Studies of the Precessing Vortex Core in Swirling Flows

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ABSTRACT

Large scale coherent structures play an important role in the behavior of the combustion regime inside any type of combustor stabilized by swirl, with special impact on factors such as flame stability, blow off, emissions and the occurrence of thermo-acoustic oscillations. Lean premixed combustion is widely used and is known to impact many of these factors, causing complex interrelationships with any coherent structure formed. Despite the extensive experimentation in this matter, the above phenomena are poorly understood. Numerical simulations have been used to try to explain the development of different regimes, but their extremely complex nature and lack of time dependent validation show varied and debatable results. The precessing vortex core (PVC) is a well-known coherent structure whose development, intensity and occurrence has not been well documented. This paper thus adopts an experimental approach to characterize the PVC in a simple swirl burner under combustion conditions so as to reveal the effects of swirl and other variables on the latter. Aided by a high speed photography (HSP) system, the recognition and extent of several different types of PVCs were observed and discussed.

Keywords: swirling flows, PVC, high speed photography

RESUMEN

Las estructuras coherentes de larga escala juegan un importante papel en el comportamiento de la combustión dentro de cualquier quemador estabilizado por arremolinamiento, impactando especialmente en factores como la estabilidad y extinción de la flama, emisiones y la aparición de oscilaciones termo-acústicas. La combustión en estado pobre es ampliamente utilizada y es sabido que impacta también en estos factores, causando una compleja interrelación con las estructuras que se forman. A pesar del extensivo trabajo experimental en el campo, el fenómeno antes mencionado no es completamente entendido. Se han utilizado simulaciones numéricas para explicar el desarrollo de diferentes regímenes, pero su extremamente compleja naturaleza y la falta de validación temporal han llevado a grandes debates en el campo. El centro de vórtice precesor (CVP) es una estructura coherente bien conocida cuyo desarrollo, intensidad y ocurrencia no se han documentado completamente. Por ello, este artículo adopta una aproximación experimental para caracterizar al CVP en un quemador sencillo bajo condiciones de combustión que revelen el efecto de arremolinamiento así como otras variables. Se llevó a cabo el reconocimiento de muchos diferentes tipos de CVP con la ayuda de un sistema de fotografía de alta velocidad.

1. Introduction

Swirl stabilized combustion is very widely used. More than 50% of all fossil fuels are burned in combustors or burners in some way stabilized by swirl. The important characteristics are extremely good mixing, good flame stability from the formation of the well-known central recirculation zone, and the potential for low emissions, especially when operated under lean conditions [1-2]. Moreover, the shear flow leaving the burner avoids direct contact with the high-temperature flame within the combustor, which increases the life expectancy of the equipment. These flows have been studied by many for decades [1-3]. Other authors such as Vanoverberghe [4] and Coghe et al. [5] have demonstrated the reduction of emissions by increasing the swirl, producing flames stabilized by the surrounding structures, such as inner and outer recirculation zones formed as a consequence of the dynamics of the swirling mechanism. However, the structures that drive

these systems are only inferred in these studies or studied partially, without full knowledge of their interaction and coexistence. Valera-Medina [6] suggests a complex panorama based on air flow rates, geometries, Reynolds number and equivalence ratio, which are discussed herein.

Large scale coherent structures play an important role in combustion and the heat release process by controlling the mixing in nonpremixed and premixed flames [7]. The most important contribution to the turbulent momentum transport and considerable mass and heat transfer are attributed to large coherent structures, making them a very important parameter in engineering applications [8]. Geometry and flow regimes are fundamental parameters in the control of such flows [9-10] since the structures inherent in the field are a manifestation of pressure decay and velocity changes. However, not only complex geometries but variation in wall surfaces can increase the number of modes in a certain regime, augmenting the structures in the flow [8]. Reynolds number and the Vortex breakdown phenomena are also important as these precede the initial formation of the central recirculation zone (CRZ) [1, 11-12].

