# Reducing noise from an oil refinery catalytic distillation column

R. D. Rawlinson,<sup>a)</sup> J. Alberola,<sup>b)</sup> P. F. Joseph,<sup>b)</sup> and M. G. Smith<sup>b)</sup>

(Received 2006 February 14; revised 2006 July 03; accepted 2006 July 04)

This paper concerns the reduction of the exhaust noise from a Catalytic Distillation Column, commonly called a Cat Cracker. A Cat Cracker is used to convert heavy oil into gasoline products. Following the upgrading of the Cat Cracker, there were persistent community complaints of an irregularly varying noise that sounded like an "overflying jet aircraft". The paper describes a detailed study of the Cat Cracker noise involving: field tests on-plant and in the community; scale model tests in the laboratory; theoretical predictions of the in-stack sound power level; and a study of atmospheric propagation effects using the Parabolic Equation method. The objectives of the study were to i) identify methods of reducing the noise levels, and ii) establish the cause of the irregularity of the noise levels in the community. The laboratory tests used a  $\frac{1}{4}$ scale model to explore qualitatively the nature of any potential interaction between the two principal elements in the stack. The study concluded that the cause of the noise was an interaction between the turbulent flow from a valve and a nearby Multi-Holed Orifice (MHO) plate downstream of the valve. The irregular variations in the noise were predicted to be atmospheric effects. Following the investigation the valve and the MHO were subsequently replaced by three MHO's in series which gave a reduction in noise levels at the stack tip of up to 14 dB. Noise measurements in the community demonstrated a similar level of noise reduction. In some weather conditions the Cat Cracker noise can still be heard, albeit at a much reduced level. © 2006 Institute of Noise Control Engineering.

Primary subject classification: 14.1.9; Secondary subject classification: 24

### **1 INTRODUCTION**

This paper concerns the noise from the exhaust stack of an oil refinery Cat Cracker. A Cat Cracker is a process plant that converts crude oil into its by-products. Following an upgrade of the Cat Cracker at a major oil refinery in the UK, complaints had been received from the local community about a noise, which occurred during certain meteorological conditions, that was likened to the sound of an overflying aircraft. The noise was observed to rise and fall irregularly when the wind was blowing towards the community. The community extends along the southern boundary of the site and the prevailing winds are from the southwest. The noise levels measured in the community were found to be more than 20 dB greater than those predicted using classical theories of valve noise and sound propagation, suggesting that an additional noise mechanism was present.

This paper addresses the procedures that were followed to identify:

- the source of the anomalously high noise levels
- the reason for the fluctuations in the noise levels in the community.

A number of approaches were adopted to resolve these issues, which included:

- field measurements in the community—during normal operation and when the process was deliberately adjusted from the noisy condition to one that provoked less community complaints
- field measurements in the plant—including measurements at the top of the exhaust stack
- scale model tests in the laboratory—using a  $\frac{1}{3}$  scale model to investigate possible interactions between components of the process

<sup>&</sup>lt;sup>a)</sup> ISVR Consulting, Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton, SO17 1BJ, ENGLAND; email: rdr@isvr.soton.ac.uk

<sup>&</sup>lt;sup>b)</sup> ISVR Consulting, Institute of Sound and Vibration Research, University of Southampton, Highfield, Southampton, SO17 1BJ, ENGLAND.



Fig. 1—Schematic diagram of the process.

- theoretical predictions of the in-stack sound power level
- a study of the variability in atmospheric propagation effects using the Parabolic Equation model

#### **2** OUTLINE OF THE PROCESS

The role of the Cat Cracker is to convert heavy oil into gasoline products within the Reactor by the distillation process. The exhaust gases discharge to atmosphere through a tall chimney. The process runs at 735 °C. The reactor catalyst is fluidised at this temperature and spent catalyst is fed back to a Regenerator. There are 55 tonnes per minute of catalyst movement. The flue gases then pass through waste heat recovery units (WHB) to the Tertiary Cyclone Vessel (TCV), which contains 25 sets of cyclones to remove process catalyst. The flue gas then passes through Valve C, as shown in Fig. 1. The volume of flue gas passing through the stack can be varied between 4800 and  $6000 \text{ Sm}^3/\text{min}$ , where the units  $\text{Sm}^3/\text{min}$  indicate the flow rate normalised to standard conditions of temperature and pressure (i.e. 15 °C and 1 Bar).

