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VISUALIZATION OF THE REACTIVE SWIRLING FLOWS IN A 150 KW WOOD POWDER BURNER

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ABSTRACT

Swirl stabilized burners are widely used in industrial combustion processes due to their benefits in terms of wider flame stability limits, improved mixing and high turbulence level [1]. However, swirl flows are prone to hydrodynamic instabilities at critical operating conditions, which can lead to local velocity and pressure oscillations. These oscillations can modulate the heat release, giving rise to a space-temporal coupling between heat release and pressure, (Rayleigh criterion), leading therefore to thermo-acoustic oscillation. Industrial experience has shown that swirl stabilized wood powder burners can sometimes cause pressure fluctuations that result in high amplitude structural vibrations in the boiler and increased emissions. The qualitative experiments with a 150 kW wood powder burner that was perturbed with a loudspeaker in the secondary air register showed that a strong effect on the flame characteristic occurred when the perturbation frequency was about 17 Hz. Flame visualisations indicated that one or more precessing vortices were present during stable combustion and that these vortices became unstable when the excitation frequency and amplitude had a critical value.

INTRODUCTION

Swirl generators have a wide variety of industrial applications, such as aeronautics, heat exchange, spray drying, separation, combustion, etc [2]. The role of swirling flow in combustion systems, (in gas turbine engines, diesel engines, industrial burners and boilers etc.) was to stabilize flame and improve mixing rate between fuel and oxidant streams via presence of toroidal recirculation zone which recirculates heat and active chemical species to the root of flame [3]. Intensity of swirling flow is characterized by non-dimensionless swirl number, S which is ratio of axial flux of angular momentum to the product of axial momentum flux and a characteristic radius but the expression of swirler number implicitly depends on the swirler geometry and flow profile [4].

Even swirling flow brings many advantages into industrial applications; it can lead to fluid dynamic instabilities via establishment of certain flow pattern which allows vortices to shed periodically. In combustion, flow pattern interacted with one or more acoustic modes of combustion system and flame dynamics can result in amplified heat release rate and pressure/velocity fluctuations. This coupling can lead to undesirable effects in the swirl stabilized combustion systems; flame flashback, loud noise, high amplitude vibrations and even failure of the mechanical systems. The potential sources of instabilities in swirl stabilized systems have been extensively investigated by Syred who pointed out the precessing vortex core (PVC) in swirl systems as three dimensional, time dependent spiral structures which are considered to be a main source of noise in swirl burners [3,5,6]. He has also reviewed large number of experimental and numerical works about the occurrence of the precessing structures by consideration of several cases; free, confined isothermal, reactive flows with different mode of fuel entry, equivalence ratios and level of confinement [3]. In work of O´Doherty et al, precessing vortex core have been visualized in a 100 kW swirl/burner system as a form of curved and twisted structure changing its shape and appearance many times within a single cycle [7]. Flow visualization experiments in works of E.C Fernandes et al have clearly showed that the PVC is formed at a boundary of a recirculation zone which is located off centred and precessing within helical pattern [8, 9, and 10]. Extensive numeric efforts have been applied to characterize the instabilities induced by precessing vortex core via visualization techniques and frequency analysis. Martin Freitag and Markus Klein have performed DNS simulation of the swirling flow in non-premixed bluff body burner and validated their results by experimental data. They have observed that close to the bluff body, the PVC exhibits single, relatively thick helical structure rotating with 21 Hz and further downstream of the burner, breaks into several branches or keeps its initial shape [11]. In the work of Garcia and Fröhlich [12], LES simulation was applied to analyze the precessing vortex structures in a free annular swirling flow surrounded with and without a weak co-annular pilot jet. In annular swirl jet which is devoid of coaxial pilot jet, two structures have been observed; outer spiralling structure located in the outer shear layer and the inner structure so called the PVC, located inner shear layer between the recirculation zone and annular swirl jet. Their LES simulations show that the structures within absence of coaxial pilot jet are more coherent, precessing at more quasi regular rate and persist over longer time. Another important conclusion from their numeric work is that in the addition of swirler into the coaxial pilot jet leads to the loss of coherence and more random appearance of structures.

