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This research consists of an experimental study of the time dependent combustion in vortex structures. Large vortices were formed utilizing pulsed flow over a downstream facing step. The technique for simultaneous shadowgraph, chemiluminescence, and laser doppler velocimeter measurements has been developed and is used regularly. For a pressure oscillation of fixed amplitude, the diameter of the vortex grows linearly with time at a rate that increases linearly with the pressure amplitude of the oscillation generating the vortex. There is complete absence of chemiluminiscence during the early stage of vortex formation. The onset of chemiluminescence - and we believe combustion - is delayed for several milliseconds, close to our estimates for the chemical time for the systems under study here.

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# FINAL REPORT

# INVESTIGATION OF COMBUSTION IN LARGE VORTICES

## AFOSR GRANT 84–0286 9/86 to 9/89

## 1. INTRODUCTION

Vortex structures play an essential role in technological combustion processes because of their role in large and small scale mixing and their essential function in combustion instability. The research effort reviewed here grew out of the investigation of a novel process for enhancing the rate of mixing between fuel vapor and air in which the production of streamwise vortices is an essential element. Detailed examination of the combustion process within a vortex requires the production of vortices large enough to permit fine spatial resolution of the combustion process. It transpired that combustion instability investigations, also sponsored by AFOSR, had allowed us to develop a technique for producing large, time dependent vortices. This existing piece of equipment has, with minor modifications, formed the basis of the experimental work. Both analytical studies and computational investigations were carried out to narrow the range of experiments to suit the time and financial support available.

Another, and larger, phase of our research was pursued under a University Research Initiative Air Force grant in which the work was aimed directly at shock enhancement of mixing and combustion for application to Scramjet engines. The success of both these efforts encouraged the design and construction of an appropriate Scramjet hydrogen injector and mixer under sponsorship of the NASA. We are now engaged in testing this device at the NASA Langley Research Center.

## 2. RESEARCH OBJECTIVES

The aims of the experimental program are to develop the understanding of the combustion processes in a vortex which is necessary to allow us to predict or at least scale the mixing, ignition and combustion processes which occur in vortices present in airbreathing propulsion systems. We need to be able to predict the growth rate and motion of the vortices, and the rate of heat release in the vortices as a function of the fluid mechanical and chemical parameters of the system.

The fluid mechanical parameters include the geometry of the system, the Reynolds number of the flow, the ratio of the velocity and pressure fluctuations which produce the vortices to their mean values, and boundary layer characterization parameters. Chemical parameters include a chemical time for reaction, which depends primarily on the characteristics of the fuel and the fuel-air ratio, and the heating value for the mixture.

All of these parameters can be varied over a wide range, but are not completely under our control and can not always be characterized precisely. For example, the chemical time can be changed by an order of magnitude by changing the hydrogen mass fraction in a fuel gas made up of a mixture of methane and hydrogen. Unfortunately, we do not have a precise understanding of the dependence of this time on the mixture ratio. Similarly, the pressure and velocity amplitudes available to us are fixed in large part by the feed back between the combustion process and the acoustic resonances of the combustion chamber. Hence they can be changed but are not under precise control.

One focus for the work is the combustion of hydrogen and air in combustion chambers such as those proposed for the National Aerospace Plane in which both fuel and air streams are supersonic relative to the vehicle and perhaps, to each other.

## 3. RESULTS AND STATUS OF RESEARCH

The basic idea behind the apparatus developed in this program is the use of a naturally occurring combustion instability to produce vortices in a combustion chamber so that the development of combustion in a vortex can be studied. The basic configuration studied was the flow of a premixed fuel-air mixture over a rearward facing step in the combustion chamber. Vortices were formed between the unburnt mixture and hot products recirculating behind the step. The development of the vortices, and the initiation and development of combustion in them are being studied.

