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D. A. Smith and E. E. Zukoski, California Institute of Technology, Pasadena, CA

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COMBUSTION INSTABILITY SUSTAINED BY UNSTEADY VORTEX COMBUSTION

D. A. Smith* and E. E. Zukoski+
California Institute of Technology
Pasadena, CA

Abstract

The determination of an internal feedback mechanism which leads to combustion instability inside a small scale laboratory combustor is presented in this paper. During combustion instability, the experimental findings show that a large vortical structure is formed at an acoustic resonant mode of the system. The subsequent unsteady burning, within the vortex as it is convected downstream, feeds energy into the acoustic field and sustains the large resonant oscillations. These vortices are formed when the acoustic velocity fluctuation at the flameholder is a large fraction of the mean flow velocity. The propagation of these vortices is not a strong function of the mean flow speed and appears to be dependent upon the frequency of the instability. Continued existence of large vortical structures which characterize unstable operation depends upon the fuel-air ratio, system acoustics, and fuel type.

Introduction

In modern ramjet combustion systems, one major concern is unsteady combustion which creates large pressure oscillations that can cause system malfunctions. The objective of the current study is to investigate the internal feedback mechanism which leads to combustion instability inside a high intensity combustor in which the flame is stabilized behind a rearward facing step.

During stable combustion, the flow field created behind the rearward facing step, or flameholder, consists of a turbulent, reacting, reattaching mixing layer(1). Within the layer, a portion of the reactants entering the combustor is mixed with hot burnt products which reside in the wake region downstream of the flameholder beneath the layer. This process is the key to maintaining continuous ignition of the incoming reactants so that the flame can propagate into the remaining unburnt combustible mixture(2).

*Graduate Student, Jet Propulsion Center, Student Member AIAA

+Professor of Jet Propulsion and Mechanical Engineering
Fellow Member AIAA

In isothermal flow, the reattaching mixing layer initially evolves like a free shear layer(3), and consists of coherent structures(4) which grow as they are convected downstream. Combustion within the reattaching layer does not alter the basic structure of the layer in that both contain coherent structures(5); however, the growth rate seems affected by the heat released within the layer(5,6).

Under certain experimental conditions, the shear layer formed downstream of the flameholder disappears and very large vortical structures are formed in a regular pattern(1,6). This flow condition is what we, the authors, refer to as a condition of combustion instability. The purpose of the work reported in this paper is to experimentally examine, in detail, this type of combustion instability and to develop a mechanism by which this unstable flow field can be maintained.

Within this paper, a portion of the results from an ongoing program to determine the influence of gas velocity, geometry, fuel-air ratio, fuel type, and system damping upon combustion instabilities are presented. In particular, the effects of gas velocity, geometry, and damping are highlighted. A more detailed description may be found in reference 6.

Experimental Equipment

The main components of the experimental apparatus are shown in Figure 1. The flow control system which delivers a premixed, prevaporized methane-air mixture to the apparatus is capable of supplying reactants in any proportion, or any fuel-air ratio, over a wide range of flow rates. The combustible mixture first enters the plenum chamber through a small diameter supply line. At the exit of the plenum chamber, a contraction is attached to change the flow from an axi-symmetric flow to a two-dimensional flow compatible with the combustor. The two-dimensional combustor geometry was chosen to simplify the flow visualization. The combustible mixture then flows from the plenum chamber into the inlet and subsequently into the combustion chamber over the rearward facing step flameholder.

The main features of this design are the moveable flameholder which enables examination of different combustor lengths, and a variable length plenum chamber to study the effects of changing the upstream acoustic properties of the system. The combustor is fitted with glass side walls for flow visualization which is based upon the focused shadowgraph technique. For the results presented in this paper, the combustor is 40 cm long with a 2.54 cm high by 7.62 cm wide cross section. The flameholder is about 8 cm long and 1.9 cm high, spanning the entire width of the duct. Ten pressure transducers are located in the upper combustor wall to measure the oscillating pressure field within the system. A moveable photo-multiplier tube apparatus is used to measure the local intensity of the radiation emitted from the flame. These two measurements are employed to determine the relationship between the local pressure and heat release rate.

