Proceedings of The Institute of Acoustics

DIAGNOSIS OF OSCILLATIONS IN A LARGE SWIRL BURNER/FURNACE COMBINATION

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ABSTRACT

This paper describes some experimental work carried out to determine the mechanism of low frequency oscillation occurring in a swirl burner/furnace combination for burning and recovering heat from low calorific value gases. The mechanism is identified as excitation of a fundamental Helmholtz oscillation of the system by a naturally occurring three dimensional time-dependent instability of swirling flows, called the Precessing Vortex Core. The problem arises from the technique used to simulate low calorific value gases in the laboratory (i.e. by dilute mixtures of air and natural gas) and the resulting need to prevent flashback by the addition of a large centre body to the swirl chamber.

INTRODUCTION

Resonant instabilities in furnaces, boilers and cavities can cause many problems especially in large installations where low frequency high amplitude oscillations, besides being undesirable from a 'noise' aspect, may easily cause sufficiently large pressure fluctuations to overstress the outer shell [1,2]. Swirl is commonly used for flame stabilisation purposes and resonant instabilities are sometimes associated with this technique of flame stabilisation [2]. In previous articles the authors have shown that there can be several modes of oscillation caused by various phenomena, including [2,3,4]

1. Organ pipe oscillations, often of quarter or half wave form
2. Helmholtz oscillations
3. Oscillations caused by fluidic dynamic instabilities generated by the swirling flow itself. This is often manifested in the form of a rotating three dimensional structure called the Precessing Vortex Core (henceforth PVC) and located close to the boundary of the reverse flow zone. This is illustrated in Fig.1 [2-7].
4. Combustion/flame generated oscillations
5. Interaction of the above mechanisms

One particular interaction mechanism investigated earlier was that occurring between 1 and 3 above [3]. In this work it was demonstrated that organ pipe oscillations could be excited when the frequency of a three dimensional rotating coherent structure located on the boundary of the reverse flow zone, coupled with a fundamental quarter wave resonant frequency of the system. This coupling was achieved by varying the length of a long exhaust nozzle attached to the exhaust of a small swirl burner. There is little doubt that several modes of coupling can occur, especially with premixed or partially premixed systems, and poor quality fuels. The reason for this is that high temperatures reduce overall swirl levels and thus the size of the reverse flow zone and hence the strength and extent of the PVC. Combustion with low calorific value gases occurs at lower temperatures, often less than 1100°C, giving rise to quite large recirculation zones and associated higher amplitude PVC [2,3].

This paper describes some recent work undertaken to diagnose the source of noise and oscillations in swirl burner/furnace combinations for burning low calorific value gases (of calorific value down to 1.4 MJ/m^3) without support fuel. Fig.2 shows the general design of the system [8]. Essentially it consists of a simple swirl burner comprising two, sometimes four, circular tangential inlets firing into a low cylindrical chamber, feeding directly into an exhaust nozzle. The area of the circular tangential inlets can be simply altered by inserts so as to vary the swirl number. Typical operating swirl number levels are between 0.8 and 1.5. The swirl burner fires into a compact refractory lined furnace and is exhausted via a conical contraction. Flame stabilisation is by aerodynamic recirculation of heat and active chemical species combined with heat re-radiation from the refractory lined furnace. Low calorific value gases are simulated in the laboratory by using dilute mixtures of natural gas. To prevent flashback into the inlets a flat centre body is inserted into the swirl burner so as to accelerate flow into the exhaust nozzle. The gap between the top of the centre body and the top plate of the swirl burner was varied between 0.087 and 0.253 De for the quarter scale unit. For the larger unit this gap was fixed at 0.253 De. Two systems were used, a full size version with a 300 mm exhaust to the swirl burner and a quarter scaled version with a 75 mm exhaust nozzle.

Noise and oscillation problems initially manifested themselves on the large system and for reasons of economy, the diagnostic work was undertaken on the quarter scale model as described in the next section.