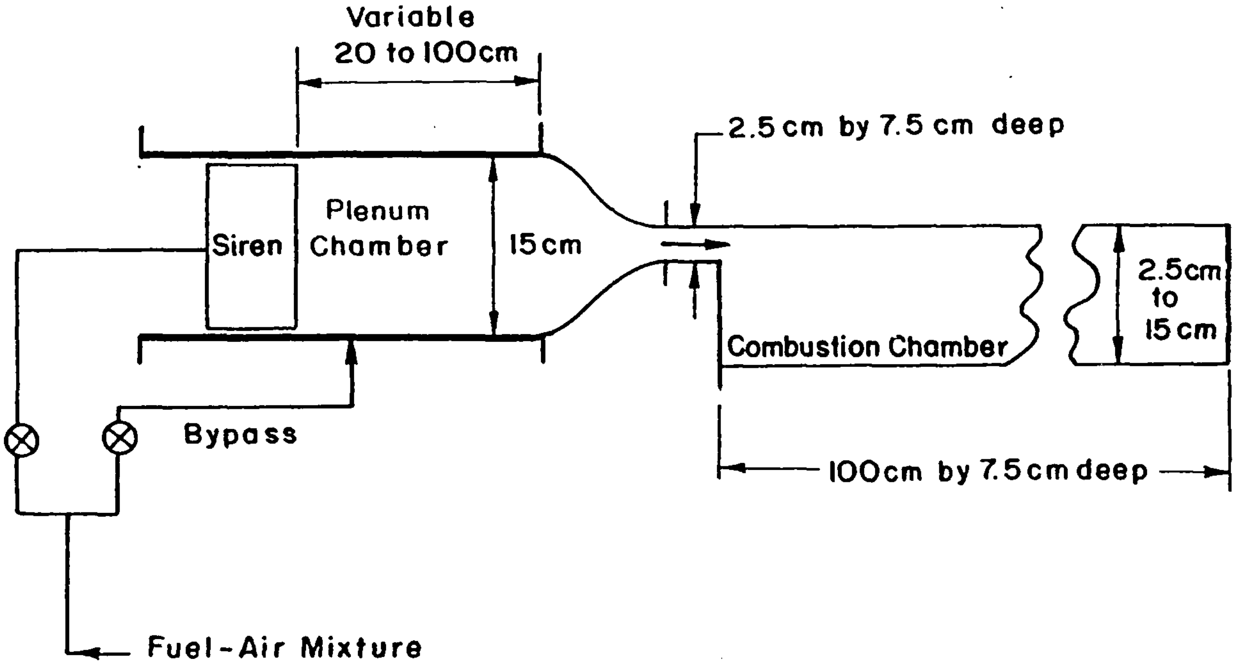


*Figure 1. Schematic diagram of the combustion chamber and supply system.*

Early in the program we showed that we could not produce large amplitude vortex shedding at an arbitrary frequency by the use of a siren placed in the plenum chamber of the duct, see Figure 1, even when a rotary-valve siren caused temporary interruption of the flow during each cycle of the oscillation. However, we were able to use the naturally occurring instabilities, which occur at resonance modes of the acoustic field, to produce the large amplitude of vortex shedding required for this study.

The naturally occurring instability is very strongly driven by the unsteady combustion process and, in our system, is characterized by a bimodal character with natural frequencies in the range 200 to 500 hz. The interaction of the two modes produces a pressure signal in which pressure oscillations of the dominant mode are amplitude modulated by the presence of the weaker secondary mode. The resulting pressure signature is a sine wave with an sinusoidal amplitude modulation. The presence of this amplitude modulation makes the use of phase averaging difficult but also allows us to study in a convenient manner the effects of pressure amplitude on the development of the vortices.

## DATA ACQUISITION:

Because two independent modes are usually excited in our tests, we have developed techniques to sort out our data so that the influence of individual pressure cycles can be analyzed separately. This process has complicated our use of phase averaging techniques, but is also giving us a much richer field to study since the pressure amplitude dependence of individual cycles are being analyzed. That is, the amplitude of each cycle is one of the variables.

