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THE GENERATION OF NOISE IN EXTERNAL COANDA-TYPE WASTE-GAS FLARES

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INTRODUCTION

External-Coanda-type waste-gas flares represent a considerable improvement in terms of combustion efficiency, pollutant emission and noise when compared to the older sonic pipe flares and vents. Nevertheless, despite this improvement in noise level, the environmental restrictions on the design of off-shore platforms make further noise reduction highly desirable. The present study of the noise generated by the Coanda flares has been undertaken as part of a research programme aimed at developing suitable noise-suppression techniques.

Brzustowski [1] and others have discussed certain aspects of external-Coanda-type flares. However, apart from Ref. [2] in which some of our preliminary results were presented, no information on the noise generated by such flares appears to be available in the open literature. The present paper is concerned with the Indair flare which is designed and marketed by Kaldair Ltd. Noise data measured in the field and from model tests are used to assess the relative importance of the various noise sources and to elucidate the main feature of the high-frequency sources.

ASSESSMENT OF MAIN NOISE SOURCES

The overall flow field and combustion zone for an Indair flare are depicted in Figure 1. The flare tip is a "tulip-shaped" body of revolution. The flare gas issues radially from an adjustable exit slot located at the base of the flare tip. Turbulent mixing occurs between the flare gas and the surrounding air immediately on exit causing air to be entrained. Owing to the Coanda effect the air/gas mixture adheres to the surface. Flame initiation occurs fairly close to the maximum cross-section.

A typical frequency spectrum [3] for an Indair flare is shown in Figure 2. Direct combustion noise is probably the main source at the low frequencies. The low-frequency peak occurs at or below 63 Hz. When the differences in scale are taken into account this seems to be more or less in agreement with equation (11) of Strahle [4] which was based on experiments with a burner of 10 mm diameter.

Indair flares are operated at pressures up to 12·5 bar but the most frequent operating range is 1·7 to 8·0 bar. Consequently the flow will be supersonic near the exit slot for most of the operating range and a complex pattern of shock waves forms near, and even inside of, the exit slot. (These shock waves can be seen in the schlieren photograph shown in Ref. [2]). Thus the two main sources of high-frequency noise are thought to be turbulent mixing noise-generated by the fluctuating turbulent stresses in the mixing-layer and wall-jet regions; and shock-associated noise-generated by the interaction of the turbulent shear flow and the shock waves. An experimental and theoretical investigation of the high-frequency sources is described in the next two sections.

The presence of the solid flare-tip surface can affect the radiated sound in two ways. First, as shown by Green and Carpenter [5], the geometrical constraints imposed on the turbulent shear flow lead to considerably higher levels of turbu-

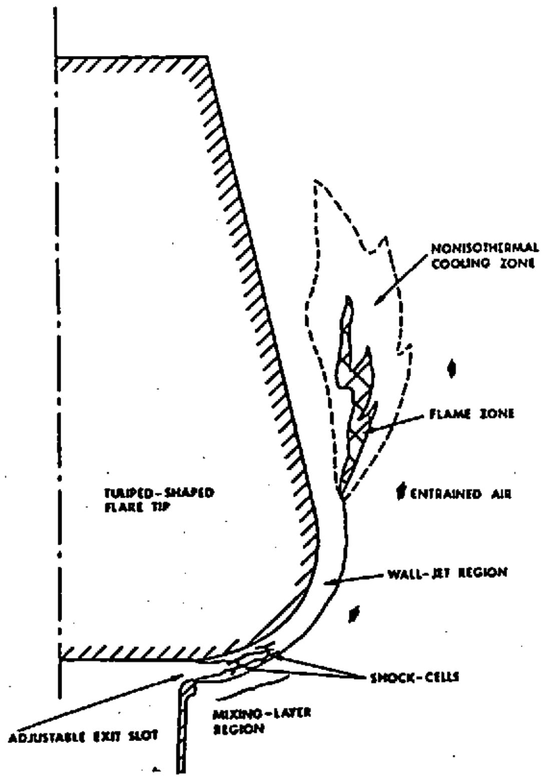


Figure 1. Sketch of overall flow field and combustion zone.

lent shear stress and hence to more powerful noise sources, as compared to conventional round jets, say. Second, as shown in Ref. [2], the scattering by the flare tip of the sound radiated by the sources is equivalent to the presence of additional sources inside of the flare tip. For low-frequency monopole sources, such as direct combustion noise, there would be a scattered field of dipole form, comparable in strength to the incident field. For high-frequency quadrupole sources, such as turbulent mixing noise, the image sources are similar in strength and form to the real sources.

