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This report is the final report of a six-month program with a six-month NCE comprising experimental work on problems arising with unsteady combustion of gases intended for use in propulsion systems. The experimental work comprises measurements providing the basis for inferring the local response function of a reacting mixture and is based on greatly extended equipment purchased before this program began, with a DURIP grant from AFOSR. The basic part of the facility is apparatus for PLIF (planar laser induced fluorescence) measurements of a combustion system exposed to a sinusoidally varying pressure field, p', with q', the local fluctuation of heat release, appropriate measurements allow inference of q'/p', proportional to the response function and $q'p'$, the integral over volume is proportional to the Rayleigh factor. In principal, knowledge of these two quantities permits deduction of all important dynamical properties of a dynamical system. The greater part of work during this year has been directed to determining the effect of fluctuations in fuel mixture ratio, most of the experimental work has been based on the use of acetone PLIF.

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FINAL TECHNICAL REPORT

MEASUREMENTS AND MODELING OF COMBUSTION DYNAMICS FOR CONTROL OF COMBUSTION INSTABILITIES

AFOSR Grant Number: F49620-03-1-0384

1 July 2003 – 30 June 2004

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Abstract

This report is the final report of a six-month program with a six-month NCE comprising experimental work on problems arising with unsteady combustion of gases intended for use in propulsion systems. The experimental work comprises measurements providing the basis for inferring the local response function of a reacting mixture and is based on greatly extended equipment purchased before this program began, with a DURIP grant from AFOSR. The basic part of the facility is apparatus for PLIF (planar laser induced fluorescence) measurements of a combustion system exposed to a sinusoidally varying pressure field, p', with q', the local fluctuation of heat release, appropriate measurements allow inference of q'/p', proportional to the response function and $q'p'$, the integral over volume is proportional to the Rayleigh factor. In principal, knowledge of these two quantities permits deduction of all important dynamical properties of a dynamical system. The greater part of work during this year has been directed to determining the effect of fluctuations in fuel mixture ratio, most of the experimental work has been based on the use of acetone PLIF.

1 Research Objectives

The overall technical objective of this program, which has been followed since the mid 1990's, is analysis and experimental investigation of nonlinear unsteady motions and other fundamental problems relating to active control of combustor dynamics, in particular combustion instabilities. It is an educational objective that all students involved in this program will gain experience in both experimental and analytical work. Moreover, they become well-versed in the fields of combustion and controls.

When this program started, we anticipated using a new continuous-flow facility operating at pressures of up to four atmospheres. However, it was to be a gift from a small commercial firm which encountered financial difficulties. The apparatus became unavailable. Therefore we revised our plan and designed and built a new device, a vertical atmospheric tube in which an oscillating field is driven by loudspeakers set in branches at the top. A combustion device producing an initially unmixed flame is set near the bottom. Much of this program has been devoted to measuring properties of species produced in the flame using PLIF (planar laser induced fluorescence). The PLIF system was constructed with a DURIP grant from AFOSR. With this arrangement and the use of the PLIF system, it became possible to make the first "point" measurements of heat release associated with an oscillatory pressure field. The values are actually obtained for a volume of 0.05 mm, not a true "point." If developed further, this method has

promise to give results for the sources causing combustion instabilities. Such results would not depend on the shape of the chamber.

Methods for predicting and evaluating the dynamical behavior and stability characteristics for given combustors are required as part of the basis for a more robust design. The objective of the current work described here is to study the effects of acoustic oscillations, as causes of unstable dynamics in a combustion chamber; to investigate the fuel/air mixing in detail; and to study the connections between flame behavior and mixing behavior under the same conditions. This is a study of the internal dynamics of combustors, building on and extending the knowledge and understanding gained in previous work (Pun et al. 2003).

This effort aims to bridge those two studies—measurements of fuel mixture fraction using fiber optic probe and OH-PLIF flame measurements—by producing mixture fraction data that can be directly compared to previous measurements. This work is based on single frequency acoustic forcing at five different frequencies, as in the previous efforts (Pun et al., 2002, 2003), to examine how the local fuel/air mixing is affected by the imposed acoustic excitation and how this relates to the observed flame behavior. Theoretical modeling on the relationship between mixing and the flame response, the heat release rate, was done by Lieuwen et al. (1998). By comparison with previous work (Fernandez et al., 2003), it also becomes possible to understand the evolution of fuel/air mixing.

We have designed and constructed apparatus similar to the equipment described here, for operation up to five atmospheres, the limit of the usual methods based on PLIF. That device has been built but is not yet operating. It has been transferred to the University of Iowa where a former postdoctoral scholar, now on the University of Iowa faculty is about to begin experiments.

This program has been extraordinarily important in providing support as well as material for the Principal Investigator's research generally on combustor dynamics. See the website www.its.caltech.edu/~culick for his latest short course "Combustor Instabilities in Liquid Rocket Engines: Fundamentals and Control" which is based largely on his course "Dynamics of Combustion Systems: Fundamentals, Acoustics and Control" which can also be accessed on the website. The PI has also recently submitted to NATO's Research and Terminology Organization (RTO) the manuscript of his book "Unsteady Motions in Combustion Chambers for Propulsion Systems" which RTO will publish as an AGARDograph.

2 Introduction

This program has been motivated by the variety of important problems arising in unsteady reacting flows present in propulsion systems. Mainly we have been concerned with situations presented with combustion instabilities. Experimentally our attention has especially been directed to measurement of the response function for a gaseous mixture in a general way, that is, unrestricted by the geometry of the combustor. One is therefore driven, almost inevitably, to use methods based on lasers. We have been developing and applying a technique based on PLIF, planar laser induced fluorescence. That this is a general and productive point of view may be seen in the following way.

Combustion instability is observed normally as oscillations in a combustion chamber. The oscillations are present because of a close connection between the dynamical behavior of the combustion processes—especially the associated energy release—and the properties of the unsteady flow, particularly the pressure, temperature, velocity and mixture ratio. Analytical and theoretical work has been to a large extent devoted to this close connection and its consequences. In order to understand the matter and formulate the connection in a useful and productive fashion, simple models have been used. These models have, practically without exception, been based on oversimplified representations, usually of the behavior of flame sheets in gaseous and liquid-fueled systems. There is generally a desperate need for models of unsteady combustion processes distributed in realistic chambers. The main goal of our numerical simulations and of the experimental work justifying this proposal is to acquire the basic information necessary as the basis for constructing such models.

So far as we know, our experimental research in this area is unique, not only in respect to the content and purpose, but also in the immediate connection with modeling and theory. We know of no other research group attempting to measure directly the local dynamics of flames and distributed combustion processes for the purposes we have in our program. The results are fundamental contributions to the field of reacting flows generally. In respect to practical applications, experimental and theoretical works on active control combustor dynamics currently tend to ignore the problem of determining the details of the mechanisms of instabilities and concentrate on trial and error *ad hoc* efforts to control the dynamics. The results are therefore almost always limited to the particular systems studied.

This program has been, we believe, the first devoted to determining quantitatively a fundamental contribution to practically all unsteady motions in combustors: the dynamical response of the rate at which energy is released locally by chemical reactions.

What we mean by 'dynamical response' and why it is crucially important to the dynamics of combustors is best seen by examining a formal representation of Rayleigh's criterion:

$$\Delta E = K \int dV \left[\frac{1}{T} \int_{t}^{t+T} \dot{Q}'_r p' dt \right] \tag{1}$$

Here $\dot{Q}'_r$ stands for the fluctuation of the combustion energy release rate per unit volume that is **in phase** with the pressure fluctuation; K is a constant; the inner integral is over one period τ of the oscillation; and the outer integral ranges over the volume of the combustor. Then ΔE represents the total energy transferred from the chemical reaction to the oscillating field in one period of the oscillation. With the formula (1), Rayleigh's criterion states that if ΔE is positive, combustion processes tend to encourage the system to be unstable. Thus the criterion is equivalent to the condition one finds for linear instability of a combustion system (Culick 1975, 2001). Culick (1987) has discussed a general form of (1) including all relevant processes and applicable to nonlinear behavior, showing its relation to the general principles of stability.

Since data were first reported by Stirling and Zukoski (1991), a number of groups have reported confirmation of (1); the most recent results are those obtained by Durox et al. (2002), and Schuller et al. (2003). In those cases, and others we are aware of, fluctuations of energy release were detected by measuring the radiation from CH, an intermediate species in hydrocarbon reactions. The radiation is typically collected through a slit or a window and measured with a photomultiplier. Thus the fluctuation of energy release is found for an extended region of the field. With PIV measurements, Durox et al. (2002) and Schuller et al. (2003) measured the velocity fluctuations in the flow field and burners' response functions up to 400 Hz of forced acoustic oscillations. These results are, however, device-dependent.

The ultimate primary objective of the work reported here has been to determine local values of the fluctuations of energy release rate, and especially the dependence on instantaneous local values of the variables defining the field: pressure, temperature, mixture ratio of the reactants, and velocity. Progress towards this objective has been accomplished by applying, to simple flow configurations, a combination of two experimental methods: planar laser induced fluorescence (PLIF) and a probe (the 'Dibble probe') for measuring initial concentrations of unreacted gaseous fuel (CH_4 here) to give spatially resolved and time-accurate results for $\dot{Q}'_r$ up to 55Hz. So far as we know, those are the first such results which are being extended by the present and future works.

Accomplishment of the objective stated in the previous paragraph will provide the basis for constructing a model (or models) of the source term $\dot{Q}'_r$ in the integral (1), a primary cause of instabilities in combustors. By 'primary cause' we mean here that $\dot{Q}'_r$ (actually its time derivative) appears as a source of unsteady motions in the equations for flow in a combustor and therefore can be given a direct

physical interpretation for a particular problem being considered. Accurate representation of $\dot{Q}'$ is essential to understanding the presence of combustion instabilities and, accordingly, how they can be either avoided or eliminated in practical systems. Quite generally $\dot{Q}'$ must be known to analyze any problem of combustor dynamics.

Mixing is a significant factor in combustion and combustor dynamics. The rate of heat production, fuel-efficiency, and pollutants (NOx, unburned hydro carbon, and etc.) formation are all affected by the mixing of fuel and air. The local distribution of equivalence ratio due to the uneven mixing of fuel and air, and its response to the combustion dynamics is of great concern in research on any combustion processes that take place without fully mixing the fuel and air prior to injection to the combustors. For example, a fuel pocket, which is formed locally inside a flame, may lead to incomplete burning of the fuel and the production of unburned hydrocarbon. Irregular burning can also be induced due to local equivalence ratio distribution. According to Lieuwen et al. (1998), their theoretical and numerical modeling on the relations between oscillations in mixing and flame behavior, combustion instabilities could be caused by the oscillatory behavior of mixing (unmixedness) especially at leaner regions.

By studying how the mixing behaves under acoustic oscillations, which in this case is supposed to simulate the condition inside combustion systems, a better understanding can be obtained on how these phenomena interact each other. And by understanding how mixing behaves, efforts will be directed to regulate the mixing, intended to improve combustor performance such as higher efficiency, better stability, and reduced formation of pollutants. The data obtained here may therefore be used to describe the fuel/air mixture flow field, and can be used to control and regulate the flow field so as to enhance combustor performance.

2.1 Combustor Dynamics, Combustion Dynamics, and Combustion Instabilities

Almost all[1] combustion chambers intended for propulsion or power generation systems are designed for steady operation, subject at most to relatively slow changes. The reacting flow in a combustor is defined entirely by the state of the reactants entering the chamber and the geometry, including the injector design. The practical and research problems we face here are related essentially to stability of the flow field. If the flow field is unstable, then the system exhibits unsteadiness i.e., in a general sense, dynamical behavior.

The dynamics of a combustor arise primarily from two sorts of instabilities: (1) instability of the steady flow field itself; and (2) instability of the intrinsic or acoustical dynamics of the chamber.

[1] The chief exceptions are pulse combustors, not the object of the work discussed here.

Instability (1) of the steady flow leads to turbulence and formation of coherent vortex shedding associated with unstable shear layers. Both types of unsteady disturbances affect the distribution of chemical activity in the chamber. It is the instability (2) of the acoustical motions, a basic property of compressible flow in any chamber, which leads to the dynamical motions called combustion instabilities.

In practical combustors, the existence of combustion instabilities cannot be considered completely independently of instabilities of the basic flow. The flows are always turbulent, affecting the rate of energy release due to combustion and the form of the macroscopic flow field, including shear layers, recirculation zones and large-scale vortices, is a primary influence on the distribution of energy release rate, $\dot{Q}$. Then the fluctuation $\dot{Q}'$ of $\dot{Q}$ appears as the primary source of the unsteady acoustic field, as discussed in connection with the formula (1).

A basic premise of our work is that the *local* values of $\dot{Q}$ and $\dot{Q}'$ are in fact determined largely by *local* values of the variables characterizing the flow field. Therefore *if* that fundamental dependence can be found for a particular system of reactants, a basis exists for understanding the causes of combustion instabilities in any combustor using the same reactants and primarily due to $\dot{Q}'$. That idealized flow of information is shown schematically in Figure 1. Current work includes the items represented by the yellow shaded blocks. As a result of work at Caltech, the essentials of the methods indicated in the blue block already exist for the most part. The procedures are general, capable of describing linear and nonlinear behavior for any geometry, but to obtain specific results, models of certain dominant processes are required. **Constructing those models for a broad range of realistic conditions is an ultimate objective of our long-term program including the work described here.** The experimental information required to construct those models is fundamental to research on reacting flows generally. Hence the methods we develop will have very broad applications.

Rayleigh's criterion in the form (1) illustrates the central importance of the fluctuation of heat addition in combustor dynamics. The general theory, from which (1) can be derived, provides the framework for investigating the dynamics of any combustor. In Appendix B we have given an elementary analysis of the Rijke tube, the simplest example of thermoacoustic or combustion instabilities. That analysis shows that due to the fluctuations of energy release the amplitude $\eta(t)$ of the fundamental acoustic mode has the exponential time dependence,

$$\eta(t) \sim e^{\alpha t} \tag{2}$$

Thus if α is positive, the amplitude grows, i.e., the mode is unstable.