Phase averaging is applied here by recording the pressure, hot wire anemometer and ionization probe signals at a rate of 10,000 hz and obtaining two component velocity and radiation field data from individual photographs at a fixed phase in any one cycle. The velocity and radiation data are then averaged, over a number of samples to obtain the mean and fluctuating values of the signal at that phase. The phase of the pressure signal being examined is then changed and the process is repeated. Because of the amplitude modulation discussed above, we must not only sort the data according to phase but also the amplitude of the oscillation being examined when the data are collected.

This technique requires that the LDA data be synchronized with the pressure data so that the phase and amplitude averaging described here can be carried out and this is made difficult because the processors for the LDA are commercial units and some redesign has been required to give us access to the appropriate signals.

The technique used here involves telling the LDA system to look for a signal during a short window, about 1.2 degrees out of a 360 degree cycle, typically 15 microseconds out of a duty cycle of 5 milliseconds period of a typical pressure oscillation cycle. The phase is fixed by using zero crossings of the pressure signal and if data are obtained for both horizontal and vertical velocities at the same time, the signal is stored by the DISA system and the successful data acquisition event is indicated on a channel of the system used to record the pressure and other signals. After the experiment, we can now identify the characteristics of the flow field at the time when each successful data acquisition even took place and can carry out the required averaging process.

Illustration of this process is the record shown in Figure 2, 3, and 4. The pressure data are shown on Figure 2 on lines i), the ionization probe data from two probes on lines ii) and iii), a photomultiplyer output from a single slice across the combustion chamber on line iv) and a signal showing when a shadowgraph photograph was taken on line v).

