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COMPACT RAMJET COMBUSTION INSTABILITY
AN OVERVIEW

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Abstract

A five year research program was sponsored by the US Department of the Navy to address the fundamental physics of combustion instabilities in compact ramjets. The program focussed on the role of fuel characteristics, evaporation and microexplosion of droplets, and the flow structure/acoustic interactions in causing pressure oscillations. In liquid-fueled ramjets, the dynamics of the spray vaporization process has a major impact on the energy release pattern in the combustor and plays an important role in the driving mechanism of combustion instability. It is shown that the development of coherent flow structures and their breakdown into fine scale turbulence can lead to periodic heat release, which when in phase with the pressure oscillation, can lead to Rayleigh's criterion and cause instability. Understanding of the physical processes associated with the vortex breakdown led to the passive control of combustion instability. Non axisymmetrical nozzles and inlets, and acoustic forcing have been successfully employed to minimize pressure oscillations. Direct numerical simulations confirmed the flow field structure/acoustic interactions. Approximate analysis of the instability problem has been formulated and solutions obtained.

I. Introduction

As longer ranges are desired for air launched tactical missiles, renewed interest has emerged on air-breathing propulsion systems. Aircraft and ship-imposed constraints on length, diameter and weight of weapons require compact ramjets. However, compact ramjets are susceptible to undesirable low frequency, high amplitude combustion instabilities. To address the fundamental issues of ramjet combustion instability, the Office of Naval Research (ONR) and the Naval Air Systems Command (NAVSEA) initiated a focussed five year research program. The experimental, analytical and numerical research program was aimed at providing basic information on mechanisms and how they interact with each other to generate pressure oscillations, and to develop better understanding of, controlling or, if possible, eliminating instability. The effort focused on identifying fuel characteristics, maximizing combustion efficiency, and minimizing amplification of pressure oscillations, and to investigate control of resonant vortex generation in reacting and non-reacting flows. This research was conducted at universities, Navy laboratories and industry. This paper gives an overview of the issues, approach and the results of this unified research effort.

Ramjet combustion instability involving longitudinal acoustic waves is generally observed as a low frequency pressure fluctuation. The phenomenon must also involve volumetric combustion energy release and the turbulent flow field with large and small scale structures. In his classical paper, Lord Rayleigh (1878) states that if the pressure fluctuation and heat release are in phase in the averaged sense, then the energy is pumped into acoustic oscillation. This result, frequently known as "Rayleigh's criterion", although is of great significance, does not explain why the fluctuations in heat release and pressure are in phase when the instability occurs. It is important to understand the mechanisms that cause the fluctuations in energy release and how one can avoid these to be in phase with the pressure oscillations. In a typical ramjet, the exhaust nozzle, the inlet diffuser, the flow field and the multiphase interactions can contribute to the problem of instability. This program addressed the following issues:

1. What are the effects of fuel spray characteristics on energy release rate and flow field structure?
2. What role do large scale gas dynamic processes have in providing and amplifying temporal and spatial delays in heat release and pressure fluctuations?
3. Can the acoustic/flow field interaction be analytically/numerically modelled to understand the mechanisms?
4. How can pressure oscillations be suppressed by modification to fuel chemistry/injection/flame holding?
5. Can the large scale coherent structure development be passively controlled to minimize pressure amplitude?
6. What are the flammability and stability limits with passive combustion control?

This paper is limited to the specific research conducted under this program. The approach undertaken to solve the technical issues, and the results obtained by the investigators are summarized. The extensive detailed information obtained from this program is omitted on purpose. The reader may refer to the extensive bibliography given at the end of the paper for further information.

II. Role of Spray Combustion Processes

This computational and experimental phase of the program focussed on: (1) to determine the effect of fuel spray characteristics on the energy release pattern in a dump combustor, and the subsequent influence on combustion instability, (2) to gain a fundamental understanding of the coupling of spray vaporization process with a unsteady combustor flow field, and (3) to investigate methods for controlling and enhancing spray vaporization rates in liquid fuelled ramjets.

Effect of Spray Characteristics on Energy Release and Combustion Instability

The effect of the extent of fuel spray prevaporization on combustion instability in a dump combustor was experimentally investigated by Bowman at Stanford University. Spray prevaporization was simulated by simultaneous injection of liquid (n-heptane) and gaseous hydrocarbon (C_2H_4) fuels. The extent of fuel prevaporization was varied by varying the liquid fuel/gaseous fuel ratio, while, while maintaining the overall fuel/air ratio constant. The diagnostics used include: planar laser induced fluorescence for instantaneous species distribution measurement, planar multiphoton dissociation for fuel vapor/pyrolysis product measurement, and planar elastic scattering for particle sizing.

It was found that at higher equivalence ratios, increasing the prevaporization tend to enhance the magnitude of pressure fluctuations (Fig. 1). Further, the extent of prevaporization alters the mode structure of the instability. As seen in Fig. 2, with liquid fuel injection, a significant reduction in the low frequency components associated with the fundamental longitudinal mode, and an increase in the higher frequency oscillations associated with harmonics, were observed. The changes in mode structure and the magnitude of the pressure oscillations appear to be associated with changes in the energy release pattern in the combustor, as inferred from the emission intensity measurements. The energy release occurs over a larger region with liquid fuel injection, than with pure gaseous fuel.

The feasibility of external flow modulation to alter the energy release pattern in the combustor was also studied by Bowman. Flow excitation in the form of a small cross-stream velocity perturbation produced by an externally driven loud speaker was applied to the inlet boundary layer. Direct shear layer modulation was found to produce significant increases in energy release rate and significant reductions in the magnitude of pressure oscillations (Fig. 3) causing combustion instability.

Droplet Vaporization in Unsteady Flow Fields

The response of individual droplets and of a spray of droplets to the uncoupled oscillation of the pressure and velocity of the surrounding gas was analytically and numerically investigated by Sirignano at the University of California at Irvine. Particularly, the amplitude and phase of the oscillating vaporization rate were analyzed to determine whether a driving force for combustion instability can be identified (vaporization rate assumed to be controlling). Further, the gas field was coupled with the droplet behavior, and the mutual influence was determined (vaporization rate was not assumed to be controlling).