According to Bradley et al. [13], instabilities in swirl combustors are explained as a periodic extinction of the flame produced in the outer recirculation zone by fluctuations in the stretch factor due to periodic vortex shedding in this area. Lee et al. [14] observed a high correlation between heat release and pressure fluctuation in the recirculation zones of their system, confirming their importance in the combustion mechanism. O'Doherty et al. [15] suggested that the appearance of vortices such as the precessing vortex core (PVC) improve the mixing because of the creation of larger turbulent scales which translate through into the dissipation range of the energy cascade. Recent studies performed by Bouremel et al. [16] attribute the excellent mixing to the interaction between large structures, especially on their boundaries where the major exchange of mass and energy occurs.

System instabilities are well known to be linked to pressure fluctuations, heat release, strength of swirl [17], and large coherent structures [2, 18-19]. These researchers have shown the effect of the above-mentioned factors on emissions and the damaging coupling of such phenomena with natural frequencies of the combustor [20]. Better understanding of the phenomenon involved in the appearance of large coherent structures and interaction with other variables and phenomena would clearly be of benefit in the evolution of combustion systems.

Swirling flows have been studied with an especial emphasis on their three-dimensional characteristics and methodology for flame holding [6, 10, 21]. During combustion, these flows are capable of recycling hot chemically active reactants in the CRZ to enable excellent flame stability to be achieved coupled with wide stability limits for diverse fuels [3, 18-19, 22]. Combustion may also occur in and around these structures [3] causing fundamental changes of flame stabilization mechanisms owing to changes in length scales, turbulent flame speed, flame stretch and other related parameters. Simultaneously or alone, combustion may occur in flame fronts which engulf these coherent structures again giving rise to different flame stabilization mechanisms [1]. Combustion may also suppress some time-dependent coherent structures, although evidence is that acoustic coupling may well re-introduce them [3].

According to Lafay et al. [18], the intensity of combustion has a low impact on the mean flow structure characteristics. This conclusion was based on the radius of the inner central recirculation zone (CRZ), which at different equivalence ratios did not show variations in shape; however, this was only carried out via a two-dimensional analysis. On the other hand, Valera-Medina et al. [21] and Syred [3] found that the process of combustion distorts the entire field, creating highly three-dimensional flows which need to be interpreted differently.

Numerical simulation has been used to attempt to explain the complex interactions between large swirling flow, coherent structures, and indeed combustion [23-27]. Despite some successes, the results obtained for more intricate cases with high flow rates, high swirl, and involving combustion leave much to be desired [28-29].

Special systems that use high swirl numbers require extensive and expensive experimentation for optimization. Here, a relatively simple swirl

burner is used to characterize some coherent structures which arise from the process.

The swirl number (S) and Reynolds number (Re) are commonly used for characterization purposes [1-2]. In this work a geometrical swirl number has been used as follows:

$$S_g = \frac{\pi \cdot r_e \cdot r_i}{A_\varepsilon} \qquad (1)$$

where S_g is the geometrical swirl number defined in the text [-], A_e is the inlet area [m²], r_e is the exit radius of the burner [m] and r_i is the radius upon which the tangential inlet jets fire [m].

Combustion located downstream of the tangential inlets does not significantly affect the axial flux of the angular momentum but alters significantly the axial flux of the axial momentum [1-2]. However, a simpler approach using the isothermal swirl number is used in this work.

Syred and Beer [2] first identified the PVC structure in swirl burners. It appeared after the vortex breakdown and was highly correlated to the strength and position of the CRZ [30]. Even though the coexistence between structures is clear and the superimposition is affected by their relative position in the field, the mechanism of manifestation of the phenomena is unclear. Studies using bubbles with isothermal flow [31] have suggested that the structure survives in very turbulent fields as a consequence of the stretching of the inner vortex whose reactive expansion maintains the cycle and quasi-stability of the core. Lieuwen et al. [19] suggested that it is the mere alignment between small vortices that form the main vortex core, precessing as a consequence of the interaction with the surrounding flow. Valera-Medina et al. [21] found that the PVC and CRZ are interconnected, with the PVC developing from the irregularities in the three-dimensional structure of the CRZ.

Realizing the importance of large scale structures such as PVCs, in this paper an experimental approach is used to increase the knowledge on the behavior of this structure to provide benchmarking for numerical simulation whilst providing explanations for many of the flow structures found by others.

