The influence of confinement geometry on spectral characteristics and bulk mode resonance in a swirl burner

J.R. Dawson, A.J. Beale, N. Syred and T. O'Doherty

Division of Mechanical Engineering and Energy Studies
Cardiff University
Queens Buildings, The Parade,
Cardiff, CF2 3TA, U.K.

ABSTRACT

The experimental work presented in this paper aims to provide insight into the excitation of bulk mode (Helmholtz) oscillations set up in a swirl burner system. By maintaining a constant volumetric flow rate and equivalence ratio, two-dimensional Laser Doppler Anemometry (LDA) measurements were taken with a swirling flame open to atmosphere and under high levels of confinement with and without exciting conditions. Velocity derived power spectral densities and time correlations were subsequently generated from the LDA results in order to investigate the role of downstream geometry and/or hydrodynamic instabilities that may be partly responsible for the excitation of the resonant state. It was found that instabilities common to swirl flows, such as vortex shedding and the precessing vortex core, were absent from the open flame power density spectra indicating that the resonance is not excited by such fluid dynamic instabilities. By investigating the different confinement geometries it was found that resonance could be achieved without the presence of an exhaust pipe. Moreover, only a subtle change in confinement geometry was required for excitation. It is suggested that confinement promotes upstream feedback to the inlet ducting which conspires with the burner and combustor geometry to resonate. Spectral analysis of the resonant condition exhibit multiple high-energy harmonics supporting the notion that the oscillating system is made up of a multiple of oscillating components upstream.

1. INTRODUCTION

To date the experimental data available on bulk mode or quarter wave oscillations generated in practical swirl burner systems is at best scarce, Syred et. al (1974), Froud et. al (1996), Dawson et. al (1998). The beneficial wake dynamics produced by swirl make their industrial application frequent, therefore identifying their susceptibility to resonance or pulsations is of significant merit both fundamentally and practically. The salient features of employing swirl is the formation of a reverse flow zone, RFZ, surrounded by a swirling jet to form an aerodynamic flame holder (Syred and Beer, 1973)(Gupta et. al, 1984). The formation of a RFZ primarily depends on the level of swirl and downstream confinement and therefore has particular implications regarding the sub-critical nature of the flow and the formation of hydrodynamic instability. Pressure data and Power density spectra obtained in a various swirl flow configurations are known to create hydrodynamic instabilities in the form of vortex breakdown, vortex shedding and vortex precession (Leibovich, 1978)(Hawethore and Goulding, 1986)(Syred and Beer, 1973). Similar phenomena have been reported showing that periodic behaviour is strongly influenced by the level of swirl and downstream confinement (Cheng et. al 1989). Despite these reports, the role of these flow instabilities in exciting resonances has not been fully realised.

The most notable advances in the field of combustion driven oscillations have focused on pulse and dump combustion systems that do not employ swirl. These include the work of Keller et. al (1989), Dec et. al.(1991), Barr et. al (1994), Sivasegaram and Whitelaw (1987) and Schadow et.al. (1989). Both, pulse and dump combustors are typically low frequency, i.e. <200Hz, high amplitude oscillations and resonate at the quarter wave or bulk (Helmholtz) modes determined by the geometry of the combustor. As such, the difference between Helmholtz and quarter wave geometry is that a Helmholtz geometry is effectively a quarter wave geometry of variable diameter. Independent of the system under consideration, the criterion for maintenance of heat driven oscillations in any system requires the pressure field and heat release to be in phase (Rayleigh, 1878). This means that the reactant supply processes, chemical kinetics and fluid mixing need to be synchronised with the pressure field such that heat is released near or at peak pressure to reinforce the resonant condition and overcome all system losses. There have been numerous valuable studies undertaken identifying the different phenomena required to phase match the heat release and the resonant pressure field, such as the role of coherent structures (Schadow et. al, 1989), characteristic times, ignition delay, and periodic flame stretch (Keller et. al. 1989)(Barr et. al (1994). Although many of these concepts are applicable to resonant conditions excited in a swirl burner system some will be less important. For example the role of flame stretch is unlikely to be as important to the ignition delay process as in pulse combustors due to the swirling flow dynamics. The system can therefore be considered a hybrid phenomenon comprising of a strong, axial, transient pressure field superimposed upon a swirling flow.