With a droplet model valid for high Reynolds number based upon relative velocity, oscillations in the vaporization rate of an array of continually injected droplets were obtained by proper summation of the vaporization rates of the individual droplets. Nonlinear response to pressure and velocity oscillations were determined for both sinusoidal and sawtooth (presence of shock wave) wave forms. By applying Rayleigh's criterion, the gain was found to be sufficient over a wide frequency range to drive combustion instability. For the first time, droplet vaporization was shown to be a viable mechanism for driving the instability.

Subsequently, the high Reynolds number limitation on the droplet was removed, and the variable properties of the gas film surrounding the droplet were accounted for. Sirignano applied a disturbance at the inlet after steady state was established. He found the resulting oscillations approach a limit cycle of finite amplitude at the natural frequency of the fundamental longitudinal mode of the combustor. A transient droplet heating and vaporization model was used to account for temporal and spatial variations of liquid temperature in the droplets. The results further indicated the significance of vaporization in influencing instability. Fig. 4 shows the oscillation in the vaporization rate for an individual droplet.

Vaporization and Combustion of Energetic Fuels

Another experimental investigation by Law of Princeton University (formerly with the University of California at Davis) focussed on the droplet vaporization and microexplosion behavior of organic azides and energetic slurries. The experiment involved downward injecting a stream of monodisperse droplets in a coflowing, 1200 K gas stream that can be varied between inert and 21 mole % oxygen (to allow both pure vaporization and combustion), and can be pressurized to four atmospheres. Droplet size and composition histories are respectively obtained from strobe-synchronized photomicrographs and analysis of samples drawn by a specially-designed sampling probe. From these data, the instantaneous droplet vaporization rate and the extent of liquid-phase reaction can be determined. The effectiveness of microexplosion is quantified by the size at which the droplet microexplodes relative to the initial size.

Fig. 5a shows the variation of the square of the instantaneous diameter of the droplet with time for monoazide (monosubstituted alkyl azide), diazide and alkane. The azides vaporize in accordance with the d^2 law, where d^2 varies linearly with time. However, the vaporization rate K, is faster for the azides compared to the hydrocarbons. This increase is pronounced for diazides. Fig. 5b quantifies the extent of vaporization rate augmentation as a function of molecular weight, and indicates that K increases for the lighter species.

Halide Addition Under Atmospheric Pressure. Pure organic azides already exhibit rapid gasification and inherent disruptive behavior. Addition of a few percent of alkyl halides intensifies the droplet microexplosion still further. In Fig. 6, the burning rate K, and in Fig. 7,the normalized microexplosion diameter (de/do), are shown as a function of addition of various dihalides of equal volatility to the test azide. The results indicate, that with only a small amount of halide addition and irrespective of the halide used, the gasification rate, K remains relatively unchanged for low levels of halide addition. However, the size at which the droplet microexplodes, is significantly increased, by a factor of 2-3. Nearly 60% of the initial droplet mass is then dispersed through explosion for only about 10% halide addition. As halide addition is further increased, the beneficial effects are diluted and result in reduced gasification rate and microexplosion size.

The coupled effects of halide addition and elevated pressure were also studied by Law, using mixtures of diazidopentane and dichlorobutane. With only 2% volume addition of the dihalide, increase in the microexplosion diameter was observed. Upon increasing the additive level to 5%, the droplets exploded so quickly that reliable vaporization constants could not be obtained.

III. Role of Large-Scale Structures,and Passive Control

In another phase of the program, the evolution of vortices in dump combustors, and the interactions between shear layer instabilities and acoustic interactions were investigated. In general, the high speed stream consists of an unburnt mixture of air and fuel, and the low speed stream is composed largely of hot combustion products forming the flame holding recirculation zone behind the dump plane (Fig. 8). In the early phase of the vortex development, with the unburnt mixture on one side of the interface and the hot combustion products on the other, intense fine scale mixing and burning are limited. When the vortex roll-up continues and is followed by interaction between vortices, or is obstructed by side walls, a large amount of interface between the air/fuel mixture and the hot product is generated leading to fine scale turbulence enhancement, combustion, and sudden heat release. This process is repeated during each cycle of the pressure oscillations resulting in periodic heat release. As mentioned earlier, when a proper phase relationship between this periodic heat release and pressure oscillations exists, Rayleigh's criterion will be satisfied, and high amplitude pressure oscillations occur.

Large-Scale Coherent Structures in Isothermal Shear Layers

Experiments were conducted to understand the development of large-scale coherent structures and their role in the combustion instability in ramjet configurations. The development of these structures depends on the relationship between acoustic frequencies and flow instability frequencies. At the Naval Weapons Center (NWC), Schadow and his associates generated coherent structures at the end of the potential core of an axisymmetric jet by matching the acoustic frequency to the preferred mode frequency. Also, In the dump configuration, the flow structures were shown to have azimuthal coherence and high spatial and temporal periodicity near the dump, whereas their coherence was reduced while convecting downstream. Forcing at the preferred mode frequency generates the largest possible coherent structure and therefore changes the shear flow characteristics more effectively. Forcing at higher frequencies produces smaller coherent vortices which are less effective.

Nosseir at the San Diego State University studied the flow field in a simulated side-dump combustor using hydrogen bubbles for flow visualization. Counter-rotating vortex pairs were generated in the impinging region of two rectangular jets with an impingement angle of 180 degrees (Fig. 9). Vorticity measurement indicated that the strength of these vortices changed periodically due to their stretching in the downstream direction. At The Georgia Institute of Technology, Strahle and his associates visualized organized flow structures in their two-dimensional dump combustor. When the flow was forced with a spanwise rotor at the exit of tunnel, coherent structures were observed (by smoke illuminated with a planar laser sheet). Coherent structures were generated at selected forcing frequencies, which were not acoustic frequencies of the tunnel, but were calculated to be unstable frequencies of the shear layer. The presence of coherent structures in nonreacting flows may alter the acoustic pressure characteristics. In these experiments, the same pressure amplitude distributions as a function of forcing frequency was found in the 2-D dump combustor with and without coherent structures present in the flow. However, the critical role of large-scale coherent structures in driving pressure oscillations will be clear, only when their effect on combustion process is considered.