EXPERIMENTAL PROCEDURE AND RESULTS

Initial appraisal of the large system indicated that low frequency oscillations /vibrations of the system (up to 40-50 Hz) were possibly caused by interactions between mechanisms 1/2 and 3/4 detailed in the introduction. To elucidate these mechanisms and associated interactions, a series of experiments were undertaken on the quarter scale model, especially to try to separate effects due to organ pipe or Helmholtz oscillations. The following configurations were investigated (and detailed in Table 1):

Test No	Gap Between Centre Body and Top Plate of Burner (mm)	Length of Furnace (mm)	Swirl No
1	6.5	344	1.08
2	19	344	1.08
3	19	224	1.08
4	19	614	1.08
5	19	344	0.92
6	6.5	344	0.92
7	19	614	0.92

The experimental procedure was to set up an initial flowrate (based on realistic operating conditions for the large furnace), establish combustion and slowly reduce the fuel (premixed natural gas and air) until blowoff occurs. Oscillation frequencies were detected by inserting a water-cooled Pitot tube (with adequate frequency response) and attached pressure transducer, close to the base of furnace. The resulting frequencies were recorded and analysed on an available Hewlett Packard frequency analyser. Two main oscillation frequencies were found, one a pre-cursor to the main oscillation, and the main oscillation (obviously of highest amplitude).

The results of the experiments are summarised in Table 1, together with calculations of the associated organ pipe quarter wave and Helmholtz oscillations. The organ pipe frequency is obtained by using the total system length from the centre body to the end of the exhaust nozzle. Examination of the table clearly shows that with none of the tests do any of the organ pipe frequencies even approach any of those measured. This is not the case with the Helmholtz oscillations. Basing the calculations on the perimetric area between the centre body and the top plate of the swirl burner, with a path length from the swirl burner nozzle to the back plate, gave the results shown. There is a clear association between many of the main and pre-oscillatory frequencies recorded and the calculated Helmholtz frequency, although the method of excitation is not immediately clear; for instance, with Test 3, no main oscillatory frequency was recorded.

Reference to [3-7] indicates how the Helmholtz resonance can be achieved. It has previously been demonstrated how the PVC can excite quarter wave organ pipe oscillations and doubtless the PVC can also excite Helmholtz oscillations. This is demonstrated below. Figs.3 and 4 show the occurrence and frequency of the PVC for the swirl burner used in this work when operating under combustion conditions, burning natural gas with 10% excess air. The PVC can exist in two modes under combustion conditions, either as a single or as a double cell structure, this being a function primarily of swirl number, Fig.2. Associated non-dimensionalised frequency data are shown in Fig.3 for both single and double cells PVCs. Little dependence on mixture ratio was shown and the frequency data can be characterised simply by a non-dimensionalised parameter fDe^3/Q. The sharp change in the value of fDe^3/Q for flow rates between 1000 and 2000 l/min for a swirl number of 0.9 is accounted for by a sharp change in the location of the flame front. This does not occur at higher swirl number as the flame is firmly located on the back of the centre body. Corresponding frequencies of the single and double cell PVCs are also shown in Table 1.

Bearing in mind the assumptions made in calculating the Helmholtz frequency and the measurements of the PVC frequency in free flames, a clear association can be seen between the two PVC frequencies, the Helmholtz frequency and the two oscillation frequencies. Test 3, where there is no main oscillation frequency, is a case where the PVC frequencies and the Helmholtz frequency do not coincide, although the pre-oscillatory frequency indicates that the double cell PVC frequency is near to exciting other modes of oscillation for flowrates less than 3000 l/min. The general trend appears to be that excitation of the Helmholtz frequency occurs due to coupling from the double PVC frequency for flowrates up to 2000-2500 l/min, i.e. Tests 4, 5 and 6. The single PVC does not excite the main oscillation frequency except at high flowrates, above 2500 l/min, i.e. Test 7; it also sometimes appears to excite the pre-oscillatory frequency at high flowrates, i.e Tests 6 and 7.

There is thus little doubt that coupling between various modes of oscillation of the PVC and fundamental Helmholtz frequencies of the system can excite large amplitude oscillations, doubtless aided by the combustion process [1]. These conclusions reinforce those found by one of the authors that the PVC and organ pipe oscillations can also mutually excite oscillations in combustion systems.

From the designer's point of view, the main criterion is how to prevent and/or minimise such phenomena in practice. Several points emerge.

1. The single PVC undoubtedly has the highest amplitude; successive harmonics have lower amplitudes and hence lower propensities to excite other oscillation mechanisms. Decoupling of oscillation mechanisms can thence sometimes be made by increasing the swirl number when excitation is due to the single PVC.

2. The gap between the centre body and top face of the swirl burner is important. Enlarging this gap increases the Helmholtz frequency and reduces the propensity of the system to oscillate, although increasing the possibility of flashback with premixed flames. Subsequent work has indicated that removal of the centre body and mixing the air and low calorific value gases via two sets of tangential inlets firing into the swirl burner body substantially reduces the problem.