2. Setup

Experiments were performed in a 100kW steel version of a 2MW swirl burner under combustion conditions. Two tangential inlets were used together with variable width inserts in order to change the swirl number for each case. Three different inserts were utilized during the procedure, blocking 50%, 25% and 0% (i.e. no insert) of the total transversal area of the inlets. In the text these are referred to as (50-50), i.e., each inlet had an insert reducing its width by 50%, similarly (25-25), (50-0), etc. The system was fed by a centrifugal fan providing air flow via flexible hoses and two banks of rotameters for flow rate control. Another bank of rotameters measured the flowrate of natural gas. The inclusion of a stainless steel mirror allowed the radial-tangential visualization of the system when flames were present. The mirror was positioned 0.5m from the outlet to avoid deformation. Figure 1 shows details of the swirl burner. Figure 2 shows details of the apparatus.
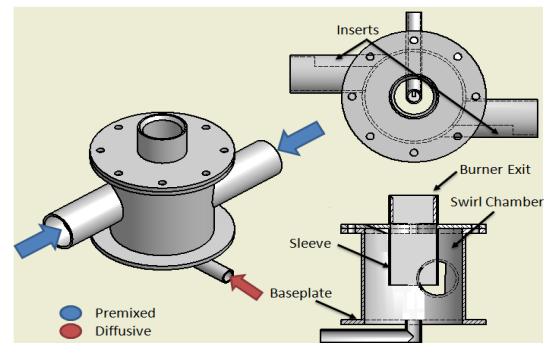

Figure 1. Details of swirl burner.

Figure 2. Burner mounted on a rig with a mirror to view the tangential radial plane.

Natural gas was used as fuel. Two different modes of fuel injection were utilized, a nonpremixed mode with fuel injected along the central axis from the burner bottom, and a premixed mode with injectors extending across the tangential inlets, located 0.01m upstream before the burner casing.

Pressure measurements and oscillation characterization was made via a water-cooled EM-1 Yoga Electret condenser microphone, with a frequency response of 20 Hz-16 kHz and sensitivity of -64±3 dB. The microphone was mounted on the wall of the burner next to the exit. Its resolution allowed the determination of high pressure peaks attributed to the existence of a banana-shaped high momentum region in the shear flow linked to the PVC [21]. The final signal was analyzed using a Tektronic DS2024B oscilloscope at 2Gsamples/s, 200MHz and four channels.

A Fastcam APX RS high speed camera operating at 4000 frames/s was used with a 105mm, 1:2.8 Nikon lens to characterize the PVC in the known 100-200Hz range [4, 6]. The resulting images were analyzed using the PFV ver 2.4.1.1 software.

The air flow and gas flow rates were also widely varied to visualize the progressive development of the coherent structure. The equivalent ratio, φ, was changed from 0.151 to 1.05. Partially premixed combustion was extensively used and the nomenclature {X-Y}_l/min was used where "X" refers to the quantity of gas inject diffusively and "Y" as premixed.

When liquid fuels were used, either as support or as an alternative fuel, it was necessary to fit an atomizing spray nozzle to the end of a fuel injector, located near the burner exit to fire the spray as a cone into the shear flow between the CRZ and the main flow leaving the burner. Conversely with baseplate nonpremixed fuel injection, mostly suitable for gaseous fuels, there was much greater flexibility in operational parameters; therefore, the latter was covered for the PVC analysis using gaseous fuels.

Investigations about the occurrence of the PVC involved the use of three different swirl numbers and burner inlet configurations for a series of experiments for (50-50), S=2.02, (50-0), S=1.16, and (25-25), S=1.08, without any fuel injector and with diffusive fuel entering the baseplate.

3. Results

Some of the results showed the existence of a PVC in some form or other. Some configurations not only showed traces of a single PVC, but the existence of a pair of vortices that intertwined spiraling in opposite directions for some microseconds. This appears to be a low Reynolds number phenomenon occurring soon after vortex breakdown and rapidly disappearing as the Reynolds number was increased from ~5000 to ~15,000, often being replaced by a single, stable PVC. The whole phenomenon can be transient with an initial single PVC forming, followed by the double PVC appearing and disappearing. A typical view of a PVC taken from a single frame from the high speed camera and showing both top and side views is shown in Figure 3.

