Proceedings of The Institute of Acoustics

ON NOISE PRODUCING MECHANISMS IN TURBULENT GAS COMBUSTION

B. Dalamagas[1], N. Kidin[2], J. Roberts[1], and M. Vuillermoz[1]

1. Polytechnic of the South Bank, London, SE1 0AA
2. Institute for Problems in Mechanics,
USSR Academy of Sciences, Moscow, USSR

1. INTRODUCTION

Combustion generated noise has been categorised by Putnam [1] as the combustion amplification of acoustic and flow phenomena. This study follows Putnam's classification where periodic flow phenomena are the result of the superposition of a pure tone acoustic signal of audible frequency on the combustible mixture flow upstream of the flame.

This project has been confined to the behaviour of flames which are essentially laminar, in the sense that without the added upstream disturbances, the flame does not constitute a noise source. Previous research by Roberts [2] on pyro-acoustic amplification has shown that fluctuations in the flow velocity of the primary air/fuel mixture reaching the flame front, which cause periodic variations in the rate of heat release may be a major source of combustion noise below $1kH_z$. That work was limited to the case of low amplitude signals. Above certain amplitudes which depend on the frequency of the acoustic disturbance, Fig.1, an additional mechanism gives rise to a more complex sound pattern.

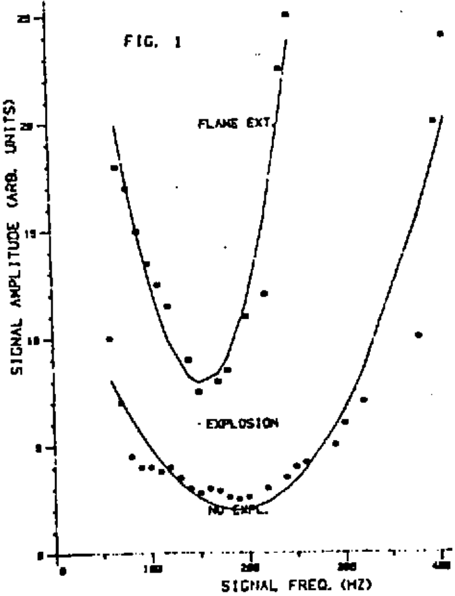
This paper examines the effects of a pure tone acoustic signal propagating in the combustible mixture flow to a premixed laminar flame cylindrical burner. An attempt is made to relate flame noise to acceleration - induced changes in the premixed laminar flame structure. Flow rate fluctuations result in particle velocity disturbances and in consequence in acceleration fluctuations which are functions of the frequency and amplitude of the applied acoustic signal. Measurements were made of both the flame structure under disturbed conditions and the generated sound pressure levels in an attempt to relate the sound power and/or pressure produced by the combustion process to the specifics of the flame shape.

EXPERIMENTAL APPARATUS

The function of the apparatus was to provide a well mixed, steady, known flow rate of natural gas and air to an open cylindrical burner supporting a laminar flame. The burner consisted of a smooth copper tube of 1 m length and 25 mm internal diameter, capped by a 1 mm thick disk with a central port of 3 mm diameter, Fig.2, on which the flames were seated. The acoustic driving signal was provided by a 5W, 3 inch loudspeaker, energised by pure tones. The acoustic measuring system was a 1 inch Bruel & Kjaer measuring amplifier with band pass filter set Fig.3. A dual channel digital memory oscilloscope was used to display the acoustic pressure waveform produced by the thermal explosion of the combustible mixture.

Shadowgraphy was used to visualize the flame movement. The flame geometry was determined from the produced negatives using a 45 mm microscope. In order to freeze the projection of the flame, a stroboscopic system was used in which a lamp was triggered by the signal generator. It was, of course, necessary to introduce a variable delay of up to one cycle in the system. This was done using a pulse generator in conjunction with a device by which the polarity of the signal could be changed by 180°. Using such a configuration the entire process of amplification could be observed and thus, any one point of the flame cycle could be examined.