Previous to this paper, the role of the exhaust pipe was considered integral in both function and behaviour as found in pulse combustion systems. In other words, it was assumed that the flow in exhaust pipe periodically reversed to recycle hot products back into the chamber and that its length influenced the resonant frequency. However, contrary to pulse combustion reports (Dec et. al 1991), it has been shown that for this system periodic reverse flow in the exhaust pipe does not occur at any time (Dawson, 2000). Moreover, Froud et. al (1996) and Dawson (2000) have shown that for various exhaust pipe lengths (from 400mm to 1050mm and various diameters) the effect on the resonant frequency was insignificant. These results are the subject of further work in progress. This paper investigates the role of confinement on the excitation process as it was found that a resonant state could be excited without an exhaust pipe and excitation only required a suitable level of confinement. This study is concerned with providing experimental data obtained during these trials in order to isolate the role of confinement and coherent structures in the excitation process.

Experimental data emphasising the spectral characteristics of a swirling flame with fixed operating conditions open to atmosphere, confined in a furnace and under resonant conditions (without an exhaust pipe) are presented. The spectral characteristics will identify the presence of any hydrodynamic phenomena, such as the presence of vortex precession or other coherent structures, as well as other perturbation frequencies, not related to the fluid mechanics of the swirl flow, that may emanate from the acoustic response of different geometric components. This aims to identify whether fluid mechanic perturbations or acoustic response of different parts of the geometry conspire to excite the resonant condition.

2. EXPERIMENTS

Two-dimensional LDA measurements were carried out on 100kW swirl burner under combustion conditions. Swirl was generated via two diametrically opposed tangential inlets fixed with inlet blockages to obtain a geometrical swirl number, S=2.18. A conventional blower supplied combustion air through several meters of flexible piping split into two by a Y junction and attached to each of the tangential inlets. Natural gas was supplied from the mains and was arranged so that fuel was injected along the central axis, perpendicular to the inlet flow, as well as into the inlet flow at the tangential inlets. This allowed a blend of piloted and premixed conditions to be employed which give rise to the steadiest oscillations. The volumetric flow rate of the reactants was regulated by rotameters. A schematic of the test rig is shown in figure 1.

The volumetric flow rate of air and fuel (split evenly between piloted and premixed injection modes) was kept constant at Q_{air}=2500l/min and Q_{fuel}=180l/min giving an equivalence ratio of 0.72. Three sets of LDA measurements were taken:

1.) with the flame open to atmosphere
2.) confined inside a furnace with a taper section with and exit diameter of 50mm
3.) confined inside a furnace of different geometry to 2.) but of similar volume.

The confinement geometries are also shown in figure 1. It is interesting to note that case 3.) is the chamber and exhaust taper section the Helmholtz type aerovalved pulse combustor used by Beale (1999) whereas case 2.) is the furnace section was based on a 1MW scale model of this test rig.

The velocity measurements were conducted using a 3D (only 2 dimensions were used) Dantec fibre optic laser system with a Coherent Innova 70 series Ar-ion laser source with an output of 1.5kW. A backscatter configuration was employed with the probe mounted on a programmable traverse to ensure accurate spatial resolution. The probe lens had a focal length of 310 mm with a beam separation of 53 mm and control volume dimensions being 0.1, 0.1, and 1.2mm in the x, y and z co-ordinates. Three measurement planes in the axial direction were adopted at x/D_e=0.13, 0.39 and 0.66 for a grid spacing of 1 mm. Titanium dioxide, TiO_2, was the seeding employed with a dry mean sauter diameter of 1μm.