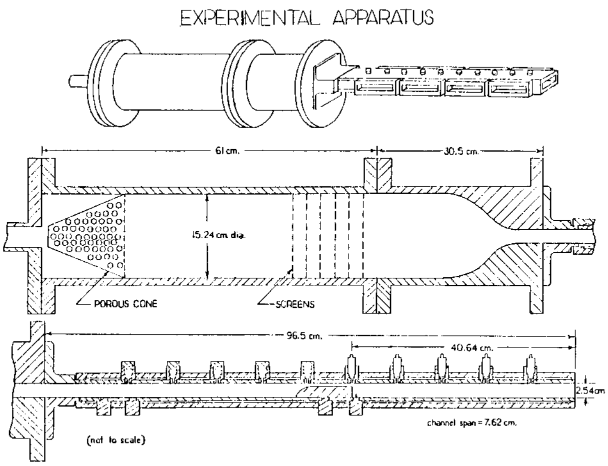


Fig 1 Experimental Equipment

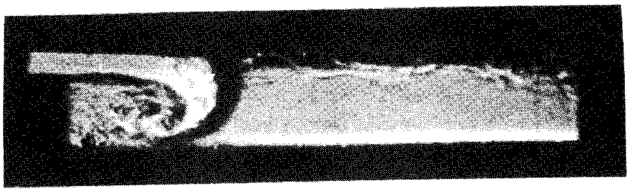
Definition of Flow Fields

The focused shadowgraph photographs shown in figure 2 emphasizes the difference between the stable and unstable flow fields. These pictures are prints made from the high speed flow visualization and show the entire height of the combustor, and about 13 cm of the flow field downstream of the flameholder. The shadowgraph images are recorded along a line of sight parallel with the downstream face of the flameholder and perpendicular to the gas velocity at the rear edge of the flameholder.

The upper photograph of this figure shows the stable flow field in which a mixing layer forms downstream of the flameholder and a continuous, steady flow of reactants enters the combustor. Within the mixing layer, discrete vortical structures exist which entrain reactants from the upper side of the layer and combustion products from the lower side of the layer. The reattachment point, or a point of no wall shear, is shown near the right-hand edge of the photograph.

The lower photograph of this figure shows the unstable flow field at a certain time. Notice the two are quite different. A large vortical structure dominates the flow field downstream of the flameholder as a surge of combustible mixture enters the combustion chamber. These vortical structures form periodically and evolve in the same fashion each time. Hence, the terminology 'unstable' refers to the condition of periodic flow into the combustor, and designates the difference between unstable and stable flow. In this sense, unstable does not mean that the amplitude of the oscillating pressure field within the combustor is increasing with time, rather it denotes the changing flow field in time.

STABLE FLOW



UNSTABLE FLOW

Fig 2 Flow Field Classification

Unstable Flows - Vortex Formation

An unstable flow field is produced inside the combustor when the dump plane velocity, or the velocity of the gas entering the combustor above the flameholder, is 22 m/sec and the reactants are mixed in a stoichiometric ratio. The pressure field measured under these operating conditions is shown in Figure 3. This figure shows the spectral decomposition of the oscillating pressure measured at the dump plane, i.e., the abrupt area change at the rear edge of the flameholder. The ordinant of this plot shows the Fourier coefficients of pressure signal, within a 5 hertz bandwidth, normalized by the atmospheric pressure.

This figure reveals two major frequency components at 188 and 460 hertz. A linearized one-dimensional acoustic analysis of the experimental apparatus indicates that these frequencies are resonant acoustic modes of the system[6]. The 460 hertz oscillation is the system frequency most sensitive to conditions within the combustor, while the 188 hertz oscillation is the system frequency affected by conditions inside the plenum chamber which, in this instance, is 86 cm long. The spectrum also shows some small amplitude pressure oscillations at 231, 377, and 535 hertz.

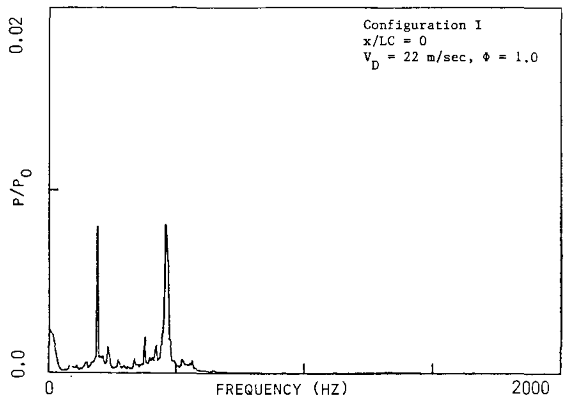


Fig 3 Pressure Spectrum

These oscillations are acoustic modes of the system that are excited to a lesser degree. The table below lists the predicted acoustic resonant modes of the system along with the frequencies obtained from the pressure spectrum. The frequencies measured in the experiment and computed from the model are shown to illustrate that the model is quite effective when used to compute the resonant modes of the system and that the measured frequencies seem to be acoustic in nature.