Figure 3. S = 2.2, Re ~ 5,600. {25-0} l/min gas flow, φ= 0.78, no fuel injector. The small flame is a pilot required for safety purposes.

When using a high swirl number at S= 2.02, at {25-0}_l/min under low Re ~11,000 and φ = 0.39, the single vortex splitted in two parts after ~0.012 ± 0.003s, with the largest portion being expelled to a more radial position because of centrifugal forces; this forced the remaining structure to also move radially, forming a twin PVC structure which only remained stable for a couple of milliseconds,

followed by their collapse into a merged vortex, which subsequently dislocated from the burner; the isolated structure remained visible for several milliseconds. The entire process from the creation of the main vortex to the disappearance of the isolated structures took ~0.046 ± 0.008s. It is thought that the PVC was stretched to a point of annihilation by the CRZ. Figure 4 shows the formation of the double PVC.

Figure 5 shows the PVC obtained as air flow rate and Re were increased for this fuel flow rate, {25-0}_l/min, for configuration (50-50). The equivalence ratio decreased from 0.62 (A) to 0.22 (F). The phenomenon was visualized as a rich burning flame in the central region of the burner, the low density fuel being entrained into the PVC, burning on its boundary.

Low density reactants and products were trapped inside the PVC, which evolved as a semi-helical structure, doubtless wrapped around a CRZ. As the equivalence ratio was decreased, the extent of visualization of the PVC decreased such that at φ=0.22 the flame burning on the PVC boundary was only visible inside of the burner. The signal obtained tended to the obtained with isothermal flows as the equivalence ratio was decreased.

Figure 6 contrasts a double PVC with another form, whereby small daughter vortices spin off the main PVC. Again this was a low Re number phenomenon <11,000 using configuration (50-0) and the same gas injection.

