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THE NOISE FROM STEAM DISCHARGES AT HIGH MACH NUMBERS

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NOTATION:

A_j	Jet Area.	c_o	Ambient speed of sound.
c_s	Speed of sound in steam.	$D(\theta)$	Directivity factor.
d_j	Jet diameter.	M_c	Convection velocity.
$I(r,\theta)$	Acoustic intensity at radial r and emission angle θ.		
U_j	Jet velocity	ρ_j	Jet density
ρ_o	Ambient density		

1. INTRODUCTION:

There are a number of occasions in the operation of a power station when it is necessary to vent large quantities of steam to the atmosphere. Whilst such occurrences are usually of a transitory nature, the acoustic powers produced are often high enough to require measures both to safeguard the hearing of staff working nearby and to avoid annoying the public. This situation has been exacerbated in recent years by the trend towards larger unit size (currently 660 MW) with their accompanying higher pressures, temperatures and flow rates (17 MPa, 825°K and 2Mg s^{-1} respectively).

Recognising this, the CEGB has for some time now pursued a policy of fitting attenuators to the vents of all steam lines handling flows in excess of 5 kg s^{-1}.

During the process of designing these attenuators, it became evident that the severe steam conditions had not been encountered before and there was a lack of knowledge regarding the noise levels to be expected from an unsilenced steam jet. Indeed, with the exception of the paper published by Bowen, Dunmore and Stevenson (1), there was virtually no data available at all.

To overcome this dearth of information, the CEGB decided to build an experimental rig at Brimsdown 'A' Power Station to obtain some steam jet noise measurements at first hand.

2. THE RIG:

The rig consisted basically of a 76 mm bore pipe which branched off the relief valve line of No. 1 boiler. This line was charged normally with live steam at a pressure of 14 MPa and a pressure of 775°K.

The pipe was taken from the branch point near ground level up through the boiler house to the bunker floor at the +26m high level where it connected to a 203mm bore test section through a control valve. The control valve had a by-pass arrangement to allow the rig to be warmed through prior to testing.

The test section contained a quickly-removable 3m length of pipe which could be replaced easily by an in-line silencer, designed to attenuate noise generated upstream by the control valve.

The silencer was followed by a further 3m length of 203mm bore pipe which protruded through the boiler house wall to terminate 2.6m out in space. This point was the centre of a semi-circular array of microphones, positioned at intervals of 7½° from 22½° to 90° to the jet axis.

Normally in modern power stations, the steam vent pipes are taken up through the flat roofs of their boiler houses. This could not be done at ar Brimsdown 'A' because the roof was completely obstructed. The geometry of a modern power station was therefore simulated by taking the vent out through the wall.

3. TEST PROCEDURE:

After warming through the rig until the metal temperatures had stabilised, the control valve was opened and the boiler effectively blown down to atmosphere for short periods. The resultant sound pressure levels measured by all the microphones were recorded simultaneously on magnetic tape for steam mass flow rates of up to 13 kg s^{-1}. This corresponded to expanded jet velocities in the range $1.0 < \frac{U_j}{c_o} < 1.8$.

4. DATA ANALYSIS:

It is well known that the acoustic intensity of jet noise is given by

$$I\ (r,\theta) \sim \frac{\rho_j^2 A_j U_j^m}{\rho_o c_o^5 r^2} \; \frac{D(\theta)}{(1-M_c\cos\theta)^n} \qquad .....(1)$$

neglecting higher-order terms in Ffowcs Williams' expression for the Doppler Factor (2).

In the present case, a plot of the intensity measured at right-angles to the jet axis ($\theta = 90^o$) against log U_j, indicated that m was about 7. This is in keeping with an analysis of the turbulence data of Lassiter and Hubbard (3) where the rms turbulence intensity is found to increase rather less than linearly with jet velocity. The value of m was taken to be 7 in the analysis of the test results.

Recent work by Tester and Morfey (4) on flow-acoustic interaction effects reveals that the results of convection and refraction are better represented above the critical angle $\theta > \theta^* = \sec^{-1}\left(\frac{c_s}{c_o} + M_c\right)$ by making the value of n equal to 3, rather than 5 as given by Ffowcs Williams (2). Below the critical angle, the intensity exhibits an exponential decay, the magnitude of which is given by

$$\Delta = 55 \frac{fd_j}{U_j} \frac{\bar{y}}{d_j} \frac{U_j}{c_o} \left[\cos^2\theta_o - (1-M_c\cos\theta_o)^2\left(\frac{c_o}{c_s}\right)^2\right]^{\frac{1}{2}} \qquad .....(2)$$

where $\bar{y}$ is the distance that a given source is embedded below the interface between the flow region and the ambient medium. As a result, the angular space $0 < \theta < \theta^*$ is often referred to as the "cone of silence".

5. DISCUSSION:

The measured overall intensities at various angles to the jet are compared with the theoretical predictions in Fig.1. Here, the value of the convection velocity was taken to be the same as that reported by Bowen et al for steam, namely 0.4 U_j. This value agrees with that found by Davies, Fisher and Barratt (5) over the frequency range of interest.