FIG. 1



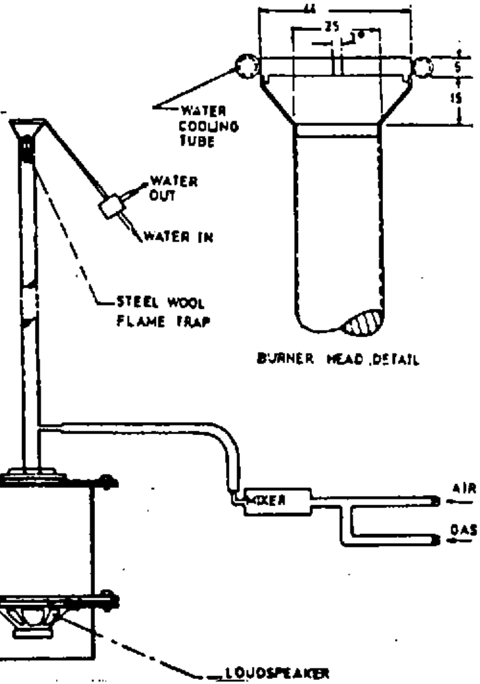


FIG 2 BURNER SYSTEM

2. RESULTS

Flame Shape

With no applied acoustic signal the premixed laminar flame was conical and stable. When a pure tone acoustic signal of sufficient amplitude was superimposed on the combustible mixture flow rate, substantial changes took place in the flame shape and, eventually, structure. A complete cycle of the flame history is shown in Fig.4. The flame lengthens under the action of the imposed acoustic signal into an extended mushroom shape with a long stalk and small head, see Fig.5. As the flame front propagates into the unburned mixture the stalk radius decreases until it disappears in a small thermal explosion, ejecting a spherical bubble of combustible mixture undergoing uniform surface burning, see Fig.6. The flame front propagates radially inwards until the bubble also undergoes thermal explosion. A new cycle then commences.

Acoustic Pressure Waveform

When no acoustic signal was superimposed on the combustible mixture flow the microphone system detected only the acoustic background level. But when a pure tone acoustic signal of sufficient amplitude propagated through the combustible mixture flow, the acoustic pressure waveform took on a distinctive form. Two pulses appeared in the acoustic waveform, Fig.7, the amplitudes of which increased as the amplitude of the applied signal was further increased. A substantial increase in the amplitude of the applied signal resulted in a lifted flame which then extinguished.

The introduction of acoustic disturbances into the combustible mixture flow can be seen to have resulted in a qualitative change of the combustion process, and a combustion cycle has been introduced. It has been shown [3,4] that the creation of the acoustic pressure pulses coincide exactly with the disappearance of the cylindrical neck and the spherical bubble in turn. But acoustic pressure pulses as sharp as those observed, can result from nothing else, in this kind of combustion process, other than thermal explosions. The shape of the pressure pulses (Fig.7), tends to strengthen the hypothesis of minor thermal explosions in the flame.

Relating flame geometry to the applied signal it was found that the length of the neck reduced sharply as the frequency of the applied signal increases, Fig.8. The same trend is observed in the measured maximum pressure which decreases sharply as the frequency of the applied signal is increased, Fig.9. Such relationships imply that the acoustic pressure generated by the thermal explosion of the stalk is a function of the length of the stalk, and that this may well be a linear relationship.

3. DISCUSSION

As the bubble or the neck undergoes uniform surface burning two main stages can be theoretically assumed to take place prior to the explosion occurring.

Stage I: Surface burning with constant normal burning velocity occurs when the radius of the neck or bubble is comparatively large, much larger than Markstein's constant μ [5]. The noise produced at this stage can be explained and estimated by the theory of Thomas and Williams [6].

Stage II: The second stage may be reached when the characteristical radius of the volume of unburned gas surrounded by the surface of the flame decreases to a value in the order of μ. Here the normal flame velocity does not remain constant and to a first approximation depends on flame front curvature which leads to an acceleration of the flame front [5].

In this case the acoustic pressure at a distance r from a monopole source of radius A will be given by,

$$p = \frac{\rho}{r}\,\frac{d}{dt}\left[A^2\,\frac{dA}{dt}\right] = \frac{\rho}{r}\,U_n^{0\,2}\,A\left[2+\frac{\mu}{A}\right]\left[1+\frac{\mu}{A}\right] \quad \ldots\ldots \quad (1)$$

Where: Markstein's constant μ has the form,

$$\mu = \left[\frac{\kappa - D}{\kappa}\;\frac{E^*\left(T_B - T_o\right)}{2R\;T_B^{\;2}} + \frac{D}{\kappa}\right]\frac{\kappa}{U_n^0} \quad \ldots\ldots \quad (2)$$

Expression (1) above reduces to that given by Thomas and Williams when $\mu/A \ll 1$.