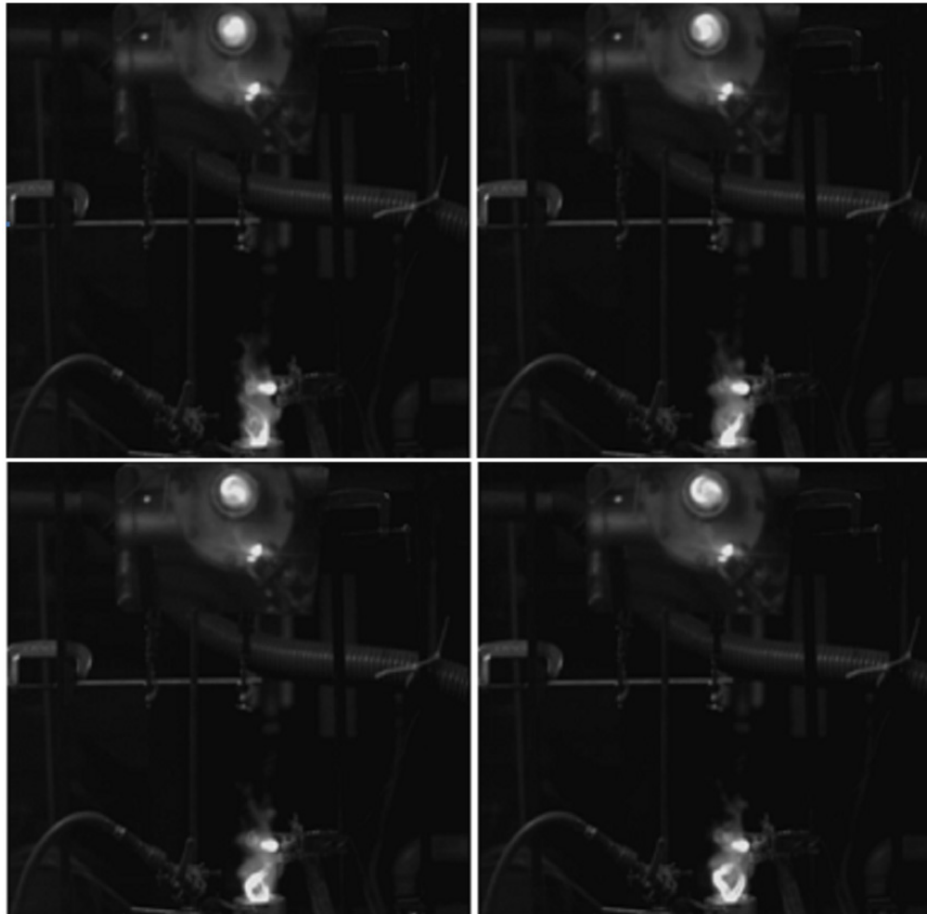Figure 4. Configuration (50-50). S = 2.02, Re~ 11,000, φ = 0.39, 25-0_l/min. Formation of the double PVC.
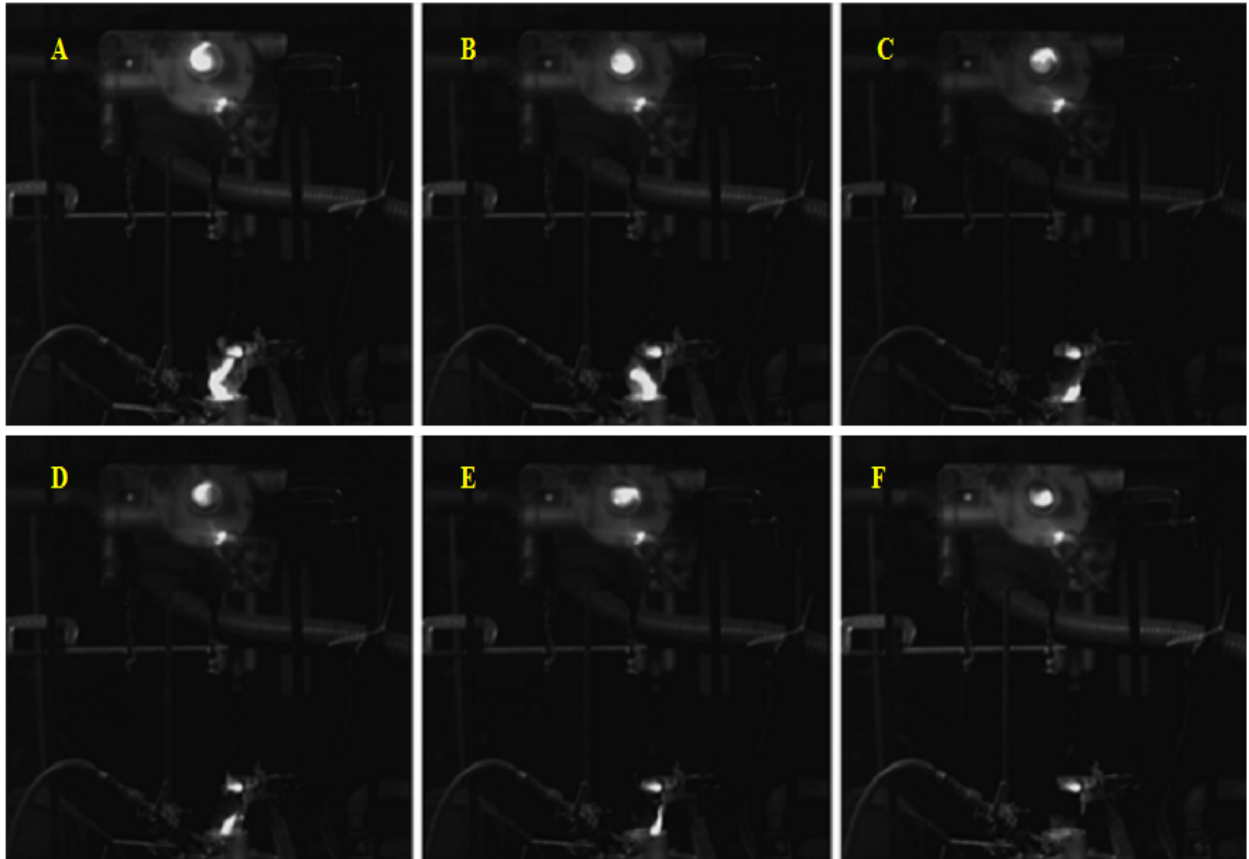
Figure 5. Configuration (50-50) at S = 2.02, {25 -0}_l/min fuel. A) Re ~ 7,000, φ= 0.62; B) ~8,500, φ= 0.56; C) Re~10,200, φ= 0.42; D) Re ~11,000, φ= 0.39; E) Re ~ 16,800, φ= 0.26; F) Re ~ 19,300, φ= 0.22. Nonpremixed fuel injection through the baseplate of the burner.
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Figure 6. Double PVCs. Pair of strong vortices (S=2.02, Re~11,000, φ=0.39) and main structure surrounded by a bifurcating vortex (S=1.06, Re~11,000, φ=0.39), respectively.

