, swirl affects the unsteady anchoring location of a flame, which also can lead to combustion instabilities, as are observed in our experiment. Interactions between the recirculation zones are observed. The observed large scale unsteady motions cause serious problems for CFD simulations, since the measured mean velocities and turbulence levels on the combustor centerline are much larger than the computed values. Reasons for this difference are associated with unsteady motions.

Introduction

Despite many years of research, it still is not possible to use CFD simulations to accurately predict the liftoff heights and blowout limits of most types of turbulent flames. This is because the base of an initially non-premixed flame usually has a triple flame structure; it consists of a lean premixed flame, a rich premixed flame, and a downstream non-premixed flame. To successfully predict the flame stabilization physics, a simulation must properly model the propagation speed of the triple flame and insure that it is located at the proper position where its propagation speed equals the incident flow velocity at that point. Turbulence at the flame base also will enhance the flame speed. Simulating this flame base structure remains a challenge. To avoid the flame stabilization problem, the Sandia jet flame D, for example, is operated with a pilot flame that anchors the flame base to the fuel injector. Measurements and simulations then can be compared without requiring complex study of the flame base. However if the pilot is turned off and the flame is allowed to lift, current models usually fail to predict the liftoff heights, blowout limits and other flame properties.

To better understand and model gas turbine combustors, the complications associated with swirl must be considered. Swirl stabilized flames always are lifted a few millimeters above the fuel injector, and this liftoff allows air to mix with fuel upstream of the flame base. The swirl results in improved

flame stabilization, improved mixing, shorter, more compact flames, and reduced nitric oxides. However, even if the flame appears to be stable and is far from the blowout limit, it may undergo high-speed periodic flame motions that require high speed diagnostics to detect. It is shown that this periodic motion (in the present experiment) is due to periodic flame liftoff and flashback, which can lead to a combustion instability. Other periodic motions are associated with a precessing vortex core. Thus flame stability, combustion instabilities and swirl are coupled phenomena.

The primary role of swirl is to create an internal recirculation zone, which creates low velocity regions where the flame can anchor. The recirculation zone also mixes hot products into the reactants upstream of the lifted flame base. The flame base is a triple flame that contains portions that propagate upstream as a stratified premixed flame. The recirculation zone created by swirl causes hot products to be mixed into the reactants, and the resulting flame speed is increased. The recirculation zone also increases the level of turbulence, which also increases the flame speed. Figure 1 illustrates the mean velocity field that was measured downstream of a commercial gas turbine fuel injector / mixer [1, 2]. As shown in Fig. 2, swirl is added by three sets of swirl vanes. The flow near the centerline passes through two annular pilot flame passages while the main flow enters through annular passage that is far from the centerline.

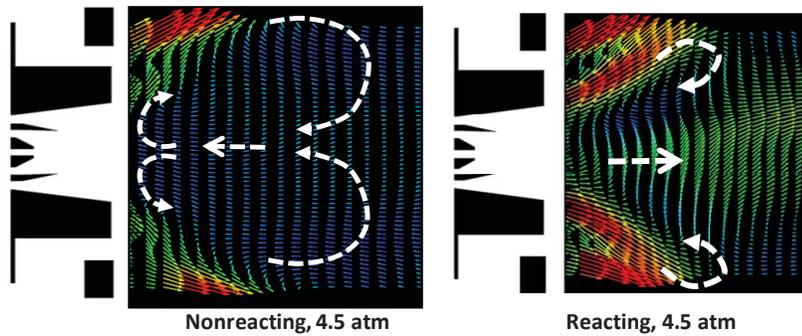


Figure 1. Velocity field measured downstream of a multi-swirling gas turbine fuel injector / mixer [1].

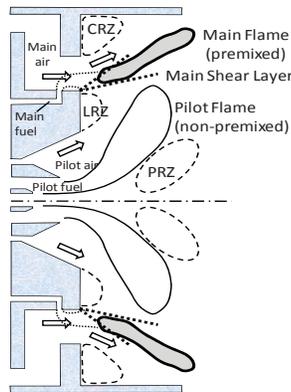


Figure 2. Schematic of the commercial LPP fuel injector / mixer of Refs. 1 and 2.

