COMBUSTION DRIVEN OSCILLATIONS IN A WASTE GAS INCINERATOR

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1 INTRODUCTION

This paper presents the results of an investigation into a low frequency tonal noise which was experienced from a new waste gas incinerator at a plant in Tunisia. During commissioning trials for the equipment, a low frequency tonal noise was experienced which led to complaints from the local community. The Acoustics and Vibration Group of Bureau Veritas (BV) was commissioned to investigate the noise problem. The study objectives were to:

i. undertake noise measurements around the incinerator during equipment trials;
ii. investigate the root cause of the characteristic noise; and
iii. make recommendations and propose remedial action to reduce or eliminate the characteristic noise.

2 EQUIPMENT DESCRIPTION

The purpose of the incinerator is to thermally oxidise any waste gas produced by the gas plant in order to reduce the amount of gas emissions to the environment. The waste gas includes traces of hydrogen sulphide (a highly toxic gas), ethane, methane, propane, benzene, toluene and many other gases. A simplified arrangement of the incinerator is shown in Figure 1, including approximate dimensions.

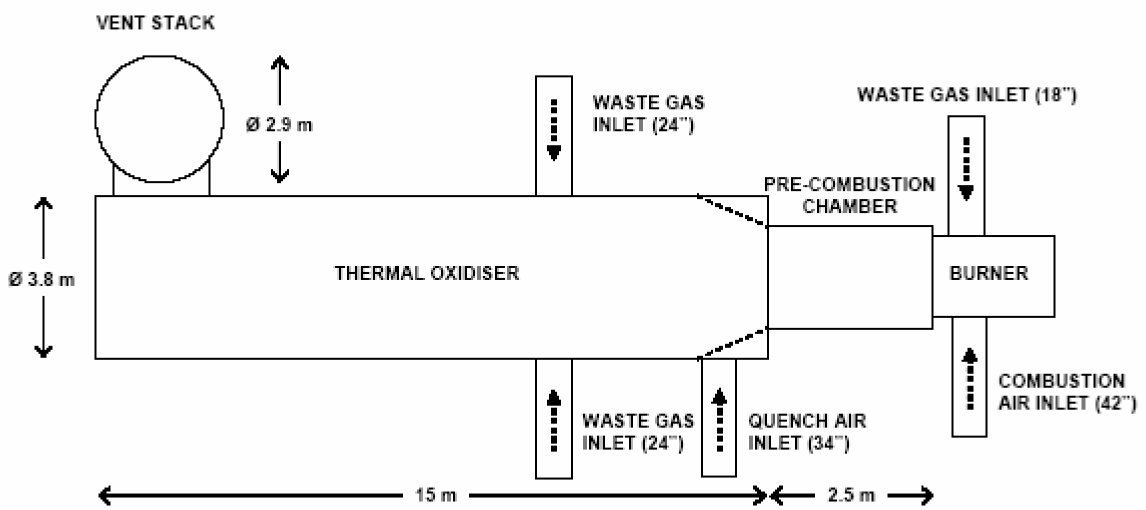

Figure 1: Simplified Arrangement of Incinerator

3 BACKGROUND

A noise survey was undertaken by a local consultancy during equipment trials in February 2006. The survey report noted that tonal noise was experienced both in the vicinity of the incinerator and at nearby community receptor locations. Tests were conducted with different concentrations of waste gas running through the incinerator. Before waste gas was introduced into the incinerator (i.e. when running with quench air only) the noise from the incinerator was not such as to cause environmental noise problems. In this operating condition, a tone was measured at 43 Hz although this was not of sufficient magnitude to cause concern. However, when the waste gas valve reached the 25% open position, the tone changed to 36 Hz and increased in magnitude such that it was very prominent in the community. (It should be borne in mind that the % open position of the valve does not necessarily directly correspond to the % of waste gas in the incinerator.)

Based on the approximate dimensions of the incinerator and information regarding the temperature and molecular weight of the gas inside the thermal oxidiser, it was possible to calculate the resonant frequencies likely to be encountered under different conditions. It was assumed that the cavity acts as a half-wave resonator (i.e. closed at both ends) using the equation $f=nc/2L$, where n = 1,2,3 etc, c = speed of sound and L = length of pipe. Although the real-life situation is more complex, this gives an initial approximation of the likely resonant frequencies which can be compared to the actual resonant frequencies measured under similar conditions. The results of the calculations are presented in Table 3.1, compared with the measurement results.

Operating Condition	Measured Frequency, Hz	Calculated Resonant Frequency, Hz		
		Fundamental	1st Harmonic	2nd Harmonic
Quench air only	43	22	**44**	66
Waste gas	36	19	**38**	56

Table 3.1: Comparison of Calculated Resonant Frequencies for Thermal Oxidiser Cavity Compared with Measured Tonal Frequencies

From Table 3.1 it can be seen that the measured characteristic frequency for each operating condition agrees well with the predicted resonant frequency for that condition, specifically the first harmonic. This would therefore appear to confirm the initial suspicions that the phenomenon encountered is an acoustic resonance of the thermal oxidiser cavity. This type resonance is likely to be a phenomenon called combustion driven oscillation.