Some noticeable differences were that the PVC at the lowest Re and low φ did not look like a compact well-formed structure but a vortex with a centralized position and various bifurcations, which gave the impression of double structures. Freitag et al [24] identified similar structures in their numerical simulations.

These small vortices were long enough to twist around the PVC, completing several cycles around it. It was verified that each of the twisting projections emanated from the main vortex, eliminating the hypothesis of helical double vortices for this case. Increments of flow rate stabilized the structure, but bifurcations were still present. A more stable PVC was observed at higher Re, even though its lifespan never surpassed the 0.090 ± 0.010s, interval in which the core would remain coherent and bifurcated. This sporadic structure was observed several times, although it appeared only after long experimental run times. The PVC was thinner than the previous cases, although it was still coherent. Finally the PVC disappeared from the visual range at higher air flow rates.

According to Vanovergerghe [4] and Vaniershot [32], certain flames can only be obtained after transition from a specified flame has occurred. This proved to be the case in which the PVC could only be obtained after a laminar flame was strained by the swirling flow. When the flame was reignited in an already strained field with active swirl, the PVC was not developed forcing to shut down the system in order to generate the latter.

As discussed earlier, when increasing Re, the double PVC disappeared and a more stable single PVC system, associated with a stable CRZ, developed. The increase of the tangential flow, and hence of velocity, produced the necessary pressure field and gradients to induce a more stable, compact CRZ [21, 33]. The higher flow velocity also stretched the vortex, creating a larger structure whose lifespan was ~0.130 ± 0.020s, one order of magnitude higher than the previous case. The system collapsed afterwards, with the creation of an isolated vortex which extended downstream. Therefore, the PVC was a structure that was born at the burner baseplate (without fuel injectors) and extended through the burner and around the CRZ that developed at the exit. A process of

compression and expansion caused by the straining of the inner flow seemed to be responsible for the movement and long life of the vortex in the vicinity of the CRZ and the exhaust shear flow.

Congruent results reported by Valera-Medina [21] show that the helical shape of the PVC only developed around the initial part of the CRZ. Therefore, a quasi-helical behavior is observed, with a clear precession in the first region of the vortex, followed by a straightening of the PVC. This contradicts numerical and theoretical predictions that claim a complete helical movement around the CRZ, at least in this type of swirl generator [3].

Using configuration (25-25) with the same gas rate, {25-0}_l/min, No PVC was observed, instead a blue attached flame envelope was found near the burner exit. When increasing the flow rate, only sporadic vortices occurred. These were elongated unattached concurrencies that showed some patterns reminiscent of the PVC with lifespan of only 0.040 ± 0.010s.

More gas was injected into the system, {30-0}_l/min, using configuration (50-50). The increase produced the unstable double PVC at low Re (Fig. 6) whose wobbling motion lasted up to 0.180 ± 0.015 s. This structure becomes intertwined with the weak CRZ formed. Increasing the air flow rate produces a single PVC and behavior similar to Figure 5. For the (50-0) configuration, the extra gas allowed the identification of more bifurcations in the flow, with some that were larger and twisted even more than the preceding condition. The higher energy output fed the system, creating structures with life expectancies over 0.350 ± 0.040s. As the Re was increased and φ decreased, the bifurcations diminished and the PVC stability increased. For the (25-25) configuration, no PVC was observed.