The radius as a function of time will have the form

$$A(t) = A_o + \mu\log_e\left[\frac{A+\mu}{A_o+\mu}\right] + U_n^0\,(t - to) \quad \ldots\ldots \quad (3)$$

Stage III: The third and final stage of the process, the thermal explosion, occurs due to the change in the mechanism of burning. The decrease in colume of the unburned mixture as the combustion process proceeds causes increasing curvature of the flame front with a consequent strong acceleration of that front and interaction of the preheat layers until the entire remaining unburned combustible mixture undergoes a sudden exothermic reaction. In this case the maximum value of the acoustic pressure pulse generated appears to be related to the volume, V, of the exploding mixture just prior to the explosion, and the characteristic time of the effective exothermic chemical reaction, t_{ch}.

$$P_{max} = \frac{\gamma(\nu-1)}{\nu(\gamma-1)}\;\frac{V_1 P_o C v T_B}{4\pi r\;c_0^2\;t_{ch}^2} \quad \ldots\ldots \quad (4)$$

where: t_{ch} from the Arrenius law of thermal reactions takes the form;

$$t_{ch} = P_1 C_v R T_B^2\,\exp\left(\frac{E^*}{RT_B}\right)\Big/\left[QE^* a_1^n\,K_1(T_B)\right] \quad \ldots\ldots \quad (5)$$

This last expression is not, of course in a convenient form for estimating the value of t_{ch}, but if the usual approximations concerning the normal burning velocity and preheat layer for laminar flames are used it follows that

$$t_{ch} = \frac{\kappa}{U^{o\,2}_{n}} \; \frac{RT_o}{E^*} \qquad \ldots\ldots \qquad (6)$$

Substituting this last expression into (4) one obtains a more convenient form for comparison with the experimental data.

$$p_{max} = \frac{\nu(\nu+1)}{(\gamma\nu+1)^2} \; \frac{\rho_o \, U^{o\,2}_{n} \, T_B \, E^* \, L_1}{4\pi r \, RT_o^{\,2}} \qquad \ldots\ldots \qquad (7)$$

We consider that the combustion mechanism described above complements modern theories of turbulent combustion, [7]. For example the model of "mushroom" and "spherical bubble" flame may be considered as any sharp "angle" or "leading" points of the flame front in a turbulent flame.

4. CONCLUSIONS

This paper has examined the effect of an acoustic signal propagating in the combustion mixture flow on a premixed laminar flame. It has been shown that above a certain minimum level of the applied acoustic signal non-linear phenomena are observed due to the explosive combustion of the fuel gas/air mixture. Indeed this non-linear mechanism might partly explain the "superturbulent" combustion noise noted by Putnam and others [1].

Quantitative measurements have been attempted and it is shown that the acoustic pressure produced by the explosions is related to observed flame parameters immediately prior to the explosion. A mathematical model has been developed and experimental results and theoretical predictions appear to agree well, see Fig.10.

REFERENCES

(1) PUTNAM, A.
"Combustion Noise in Industrial Burners".
Noise Control Engineering, 7, 1, pp.24-34 (1976).

(2) ROBERTS, J.P.
"Amplification of an Acoustic Signal by a Laminar, Premixed, Gaseous Flame".
Combustion and Flame, 33 (1948), pp.79-83.

3. DALAMAGAS, B.C.
"On Non-linear Acoustic Sources in Gaseous Combustion".
MSc Thesis (CNAA), South Bank Polytechnic (I.E.S.T.) (1982).

4. SMITH, J., ROBERTS J., and VUILLERMOZ, M.
Acoustic Letters 5 (1983) pp.66-69.

REFERENCES (Cont'd)

5. MARKSTEIN, G.H.
"Experimental and Theoretical Studies of Flame Front Stability".
J. Aero. Sci. 18 (1951) p.119.

6. THOMAS, A and WILLIAMS, G.
proc. Roy. Soc. A 234 (1966) pp.44-66.

7. BRAY, K.N.S.
"Turbulent Flows with Premixed Reactants".
In the book by LIBBY, P.A., and WILLIAMS, F.A.
"Turbulent Reacting Flows". pp.115-184 (1980).