Combustion driven oscillations are known to occur when a turbulent flame is enclosed in a tube or cavity (as described in References 1 - 3). Interaction between heat fluctuations and the internal standing wave field at one of the natural frequencies can produce strong tones. When a burner nozzle sees a sinusoidal varying backpressure (caused by the standing wave resonance), the fuel emerges at the same varying rate. Depending on the jet velocity and flame speed, there will be a small delay between when the fuel 'pulse' emerges from the nozzle and when it ignites to cause an increase in pressure within the cavity. If the heat release coincides with the positive pressure pulsation due to the cavity resonance, then a positive feedback mechanism is set up. Alternatively, if the flame speed or jet velocity are changed such that the heat release coincides with a pressure minima, then the feedback mechanism is suppressed. In other words, if the fluctuating heat release is more in-phase than out of phase with the natural resonance, then conditions are right for the flame to feed energy back into the acoustic resonance.

The two approaches typically utilised to mitigate problems associated with combustion oscillation (Reference 2) are to either install a single-hole orifice at the centre of the cavity or to shift response time between output and input by changing the fuel mixture ratio or the burning delay time (i.e. by adjusting the flame speed and jet velocity). Indeed, the equipment manufacturer, Callidus

Technologies, had previously utilised the second of these techniques in this case such that it is possible, by careful manipulation of the fuel gas supply valves, to avoid the 'resonant zone'. This involved using only the centre burner nozzle with an increased pressure (and, hence, increased jet velocity) instead of using both the centre nozzle and one of the outer rings at a lower pressure.

4 METHOD

4.1 Survey Approach

Although the local consultant's report presented the results of noise and vibration measurements under several operating conditions, it was considered that the report contained insufficient detail to identify the "worst-case" operating condition of the incinerator. It was therefore decided to take on-site and environmental noise measurements whilst introducing different concentrations of waste gas into the incinerator in stages. This would allow the worst-case operating condition to be identified.

4.2 Off-Site (Environmental) Survey

The principal objective of the environmental measurements was to identify the amount that the characteristic tone emerges above the background level in order to quantify what reduction in that noise would be required in order to reach an acceptable solution. However, a secondary objective was to obtain a measurement of noise from the incinerator which would include noise emitted from the stack. This was required because it was not possible to get measurements near the stack exit, due to safety considerations. Due to stack exit directivity characteristics, it was necessary to take readings some distance from the stack. In addition to taking far-field measurements, a series of in-stack sound pressure level measurements were obtained using a microphone probe.

Sound pressure levels were recorded in 1 minute intervals at a location some 530 m north from the incinerator stack. This location is an equivalent distance from the site as the nearest residential properties. Figure 2 shows a view of the measurement location looking towards the plant. The waste gas incinerator stack is near the centre of the picture with red and white stripes.

Figure 2: Environmental Noise Measurement Location

In addition, narrowband noise measurements were undertaken during each operating condition using an FFT analyser fitted with an ICP microphone.

4.3 On-Site Survey

The purpose of the on-site surveys was to identify the source of the characteristic noise and to collate any data which may help in determining a solution. A fixed noise monitoring point was established some 10 m from the incinerator and both overall linear and narrowband measurements were recorded for each waste gas valve position. In addition, investigative noise and vibration measurements were conducted on and around the incinerator and associated equipment. Measurements included third-octave and narrowband sound pressure levels.

The investigative noise measurements were conducted at various locations around the incinerator, air supply fans and associated pipework and valves. Surface velocity vibration measurements were taken on the surface of the incinerator, stack, air supply duct and waste gas duct (downstream from valve).

Once the worst-case condition was identified, a series of more detailed investigative measurements were undertaken around the incinerator. The incinerator was then run up under a variety of operating conditions in order to help understand the noise generating mechanism and to help determine possible noise control measures. Parameters which were varied included the quench air flow rate, fuel gas pressures and spading off one of the waste gas inlet pipes.

5 RESULTS AND DISCUSSION

Figure 3, below, shows the relationship between the waste gas valve position and the measured community noise level (530 m north of the incinerator). Since the tone appeared at 57 Hz on this occasion, the sum of the 50 and 63 Hz third octave bands was used to measure the characteristic noise. The graph clearly shows that the characteristic noise appears once the valve is approximately 20% open. It would also appear as though the sound pressure level decreases slightly after the valve reaches 45% open, although this could be due to changes in meteorological conditions or other variables. It was noted during the tests that the waste gas line was clearly audible at the community monitoring location when the valve was first opened. This noise was broadband in nature as opposed to the characteristic tonal noise.