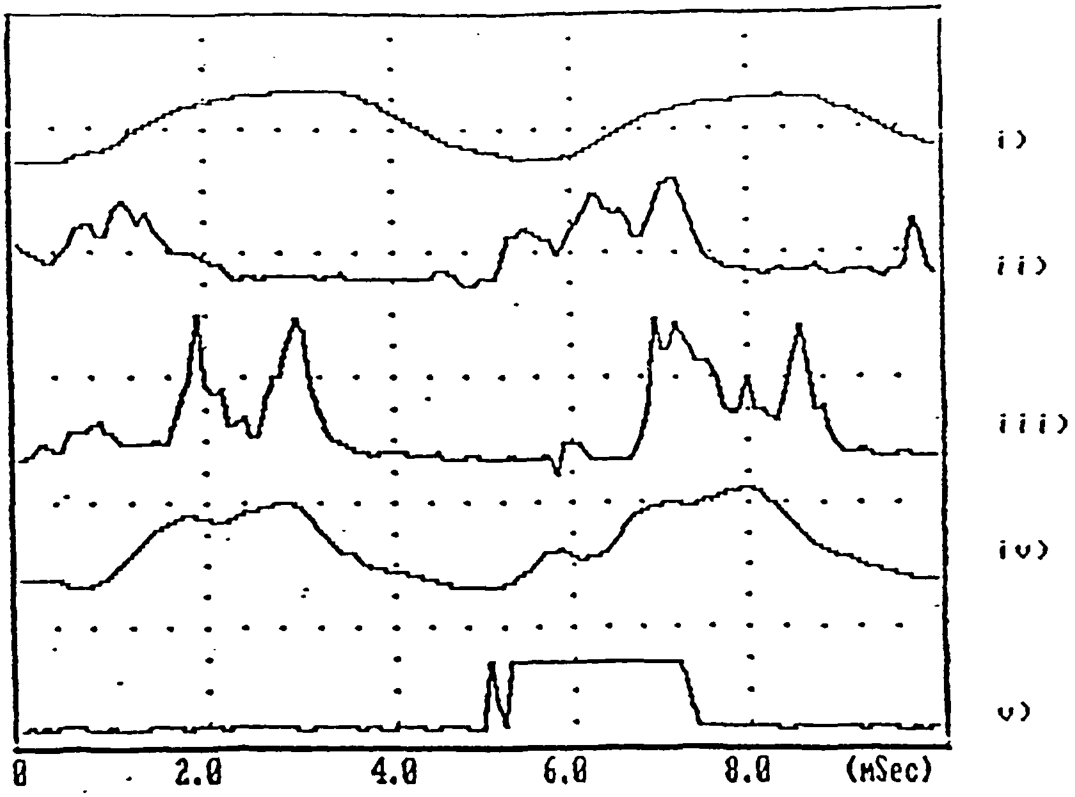


*Figure 2. Data record showing: line 1, pressure trace; lines 2 and 3, ionization probe data; line 4, output of a photomultiplyer tube located immediately downstream of second ionization probe; and, line 5, signal used to identify the time at which the shadowgraph photograph was taken. Period covered is about 10 milliseconds.*

Because the enhanced video pictures of the chemiluminescence can only be taken at a 30 HZ rate and the shadowgraph photographs are single events, the time when they are taken must be recorded on a separate data channel as shown here so that they can be synchronized with the acquisition of the pressure and velocity data. The data illustrated in Figure 2 gives some indication of the accuracy with which the phase of the various signals can be obtained in these experiments.

A longer time frame is shown in Figure 3 of this type of data with the photographic marker absent. Finally, in Figure 4 we show the signals recorded to illustrate the data acquisition output for the LDA data. The pressure signal is shown in the upper trace of Figure 4; the second trace is the indication from the LDA that data were obtained

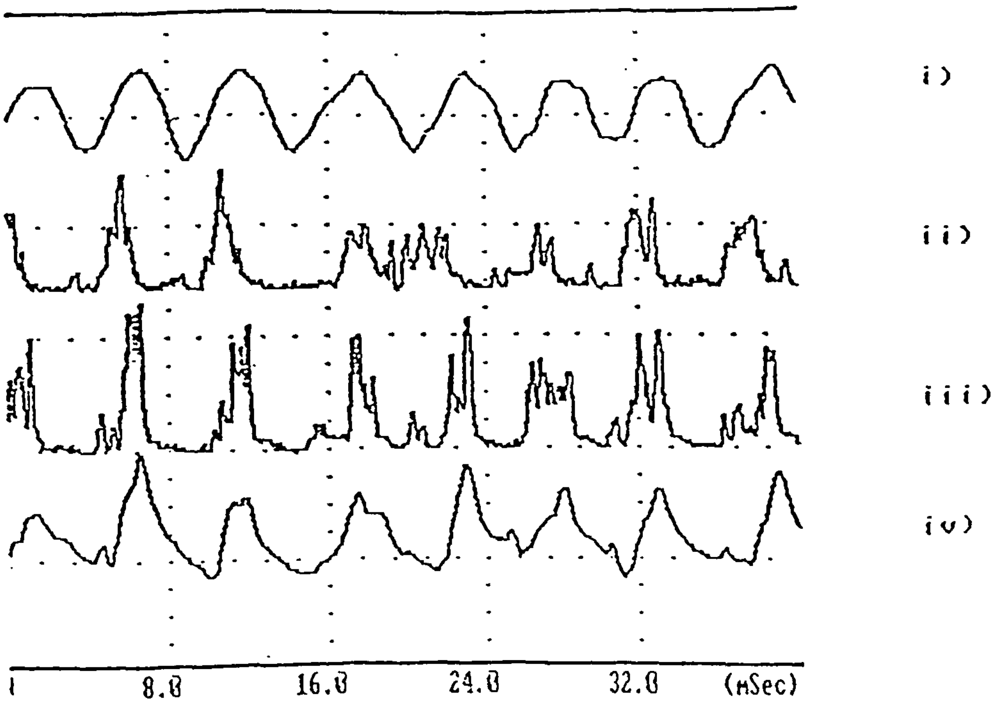
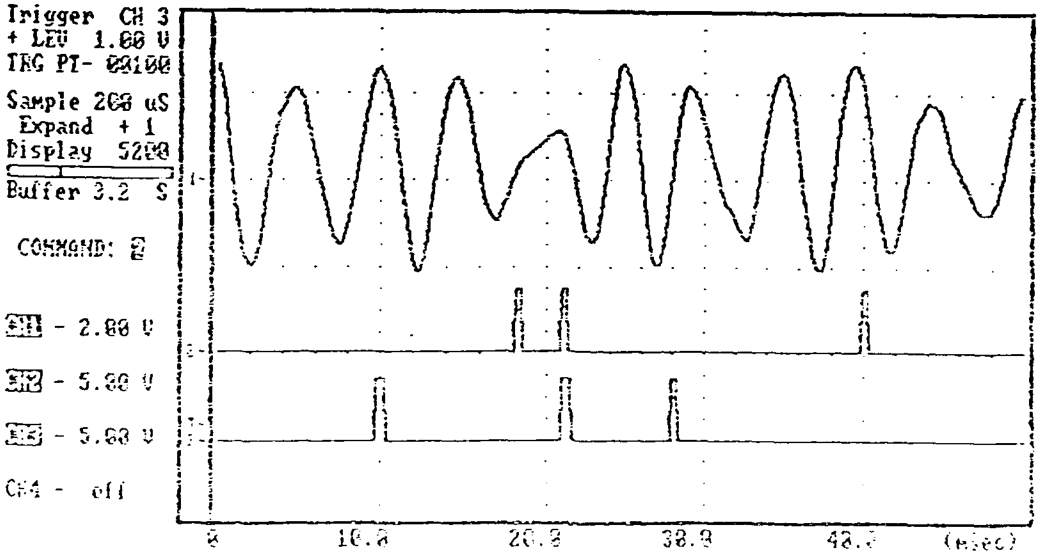