The flow rate through the system is normally controlled by Valve C. Downstream of this valve is the Multi-Holed Orifice (MHO), which was installed to assist in controlling the velocity through the system to minimise erosion of the waste heat recovery units. Control can be maintained using Valve A but this adversely affects the process.

Two silencers are positioned downstream of the MHO plate. The stack discharges to atmosphere at an elevation of 89 m. The process runs 24 hrs per day, 7 days per week. It is a steady process and not subject to sudden changes. Prior to December 2001 the cat cracker ran without complaints. At that time there was a single stack silencer to reduce an earlier tonal

problem. A new blower was installed during the upgrade to increase the air rate from approximately  $3500 \text{ Sm}^3/\text{min}$  to  $6000 \text{ Sm}^3/\text{min}$ . Following community complaints the stack was extensively altered and an additional silencer was fitted. Although this reduced the stack tip noise by 14 dB(A), complaints persisted.

It had been observed that the noise problem mainly occurred when Valve C was in control and the wind was blowing from a northerly direction. The community complaints could be reduced by switching control of the process to Valve A. However, the process could not be run in this configuration for extended periods.

#### **3 FIELD SURVEYS**

#### 3.1 Noise Levels and Frequency Content

An initial environmental noise survey was carried out in the community to determine typical background noise levels during the day and night. This survey included periods when community complaints were vigorous and when they were reduced by switching control to Valve A. The methodology adopted was based on that in current standards.

A second survey was carried out when the process was changed deliberately from Valve A being in control to Valve C being in control, then returning to Valve A. This changeover took about 8 hours to complete and throughout this time simultaneous recordings of the noise were taken on-site and in the community. Five recording systems were used: three were in the community, one recorded the noise at the stack tip and a fifth was at ground level in the refinery. Norsonic NOR 121 sound analysers were used to make direct measurements and audio recordings for later analysis. The stack tip measurement technique did not conform to any national standards because of the difficulty of gaining access. However, repeated measurements, taken under similar conditions, demonstrated that good repeatability was obtained.

During the second survey some dynamic pressure measurements were taken in the stack, downstream of the MHO, to try and determine the in-duct sound pressure levels. Unfortunately there was only one small port into which the probe could be inserted and time constraints did not allow special techniques to be employed. It was recognised at the time that these measurements would need to be treated with caution because the probe could not differentiate between acoustic signals and turbulence.

From the audio recordings individual noise fluctuations, or "roars," were isolated more easily by low pass filtering the recordings then analysing them to determine their temporal and frequency characteristics. Since initial results indicated that the frequency of the





noise of concern lay predominantly between about 125 Hz and 630 Hz, a low-pass cut-off frequency of 800 Hz was used to isolate the noise from the other, higher frequency sounds that were also recorded.

Figure 2 shows a comparison of the 1/3 octave band analyses for three typical "roars" occurring during a 1-hour period when Valve C was in control. Similar repeatability was obtained for the recordings immediately before and after the roars, and when Valve A was in control.

#### 3.2 Noise Variability

Analysis of the data measured at the stack tip did not reveal any significant time-varying fluctuations in noise that corresponded to the variations heard, and measured, in the community at distances between 650 m and 1250 m from the stack. This strongly suggested that the fluctuations in the community noise were a propagation effect and not caused by changes in the characteristics of the source. Meteorological data was routinely collected by the refinery and the important tests, that were fundamental to the diagnosis of the problem, were only carried out when the weather pattern was stable, with light winds blowing from the Northerly sector. The weather data was only collected at ground level because of the difficulties of supporting instrumentation at elevated positions in the refinery.

Comparison between the community noise recordings suggested that the largest fluctuations in noise occurred downwind of the exhaust stack. When the time histories of the noise at each location were compared, after adjustments to allow for the propagation times from the stack, there was no correspondence between the fluctuations at each location. This provides further support for the conjecture that the community noise fluctuations were due to meteorological effects.