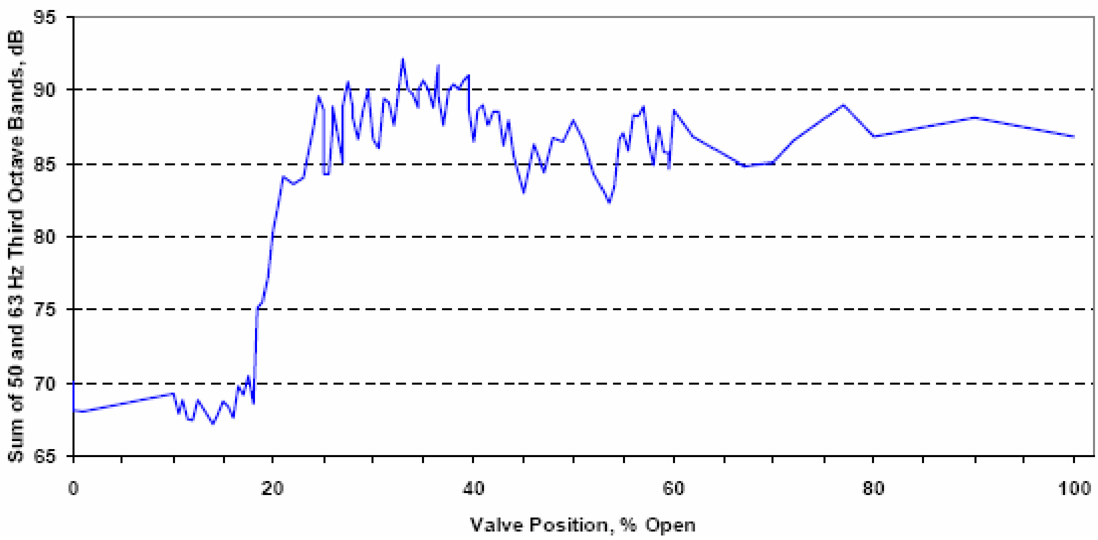

Figure 3: Relationship between Waste Gas Valve Open Position and Characteristic Noise - 500 m North of Incinerator

Figure 4 shows a comparison between the narrowband measurements with the waste gas control valve set at 21% and 100% open conditions. There is a strong, prominent tone at 55.7 Hz for the 21% condition and at 56.7 Hz for the 100% waste gas condition.

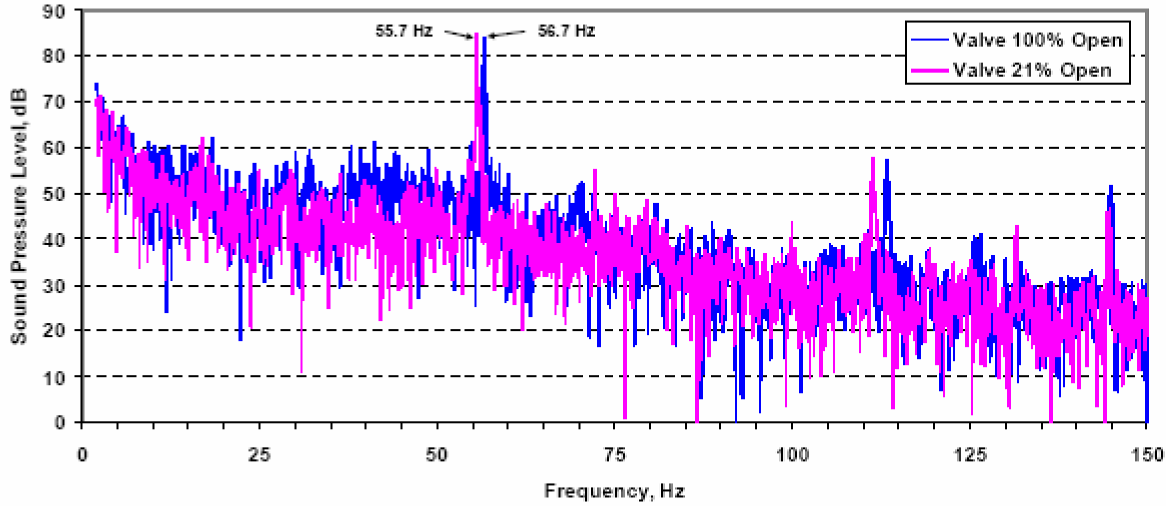

Figure 4: Narrowband Sound Pressure Level Measurements at 21% and 100% Waste Gas Valve Position – 500 m North of Incinerator

Given that the tone measured in the community is some 50 dB above the hearing threshold for a pure tone, according to the standard BS ISO 226:2003 (Reference 4), it is not surprising that local residents have complained of annoyance. Furthermore, the low frequency noise was reported to cause windows and fittings to rattle inside properties, thus causing further annoyance and disturbance.

From Figure 4 it can be seen that the frequency of the tone increases by 1 Hz between the valve's 21% and 100% open positions. This shift would be expected for an increase in molecular weight within the cavity, such as for an increased concentration of waste gas. It should be noted that the control valve is not necessarily linear and that, subsequently, the 21% open condition does not mean that the waste gas flow rate was at 21%. Once the valve had reached the 100% position, the fuel porting was changed to suppress the tone.