*Figure 3. Data record showing: line 1, pressure trace; lines 2 and 3, ionization probe data; and line 4, output of a photomultiplyer tube located immediately downstream of second ionization probe. Period covered is about 40 milliseconds.*



Trigger CH 3
+ LEV 1.00 V
TRG PT- 00100
Sample 200 uS
Expand + 1
Display 5200
Buffer 3.2 S
COMMAND: 2
CH1 - 2.00 V
CH2 - 5.00 V
CH3 - 5.00 V
CH4 - off

*Figure 4. Data record showing: line 1, pressure trace; line 2, indication of data acquisition for the horizontal velocity component; and, line 3, indication of data acquisition for the horizontal velocity component. Period covered is about 50 milliseconds.*

during the short window for the horizontal velocity component, and the third, for the vertical component. In this example, one good data point for both vertical and horizontal velocities was obtained at 22 milliseconds and only 'good' data are recorded. However, given the unusual shape of the accompanying pressure trace this data was rejected in our averaging process.

These techniques allow us to identify characteristics of the vortices which depend on the amplitude of the pressure signal during the cycle in which the data are acquired.

## NEW COMBUSTION DUCT:

The new, water cooled duct, is shown schematically in Figure 1 and the rearward facing step which acts as the flame holder is located at the entrance of the combustion chamber. The bottom wall of the combustion chamber can be moved vertically so that the duct height can be changed from 2.5 to 15 cm and variation in the height of the duct at the step from 0.5 to 2.5 cm. Glass side walls can be used over the 100 cm length of the combustion chamber. This duct allows access for instrumentation from the bottom wall of the duct. No downstream blockage has been used in current tests. The arrangement of the siren and bypass allow a weak control of the resonant frequencies of the system.

## DIAGNOSTIC TECHNIQUES:

The apparatus developed during these experiments includes high frequency response pressure transducers placed along the top of the chamber, ionization gauges inserted through the bottom wall, a spark lighted shadowgraph system, an intensified-video photographic system for measuring the time resolved intensity of chemiluminescence of the combustion products which is related to the local heat release rate, hot wire and LDA velocity measurements, and ionization probes. Several of these systems are described below.

Pressure Measurements – High frequency pressure transducers have been successfully used in this program in the past, see Smith (1985) and their continued use here required no new instrumentation.