3. Other work indicates that a centre body in the furnace exhaust can de-couple the oscillations [9]. Calculations for the large full-size furnace indicate a fundamental Helmholtz oscillation frequency of about 40 Hz. Corresponding PVC frequencies are approximately 25% of those shown in Table 1 for a corresponding air and gas loading (closest correspondence between the quarter- and full-sized systems occurs for Tests 2 and 5). Thus it is the double PVC structure which is exciting the Helmholtz oscillation in the swirl burner/furnace combination as the single PVC frequencies are too low. The problem can be alleviated by increasing the gap between the centre body and the swirl burner top plate; in practical systems it can be alleviated by using four tangential inlets (two for low calorific value gases, two for air) and mixing the gases in the swirl chamber, eliminating the need for the centre body as a flashback protector.

CONCLUSIONS

Coupling between the precessing vortex core and the first harmonic naturally occurring three dimensional time-dependent instabilities generated by many swirling flows with recirculation zones can give rise to oscillation problems by coupling with fundamental Helmholtz frequencies of the system.

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Table 1. Swirl burner/furnace combinations - oscillation frequencies

Experimental condition	Flowrate l/min air/gas	Helmholtz frequency Hz	Quarter wave organ pipe frequency Hz	Main oscillation frequency Hz	Pre-oscillatory frequency Hz	Double cell PVC (1st Harmonic) frequency Hz	Single PVC freq. Hz
1. Total furnace length 344 mm Swirl No 1.08 *Gap 6.5 mm	1100/70	129	404	-	63	94	31
	1100/80			111	-	95	31
	1600/110			-	184	137	45
	1600/120			116	-	138	45
	2000/140			111	-	176	55
	2500/180			119	-	215	69
	3000/180			-	111	254	82
	3000/200			125	-	256	82
2. Total furnace length 344 mm Swirl No 1.08 Gap 19 mm	1600/120	220	404	143	-	138	45
	2000/140			184	180	176	55
	2500/175			196	-	215	69
	3000/220			246	-	257	82
3. Total furnace length 224 mm Swirl No 1.08 Gap 19 mm	2000/160	292	547	-	186	177	55
	2500/195			-	195	178	69
	3000/240			-	109	258	82
4. Total furnace length 344 mm Swirl No 1.08 Gap 19 mm	1600/120	156	254	-	134	138	45
	1600/130			168	-	139	45
	2000/135			-	168	176	55
	2000/140			181	-	176	55
	2500/170			-	101	215	69
	2500/180			103	-	216	69
	3000/200			105	105	256	82
5. Total furnace length 344 mm Swirl No 0.92 Gap 19 mm	2000/150	220	404	-	180	176	55
	2000/160			182	-	176	55
	2500/173			-	185	215	69
	2500/180			186	-	215	69
	3000/220			-	106	256	82
	3000/225			226	-	256	82
6. Total furnace length 344 mm Swirl No 0.92 Gap 6.5 mm	1600/130	129	404	-	103	139	45
	1600/135			112	-	139	45
	2000/140			-	179	176	55
	2000/145			183	-	176	55
	2500/180			-	106	215	69
	2500/185			208	-	215	69
	3000/205			-	110	255	82
	3000/205			246	-	256	82
7. Total furnace length 614 mm Swirl No 0.92 Gap 19 mm	1600/120	136	254	-	136	139	45
	2000/140			-	171	176	55
	2000/145			179	-	176	55
	2500/170			-	181	215	69
	2500/175			188	-	215	69
	3000/205			-	104	255	82
	3000/210			105	-	256	82

Notes Helmholtz and organ pipe frequencies calculated with assumed average gas temperature of 1100°C to give an acoustic velocity of 740 m/s.

*Gap - this is the gap between the top of the centre body and the top plate of the swirl burner

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ACKNOWLEDGEMENTS

The authors acknowledge the financial support of National Smokeless Fuels and NCB Coal Products Ltd in this work.