The first on-site survey was conducted concurrently with the off-site survey. Figure 5, below, shows the typical on-site narrowband sound pressure levels with the waste gas control valve set at 100% open conditions with various pressure adjustments on the fuel gas valve for the centre nozzle at 2 bar and 2.5 bar*. It can be seen from the graph that the tone at 57 Hz was replaced by tones at 32 and 36 Hz (with 2.5 bar pressure). As previously discussed, the 36 Hz tone roughly coincides with the first harmonic of the thermal oxidiser cavity longitudinal resonance.

At first, the presence of the tone at 32 Hz appeared to disprove the theory that the natural acoustic frequency of the oxidiser cavity was being excited through an interaction with the flame oscillations. However, further calculations showed that the 32 Hz tone coincides with the first harmonic of the longitudinal resonance of the thermal oxidiser cavity and the pre-combustion chamber combined. This change in tone coincides with a change in primary nozzle, from the outer ring to the centre fuel gas nozzle. Therefore, it would appear as though changing the gas nozzle position causes an excitation of the larger combined cavity rather than the oxidiser cavity alone. This occurs due to a change in the cross-sectional area from the oxidiser to the pre-combustion chamber resulting in the acoustic wave experiencing a partial reflection. It is, therefore, possible to experience a standing wave at both frequencies, as observed in Figure 5.

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* *The measurements presented in Figure 5 were conducted by the consultancy Hessler Associates.*

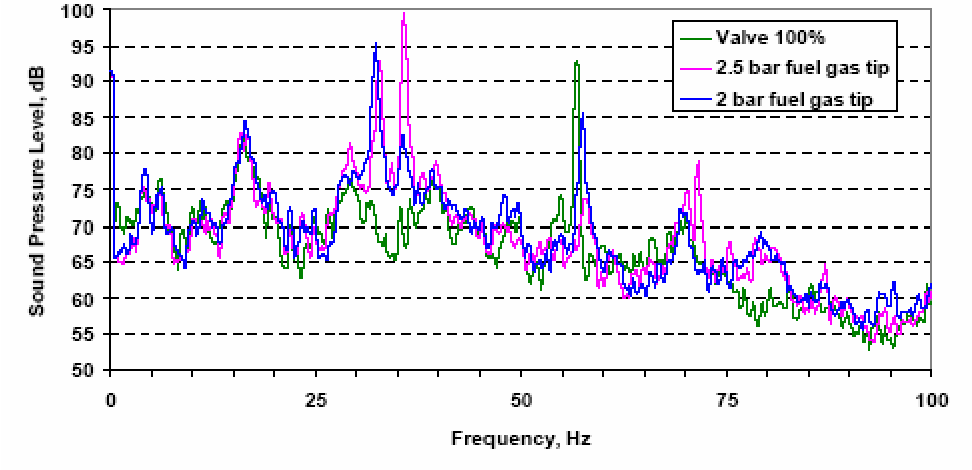

Figure 5: Narrowband Sound Pressure Level Measurements at Different Fuel Gas Valve Positions – 10 m from Incinerator

The results confirmed the off-site measurement results which show that the characteristic tone occurs once the waste gas valve position reaches approximately 20%. It also confirms the lower frequency tones which were measured at the community, although the relative magnitude of these lower frequency tones is higher when closer to the equipment. This is, perhaps, because the attenuation afforded by the walls of the incinerator will be less for lower frequencies than for higher frequencies which would result in a higher relative magnitude, whereas the community noise level is more likely to be dominated by noise from the stack exit.

The next test was to repeat the test with a higher quench air flow rate (using both the centre and outer fuel gas ring nozzles at the same time) in order to understand what effect, if any, the rate of quench air flowing through the incinerator has on the characteristic tone. Figure 6, below, shows the relationship between the waste gas valve position and the magnitude of the characteristic noise (plotted as the sum of the 50 Hz and 63 Hz third-octave bands).

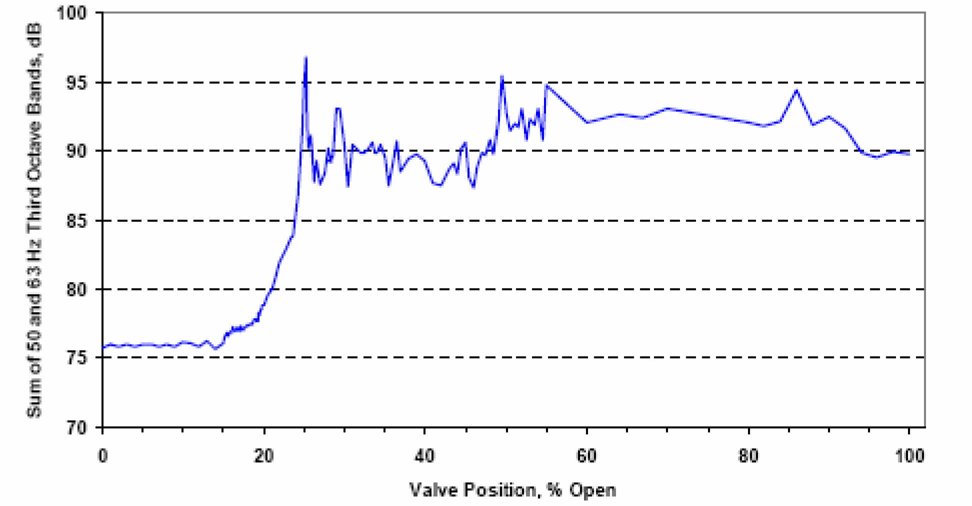

Figure 6: Relationship between Waste Gas Valve Open Position and Characteristic Noise – 10 m from Incinerator (Increased Quench Air Flow, Outer Ring and Centre Nozzle Combined)

Figure 7 shows the narrowband sound pressure levels at different positions for the fuel gas valve with increased quench air flow through the oxidiser and with the waste gas valve at 100% open.