Large-Scale Coherent Structures in Reacting Shear Layers

Vortices have been observed to be shed at the dump and dominate the combustor shear layers. These vortices can persist downstream and impinge upon the exit nozzle. The impingement and convection of vortical structures through the exhaust nozzle provide a feedback mechanism that may trigger a resonant interaction causing sufficient velocity and pressure fluctuations. In the reacting scenario, the flows couple with the system acoustic eigenmodes through Rayleigh's criterion. Feedback to the acoustic field, then, occurs due to combustion-induced volumetric expansion. If the expansion is in phase with the acoustic field, the field can grow until limited by loss mechanisms. Daily of the University of Colorado (formerly with the University of California at Berkeley) investigated these mechanisms in a specially designed and built ramjet combustor set up.

Dried and filtered air was supplied to the inlet side. To promote thorough mixing prior to its entry to the inlet section, the fuel (propane) was injected opposed to the air flow in the upstream piping. The inlet section is long enough to reduce the turbulence length scales. The combustor section which follows the inlet is of modular construction to vary the geometry. The air can be electrically preheated (600 K) and delivered at pressure (6 atm.).

The geometry and operating conditions were selected to maintain a highly unstable combusting flow (Fig. 10). Phase sensitive Schlieren visualization technique was used to take several images throughout the instability cycle. Fig. 11 shows these images, and they correspond to the times shown in Fig. 12. The flames stabilized behind the steps are seen to roll up into large vortices and entrain fresh mixture into the hot recirculation zones (Fig. 11a, pressure is low and acceleration of flow structures is maximum). The vortices are convected downstream (Fig. 11b and 11c), and the coherent structures impinge on the downstream nozzle (Fig. 11d). Intense mixing results as small-scale three dimensional turbulence is produced, and energy release is at its maximum. The pressure reaches a maximum (Fig. 11e) and the flow is reversed (Fig. 11f and 11g) indicating a very high amplitude of velocity oscillation. Chemical reaction terminates due to shortage of fresh reactants (Fig. 11g). The pressure reaches a near minimum (Fig. 11h), with the velocity perturbation becoming positive again. This cycle is repeated. Thus the driving mechanism appears to be large amplitude pulsation of the mass flow rate into the combustor. As the large mushroom vortex shed, reaches the nozzle, it breaks up resulting in intense mixing and large heat release. If this is in phase with the pressure field, Rayleigh's criterion will be satisfied, and acoustic pressure amplification occurs.

In combustors with flame holders, multiple shear layer interaction is a likely source of fine scale mixing enhancement and sudden heat release. Zinn of the Georgia Institute of Technology, experimenting with two cylindrical flame holders (Fig. 13) found that during one cycle of the pressure oscillation, two vortices of opposite sign are shed symmetrically from both the top and bottom surfaces of the flame holder. As these vortices convect downstream, they distort the flame surface and cause flapping of the flame branches. This distortion results in an oscillatory increase in the flame surface area, and hence in an oscillatory heat release rate. The flapping of the flame branches may also cause periodic interaction of the flame front with the side wall, contributing to the periodic heat release.

Passive Control

The experiments suggest that the combustor flow, dominated by vortex flow in the flame holding region, is associated with periodic heat release. Simultaneous generation of fine scale turbulence or the manipulation of the chamber acoustics to reduce the shear layer forcing level can minimize this.

Schadow and his associates at NWC investigated nonreacting and reacting shear flow dynamics of nozzles with corners and multisteps. Studies of jets emerging from triangular or square nozzles showed that the introduction of sharp corners in the nozzle can significantly increase the small scale turbulence at the corners relative to the flat segments of the nozzle. Even with acoustic forcing of the triangular shear layer, only small-scale turbulent flow emanated from the corners, while highly coherent structures were generated at the flat sides. In a reactive flow of non circular flames, the combustion at the flat segments was confined in periodic, large-scale coherent structures, and at the corners combustion occurred in randomly distributed small-scale flamelets (Fig. 14).

Fuel injection into the highly turbulent flow field at the vertices of a triangular inlet duct suppressed the pressure amplitude below 10% of the mean pressure over the entire equivalence ratio range (Fig. 15). Experiments by Whitelaw at Imperial College showed that the triangular inlet duct also extended the lean and rich flammability limits.

A multi-step dump having several backward facing steps was found to enhance fine-scale turbulence and prevent large-scale structure development. In the NWC multi-step dump combustor, the pressure oscillations were reduced below 10%. The lean flame blow-out limit was slightly extended to lower equivalence ratios with the multi-step dump relative to the sudden dump. However, rich flame blow-out occurred at a lower equivalence ratio for the multi-step dump (0.8 - 0.9) than for a sudden dump (1.3).

Zinn (Georgia Institute of Technology) was successful in reducing the combustion oscillations by controlling the acoustic driving provided by the flame merging and wall-flame interaction regions. By displacing the two flame holders relative to each other, the vortex travel time from each flame holder to the flame merging and wall-flame interaction zones, is changed. Thus the local phase of the unsteady heat release was made to be out of phase with the acoustic pressure. When the acoustic driving generated is opposed by the acoustic damping, instability can be eliminated (Fig. 16).

IV. Numerical Simulations of Pressure Oscillations in Ramjet Combustors

In the practical engineering analysis of turbulent combustion flows, global empirical descriptions of the effect of turbulence on the transport of mass, momentum and energy are used. However, in attempting to find out the details of an oscillatory flow, these global models become ineffective, as the time evolution of the flow - even at low frequencies - are averaged out, and hence the resulting model cannot account for the oscillatory nature of the flow. Again, a global model cannot provide the oscillatory nature of heat release. Hence the computational phase of the program focussed on direct numerical simulations. In this method, the whole set of Navier Stokes equations is discretized on a finite number of grid points, and a detailed time evolution of the solution is then sought by the use of supercomputers.

In a turbulent flow, eddies of all sizes are present. While the large eddies are in integral scale, the smallest eddies are in the dissipation scale (Kolmogorov scale). It can be seen that the computing effort increases as the 11/4 power of Reynolds number. In a ramjet combustor, the Reynolds number is high, and the limitation on Reynolds number for such simulations is obvious. An assumption is made that only the large eddies in a turbulent flow are involved in the combustion instability. Hence, by capturing the dynamics of large eddies in a numerical simulation (Large Eddy Simulation, LES), the complex mechanism of combustion instability may be unravelled. The small eddies that cannot be resolved by the finite computational grid, are assumed to provide only dissipation to the large-scale flow field and can be modeled using eddy viscosity.