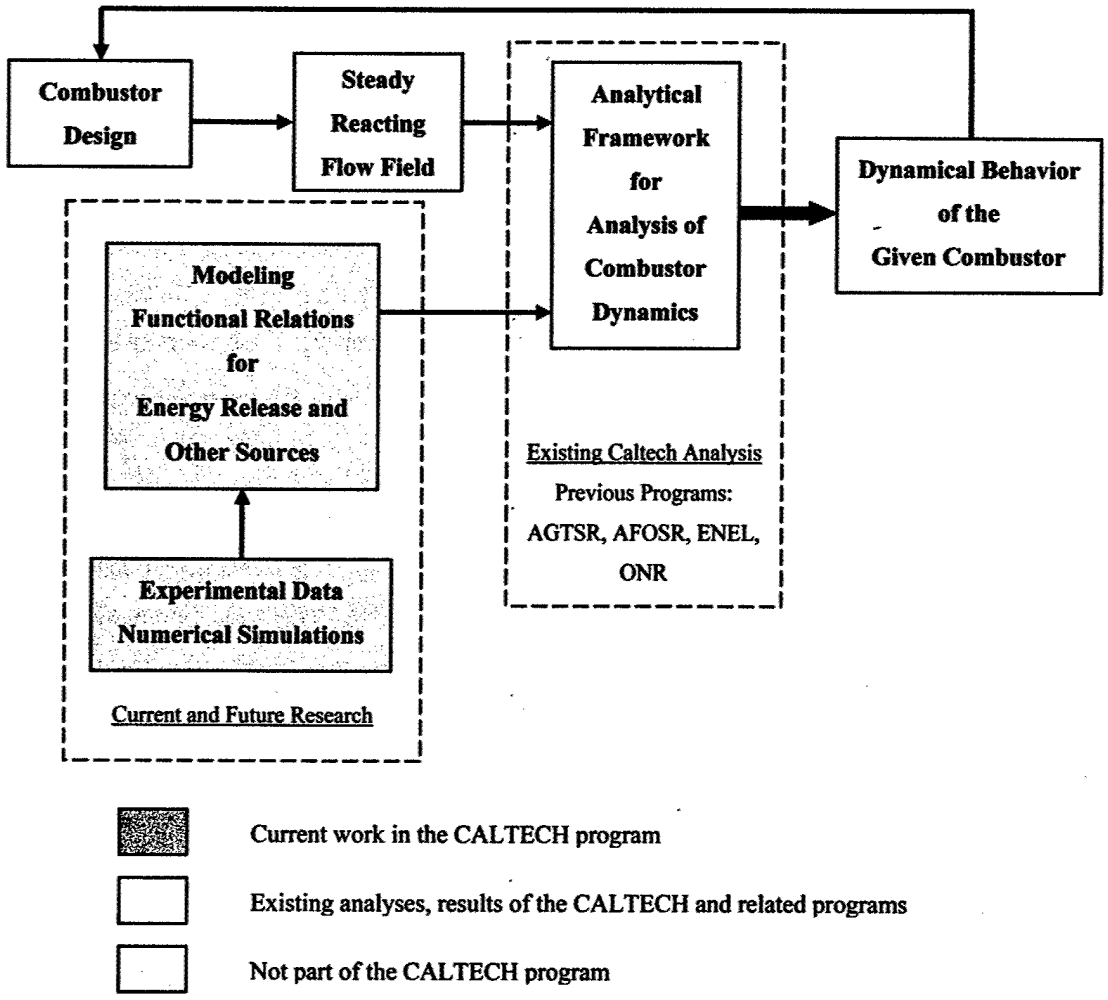


Figure 1. Idealized Flow of Information.

The analysis shows also that the growth (or decay) constant is proportional to the real part of the combustion response to pressure fluctuation,

$$\alpha \sim R_p^{(r)} \tag{3}$$

where the complete complex response function is proportional to the ratio of the fluctuation of energy release to the local fluctuation of pressure,

$$R_p^{(r)} \sim \frac{\dot{Q}_r'}{p'} \tag{4}$$

That R_p is complex means that in general an oscillation of energy release has a phase lead or lag relative to the pressure oscillation. According to (3) and (4), if the energy fluctuation has a part in phase

with p (so $\dot{Q}'_r$ is positive) $R_p^{(r)}$ and therefore α are positive. Hence (2) shows that the amplitude of the mode grows in time and is unstable. That $\dot{Q}'_r$ appears both here and in the formula (1) for Rayleigh's criterion suggests (what is true) the equivalence of Rayleigh's criterion and the principle of linear stability (Culick 1987, 1992, 2001, 2004).

The preceding is the simplest reasoning to show the fundamental role of energy fluctuations in causing combustion instabilities. Extension of the reasoning (see Appendix C) shows that the fluctuations are fundamental as well to applications of active control of combustion systems.

In the context of the dynamics of combustion systems, notably combustion instabilities and active control, fundamental combustion dynamics occupies a central position. Knowledge of the combustion response function is essential to understanding and modifying the dynamical behavior of a combustor. Several combustion response functions exist, representing the fluctuations of the rate at which energy is released in chemical reactions in response to changes of pressure, velocity, temperature, and mixture ratio. For use in applications to active feedback control, those response functions are interpreted as transfer functions.

Response or transfer functions must be modeled in some way to carry out analysis of the dynamical behavior of a combustion system and to do a prior design of active control. Currently, in the absence of theoretical and experimental information, simple *ad hoc* models are used in all applications. **The main purpose of the research described here is to continue developing, extending and improving methods for inferring response functions by using data obtained with laser-based diagnostics, principally PLIF and, eventually PIV.** Roughly, the strategy is the following.

The basis for the method generally is that the chemical process of producing energy is accompanied by generation of short-lived species. For combustion of hydrocarbon fuels, the radicals OH and CH are especially significant because many previous works have established that to good approximation the rate $\dot{Q}_r$ at which energy is released by the combustion processes locally is proportional to the concentrations of those species. How good the approximation is depends on, among other factors, the local macroscopic flow and mixing rates, and the collisional destruction of the radicals.

Hence, to some (often good) approximation, measurement of the concentrations of OH and CH can be related to the rate of energy production. This conclusion holds true under unsteady conditions, to some approximation, if the characteristic time of the unsteadiness (here the period of impressed oscillations) is long compared to the measurement time, which in turn is short compared with the time in which the concentrations change significantly.

The first purpose of this research is to impress oscillations of pressure and measure the fluctuations of one of the radicals in question, OH being the simplest to observe. Then by assumption, the average and

fluctuating heat release ratios ($\overline{\dot{Q}}$ and $\dot{Q}'$) are proportional to the average and fluctuating values of the OH concentration (denoted $\overline{[OH]}$ and $[OH]'$, respectively). So by assumption,

$$\overline{\dot{Q}} = \overline{K}\,\overline{[OH]}$$
$$\dot{Q}' = K'[OH]' \qquad (5)\ a,b$$

If $\overline{K}$ and K' have the same values, then we can write,

$$\frac{\dot{Q}'}{\overline{\dot{Q}}} = \frac{[OH]'}{\overline{[OH]}} \qquad (6)$$

As in (4) above, a response function R_p is conveniently defined as fluctuation of the heat release rate to the value of the impressed pressure fluctuation,

$$R_p = \frac{\dot{Q}'}{p'} \quad \text{or in dimensionless form} \quad R_p = \frac{\dot{Q}'/\overline{\dot{Q}}}{p'/\overline{p}} \qquad (7)$$

Hence with (6), R_p is expressed as a ratio of measurable quantities:

$$R_p = \frac{[OH]'/\overline{[OH]}}{p'/\overline{p}} \qquad (8)$$

where PLIF measurements give the numerator, and the denominator is obtained with pressure transducers. It is this ratio, R_p or $R_p^{(r)}$ which appears explicitly in analysis of the dynamics of combustion systems as described above.

2.2 Previous Work on Measuring Combustion Dynamics

Three methods have been used to gain data for combustion dynamics. In order of increasingly finer spatial resolution, they are:

(i) measurement of the transfer function for a combustion region by detecting transmission and reflection of acoustic waves (e.g., Culick 2001);
(ii) chemiluminescence, measuring radiation from certain species participating in a combustion zone exposed to pressure oscillations; and
(iii) planar laser-induced fluorescence, measuring radiation induced by pulses of laser output incident on a combustion zone exposed to pressure oscillations.

We are using both the second and third methods. In fact one unforeseen result has been to clarify the serious limitations of chemiluminescence.

Put briefly, the method based on chemiluminescence involves observation of 'natural' radiation by using either (1) a photomultiplier tube (PMT) with a slit obscuring all but a portion of the combustion zone, giving resolution in two dimensions; or (2) a CCD camera capable of giving resolution in two dimensions. The great disadvantage of this method is that the radiation collected is emitted along the entire line of sight in the direction defined by the orientation of the PMT or camera. Since radiation may also be absorbed, the final intensity at the observation point does not in general represent only the activity of species produced in chemical reactions. Consequently, as we have shown (Pun *et al.* 2001) seriously misleading results are often obtained. Nevertheless, the method was the first to provide results for combustion dynamics (see Table 1) and has given useful contribution to understanding combustion instabilities.

Chemiluminescence of the CH radical, an excellent marker for the reaction zone, has been used by a number of researchers to study heat release in an unsteady flame. They can be categorized into two groups; measurements using a PMT with a slit obscuring a portion of the flame to obtain some spatial (typically axial) resolution (Sterling 1991; Chen *et al.* 1993; and Kappei *et al.* 2000); and fully two-dimensional imaging using a CCD based camera (Broda *et al.* 1998; Kendrick *et al.* 1999; and Venkataraman *et al.* 1999). Of these works, only Chen *et al.* (1993) involved an acoustically forced flame, but used a PMT with a slit configuration that obtained only integrated one-dimensional information.

The first demonstration of 2D (planar) LIF of the hydroxyl radical in a flame was apparently performed by Dyer and Crosley (1982). This technique has been used to measure a variety of chemical species in unsteady reacting flows, including OH as a measure of the heat release (Cadou *et al.* 1991; and Shih *et al.* 1996), and NO seeded fuel to measure the temperature field (Cadou *et al.* 1998). A summary of these various works involving both chemiluminescence and PLIF is provided in Table 1, including the acoustic frequencies in the studies.

Most experimental work to characterize various combustor configurations has been done on naturally unstable systems (see Table 1). However, the results are specific to the combustors tested, and provide little insight to how a particular injector or burner design will behave in a different combustor. A study of the acoustic coupling between fuel injectors and an applied acoustic field has been carried out by Torger (1998), but only includes cold flow experiments. Work by Chen *et al.* (1993) with premixed flames was specifically designed to simulate solid rocket propellants. It contained one-dimensional spatial results and used only two forcing frequencies. The study by Cadou *et al.* (1998) was based on a specific 2D dump combustor configuration, and showed little response to non-resonant forcing. Durox et al. (2002) and Schuller et al. (2003) measured the flame response to forced acoustic oscillations of up to 400Hz, but the burner was placed open air, and the response function was based on the pressure and velocity

measurements though they measured the CH fluorescence without phase-resolution. A more generalized body of work is required to provide industry with guidelines that will be useful in designing stable combustion systems.

	Chemiluminescence	PLIF
Naturally Unsteady	• Sterling and Zukoski (1991) (188 Hz) • Broda *et al.* (1998) (1750 Hz) • Kendrick *et al.* (1999) (235 Hz, 355 Hz) • Venkataraman *et al.* (1999) (490 Hz) • Kappei *et al.* (2000) (370–460 Hz)	• Cadou *et al.* (1991) (43 Hz) • Shih *et al.* (1996) (400 Hz) • Cadou *et al.* (1998) (328 Hz)
Acoustic Forcing	• Chen *et al.* (1993) (300 Hz, 400 Hz) • Durox *et al.* (2002) (0–400 Hz) • Schuller et al. (2003) (0–400 Hz)	• Cadou *et al.* (1998) (360 Hz, 420 Hz)

Table 1. Previous work in oscillating flames.

In Section 4.1 we describe our apparatus for applying PLIF to an acoustically forced flame. Only Cadou (1998) previously used PLIF to investigate the dynamics of a forced combustion system. Our experiments began (with his help) essentially where Dr. Cadou finished. Otherwise, as Table 1 shows, in previous applications of PLIF, to unsteady flames, results were obtained only for naturally oscillating systems. Cadou forced his system at only two frequencies. Only by forcing over a range of frequencies can one obtain data for transfer functions and truly informative results for the combustion dynamics.

2.3 Work at Caltech on Measuring Combustion Dynamics

Before 1995, the work by the Principal Investigator and his students on dynamics of combustion systems was devoted almost entirely to theory and analysis, supported chiefly by AFOSR and ONR. In parallel, from about 1981 to 1994, in separate programs funded by AFOSR and ONR, continuous research had been devoted to instabilities in dump combustors; vortex shedding and associated periodic combustion was the primary mechanism. In 1996–1997, the PI and three students carried out a small project successfully showing that hysteresis in a region adjacent to the stability boundary could be used as the basis for nonlinear active control to extend stable operation over a broader range of mixture ratio (Isella, Seywert, Culick and Zukoski 1997).

Analytical work at Caltech on active control of combustion systems was supported by AFOSR, ONR, and, beginning in the mid-1990s, by the Department of Energy. Our emphasis was on the dynamics of combustors generally with attention paid to various classes of problems within that subject. For example, we have worked out the only analytical method for investigating active control of instabilities in the presence of noise (Seywert, Isella and Culick 2000). It became increasingly clear that for understanding

both the laboratory results and the behavior observed in full-scale systems, the real obstacle was understanding the fundamental mechanisms; namely the dynamical conversion of chemical energy to the mechanical energy of unsteady motions in flames and on the reacting flows. That understanding can come only from detailed experimental results taken for sufficiently large frequencies covering the range of actual behavior, at least to 1000 Hz.

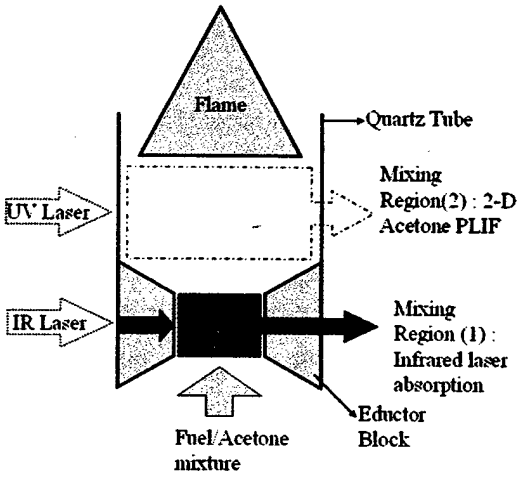


Figure 2. Regions of interest; mixing is measured with IR laser absorption method at region (1) at the neck of the eductor block, acetone PLIF at region (2) in the mixing zone.