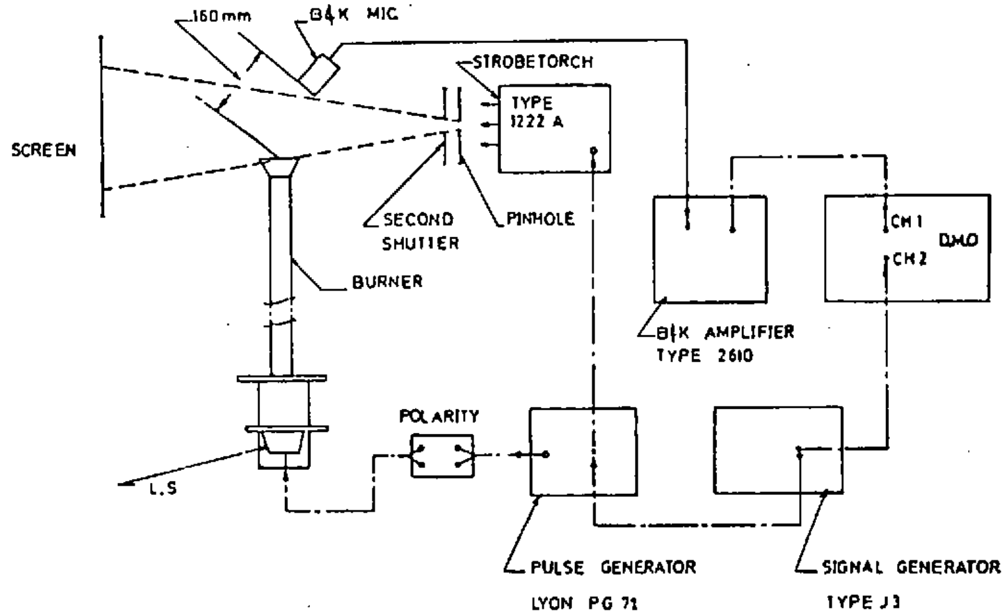
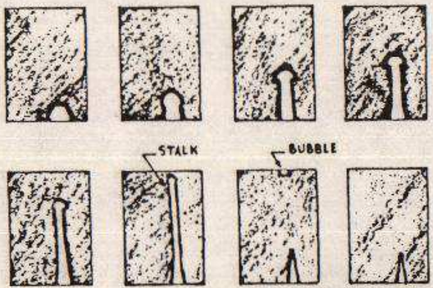
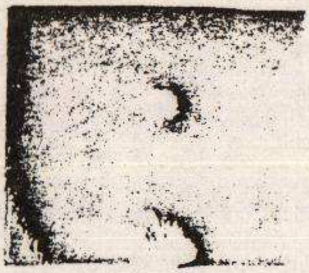


FIG. 3 INSTRUMENTATION ARRANGEMENT

FIG 4 FLAME CYCLE





Spherical bubble before explosion.

2 Pulses

d2 = 0.58 mm
12 = 3.6 mm
V2 = 3.80 mm^3

FIG. 6 Air = 0.3 l/m
Gas = 0.06 "