Computed	Measured
180	188
229	231
385	377
470	457
533	535

The acoustic model is also capable of computing the acoustic velocity fluctuations throughout the system given an experimental pressure measurement at one location as a reference. Calculations using the spectral results of Figure 3 show that the major velocity fluctuations in the vicinity of the flameholder are due to the 188 hertz oscillation. All other frequencies produce negligible velocity fluctuations so that the resonance, associated with conditions inside the plenum chamber, produces large velocity fluctuations at the flameholder.

The flow field established under these operating conditions is shown in Figure 4. The pressure fluctuation at the frequency of the large velocity fluctuation near the flameholder, 188 hertz, is shown on the left-hand side of the figure. This pressure is the pressure measured at the dump plane and is shown as a time reference. Evolution of the flow field is shown to the right. At the point of maximum pressure, namely time equal to zero, the uppermost photograph shows a nearly vertical flame surface above the flameholder which then curves sharply downstream, following along the upper combustor wall. The upstream propagation of this flame surface suggests that the fluctuating velocity component is nearly equivalent to the mean velocity, and, in fact, computations, using the acoustic model and experimental pressure measurements at the flameholder, reveal that the acoustic velocity fluctuation is 21 m/sec: just about equal to the 22 m/sec mean velocity at the dump plane.

As the pressure begins to fall, the flow begins to surge into the combustor and a vortex structure forms as shown in the fourth picture from the top. The region underneath the flame sheet is primarily burnt combustion products while the small region above the vortex consists of fresh reactants. As the vortex grows, a finger of unburnt combustible mixture protrudes downward between the front of the vortex and the outer flame front as can be seen in the fifth picture from the top. This region of unburnt gas has a sizeable velocity component directed down towards the wall.

About three-quarters of the way through the cycle, picture 8, the vortex impinges against the lower combustor wall. Since the downward velocity of the vortex is sizeable, we expect that vigorous mixing occurs between the remaining unburnt reactants and combustion products at vortex impingement. The shadowgraph records indicate that such mixing occurs. In addition, the region between the front of the vortex and the flame front preceding the finger of unburnt reactants, or rather now a region of reacting gases, expands rapidly, suggesting a sizeable volumetric expansion. This volumetric expansion occurs in unison with the pressure rise at the flameholder, and helps to inhibit the flow of fresh reactants into the combustor. As the pressure peaks, the flame front propagates upstream and becomes nearly vertical at the rear edge of the flameholder. When the pressure falls, a new vortex is formed which evolves in the same way as the one just described. New vortices are formed at the frequency which produces sizeable velocity fluctuations in the vicinity of the flameholder, namely at 188 hertz.

Subsequent testing revealed that no large 188 hertz oscillations could be sustained when a damping material, steel wool, was inserted into the plenum chamber to suppress the resonance of this section of the apparatus. This clearly shows the importance of the system's acoustic properties upon the burning within the combustion chamber.