In this context, this paper addresses the presence of large scale precessing vortices in a 150 kW swirl stabilized burner/furnace system during wood powder combustion. High speed photography technique was applied to visualize the large scale helical structures induced by an acoustically forced secondary air registers at a frequency of 17 Hz.

2 EXPERIMENTAL METHOD

2.1 EXPERIMENTAL SET UP

The wood powder was mixed and burnt with air in a 3300 mm long furnace which has rectangular cross sections (550x550 mm^2). The burner was mounted to a 1300 mm long, adaptable window box which gives an optical access to visualize flame motions. Soot deposition on both side of windows during the combustion are blocked by slit air system stretching along the inside of the window frames. Flame visualization experiments were performed by the high-speed camera Imager Pro HS by LaVision with maximum rate of 636 per second at full pixel resolution (1280x1024). Frames were acquired and registered in a computer via frame grabber. Flow pattern through secondary air intake was perturbed by a 10 inch loudspeaker with 180 W rated input powers which was equipped into a cylindrical box. A stereo amplifier (Pioneer stereo amplifier model no SA 520) and a function generator (Wavetek) were used to drive the loudspeaker at certain amplitudes and frequencies. The amplitude and frequencies of signals, from the signal generator and the stereo amplifier were simultaneously logged into the oscilloscope (Agilent technologies model 6000). The view of test section and equipments were presented in figure 1.

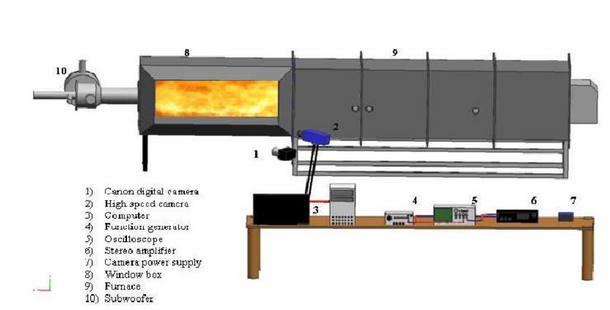


Figure 1 View of experimental setup

2.2 BURNER GEOMETRY

The burner is dimensioned for a maximum power of 150 kW and used as a combined oil/powder burner shown in figures 2 and 3. Air is charged into the furnace by a screw compressor via three air inlets; primary, secondary and tertiary. All the inlets are given rotational movement by guide vanes which improve the mixing between fuel and air streams. Each of combustion air registers are controlled by mass flow controllers. The burner is embedded into a refractory line cone which helps ignition of wood particles. The powder is transported into the furnace from a powder screw feeder with help of air flow via a 19 mm tube located in the centre of the burner. At the end of the tube, a conical plug is used to distribute the powder more efficiently into the mixing zone of the burner.

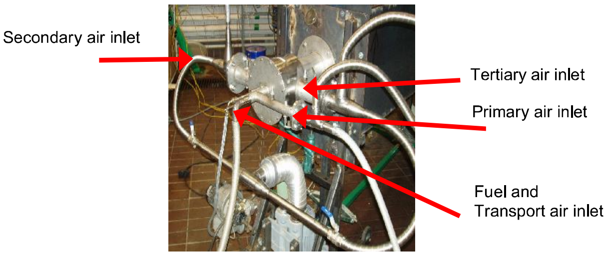


Figure 2 A powder burner with combustion air registries

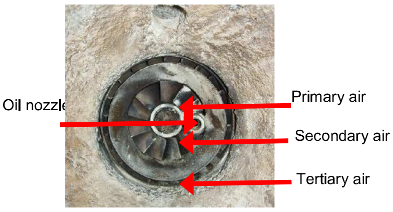


Figure 3 Front view of powder burner

2.3 OPERATING CONDITIONS

Mass flow controllers for primary, secondary and tertiary air registries were set to 401 l/min, 703 l/min and 302 l/min respectively. The furnace was run at 20 Pa below atmospheric pressure with 11 % of excess oxygen in total volume of flue gas. Average gas temperature in the near field of mixing zone was about 800^{0}C.