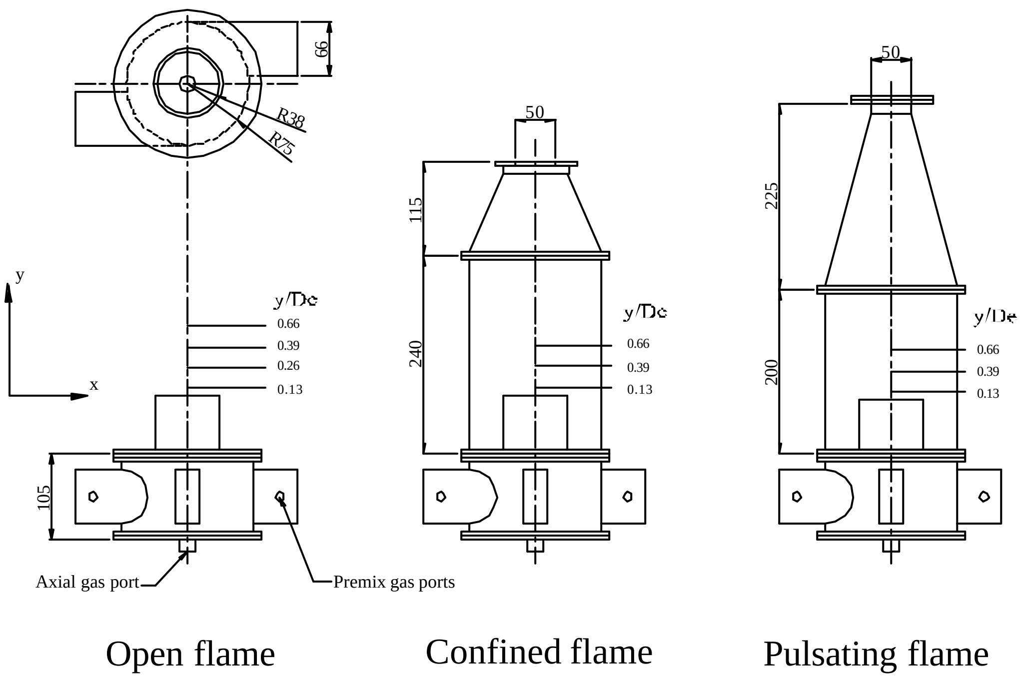


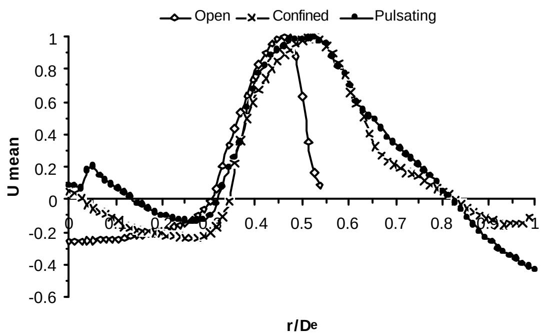
Figure 1 – Test rig schematic showing confinement geometries and LDA measurement positions

Under resonant conditions a water-cooled PCB pressure transducer monitored the pressure at the furnace wall. The output signal from the pressure transducer was amplified and sent to a PL 202 FFT analyser and to the BSA's for triggering purposes. Typical phase-averaged behaviour can be found elsewhere (Froud et. al., 1996)(Dawson, 2000) thus the phase-averaged data obtained during these tests are not included. The power spectral density and time correlations were calculated using the updated spectral and correlation analysis module in Burstware 3.2.1.