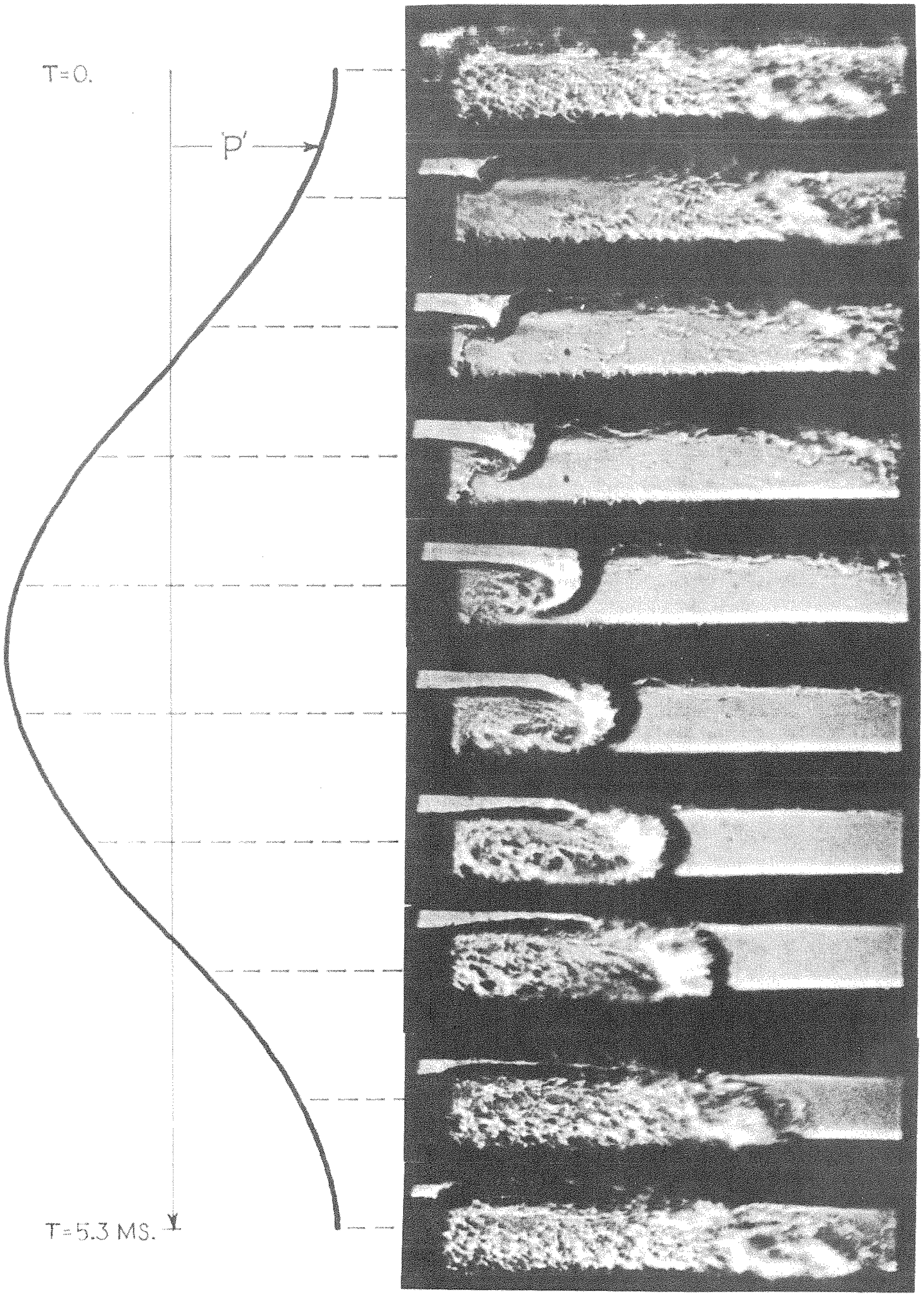


Fig 4 Vortex Evolution at 22 m/sec, $\Phi = 1.0$

Figure 5 shows the light intensity spectra at two locations downstream of the flameholder, during instability. One observation location is about 3.8 cm, x/LC = 0.094, downstream of the flameholder while the other is about 7.6 cm, x/LC = 0.188, downstream. The parameter x and LC refer to the axial distance downstream from the flameholder, and the combustion chamber length, respectively. The flame is viewed by a photomultiplier tube through optical elements which limit the axial distance viewed to approximately 0.6 cm, but the entire height and width of the combustion chamber at this observation position is viewed.