Our experimental work in this area began in 1998 with a DURIP Grant from AFOSR, with additional funding from Caltech, DOE and ENEL, the Italian Power Company. Those funds allowed us to construct the PLIF system now in place, that produced the very promising results reported first in July 2000 and recently published (Pun, Palm and Culick, 2003). Following Culick's formulation (1987) of a theoretical basis for quantifying the stability margin inside the combustors by formulating Rayleigh's statements for acoustic waves and flame behavior (Rayleigh index), the coupled effects of acoustic forcing with combustion heat release on species concentration were examined by Pun et al. (2002, 2003) using OH-PLIF under atmospheric pressure. The behavior of the flame base was studied; the phase and magnitude were calculated to form a part of the flame response function over the low frequency region of 22 ~55Hz from the OH-PLIF and chemiluminescence images. Fernandez et al. (2003) used a fiber optic probe to measure point-wise fuel/air mixing in terms of 'unmixedness factor' under the same experimental conditions as in the work on previous flame measurements using the OH-PLIF technique. The fiber optic probe measurements did demonstrate that fuel/air mixing within the eductor block (see Figure 2) is heavily affected by the acoustic excitation. Unfortunately, a direct comparison of these two works is not possible because the technique using a fiber optic probe is time-, but not phase-, resolved.

In Figure 2, the flame region is marked as the triangle at the top section of the burner. Phase-resolved imaging of flame region using OH-PLIF (Pun, 2002, 2003) revealed the phase-dependent response of the combustion process under low frequency (22 ~ 55Hz) acoustic excitations. The current work and the previous imaging of flame region are closely related in that both works used the same experimental configuration. It would therefore be meaningful to compare the effects of acoustic forcing on energy release, the previous work by Pun (2003), with fuel/air mixing, the present work.

2.4 Study of Fuel/Air Mixing

This work is, to a large extent, a visualization of how mixing and fuel flow occur. Study of flame behavior only does not give sufficient knowledge of combustor performance and issues such as the formation of pollutants.

Investigations having intentions similar to those motivating the present work have been previously reported, beginning more than a decade ago. Work by Chen (1993) with premixed flames, that was designed specifically to simulate solid rocket propellants, contains only one-dimensional results, and used only two forcing frequencies. A study of the acoustic coupling between fuel injectors and an applied acoustic field has been carried out by Torger (1998), but only includes cold flow experiments. Cohen et al. (2001) studied the impact of degree of mixing on the performance of a combustor by modulating part of the fuel flow for use in active control. The acetone PLIF technique was used for measuring fuel/air mixing in that work.

Fric (1993) used NO2 laser induced fluorescence (LIF) and showed that temporal unmixedness, mixing, is related to higher pollutant (NOx) production. Gulati et al. (1994) used same NO2-LIF to study mixing without combustion under high pressure (up to 10 atm) for the purpose of calibration. Those studies employed an argon ion laser to induce fluorescence (LIF) in NO2, which had been doped into the flow as a fuel marker. The drawback of this technique is that NO2 is toxic and its transport properties are not identical to the methane it was being used to study.

Shih et al. (1996) carried out studies to assess the importance of reactant unmixedness on combustion stability, and found that instabilities occur in certain ranges of equivalence ratio near stoichiometric operating conditions. They suggested that the fluctuating fuel distribution under incompletely mixed conditions could significantly contribute to the heat release fluctuations that drive unstable combustion. For our work, the results reported by Shih et al. (1996) formed the starting point in that the non-premixed flow field with fluctuations in mixing caused by the acoustic field may be highly susceptible to the fluctuating and even unstable combustion.

Motivated by Shih et al. (1996)'s observations, Lieuwen et al. (1998) performed a theoretical modeling to study the potential causes of frequently observed combustion instabilities in low NOx gas turbines (LNGT) which are lean-premixed combustors, motivated by the fact that such systems are highly sensitive to equivalence ratio perturbations. Temperature, inlet flow rate, and equivalence ratio (unmixedness) were perturbed. This work showed that lean systems may be prone to combustion instabilities because the magnitude of the heat release oscillations produced by unmixedness dramatically increases as the mean equivalence ratio decreases.

Mongia (1998) and Hase et al. (1996) combined positive aspects of the previous techniques to develop and demonstrate continuous measurement of methane concentrations. The measurement is performed with methane absorption of a 3.39 micron wavelength He-Ne laser beam. The continuous nature of the measurement allows for sampling rates of several kilohertz with no additional chemical markers. Both of these studies developed probes, with Mongia's probe employing fiber optics as the medium for the signal transmission. This is one of the techniques used in this study for point-wise measurements using a replica of Mongia's probe.

The imaging reported here used planar laser induced fluorescence (PLIF) of acetone. The acetone was used as a fuel marker to visualize the fuel/air mixing region directly beneath the flame, as illustrated in Figure 2. Acetone is seeded into the fuel stream and then imaged to show the distribution of fuel in the flow prior to combustion. This technique enables us to see the two-dimensional distribution of fuel, and consequently, compute the degree of fuel/air mixing prior to combustion in the flame.

Acetone PLIF has been previously used for various purposes. Thurber et al. (1997, 2001) used this technique to determine temperature. Many of the other studies (Thurber et al., 1997, 2001, Meyer et al., 2002, Demayo et al., 2003, Yip et al., 1994) focused on measurement of fuel concentration using the acetone-PLIF where the acetone had been similarly introduced as a fuel marker. In the present work, acetone is seeded into the fuel stream with a three-way valve system shown in Figure 9. The fuel/acetone mixture is intended to be homogeneously mixed, and the distribution of acetone in the fuel/acetone-air mixture is expected to be 'marking' the fuel distribution in the fuel-air mixture stream.

For most of these studies, following the method introduced by Demayo et al. (2003), a single image was taken as a representative of the system, and then the unmixedness was calculated based on this. In effect, the two-dimensional image was collapsed to a single unmixedness value. In this work, 2-D maps of unmixedness factor (equation 10) at each point of the image are calculated, as well as the global unmixedness values as defined by equation (9). The phase and frequency dependence of global unmixedness is to be observed.

The global unmixedness is defined as

$$U_g = \frac{\sigma_g^{\,2}}{(1-\langle x \rangle_g)\cdot(\langle x \rangle_g)}, \tag{9}$$

where σ_g is the standard deviation and $\langle x \rangle_g$ average of fuel concentration over the entire 2-D image, instead of one point with many measurements. The unmixedness is a normalization (Dimotakis et al. 1990) of the variance σ_g^2 by the maximum possible value for the given $\langle x \rangle_g$, evaluated by the variance of Housdorf relation, $\sigma_{max}^2 = \langle x \rangle \cdot (1-\langle x \rangle)$. When the fuel is completely mixed and homogeneously distributed, U is zero; when no mixing occurs, U is unity. A two-dimensional image collapses to a single

value by this definition, which gives a quantitative measure of the magnitude of the variation of fuel/air mixing, the degree of fluctuation in fuel concentration over the entire region.

The local temporal unmixedness is defined as in the work by Fric (1993),

$$U_t = \frac{\sigma_t^2}{(1 - \langle x \rangle_t) \cdot (\langle x \rangle_t)}, \tag{10}$$

where σ_t is the standard deviation of the fuel concentrations drawn from repetitive measurements at the specific location, and $\langle x \rangle_t$ is the average of fuel concentration at that location. In respect to temporal unmixedness (U), higher values of U mean greater fluctuations in the fuel concentration. Thus, where U is larger can be interpreted as a region where more mixing occurs than in locations with lower values of unmixedness values. It is therefore expected that the high unmixedness region becomes wider down stream with the flow, or upwards in Figure 2.

3 Experimental Methods

The methodology adopted in the described here is based on making fundamental measurements with results that can be related to practical issues. This approach produces results that are broadly applicable and not as dependent on the peculiarities of a specific experiment. The configurations used were a horizontal electric Rijke tube and vertical, externally driven Rijke tubes (also referred to as acoustic chambers). While the horizontal tube provides clear separation of the parameters defining the air flow and heating, acoustics of the vertical tubes provide a separation of the burner and flame from the chamber natural modes. Our results for the horizontal Rijke tube were reported in a previous AFOSR Final Report (Culick 2003) and in references cited there.

3.1 Acoustic Chamber

The experiments performed in the acoustic chambers (vertical tubes) are all focused on measuring the flame transfer function. Since the flame is dependent on multiple parameters (local pressure, local pressure time derivative, velocity field [local strain rate], local temperature, local fuel mixture fraction, and even local flow reaction history), the experiments have assessed the transfer function between external pressure and local heat release, nitric oxide (NO) production, and fuel mixture fraction oscillations. The experiments involving NO production also demonstrated the lack of data concerning the accuracy and reliability of laser-induced fluorescence (LIF) measurement of NO concentrations for even

moderately rich flames. A set of experiments were hence performed to assess NO LIF behavior in rich flames and associated computational models for NO concentration in such environments.

The first two experiments utilized the same burner, chamber, and data acquisition configuration. The first experiment involved planar LIF (PLIF) imaging of the hydroxyl radical (OH) as a marker for heat release. The technique employed examines the *variation* in OH concentration. The incremental change in OH concentration is closely tied to changes in local temperature which (for similar flame conditions) is directly tied to changes in the heat release rate. For small variations in OH concentration (~10%), the correlation to heat release rate is very good. The other important technical insight involves measurement and use of Raleigh index. A local Raleigh index is calculated at each point in the flow field, based on the local heat release rate and the known pressure variation. The pressure variation is designed to be spatially uniform, temporally oscillating (externally driven and verified by measurement near the flame zone). Raleigh index allows for the calculation of a general flame transfer function that is not chamber dependent.

The second experiment was very similar except for the measurement of NO vs. OH concentration. For NO, the correlation is direct and the results are reliable for any size of variation. The major errors for the NO transfer function are in the initial NO concentration measurements. This led to the set of experiments characterizing NO line shape behavior for typical rich flames. These experiments utilized NO PLIF techniques to acquire NO LIF type data. This is a benefit because careful measurement of flame, laser, and flow chemical conditions can be performed as data is acquired.

The last two experiments focused on the three-way coupling between pressure oscillation, fuel mixture fraction oscillation, and flame oscillation. This type of coupling makes it harder to define global transfer functions, so the initial focus has been to characterize the coupling between pressure oscillation and fuel mixing. This has been done two different ways. One experiment employed a fiber optic probe to perform infrared laser absorption. The laser frequency was chosen such that it was only significantly absorbed by the fuel (methane). This probe method has the benefit of high temporal resolution (several kilohertz) and does not require a secondary fuel marker. The method yields data that accurately characterizes the local fuel oscillations across a wide spectrum. The second method provides images, but with poor absolute accuracy for fuel concentration. The second method uses acetone added to the fuel as a marker. Acetone PLIF is then performed and fuel concentration inferred from the acetone density. The structures seen in the acetone images are then correlated with the patterns found in the probe data. This method provides significantly better results than either method alone.

3.2 The Acetone Planar Laser Induced Fluorescence

3.2.1. Why Acetone-PLIF

Acetone PLIF is a widely used technique for measuring distributions of species concentrations (acetone) (Lozano et al., 1992, Ritchie et al., 2001); temperature (Thurber et al., 1997, 1998); and flow visualization (Bryant et al., 2000). The experimental arrangement is the same as PLIF for measuring species concentrations, but usually it is simpler to perform than other methods. The attractive properties of acetone PLIF are that it 1) is non-intrusive; 2) is instantaneous with a life time of 4 ns; 3) is very effective in molecular-marking flows of fuel or air with little possibility of affecting the flow significantly; and 4) allows high spatial and temporal resolution with high signal to noise ratio in general. Acetone has a high vapor pressure, so it is easy to seed into any kind of gaseous stream. Moreover, acetone is also cheap and relatively safe to use compared to other fluorescing molecules.

This method is particularly useful for studying fluid mixing behavior in flow systems by examining the behavior of acetone molecules as the tracer molecules. Acetone is a very strong absorber and emitter over a broadband of wavelengths, which allows measurement of low concentration levels. For a given temperature and pressure, acetone fluorescence is linear with acetone concentration (many molecules are not linear with concentration).

The first research works for acetone vapor luminescence date back to as early as 1933, with the work by Damon and Daniels (1933) who observed a strong green emission. Later Matheson and Zabor (1939) argued that the green emission was from the biacetyl, CH3-(CO)2-CH3, which forms from acetone photolysis. Epstein (1974) proposed its use as a tracer in fluid mechanics experiments, subsequently acetone PLIF has been successfully applied to non-reacting and reacting gaseous flows (Kychakoff, 1982) to measure species concentration (Dyer, 1982); temperature (Seitzman, 1985 and Lee, 1987); and pressure and velocity (Hiller and Hanson, '98) (Lozano et al., 1992).

3.2.2. Characteristics of Acetone-PLIF

Acetone (CH3-CO-CH3)'s molecular weight is 58.08 with melting point at –95°C, and boiling point at 56°C, ignition temperature around 465°C depending on the mole fraction. Figure 3 shows the temperature dependence of the saturation vapor pressure of acetone. The equation (11) fits the vapor pressure well:

$$\log_{10} P(torr) = 7.125267 - \frac{1214.208}{230.002 + T(C)}, \qquad (11)$$

Acetone PLIF uses a UV laser sheet to excite the acetone molecules to the first excited singlet state (S1). Acetone is a broadband absorber in the UV (225–320 nm, see Figure 4). Acetone molecules absorb relatively strongly, so many molecules are raised to the first excited singlet state, S1. This is the principal process. About 98% of excited state acetone molecules return to the ground state without any emission of radiation or fluorescence. About 1.8 % of the excited state molecules are excited to the first triplet state, T1, which requires spin changes. This state is lower in energy level than the first excited singlet state, S1, and relaxes back to the ground state either by collisional quenching or by phosphorescence. The remaining 0.2%, for vapor, relaxes through fluorescence. As shown in Figure 4, acetone is a broadband absorber in the UV. The phosphorescence is very strongly quenched by oxygen, so phosphorescence is negligible in experiments performed in the presence of oxygen.