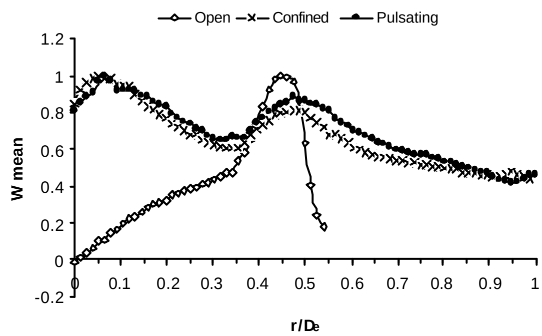
3. RESULTS

3.1 Velocity Profiles

Although time averaged data does not accurately describe periodic flow it is important to get a sense of the burner dynamics as the effects of the oscillation will be studied via the spectral and correlation data. The axial, u, and tangential, w, mean velocity profiles obtained at x/D_e=0.13 for the open, confined and resonant case are shown in figure 2. The open flame case shows the expected axial profile for this type of burner, i.e. the formation of a RFZ surrounded by a strong swirling annular jet. Moreover, the profile (as well as the spectral data) indicates the flow is highly symmetrical. The flow decays rapidly outside the jet and is completely dissipated between r/D_e=0.55-0.6 whereas the tangential velocity is undeveloped due to the close proximity of the burner exit. Under confinement and resonance the u and w profiles exhibit virtually similar behaviour. The downstream pressure induces a region of positive flow in the centre of the burner creating an annular shaped RFZ and increases the overall size of the swirling jet. Interestingly, there is little change in magnitude. Additionally, a region of reverse flow is also noticed in the wall region. The w velocity profiles are also similar showing a peculiar double peaked vortex structure each located at the corresponding positive regions of flow in the u velocity profile. Interestingly, the centre of the vortex flow has shifted away from the geometrical centre compared to the open flame condition suggesting vortex precession may be present. These results agree well with the confinement studies by Syred and Dahman (1978).



a.)



b.)

Figure 2 – Normalised mean a.) axial and b.) tangential velocities obtained under open, confined and resonant conditions

By comparing the profiles of the confined and resonant conditions little information regarding the behaviour of the system is obtained, nor can the resonant condition be easily distinguished from the effects of high confinement. Aside from the difference in taper and chamber geometries the exit diameters and chamber volumes are virtually identical. This means that a slight change in the shape of the geometry is enough to excite a resonant state. This is a particularly valuable result as the system can oscillate without the presence of an exhaust pipe and only requires a suitable level of confinement. It is clear from figure 2 and the phase averaged data reported in Froud et. al. (1996) and Dawson (2000) that the oscillating significantly alters the fluid mechanics by introducing periodicity to the RFZ and the swirling jet. The level of swirl has also been shown to influence the excitation process (Dawson, 2000) by altering the fluid dynamic mixing times affecting the timing between the heat release with the pressure field.

3.2 Power Spectral Density

The identification of coherent structures, periodic instabilities and discrete perturbations are easily detected by obtaining the Power Spectral Density, PSD. This is particularly apt when dealing with swirling flows which frequently exhibit instabilities in the form of vortex breakdown, vortex shedding and the precessing vortex core. Using PSD results to identify the presence, frequency and bandwidth of instabilities in swirl flows has been shown by Hawethore and Gouldin (1986), Chao et. al. (1991), and Hoekstra et. al (1998). The PSD can, in this case, also be used to identify the perturbative frequencies involved in the resonance and the role of any coherent structures in the flow prior to confinement. These can also provide insight into the turbulent fluctuations and perturbative energy but are the subject of further work.