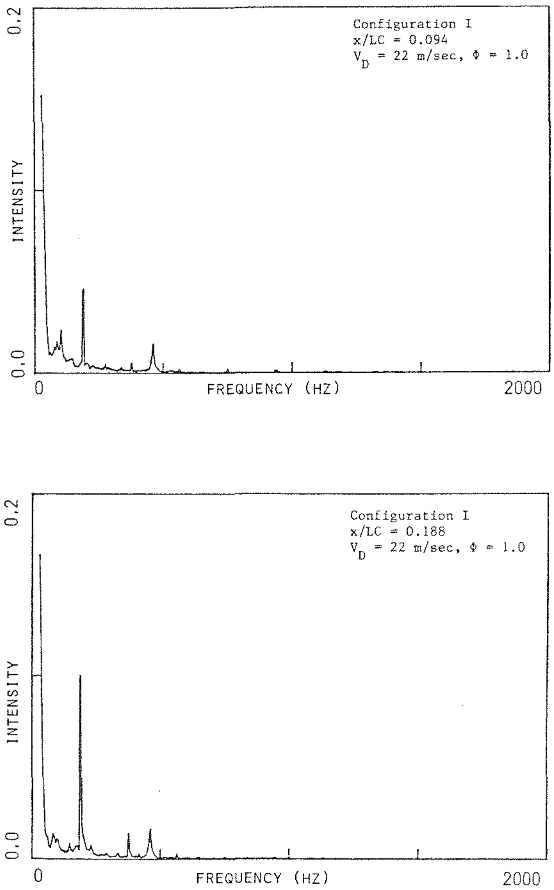


Fig 5 Light Intensity Spectra

The light radiated from the flame is monitored so that the quantity of heat released locally can be established. Unfortunately, no entirely satisfactory method exists for determining the heat release rate; however, several investigators have used this technique to evaluate the heat released by a small reacting mass of gas(7,8,9). In general, a monatonic relationship exists between the flame emission and the heat release rate. In many circumstances, a linear relationship exists between the two, and this is the interpretation used in evaluating the light intensity spectra(8,9).

At the observation point nearest the flameholder, x/LC = 0.094, the upper plot of Figure 5 shows that the major component of the fluctuating light intensity occurs at 188 hertz, the vortex formation frequency. The amplitude of the intensity at 188 hertz is about 3 times larger than the next largest fluctuation at 460 hertz; consequently, the major fluctuation in the heat release rate occurs at the instability frequency, or the frequency which produces large velocity fluctuations in the vicinity of the flameholder.

Further downstream at x/LC = 0.188, the lower spectrum of Figure 5 indicates that the 188 hertz component becomes even larger and is clearly the dominant fluctuating heat release mode. The light intensity amplitude at 188 hertz is about 8 times larger than any other component of fluctuating light intensity. This measurement position is close to the location in which the vortex impinges against the lower combustor wall. Therefore, the data indicate that a substantial fluctuation in the heat release rate occurs at the point of vortex-wall interaction.

When the flow speed of the mixture entering the combustor is increased by 80 percent to 40 m/sec, the pressure field measured at the dump plane is not much different than the pressure field observed at 22 m/sec as shown in Figure 6.

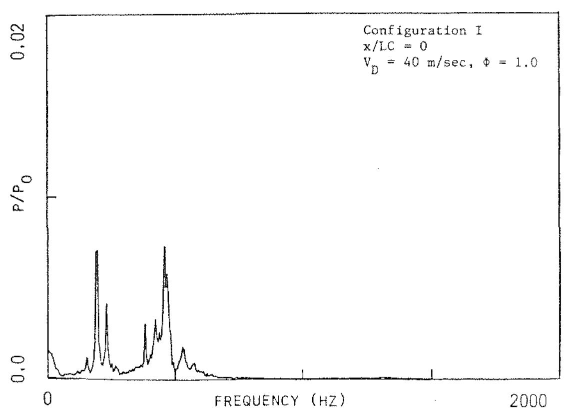


Fig 6 Pressure Spectrum

Remember, only the flow speed has been changed for this case, the geometry and stoichiometry are identical to the instability case just discussed. The major pressure oscillations still occur at 188 and 460 hertz, even though the magnitude of their Fourier coefficients have decreased slightly, down about 10%. Therefore, the velocity fluctuation in the vicinity of the flameholder is approximately the same as for the previous instability at about 22 m/sec. The flow visualization records for the 40 m/sec instability case (Figure 7) indicate that the velocity fluctuation is not nearly as large a portion of the mean flow velocity, 40 m/sec, because the flame front at the point of maximum pressure (top photograph) is only modestly bowed and does not propagate upstream above the flameholder. Furthermore, some combustible mixture passes over the upper flame sheet as the vortex evolves and moves downstream.