Kailasanath and his associates at the Naval Research Laboratory (NRL) used a simulation based on the solution of Euler's equations to capture the physics, based on the hypothesis that the dynamics of large vortices is essentially governed by an inviscid mechanism. In their model, the flux-corrected-transport algorithm is used. The method marches the solution of inviscid, compressible flow equations in time. The salient feature of the numerical scheme is a specially designed numerical diffusion coefficient that affects only the sharp-gradient regions and maintains the sharpness of the flow discontinuity, without producing non physical oscillations of the flow variables in the neighborhood. This numerical diffusion coefficient serves as a subgrid eddy viscosity in the LES model.

Fig. 17 shows a set of time sequence instantaneous streamlines obtained in the simulations. Closed instantaneous streamlines indicate vortices. The shear layer is seen to roll up into concentrated vortices that subsequently merge to form large structures. The initial roll-up is shown to occur at the most unstable frequency based on the stability analysis of the shear layer. The model was then extended to include combustion heat release and simulations were performed. The global heat release rate in different sections of the combustor would depend mainly on the length of the reaction front. Hence it can be inferred that if the hydrodynamics is captured by the simulations, the heat release in the combustor is closely modeled, though a simple subgrid model for chemical heat release was employed. The instantaneous streamline patterns and the corresponding temperature contours are shown in Fig. 18. It can be seen that only large vortices are present in the combustor, and the reaction front is contorted by the vortical motion. Fig. 19 shows the time evolution of instantaneous pressure fluctuation (a low frequency oscillation is evident), and local Rayleigh's criterion in the axial direction. The destabilizing pressure-heat release interaction at the downstream is stronger than the upstream stabilizing effect, indicating combustion instability.

In another effort Jou (presently with the Boeing Corporation) and his associates at Flow Research, in their model solved the unsteady, compressible Navier-Stokes equations using an explicit MacCormack method. The laminar viscosity was increased from the actual value to represent the subgrid eddy viscosity. Axisymmetric flows in a central dump combustor were considered. The downstream nozzle was choked and the supersonic region downstream of the throat was included as part of the computational domain. Therefore, no information from the outflow boundary can propagate upstream through the supersonic region, thus acoustically isolating the combustor.

Fig. 20 shows the time sequence of the vorticity contour plots in the dump combustor. The process of shear layer roll-up and merging, and the large vortices impinging on the nozzle wall and inducing secondary contra-rotating vortices are demonstrated. To extract acoustic information, the instantaneous volume expansion (dilatation) of the fluid was computed. Analysis shows that the instantaneous dilatation field provides information on the nature of acoustic sources due to vortical motion. Close-up views of the dilatation field and the corresponding vorticity field for the rolled up vortices are shown in Fig. 21. Jou identified the vortex/choked nozzle as the strongest candidate for the conversion of flow energy to acoustic energy in a cold flow.

V. Approximate Analysis and Stability of Pressure Oscillations in Ramjets

Computational results, in the ideal limit should provide precise and complete information of ramjet combustor flow fields. Apart from numerical inaccuracies, which can in principle be reduced to acceptable levels, uncertainties will exist in the input data associated with the chemical processes and turbulent flows. Further, the extensive computer time required, and the case-specific results obtained, computer simulation is not a reasonable approach for the designer. On the other hand, for preliminary design work, investigating parametric effects, and for planning experiments, approximate analytical methods are greatly superior. However, because assumptions and approximations are involved, the accuracy of any approximate analysis is difficult to assess.

Culick at the California Institute of Technology (Cal Tech), performed approximate analysis of the compact ramjet combustion instability problem, by extending the ideas developed in classical acoustics. Vortex shedding and convective waves as mechanisms causing combustion instability were also accommodated within the framework of approximate analysis. In order to examine entropy fluctuations (local inhomogeneities of temperature or density caused by irreversible processes), combustion, flow separation and oscillations of shock waves and to analyze the stability of pressure oscillations, an idealized model of a dump combustor was considered. The inlet shock system was represented by a single normal shock, with a uniform inlet to the combustor. All combustion processes were collapsed to a single plane flame, and the flow downstream to the exhaust nozzle was considered to be uniform. Linear acoustic and entropy waves were coupled at the inlet shock, the flame and the nozzle. Analysis was carried out for steady waves; results were then found for stability and mode shapes of the various normal modes of the system.

Special cases have been computed for a flame with a downstream choked nozzle and a perfectly reflecting upstream inlet, but with incident entropy waves. The results show unstable modes in the low frequency range, providing the entropy fluctuations are sufficiently large. Some results have been obtained for the influence of entropy fluctuations on nonlinear acoustics.

An explicit formulation of Rayleigh's criterion was made and generalized by Culick to account for all sources of energy gain and loss.

VI Summary

A five year research effort was sponsored by ONR and NAVSEA to understand the mechanisms involved in the low frequency, high amplitude combustion instabilities in compact ramjets, and to obtain the scientific base for their control. This multi-disciplinary effort focussed on fuel properties and their vaporization, role of coherent structures in the flow, and the acoustic/flow field interactions. The significant results obtained include the following:

1. Passive control using non axisymmetrical nozzles to alter the vortical flow in the combustor has resulted in a break-through in combustion control.
2. A secondary flame holder, appropriately positioned, is demonstrated to damp pressure oscillations.
3. Direct numerical simulation of the unsteady flow in ramjet combustor, confirmed the interaction of flow/acoustic fields.
4. Role of large scale coherent structures and vortex shedding in ramjet pressure oscillations has been explained.
5. Acoustic forcing can improve ramjet combustor performance, and reduce pressure oscillations.
6. Oscillatory vaporization rate can be sufficiently large over a wide range of frequencies to drive instability.
7. Approximate solutions to the combustion instability problem were obtained to aid the designer.

This program has paved the way for another follow-up special focus research initiative by ONR on Active Control of Complex Flows, and several research programs in supersonic combustion control, three-dimensional imaging of turbulence/combustion interaction, and energetic fuels combustion. Further, rational passive shear flow control in practical combustors has resulted. The understanding obtained has been applied to solid fuel ramjets, ducted rockets and ejectors. This research effort can be translated into very valuable tool for the design of combustors, where unsteady heat release and pressure oscillations are involved.