Radiation Measurements – Radiation from the chemiluminescence produced by the combustion reactions is being measured with an enhanced video camera which is triggered to take pictures within a few microseconds of a command signal. The time at which the photographs are obtained is recorded with the pressure signals and thus allows the signals to be synchronized.

The enhanced video camera has been reworked to give the intensification required to properly record the weak radiation signals in the brief period required. We use a period corresponding to 1 degree of the cycle or about 0.3% of the period of the oscillation which varies from of 2.5 to 5 milliseconds. The camera has 280 by 360 pixels area which is used to observe a physical area of 10 by 15 cm and hence gives a resolution of about 2 pixels per millimeter. A linear relationship exists between the intensity of the radiation and the local volumetric heat release rate for a fixed fuel-air ratio.

Velocity Measurements – After a good deal of trouble, the two component LDA system, manufactured by Dantec with a 5W argon-ion Spectra Physics laser, has been put into operation. Light scattered off nominally 0.3 micron diameter alumina particles is used in making the velocity measurements and small particle loading is used to keep the interaction of the processes under investigation independent of the presence of the particles.

Because phase averaging was used here and because we are attempting to differentiate data obtained at a given phase but for different amplitudes of the pressure signal, the data acquisition system for this apparatus has been modified to make possible the identification of the time on the pressure data trace at which successful acquisition of both velocity components was achieved. This process is described above.

Ionization Probes – Several ionization probes are typically placed in the duct. These probes sense when the gas passing over their tips is ionized and the presence of ions is assumed to be associated with a region of intense chemical reaction since the gas temperature is too low to support equilibrium ionization. Data from these probes verify that regions exhibiting chemiluminescence also give a strong signal from the ionization probes and vice versa, and thus support our interpretation of these data.

# EXPERIMENTAL RESULTS

The apparatus discussed briefly is now being used to determine the influence of the fluid dynamic and chemical parameters on the mixing, ignition and combustion processes in a vortex. A considerable body of data is being accumulated and will be analyzed in the ongoing program.

Shadowgraph photographs are being used to study the growth rate of vortices and phase relationships between the shedding and the pressure oscillations. A typical set of shadowgraph photographs are shown on the left hand side of Figure 5, which illustrate the development of the vortex from a time just after its formation, in the bottom photograph, to a large scale in the upper frame. The photographs were obtained during different cycles of the pressure oscillations but are arranged here to show the development process. For a pressure oscillation of a fixed amplitude, the diameter of the vortex grows almost linearly with time. The growth constant also increases almost linearly with the amplitude of the pressure oscillation.

Analysis of photographs of the chemiluminescence produced by the combustion process has shown that combustion starts at least several milliseconds after the formation of the vortices and long after their growth to a large size. For example, see the chemiluminescence photographs on the right hand side of Figure 5. Although shadowgraphs shows where strong density gradients are present, they gives no information concerning combustion. The intensity contours of chemiluminescence were obtained from reconstructions of data obtained from an intensified video camera. The video pictures were taken of the same region and within 10 microseconds of the same time as the corresponding shadowgraph pictures. We believe that these photographs do indicate where combustion occurs.

The lower shadowgraph and chemiluminescence photograph were obtained about .25 milliseconds after a 'new' vortex was shed from the lip of the step, seen as the dark edge at the left hand side of the photograph, and the remains of the 'previously' shed vortex can be seen at the right hand side of the shadowgraph photograph. The only chemiluminescence present is at the right hand side of the picture and is associated with the previously shed vortex; none is observed in the well formed new vortex structure.

