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GAS COMBUSTION NOISE PRODUCED BY FLOW TURBULENCE IN OPEN PRE-MIXED FLAMES - J. P. Roberts, Chelsea College and South Eastern Gas Board

Experimentally we may observe two types of open, turbulent gaseous flame, either attached or free. The attached flames that are usually observed are either simple Bunsen burner type flames attached to the rim of the burner or to a holder, such as a pilot or rod perpendicular to the flow.

Examined here are attached Bunsen burner type flames, associated with a pipe flow Reynolds number of between 10,000 and 20,000, so that the flame front lies within the turbulent core of the air/gas jet, and where average velocities and turbulent fluctuating velocities are of the same order of magnitude as at the mouth of the burner.

It is generally agreed that, acoustically, a turbulent flame may be represented as a random array of monopole sources. In the region of turbulent flow for which pipe flow Reynolds number is between 10,000 and 20,000 one can assume for Bunsen burner type flames a flame speed associated with small scale turbulence and a continuous wrinkled flame front where the wrinkling is due to the largest turbulence eddies generated in the flow. The possibility is examined that, for a homogeneous air/gas mixture these eddies may be considered pockets of combustible gas which, when they reach the flame front causing it to wrinkle, are heated on all sides, ignite and as they burn evolve an increased volume of heated gas, so acting as monopole sources.

It may be shown (1) that, assuming a sphere of combustible gas ignited simultaneously at all points on its surface, an infinitely thin flame front propagating radially into the sphere at constant flame speed and that the combustion takes place at constant pressure, the magnitude of the pressure pulse will be directly proportional to the radius of the sphere of combustible gas and the square of the flame speed, according to the formula

$$p = \frac{\rho(E-1)}{4\pi d}\left\{2\pi r v_b^2 + 4\pi r^2 \frac{dv_b}{dt}\right\}$$

where p is the amplitude of the pressure fluctuation at a distance d, ρ is the density of the medium through which the sound is propagating, r is the radius of the combustible sphere, E is the volume ratio of burnt to unburnt gas, v_b is the flame speed. The radial velocity of the flame front into the air/gas mixture is dr/dt.

For natural gas/air spheres of initial radius 0.01m and a flame speed of 0.5m/s the pressure pulse from a single sphere will be of magnitude 11dB re $2x10^5$ N/m^2.

Physically the bubble of combustible mixture ignites at its surface, the flame front accelerates to the flame speed of the mixture, v_b, and there then follows a period when the flame front travels through the mixture at constant speed. Finally, as the combustible mixture is reduced to a small volume the flame front accelerates due to the increase in temperature of the remaining mixture. The products of combustion as they expand outwards will cool, effectively decreasing E, leading to a tailing off of the pressure pulse. Thus from the above equation there will be an initial period when p grows rapidly. There then follows a period when v_b is constant and p falls linearly with time as r decreases. Finally the pressure will become negative before tailing off to zero. The peak frequency from such a pulse will be of the order of $1/\tau$, where τ is the time of combustion.

Fluctuations in Flow Velocity and Flame Speed as Sources of Flame Noise.

Another possible source of flame noise is the generation of pressure pulses by fluctuations in the flow of the combustible mixture as it meets the flame front.

By considering the momentum equation, the continuity equation, the energy equation and the equation of state, assuming that the combustible mixture and products of combustion are perfect gases, and making several other simplifying assumption it is possible to show that the pressure pulses generated at a flame front by a velocity fluctuation in the flow will, for a constant flame speed, be proportional to $dU.dP/(U.M^2)$. Where M is the ratio of the mean velocity of the combustible mixture flow, U, to the local velocity of sound, c, dP is the pressure drop across the flame front and dU is the fluctuation in U. Substituting typical values for hydrocarbon gases, the pressure pulse generated at the flame front is of the order of 160dB re 2×10^{-5} Nm^{-2}. The pressure pulse produced by a fluctuation in the flame speed of the mixture will be proportional to $dv_b.dP/(U.M^2)$. For natural gas the pressure pulse generated at the flame front will be of the order of 200 dB re 2×10^{-5} Nm^{-2}. It is to be expected that the shape of the noise spectrum produced by these flow fluctuations would be similar to that of the turbulence.

Apparatus and Procedure.

Noise production in a model burner was investigated first using suitable smooth bore tubes fed with premixed gas/air mixtures which issued from the orifice in the form of a jet. The flame could be seated in any position along the jet by an arrangement of silent auxiliary pilots and thus burns under different conditions of turbulence.

Mean flow, fluctuating velocities and turbulence spectra were measured at various points within the jet with an anemometer, both with and without various wire meshes in the flow. The meshes were inserted to produce variations in the turbulent energy spectrum of the jet.

Holding a pre-mixed gaseous flame seated at various heights above a circular port enablesone to examine the possible variation in flame noise due to variation in the velocity fluctuations and turbulent eddy size. Using a homogeneous gas mixture eliminates, as far as possible, fluctuations in the flame speed.

If the turbulent eddies behave as spheres or bubbles of combustible gas then not only should the peak frequency of the combustion noise spectrum vary with flame speed, but it will also vary inversely with the size of the turbulent eddy.

In fact the air/gas ratio, and consequently the flame speed, have little, if any, effect upon the frequency at which the combustion noise spectrum reaches its peak. The determining factor appears to be solely the height of the flame above the orifice. This was confirmed changing from town gas to natural gas. Although, relatively, town gas has a much higher flame speed than natural gas this increase has no appreciable effect upon the frequency of the combustion noise spectra peak. Also for the flame seated a distance of more than eight diameters above the port orifice the turbulent eddy size decreases with distance, whereas the frequency also decreases.

