NON-LINEARITY IN PYROACOUSTIC AMPLIFICATION

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1. ABSTRACT

A satisfactory solution to the problem of combustion driven oscillations in industrial furnaces can usually be obtained if the flame is treated as a linear amplifier of acoustic pressure. There are certain cases, however, where such an approach cannot wholly account for the observed properties of a particular plant. Two models of the amplification process are considered which show that non-linearities in the interaction between the flame and acoustic oscillations in the plant can account for certain hitherto unexplained experimental observations. This alternative approach forms the basis for a current theoretical and experimental research programme.

2. INTRODUCTION

Self sustaining acoustic resonances in combustion chambers are known, in certain cases, to cause serious fatigue of chamber components with a consequent loss of production efficiency and shortened plant life. It is generally accepted that the intense resonances produced can be the result of acoustic coupling between the combustion process and some resonant cavity such as the furnace chamber or flue, but the actual driving mechanisms for initiating and maintaining the necessary acoustic feedback loop are still not completely understood. For many cases the flame may be treated as a simple linear amplifier of an acoustic oscillation and the resonant condition inhibited by adjusting the air supply duct or other appropriate acoustic cavity so that the phase and impedance match at the burner does not support the resonance at the single frequency.

There are cases, however, when power to sustain the resonance would appear to originate from two or more sources of remote frequencies present in the system, which combine to produce a sum or difference tone which, by chance, comes close to the frequency of resonance. This clearly implies that in such cases non-linearities in the amplification mechanism must make a significant contribution to the overall feed-back process.

NON-LINEARITY IN PYROACOUSTIC AMPLIFICATION

Adams[1], extending the work of Putnam[2], Baade[3], Cummings[4] and Lawn[5], has proposed a non-linear model where he treats the flame as a parametric amplifier. In this paper we give a resume of his model for comparison, and introduce a new model which has been developed specifically to account for some recent experimental observations.

3. PHASE MODULATION

The linear models thus far proposed assume that the passage of an acoustic wave through the reacting mixture modifies the rate of heat release from the flame and that this leads to the build up of the acoustic pressure. Adams [1] argues that the change in the rate of heat release due to the passage of such an acoustic wave must be accompanied by a temperature perturbation in the medium. This results in a non constant propagation coefficient that undergoes a periodic variation and means that the phase of the pressure wave at some point along the flame is no longer fixed in time but is subject to modulation due to this change in temperature. Because the rate of heat release at the surface of the flame depends on the mixture quality arriving at that point it must therefore be governed not only by the flow conditions at the inlet but also on the transport lag down the flame. It then follows that the phase of the heat release wave down the flame is no longer constant but is subject to modulation due to the passage of the acoustic waves.

The effect of a small temperature change on the sound propagation velocity in the medium is used to predict the result of any cyclic movement encountered at the root of the flame. The temperature pertubation in the medium modifies the phase of any pressure waves entering the system and yields an equation for describing them which may be simplified to

$$p(x,t) = p_o(w) \sin [Y - \sum_n m_n \sin w_n t] \qquad (1)$$

where Y represents the usual space and time dependent phase of the wave and m_n defines the amplitude of modulation due to the n th wave. Other symbols have their usual meaning.

The importance of this result is that it would give rise to the possibility of two or more external sources transferring acoustic power into the system at their sum and difference frequencies and which could then cause the excitation of resonant modes of the chamber as discussed earlier.

4. GAS DYNAMIC MODEL

In the new model we treat the flame as a gas-dynamic discontinuity in one dimension only and with the absence of dissipation, but introduce non-linearity through an additional heat conduction process as the flame moves with respect to the burner.

Consider the flame propagating in a tube of unit cross sectional area (see Fig. 1). In the absence of disturbances the parameters of the hot and cold gases are denoted by the symbols as shown, where represents the density of the medium, p the pressure, T the temperature and u the gas velocity relative to the tube. Subscripts 1 and 2 refer to the cold and hot gases respectively. The equations of continuity of mass, energy and momentum for the system are linearised using first order perturbation methods to arrive at the following equations governing the passage of small pressure and velocity perturbations as they travel through the flame front. The perturbations are denoted by ', and the parameter B takes account of the variation of flame speed, U, with pressure.

$$u_2' = u_1' + B(\rho_1/\rho_2 - 1)\ p_1' \qquad (2)$$

$$p_2' = p_1' \qquad (3)$$

$$T_2' = \frac{(\gamma-1)}{\gamma}\ T_1\ \frac{p_1'}{p_1} \qquad (4)$$

These equations show that there will be an increase in the acoustic particle velocity as the signal passing through the flame, which will thus lead to signal amplification, provided there is a positive change of burning velocity with pressure.

In descriptive terms we would see a pressure perturbation arriving at the flame front accompanied by a corresponding change in particle velocity. At the higher pressure, the reactants will be more concentrated and there will be a momentary increase in the reaction rate and a small increase in the rate of heat release from the reaction. It is known that the actual burning velocity of a methane-air mixture changes very little with pressure alone, so that in that case the increased reaction rate must almost exactly compensate for the increase in the amount of reacting material present at the higher consentration.

The change of flame velocity with temperature, on the other hand, is a much stronger function and an increase in the flame velocity would be expected as a result of the higher temperature following the increase in heat release.