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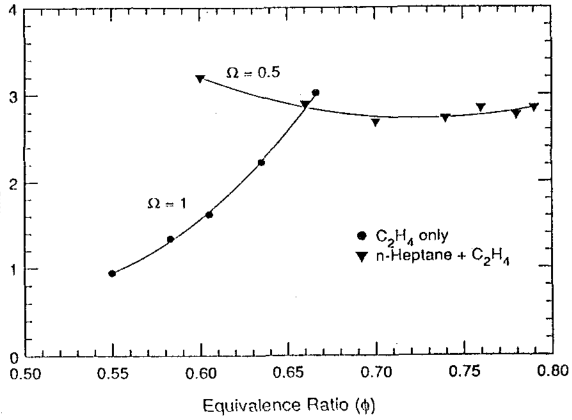


Figure 1. Variation of Pressure Fluctuations with Equivalence Ratio

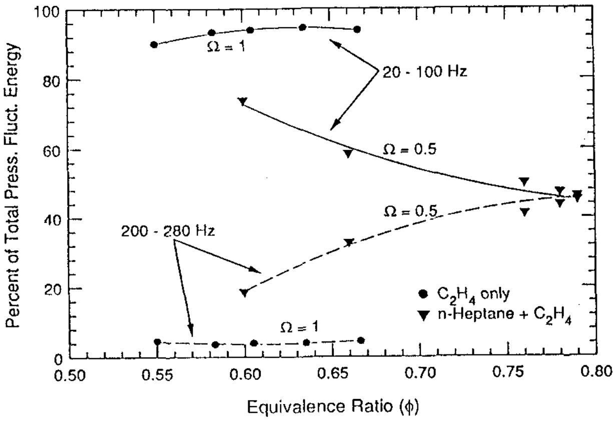


Figure 2. Effect of Equivalence Ratio on Mode Structure of Instability

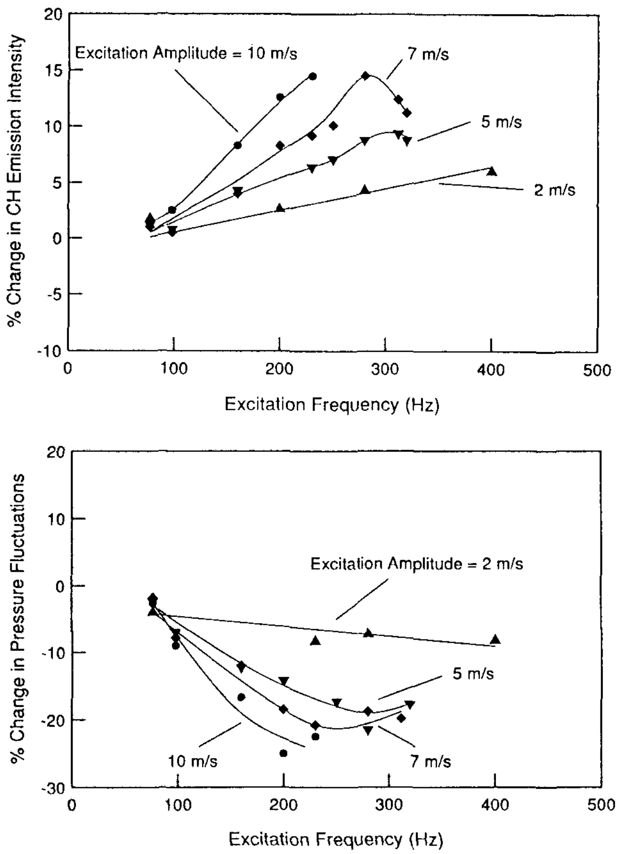


Figure 3. Effect of Direct Shear Layer Modulation on Energy Release and Pressure Oscillation

