BROADBAND COMBUSTION NOISE OF TURBULENT NATURAL GAS FLAMES

B.D. Mugridge and D.J. Whitman

Midlands Research Station
British Gas Corporation

SUMMARY

This paper describes an experimental investigation into the broadband sound power output of turbulent natural gas flames. In the first part the sound power output of premixed circular port burners is correlated with mean flow parameters which also describe the steady thermal output of combustion. A noise prediction formula is developed and this compares favourably with previously published data which was derived for smaller diameter burner ports. The thermal-acoustic efficiency of combustion is shown to be of order 10^{-7}. The influence of burner head design on noise output is then briefly considered using test data from two annular port burners. The effect on sound power of both full and partial premix, and the fitting of a refractory tunnel, is also examined. All data is compared with the noise output of a range of industrial burners designed for use on metal reheating furnaces. The comparison indicates which operating/design parameters can be altered to reduce combustion noise and a suitably modified test burner is shown to be 14dB(A) quieter than a conventional industrial design at the same thermal output.

1. INTRODUCTION

Previously published data, [1-4] suggests that the major sources of flame broadband noise are the fluctuations in temperature and mass concentrations within the combustion zone. The distribution and coherence of these two quantities within the total flame volume determines the rate of unsteady heat release which is directly related to the radiated sound power. A detailed study of these source parameters is not yet possible since no viable technique for measuring the spectral content of mixture concentrations has yet been developed and there is virtually no data on the spatial coherence of temperature fluctuations even for the simple turbulent premixed flame. It has therefore been recent practice to examine flame broadband noise as a function of several readily measured mean flow parameters. These include, mean exit velocity, laminar burning velocity, burner port diameter, heat output and a term expressing the air to fuel ratio, e.g. mass fraction or fraction of stoichiometric gas. It is probable that some of these are in fact a measure of other parameters, for example the burner dimensions and mixture velocities may relate to port efflux turbulence.

Correlations between mean flow quantities and noise output have previously been shown to be extremely useful in assessing the acoustic performance of industrial burner flames [5,6]. Unfortunately these results shown considerable scatter in the sound power data for different burner head configurations operating at nominally the same steady thermal output. Some of the scatter is thought to be due to the variations in flame structure that occur with the different nozzle mixing processes and bluff body stabilisers used in commercial burner designs.

The remaining scatter is attributed to the variation in combustion intensity brought about by the range of flow velocities, turbulence intensities, port sizes, burning velocity and air-fuel ratio which may be used to obtain a particular value of steady heat output. These latter effects were of prime interest in the earlier phases of the present investigation and were reproduced by initially concentrating on one type of flame and burner geometry, namely an unconfined, turbulent, premixed air-natural gas flame stabilised on a simple circular port. The range of port diameters (20.5mm$<$D$<$ 40.5mm) and the exit velocities (U$<$ 45 m/s) examined are consistent with these encountered in industrial burner design and, coincidentally, fill a gap in the range covered by other research workers [e.g. 7,8], with which the present data is compared.

Some indication of the increase in sound power that can occur if the burner head design is changed, is shown in a series of tests on an annular port burner which was constructed by inserting a circular concentric bluff body into the centre of one of the simple ports. This modification alters the flame structure with the flame root stabilising on the edge of the bluff body rather than on the outer rim of the port. Further modifications to the annular burner then allowed the gas to be introduced through radial holes in the central bluff body just upstream of the port exit plane. In this arrangement the air and gas flows are only partially mixed within the burner head and represents a type of nozzle mixing burner.

Finally, many high velocity burners used on metal reheating furnaces, operate with flames confined in a circular open ended refractory tunnel (sometimes referred to as a burner tile). This tunnel ensures that the combustion products are ejected with the high velocities considered necessary for good convective heat transfer. It also changes the shape of the flame at its base due to the additional stabilising influence of hot recirculating gases. The increase in sound power associated with this condition was examined by fitting the annular port burners in an appropriately sized tunnel.

Comparison of the present data with that for a range of industrial burner designs goes some way towards explaining the scatter in the sound power data for the latter.

2. EXPERIMENTAL FACILITIES

Each burner was tested in a ventilated reverberant room. Sound power data were calculated from microphone traverses within the room space using a Bruel and Kjaer type 4144 microphone and type 3347 one third octave analyser. The power computation program produced both 1/3 octave and octave band frequency spectra together with overall power levels.

The simple circular port premix burner was constructed as shown in Figure 1. Air and gas mixing was induced by an injector sized to give the desired mixture flow rates. Four circular port diameters were used 20.5mm, 27mm, 35mm and 40.5mm. Mixture efflux velocities up to 45 m/s were obtained which gave a maximum thermal rating of nearly 200 kW. All tests were carried out using natural gas (92% methane) and for these burners a hydrogen retention flame was used. The retention flame only influenced the sound power data in the sense that it maintained a stable main flame over the required range of air/gas ratios $0.8 < f_s < 1.2$.