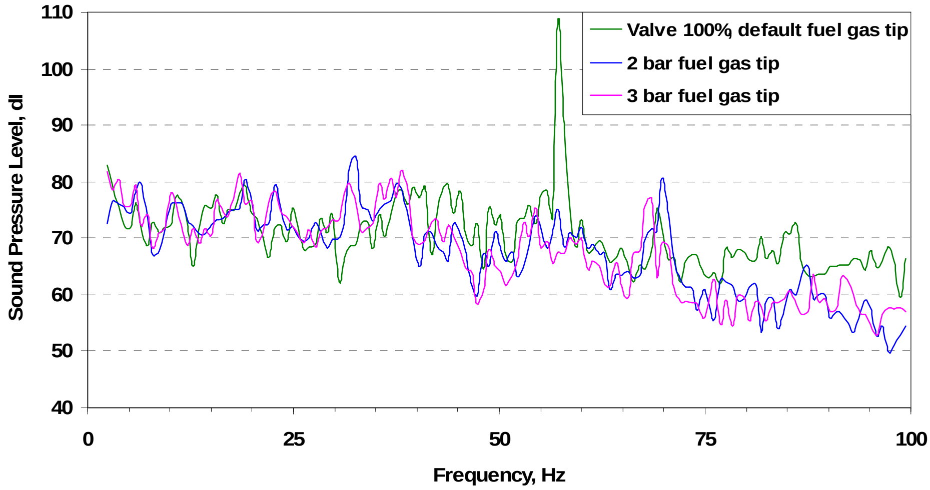

Figure 7: Narrowband Sound Pressure Level Measurements at Different Fuel Gas Valve Positions– 10 m from Incinerator (Increased Quench Air Flow, Outer Ring and Centre Nozzle Combined)

From the above figures, it can be seen that increasing the quench air flow rate through the oxidiser cavity had a minimal effect on the characteristic noise when using both the inner and central fuel gas nozzles at the default settings for operation. However, there is a reduction in the magnitude of the lower frequency tones with the fuel gas nozzle pressures increased to 2 bar and 3 bar. This showed that utilising higher quench air flow through the incinerator slightly reduced the extent of the 'resonant zone', thus allowing the incinerator to operate with a wider band of operating conditions.

The next test was to repeat the above measurement exercise but with only the centre fuel gas nozzle (operating at 2 bar) and with the higher quench air flow through the cavity. The relationship between the gas valve position and the magnitude of the characteristic noise is shown in Figure 8.

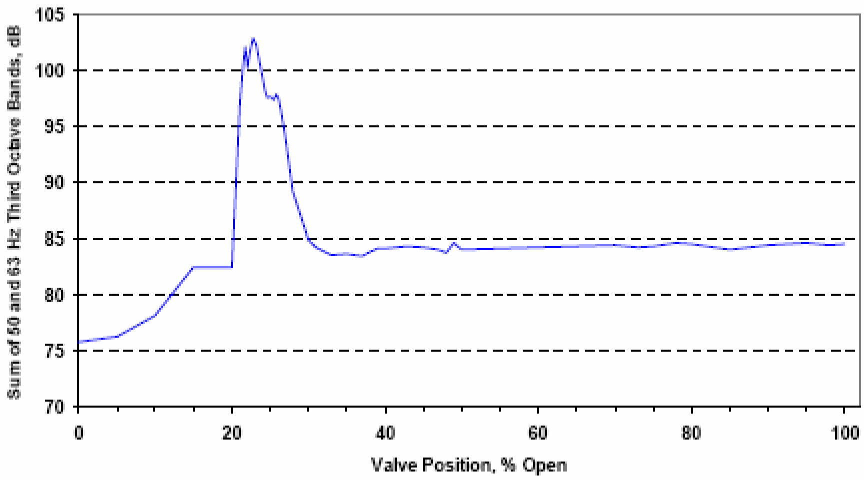

Figure 8: Relationship between Waste Gas Valve Open Position and Characteristic Noise – 10 m from Incinerator (Centre Fuel Gas Nozzle Fully Open)

It can be seen that when operating on just the centre nozzle and with increased quench air, the characteristic noise only occurred with the waste gas valve position between 20% and 30%.