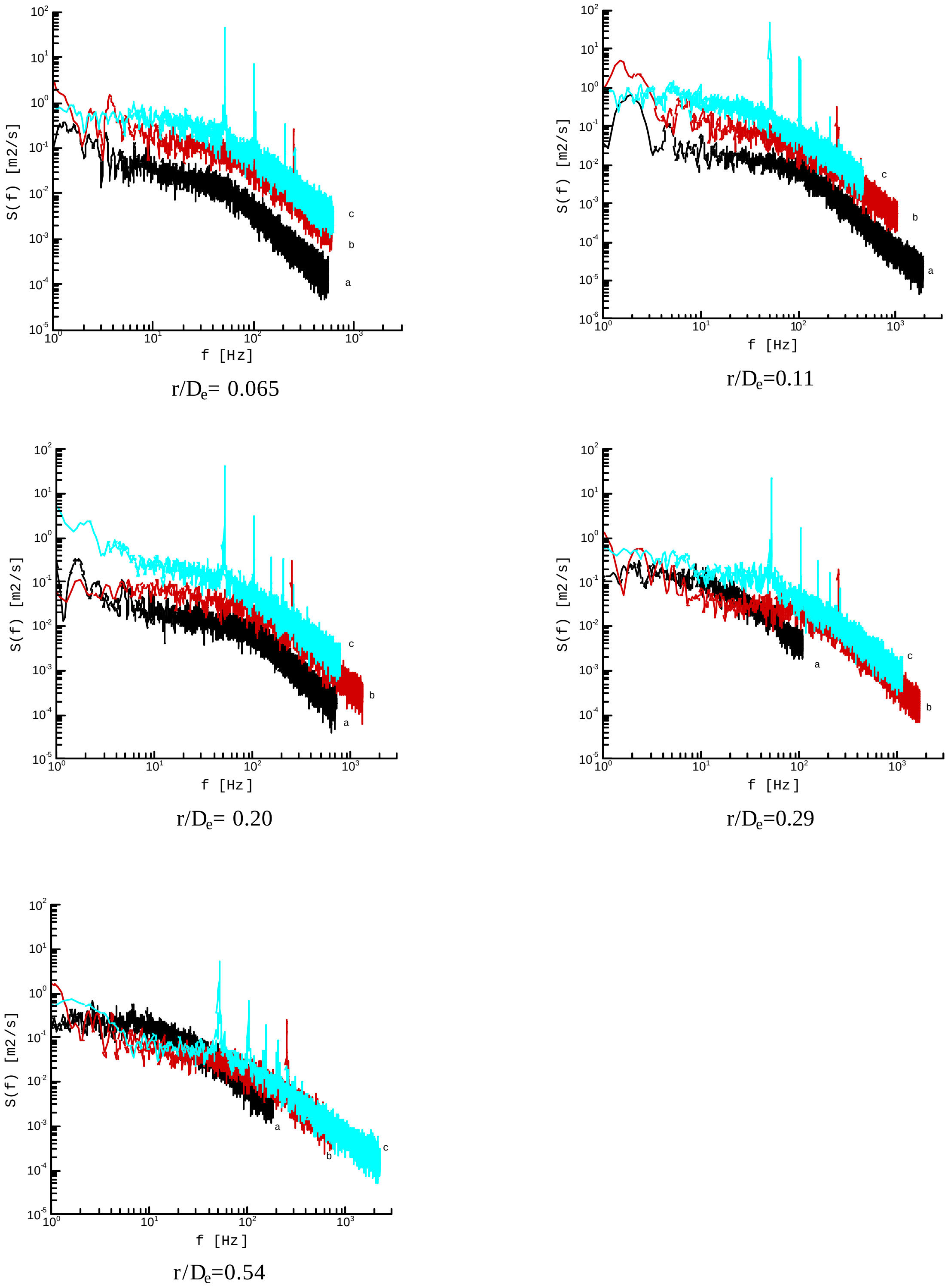


Figure 3. – Power Spectra for a) unconfined, b) confined and c) resonant conditions at x/D_e=0.13