A simple annular port burner was constructed by fitting a long 18mm diameter bar centrally located in the 27mm diameter circular port burner. A premixed air-gas mixture was supplied through the concentric annulus and the flame stabilised on the rim of the central bluff body. No hydrogen retention flame was used. In one series of tests this burner was fitted with a refractory tunnel 57mm diameter and 160mm long as shown in Figure 2a. The modular burner shown in Figure 2(b) was also tested to investigate the influence of both partial and full premix, and the effect of a refractory tunnel, for burner dimensions typical of many medium sized furnace burners.

3. RESULTS

3.1 Fully Premixed Circular Port Burners

The test programme for the circular port burners examined the influence of the three main parameters U, D and f_s. In each test the flame inlet turbulence level u_{rms} was measured to be a fairly constant proportion at 7% of the mean exit velocity U. Thus in all the tests the turbulent velocity (u_{rms}) was greater than the maximum laminar burning velocity S_L.

3.1.1 Sound power spectra

Figures 3 and 4 show the dependence of the sound power 1/3 octave spectra on the parameters D & U. All these spectra exhibit some distortion of the combustion noise in the 31.5 Hz and 63 Hz octave bands due to the reverberant room reponse. Figure 3 suggests that there is a small shift of the maximum energy bands to lower frequencies with an increase in port diameter. If a representative 1/3 octave centre frequency f_c is defined within each spectra (the term 'peak frequency' often used in combustion noise analysis is not really applicable to the broadband spectra commonly observed), then Figure 3 suggests a relationship of the type

$$f_c \propto (D)^{-0.7}$$

Figure 4 shows that there is virtually no shift in f_c for changes in U, a result which applied for all the burner diameters tested. Although not shown, there was also no discernable change in the measured spectra for different f_s.

3.1.2 Overall sound power level data

Since the sound power spectral shapes were substantially invariant with changes in the operating parameters U, D and f_s, it was possible to compare the noise output for different sizes and thermal ratings on the basis of the overall linear sound power level. From a multi-linear regressional fit to all the data the following empirical relationship between the sound power, W and heat output, Q, was derived;

$$\frac{W}{Q} = \eta = 2.037 \times 10^{-8}\ U^{1.55}\ D^{0.58}\ S_L^{\ 2.66}\ f_s^{-2.06} \qquad (1)$$

for $0.77 < f_s < 1.13$; $0.02 \quad D < 0.041$m ; $U < 45$ m/s

All points were within a ± 2 dB band as shown in Figure 5. Inclusion of the data for the very gas rich flames, $f_s = 1.2$ increased this error band to ± 3 dB. Comparison of Equation (1) with the results of Shivashankara [7] Strahle [9] and Kilham [10] which were mainly derived for smaller diameter burners, necessitates rewriting f_s in terms of the fuel mass fraction F. In this case equation (1) becomes

$$W = 2.3 \times 10^{-3} \quad U^{2.55} \quad D^{2.58} \quad S_L{}^{2.66} \quad F^{-1.06} \text{ watts} \qquad \text{.....(2)}$$

The Strahle [9] prediction, rewritten for SI units, is

$$W = 37 \times 10^{-3} \quad U^{2.67} \quad D^{2.81} \quad S_L{}^{1.83} \quad F^{-0.26} \text{ watts} \qquad \text{.....(3)}$$

applicable for $D < 0.025$m, $U < 180$m/s

The agreement between the two correlations is good considering the different range of burner sizes and flow velocities used in the investigations and the fact that the present results were limited to natural gas.

It was originally intended to supplement the experimental programme, embodied in the result of equation (1), with a more detailed examination of the basic noise generating mechanisms within premixed gas flames. A study of the acoustic source correlation volumes based on CH band light emission data was considered but difficulties were encountered in properly calibrating the equipment. However an examination of the total visible flame volume did support the originally held view that for these simple burners the higher sound power output for increased port exit velocity was associated with a decrease in flame volume and hence higher combustion intensities (incresed unsteady heat release). Taken at face value Equation 2 implies that lower noise levels are achieved by having the lowest possibly port efflux velocity for a given heat output, that is, either the port diameter should be large or, if port size is limited, then an arrangement of many ports each of which operate at low port velocities.

3.2 Annular Port Sound Power Data

3.2.1 Simple premix annular port burner

For these tests the 27mm outside diameter circular port nozzle was fitted with a centralised bluff body of 18mm diameter (45% blockage), using the same supply system as that for the previous circular port tests (Figures 1 and 2a). The test results are given in Figure 6 (corresponding to the left hand labels). When fired into the open the sound power of this annular port burner was some 4 dB higher than that of the simple 27mm diameter circular port burner at the same heat rating but this was primarily because the circular port flame had a higher port area and hence lower mixture efflux velocity. The sound power of an equivalent, smaller diameter (D = 20mm) circular port burner operating at the same mean efflux velocity was approximately the same as the annular port burner despite the different method of flame retention.