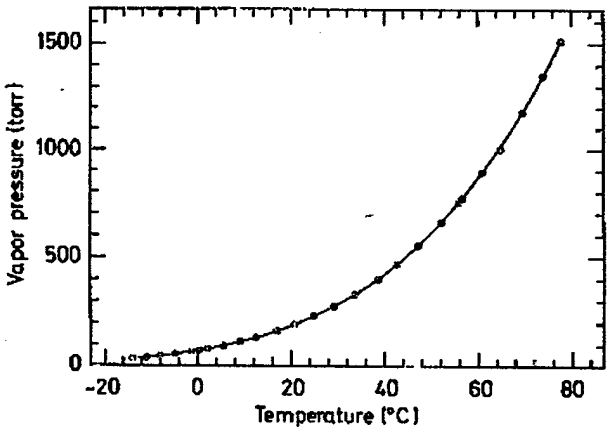


Figure 3. Acetone vapor pressure as a function of temperature (Lozano, 1992)

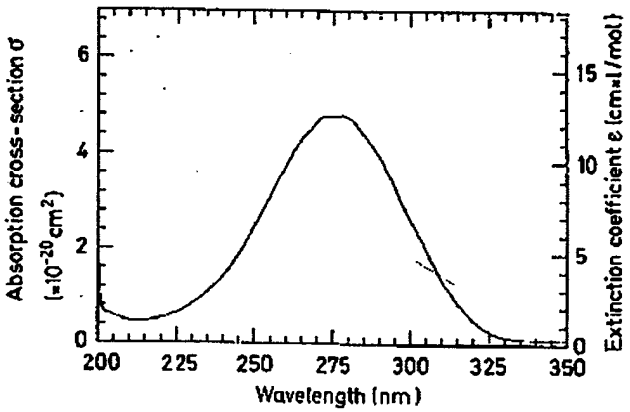


Figure 4. Acetone absorption spectrum corresponding to excitation from the ground state to the first excited singlet (Lozano, 1992).

The primary dissociation process is given by

$$CH_3COCH_3 + h\nu \rightarrow CH_3CO + CH_3, \qquad (12)$$

The free acetyl radical can recombine with another one to form a biacetyl molecule. This is responsible for the green biacetyl phosphorescence emission observed in some static cell acetone experiments (Lozano et al., 1992) but it is negligible in the experiments reported. It occurs only for temperatures below 100°C, and originates from acetone triplets. For excitation wavelengths shorter than 312 nm (our current apparatus operates at 280 nm), dissociation occurs via the alternative path

$$CH_3COCH_3 + h\nu \rightarrow 2CH_3 + CO, \tag{13}$$

The efficiency of fluorescence of the biacetyl molecules is very low when the excitation wavelength is less than 320 nm (ours, 280 nm), and the phosphorescence is quenched by oxygen, as mentioned above, almost entirely. Moreover, the phosphorescence from the biacetyl molecules takes too much time (life time of about 200μs), while acetone fluorescence takes only about 4 ns. Hence it is suitable only for very slow flows. Especially at the 280 nm excitation, current setting, it has shown that the fluorescence life time is around 1.7±0.3 ns (Lozano et al., 1992).

One of the very attractive features of acetone PLIF is that the relative fluorescence signal can be directly interpreted as the relative mole fraction of acetone. The strength of the fluorescence signal, the vapor pressure of the species, and the excitation laser strength are in linear relationships (equation (14)). Figure 5 shows the linearity of the acetone fluorescence with respect to the incident laser energy intensity.

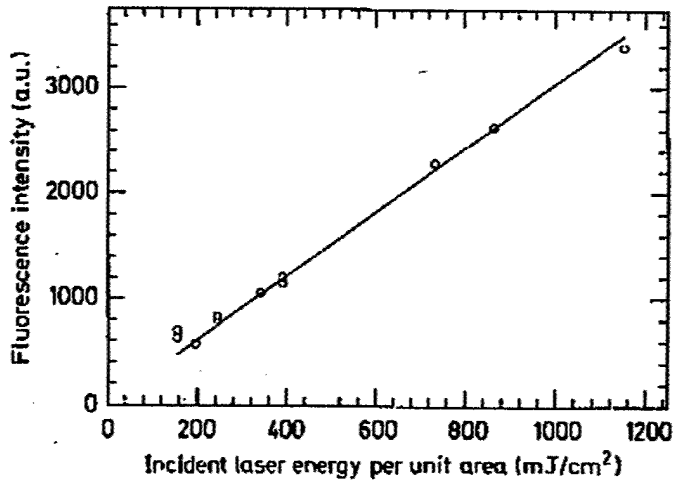


Figure 5. Relation between fluorescence signal and the intensity of laser excitation (Lozano et al., 1992).

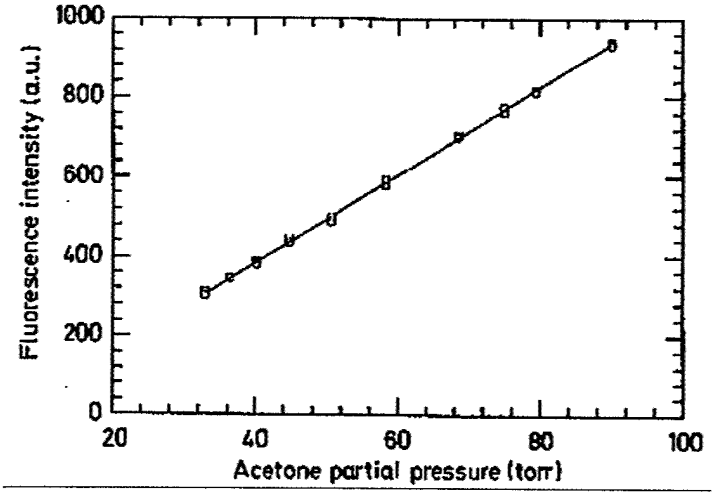


Figure 6. Relation between acetone partial pressure and the fluorescence signal (Lozano et al., 1992).

$$\begin{aligned} S_f(\lambda,T) &\propto E \cdot n_{abs}(T), \\ n_{abs}(T) &\propto p_{vap,acetone} \end{aligned} \tag{14}$$

Figure 6 shows the linearity between the acetone partial pressure and the fluorescence intensity. Collisional quenching rates vary with temperature and local gas composition, thus complicating the

interpretation of PLIF signals when such quenching is significant. However for acetone PLIF, the collisional quenching is negligible at least under atmospheric pressure, and the quantum yield is independent of molecular collisions, and therefore independent of temperature and local gas composition. Hence for the concentration measurements, the signal from acetone fluorescence is very easy to handle.

There are several other species used as tracer molecules, each having different characteristics. As shown in Table 2, for example, acetone absorbs around 225 ~ 320 nm, and emits at 350 ~550 nm, peaking at 435 nm with a duration of 4 ns. Here B.P. means boiling point; σ, the molecular absorption cross section; and ϕ, the fluorescence efficiency (the quantum yield).

	B.P.	Absorption	σ_{max} ($\times 10^{-20}$ cm^2)	ϕ_f	Emission (nm)	τ_f	$N\sigma\phi C$
Acetone	56 °C	225–320 nm	4.7 (275 nm)	0.2%	350–550 (435)	4 ns	7.2×10^{13}
Biacetyl	88 °C	340–470 nm	8 (417 nm)	0.25%	420–520 (485)	15 ns	7.0×10^{12}
Acetaldehyde	21 °C	250–340 nm	4.6 (290 nm)	0.15%	350–480 (420)	4 ns	1.0×10^{14}
Hexafluoroacetone	−26 °C	245–355 nm	3.1 (302 nm)	1.85%	410–580 (430)	84 ns	1.2×10^{15}

Table 2. Comparison of various tracer molecules (Lozano et al., 1992).

Temperature measurement is another important use of acetone PLIF (Thurber et al., 1997, 1998). The fluorescence signal of acetone is dependent on the temperature of the flow field, as given by (15).

$$S_f(\lambda,T) = \eta_{opt}\frac{\Omega}{4\pi}\frac{E}{hc/\lambda}dV_c n_{abs}(T)\sigma(\lambda,T)\phi(\lambda,T) \tag{15}$$

where η_{opt} is the transmission efficiency of the collection optics; $\Omega/4\pi$ is the fractional solid angle of collection; E is the incident laser intensity (joules per square centimeter); hc/λ is the energy of a photon at the excitation wavelength λ; n_{abs} is the number density and dV_c is the collection volume in cubic centimeters. For a given pressure and other parameters, we have the reduced form (16).

$$S_f^{+}(\lambda,T) \propto \frac{p}{T}\sigma(\lambda,T)\phi(\lambda,T) \tag{16}$$

where σ, the molecular absorption cross section; and φ, the fluorescence quantum yield, are the temperature dependent parameters. Then for a given pressure p and wavelength λ, $S_f(T)/S_f(300K)$ can be calculated and plotted. This can be done over a range of temperatures so that the relative values can be mapped and used to evaluate the temperature distribution.

3.2.3. Experimental Conditions and Settings

Figure 7 is a simplified layout for acetone PLIF imaging. An intensified CCD camera is used for image acquisition, while a National Instrument data acquisition board (NI PCI 6014) along with pressure transducer (PCB 106B50) is used to measure and record the pressure and other signals. PLIF imaging of acetone is performed in the bottom portion of the quartz tube where no flame is present, as shown in Figure 2. All timing is linked to the ND:YAG pump laser. The ND:YAG provides a high power laser beam at 532 nm which then drives a dye laser. The dye laser tunes the pumping beam to 560 nm which, in turn, is frequency doubled to 280 nm for the excitation of acetone. The laser power for this experiment is 8.4 mJ/pulse, which is approximately 0.373 mJ/pulse/cm^2 of intensity.

The PLIF signal is captured by an intensified CCD camera with a maximum size of 512 by 512 pixels. An area of 5.5 by 4.1 cm is imaged with size of 300 by 225 pixels. The PLIF signal goes through a UV high-pass filter which filters out the scattered beam with wavelength 300 nm or lower before the signal is imaged. Fluorescence occurs between 350 and 550 nm in wavelength. Images are taken at random phase, then the camera gating signal is taken by the data acquisition system along with the pressure signal that they are matched to give the phase information for each image. These images are tagged with their phase information and then distributed into each phase bin for the post-processing.

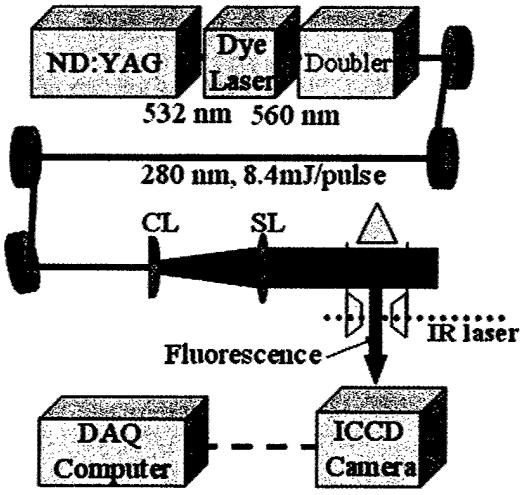


Figure 7. Schematics of the acetone PLIF.

The phase dependence of the mixing process is evaluated by collecting images at random phase values for each frequency. These images are then sorted by phase, with phase defined as a best-fit sinusoid of the acoustic oscillation (as measured by the pressure transducer). Fuel/air mixture behavior is assumed to vary only with phase and spatial location, which enables averaging of images in each portion of phase (10° degree-spaced bins for this study). The phase-averaged images can then be compared to assess phase-dependent behavior. This is similar to the technique employed by Pun (2002, 2003) in the studies of OH PLIF.

4 Experimental Apparatus

4.1 The PLIF System

The PLIF system (Figure 8) is based on an Nd:YAG laser operating at 10 Hz, pumping a tunable dye laser, which in turn drives a mixer/doubler system. The Nd:YAG laser outputs 2 J/pulse at 1064 nm (IR) and is equipped with a secondary harmonic generation system to provide 1 J/pulse at 532 nm (green).

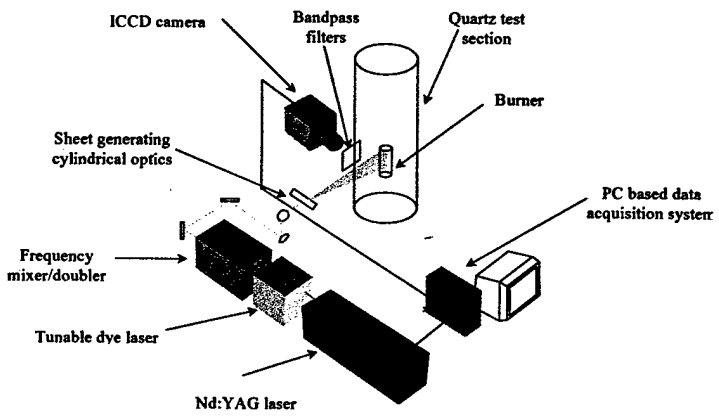


Figure 8. Schematic of the PLIF and CCD camera system, including a Nd:YAG laser, a tunable dye laser, and a frequency mixer/doubler.

The output of the Nd:YAG laser is used to pump a dye laser. The dye and laser excitation frequency are chosen based on the type of measurement to be performed. The output of the dye laser is then doubled to 280 nm (for acetone). The final laser beam is narrowed using a plano-concave cylindrical lens and spread into a sheet by a plano-convex cylindrical lens. Final laser power varies between 5 mJ/pulse at 226 nm to 40 mJ/pulse at 282 nm of energy entering the test section to stimulate the species of interest (resulting in saturated fluorescence for most conditions). The resulting signal is detected by intensified CCD camera with 512x512 pixels resolution.

4.2 The Acoustic Chamber

Figures 9 and 10 show the atmospheric pressure acoustic chamber and the elevated (5 ATM) pressure acoustic chamber, respectively. The acoustic driving system is located in the upper portion of each chamber. The upper portion is made of a large tubular stainless steel section, in the shape of a cross, approximately 30.5 cm in diameter and 71 cm in height. For the atmospheric pressure acoustic chamber, the exhaust section is open to the atmosphere which provides an acoustically open exit condition. For the 5 ATM chamber, the exit is acoustically closed, and the exhaust is cooled before being released through pressure-controlling blow-down valves. The acoustic drivers in the upper portion of each chamber are protected for thermal extremes by a pair of air jet film cooling rings (to prevent heat failure of the drivers). The bottom acoustic condition is a closed-end condition for both chambers. Air is supplied at the bottom of each chamber. The total height of both chambers is approximately 1.78 m.