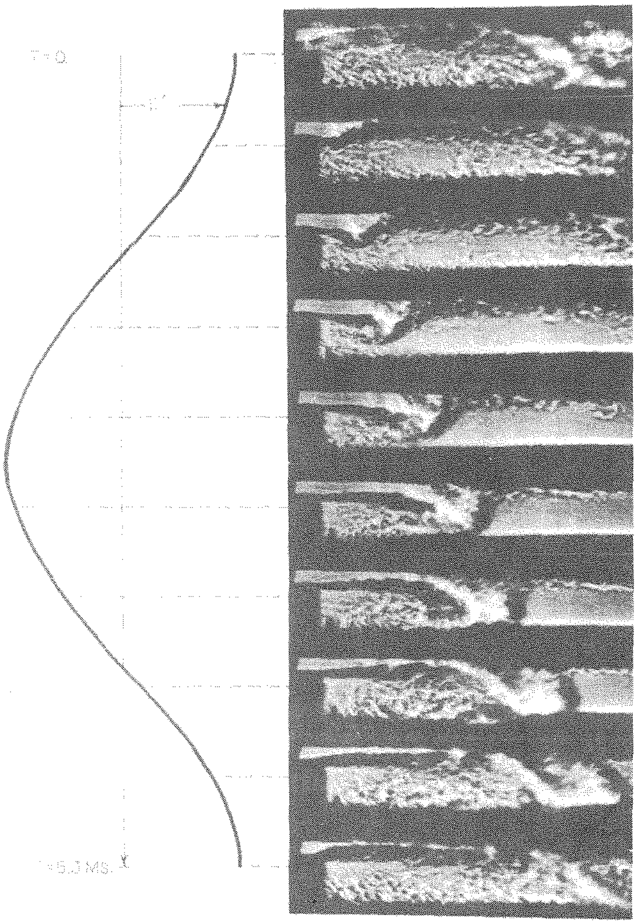


Fig 7 Vortex Evolution at 40 m/sec, $\Phi = 1.0$

Figure 7 illustrates that the frequency of vortex formation remains 188 hertz, and is not affected by the mean flow speed when the velocity is changed from 22 to 40 m/sec. In this speed range, the vortex formation is not dependent upon the mean flow speed and, consequently, is not a Strouhal type shedding phenomenon.

Examination of Figure 7 also reveals that the vortex evolution at 40 m/sec is very similar to the evolution at 22 m/sec. The vortex formation is triggered by the fall in pressure at the flameholder. The vortex structure forms, grows, and impinges against the lower combustor wall about three-quarters of the way through the pressure cycle. At impingement, the shadowgraph visualization, eighth photograph from the top, indicates that rapid reaction takes place because of the vigorous mixing between reactant and products at this time. The location at which the vortex impinges against the wall is only about 20% farther downstream than the impingement location of the vortex formed at 22 m/sec. This suggests that the motion of the vortex is not strongly dependent on the mean flow speed. Rather, we believe that it is linked to the actual magnitude of the velocity fluctuation at the flameholder. After all, the mean flow speed has increased by 80%, but the magnitude of the velocity fluctuation has remained approximately the same, as well as the impingement location.

Figures 8 and 9 show the pressure field and vortex motion under different upstream acoustic conditions. The plenum chamber length is shortened from 86 cm to 56 cm and the dump plane velocity is set at 50 m/sec, but the mixture ratio is the same as in the two previous cases, namely stoichiometric. The pressure spectrum evaluated from the pressure measurements at the dump plane, indicates that large oscillations occur at 460 hertz and 520 hertz. In fact, the amplitude of these oscillations are about 8 times larger than the amplitude of the oscillations sustained at 22 and 40 m/sec. Both of these pressure oscillations are acoustic resonant modes of the system. The 460 hertz is, of course, the system mode sensitive to conditions within the combustor, and the 520 hertz oscillation is another acoustic mode of the system as computed from the acoustic model.

The vortex motion, during this instability, is shown in Figure 9. The frequency of vortex formation is 520 hertz under these conditions and the curve on the left-hand side of the figure illustrates the pressure oscillation above the flameholder at this frequency. Notice that the vortex motion is similar to the two previous instability cases. The vortex forms, travels downstream, and impinges against the lower combustor wall about three-quarters of the way through the pressure cycle which creates the large velocity fluctuation in the vicinity of the flameholder. However, the time required to reach the impingement location, during the 520 hertz instability, is about one-third of the time required for the vortex, formed at 188 hertz, to reach the combustor wall.

Further examination of Figure 9 shows that the flame front at the point of maximum pressure, the top photograph, has propagated upstream and is nearly vertical above the flameholder, indicating that the velocity fluctuation at 520 hertz is of the same order as the mean flow speed of 50 m/sec. This velocity fluctuation is clearly much larger than the velocity fluctuations observed during the 188 hertz instability cases. Consequently, the vortex propagates downstream and impinges against the wall in one-third the time. This result reinforces our feeling that the vortex motion seems to be a function of the velocity fluctuation at the flame-holder which, for this type of instability mechanism, appears to be directly related to the frequency of the instability. For these two instability frequencies, 188 and 520 hertz, the ratio between the velocity fluctuations is about 2.3, while the ratio between the instability frequencies is 2.7.