The annular port burner was then fitted with a 57mm diameter, 160mm long refractory tunnel. Figure 6 indicates that an 8 dB increase in sound power level was observed when compared with the burner firing into the open and operating at the same heat output. The fitting of a tunnel, which partially confines the flame, influences the noise output by imposing a different acoustic radiation impedance condition. It also changes the combustion reaction rates by increasing the recirculation of hot gases within the combustion zone and therefore altering the conditions under which the flame is stabilised. Not only does this extra flow agitation alter the flame volume but the turbulence levels within the flame are increased. Both conditions clearly lead to higher noise levels although the rate of increase with thermal rating was similar for all the flames so far tested.

3.2.1 Modular annular port burner with either full or partial premix

The modular annular port burner configuration of Figure 2b follows more closely the nozzle arrangement of commercially available burners designed to operate with partially premixed air/gas mixtures. When operated in the fully premixed mode the sound power data were similar in character to that of the simpler annular burner described above, namely that the open annular flame could be represented by an equivalent circular port flame having the same efflux velocity. Partial confinement in a combustion tunnel caused a significant increase in the total sound power output. In this case the increase was of order of 6 dB (Figure 6). In the partial premix mode (ie nozzle mixed), where the air and gas are supplied separately (Fig 2b) and some mixing takes place in the annular gap prior to the flame front, an additional noise increase occurred the extent depending on whether or not the tunnel was fitted. The cause of this increase in sound power output is not known since the flame structure could not be studied in detail. It is possible that in the partial premix mode part of the combustion process is delayed and subsequently occurs in areas of flow recirculation which have higher levels of turbulence. Thus "localised" combustion zones may occur which have higher combustion intensities than for fully premixed flames which stabilise much closer to the burner head.

3.3 Summary of Test Burner Data

The spectral data shows that the frequency distribution of the radiated sound power is not markedly altered by changes in U, D and burning velocity S_L (through f_s). Maximum sound energy is radiated in the 125Hz to 500Hz octave bands. Simple circular port and annular port premixed flames generate similar levels of broadband noise provided the port mixture velocities are the same. This is an unexpected result since different methods are used for flame retention. Partially enclosing the flame in a refractory tunnel alters both the flame structure and significantly increases the sound power output, as does a change from full to partial premixing of the air and gas supplies. The most effective method of reducing flame noise for a given burner configuration is to reduce the port mixture velocities which for a given thermal output implies either larger port diameters or many smaller ports.

4. INDUSTRIAL BURNER SOUND POWER DATA

The data for the simple circular port burners and the two annular port configurations may be compared with the sound power output of a range of commercially available, high velocity, industrial burners. This comparison is shown in Figure 7 for thermal ratings up to 150 kW. Each industrial burner shown has a different head design but all use separate air and gas ports and therefore may be classified as nozzle mixing burners with different degrees of air-gas premixing prior to combustion. In this context the designs are similar in concept to the annular port test burner of Figure 2b and the sound power data of Figure 7 shows that the latter falls well within the noise output range of the industrial designs.

The variation in sound power between the individual industrial burners at any given heat output is due to the different efflux velocities at the tunnel exit, which in part reflects the different mixing and burning conditions associated with each nozzle design. The theoretical mean velocities at the tunnel exit are given in Table 1. Note that for both burner number 9 and the modular test burner, combustion was not complete at the tunnel exit and the theoretical mean velocity was greater than the measured value. In the case of the modular burner the exit velocity was only 70% of the predicted 85 m/s. The resultant lower combustion intensity reduced both the sound power and the steady thrust associated with the tunnel exit flow velocities.

5. INDUSTRIAL BURNER NOISE REDUCTION

The industrial burners considered in Figure 7 are used on gas fired furnaces which are specifically designed for the rapid reheating of metal billets. This application justifies the relatively high velocity of the combustion products at the tunnel exit plane. One consequence of this high velocity is an acoustic efficiency, relating sound power output to thermal output, in the range $10^{-7} < \eta < 10^{-5}$. In many applications this conversion efficiency does not lead to excessively high sound pressure levels adjacent to the furnace and most systems meet the 90 dB(A) criterion recommended in current Codes of Practice. However, the need for larger furnaces, or improved furnaces with higher thermal ratings, plus the probability that future legislation may require a lowering of industrial noise levels to below the 90 dB(A) limit, implies that, where practicable, combustion noise levels should be reduced. The results of this paper highlight several techniques for achieving this objective.

The first significant result is that the combustion intensity should be reduced to the lowest practical value permitted by the particular furnace application. For the burner designs used in Figure 7 a lower combustion intensity corresponds to a lower tunnel efflux velocity. The extent of the noise reduction which can be achieved is indicated by equation (1) which implies;

Sound power $W \propto Q/D^{2.6}$

Thus for a given heat release/unit time, Q, the larger the area of the combustion zone (restricted by tunnel diameter D) the lower the noise output. For the type of industrial burner considered here this may lead to an unacceptably large size of unit.

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The present investigation suggests an alternative approach. Open fully premixed flames generate less broadband noise than open partially mixed flames as indicated in Figures 6 and 7. A considerable portion of this noise reduction can be retained for premixed tunnel burners provided that the influence of the tunnel can be minimised. This can be done, for example, by a suitable choice of port arrangement, tunnel size and shape such that the combustion intensity is low but the products are accelerated within the tunnel to the required efflux velocity. In acoustic terms this is a trade off between combustion generated noise and jet noise.