The last tests involved introducing a spade to the 18” waste gas line so that waste gas was only introduced into the incinerator after the pre-combustion chamber. These tests, as shown in Figure 9, were undertaken by the local consultancy following the demobilisation of BV from site and, as such, the measurements are less detailed than for other operating conditions (e.g. no narrowband results).

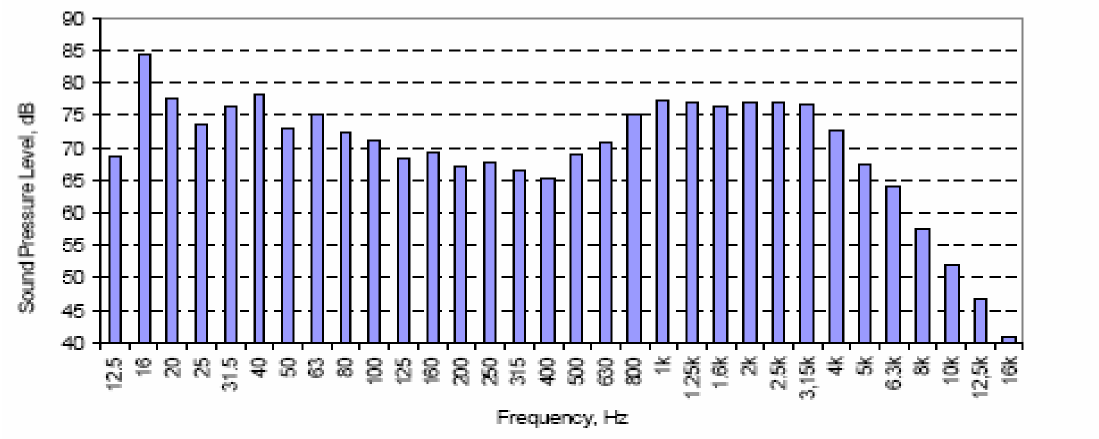

Figure 9: Third-Octave Sound Pressure Level Measurement at 20% Waste Gas Valve Position – 10 m from Incinerator (Centre Fuel Gas Nozzle Fully Open with 18” Waste Gas Line Spaded)

Inspection of the third-octave spectra for this operating condition shows a distinct increase in the 16 Hz third-octave band. It should be borne in mind that the fundamental of the longitudinal resonance of the thermal oxidiser cavity and the pre-combustion chamber combined is 16 Hz. It is, therefore, likely that the resonance was encountered at the fundamental frequency during this test, although narrowband measurements would be required to confirm whether this was the case. Although the noise might be inaudible on site or in a free-field environment, there is a possibility that it could cause windows and fittings to rattle inside residential properties. In any case, the characteristic noise appeared when the waste gas valve was about 20% open and died off very quickly with further opening of the waste gas valve.

6 CONSIDERATION OF POSSIBLE RECOMMENDATIONS

6.1 General

It may be possible to mitigate the characteristic noise by a variety of techniques. An evaluation of the techniques which were considered throughout the trials is summarised in the following sections.

6.2 Operating Parameter Changes

The tests demonstrated that it is possible to avoid the resonant condition causing the characteristic noise by altering the configuration of the burner; specifically by altering the fuel gas nozzle valves such that the majority of flow goes through the central nozzle. This essentially avoids the ‘resonant zone’ of the system by altering both the position of the flame and the phase relationship between the flame oscillations and the standing wave. The most effective operating condition for reducing the characteristic noise was as follows:

a) Centre fuel gas nozzle valve fully open (pressure of at least 2 - 2.5 bar);
b) One of the outer fuel gas rings set at 33% position.

In addition, there appears to be some benefit in continuing to operate with the 18" waste gas line spaded off.

This method of controlling the resonance may well prove to be the most effective and least costly solution. However, it is not known whether this configuration is sustainable under the full range of operating conditions under which the incinerator may be required to operate. For example, it may be that by increasing the waste-gas throughput or by changing its constituency, a further 'tweaking' may be required in order to avoid the 'resonant zone'. Such a scenario may occur when the waste gas throughput is increased in the future.

Although it was asserted by Callidus that increasing waste gas throughput would normally result in a reduction in the characteristic noise, it is not possible to confirm this until additional waste gas is introduced. That said, the evidence from the tests appears to support this assumption – i.e. that the characteristic noise is reduced by higher waste gas flow rates.

It may therefore prove necessary to undertake further tests once the full waste-gas capacity of the system has been reached (currently, the available fuel gas rate is 50% of the design capacity). It would then be possible to plot the boundaries of the resonant zone for the incinerator and adjust the control programme to avoid operating within that zone. However, there is no guarantee that, if a different waste-gas or fuel-gas mixture is introduced, the problem would not re-occur.

As the tonal frequency can emerge under different operations conditions, even with a change in configuration of the burner, it was recommended that a permanent noise monitor should be installed on the site boundary. The monitor could be set up to continuously monitor noise levels and to provide a warning (for example, by the use of a warning tone or light in the control room) whenever low frequency noise exceeds a specific threshold. This could be used as an early warning system so that operating parameters can be changed in order to avoid the resonant zone of the incinerator.