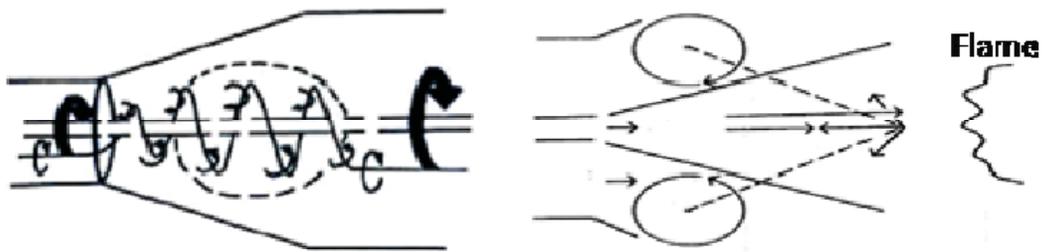


Figure 3. Schematics showing how swirl creates a recirculation zone (Batchelor [3]), and how the recirculation zone induces a negative velocity on a central jet, which reduces its velocity [10].

The physical reason why swirl creates an internal recirculation zone has been described by Batchelor [3]. As seen in Figure 3 the swirling flow that enters has a vorticity vector that points in the axial (x) direction. A recirculation zone contains vorticity vectors that point in the aximuthal (θ) direction. There is no additional source of vorticity in this problem, so the vorticity transport equation states that the only way to create a recirculation zone is to convert some of the axial vorticity into azimuthal vorticity. This is accomplished by the diverging side walls. Each fluid element follows the helical path seen in Fig. 3, and as the radius of this helical path increases (due to sidewall divergence) the direction of the vorticity vector is altered such that its axial component is decreased and its azimuthal component increases. Batchelor [3] describes the details of how a recirculation zone thus is formed.

While a recirculation zone does add complexity to the flow field, the basic flame stabilization process still can be understood by considering the simple “unit-physics” problem of a flame in a shear layer, which is shown in Fig. 4. The fuel and air are initially premixed, but the flame base is lifted so there must exist a stoichiometric contour between the fuel and air streams. The flame in Fig. 4 exists in a shear layer that has higher speed air on the radially outward side and lower speed fuel and products on the radially inward side. The temperature of the stratified premixed reactant mixture in the liftoff region depends on how much of the product gas is recirculated. This gas temperature is important since the burning velocity of the flame base is greatly enhanced if the reactant temperature is increased. Using the concept of a shear layer is useful, but one difficult task that remains is determining the boundary conditions (the gas velocity and temperature on the fuel/product side, and on the air side of the shear layer).

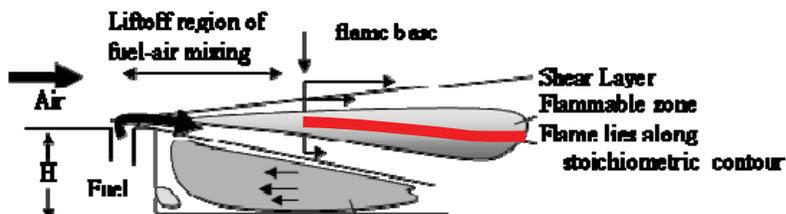


Figure 4. Schematic of a triple flame stabilized in a shear layer, such as the shear layer created by the recirculation zone due to swirl.

Figure 5 illustrates the basic flame stabilization concept [4]. The curve marked $U_s(x)$ is the gas velocity along the stoichiometric contour in the shear layer. This curve indicates that $U_s(x)$ decreases in the axial (x) direction. Consider the curve marked $S_{\text{base},1}$; it is the burning velocity of the flame base for a mass flow rate of fuel that is called condition 1. The curve indicates that $S_{\text{base},1}$ does not vary much in the x direction until x exceeds the length of the recirculation zone, where $S_{\text{base},1}$ drops rapidly. If a flame lifts to a position that is downstream of the recirculation zone, hot products may not preheat the reactants so the burning velocity may decrease. Vanquickenborne and van Tiggelen [5] proposed that the lifted base is a premixed flame and the equilibrium requirement is that the incident gas velocity is matched to the burning velocity of the flame base:

$$U_s = S_{\text{base}} \quad (1)$$

This condition is met in the graph shown in Fig. 5 where the curve $S_{\text{base},1}$ intersects the curve $U_s(x)$. The x location where this condition is satisfied is marked as the flame liftoff height h_1 . A second requirement is that the flame remain stable, and this requires that:

$$dS_{\text{base}}/dx > dU_s/dx \quad (2)$$

The relation in Eq. (2) is valid for the curves drawn in Fig. 5. Note that at location $x = h_1$ the quantity dU_s/dx is negative and the quantity dS_{base}/dx is nearly zero. Consider the case of the flame being perturbed to move to a downstream location for which x is slightly larger than h_1 . Fig. 5 indicates that at that new location S_b will exceed U_s , so the flame base will propagate back upstream to its equilibrium location at $x = h_1$. This is a stable situation. Similarly, if Eq. 2 does not hold, a small perturbation that moves the flame base downstream will force the flame to move farther downstream until it blows out.

Figure 4 also shows that if the mass flow rate of the fuel is increased, the flame lifts off until the rich limit blowout occurs. Increased fuel flow rate forces more cold fuel into the recirculation zone which reduces the temperature of the hot products that mix with the reactants. The curve marked $S_{\text{base},2}$ is the new burning velocity of the flame base and it lies below the curve marked $S_{\text{base},1}$. The equilibrium liftoff height given by Eq. 2 is seen to move downstream to location h_2 . When h exceeds the length of the recirculation zone, rich blowout occurs.

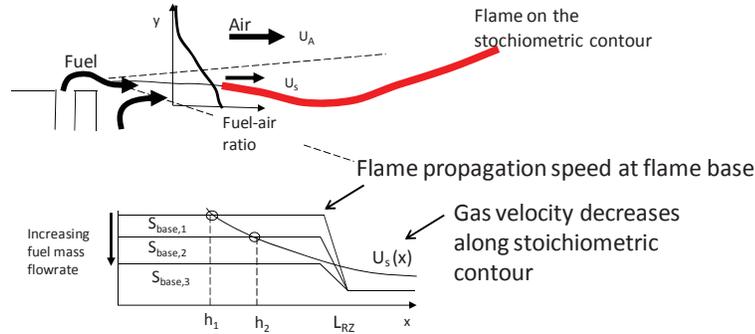


Figure 5. Schematic of how the velocity of the flame base and the gas velocity at the flame base vary as the fuel mass flow rate is increased.

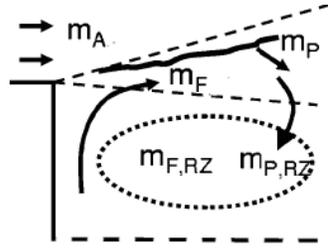


Figure 6. Major unknowns that control flame stabilization: the mass flow rates of air that enter the shear layer on the radially outward side, and the mass flow rates of fuel and products that enter the shear layer from the recirculation zone on the radially inward side of the shear layer.

Turbulence intensity theory

To model the burning velocity of the flame base (S_{base}) several theories have been proposed. Kalghatgi [6] assumed that the intensity of the turbulence controls the propagation speed of the base. He assumed that the base propagates with a turbulent burning velocity that is proportional to the square root of the local velocity fluctuations (u'). He assumed that the mean and fluctuating velocities are those of a non-reacting turbulent jet, so the effect of the flame on the flowfield was neglected. Kalghatgi's analysis predicts the following relation for the liftoff height h :

$$h = c_1 U_F / (S_L^2 / \alpha) \quad (3)$$

U_F is the exit velocity of the fuel jet, $(S_L)^2/\alpha$ is the characteristic chemical reaction rate. The thermal diffusivity is α and S_L is the stoichiometric unstretched laminar burning velocity.