Figure 8 shows the noise reduction which is possible based on the above philosophy. The higher sound power spectrum level is for an existing fully premixed industrial burner incorporating several separate high intensity combustion tunnels. The second spectrum, which represents a 14 dB(A) noise reduction is for a prototype multiport premix burner with a single tunnel which has a lower combustion intensity but which through a judicous choice of the port and tunnel sizes gives the same tunnel efflux velocity. This new burner is the result of an optimisation study and in its present form gives a thermal-acoustic effinency of approximately 10^{-8}. This is a significant reduction when compared with the other burner designs quoted in Figure 7. It is hoped to publish further details of this burner development in the near future.

6. CONCLUSIONS

This study shows that turbulent natural gas flames generate broadband noise within the frequency band 60 Hz to 2000 Hz. The overall sound power level is a function of port mixture velocity and the degree of air and gas premix. The noise level is also significantly increased by the presence of a refractory tunnel which, in some industrial burner designs, is used to promote vigorous flow recirculation within the combustion zone and hence shorter, more intense flames with higher product efflux velocities. By comparing the noise output of typical industrial burners with data from several carefully selected test burners it has been possible to assess qualitatively the operating/design features which give the lowest noise levels for a given thermal output. This data has been used to produce a prototype premix burner which is at least 14 dB(A) quieter than existing designs

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APPENDIX A : LIST OF SYMBOLS

D port diameter, m

F fuel mass fraction = $\dfrac{0.54 f_s}{10.55 - 0.45 f_s}$

f_c Characteristic frequency, Hz

f_s air-gas fraction = $\dfrac{\text{1+ stoichiometric air/fuel ratio}}{\text{1+ actual air/fuel ratio}}$

Q heat release/unit time, W/s

S laminar burning velocity, m/s

U velocity, m/s

u turbulence-velocity, m/s

W sound power, dB re 1pW

η thermal-acoustic efficiency (equ 7)

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TABLE 1

DETAILS OF INDUSTRIAL BURNER DESIGNS TESTED

HEAT OUTPUT 147 kW

BURNER NO.	AIR-GAS MIXING MODE	TUNNEL EXIT DIAMETER (mm)	MEAN PORT EFFLUX VELOCITY m/s	THEORETICAL TUNNEL EXIT VELOCITY m/s
17	PARTIAL PREMIX	76	32	77.5
2	PARTIAL PREMIX	120	32	31
9	SMALL DEGREE OF PREMIX	114	21	34
5	PARTIAL PREMIX	76	17	77.5
4	FULL PREMIX	89	50	57
EXPERIMENTAL MODULAR BURNER	FULL AND PARTIAL PREMIX	72.5	34	85