3 RESULTS AND DISCUSSION

Aim of the visualization experiments is to observe the behaviour of (un)steady wood powder flame and investigate the presence of large scale precessing structure(s) identified in the previous works within swirling flows [3,7,9]. Due to better understanding of unsteady powder flame behaviour, the flame was initially visualized under the operating conditions where no sinusoidal excitation was applied to any of air registries. Figure 4 (a) shows a stable powder flame which expands and stretches further along in the window box. The unburned carbon escaped from powder flame sticks and deposits on the base of the window box which renders visibility of main powder flame further downstream the burner exit inefficient by developing a secondary flame. The next step is to perturb the stable flame by imposing a sinusoidal modulation to the secondary air registry at wide ranges of frequency and amplitudes without changing any flow rate and thus oxygen excess level. In figure 4 (b), (c) and (d); the flame exhibits dramatic changes in its shape and size when a sinusoidal wave at 17 Hz and 34 $V_{p\text{-}p}$ (peak to peak voltage) is applied to the secondary air registry.

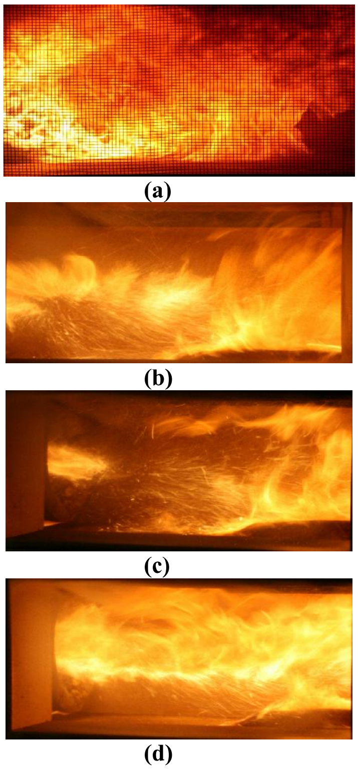
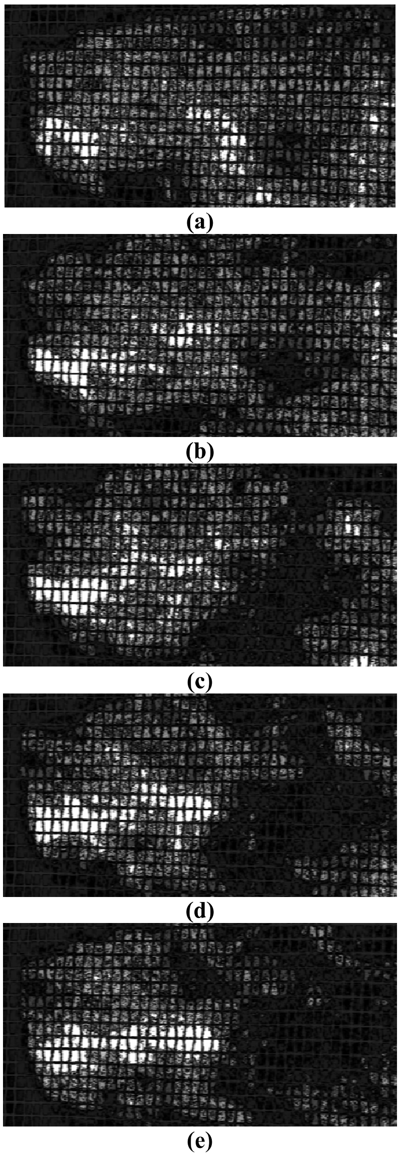


Figure 4 Snapshots of wood powder flame, (a) without acoustical excitation of any of combustion air registries (b), (c), (d) subjected to acoustical excitation of secondary air flow at 17 Hz and 34 $V_{p\text{-}p}$.