The PSD results are presented in figure 3 for five radial positions and correspond to the velocity profiles in figure 2. Each graph shows the PSD at a given r/D_e and is labelled a) for open flame conditions, b) for confined conditions and c) for resonant conditions. The spectra show numerous high-energy peaks of discrete frequency inline with the fundamental frequency of 52Hz, and its harmonics. Overall, two trends are immediately noticed. Firstly, the resonant condition possesses the highest turbulent energy, the confined condition the next highest and the open flame the lowest of the three. At r/D_e=0.54, the energy of all three conditions become comparable. This is because the turbulence is strongest in and around the swirling jet and more quiescent in the near wall region. Secondly, as many as five, high energy, harmonic perturbations are easily found for the resonant state. The confined condition consistently shows a single peak at approximately 250Hz whereas the open flame does not exhibit any discrete high-energy frequency perturbations at any time. These confined results suggest that the high frequency perturbation represents a flow response but with an insignificant pressure amplitude to induce periodicity in the pressure and velocity fields. This prevents the excitation of the bulk mode resonance. The resonant conditions show a minimum of three harmonics at all times implying that several perturbations are required in concert to excite and or maintain the oscillation. Moreover the peaks are discrete, i.e. do not exhibit a bandwidth of response, and are present across the entire radius. Hydrodynamic instabilities such as the precessing vortex core, PVC, and other instabilities tend to show a response bandwidth and are normally isolated to specific regions of the flow like the RFZ boundary as shown in Chao et. al. (1991) and Hoekstra et. al. (1998). The open flame spectra also show no evidence of instability in the flow such as the PVC even at the RFZ boundary. Thus the harmonic response of the resonant PSD represent perturbations in the flow, which were not there prior to the resonant state, caused by acoustically excited components of the geometry which couple together to form the oscillation. This does not imply that the fluid dynamics are not coupled with the resonant state but rather that any coherent structures associated with the fluid dynamics do not appear to be responsible for exciting the resonance as shown by the spectra of the open flame. However, any periodic fluid dynamics occurring under the resonant state may serve to maintain the oscillation, the open flame spectra suggest that they are not responsible for excitation. It is clear from the figures that the higher order harmonics, i.e. 3rd and 4th etc., lie on the inertial slope -5/3. As these peaks lie in the inertial regime and they represent discrete high-energy disturbances in the micro-scales. This further indicates that the resonance is driven through the micro-scales as well as the macro-scales the latter affecting the coupling between the pressure, heat release and velocity the former perhaps involved in fine scale mixing and characteristic timing as put forth by Keller et. al (1989).

3.3 Time Correlations

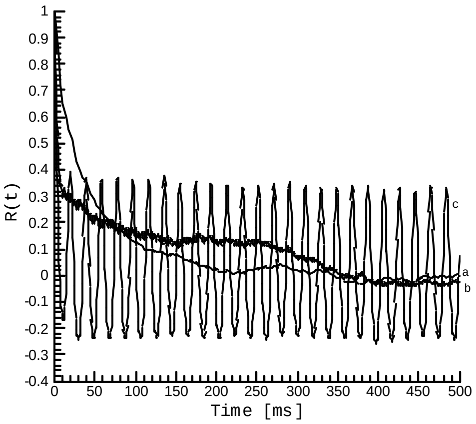
The following section assesses the effect of confinement and the resonant state on the average eddy lifetimes. Table 1 shows estimated eddy lifetimes obtained at various radial locations for all three cases. The lifetimes were calculated by normalising the time correlations and integrating the area above y=0. Two typical normalised time correlations at r/D_e=0.065 and 0.29 are shown for open, confined and resonant conditions in figure 4. The open flame eddy lifetimes are largest in the RFZ with maximum lifetimes ranging from 65-86ms and the smallest between 10-30ms. Under confinement the corresponding eddy lifetimes tend to decrease although with slightly different size distributions across the radius. This is due to the difference in fluid dynamics induced by confinement. The central positive flow sees the largest eddy lifetimes 51.6ms which rapidly decay to 2-3ms at r/D_e=0.14 and 0.19. The shortened lifetimes indicate the presence of perturbations. The confined swirling jet has average eddy lifetimes between 25-35ms between r/D_e=0.30 to 0.54 the latter being the centre of the swirling jet. Comparing the average eddy lifetimes in the RFZ, confining the flame reduces eddy lifetimes by a minimum of 8% whereas the lifetimes in the swirling jet are reduced by almost half. Resonant conditions show the average eddy lifetimes are significantly reduced ranging from 2.5-3.5ms across the whole radius. Interestingly, the lifetimes show no dependence on the time averaged flow zone distribution and as such is the first noticeable difference to the confined case.