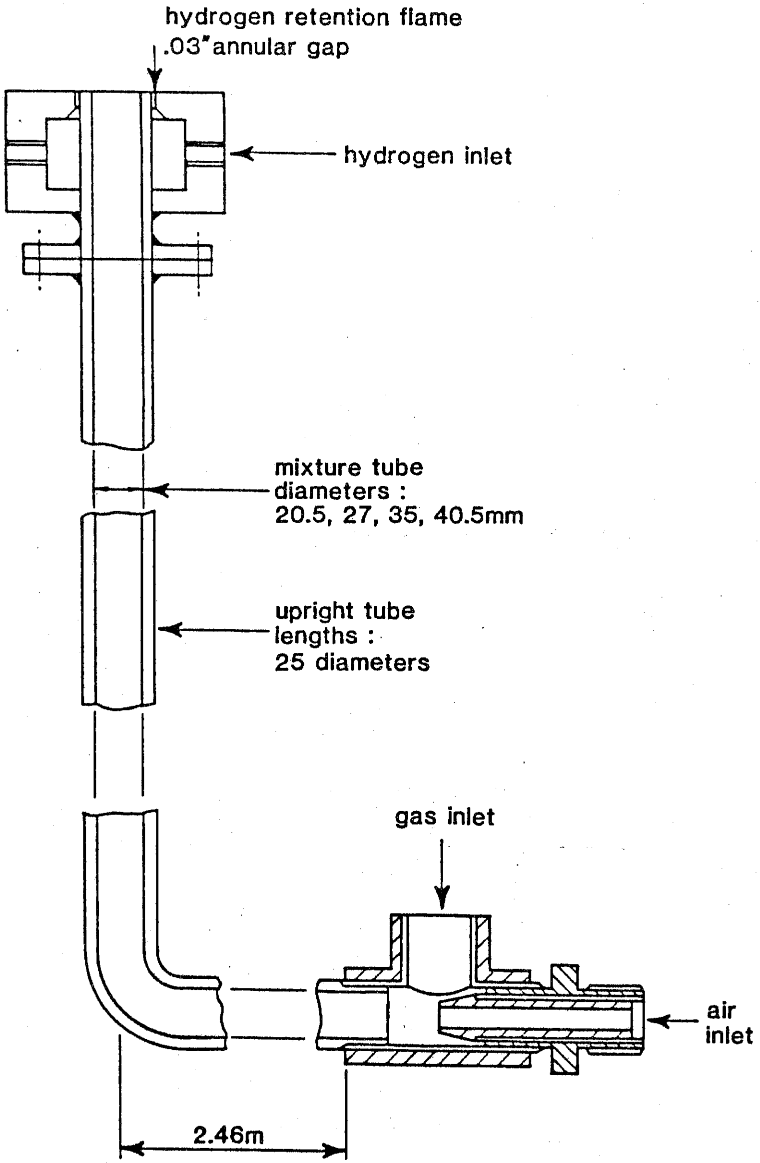

FIG. 1. SIMPLE CIRCULAR PORT PREMIXED BURNERS

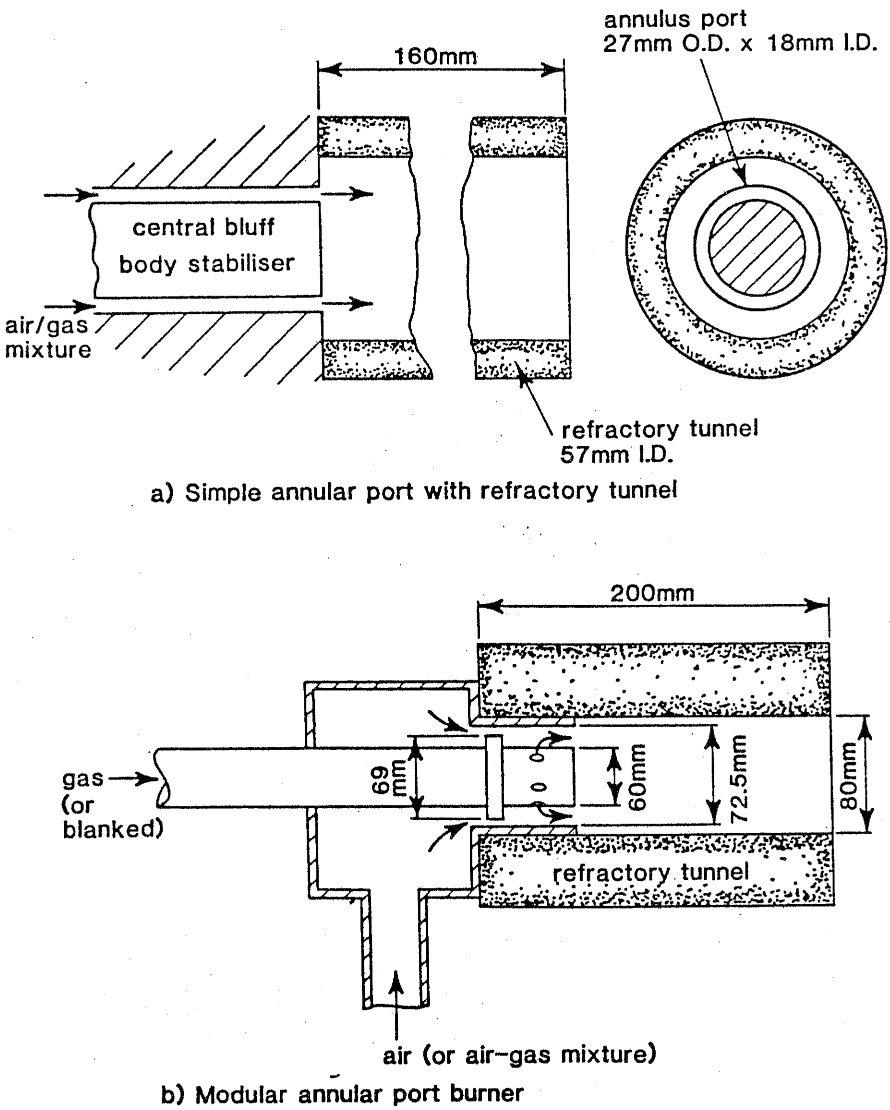

FIG. 2. EXPERIMENTAL ANNULAR PORT BURNERS

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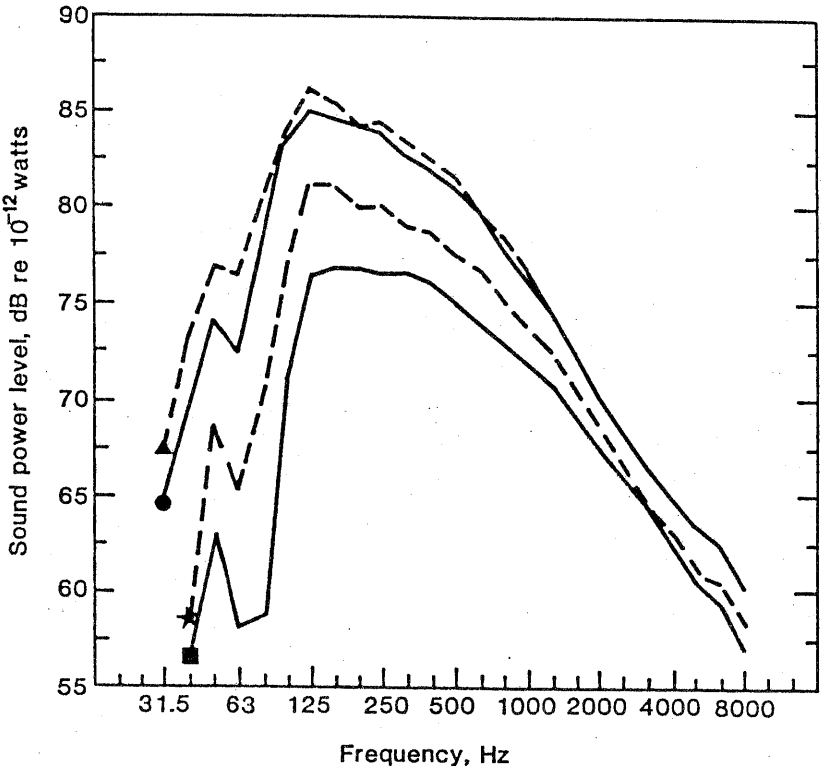

Curve	Burner diameter	Mean exit velocity
■	20.5mm	$19.4ms^{-1}$
★	27mm	$19.8ms^{-1}$