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NOMENCLATURE

De	Exit chamber of swirl burner
f	Frequency of oscillation - Hz
PVC	Abbreviation for the Precessing Vortex Core
Q	Inlet flowrate of gases at NTP conditions
Sg	Geometric swirl number [2] - ratio of axial flux of angular momentum to axial flux of axial momentum - non-dimensionalised by the exhaust radius

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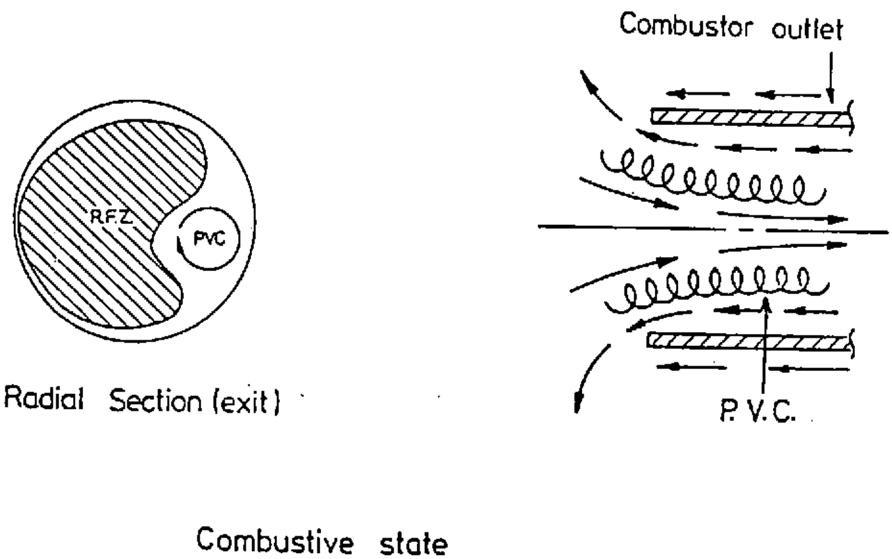

Fig. 1 Precessing Vortex Core in Swirl Burners

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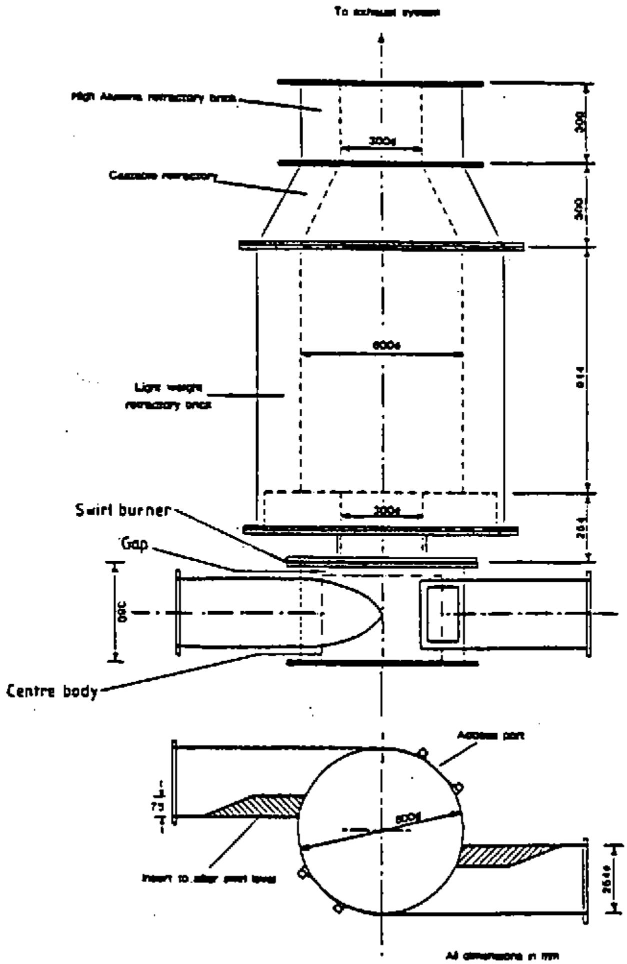