300HZ
30 VOLTS

300HZ
30 VOLTS

Cylindrical neck
before explosion
2 Pulses

d2 = 0.61 mm
12 = 10.0 mm
V2 = 11.68mm^3

d4 = 0.71 mm
V4 = 0.18 mm^3

FIG. 5 Air = 0.60 l/m
Gas = 0.08 l/m

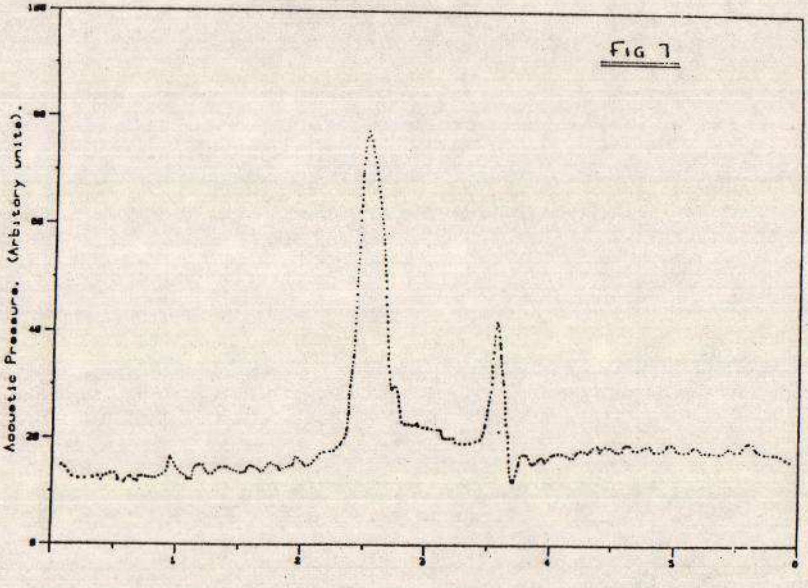


FIG 7

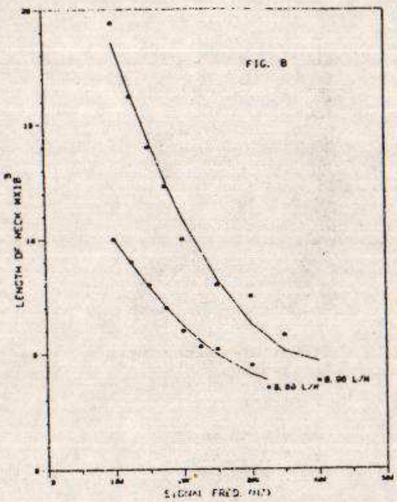


FIG. 8

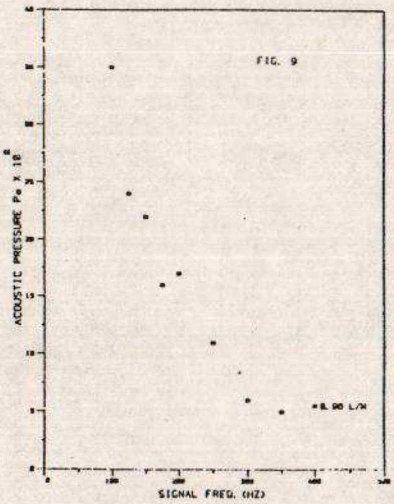


FIG. 9

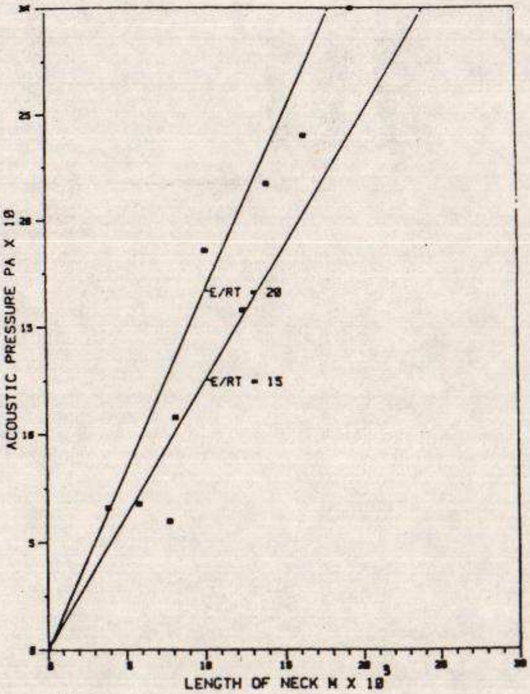


FIG. 10

ON NOISE PRODUCING MECHANISMS IN TURBULENT GAS COMBUSTION

NOMENCLATURE

ρ	-	Density	kg/m^3
T	-	Temperature	K
γ	-	Specific heat ratio	
ν	-	Symmetry parameter = 2,3 for neck, sphere	
C_o	-	Velocity of sound	m/s
P	-	Acoustic pressure	Pa
V_1	-	Volume of sphere or neck before explosion	m^3
C_v	-	Specific heat (constant vol.)	J kg^{-1} K^{-1}
r	-	Microphone distance from flame front	m
t_{ch}	-	Characteristical time of chemical reaction	sec
R	-	Gas constant for unity mass	
*E	-	Effective activation energy	J kg^{-1}
Q	-	Heat of chemical reaction	J kg^{-1}
a_1	-	Concentration	Kg m^{-3}
n	-	Order of Reaction	
K_1	-	Rate constant	s^{-1}
U^o_n	-	Constant normal burning velocity	m
κ	-	Thermal diffusivity	m^2 s^{-1}
L_1	-	Length of neck prior to explosion	m
A	-	Bubble radius at time t	m
A_o	-	Original bubble radius	m
t	-	Time	sec.
μ	-	Markstein constant	
D	-	Diffusion coefficient	m^2 s^{-1}
T_B	-	Steady flame temperature	K
T_o	-	Temperature of reagents (cold)	K
t_o	-	Original time	sec.