●	35mm	$19.9ms^{-1}$
▲	40.5mm	$19.4ms^{-1}$

FIG. 3. VARIATION OF ⅓ OCTAVE BAND SOUND POWER SPECTRUM WITH PORT DIAMETER. VELOCITY AND fs CONSTANT

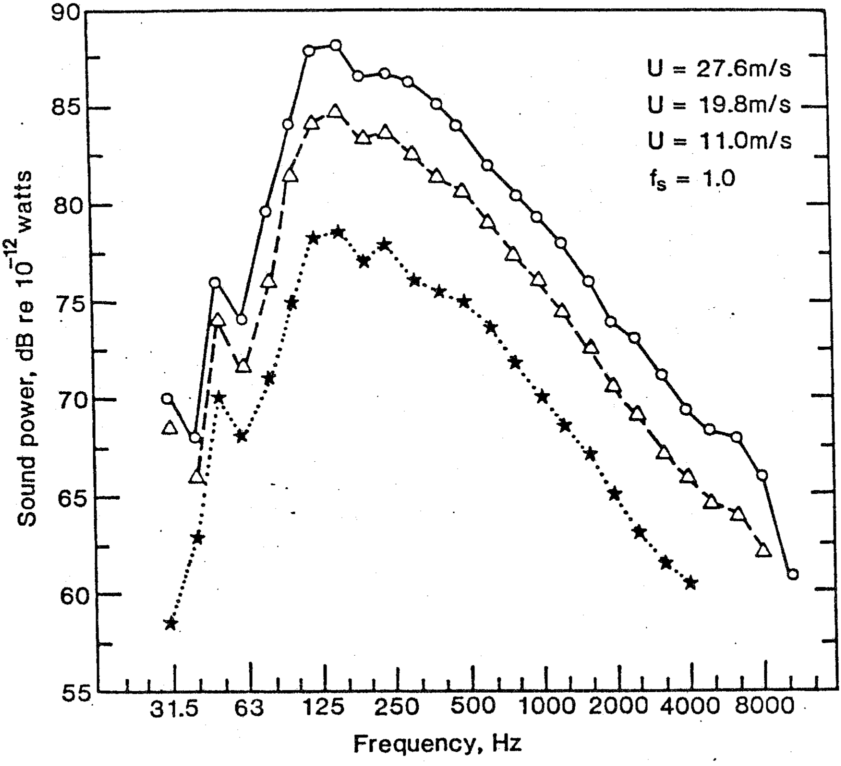

FIG. 4. ⅓ OCTAVE BAND FREQUENCY SPECTRA FOR CONSTANT BURNER DIAMETER, D = 35m, AND STOICHIOMETRIC AIR-GAS RATIO, AS A FUNCTION OF PORT EXIT VELOCITY