The roar was characterised by averaging three randomly selected samples which were taken from a 1-hour recording of the noise with the process held steady. The three samples of the noise were taken at the beginning, middle and end of the 1-hour period. Figure 3 shows a comparison between the: averaged noise levels for the "roar," the averaged noise levels immediately before or after the "roar," and the difference in these levels. These spectra correspond to the condition of maximum community complaints when Valve C was in control.

The noise survey results confirmed that the noise emitted at the stack tip was very stable, did not fluctuate over short periods and was broadband and low frequency in character. The difference in overall, low-pass filtered noise level at the stack tip increased by 4 dB from Valve A being in control to Valve C being in control although the  $\frac{1}{3}$  octave band sound pressure levels varied by up to 10 dB.

# 4 THEORETICAL PREDICTIONS OF VALVE-MHO INTERACTION NOISE

A simple analysis of the total sound power level in the stack was carried out using established valve noise prediction theory.<sup>1</sup> The approach was to combine the sound power levels generated by the individual sources within the system leading to and including the stack. It was assumed that the only form of attenuation in the system was due to the stack silencers. Since there was no valve type in the published data that compared to the



Fig. 3—Noise levels in the community for loud and quiet parts of the "roar" and the difference in levels.



Fig. 4—Overall low-pass filtered sound pressure levels in exhaust.

Valve C the nearest matching type was chosen. Predictions were made for the two situations when Valve C was in control, and Valve A was fully open, and then when the operating conditions of the valves were reversed.

A sensitivity check was made for the range of valve types in the prediction method to establish the possible range of noise levels that might be generated. No interaction effect, between the valve and the MHO, was included in the calculation.

When the results were compared to the levels that were measured at the stack tip, and in the stack, it was apparent that there was another stronger source of noise that had not been accounted for.

The in-stack measurements were made using a single high pressure transducer. Some contamination of the acoustic measurements by turbulence was anticipated so the results were treated with caution. Nevertheless, they gave an upper limit to the in-stack noise. Figure 4 shows the three estimates of the in-stack sound pressure levels, two upstream of the silencers and one downstream of the silencers. The levels are the linear, 800 Hz low pass filtered sound pressure levels. There is a 20 dB difference between the two estimates of the sound pressure levels upstream of the silencer. When the predicted upstream noise level is compared to the downstream level the 16 m of stack silencing appears to give only 5 dB of dynamic insertion loss.

The exact value of the upstream sound pressure level lay somewhere between the two estimates. It was conjectured that the noise source that was not accounted for in the predictions was possibly an interaction effect between the turbulence shed from Valve C and the downstream MHO.

### **5 LABORATORY MODEL TESTS**

The interaction hypothesis was explored further in the laboratory by the use of a  $\frac{1}{3}$  scale model of the duct—valve—MHO system and exploring the changes in sound pressure level when changes were made to the arrangement. Figure 5 shows a schematic representa-



Fig. 5—Schematic diagram of laboratory arrangement.

tion of the rig and Fig. 6 shows a view down the model duct. The test rig was made of plywood with a square cross-section, for ease of construction. A high volume, high pressure air supply was attached to the duct to represent the flow in the stack. The in-coming air entered through a 70 mm diameter hole, which represented the outlet of the valve when Valve C was in control.

The multi-holed orifice was represented by a panel with scaled holes to the pattern of the MHO. A number of other patterns of MHO were tested, as well as a combination of MHO's in series.

The laboratory tests were carried out in the ISVR's reverberation chamber. Not all of the controlling parameters could be scaled, however, such as the temperature of the fluid in the stack, which can reach up to  $500 \,^{\circ}$ C.

Noise levels in the reverberation chamber were measured for:

- varying separation distance between the valve and the MHO
- varying jet velocity for a fixed arrangement of valve and MHO
- different designs of MHO plate



Fig. 6—View downstream of the model duct.





• using multiple MHO's downstream of the valve The results of the laboratory tests clearly demonstrated that an "interaction effect" occurred when the MHO was close to the valve outlet. The interaction effect increased the low frequency content of the noise.