Many interesting observations can be gained from figure 4. The reduced eddy lifetimes are easily noticed from the obvious changes in area under the curve to the y=0 intercept. Of particular interest are shape of the correlation maps for the confined and resonant conditions. The confined condition shows periodicity superimposed upon the decay gradient. This fluctuation corresponds to a frequency of 250Hz and agrees with the frequency peak in the energy spectra. The frequency peak influences the turbulent structure, shown by the reduced eddy lifetimes, although the curve is closer to the behaviour of the open flame correlations than those of the resonant case. The resonant correlation shows strong periodicity about y=0. The signal appears sinusoidal at a frequency corresponding to the 52Hz fundamental, however superposition of higher harmonics is noticed showing that the oscillation is not solely influenced by the fundamental frequency.

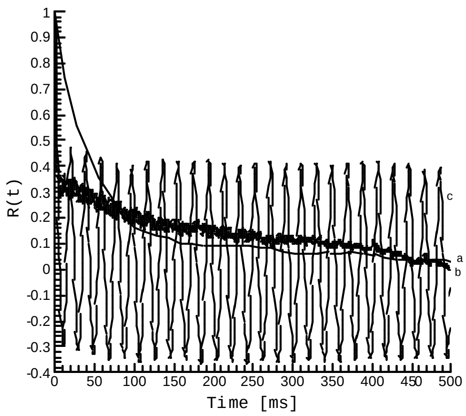
Table 1 – Estimated average eddy lifetimes for open, confined and resonant conditions

Radial Distance r/D_e	***Open Flame (ms)***	***Confined Flame (ms)***	***Resonant (ms)***
0.065	43.84	51.60	2.81
0.11	11.86	38.96	3.22
0.14	13.48	2.35	3.50
0.19	13.70	1.70	3.24
0.22	27.22	25.07	2.52
0.23	27.22	25.07	2.52
0.28	86.33	71.75	2.64
0.30	71.29	30.97	3.56
0.33	65.16	33.54	3.46
0.51	4.84	24.96	2.53
0.54	118.14	32.71	2.50

The effects of harmonic superposition are shown by the fact that the areas of the peaks and troughs about R(t)=0 are not equal. At r/D_e=0.065 the amplitude of the peaks are almost double the amplitude of the troughs, i.e. 0-0.4 vs. 0-0.2. An FFT analysis of this wave (not shown) shows a second harmonic at 102/103 Hz but is only 25% the magnitude of the fundamental. At r/D_e=0.29 the amplitude of the peaks and troughs are more comparable indicating that the harmonic influence, although important, is less in this region of the flow. The relative magnitude of the 102/103Hz harmonic at this position is less than 1% the magnitude of the fundamental. These observations also support the notion that several geometrical components lump together to form the resonant state. The sources of these harmonics are integral to understanding the excitation process.



r/D_e=0.065



r/D_e=0.29

Figure 4. – Normalised time correlations for a) unconfined, b) confined and c) resonant conditions at L/D_e=0.13

4. DISCUSSION

Based on the results presented several conclusions arise. Firstly, a high amplitude, low frequency bulk mode resonant condition has been excited without the presence of an exhaust pipe. Prior this it was thought that the exhaust pipe was critical in exciting the resonant state. Furthermore, the higher order harmonics present in the PSD were presumed to be frequency response of the pipe geometry and that its' behaviour was comparable to Helmholtz type pulse combustors, i.e. it influenced the resonant frequency etc. The results show that both the level and shape of the downstream confinement are important and show that an exhaust pipe is not an integral part of the oscillating system. This is emphasised by the fact that the volumetric differences between the confined and resonant geometries is less than 1% (Dawson, 2000). Thus in order to excite the bulk mode resonance, a suitable downstream geometry is required to impose an adverse pressure gradient on the flow upstream. This aids in influencing the characteristic time arguments proposed by Keller et. al. (1989), i.e. resonant, flow and chemical times, which together sustain the oscillation by ensuring the periodic heat release occurs in sync with the resonant pressure field. Preliminary results have shown that the resonant time is strongly linked to the approach flow geometry, which in turn may influence mixing and therefore the flow and chemical times. This is the opposite to pulse combustion systems where the exhaust pipe serves alter the resonant frequency by changing the resonance time with respect to the energy release (Keller et. al, 1989).