Edge-flame theory

The idea that the lifted flame base is an "edge flame" has been proposed by Buckmaster and Weber [7] and others; some relevant measurements appear in Ref. 11. Figure 7 is a schematic of the images of the lifted flames reported by Watson et al. [8]. The reaction layer normally is nearly parallel to the incident stream and the parabola shown represents the 600 K isotherm. The flow field is disturbed by the edge flame and these disturbances can be important for the following reason. If the flow remained self-similar (and the mean values of mixture fraction and U/U_F were equal everywhere) then the mean gas velocity would be constant along the mean stoichiometric contour from the base to the tip. This concept would contradict the idea that increasing the jet velocity forces the lifted flame base to move to a lower velocity region downstream. Therefore several theories assume that the deviations from self similarity caused by an edge flame govern the liftoff location.

One promising concept is that the strain rate on the edge flame is larger if the base is located farther upstream. This larger strain rate is assumed to reduce the burning velocity of the base, so the base must move downstream to find a lower strain location to meet the condition of Eq. 1. Thus it has been assumed that:

$$S_{base}/S_{L,0} = 1 - Ma (U_s/x)/(S_{L,0}/\alpha) \quad (4)$$

When Eq. 4 is combined with Eq. 1, and x is set equal to the liftoff height h , then a relation similar to the measured result (Eq. 3) results. Ma is the stoichiometric Markstein number, which is an empirical constant for a given fuel and oxidizer combination.

Another idea is that the effective propagation speed of an edge flame can be enhanced by the divergence of the streamlines associated with heat release, as seen in Fig. 7. At location B the equilibrium condition is Eq. 1. At location P, the equilibrium criterion is that the effective propagation speed of the entire edge flame is equal to the undisturbed gas velocity at point P. There can be a large change in the gas velocity between points P and B. Thus the local flame base only has to propagate against the relatively low gas velocity at point B, while the overall flame base effectively propagates against the larger velocity at point P. Therefore the effective propagation speed of an edge flame is enhanced by streamline divergence. The edge flame helps to stabilize itself by decelerating the oncoming flow, so it only has to propagate against a reduced gas velocity.

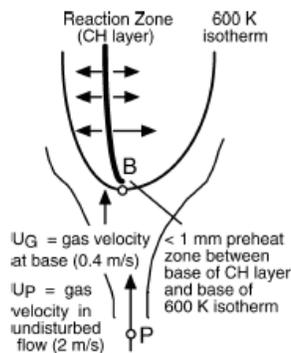


Figure 7. Schematic of a triple flame (also called an “edge” flame at the base of a lifted non-premixed turbulent flame).

Enhanced Flame Stabilization due to Swirl

When a fuel jet is surrounded by a coaxial stream of air, the resulting flame will be made much shorter due to the fact that air is forced into the fuel jet. The coaxial air creates a shear layer and the air flow rate that enters the shear layer exceeds the air flow rate that would be entrained into the jet if there was no coaxial air. However, the flame will be made less stable due to the coaxial air stream, if there is no swirl added to the air stream. Blowout limit measurements in Refs. [9, 10] appear in Fig. 8. The curves on the left are for no swirl; the horizontal axis is the coaxial air velocity. The vertical axis is proportional to the fuel velocity at blowout. If there is no coaxial air, the simple jet flame blows out at a fuel velocity associated with the location where the upper portion of the curves on the left intercept the vertical axis. Adding coaxial air cause all of the curves on the left to have a negative slope near the y-axis intercept. This means that coaxial air in all cases is destabilizing, if there is no swirl. Each of these blowout curves has the shape of a parabola; the stable conditions lie inside the parabola while the upper boundary of the parabola is the rich blowout limit. The lower boundary is the lean limit.

The physical reason why coaxial air (with no swirl) is destabilizing is explained by Eq. 1. Consider the radial profile of the gas velocity near the jet exit. With no coaxial air the velocity profile has

the shape of a Gaussian curve. The flame is located near the stoichiometric contour and the stoichiometric mixture fraction typically is a small number; for methane-air it is 0.055. Thus the flame will be located at a large radial location that is far from centerline where the local axial velocity is very low. When even a small amount of coaxial air is added, it superimposes a gas velocity on this local axial velocity which may double or triple its value, leading to severe liftoff and possible blowout.