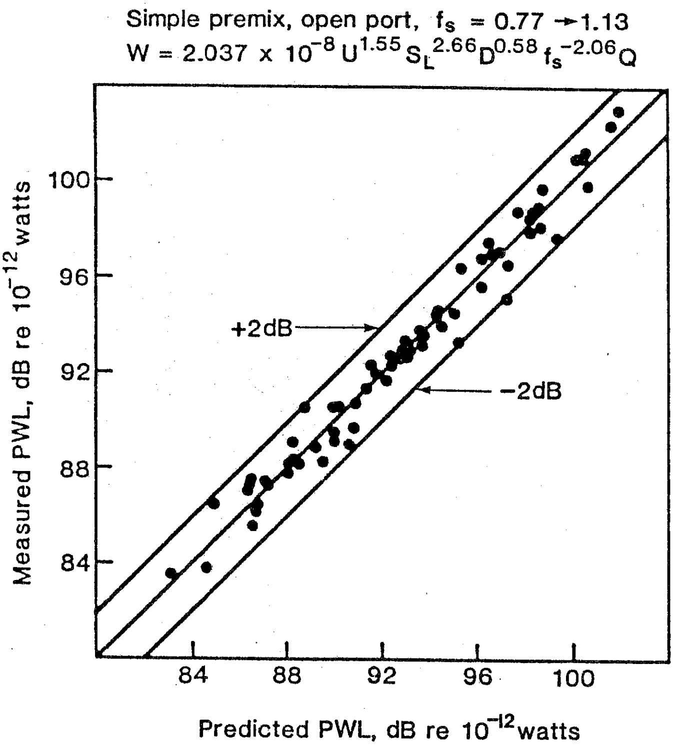

FIG. 5. RESULTS OF MULTI-LINEAR REGRESSION FOR SOUND POWER DEPENDENCE ON U, S_L, D AND fs CIRCULAR PORT PREMIX BURNERS ONLY

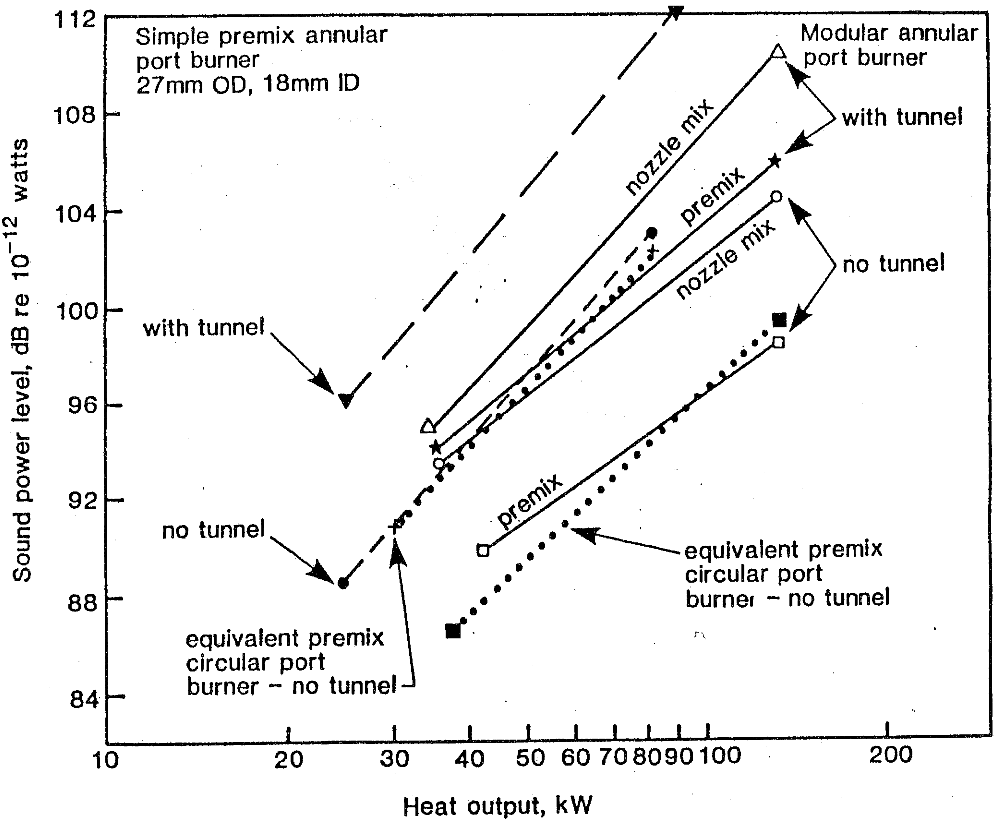

FIG. 6. COMPARISON OF CIRCULAR PORT SOUND POWER WITH TWO DIFFERENT S OF ANNULAR PORT NOZZLES OPERATING WITH AND WITHOUT A REFRACT TUNNEL fs – 1.0