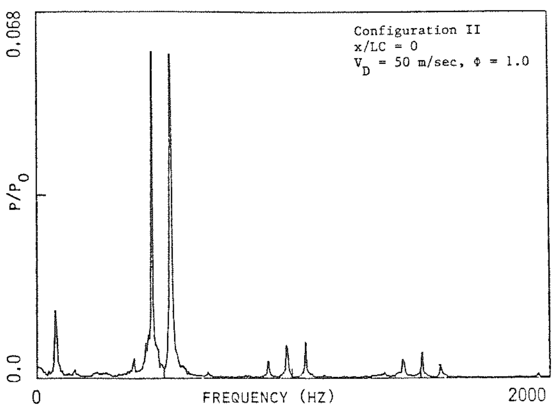


Fig 8 Pressure Spectrum

<u>Mechanism for Sustaining Instabilities</u>

The internal feedback mechanism for sustaining the instability, namely the large velocity fluctuation in the vicinity of the flameholder, is based upon the energy supplied to the acoustic field by the unsteady burning within the large vortical structure. The Rayleigh criterion relates the change in energy of the system to the pressure and heat release rate. It states that the energy is supplied to the acoustic field if the local heat release rate is positively correlated with the naturally available pressure fluctuation. Mathematically, the criterion may be expressed as:

$$\Delta E_{cycle} = \int_{cycle} p'q'dt \; .$$

Figure 10 shows simultaneous pressure and light intensity measurements which illustrate the relationship between the local pressure fluctuation and the local heat release rate. The pressure and light intensity measurements for the 188 hertz instability at a dump plane velocity of 22 m/sec are shown in this figure. The pressure signal is filtered to highlight the 188 hertz component which is the dominant frequency of the heat release fluctuation.

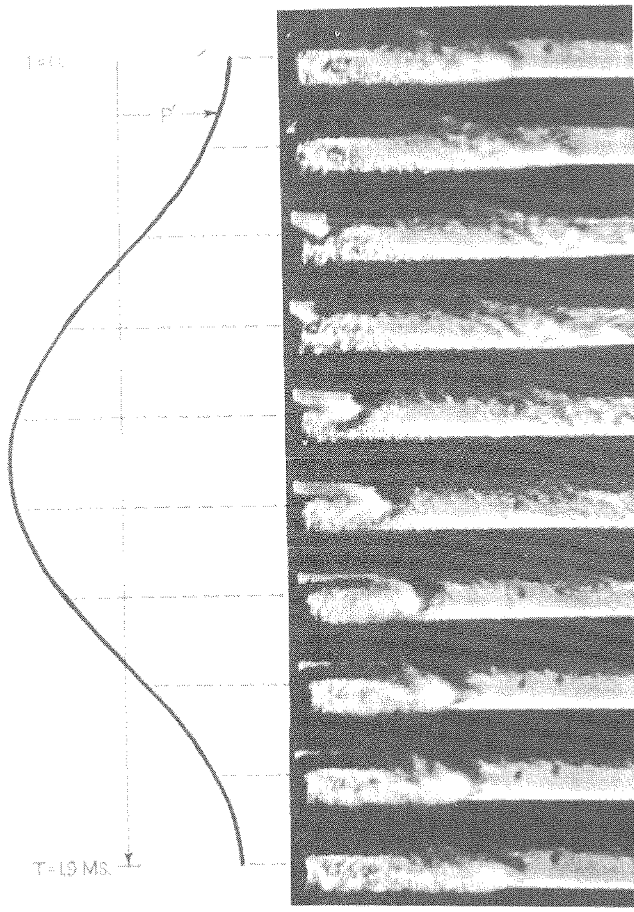


Fig 9 Vortex Evolution at 50 m/sec, $\Phi = 1.0$

The upper two sets of curves in this figure show the fluctuations in light intensity and pressure about 3.8 cm downstream of the flameholder. The two curves are clearly in phase and the Rayleigh criterion states that energy is supplied to the flow field at this location. Farther downstream, about 7.6 cm from the flameholder, the middle set of curves again indicate that energy is supplied to the acoustic field. The shape of the light intensity curve is somewhat different at this location. A sharp rise in the intensity is observed as the pocket of reacting gases pass the measurement location. After passage, the intensity decreases until another region of reacting gas passes. This reaction zone is the remnant of the vortex and the reacting gases preceding it. So, the rapid rise in the light intensity is the passage of the vortex across the observation window, during each cycle.