In the middle photographs, about one millisecond later in the shedding cycle, the new vortex has grown substantially but no chemiluminescence is associated with it and only a little is left over from the previous vortex which is moving out of sight at the right hand side of the photograph. Finally, in the upper photograph taken at about 2.6 milliseconds after the first photograph was taken, the new vortex has grown to a large size and the previous vortex is out of sight. Strong chemiluminescence is present now in the new

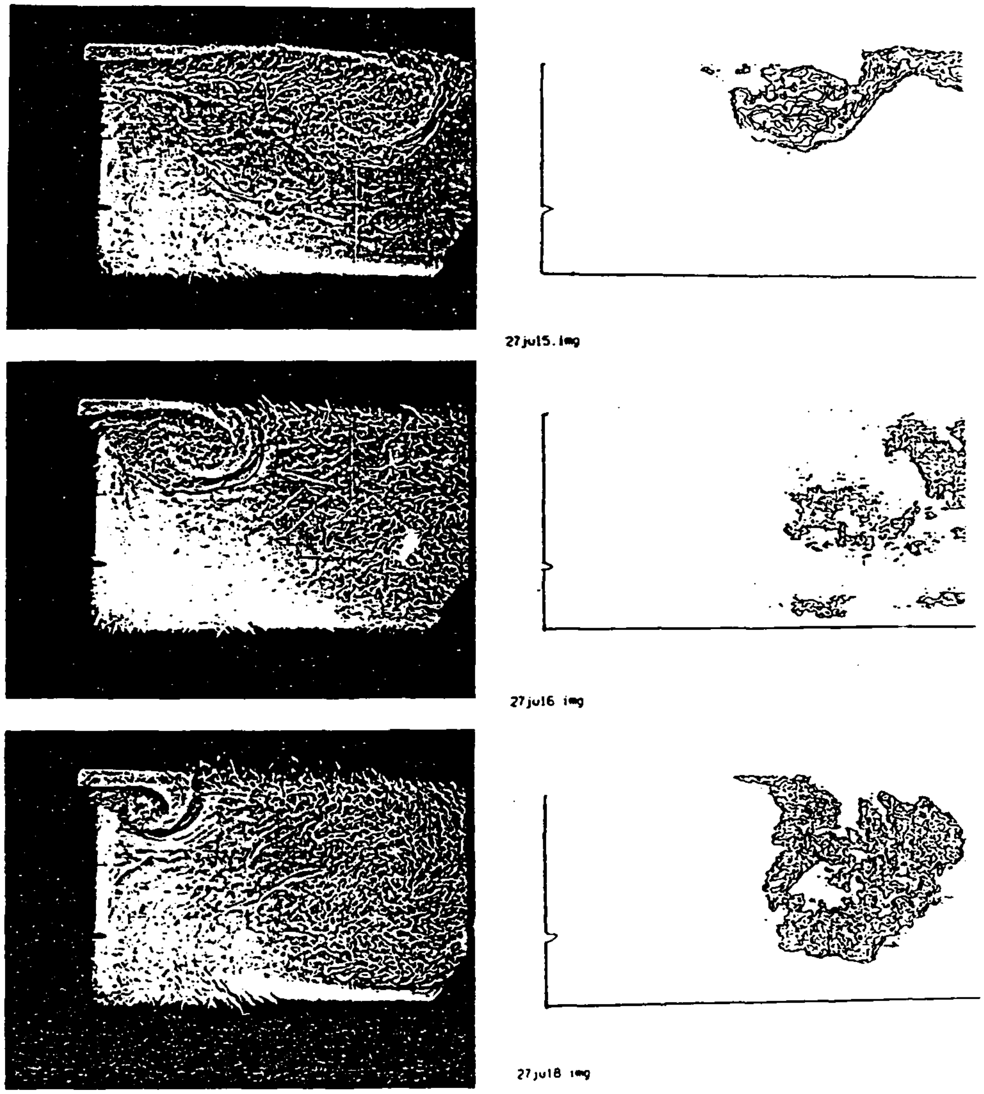


*Figure 5. Left hand column: three shadowgraph photographs showing the development of the vortex, with earliest time at bottom. Right hand column: chemiluminescence contours obtained from intensified video camera photographs which were obtained about 10 microseconds after the corresponding shadowgraph photographs. The right hand edge of the video camera photographs is slightly to the right of the corresponding edge of the shadowgraph pictures.*

vortex. Observe that no chemiluminescence is visible in the shear layer which stretches from the flame holder lip to the body of the vortex in any of these photographs.