Figure 7 shows the mid-frequency noise levels when the separation between the MHO and the valve was increased for a constant exhaust velocity.

Figure 8 shows the effect of varying the exhaust velocity for fixed arrangements of the valve and MHO.

The relationship between the increase in noise and the change in velocity of the air was approximately

$$\Delta Lp = 10^* Log_{10} \left(\frac{v^2}{v^1}\right)^5$$

where v2 and v1 are the two values of velocity.

The 5.5 exponent is commonly associated with a dipole sound source, which gives an increase of 16.5 dB in the noise level for a doubling of velocity.

The laboratory tests concluded that:

• the close proximity of the MHO to the valve caused an increase in the low frequency noise, which was consistent with that found at the stack tip

- noise level increased for reduced separation between the valve and the MHO
- noise level increased for increased outlet velocity for a fixed arrangement of valve and MHO
- the interaction effect behaved like a dipole sound source.

# 6 THEORETICAL PREDICTIONS OF THE SOUND PROPAGATION USING A PARABOLIC EQUATION MODEL

The most annoying aspect of the noise in the community was its high level of variability. One of the conclusions of the surveys described in Sec. 3 above was that the noise measured at the stack tip was steady and the fluctuations were due to atmospheric effects. The Parabolic Equation model was used to try and understand this behaviour more clearly.

The Parabolic Equation model considered both the steady state observed wind effect and the effect of atmospheric turbulence along the sound propagation path from the chimney stack to the observer. The turbulence model used here only accounts for typical turbulence fields produced naturally in the atmosphere, as the characteristics of the induced turbulence fields by the heat transfer activities of the refinery were unknown.

It is assumed that the turbulence field  $\mu$ , does not change as the sound waves propagate through it. This approach is known as the frozen medium approach and is based on the fact that sound waves take less time to travel from source to receiver than the sound speed profile takes to fluctuate. This means that each realization will be like a "snapshot" of the turbulent atmosphere.

Atmospheric turbulence is included in the PE model as small fluctuations of the sound speed, where n is the sound speed fluctuation, described mathematically as:



Fig. 8—Effect of increasing jet velocity for MHO A at 800 mm from valve.



*Fig. 9—Theoretical predictions of variability in sound propagation due to wind and atmospheric turbulence.* 

$$n = \bar{n} + \mu \tag{1}$$

where  $\bar{n}$  is the average value of the sound speed and  $\mu$  denotes the random perturbation representing the turbulence (with  $\mu \ll \bar{n}$  and  $\bar{\mu}=0$ ).

The mathematical function describing the turbulence has been derived assuming that the fluctuating part of the sound speed  $\mu(r,z)$  has an autocorrelation function defined by:

$$C(s) \equiv \langle \mu(R+s) \cdot \mu(R) \rangle \tag{2}$$

where  $\langle \rangle$  denotes an ensemble average over many realizations of  $\mu$ , R = (x, y, z) is a position vector and s represents some spatial separation distance in the r-z plane. It is assumed that for small-scale atmospheric turbulence, C(s) can be approximated by a Gaussian distribution,

$$C(s) = \mu_0^2 \cdot e^{-s^2/l^2}$$
(3)

where  $\mu_0$  is the root-mean-square fluctuation of  $\mu(r,z)$ and *l* is the correlation length.

There are other possible distributions, like the Kolmogorov and von Karman distributions, however the majority of authors use the Gaussian distribution, and its universality makes it more suitable for this study. Daigle, Gilbert and Salomons<sup>2–5</sup> recommend orders of magnitude for  $\mu_0$  and *l* of about 10<sup>-3</sup> and 1 m,



Fig. 10—Process changes to the stack.

respectively. Following these recommendations, the values that were used were  $1.42 \times 10^{-3}$  for  $\mu_0$  and 1.41 m for *l*.

To obtain approximations of  $\mu(r,z)$ , the square-root of the wave number spectrum is calculated from the autocorrelation function C(s), then multiplied by a random phase function and finally computed using the inverse Fourier transform.