The curves for angles $\theta = 45^o$ and $\theta = 75^o$ have not been adjusted to give the "best fit", but have been plotted relative to that for $\theta = 90^o$. Hence they show the correct amount of amplification.

Similar curves were obtained for the one-third octave-band intensities when the results were computed for constant values of source Strouhal numbers,

$S_\sigma = \frac{fd_j}{U_j}(1 - M_c \cos\theta)$, in order to ensure that they would be independent of frequency. In this case, it was found that, at low frequencies, there was good agreement between theory and experiment for the larger values of θ, but that the theory progressively underestimated the observed intensity close to the jet axis. However, this was not so at the higher frequencies where the agreement was good at all angles.

No temperature effects were discernable, but there was some evidence from associated tests with a "pepperpot" diffuser bolted to the end of the vent pipe of the presence of a U_j^4 term in addition to that involving U_j^7 in the equation for intensity at low velocities.

In order to examine the departures from the theoretical predictions in greater detail, it is informative to investigate the frequency content of the intensities.

Above the critical angle, the spectra exhibited the typical broad, smooth shape which is characteristic of jet noise observed at large values of θ and the peak values scaled on a Strouhal number basis.

As the emission angle fell below the critical value, the spectrum shape changed somewhat: the peak became more pronounced and shifted to a lower frequency as shown in Fig. 2. Furthermore, the peak frequency no longer scaled as the Strouhal number, but remained constant at about 400 Hz over the entire velocity range.

There was no evidence of shock-associated noise, which is consistent with the vent pipe being operated below the critical pressure ratio of 1.8 for superheated steam.

Finally, turning to the directivities of the one-third octave-band intensities, it was found that the three powers of Doppler Factor theory markedly underestimated the observed directivity at low frequencies as, indeed, did the original five powers of Doppler Factor theory. As the frequency increased, the agreement between theory and experiment improved.

Fisher and Szewczyk (6) have conducted an order-of-magnitude feasibility study of the exponential decay mechanism within the cone of silence and have computed values of $\frac{\bar{y}}{d_j}$ in equation (2) for source Strouhal numbers between 0.3 and 20. Some of their data have been combined with the three powers of Doppler Factor theory to yield the theoretical curves shown here in Fig. 3.

6. CONCLUSION:

It was found that the noise produced by a high-velocity superheated steam jet may be described adequately by the expressions given in the paper and assuming the steam to act as a pure gas.

7. REFERENCES:

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(3) L W Lassiter and H H Hubbard, 1955, J Acoust. Soc. Amer. Vol. 27, pp 431-437, "Some Results of Experiments Relating to the Generation of Noise in Jets".

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8. ACKNOWLEDGEMENTS:

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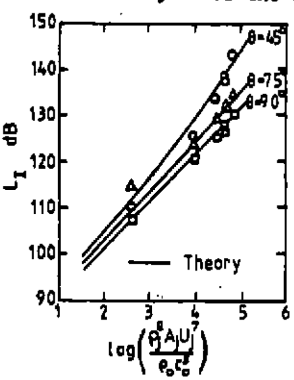

Fig.1 Variation of Overall Intensity with Jet Exit Conditions

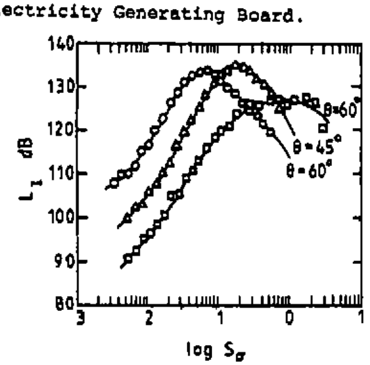

Fig.2 Variation of Intensity Spectrum with Emission Angle

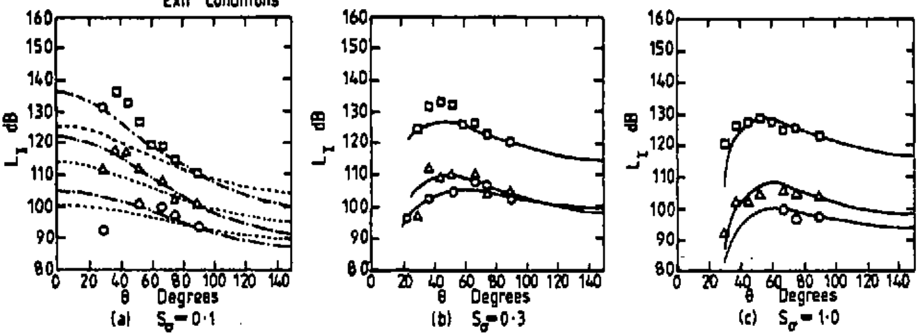

Fig.3 Directivity of One-Third Octave-Band Intensity

○ ~ $\frac{U_j}{c_o} = 1{\cdot}0$; △ ~ $\frac{U_j}{c_o} = 1{\cdot}5$; □ ~ $\frac{U_j}{c_o} = 1{\cdot}8$; —·— ~ Five Powers of Doppler Factor; ------ ~ Three Powers of Doppler Factor; ——— ~ Three Powers of Doppler Factor plus Exponential Decay Mechanism of Fisher & Szewczyk