When swirl is added to the coaxial air the flame stability is enhanced, as is documented by the measured blowout limits are seen on the right side of Fig. 8. For low values of coaxial air velocity, blowout is seen to occur for a fuel velocity of 40 m/s. If sufficient swirl is added, the curves in this plot have a positive slope and they extend upward to fuel velocities that greatly exceed 40 m/s. More measurements appear in Fig. 9. These plots quantify the enhanced values of the fuel velocity that can be achieved without blowing out the flame, if sufficient swirl is added to the coaxial air stream. The stable region inside the peninsula-shaped curves Fig. 9 indicates that there is both a rich and a lean blowout limit. The rich limit is the upper boundary while the lean limit is the lower boundary.

The reasons for the shapes of the blowout curves have been discussed by Dahm and Mayman [9] for the zero swirl case, and by Feikema et al. [10] for the case of swirl. The basis concept is believed to be that an edge flame must follow the requirements of Eqs. 1, 2 and 4. However, it remains difficult to quantify the burning velocity of the flame base, the local gas velocity just ahead of the flame base, the strain rate on the flame, and the role of turbulence.

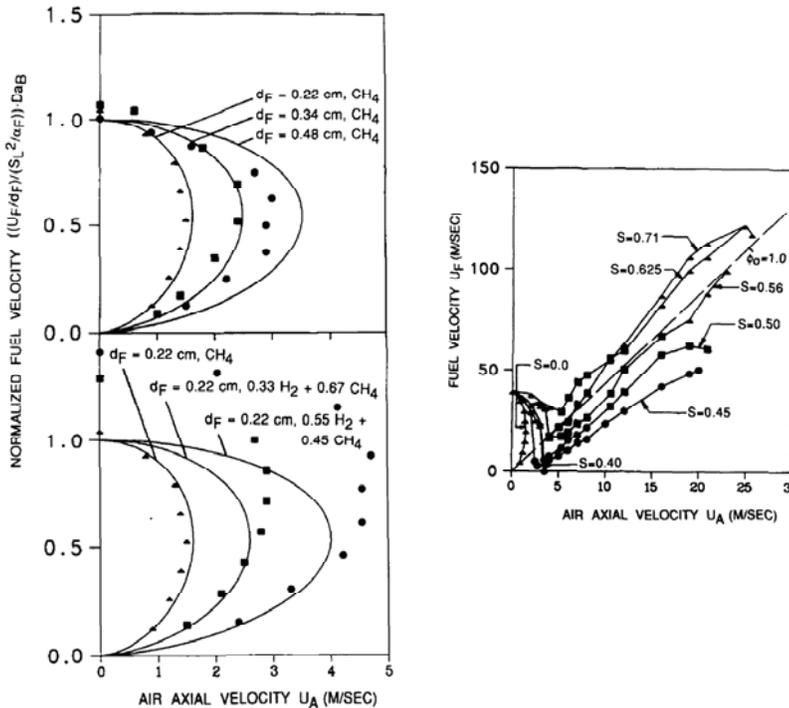


Figure 8. Measured flame blowout limits for a fuel jet surrounded by coaxial air [10]. Left side: no swirl, right side: with swirl.

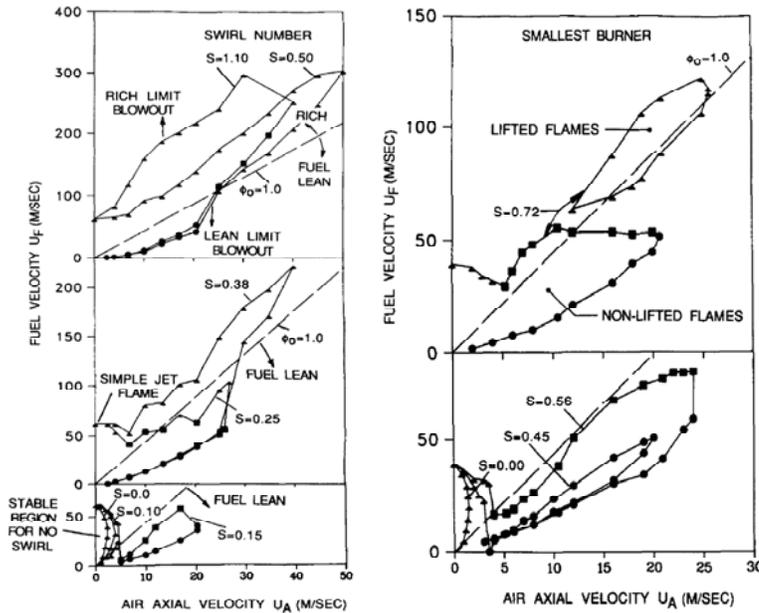


Figure 9. More measurements [10] showing that swirl greatly enhances the flame blowout limits.