THEORETICAL ANALYSIS OF THE TURBULENT MIXING NOISE

Consider an acoustic source located within the mixing-layer or wall-jet regions. According to the Lighthill [6] theory the acoustic intensity of this source, in the absence of the solid surface, would be given by

$$I_{ff} \sim \rho\ \tau^2\ U^4/\{bc^5\ (1 - \underline{M}_c \cdot \underline{e}_o)^5\ R_o^{\ 2}\} \qquad (1)$$

where ρ and c are respectively the density and speed of sound of the ambient

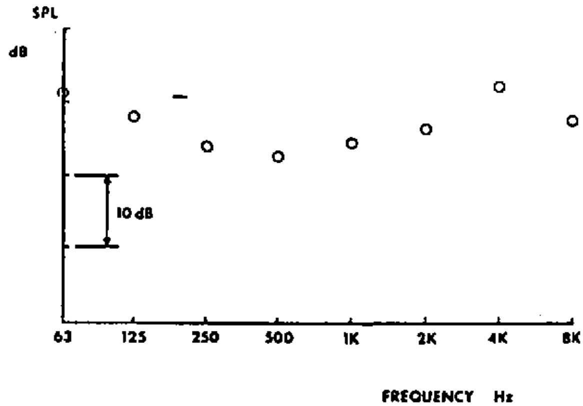


Figure 2. Averaged octave band sound power levels taken from field data for the full-size flare. Operating pressure is 2·6 bar.

fluid, τ denotes the turbulent shear stress. U is the maximum local mean velocity, b is the local width of the turbulent shear layer, $\underline{M}_c$ is the convective Mach number vector, $\underline{e}_o$ is a unit vector in the direction of the observer, and R_o is the distance from source to observer.

Since the source is a high-frequency quadrupole and is close to the solid surface an image source can be introduced in the same way as for a flat surface. Thus the actual acoustic intensity is given by

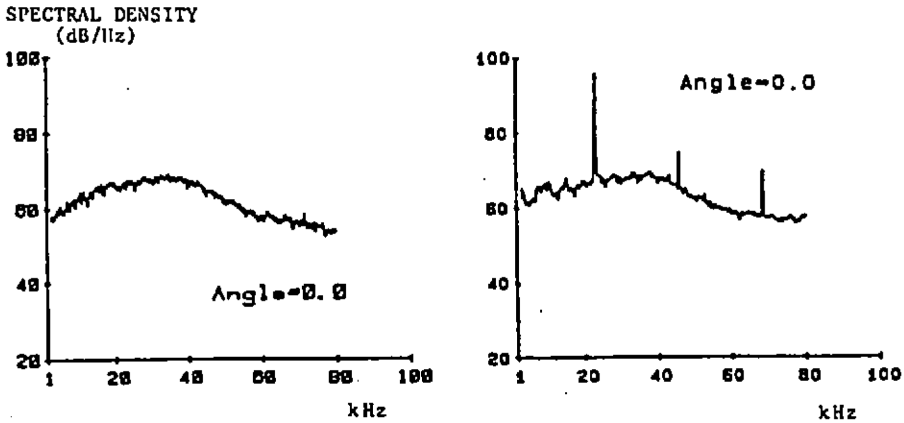
$$I = 2\, I_{ff} \cos^2 (k\delta \cos \phi) \; : \; \phi \leq \phi_H \qquad (2)$$

where ϕ is the angle between $\underline{e}_o$ and the normal to the surface passing through the source, δ is the distance from the source to the surface and k is the wave number, appropriately Doppler corrected. ϕ_H is the angle between the normal and the tangent to the surface passing through the source. $I \simeq 0$ when $\phi \geq \phi_H$.