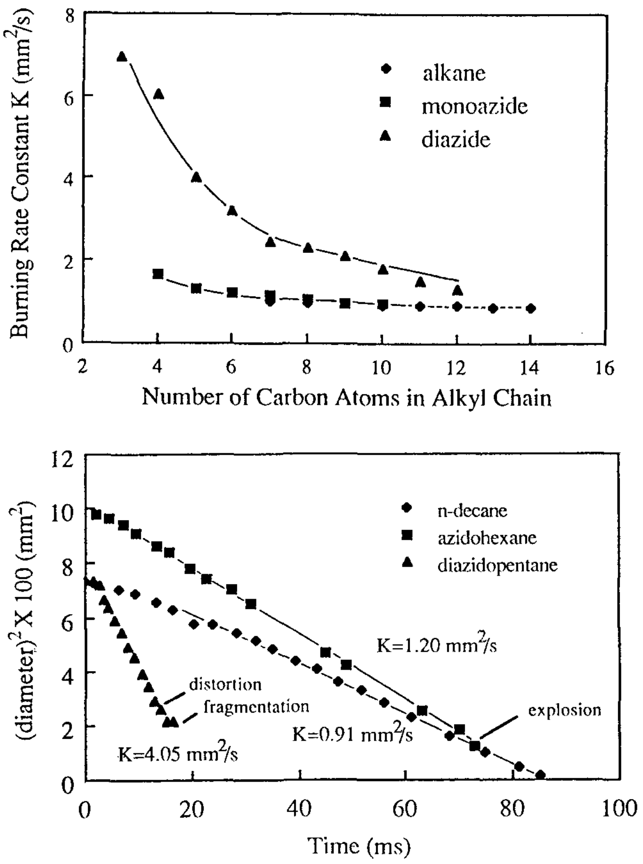


Figure 5. Vaporization of Azides

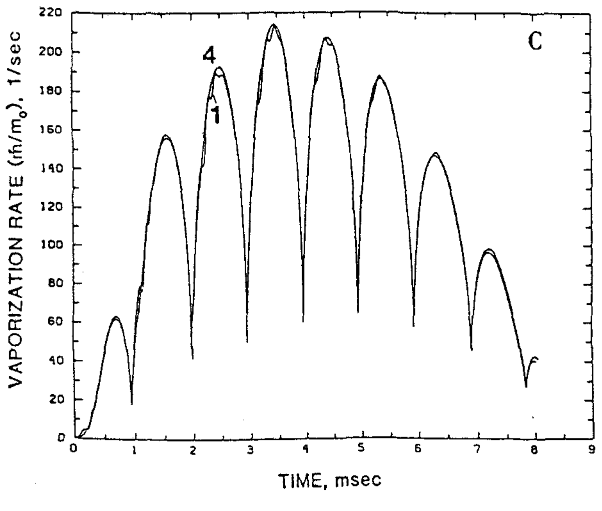


Figure 4. Vaporization Rate Oscillations

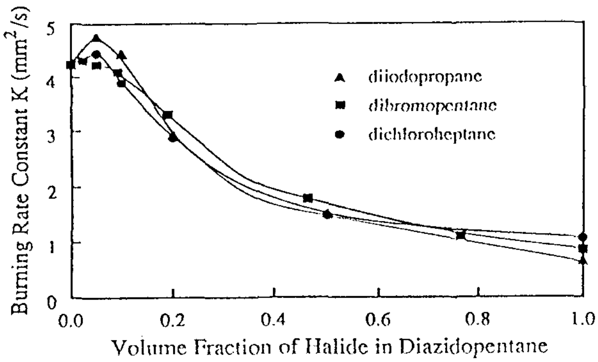


Figure 6. Burning Rate With Halide Addition

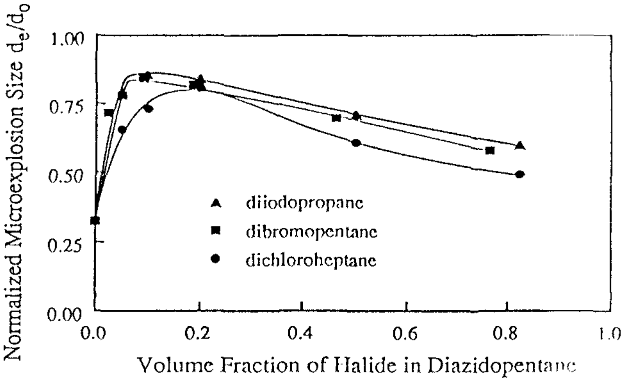


Figure 7. Microexplosion with Halide Addition

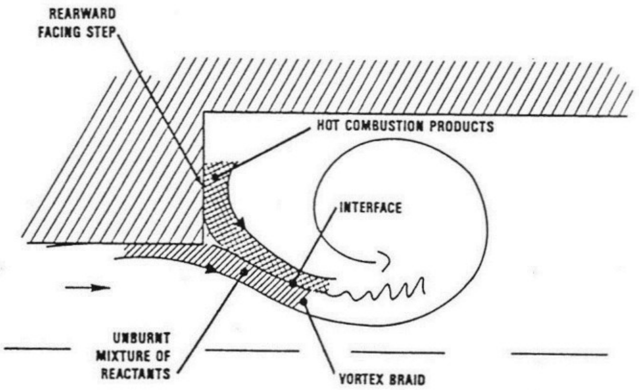


Figure 8. Vortex Roll-Up in a Dump Combustor

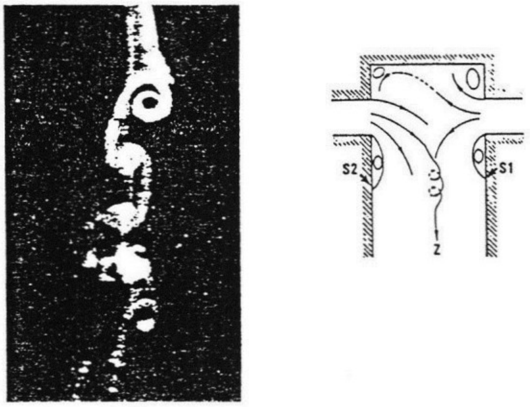


Figure 9. Counter-Rotating Vortex Pairs in Side Dump Combustor

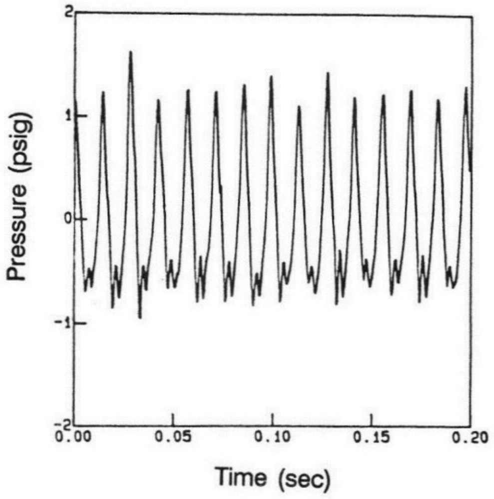


Figure 10. Pressure Record During Unstable Combustion