Role of Swirl in Combustion Instabilities

Unsteady motions are caused by swirl and they have been found to drive certain combustion instabilities in gas turbine combustors. Measurements in Refs. 1 and 2 quantify the role of swirl. Figure 10 shows that the time-averaged velocity field with combustion is very symmetric but it displays one surprising feature: the axial velocity is positive all along the centerline. This is not consistent with the non-reacting flow velocity field that was shown in Fig. 1 above for the same operating conditions and geometry. In the non-reacting case the axial velocity is negative all along the centerline, as would be expected with a stable central recirculation zone. The reason for the difference is shown on the right of Fig. 10. At any one instant, the recirculation zone is not symmetric about the centerline but at this instant the portion of the recirculation zone that is above the centerline is much larger than the portion below centerline. Both regions are displaced downward. This means that on the centerline at this instant, the axial velocity is positive. This explains why the mean velocity is positive in Fig. 10 on the centerline. The fluid mechanical center of the recirculation zone, which contains negative axial velocities, is infrequently located on the geometric centerline. This is due to the precession of the vortex core.

Another surprising measurement is shown in Fig. 11. The locations of large turbulence intensity (red) are confined to two regions; the slanted upstream red region is the shear layer where large turbulence levels are expected. However, large turbulence levels also were measured along the centerline. This is not expected because the axial velocities are expected to be low and the turbulence levels are expected to be nearly zero deep within the recirculation zone. However, the instantaneous image on the right side of Fig. 10 offers the explanation. The asymmetric recirculation zone oscillates such that at times its fluid dynamic center is far above the geometric centerline, while at other times it is far below, as seen in Fig. 10. These oscillations lead to large variations in the axial velocity on the

centerline, and thus large value of r.m.s. velocity fluctuations are observed. It is clear that these oscillations of the recirculation zone present problems for standard CFD models. To simulate the measured velocity field, the CFD simulation must accurately reproduce the unsteady motions and precessing vortex core.

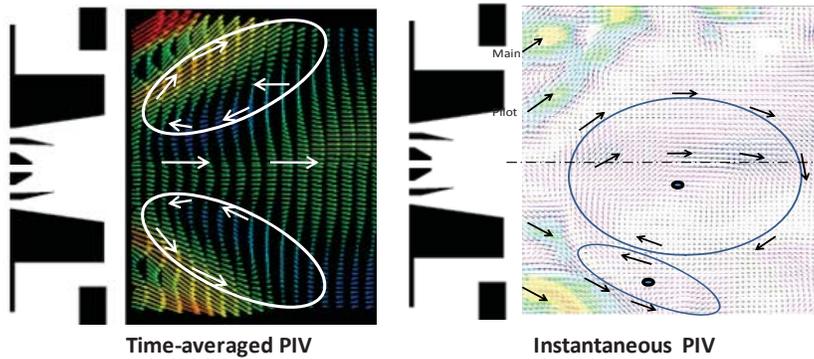


Figure 10. PIV measurements downstream of a commercial LPP gas turbine fuel injector / mixer [1]. Left side: time averaged velocity; right side one instantaneous velocity field, showing large asymmetries due to the precessing vortex core.

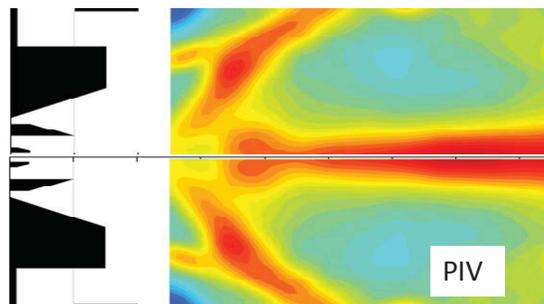


Figure 11. Turbulence levels measured downstream of a commercial LPP gas turbine fuel injector / mixer [1]. Large turbulence levels on centerline are due to the precessing vortex core.