In the mixing-layer region U is constant, and as shown in Ref. [5] both b and τ_{max} grow roughly linearly with distance, x, around the flare-tip surface. In the wall-jet region both τ_{max} and U drop fairly sharply as x increases. It follows, therefore, that the most powerful sources would be located at the end of the mixing-layer region. Accordingly, in order to simplify the problem we have evaluated equation (2) for these sources, numerically integrated the values of I for the band of sources located at the end of the mixing layer, and multiplied the result by the total volume of the mixing layer in order to arrive at an estimate for the overall intensity. This approach will lead to an under-estimate of the sound radiated to angles below the horizontal plane but should preserve the main features of the sound field.

EXPERIMENTAL STUDY OF HIGH-FREQUENCY NOISE SOURCES

The experimental investigation was carried out on ⅛-scale models of the flare tip in an anechoic chamber measuring 3m × 3m × 5m. Air at high pressure was used to



(a) Operating pressure is 1·5 bar. (b) Operating pressure is 1·7 bar.

Figure 3. Sound pressure spectra from model data.
Slot width is 0·012 W.

model the flare gas. Eight B. and K. Type 4315 ¼" microphones were used to measure the sound pressures simultaneously at eight separate locations on a vertical arc around the model. The signals were fed via preamplifiers and amplifiers to a eight-channel precision tape recorder. Subsequently the data were transmitted via an analogue-to-digital converter to a PRIME 550 computer where fast-Fourier transform techniques were used to process the data. The power spectra were averaged 50 times to obtain adequate statistical reliability.

A typical power spectrum, for the low end of the operating pressure range, is shown in Figure 3(a). The peak-noise frequency does not vary greatly with exit slot width or pressure but is highly dependent on direction. For the particular slot width value of 0·012 W (where W is the maximum width of the flare tip) discrete tones are generated at the slightly higher pressure of 1·7 bar, as shown in Figure 3(b). These tones are only present over a narrow range of pressures (roughly 1·7 to 2·0 bar). For 2·4 bar the spectra are similar to Figure 3(a). At higher pressures there is evidence of shock-associated noise and discrete tones re-appear at 6·5 bar. The mechanism, responsible for generating the discrete tones at the comparatively low pressures, has not been definitely identified but it is thought to be connected with internal shock waves giving rise to locally separated flows.

Typical directivity patterns for overall SPL are plotted in Figure 4. Apart from the curves corresponding to 1·7 and 2·0 bar which are highly distorted by the presence of discrete tones, the remaining curves show that the peak-noise direction moves upwards with a rise in pressure. This trend continues for the pressures above 2·4 bar and is also predicted by the theoretical model.

SPL vs. jet velocity is plotted in Fig. 5 for various slot widths. Note the increased levels for a slot width of 0·012 W at intermediate velocities; these are due to the discrete tones. Also plotted in Fig. 5 is the theoretical curve corresponding to a slot width of 0·012 W. At the lower velocities the theoretical

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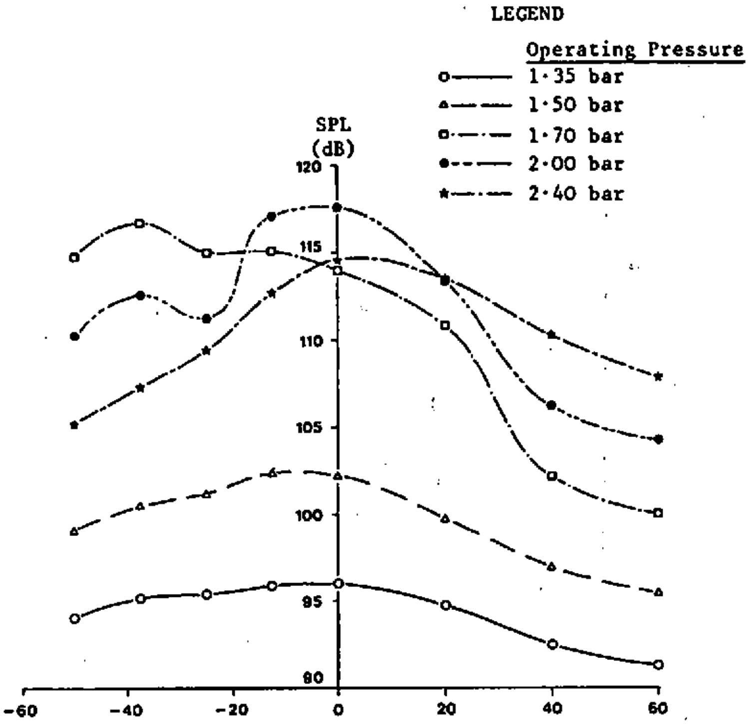