The PE model was run using 100 approximations of the fluctuating sound speed for each frequency of interest. Figure 9 shows the predicted transmission loss for frequencies from 63 Hz up to 500 Hz, where the transmission loss is defined here as the difference in sound pressure levels between the stack tip and the community.

The results indicate increased variability with increased frequency, up to 500 Hz. Some of the sharp dips in the propagation characteristics are due to interference effects but the enhancements are solely wind and turbulence effects.

Subject to the restriction that the predictions are presented in single frequencies and cannot be directly compared to the  $\frac{1}{3}$  octave band measurements, the predictions provide a useful indication of the effects of







Fig. 12—Sound pressure levels in the community at "loud" part of fluctuation.

atmospheric turbulence for the particular site conditions. However, the magnitude of the variation experienced at the site is greater than predicted. The prediction at 250 Hz, and at a distance of 1200 m from the stack, is  $\pm 5$  dB about a mean attenuation of 60 dB from the stack. Comparing these predictions with the measured results from Figs. 11 and 12, the measured differences in levels between the stack and the community values at 250 Hz are 35 to 38 dB. This suggests an under prediction of the fluctuations by about 20 dB. Such discrepancies due to atmospheric effects are unusual but have been noted elsewhere.<sup>6</sup>

#### 7 THE NOISE CONTROL SOLUTION

No one test of the many described above proved conclusively the causes of the excessive noise levels and their fluctuations but the accumulated evidence strongly supported the theory that the source of noise was due to turbulent interaction between Valve C and the MHO. This arose because of the close proximity of the MHO to the valve. The effects of the wind and turbulence caused the irregular fluctuations in the measured noise in the community.

Following the investigation the client considered a range of solutions. The first solution that was considered was to increase the separation between the two components. Unfortunately there was not sufficient space to do this. The final solution was a compromise between the requirements to meet stringent chemical engineering objectives and the noise control objectives. The chosen solution was to replace the existing MHO and Valve C with three, widely separated MHO's in series. This arrangement enabled Valve C to be removed and the required total pressure drop maintained. The arrangement is shown in Fig. 10.

Following these modifications another noise survey was carried out in the community. The results are given in Fig. 11 and show a reduction in the stack tip noise of between 10 and 14 dB. A similar level of reduction in the community noise is illustrated in Fig. 12.

## 8 CONCLUSIONS

This study has investigated the cause of the fluctuating noise heard in the community near to an oil refinery. The range of tests carried out in the field, and in the laboratory, strongly suggested that the noise was due to the turbulence shed by the Valve C striking the downstream Multi-Holed Orifice Plate (MHO). The noise emitted by the stack tip was steady but the effects of atmospheric turbulence caused the noise received in the community to fluctuate by more than 10 dB above the mean level at some frequencies. Removing the valve and MHO and replacing them with three new, widely separated MHO's reduced the noise at the stack tip and in the community by up to 14 dB at some  $\frac{1}{3}$ octave band frequencies.

#### 9 ACKNOWLEDGMENTS

The authors would like to thank Stuart Dyne, Prof Frank Fahy, Matt Parker and Christos Karatsovis, all of ISVR Consulting, for their assistance in the project.

## **10 REFERENCES**

- 1. D. A. Bies and C. H. Hansen, "Engineering Noise Control," Third Edition, E & FN Spon.
- Daigle, G. A. "Effects of Atmospheric Turbulence on the Interference of Sound Waves above a Hard Boundary," J. Acoust. Soc. Am. 64(2), pp. 622–630 (1978)
- Gilbert, K. E., White, M. J., "Application of the Parabolic Equation to Sound Propagation in a Refracting Atmosphere," *J. Acoust. Soc. Am.* 85(2), pp. 630–637 (1989)
- Gilbert, K. E., Raspet, R., Di X. "Calculation of Turbulence Effects in an Upward-Refracting Atmosphere," J. Acoust. Soc. Am. 87(6), pp. 2428–2437 (1990)
- 5. Salomons, E. M., "Computational Atmospheric Acoustics," Kluwer Academic Publishers, Dordrecht (2001).
- "Guide to the Use of Noise Procedure Specification," The Engineering Equipment and Materials Users Association (EEMUA), Publication Number 141 (1985).