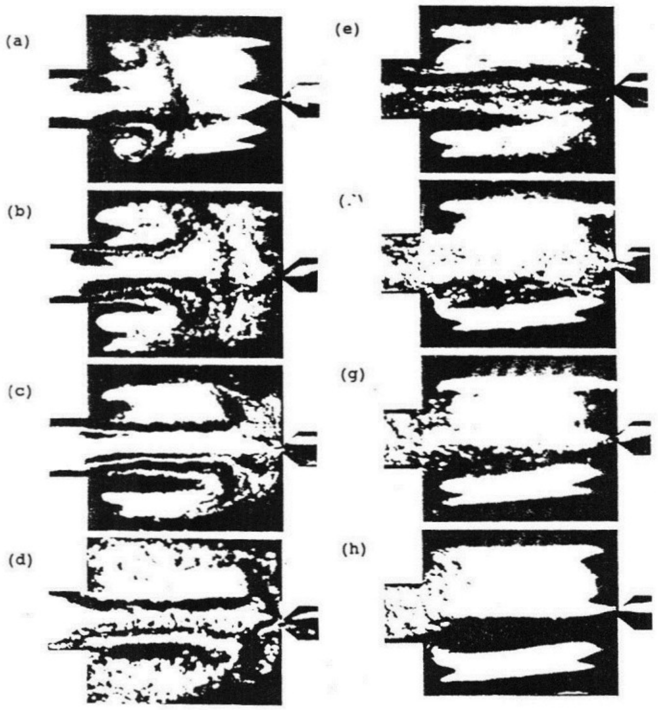


Figure 11. Phase-Locked Schlieren Photographs of Combustor Test Section

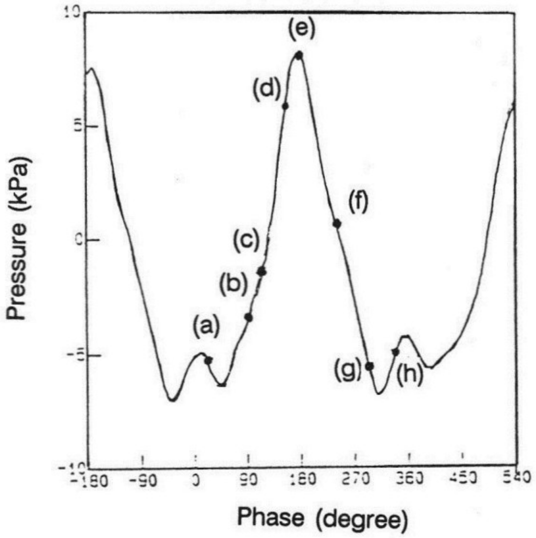


Figure 12. Pressure Oscillation Cycle

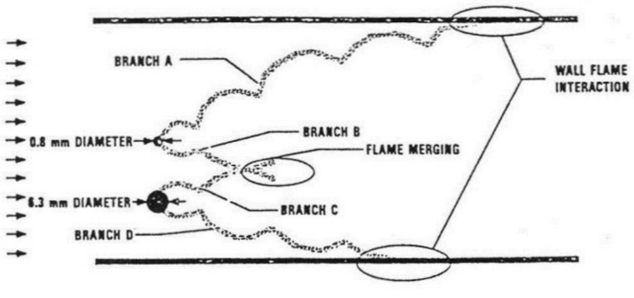


Figure 13. Twin Flame Holder Combustor

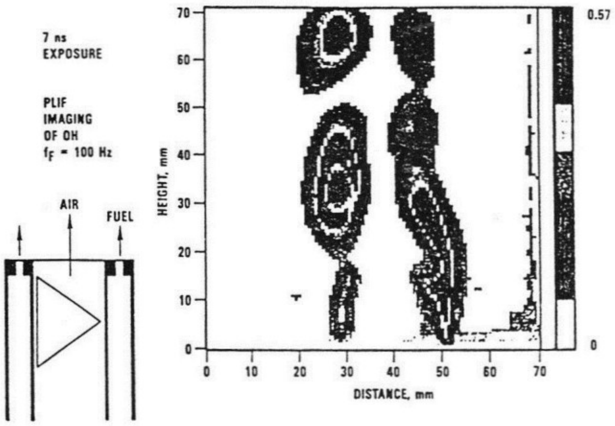


Figure 14. Flame Characteristics of Equilateral Triangular Burner

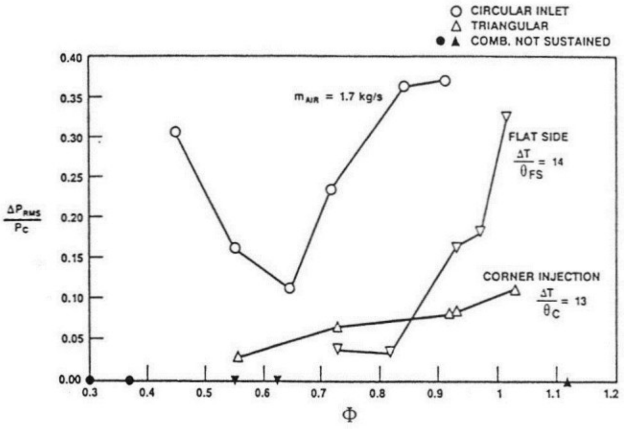


Figure 15. Pressure Amplitude With Circular and Triangular Inlet Ducts

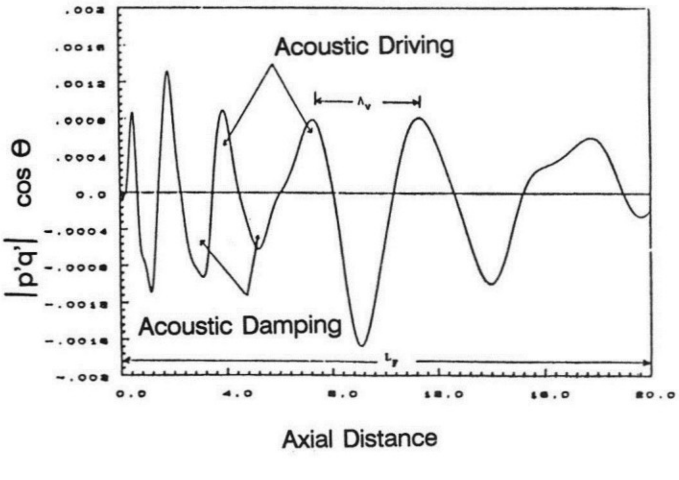


Figure 16. Control of Instability by Acoustic Forcing