Fig.2. Large Swirl Burner/Furnace Combination to burn Low Calorific Value Gases

DIAGNOSIS OF OSCILLATIONS IN A LARGE SWIRL BURNER/FURNACE COMBINATION

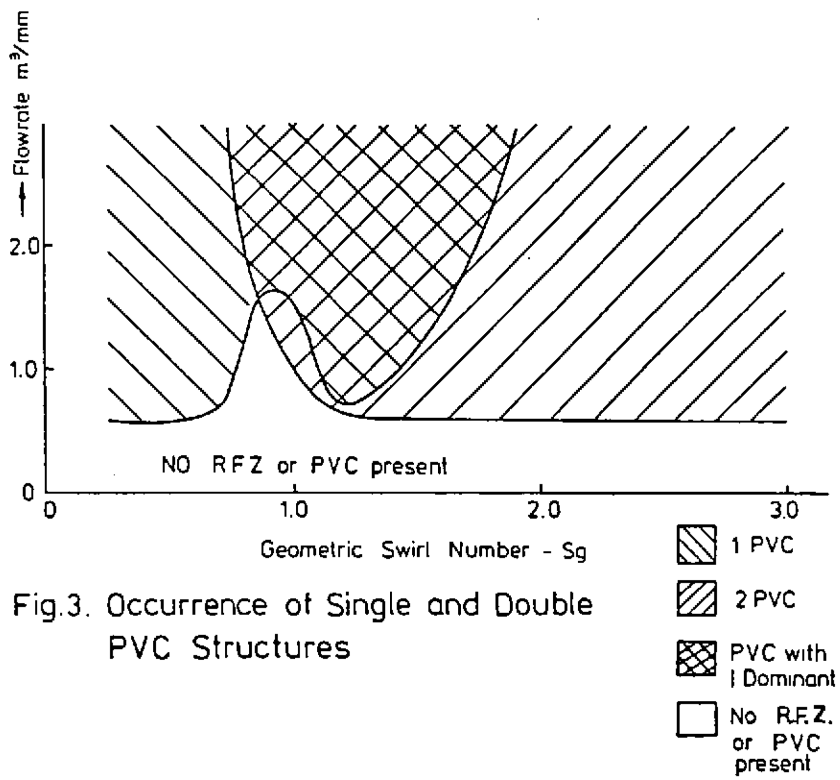
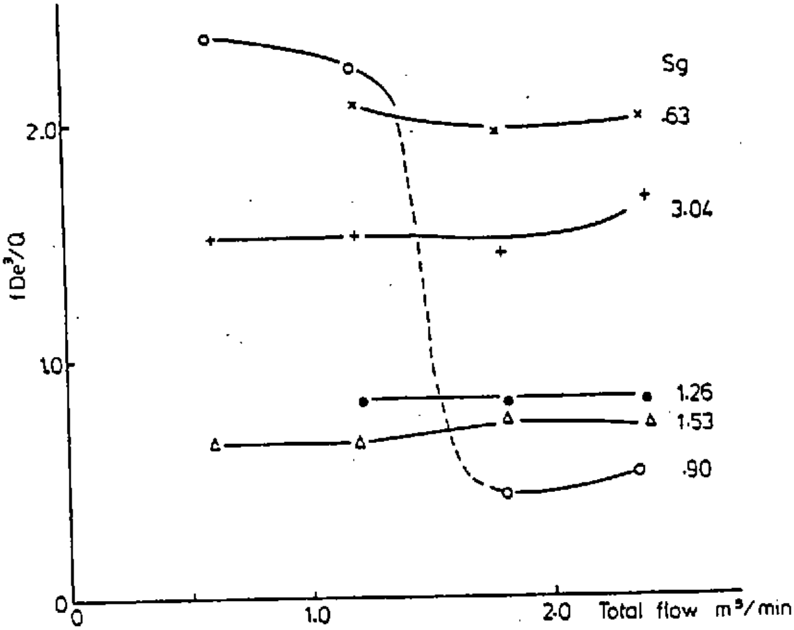
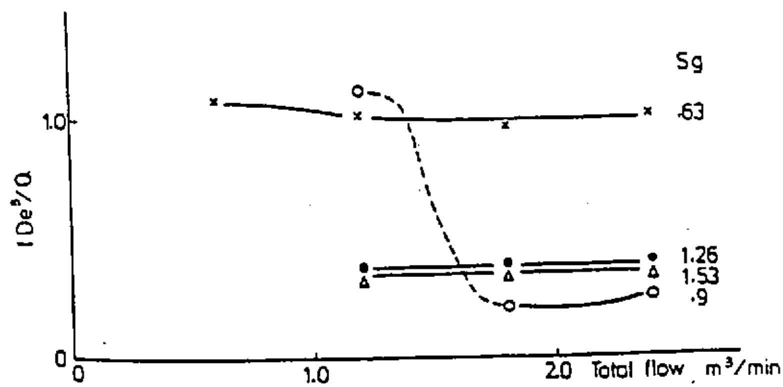


Fig.3. Occurrence of Single and Double PVC Structures

Fig4. Variation of Non Dimentionalised frequency Parameter with Flowrate for Quater Scale System



a) For 1st. Harmonic (double P.V.C.)



(b) Single P.V.C.

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