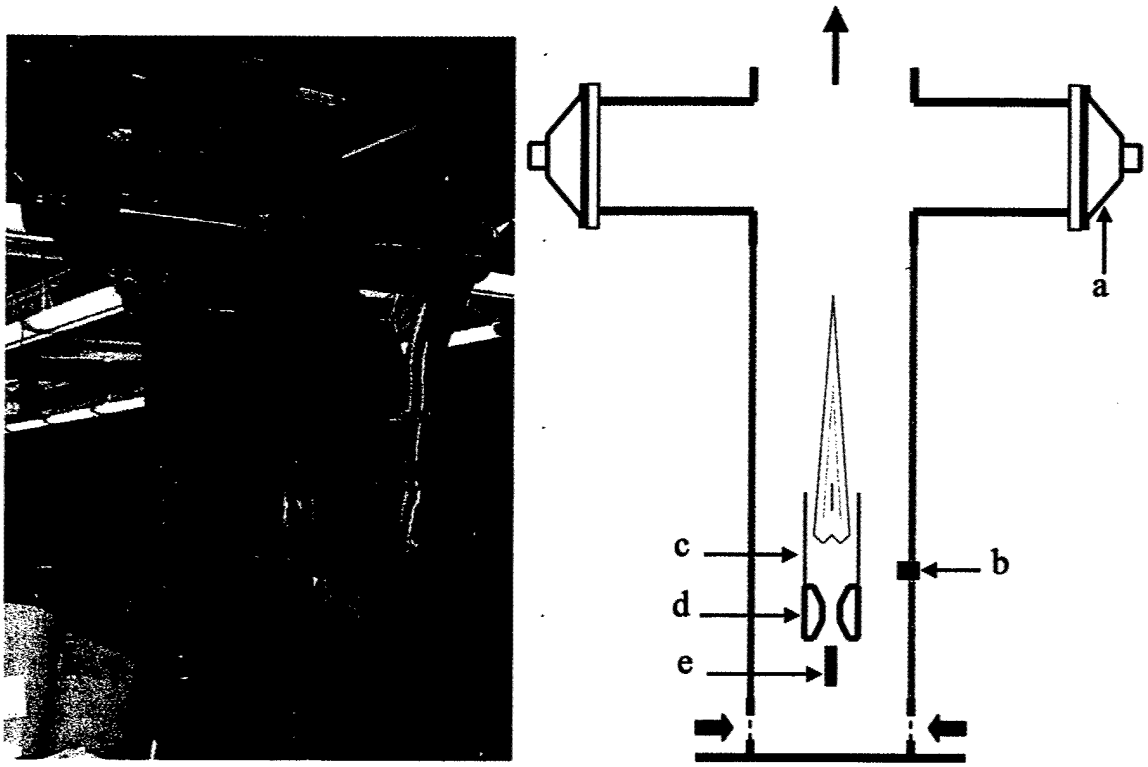


Figure 9. Photo (left) and schematic (right) of the atmospheric pressure acoustic chamber. The major components of the chamber are (a) acoustic driver, (b) pressure transducer, (c) fused-silica enclosure, (d) eductor block, and (e) fuel spud.

The acoustic drivers are 30.5 cm diameter subwoofers with a continuous power handling capacity of 400 W in the atmospheric chamber and 500W for the higher pressure chamber. The elevated pressure chamber employs 4 speakers (rather than 2) since the system is sealed and half of all speaker power is dissipated outside the main cavity. Both chambers have a power amplifier and a function generator that provide the power and signal to the acoustic drivers. The amplitude of the fundamental driving mode is actively controlled by custom-designed electronics, which measure the pressure in the acoustic chamber at the burner with a pressure

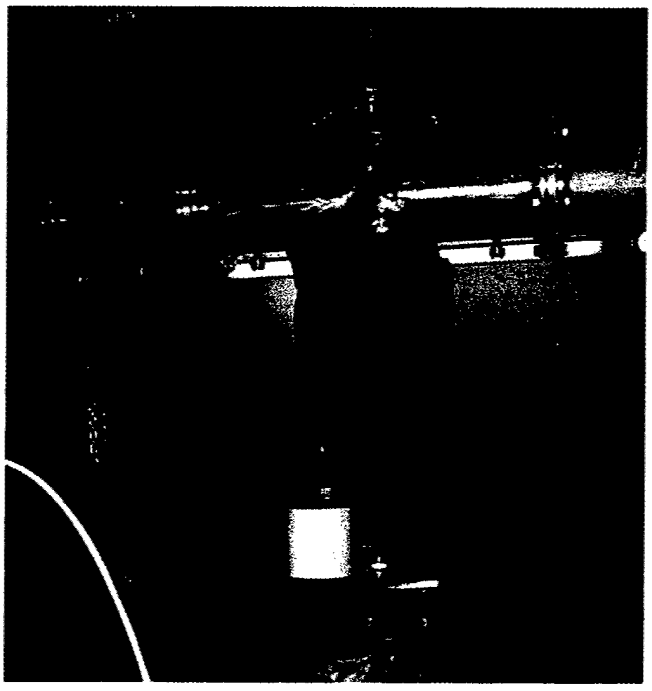


Figure 10. 5 ATM acoustic chamber. Lower portion of chamber covered with black cloth to reduce laser scatter. Chamber is symmetric across the vertical axis. A portion of the chamber is cut off in this picture (right edge).

transducer, and appropriately scale the power output of the speakers. The piezoelectric pressure transducer is located at a height of 7.62 cm above the fuel spud, where the flame is stabilized in the burner. The signal from the transducer is notch-filtered to ensure the intended driving mode is correctly amplified or attenuated.

The burner used in these experiments consists of a fuel jet, an eductor block, and a flame enclosure (Figure 9). The fuel jet entrains air and partially premixes as it passes through the eductor. The flame is stabilized in the low velocity zone created as the flow exits the eductor, and expands into the fused-silica enclosure. The fuel jet is 0.428 cm in diameter and is located 2 cm below the eductor block. The eductor is 4.5 cm in height, has a 3.6 cm throat diameter, and is made of high temperature ceramic. The square-profile fused-silica enclosure mounts on top of the ceramic eductor. The enclosure is 11.43 cm in height and 5.72 cm in length on each side. The fuel jet is 50% methane premixed with 50% N_2 gas to increase the mass flow and produce a permanently blue flame. The outlets for each gas are choked, in order to prevent disturbances from propagating upstream and affecting flow rates.

4.3 The Acetone Seeder

For the purpose of seeding acetone into the fuel stream, a three-way valve type seeder was devised as shown in Figure 11. Fuel stream is branched at the three way switch, one stream going straight in to the nozzle, while the other goes through a can (6 inches in diameter, and 15 inches in height) of acetone to form a plenum where acetone is saturated in the fuel flow. The cap is for refilling liquid acetone. The whole can shown in Figure 11 are submerged in a big water bucket to keep the temperature of acetone pool constant, which helps maintaining steady saturation pressure.

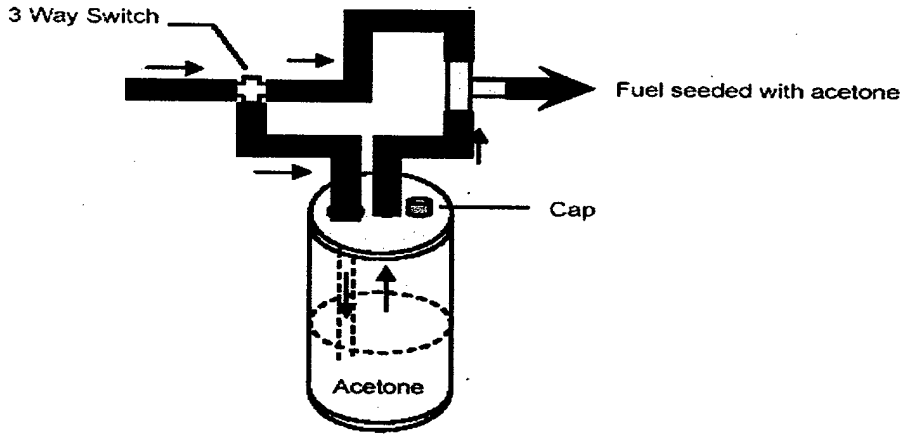
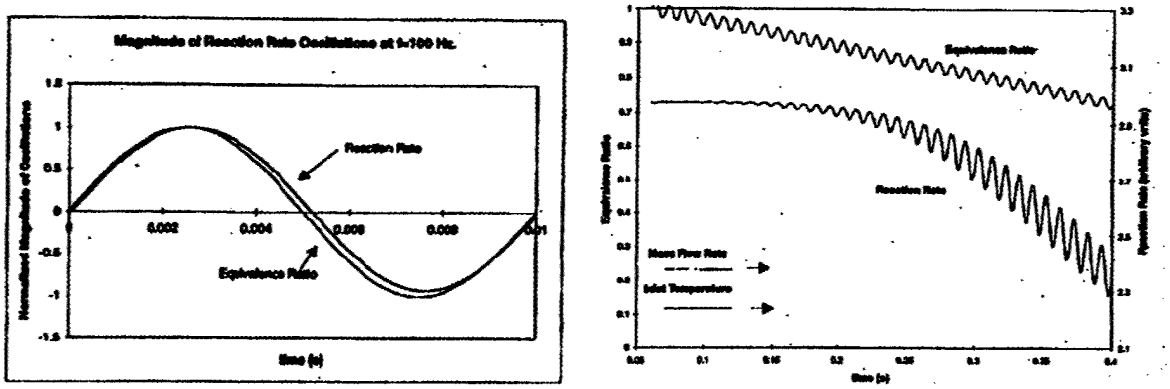


Figure 11. Acetone seeder

5 A Précis of Results

Lieuwen et al. (1998) showed that the magnitudes of reaction rate and heat release oscillations with the equivalence ratio perturbation were significantly (factor of 5–100) increased (Figure 12(b)), while the effect of temperature died out and that of flow rate perturbation was conserved without being amplified.



(a) (b)

Figure 12. Relationship between fluctuations of equivalence ratio (unmixedness) and heat release rate, 100Hz, (a); and response with time (b). Theoretical modeling by Lieuwen et al. (1998).

Mixing is a significant factor in causing unstable combustion according to this work, and our work here experimentally showed that the root of this phenomenon—the onset of unstable burning due to the oscillations in mixing—can be caused by acoustic oscillations inside combustors. In the current experiment, imposed acoustic field resulted in fluctuations in local equivalence ratio (unmixedness) in the mixing region. The temporal and global behaviors of mixing in terms of unmixedness factor are observed and presented here.

It has been shown by fiber optic probe measurements that high values of the temporal unmixedness occur in the shear mixing layer of the flow (30–60% from the center, see Figure 13, Fernandez et al, 2003). There is not much variation between cases with different excitation frequencies, but they show clear position-wise dependency. In Figures 14(a) and (b), lighter shading indicates a region with a higher value of unmixedness, thus marking a region of high fuel concentration fluctuation. Further downstream from the eductor block (Figure 14(a)), the shear mixing zone widens to 30–80% as expected. The low temporal unmixedness in the core region, of 0–30 % distance from the center, is due to the high, and relatively uniform, fuel concentration. Cross sectional views cut from Figure 14 at longitudinal distances of 1–3 cm are shown in Figures 15(a), (b).

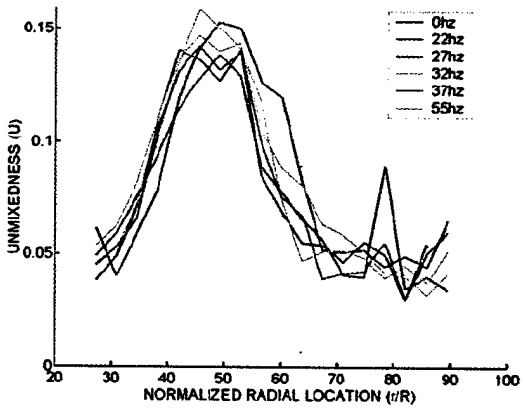


Figure 13. Temporal Unmixedness factor at the neck of the eductor block by fiber optic probe measurement, reacting flow (Fernandez et al., 2003).

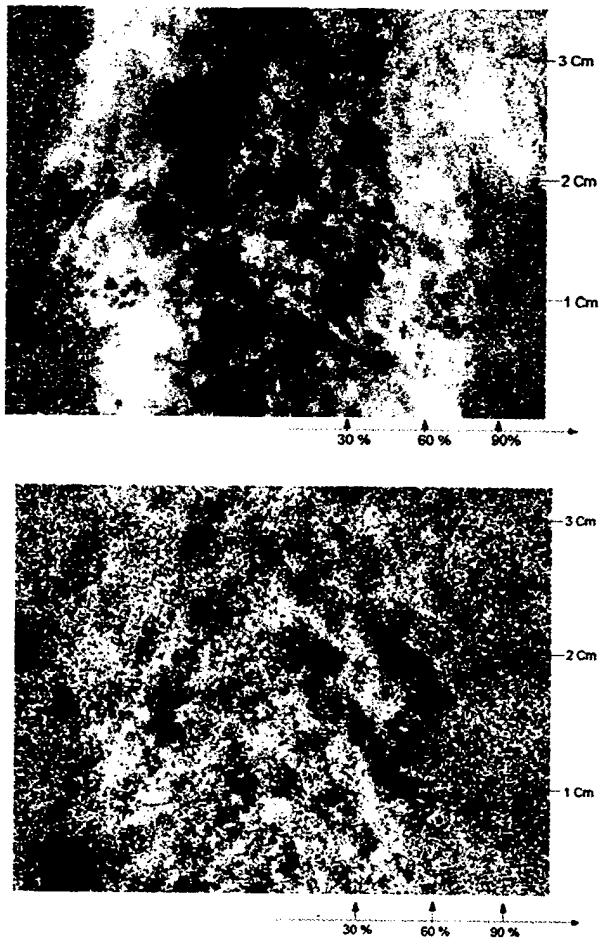
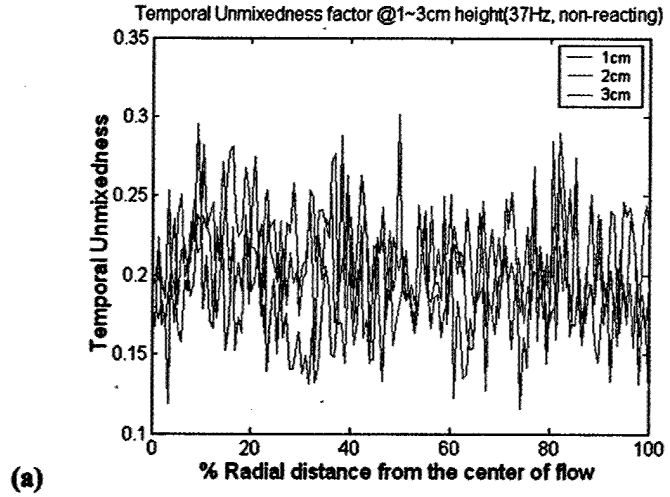
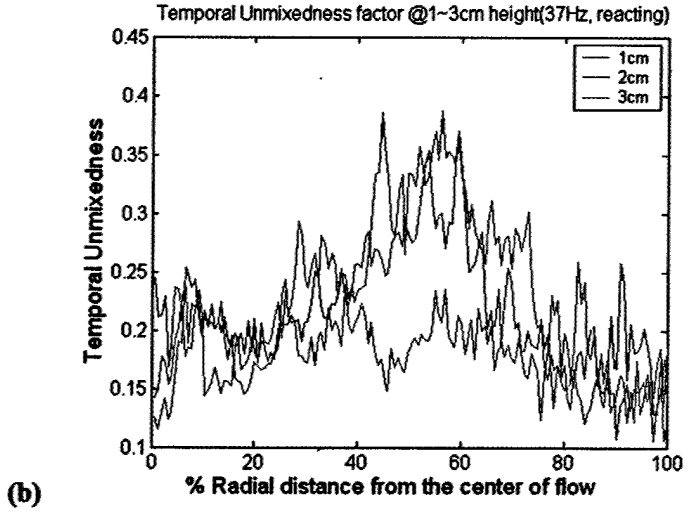