Since the above figures indicated that the recirculation zone undergoes large periodic oscillations, it is not surprising that the flame also undergoes periodic oscillations. Thus the swirling flow helps to drive the observed combustion instabilities. Figure 12 shows that the flame size and luminosity varies in a very periodic manner in the experiment described in Refs. 1 and 2. The central pilot flame remain attached and its location does not vary significantly. The outer Main flame is fed from outer annular air and fuel streams that are separate from the inner pilot streams. The Main flame is periodically lifting off, partially extinguishing, re-igniting, and then flashing back into the reactants that have filled the space where it used to be located. This creates local mini-explosions that periodically raise the pressure by 1-2 psi. Figure 13 indicates the first the flame becomes more luminous, then a short time later the pressure in the combustion chamber rises due to the “mini-explosion” caused by flashback.

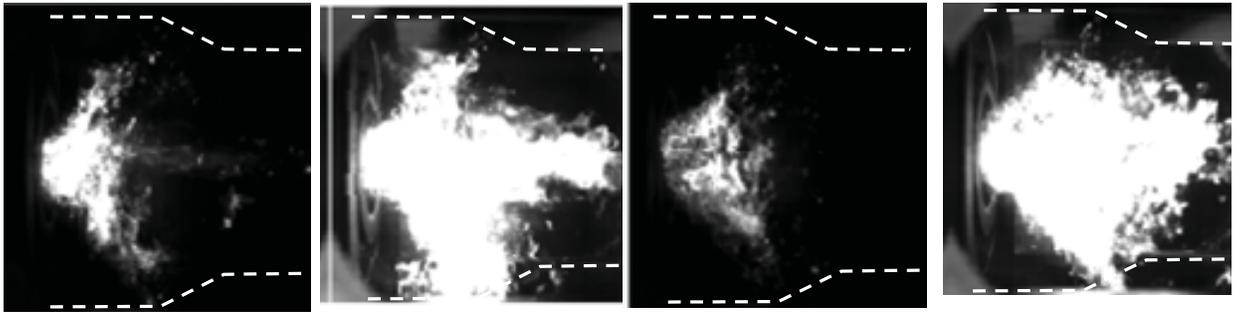


Figure 12. Combustion instability observed in the LPP combustor of Ref. 2, due to unsteady flame anchoring of the Main flame. Main flame is observed to blow downstream then flash back upstream in a very periodic manner.

The combustion instability results in the flame motion seen in Figs. 12 and 13; this indicates that flame stability plays an important role in creating the pressure oscillations associated with combustion instabilities. That is, if the base of the gas turbine flame can be securely anchored, then the periodic flow motions due to swirl and the precessing vortex core would not lead to the violent flame motions seen in Fig. 12. More research is needed to determine if the motion of the flame base (associated with periodic liftoff and flashback) plays a dominant role in many types of combustion instabilities. In previous theories it has been assumed that the flame base is securely anchored, but that the length of the heat release zone varies in a periodic manner. This assumption is contradicted by the observations in Refs. 1 and 2.

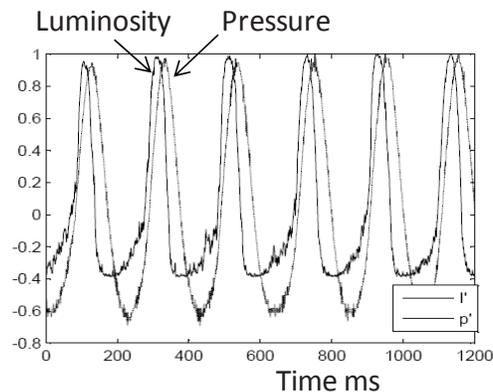


Figure 13. Pressure and flame luminosity oscillations in the gas turbine experiment of Refs. 1 and 2.

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