6.3 Burner Tip Design

It may be possible to achieve a similar effect to that described above (for operating parameter changes) by redesigning the fuel gas tips. The current design produces three jets of fuel gas per head. By redesigning the tips with two holes instead of three, it is possible that the increased jet speed of the gas will allow a greater operating range outside of the resonant zone. The manufacturer is currently producing an alternative design of burner tip with two holes to trial on the incinerator later this year. If successful, this method of avoiding the resonant tone would probably be the most effective solution, both in terms of permanence and cost.

6.4 Orifice Plate / Mesh Insert

Another method of reducing or eliminating combustion oscillation could be to install a single-hole orifice plate or mesh insert inside the thermal oxidiser cavity (as suggested in Reference 2). This would work by introducing a resistance to particle movement at the point of highest oscillatory particle velocity (i.e. pressure minima) within the cavity. Figure 10 shows the pressure standing wave for a vessel which is closed at each end. The figure shows the fundamental frequency (f_1), the first harmonic (f_2) and the second harmonic (f_3).

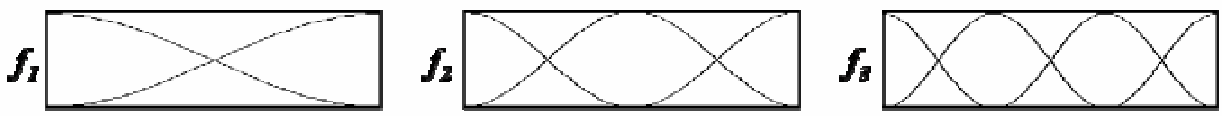

Figure 10: Standing Wave Patterns (Pressure) for Closed End Vessels

As the frequency of concern is the second harmonic, the most effective location for the orifice plate would be half way along the cavity since this would affect both the fundamental and the second harmonic. However, a second orifice plate may be required in order to mitigate the first harmonic. Due to the cavity temperature, it is likely that the orifice would need to be constructed from refractory brick. The likely configuration is show in Figure 11.

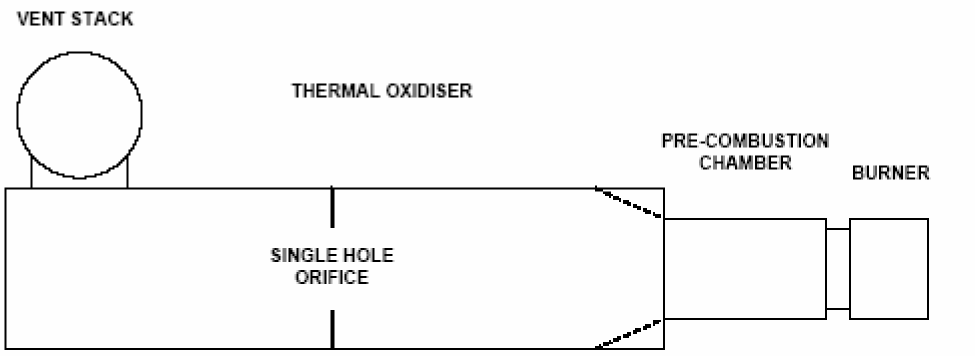

Figure 11: Proposed Arrangement for Single-Hole Orifice in Thermal Oxidiser

The diameter of the open section through the orifice should be half the diameter of the cavity. However, this could result in a higher velocity gas flow through the thermal oxidiser, thus reducing the residency time and burning efficiency. An alternative to utilising a single orifice with 50% diameter would be to use two orifices of nominally 65% diameter, although this may also prove to be impractical for the previously stated reasons. It is therefore concluded that this method of mitigation would not be a practicable solution.

An alternative to utilising an orifice plate would be to introduce some form of damping material at the point of highest oscillatory particle velocity. Suitable materials could include sintered steel mesh filters similar to those used in aircraft engines. Such materials can withstand temperatures in the order of 800 ^{o}C and would not introduce a large back pressure. In order to mitigate the first and second harmonics, it may be necessary to install two mesh filters inside the cavity, as discussed above. Since it is preferable to install the filters as far from the flame as possible, the filters should be located approximately 1/6 and 1/4 along length of the cavity, nearest to the stack. Since the real-life situation is more complex than the simplistic calculations performed thus far, it was recommended that a computer model should be built in order to more accurately assess the most effective locations for any mesh filters and in order to quantify the likely effect of installing such filters. In any case, the relative difficulties and uncertainties involved with this potential solution mean that other mitigation measures – especially changes to the fuel gas porting and modifications to the fuel gas tip – should be tried first.

6.5 Helmholtz or ¼ Wave Stub Resonator

It may be possible to install a Helmholtz or ¼ wave stub resonator on the stack in order to reduce the low frequency tones. However, this possible mitigation measure is unlikely to be practicable because a different resonator would be required for each tone. The advantage of a ¼ wave stub resonator is that it would reduce the harmonics in addition to the fundamental frequency, as opposed to a Helmholtz resonator which will only reduce one frequency, thus requiring several devices to be installed – one for each frequency and harmonic of concern. As with the mesh insert discussed above, the potential cost of this option means that consideration should only be given to its implementation if other solutions prove unsatisfactory over the full operating range of the equipment.