The PSD results for the open flame do not exhibit any regular periodicity normally associated to phenomenon such as the PVC, vortex shedding or other coherent structures. If the PVC or any other periodic hydrodynamic phenomena were present the spectra would exhibit frequency response as reported by Chao et. al. (1991), Hoekstra et. al. (1998) and Hawethore and Gouldin (1986). The results presented imply that the role of coherent structures in the excitation process is negligible. Thus coupling of the fluid dynamics with the resonant state, such as the periodic changes to the shape and magnitude of the RFZ induced by the resonance (Froud et. al., 1996)(Dawson, 2000), exist but only serve to maintain the resonance not excite it. Moreover, the frequency response shown in the spectra of the resonant case is discrete whereas normally hydrodynamic phenomena tend to exhibit a small but discernible frequency bandwidth as shown by Hoekstra et. al (1998) as well as Hawethore and Goudlin (1986). This further suggests that any fluid dynamic coupling with the resonance is driven by the resonance and not vice versa.

So the question arises what are the origins of the harmonics? Combustion driven oscillations normally arise when several parts of the geometry resonate at their natural frequencies and interact with the combustion process to form a periodic heat release. This forms a feedback mechanism between the combustion process and the resonating components of the geometry which is maintained if Rayleigh criterion is satisfied. In this case, the geometrical components conspiring to form the resonance are the combustion chamber, the swirl burner and the inlet ducting. Preliminary results of spectra measured in the inlet supply lines (not presented here) show the presence of numerous harmonics. It is therefore considered that some of the frequency peaks represent the resonant modes of the inlet piping. This preliminary work also shows that the systems resonant frequency can be altered with a change in the inlet piping in the same way the resonant frequency of a pulse combustor is affected by a change in exhaust pipe length.

The time-correlations show that the average eddy lifetimes (turbulence macro-scales) reduce as the harmonic response increases (induced by confinement), the shortest average lifetimes achieved by the resonant state and the largest for the open flame. The correlation curves also exhibit phase differences and superposition of the higher order harmonics. Interestingly, the higher order harmonics primarily lie on the inertial slope, i.e. –5/3, showing how that the high frequency resonant feedback influences the velocity field in the inertial flow scale. As these data are velocity derived, the energy peaks do not represent the amplitude of actual acoustic or resonant disturbances themselves but the rather the flow scale at which the resonant influence upon the velocity field becomes noticeable, i.e. the micro-scales. The number of harmonics in the spectra and their additive and subtractive effect on the time-correlations show that feedback between the flow and the resonance occurs in the inertial region emphasising that the feedback mechanism incorporates all the turbulent flow scales.

5. CONCLUDING REMARKS

Spectral and correlation results were obtained for a swirling flame open to atmosphere, confined in a furnace and under resonance each with a constant equivalence ratio and swirl number. A bulk mode oscillation of 52Hz was excited without the presence of an exhaust pipe showing that the resonant condition can be achieved by a suitable level of confinement to form a pressure balance between the inlet pipe work and the combustion chamber.

The spectra of the open flame did not reveal the presence of any periodic phenomena along the measurement plane indicating that these phenomena are not responsible for the excitation process. Thus any fluid dynamic coupling with the resonance serves to maintain the resonance as opposed to exciting it. Numerous high energy frequency peaks corresponding to a fundamental frequency of 52Hz and its harmonics were found in the spectra of the resonant case. The confined case exhibits a discrete frequency peak corresponding to the 5^{th} harmonic, i.e. ≅ 250Hz as found in the resonant condition. This shows that more than one perturbation frequency is required to excite the resonant condition and that subtle changes to the shape of the confinement promotes upstream feedback to the inlet ducting which conspires with the burner and combustor geometry to resonate.

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