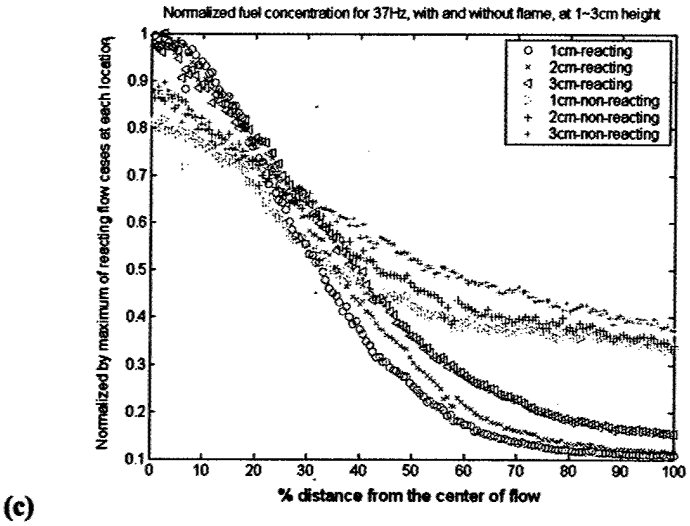
Figure 14. Two-dimensional maps (adjusted) from PLIF measurements at 37Hz, (a) reacting case and (b) non-reacting case.



(a)



(b)



(c)

Figure 15. Temporal Unmixedness factor at each location with excitation frequency 37 Hz for (a) non-reacting and (b) reacting flow at 1, 2, 3 cm above the eductor block, (c) the fuel concentration distribution.

The basic structure of the unmixedness distribution seems only to have been smeared (as expected for a mixing process, as in Figure 15(b)). Figure 15 shows that the temporal variation due only to the acoustic field is rather randomly or evenly distributed over the entire region (a), but in the reacting flow case, it has the structure similar to that in Figure 14. In the reacting case, due to the turbulent flow field generated by the heat release from the combustion processes, the unmixedness values in general are much higher than those in the cold flow as well as in the buoyancy driven flow structure in the reacting case. Qualitatively speaking, while the fuel/air mixing keeps the same structure of high unmixedness in the 30–80% region further downstream, the gradients are less stiff; meaning the degree of fluctuation in the fuel/air mixing is decreasing downstream. In the core region close to the center, the variation is very small as expected from previous results. This shows the core region is still fuel dominant and needs further mixing. Figure 15(a) is presented here for the non-reacting case. The low temporal unmixedness in the core region of 0–30 % distance from the center means that the temporal variation in fuel concentration is relatively low, but the fuel concentration is highest in that region. Figure 15(c) shows the actual fuel distribution in that region at the same condition normalized by the maximum.

Regarding the temporal mixing behavior (Figures 14, 15(a), and (b)), this is most likely a direct result of buoyancy. The reacting cases have a flow with significant post-reaction buoyancy, creating an enhanced vertical velocity component. This means that for the same vertical location, the reacting flow cases will resemble lower vertical locations (earlier times) in the non-reacting cases. This is evidenced by the fact that the non-reacting cases are mostly mixed by the time the flow reaches the imaging area while the reacting flows are still undergoing mixing (Figure 14). Direct comparison of mixing processes with and without combustion in this work is a rare observation.

Figure 16 shows that there is a very strong spike in the mixture fraction oscillations in response to an imposed acoustic field (Fernandez et al., 2003). This spike is not only narrow in frequency, but also matches the driving frequency as the frequency was varied from 22 to 55 Hz. The spike was between 2 and 3 orders of magnitude stronger than the natural, low frequency oscillations that are present. This clearly demonstrates that

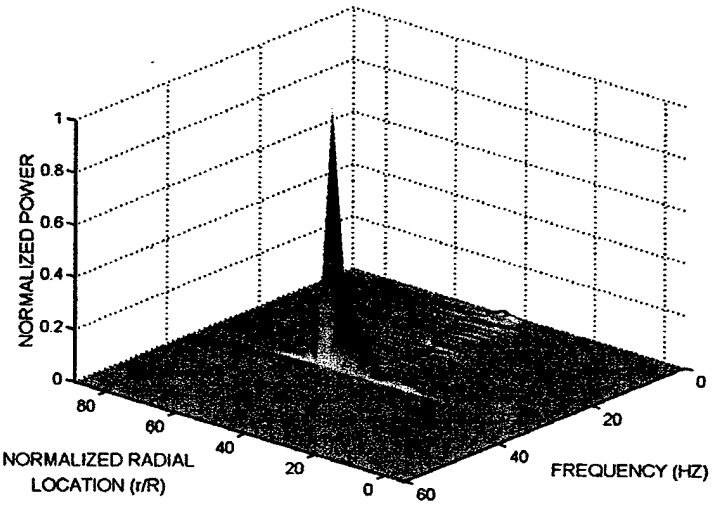


Figure 16. Power density spectrum for 32Hz, reacting flow (Fernandez et al., 2003).

the acoustic oscillations cause oscillations in the fuel mixture fraction in the pre-flame zone at each driving frequency and, that there is a strong complex coupling between flame oscillations, and the resulting acoustic field. Figure 16 is a plot of the power density spectrum; radial location versus the Fourier transforms of the time series data at each location vs. intensity of each frequency at each radial location. This particular plot is for a 32 Hz, reacting flow. Across the mixing layer (30% to 60% r/R distance), small ripples can be seen corresponding to the flow structures of various sizes occurring at different frequencies from the driving one. Of particular interest is the very strong peak at 32 Hz, the driving frequency for this case. Similar peaks are evident in all of the acoustically forced tests, corresponding in all cases to the driving frequency.

This result indicates that strong coupling occurs between the acoustic field and the mixing layer. Also, since no strong frequency preference is seen in the outer portion of the flow, it is most likely that the coupling is not a strong function of the vortex shedding from the fuel tube exit. Those vortices would be larger in size and could be expected to produce an effect in the outer flow. Since the oscillations are seen purely in the mixing layer, 30–60% distance from the center, it seems plausible that there is an instability or vortex roll-up mechanism that is pumped by the acoustic field.

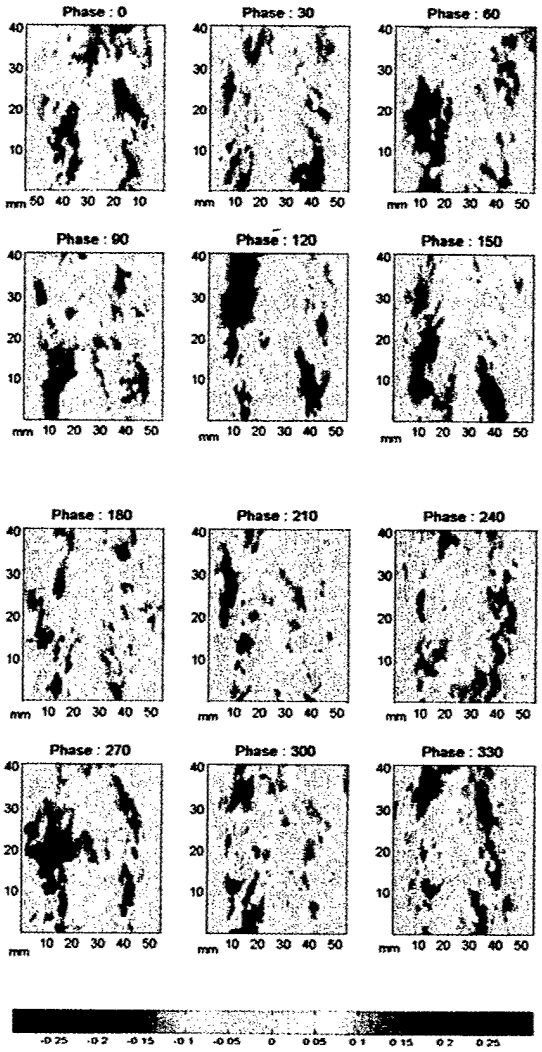


Figure 17. Distribution of fuel concentration by phase at 37 Hz, reacting flow. Contours show the difference from the average fuel distribution, normalized by the average value at each point.

The phase dependence of the mixing behavior is shown in Figures 17, 18, and 19. In Figure 17, higher valued contours indicate higher than average fuel concentration for that region (reds and yellows), while the low value contours indicate lower than average fuel concentration (dark and light blue).

The domain size is 55 x 42 mm. All the domains indicated are scaled to values from –0.3 to 0.3. The phase is that of excitation acoustic wave. For 37 Hz, the highest overall fuel concentration occurs at the pressure node (0, 180 degree), then decreases subsequently through 30(210) and 60(240) degrees until the pressure anti-nodes (90, 270 degree), and so on. This makes about 2 periods in 360 degrees.

In Figure 18, the phase-resolved unmixedness at each phase for 37Hz is shown. The curve was fitted with eighth order polynomial with (1 – σ) error bounds indicated in dots. As shown, the overall value of unmixedness is much higher for the reacting case, while the magnitude of unmixedness fluctuations is about the same. This is true for all other excitation frequencies as well, showing that the effect of the presence of flame is to cause less effective mixing and more uncertainty.

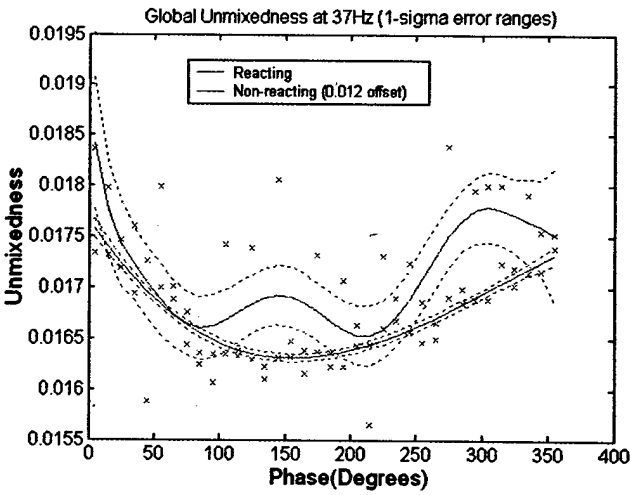


Figure 18. Behavior of mixing in term of global unmixedness at 37Hz of excitation with offset of 0.012 added to non-reacting case. Dotted lines indicate (1–σ) error bounds (68%).

The first mode of mixing fluctuation is shown by the 'Non-reacting' case in Figure 18; the second mode is fluctuations of unmixedness, superposed on the first mode. Here the first mode means the oscillation of unmixedness with one period in 360 degrees in excitation phase, higher modes meaning higher number of periods in 360 degrees that the oscillation is at frequency higher than the driving frequency. The same tendency is observed at other excitation frequencies. It seems that the frequency of the second mode is about two periods per 360 degrees, double the excitation frequency. In the latter part of the phase, in Figure 18, the fluctuation seems a bit smeared by higher modes which are hard to see clearly at the present phase resolution. The phase lead or lag is different for each frequency.

However, due to the limitation on the phase-resolution (10 degrees resolution, 36 data points), the FFT result only shows very dominant first mode but about 5% of the second mode (Figure 19). For both reacting and non-reacting cases, second mode and higher modes are clearly observed at integer multiples of the first mode (37 Hz).

The role of combustion processes in causing higher uncertainties in fuel/air mixing is observed from the comparison with

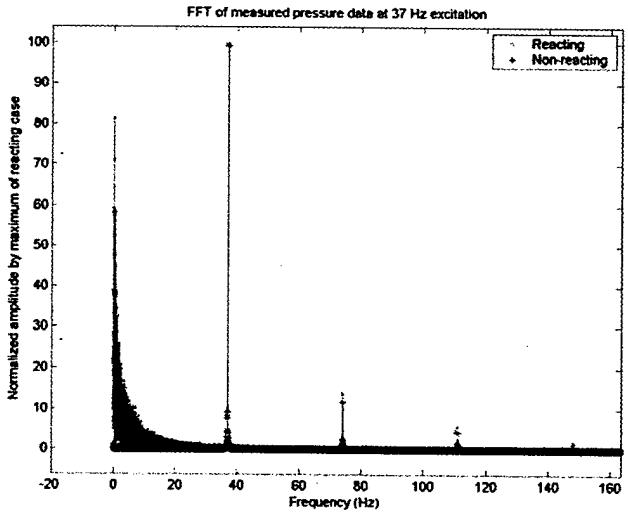


Figure 19. Fast Fourier transform results of measured pressure signal at 37 Hz of excitation.

the non-reacting case (blue, in Figure 18, 19), where the only difference is the presence of flame. Moreover, though all the experimental conditions are kept the same, a low frequency region with significant amplitude of pressure signal is seen for the reacting case only (Figure 19).