Ionization probes placed in the regions showing chemiluminescence in these photographs exhibit large amplitude, sharply peaked signals when photographs obtained with the intensified video indicate that chemiluminescence is present around them, see the data shown on Figure 2 and 3, and thus they confirm our interpretation that combustion does occur in these regions of strong chemiluminescence.

Judging from data of this type, the times between the initial formation of the vortex and the onset of chemiluminescence, and hence we believe combustion, is several milliseconds. This time delay is close to our estimates of the chemical time for the systems under study here. However, the complete omission of chemiluminescence in the early stages of the development of these vortices and in the shear layers is of great interest if verified and will be a primary focus of our ongoing study.

One explanation for the absence of chemical reaction in the shear layer is that the straining field of the flow is so large that the reaction is suppressed. The effects of straining of the flow field on the properties of laminar and turbulent flames has received considerable experimental and theoretical attention in the last ten years. The strain rate of the shear layer and flow in the vortices studied here probably vary between 250 to 1000 sec$^{-1}$ and are probably large enough to affect the chemical reaction rate. Hence, straining of the flow in the shear layer and in the vortex may account for the lack of chemiluminescence discussed above.

Given our success with these preliminary experiments involving all of our diagnostic techniques we expect now to be able to determine the influence on formation, ignition and heat release in vortices of the fluid dynamic and chemical parameters discussed in the introduction. The influence of strain rate will also be examined carefully.

Finally, the control of vortex shedding with simple acoustic drivers or heavy duty sirens requires heroic measures in our system, and perhaps in other systems of this type which use bluff body flame holders such as rearward facing steps. We found that a variety of acoustic drivers could force small amplitude acoustic oscillations at an arbitrary frequency in our combustion chamber duct, but were not able to affect the combustion or produce strong vortex shedding from the step.

In contrast, the combustion instability mechanism produced regular shedding of very large amplitude vortices which were often associated with pressure fluctuation amplitudes as large as 50%. This result is no great surprise, but does emphasize that control of well developed oscillations, of the type studied here, by acoustic drivers will probably not be possible in most propulsion systems. Catching the instability process before the amplitudes of the pressure oscillations have grown to values fixed by limit cycles will be difficult because only 5 to 10 periods, say 50 milliseconds, are required to reach large amplitudes. Hence, some chemically driven actuator will probably be required to control these combustion instabilities.

## 4. PUBLICATIONS

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Sterling, J. D., PhD Thesis, "Longitudinal Mode Combustion Instabilities in Air Breathing Engines," California Institute of Technology, 1987.

Sterling, J. D. and Zukoski, E. E., "Longitudinal Mode Combustion Instabilities in a Dump Combustor," AIAA 25th Aerospace Sciences Meeting, January 1987.

Sterling, J. D. and Zukoski, E. E., "Nonlinear Dynamics of Laboratory Combustor Pressure Oscillations," Submitted to *J. of Comb. and Flame*, 1990.

## 5. PERSONNEL

| | |
|---|---|
| Faculty | F. E. Marble<br>E. E. Zukoski |
| Research Fellow | G. J. Hendricks |
| Graduate Students | J. Sterling<br>T. Zsak |

## 6. INTERACTION WITH INDUSTRIAL GOVERNMENTAL LABORATORIES

Association of work under this grant with problems of the National Aerospace Plane has provided several new and strong contacts. During a recent visit, Charles W. Anderson, NASP Deputy Manager spent several hours becoming acquainted with this work and discussing how it might fit into the NASP program through 1993. We have also presented the work to Pratt & Whitney (Florida), Rocketdyne, United Technology Research Center, and to the NASA Langley Research Center. At NASA Langley, Dr. Dennis Bushnell and Dr. Burt Northam have been particularly interested and helpful. The work has been discussed briefly with the Combustion Group at the Astronautics Laboratory, Edwards Air Force Base.