The amplification of an acoustic signal brought about by this process has been observed experimentally and is certainly one of the causes for the formation of resonant oscillations in combustion systems generally.

5. NON-LINEARITY

All the processes involved thus far in the model are linear to the degree of accuracy normally associated with acoustic phenomena. It is proposed that non-linearities enter the amplification process through the variation of the parameter B as movement of the flame front brings it closer to or further from a cold surface. Such a surface in practice might be the surface of the burner on which the flame rests or even the walls of the boiler. The movement will occur because of particle velocity variations in the incoming gas and also because of changes of flame speed and hence flame position resulting from the pressure and temperature changes discussed earlier. The varying proximity to the cold surface will then change the rate of heat conduction away from the flame and so alter its mean temperature and hence its burning velocity. The parameter B used in the model to provide the relationship between the small change in burning velocity resulting from a small change in input pressure is defined $U' = B p'$ and may be written

$$B = (\partial U/\partial p_1)_T + \frac{(\gamma - 1)}{\gamma} T_1 (\partial U/\partial T_1)_p \qquad (5)$$

For a methane-air mixture $(\partial u/\partial p)_T$ is approximately zero so for a burner using such fuel (as in the experiments carried out), B may be taken as the temperature dependent function only.

Making the further assumption that the mean flame temperature is a function of the displacement, ξ, of the flame from some equilibrium position, and taking only the first term of its Taylor expansion we may write $T' = \alpha\xi$. Applying the perturbation methods previously used, we then obtain for the acoustic velocity in the hot gas

$$u_2' = u_1' + B(\rho_1/\rho_2 - 1)p_1' + (B\alpha\xi/T_1)(\rho_1/\rho_2 - 1)p_1' \qquad (6)$$

As the displacement is proportional to the acoustic pressure the third term on the right hand side of this equation gives a measure of the non-linearity in the amplification process.

6. DIFFERENCE TONES

The effects of the non-linearity in amplification has been examined experimentally using the apparatus shown in Fig 2. It contained a small premixed laminar flame burning at the end of a supply tube which was in turn surrounded by an open cylindrical can representing a combustion chamber. Two sinusoidal signals were injected into the incoming cold gas using a loudspeaker arrangement positioned in the supply tube. The amplification of these signals by the flame was monitored using two microphone probes, one mounted in the supply tube and the other in the outer chamber, and the transfer function across the flame obtained for a range of frequencies of the input signals, (see reference [6]).

For all the cases examined it was found that when the separation of the frequencies of the input signals was close to the resonant frequency of the system, a strong difference signal was detected in the outer chamber which vanished when one or other of the input signals was removed. It was also found that the relative amplitudes of the original signals, the difference signal and the higher harmonics downstream of the flame were consistent with order of magnitude predictions from the theory.

7. REFERENCES

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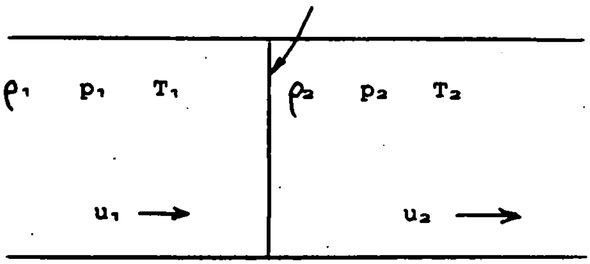
Flame front
ρ1 p1 T1
ρ2 p2 T2
u1
u2

Fig.1

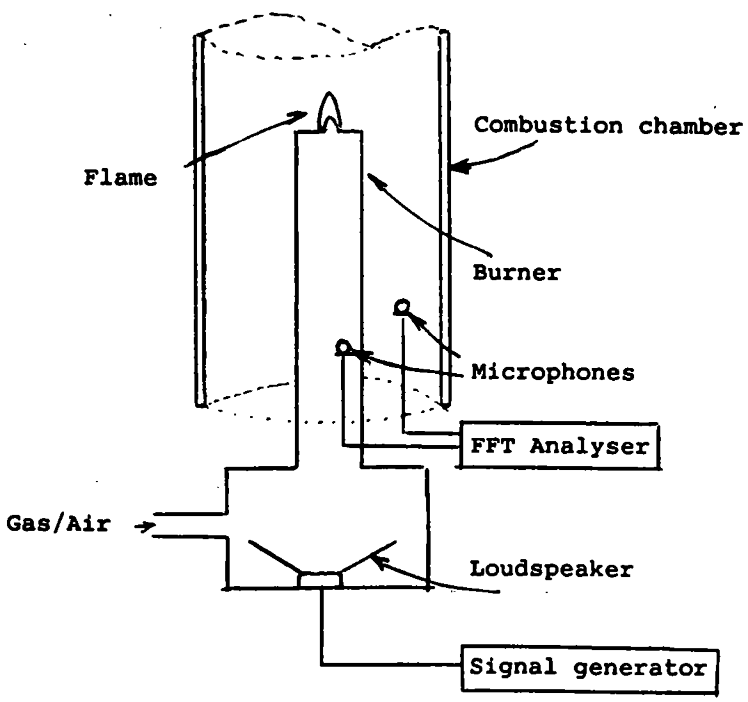
Combustion chamber
Flame
Burner
Microphones
FFT Analyser
Gas/Air
Loudspeaker
Signal generator

Fig.2