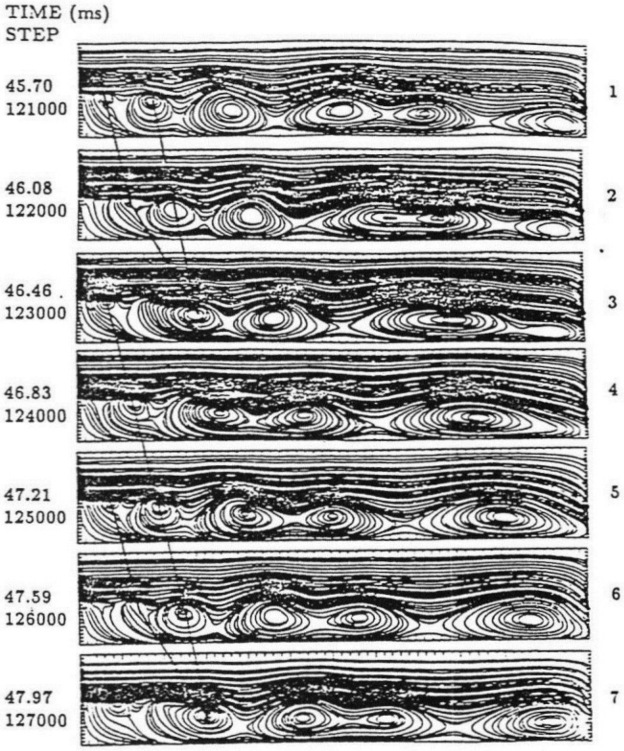


Figure 17. Vortex Shedding and Merging Near Steps

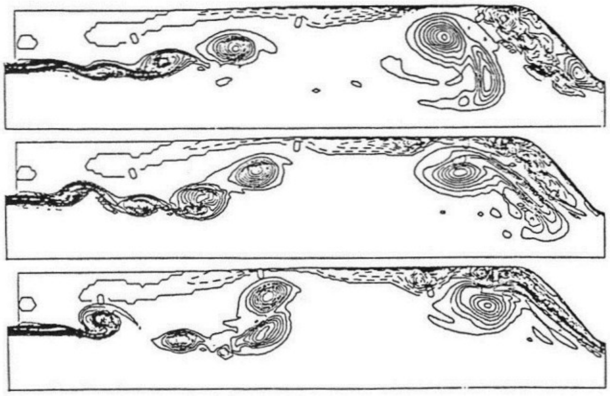
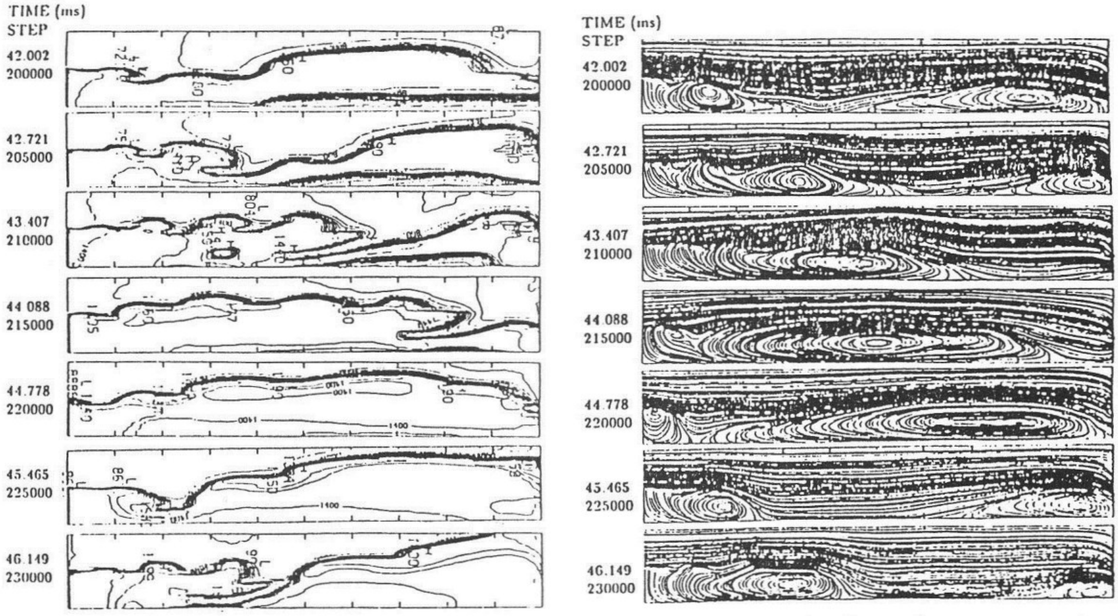


Figure 20. Time Sequence of Vorticity Contour Plots



a. temperature

b. Streamlines

Figure 18. Effects of Energy Release on Flow Structure

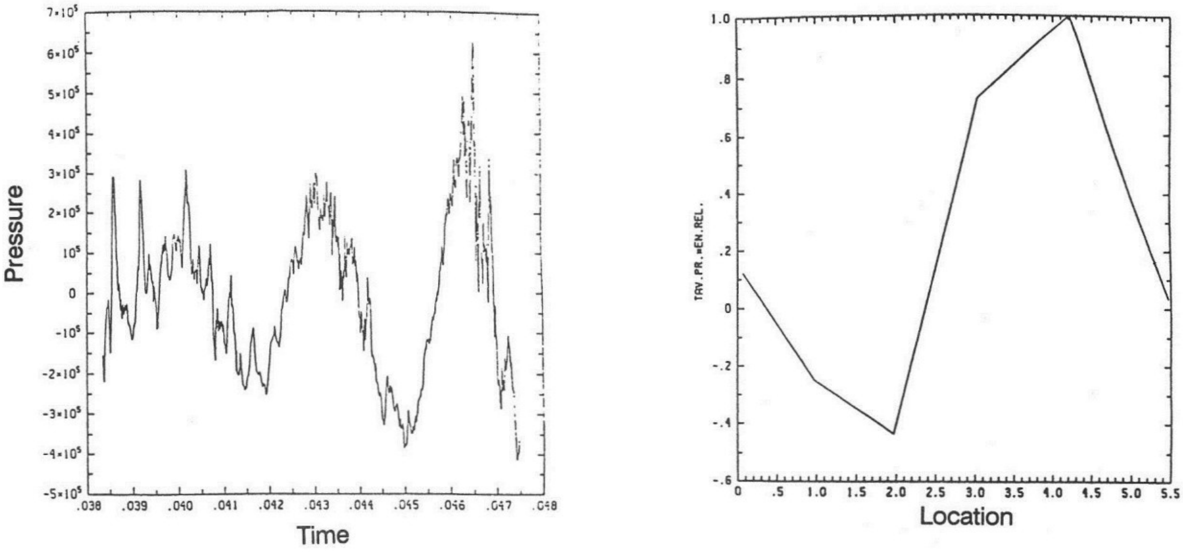
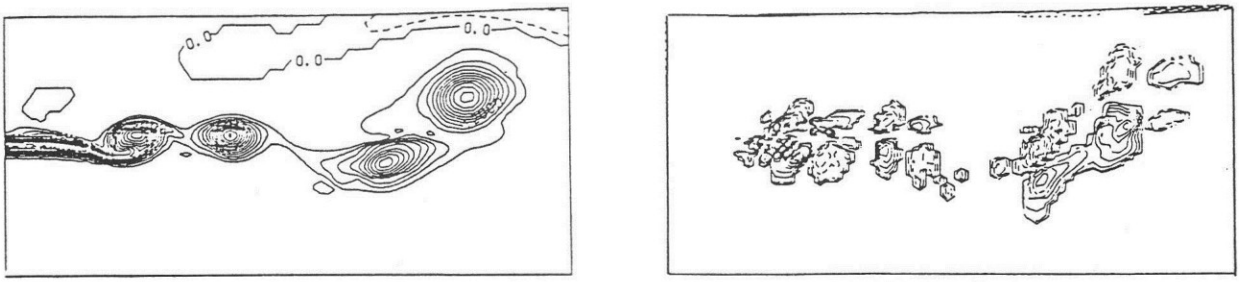


Figure 19. Time Evolution of Instantaneous Pressure Fluctuations and Local Rayleigh's Criterion



a. Vorticity Contours

b. Dilation Contours

Figure 21. Dilatation and Vorticity Field