Unsteadiness in flame motion, shape and size manifest itself in various forms of flame front. In figure 4 (b), the flame diffuses into the combustion chamber within a helical pattern which falls in with previous visualizations and interpretations of large scale helical or spiral vortices in the literature[2,3,8,9,10]. However, the secondary flame generated further downstream makes it difficult to interpret the boundaries and tip of the powder flame. In figure 4 (c), the main powder flame exhibits a compact shape close to the powder burner and is relatively smaller in length than the length of flame shown in figure 4 (b). Figure 4 reveals the existence of a large scale helical structure embedded into large rotating powder flame.

The motion of the flame perturbed at a frequency of 17 Hz and 34 $V_{p\text{-}p}$ was captured by a high speed camera with a frame rate of about 600 Hz. The specified frame rate enables to resolve the large scale coherent structure(s) within the turbulent powder flame. The time step between two frames is set to 0.001667 s.

After image enhancement and segmentation process, flame images show that flame is interacted with a large scale coherent structure which is reformed in the flame boundaries quasi periodically and subjected to continuous variations in its shape and size. Boundary of flame front is dependent on the presence of the PVC and its form of breakdown. In the work of T.O' Doherty et al, PVC has been visualized as a curved and twisted structure. The time evolution of the twisted flame is shown in Figure 5. The image sequences reveal the presence of PVC structure in the wood powder burner. The vortex is convoluted from its core and extends to couple of diameters the downstream of the burner exit.



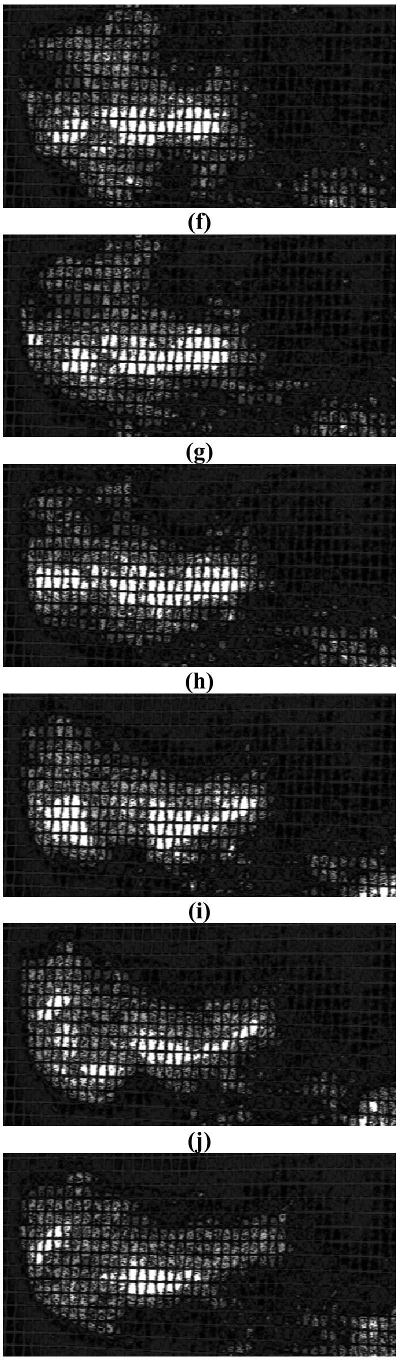

(f)
(g)
(h)
(i)
(j)
(k)

Figure 5 Evolution of precessing vortex core in a wood powder burner; via sequence of images, starting at time of (a) 0.288391 s, and stopping at time of (k) 0.308385 s

Observations on the basis of Figure 6 indicate that the motion of vortical structure is shifted away from the burner axis and it rotates around the burner exit. The PVC pattern is generally described as a remarkable helical form wrapping itself around the reverse flow zone [3]. The result from figure 6(b) validates the helical nature of the precessing vortex core described in the previous works [2, 3, 4, 7, 9].