By augmenting the gas rate to {35-0} l/min at low Re <15,000, any trace of the PVC was eliminated. Only a lifted blue flame was noticed, with no clear attachment to the burner. By increasing the flow rate, the flame touches the rig and a blue envelope starts to form. At this moment, a very weak and unstable PVC develops, which lasts only a few milliseconds before annihilation. This tendency

continues as the Re increases with the formation of a more regular PVC. After a quasi-stable regime, the PVC starts to compact. From this point, the stability of the PVC decreases and its lifespan is reduced considerably, although it can still extend out of the burner exit. The disappearance of the PVC at low Re is attributed to the effects of combustion and reduction in S. The addition of more diffusive gas showed similar patterns, with longer flames but similar characteristics at similar values of φ.

For the (50-0) condition, some isolated vortices appeared in the flame. These vortices had a relatively high life expectancy of 0.120 ± 0.011s. Due to the reduced straining force of the CRZ, these vortices evolved gradually and slower than their counterparts at higher S, thus lasting longer. A higher air flow rate created longer structures that bifurcated into several eddies which lasted up to 0.080 ± 0.019s. Only small and intermittent flashes were observed at low flow rates, with no coherent structure in the burner exit vicinity.

The (25-25) configuration behaved as previously, with no clear appearance of the PVC.

In order to confirm the existence of helical PVCs under different conditions, studies were carried out with partial premixing, {25-40}_l/min. Using the (50-50) configuration at low Re <15,000 with premixed fuel introduced through both tangential inlets, the system produced a completely lifted, noisy, toroidal flame with no attachment to the burner. After increasing the air flow, the flame envelope reattached to the nozzle, but it was not until Re ~22,200 that a sporadic, weak PVC could be visualized, which gained strength with the increment of the flow. However, at higher Re, an unstable, irregular, PVC could be discerned. Similar tendencies were observed for the case with premixed fuel introduced through one tangential inlet.

When configuration (50-0) was used with this fuel injection, no PVC was observed, not even when increasing the Re number. For configuration (25-25), the gas injection significantly changed the previously observed flame shapes. At Re~15,200 and φ=0.77, an extremely large, blue sporadically lifted flame envelope developed. At higher flow rates, the flame moved back into the burner body, and the toroidal shape changed to a conical one.

However, the central elongation was still present. More air flow only compressed the flame, keeping its shape up to Re ~24,000 and φ=0.36, when a compact slightly irregular flame formed. No PVC was observed.

The previous results can be observed in Figures 7 and 8, with the recognition of several regions of stability of the PVC. As previously mentioned, No PVC was observed for the (25-25) configuration. The figures show a complex scenario for both cases.
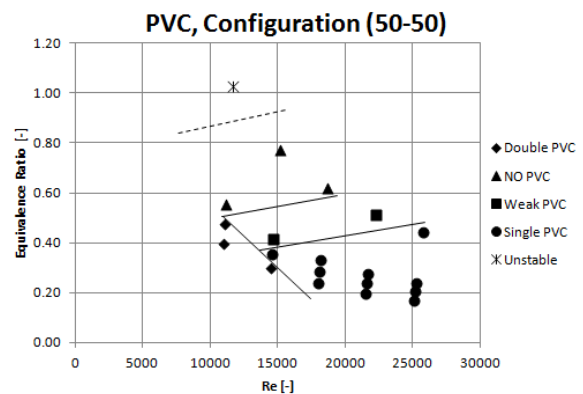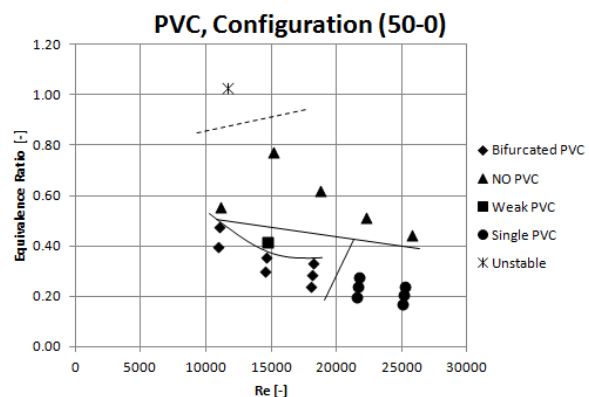

Figure 7. PVC; configuration (50-50).