Figure 4. Directivity of overall sound pressure level from model data. Slot width is 0·012 W.

curve follows Lighthill's [6] U^8 law, but convective amplification becomes more important at the higher speeds giving rise to a steepening of the theoretical curve. Bearing in mind that the theoretical curve can be moved up and down at will, there is good agreement between theory and experimental data except when the discrete tones are present. Field data [3] from the full-size flare are also correlated reasonably well by the U^8 law for the high-frequency components. (See Ref. [2]). At higher pressures broad-band shock-associated noise probably makes a marked contribution to the total noise but, at present, this is difficult to quantify.

A number of factors affect the variation of SPL with slot width, h. Firstly, the total volume of turbulent shear flow rises, very approximately, as h^2. Secondly, the level of turbulent shear stress rises considerably as h increases. Thirdly, the strongest sources tend to move further away from the surface as h rises. This leads to a reduction in intensity because of an increase in partial cancellation of the actual sources by the image sources (cf. the $\cos^2(k\delta \cos \phi)$ term in

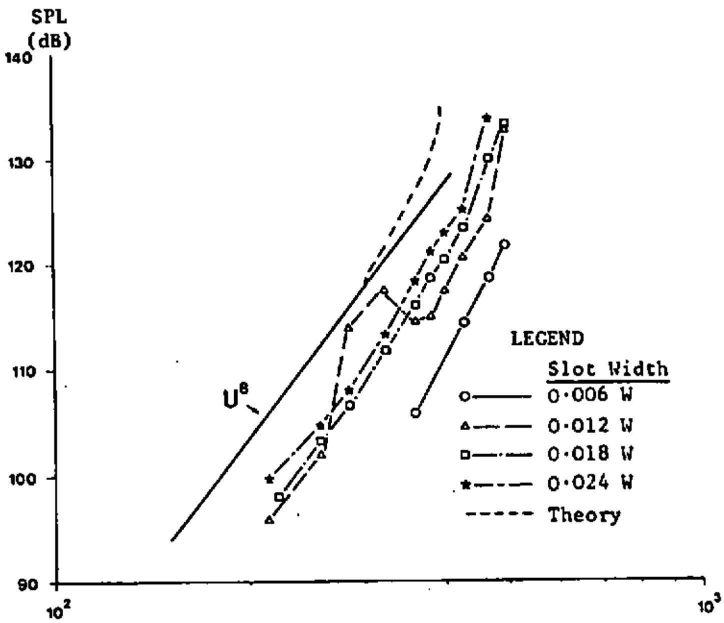

Figure 5. Sound pressure level vs. jet boundary velocity from model data. Angle relative to the horizontal is zero.

eqn. (2)}; but, at the same time, more sources can radiate to the observer owing to an increase in ϕ_H. This combination of factors leads to a theoretical SPL which, at a pressure of 2 bar, varies as $h^{1\cdot 2}$ for slot widths ranging from 0·006 W to 0·018 W. For smaller slot widths the SPL rises more steeply with h and for larger slot widths much less steeply. Both the model and field data agree well with theoretical predictions for slot widths up to 0·018 W. For larger slot widths, however, the experimental data continue to follow the $h^{1\cdot 2}$ variation, showing no tendency to increase less rapidly with h. There is, as yet, no definite explanation for the discrepancy between theory and experiment.

CONCLUDING REMARKS

A comparison between the theoretical model and experimental data suggests that turbulent mixing noise is the dominant high-frequency source at low pressures, at least. At the higher pressures shock-associated noise becomes more significant.

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