The global unmixedness is presented versus the excitation frequency and the phase during a cycle of excitation at each frequency in Figure 20(a). Greater values in global unmixedness factor, the degree of inhomogeneous mixing in the region, is observed in the presence of flame, and the mixing at higher frequencies (32 ~ 55Hz) is much more affected by the presence of the flame than at lower frequencies (22, 27Hz, Figure 20(a)). At 0 Hz of excitation the values of unmixedness are 0.0027 and 0.0075 for the non-reacting and reacting cases respectively. The combustion process alone causes huge differences in mixing, as in Figure 20, with increase in the unmixedness value up to a factor of 3 for the non-excited (0 Hz) case. The increase in unmixedness with frequency for the reacting flow case seems to be caused by the interaction between the combustion process and the acoustic excitation, and it seems more plausible when compared to the non-reacting case where the tendency is actually in the opposite direction. While the effect of combustion process has a great effect on the behavior of mixing, mixing is affected by the

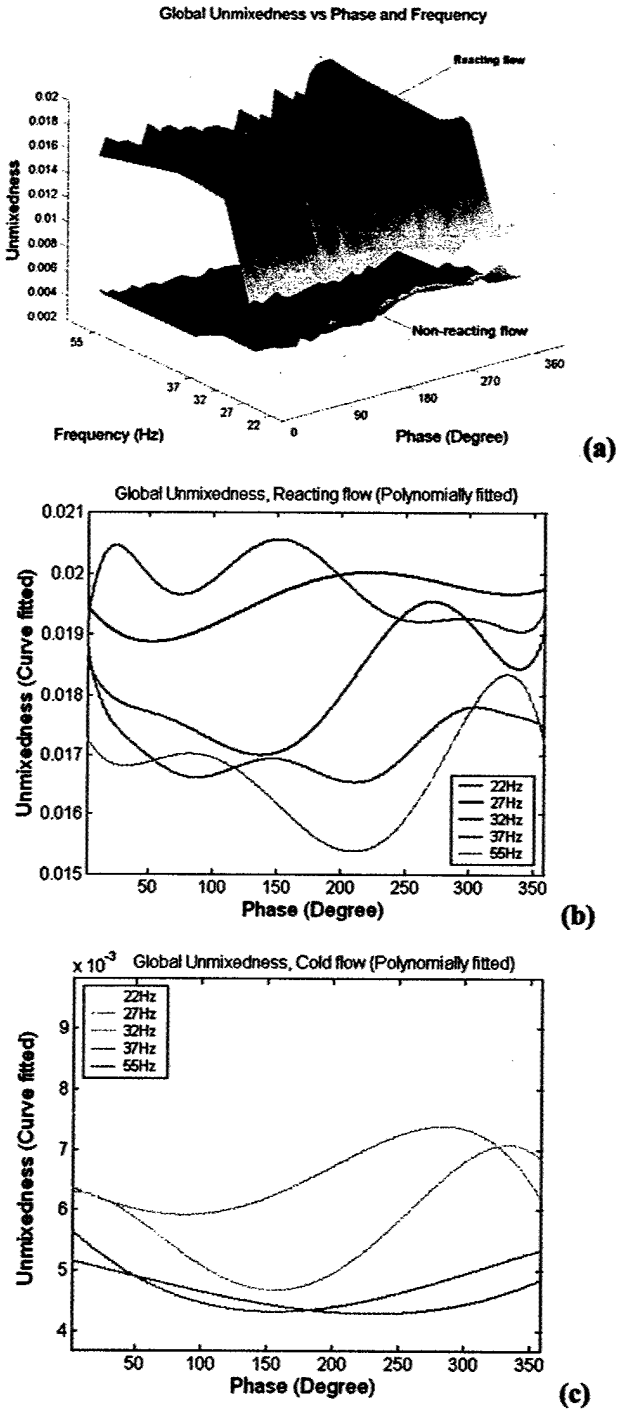


Figure 20. (a) 3-D representation of global unmixedness vs. excitation frequency and phase, and (b) Reacting cases with offset added to 22 and 27Hz, (c) non-reacting cases. (b) and (c) are curve-fitted by polynomials of order 8. For no excitation (0Hz), there's no phase dependence on the global unmixedness and they (0.0075 for reacting, and 0.0027 for non-reacting) are lower than the minimum of other values, so they are not indicated here.

phase of excitation as well. Figures 20(b) and (c) show how mixing behaves according to the excitation frequency and phase. All curves are fitted by polynomials of order 8, with $(1 - \sigma)$ errors estimated at the same level as shown in Figure 20. For reacting flow cases (b), an offset of 0.012 was added to 22 and 27Hz for comparing the qualitative behavior of mixing. The direct comparison of curve shapes shows that reacting flow cases have modes of fluctuation at frequencies higher than the first mode while non-reacting flow cases shows only the first mode of oscillations. The differences in the mixing behaviors are caused by the coupling between the combustion process and the acoustic waves, and this, in turn, affects the flame behavior in the flame zone subsequently.

6 Concluding Remarks

The many accomplishments of this program provide a roadmap for future research. The importance of fuel mixing and the coupling of that process to acoustic behavior has been greatly clarified. It was well understood that mixing directly affects flame stability, and by extension, it would be expected to impact acoustic sensitivity.

According to the current results, there exists a strong coupling between mixing and the acoustic field imposed. It is also evident that the two-dimensional temporal unmixedness distribution map gives information about how fuel/air mixing is structured in the mixing region, and where the fluctuations in temporal unmixedness are strongest. It also shows that the presence of a flame makes the distributions of uncertainties in the mixing zone, in terms of temporal unmixedness, more structured than those in the non-reacting case, though both cases have almost identical concentration profiles. This means not only the imposed acoustic waves, but also the heat released and buoyancy produced by the combustion process, play important roles.

The phase-resolved global unmixedness shows that the first mode of oscillation is the same frequency as the excitation, with phase differences from the imposed acoustic oscillations. There seem to be phase differences between the global unmixedness obtained here and the flame base oscillations for corresponding frequencies observed in previous works (Pun et al., 2003), too, and this is yet to be verified. Also, the seemingly higher modes or frequencies of oscillations due to the presence of the flame are found in the reacting flow cases. It is clear that the acoustic forcing causes a strong periodicity in the mixing layer at the driven frequency. This seems to be one of the main causes of fluctuations in local equivalence ratio in the flame region, which, in turn, may induce the periodic flame motion observed in the previous work by Pun et al. (2002, 2003).

In this work, the effects of the oscillations in mixing (unmixedness) and mass flow rate could not be decoupled due to the inherent experimental limitations. Still, the acoustic waves made oscillations in the overall mixing of fuel and air. According to Lieuwen et al. (1998), this is the primary cause of the flame oscillatory behavior observed by Pun et al. (2003)

The present work demonstrated that for systems in which fuel and oxidizer mix in the combustion chamber, acoustic instabilities tend to have a dominating effect on the mixing process. This is important in future modeling of these systems in that oscillatory mixing is expected to be a major driving force for combustion instabilities in lean gas-turbine engines. The importance of measuring mixing behavior is due to the difficulty in decoupling the effects of acoustic wave induced oscillatory mixing versus the oscillatory behavior induced in the flame zone.

To examine natural system instability, the chamber was operated over an extremely wide flow range with no imposed acoustic driving. During this test, the combustor exhibited no tendencies towards instability nor produced any acoustic emission. With a clear understanding of system behavior at atmospheric pressure, future research will be concentrated on studying the dynamic behavior of the flame at mean pressures of up to 5 bar. The planned work involves operating and measuring the swirl burner at these elevated pressures to examine the stability of the combustion process. This will provide a basis for both extrapolating to practical conditions and data with which to assess the correctness of computer models in their treatment of pressure sensitive effects. This work is unique in that it is continuous flow in nature with applied acoustic fields, with well-defined, time-dependent boundary conditions that have proven to be critical in modeling of such complex systems.

The research efforts described here have shown that progress can be made through enhanced understanding, as opposed to the prevalent emphasis on increased computer speed to enhance CFD. The complexity of a modern combustion system will (for the foreseeable future) require extensive sub-grid or reduced-order modeling to make computation possible. While the leaps in understanding produced by basic research into combustion fundamentals are harder to predict than CFD's continual incremental improvement, they occur with regularity and have a much broader impact. The research performed as part of this project has impact on many critical areas of gas turbine research.

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8 Appendices

Appendix A — Some Remarks on Combustion Instabilities and the Dynamical Behavior of Combustion Systems

Combustion instabilities should be regarded as merely the most common periodic forms of the dynamical behavior of combustion systems. Hence they serve as convenient examples of the general ideas defining combustors as dynamical systems.

Since they were discovered more than sixty years ago, combustion instabilities have presented continuing problems in the development of all high-performance propulsion and power-generating systems. In practice, treatment of such problems has been based largely on empirical methods supported by a growing body of understanding provided by basic and applied research. The field has not reached the stage at which designers have methods available allowing them to design new systems with reasonable confidence that expensive problems of instabilities will not arise during development. This proposal is based on the premise that advances in the past three years or so permit development of such methods if the appropriate basic research is continued and exploited in the interests of practical applications.

The particular advances in question are in the areas of experimental methods and numerical simulations. Rapidly developing nonintrusive optical diagnostics allow spatially resolved and time-accurate measurements of unsteady reacting flows simply not possible two years ago. Quite independently of those developments, methods of numerical simulations have progressed remarkably, reached a level at which realistic, though approximate, computations of time-dependent reacting flows can be carried out, both for laboratory devices and for practical combustors. Almost without exception, the experimental research and the development (and applications) of numerical simulations have been carried out by separated groups of researchers, even when both kinds of activities proceed within the same institution. Only experimental work is covered by this proposal, but the results are intended to be coordinated with numerical simulations carried out under separate funding. A second premise of the work described here is that the time is right to merge experimental work and numerical simulations in novel fashion possible only within one group engaged in closely coordinated efforts.

That assertion is based on the Principal Investigator's four decades of experience in the field, and especially his collaboration with students and postdocs in the past five years. To understand why this point of view makes sense it is helpful to have a broad qualitative appreciation for the subject of combustion instabilities and dynamics of combustion systems generally.

Combustion instabilities are best regarded as one subject in the general field of unsteady combustion. That they have received so much attention for such a long time is, of course, due to their serious practical consequences. In general, the most serious effects of a combustion instability are due to the vibrations of the system involved, affecting chiefly lifetime, payloads and performance of the system. Thus, for practical reasons, attention has always been focussed on oscillations of pressure, directed particularly to reducing their amplitudes or eliminating them entirely. In the past decade, especially for gas-turbine combustors, there has been growing concern with connections between unsteady motions, including combustion instabilities, and the rates of generation of pollutants, especially NO_x. That expanded point of view draws attention to the chemistry of the reacting flows, matters of chemical and combustion dynamics. That broadened emphasis is an important part of the motivation for the work covered by this proposal.

A.1 Unsteady Motions in Combustion Systems

From the earliest discoveries of pressure oscillations in combustion chambers it has been recognized that their causes—generically called 'mechanisms'—must be related to the energy released in combustion processes. With the exceptions of oscillations driven by purely fluid dynamical mechanisms—vortex shedding is the usual process—the unsteady motions are driven by direct interactions between the

combustion processes and the motions in a combustion system, may therefore be represented by the simplified block diagram shown in Figure A-1. Whether we are dealing with a laboratory combustor or the combustion chamber in a practical system, we can regard any unsteady motions as the dynamics of two coupled dynamical systems: the combustor itself, including the medium (largely combustion products); and the combustion processes. This view is necessarily an abstraction because the two systems are not spatially distinct: but they *are* dynamically distinct. That point of view conditions our approach to both our experimental and theoretical work.

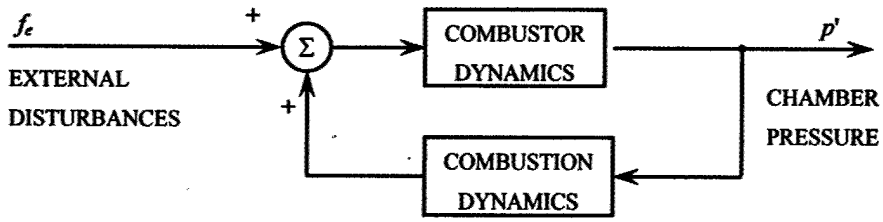

Figure A-1. Global View of Unsteady Motions in a Combustion System.

According to Figure A-1, the general subject of unsteady motions in combustion chambers may be divided into two parts: *combustor dynamics* and *combustion dynamics*. Practically all works on combustion instabilities can be classified into one or the other of those two parts. Historically, limits on available observational methods have restricted data to time histories of chamber pressure and accelerations of the surrounding structure, or components, measured with accelerometers on strain gages. Such information reveals some behavior of the combustor dynamics and nothing directly about the combustion dynamics. Many special experimental works have been performed to discover details of the fluid mechanics of combustors, notably characteristics of vortex shedding. Moreover, a large amount of theoretical work exists for combustor dynamics, based largely on a method of spatial averaging.

It is fair to conclude that the subject of combustor dynamics is practically closed so far as the principles of linear behavior are concerned. Especially, linear stability is in principle entirely understood. The problems remaining are largely those associated with modeling the contributing physical processes, the most important of which arise from combustion dynamics, i.e. the dominant mechanisms for instabilities.

Matters of nonlinear combustor dynamics still pose significant problems. However, the general framework of analysis based on spatial averaging seems entirely adequate for treating the subject. Current work continues to yield fruitful results.

Numerical simulations almost always treat combustor dynamics and combustion dynamics together and inextricably. That is, the results published to date do not reveal the behavior of the combustion dynamics as fundamental information. The chief aim has been to investigate the evolution of small disturbances in a chamber, the behavior being normally characterized by the unsteady chamber pressure. Thus the results are valid for the special problems treated but are of relatively little help to general understanding and hence provide practically no aid to designers of practical combustion systems.

A.2 Remarks on Combustion Dynamics

It is impossible to extract detailed information about combustion dynamics from full-scale tests. With experimental methods currently available, it is possible to infer some global characteristics of unstable motions in combustors. By far the greatest amount of expense and effort in this field has been devoted to determining the combustion dynamics of burning solid propellants. In that case, the demands are somewhat less than those placed on other reacting systems. Most of the information required for

practical purposes can be obtained from a single quantity, the response function, defined as the ratio of the fluctuation of mass flux issuing from a unit area of burning propellant, to the fluctuation of imposed pressure or velocity fluctuations. At least six different experimental methods have been developed during the past forty years. Only one (the T-burner) is capable of giving results for realistic ranges of frequency and pressure. Even the T-burner has such intrinsic uncertainties in the data that it is impossible to distinguish small differences in behavior between different propellants at the levels required for practical applications.