Farther downstream, 14 cm from the flameholder, the light intensity and pressure oscillation are totally out of phase as shown in the bottom set of curves of Figure 10. At this location, negative energy is added to the system, or, in other words, damping occurs. These three measurements indicate that energy is supplied to the 188 hertz acoustic field from vortex formation until after it impinges against the lower combustor wall.

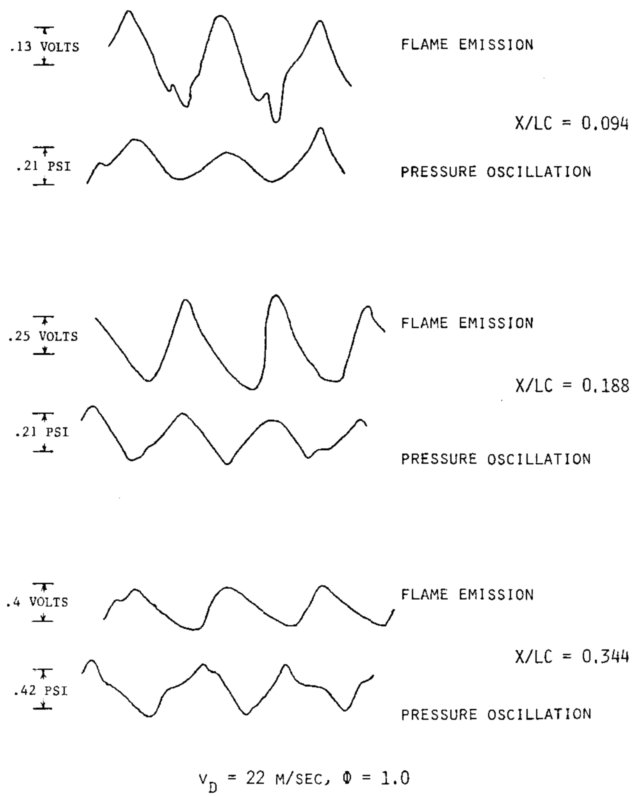


Fig 10 Simultaneous Pressure and Emission Measurements

The unsteady flow of reactants into the combustor causes unsteady combustion which, in turn, produces an unsteady heat release. The heat release rate is such that energy is added from initial vortex formation until the vortex has impinged against the combustor wall. Furthermore, the magnitude of the heat release fluctuation, at the frequency of instability, increases rapidly as the vortex grows. In addition, the data suggest that the maximum energy input occurs near the point at which the vortex impinges against the lower combustor wall. The energy supplied to the system is sufficient to reinforce the resonant mode which produces large velocity fluctuations in the vicinity of the flameholder. Since this resonant mode is reinforced, conditions are sufficient to form another vortex structure. The unsteady burning associated with this new vortex continues to reinforce the instability mode and create yet another vortex. Consequently, vortices are shed periodically at the frequency of the instability.

Conclusion

An experimental investigation of the internal feedback mechanism, capable of sustaining combustion instabilities, is explored in a small laboratory combustor in which the flame is stabilized behind a rearward facing step. The local heat addition and the pressure field are examined to determine the energy release characteristics inside the combustion chamber. The development of the reacting, kinematic flow field inside the combustor is studied by employing a shadowgraph flow visualization technique.

Excitation of the system's resonant modes may create combustion instabilities. In the presence of strong acoustic oscillations, which accompany combustion instability, a large velocity fluctuation in the vicinity of the flameholder produces a surging flow into the combustor. This unsteady flow produces a large vortex at the frequency of the velocity fluctuation, and the mechanism that supplies energy to the acoustic field depends upon the unsteady combustion within the vortex. Energy is supplied to the acoustic field because the fluctuations in the heat release rate and the pressure oscillations are in phase from initial vortex formation, until the vortex has grown, propagated downstream, and impinged against the combustor wall. Furthermore, the location of the maximum energy input appears to occur when the vortex impinges upon the wall.

The motion of the vortex is a function of the instability frequency, and is meagerly affected by the mean flow speed. However, the time required for vortex impingement is determined by the magnitude of the velocity fluctuation, and the instability frequency seems to be directly proportional to the amplitude of these fluctuations. This dependence of the vortex motion upon the magnitude of the velocity fluctuation creates the possibility of exciting a large range of system frequencies.

The mean flow velocity is important in this mechanism because the ratio of the fluctuating velocity to mean flow velocity must be substantial to produce the large vortices which sustain the instability. For some limiting velocity, the energy feedback is too weak to produce the necessary amplitude of fluctuation and the instability dies out.

Acknowledgements

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