6.6 Stack Silencer

It is considered possible to reduce magnitude of the characteristic noise by installing a stack silencer. BV has encountered silencers on incinerators similar to the one at this plant in the past. On one occasion, a silencer was installed on an incinerator in the UK with an operational temperature of 900 ^{o}C. The unit introduced a back pressure of 1.25 mBar onto the system at the design flow rate of 99.7 m^3/sec. The silencer was 3 m in diameter and 5.25 m long and had a weight of 7,000 kg. This particular silencer cost £250,000 to design and build three years ago.

Although the low frequency performance of any absorptive silencer will always be modest, the silencer still gives 6 – 8 dB attenuation in the 63 Hz octave band. This would reduce any residual tones which are still audible in the community once the incinerator is running in a stable mode with the centre fuel gas nozzle valve set at 2 – 3 bar. If higher attenuation was required (i.e. to reduce the tones at 32 and 35 Hz), then it would probably be necessary to construct a reactive silencer.

It was recommended that, if serious consideration is to be given to installing a silencer, then in-stack sound pressure level measurements should be undertaken in order to quantify the emissions from the stack and to determine more accurately the likely reductions encountered in the community. This data can then be used to predict environmental noise levels due to the stack tip.

In any case, it was concluded that this mitigation measure should only be used as a last resort if other practicable mitigation measures fail to provide the desired level of reduction.

6.7 Waste Gas Line Lagging

As the waste gas line was clearly audible at the community measurement location during the tests, it is recommended that this line be acoustically lagged. This noise was broadband in nature and quite different from the low frequency tonal noise caused by the combustion driven oscillations. It was recommended that valves and pipework associated with the waste gas line be treated with a minimum of Class B acoustic lagging, as defined in the OCMA Specification (Reference 5).

7 CONCLUSIONS

This paper presents the results of an investigation into a low frequency tonal noise which was experienced from a new waste gas incinerator. Several tests were performed under a variety of operating conditions. It is considered that the basic mechanism behind the characteristic noise was combustion driven oscillations. However, the effect which occurs is more complex than a simple interaction between the burner flame oscillations and the standing waves of the cavity since the tone does not occur until waste gas is introduced into the system. There is, therefore, apparently a more complex interaction between the flame, standing wave and waste gas flow.

One possible theory for the reduction in the magnitude of the tonal noise for higher waste gas flow rates is that the turbulence of waste gas at higher velocities could introduce acoustic damping into the system – thus reducing or eliminating the tone. It is possible that this was the reason for the reduction in tone magnitude during higher waste gas flows for the tests with the centre fuel gas nozzle valve fully open. Conversely, the turbulence may not be enough to mitigate the effect when the centre nozzle and outer ring nozzles are used concurrently. This may also help explain why the characteristic noise does not occur when the 18” waste gas line is spaded – the higher flow rate causes a greater degree of turbulence within the cavity which reduces the efficiency for a standing wave to build, thus reducing the effect. It is also possible that the effect is dependent upon the location at which waste gas is introduced into the system and, therefore, where the oxidisation process takes place inside the cavity.

Additional tests could be conducted to confirm the mechanisms and parameters which are most important for the characteristic noise. In particular, a test could be performed by running the incinerator with an increased flow through the outer fuel gas nozzles and reducing the flow through the centre nozzle.

In any case, it was found that the characteristic noise could be reduced by adjusting the pressure at the fuel gas valves. However, whilst this reduced the principal tone, a smaller magnitude and lower frequency tone was sometimes encountered.

Several possible mitigation measures were considered. Of these, it was considered that changing the operational parameters of the incinerator offers the most straight-forward and effective solution. Specifically, it was recommended that:

- The incinerator should be operated with the centre fuel gas nozzle valve fully open (or at a minimum of 2 – 2.5 bar);
- The outer fuel gas ring nozzle valve should be set at 33% open or less;
- The 18” waste gas line should be left blanked off.

The incinerator manufacturer has also proposed to trial an alternative burner tip design using two holes instead of three, thus increasing the gas jet speed.

It is anticipated that the combination of the improved burner tip design and management of the ‘resonant zone’ of the system will allow the incinerator to operate in its desired operating range. However, it was also recommended that a permanent noise monitor should be installed on the site boundary to continuously monitor noise levels and to provide a warning whenever low frequency noise exceeds a specific threshold.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

1. Combustion-Driven Oscillation in Process Heaters, James G. Seebold, IFRF Combustion Journal, October 2005

2. Combustion Noise in Industrial Burners, A. Putnam, Noise Control Engineering 7 (1), p.24, 1976.

3. Lord Rayleigh. The Theory of Sound, volume 2. Dover Publications, 1945. re-issue.

4. BS ISO 226:2003. Acoustics - Normal equal-loudness-level contours.

5. OCMA Specification No. NWG-5 Acoustic Insulation of Pipes, Valves and Flanges.