Figure 8. PVC; configuration (50-0).

4. Discussion

Experiments with combustion showed the existence of the PVC with a well-defined shape at moderate equivalence ratios and low Re <15,000.

There are cases that show the existence of two internal vortices or double PVCs, a phenomenon

studied before by other authors [3, 34] but with clear visualization obtained during this work. This seems to be caused by centrifugal forces created as the mass of the precessing vortex core increases and cannot be maintained stable by the precessing motion of the structure, bifurcating and producing a vortical body of similar length and strength. Contrary to models that only characterize the field as a single PVC system, the existence of this double system confirms that the PVC keeps its energy as a consequence of its interaction with the CRZ, which under these high equivalence ratio-low Re conditions has not entirely formed yet. Thus, the precessing energy of the body is weak enough to impede a better coherence of the vortex, allowing its bifurcation as a consequence of external forces. It should be noted that the swirl number is quite high, hence giving enough angular momentum to the structure to split in two parts. According to Aleseenko et al. [31], the PVC remains coherent as a consequence of internal forces that due to the precessing motion try to compact the vortical structure, and when the vortex is compressed enough. the system will try to expand itself again to regain balance. This seems to be correct with the inclusion that this precessing energy is obtained from the interaction of the PVC with the CRZ.

Other experiments denoted the existence of the vortex core with bifurcations which spiraled around the principal body. This is probably the system that modelers have followed [35], as the secondary vortex is extremely weak compared to the main PVC. Therefore, the new structure is caught in the precessing movement of the latter. The bifurcations follow the tangential movement of the swirling flow appearing as a spiraling body which complete more than two cycles around the strongest structure, normally the CRZ. Contrary to the twin PVC, this was created with a moderate swirl number, which does not provide enough momentum for the entire split of the structure, only giving some energy to the small bifurcations that are trapped around the vortical structure and the recirculation zone in a helical manner.

Finally, a moderate S and symmetric air flow entrance showed the most stable results. Unfortunately, this also affected the visualization of the PVC, which was impossible to be observed.

Nevertheless, other authors recognize [36] that the presence of the CRZ is stronger and well formed coherent structures are present under these conditions. This phenomenon is probably caused by the high coherence of the CRZ that produces a very stable flame whose emissivity avoids any direct visualization of the PVC. Moreover, the interaction between both structures does not allow a clear distinction of the latter by this technique.

Figures 7 and 8 show a complex scenario for both visualized conditions, (50-50) and (50-0). It seems that the PVC follows a pattern based on the Re number and equivalence ratio. There is a region of high gas inflow that does not allow the clear formation of the PVC. This is caused by a decrement of S, high emissivity of the flame and reduced strength of the PVC. The use of other techniques has shown that there is a CRZ in this region, although it is weak compared to leaner conditions. When the gas is reduced and the flow is slow enough, there is a region where the CRZ is still forming from the vortex breakdown. It is in this moment when the CRZ is not strong enough to provide the required energy for a coherent PVC, allowing the split of the latter in bifurcated or double structures. Then, a region of quasi-stability appears when the CRZ is finally forming, leading to a region of higher stability when the latter has finally become stable. This structure provides enough energy to the PVC to form and be visualized with this technique under low equivalence ratios, trapping most of the burned products in the structure. Therefore, it can be concluded that the formation and shape of the PVC is highly correlated to the state of formation of the CRZ.

5. Conclusions

This paper has described the characterization of the PVC using a swirl burner designed for the utilization of alternative fuels. Important conclusions are

1. Reynolds number effects are very important and can seriously affect the PVC.

2. High temperature gases can affect the vortex breakdown phenomena and the size and shape of this structure, dissipating the PVC.

3. Coherent structures such as s are well-known to occur in these systems, especially with premixed and partially premixed burners. At low Re <15,000, interesting double PVC structures occur as well as vortex bifurcations off PVCs. The existence of interacting PVCs and CRZs has also been indicated for the combustion state.

4. There is also evidence that the PVC can be transient and intermittent in nature, periodically forming and being extinguished for certain configurations. This has considerable ramifications for the stability of the associated CRZ.

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