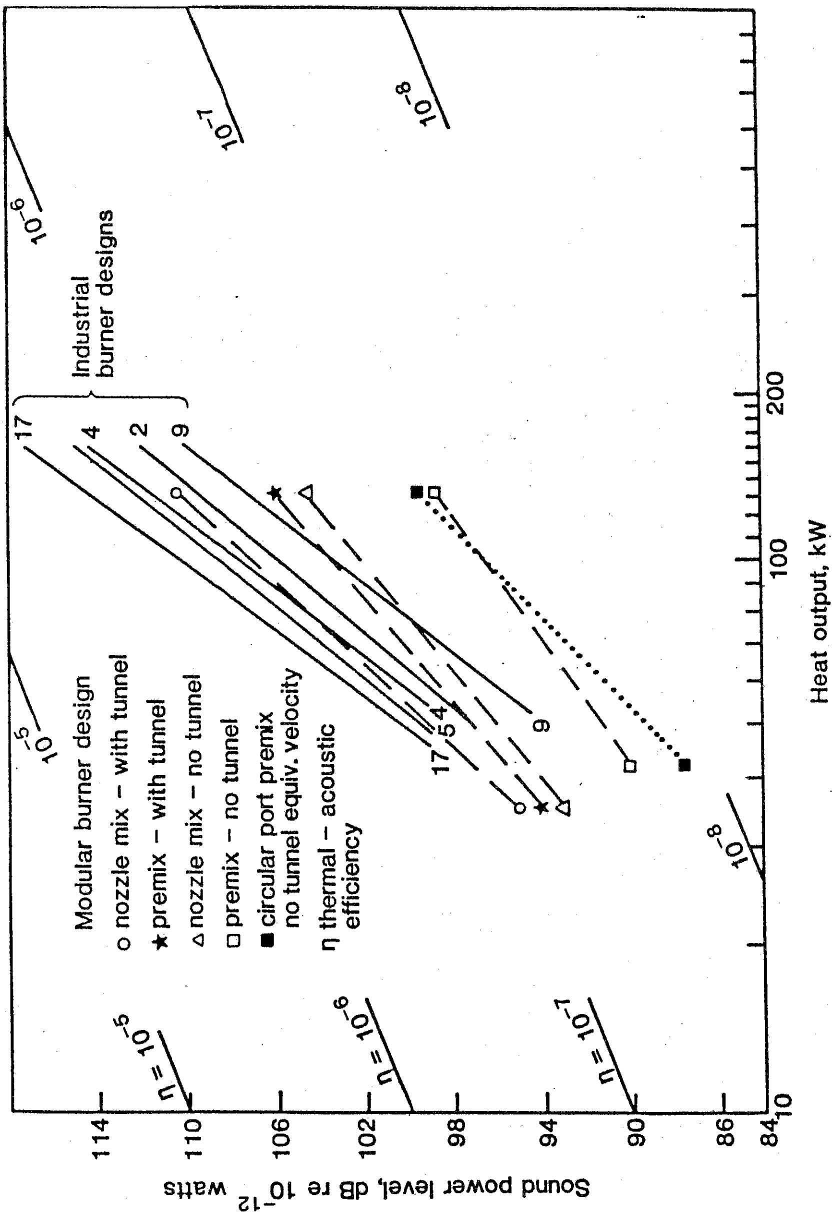

FIG. 7. COMPARISON OF EXPERIMENTAL MODULAR BURNER WITH INDUSTRIAL BURNER DESIGNS

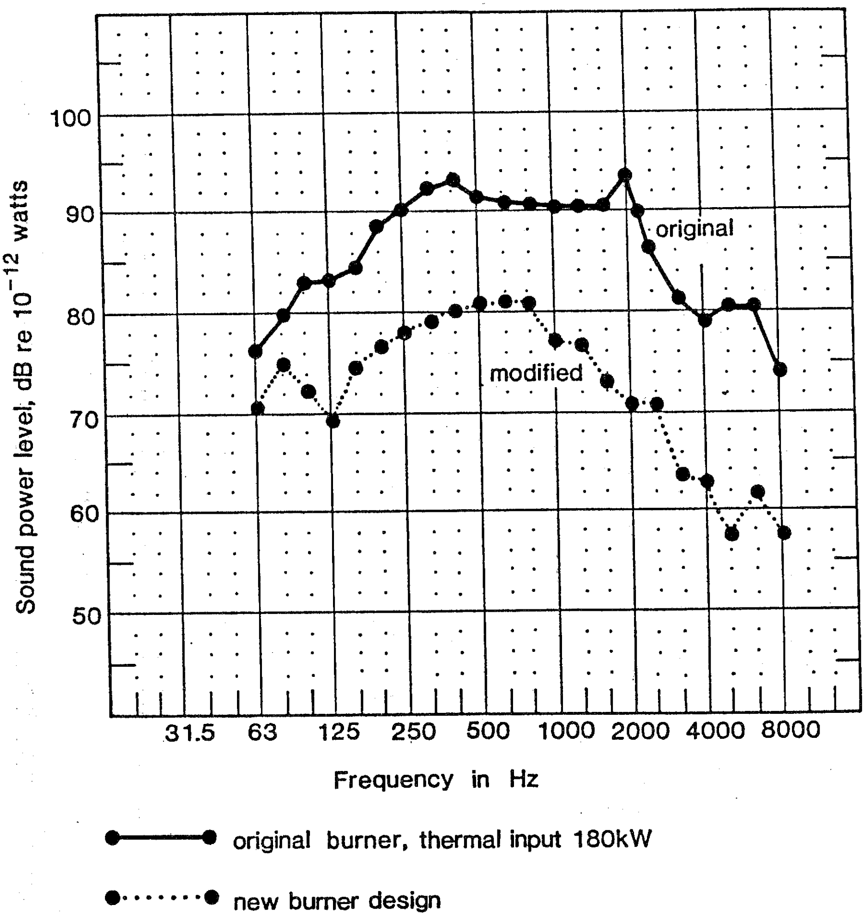

FIG. 8. NOISE REDUCTION ACHIEVED THROUGH MODIFICATIONS TO PORT CONFIGURATION AND TUNNEL SIZE. FULLY PREMIXED BURNER