Despite the fact that the flame front oscillates in a turbulent flame there was good agreement between the peak frequencies of both the flame noise and turbulence energy spectra, decreasing from the 250Hz octave band five port diameters downstream to the 32.5Hz octave twenty port diameters downstream.

The effects of flow velocity fluctuations on the flame noise, using a circular port, were examined directly with an analogue time delay correlator. Three separate methods were used to detect velocity fluctuations at the heel of the flame: (a) a probe microphone pointing into the heel of the flame, (b) utilising known flame ionization techniques, and (c) directly measuring flow velocity fluctuations with a hot wire anemometer. In each case a definite peak was observed in the cross-correllograms of flame noise with flow velocity fluctuations at a time delay equal to the time taken for the velocity fluctuations in the combustible mixture to proceed from the detector to the flame front and the consequent pressure pulse to travel to the microphone. A normalised cross-correlation coefficient of 0.3 was obtained, this compares quite well with a value of 0.5 obtained when the noise from the turbulent flame was cross-correlated with itself using two microphones a known distance apart.

The pressure pulse emitted by a burning sphere of combustible gas is proportional to the rate of change of rate of volume evolution. Cross-correlation of the differential of the ionization current within the flame and flame noise sound pressure revealed no peak, confirming the previous results that the turbulent eddies do not act as bubbles of combustible gas.

The noise from a range of typical commercially available packaged burners using both town gas and natural gas was investigated in the Industrial Laboratory of the South Eastern Gas Board. Cross-correlation techniques similar to those employed with the model burner were used to examine the relationship between flow velocity fluctuations, turbulence eddies and flame noise. The air/gas stream issuing from the ports of the packaged burners was highly turbulent with vortices, inhomogeneity of the mixture, turbulence eddies and a heterogeneous distribution of velocities. Thus all three noise producing mechanisms analysed theoretically were considered potential sources of noise.

A value of 0.5 for the normalised cross-correlation was again obtained when the noise from a packaged burner was cross-correlated with itself using two microphones a known distance apart. Cross-correlation of flame noise with flow velocity fluctuations gave a normalised cross-correlation coefficient of 0.35. (See Fig. 1).

Because of the inhomogeneity of the combustible mixture in the packaged burners it was considered that the volumes of gas reaching the flame front may have acted as bubbles of combustible mixture and given rise to pressure pulses. However, cross-correlation of the flame noise and the differential of the ionization current across the flame front gave no discernable peak on the cross-correllelogram indicating that again there was no apparent contribution to the flame noise from this source.

Typical octave band analyses of the sound pressure level of the flame noise and the flow velocity fluctuations correspond well for the lower octave bands (Fig. 2), but there is some disagreement in the 1 kHz octave band and above. However, similarity of shape of the octave band spectra is not a necessary condition for the flow velocity fluctuations to contribute to the flame noise. What is indicated is that another noise producing mechanism is present, probably fluctuations in the flame speed.

Reference. (1) Thomas and Williams, Proc. Roy. Soc. A 294 (1439) 1966.

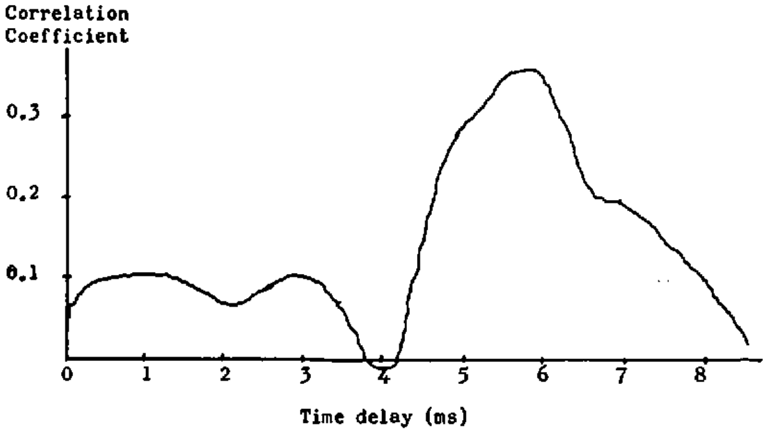

Fig. 1. Cross-correlogram of flame noise and flow velocity fluctuations for packaged burner

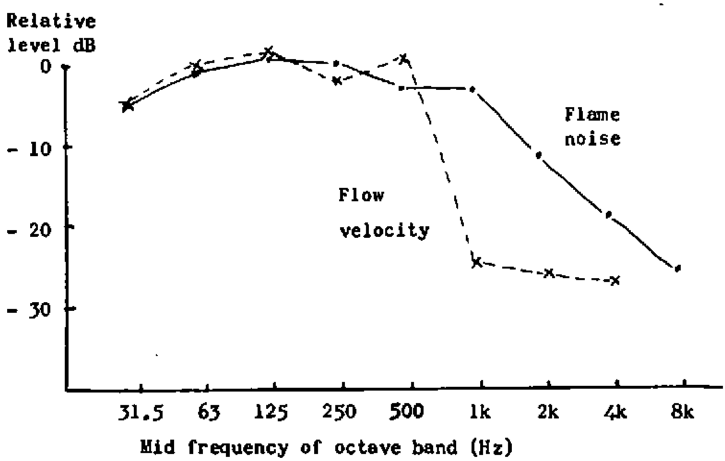

Fig. 2. Flame noise and flow velocity fluctuation spectra for packaged burner