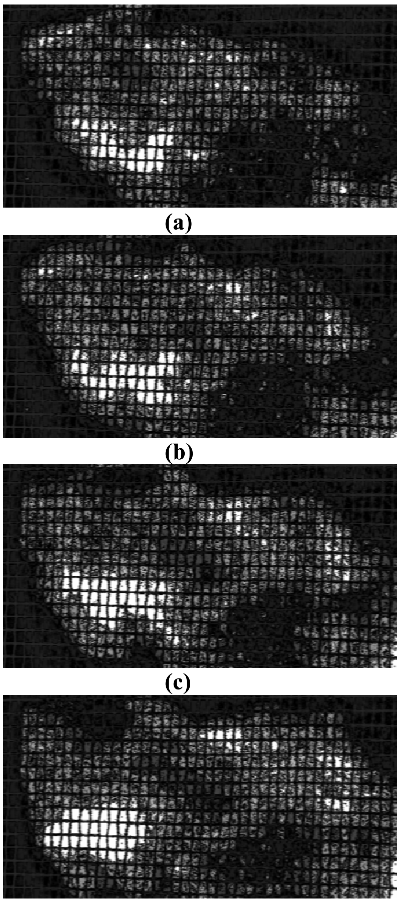
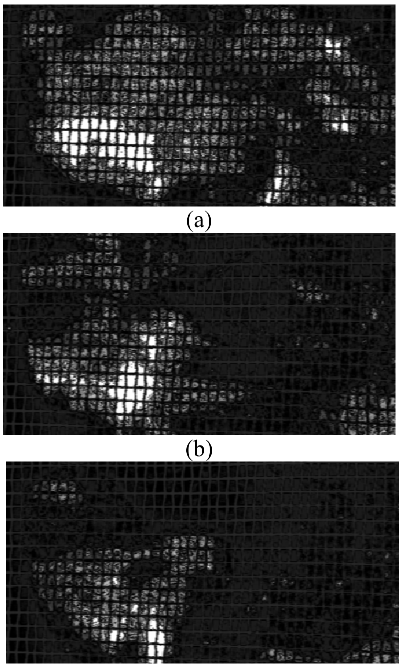

(a)
(b)
(c)
(d)

Figure 6 Visualization of helical nature of the PVC generated in wood powder flame; at time of (a) 0.315063 s, (b) 0.3167s, (c) 0.318397 s, (d) 0.320064 s

Large coherent structures have quasi-periodic recurrences unless they are excited by a natural feedback mechanism or acoustic equipment [13]. The reoccurrence of the PVC structure are captured on every 36 or 37 frames which is corresponding to about 17 Hz.

The precessing vortex core structures are often changing their shapes and appearances within a single cycle [7]. Figure 7 shows the appearance of the precessing vortex core within a single cycle. Appearances are obtained at 0.173368 s, 0.178369 s and 0.18337 s. The vortex core is present in the flame front as a curved and twisted structure and within 10 ms, it firstly transforms into the bubble mode of vortex structure with a longer and thinner core size and later is turned into a spiral shape whose appearance is totally different than the initial appearance.



(a)

(b)

(c)

Figure 7 Visualization of continuous variation of the PVC shape and appearance within a single cycle; at time (a) 0.173368 s, (b) 0.178369 s (c) 0.18337 s

CONCLUSION

Visualization results indicate that the disturbances in the secondary air register can create large scale coherent structures in a 150 kW swirl stabilized wood powder burner. The PVC structure manifests its existence changing the boundaries of powder flame continuously. Powder flame gives response to acoustic disturbances at a frequency of 17 Hz with drastic changes in its shape, size and motion. The aim of the visualization experiments is to investigate the occurrence of the precessing vortex core which is referred to as a main source of noise in swirl burners [5]. This result will enable further investigation of flow pattern of the precessing vortex structures and their effects on noise generation.

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