The situation is much worse for other systems. Presently there are no methods available for investigating the local combustion dynamics of liquid- and gas-fueled systems. Methods of global flow visualization have long been used: for example early schlieren observations of unsteady combustion in shed vortices was discovered as a mechanism for combustion instabilities. More recently, photomultipliers have been used for one-dimensional and CCD cameras for two-dimensional observations of unsteady radiation produced by chemical reactions. Results have been very useful in clarifying qualitative and, in some cases quantitative, aspects of the combustion field in a chamber. However, those methods cannot provide results for local—i.e. spatially resolved—behavior of the combustion dynamics.

Failure to have fundamental understanding of combustion dynamics means having a weak foundation for constructing models. Without good models, linear stability, nonlinear behavior and the time evolution of unsteady motions in combustion chambers cannot be predicted. Moreover it is correspondingly difficult to interpret observed behavior. The great deficiencies in knowledge of combustion dynamics constitute by far the most important reason that problems of combustion instabilities continue to arise unexpectedly in new propulsion and power-generation systems, a situation that will continue for the foreseeable future.

The current status of applications of active feedback control to treat combustion instabilities is a striking example[2]. During the past 12–14 years many demonstrations have been given of the 'control' of combustion instabilities by introducing a feedback loop. In almost all cases, linear, single-input single-output control has been used, already seemingly an inadequate approach to control nonlinear infinite-dimensional systems. Nevertheless, a considerable number of successful results have been achieved, including at least three full-scale demonstrations by Rolls-Royce (an afterburner), Siemens, and Westinghouse, the last two using gas-turbine combustors. In all cases, however, the reasons for the initial presence of instabilities could not be explained; i.e. neither the nature of the instability nor the limiting amplitudes of oscillations could be predicted. The reasons for the success of feedback control, or in some instances failures, remain unknown. There are no methods available for use in design, prediction and quantitative interpretation. At the present state of the field, use of feedback control is purely *ad hoc* and after the fact. There is no rational basis for design of laboratory experiments or of full-scale devices to know whether or not feedback control should be used, or what its consequences will be if it is used. Furthermore, the principals in the three full-scale demonstrations (Rolls-Royce, Siemens, and Westinghouse) have admitted to the PI that the successes they achieved have yielded practically no information applicable to future designs of new systems.

Broadly, then, we may conclude that the field of dynamical behavior of combustion systems, including the use of feedback control, is well developed in one important respect: the basic principles are, for the most part, well understood. Moreover, many years of full-scale testing and laboratory experiments and demonstrations have established a reasonably sound basis for formulating those principles. Nevertheless, use of those principles in design of new systems and for interpreting new observational results remains disturbingly limited. The chief reasons are that the problems posed in this field are extraordinarily complicated and multidisciplinary. Theoretical methods alone are far from producing even approximate solutions at the level required. Thus results obtained to date reflect to a large extent the limitations of experimental methods required to investigate fundamental behavior. As experimental methods progress, so also will the results and usefulness of work in the dynamical behavior of

[2] See Appendix C for a brief description of the role of combustion dynamics (i.e. combustion transfer functions) in feedback control.

combustion systems. The chief premise of this proposal is that recent progress with experimental methods and numerical simulations now offer an exceptional opportunity for significant advances in this field.

Appendix B — The Rijke Tube: Combustion Dynamics & Stability

Analysis of the Rijke Tube

The instability of a Rijke tube has long been regarded as the simplest surrogate for actual instabilities in full-scale combustors. It's a valid view and good justification, but in fact the reported results have not been particularly helpful in interpreting combustion instabilities of any sort. Part of the reason is that analysis of the Rijke tube has not been related to the kind of analysis useful for full-scale combustors. The approach taken here is identical to that forming the basis for the general analysis cited in Section 4.2 and widely used to investigate the behavior of combustion systems used for propulsion and power generation.

Here we cover only enough of the analysis to illustrate how the main source or mechanism for instabilities (i.e. $\dot{Q}'$, the fluctuation of the rate of energy or heat addition to the motions) fits in the theory. The main point is to show why careful detailed experimental results for $\dot{Q}'$ are essential to continued progress in understanding combustion instabilities and for applying active feedback control. To simplify the following analysis, we suppose that the source of energy in the Rijke tube is an electrically heat grid. However, the analysis works as well for a thin flame and, with small adjustments, to a distributed flame as well.

Consider the simplified form of a Rijke tube open at both ends, supported vertically, and containing a heated wire grid. The grid may be heated electrically, or by a flame subsequently removed. If the grid is in the lower half of the tube, steady oscillations can be sustained, having frequency hardly distinguishable from that of the fundamental frequency of the tube, $\overline{a}/2L$ where a is the speed of sound. The basic questions to be

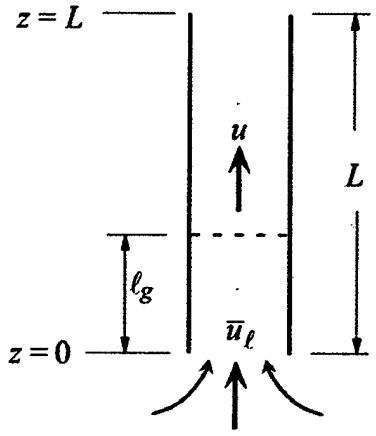

Figure B-1. Sketch of the Simplest Form of Rijke Tube.

Answered here are: Why are the oscillations excited and sustained?; and how does the presence of oscillations depend on the location of the grid?

For several reasons, the Rijke tube is a marvelous case to investigate as an example of 'thermoacoustic oscillations'; acoustic waves excited and sustained by heat addition. This is a situation in which the part of the system that is the source of energy, and provides internal feedback, is clearly distinct from the system that is oscillating, the acoustic field. Thus we can separate analysis of the two parts of the system with minimal approximations.

Because of heating by the grid, vertical mean flow is induced in the tube. The temperature is higher, the density is lower, and the velocity is greater, in the region above the grid. For simplicity we assume that the flow properties have discontinuities at the grid and are uniform upstream and downstream.

Superposed on the average flow is the acoustic field, uniform in transverse planes and varying in the axial direction, having nearly the form of the fundamental acoustic mode for a tube open at both ends, Figure B-2. Due to the presence of the grid, and the different speeds of sound in the flows downstream and upstream of the grid, the actual field is slightly different from the classical value. However it is a good approximation for calculating linear stability with the method of spatial averaging to ignore those difference if we assume a small temperature difference across the grid (weak heating). This is not realistic and is assumed here to simplify the analysis for purposes of illustrations.

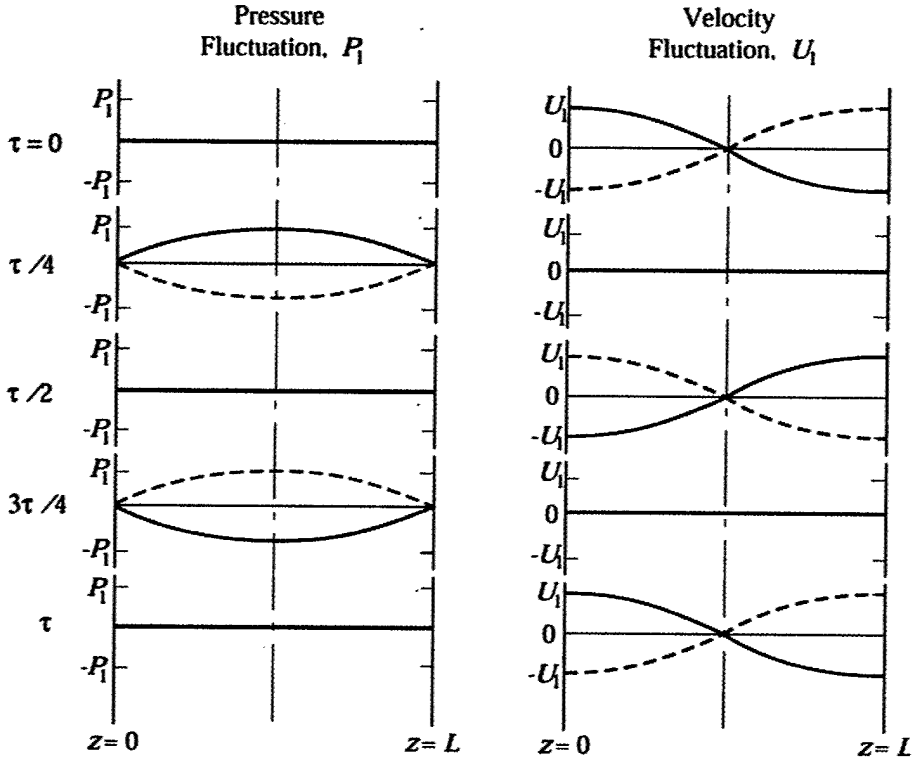

Figure B-2. Approximate Acoustic Field in a Rijke Tube.

The problem of driving the acoustic pressure mode having nodes at the ends of the tube is analogous to driving a string tied at its end, by forcing at the location corresponding to the grid's position. Heat addition in the Rijke tube to drive the pressure field is analogous to wiggling the string by grabbing it. Just as the shape of the string is approximately half of a sine wave even when forced, so also is the acoustic pressure, as noted above.

Let $\dot{Q}'$ be the fluctuation of heat addition, having arbitrary distribution in space and time. Then the linear wave equation for the pressure in the tube is

$$\frac{\partial^2 p'}{\partial t^2} - \bar{a}^2 \frac{\partial^2 p'}{\partial x^2} = \frac{R}{C_v} \frac{\partial \dot{Q}'}{\partial t} \tag{B.1}$$

The source of pressure waves is the rate of change of the fluctuation of the heat addition rate. This is the same $\dot{Q}'$ that appears in Rayleigh's criterion and is the quantity we intend to measure in the described work. The nature of the acoustic field will clearly depend on $\dot{Q}'$, a result that holds generally.

If one is to find accurate predictions for the acoustic field excited by the heat addition, then the source must be known accurately: its distribution and dependence on flow variables determine the linear stability of waves and, when nonlinear processes are active, the nonlinear behavior—e.g., amplitudes of limit cycles.

According to earlier remarks, we assume that the spatial form of the pressure field remains the classical form, but with varying amplitude $\eta_1(t)$, devoting the fundamental mode. Hence assume

$$p'(x,t) = \bar{p}\eta_1(t)\sin k_1 x \tag{B.2}$$

where $k_1 = \omega_1 / \bar{a}$ and ω_1 is the frequency of the classical fundamental mode. Substitute (B.2) into (B.1) to find

$$\bar{p}\sin(k_1 x)\left(\frac{d^2\eta_1}{dt^2} + \omega_1{}^2\eta_1\right) = \frac{R}{C_v}\frac{\partial \dot{Q}'}{\partial t}$$

Now apply spatial averaging. Multiply this equation by $\sin(k_1 x)$ and integrate over the length of the chamber, giving

$$\frac{d^2\eta_1}{dt^2} + \omega_1{}^2\eta_1 = \frac{2}{\bar{p}L}\frac{R}{C_v}\int_0^L \sin k_1 x \frac{\partial \dot{Q}'}{\partial t}dx \tag{B.3}$$

Equation (B.3) is a special case of a very general result derived in the analytical framework used in all of our work on dynamics of combustion chambers. The right hand side expresses explicitly the interaction between the combustion dynamics—all contained in $\partial \dot{Q}' / \partial t$ and the acoustic field having structure $\sin(k_1 x)$ in this case. Spatial averaging with the mode shape as the weighting function tends to smear out errors in the modeling of $\dot{Q}'$.

In the case here, with the heat addition non-zero only at the location l_g of the grid, we write $\dot{Q}'$ as some function of time $\dot{Q}_0(t)$ of the flow variables multiplied by the delta function $\delta(x - l_g)$. The integral on the right hand side of (B.3) is

$$\int_0^L \sin(k_1 x)\frac{d\dot{Q}_0}{dt}(x - l_g)dx = \frac{d\dot{Q}_0}{dt}\sin(k_1 l_g) \tag{B.4}$$

It is reasonable to suppose that $\dot{Q}'$ depends on the local pressure and the velocity, both mean and fluctuating values, and possibly explicitly on time. From acoustics, the fluctuating velocity is proportional to $d\eta_1 / dt := \dot{\eta}_1$ with (B.4), equation (B.3) is

$$\frac{d^2\eta_1}{dt^2} + \omega_1{}^2\eta_1 = \frac{2}{\bar{\rho}L}\frac{R}{C_v}\frac{d}{dt}\dot{Q}(\eta_1, \dot{\eta}_1; t)\sin(k_1 l_g) \tag{B.5}$$

B.1 Velocity-Dependent Energy Addition

For the electrically heated grid, we can reasonably model $\dot{Q}'$ as energy addition to the flow by convective heat transfer, proportional to the magnitude of the local velocity relative to the grid, $\left|\overline{u}+u_1'\right| := \left|\overline{u}+\kappa\dot{\eta}_1\right|$. With this model the amplitude of the fundamental mode satisfies the equation

$$\frac{d^2\eta_1}{dt^2} = \omega_1{}^2\eta_1 = \frac{2}{\overline{\rho}L}\frac{R}{C_v}H\sin\left(k_1 l_g\right)\frac{d}{dt}\left|\overline{u}+\kappa\dot{\eta}_1\right| \tag{B.6}$$

where H and κ are parameters independent of position, but possibly dependent on time.

Solution to this equation is not required for this discussion. It is sufficient to note that (B.6) does contain answers to the two basic questions posed earlier: (1) it appears that the instability is indeed explained by the model of the heat addition chosen here; and (2) the placement of the heating in the lower half of the tube is necessary in order that this model for the energy addition, $\dot{Q}' \approx \left|\overline{u}+u_1'\right|$, should provide the energy addition in proper phase with the pressure oscillation.

Further details are unimportant. The chief purpose of this brief analysis is to emphasize that the model of the energy addition is crucial to explaining and understanding an instability. That is no less true for a full-scale combustor than it is for a Rijke tube, and is the most important justification for the experimental work proposed here.

B.2 Pressure-Dependent Energy Addition

An instructive solution to equation (B.5) is immediate if we assume that the interaction between the acoustic wave and the energy source is dependent on the pressure. Hence we can introduce the pressure response function defined by (B.7). For the case of combustion limited to a thin region (*e.g.*, a flame front) and R_p assumed real, we write

$$\dot{Q}' = \dot{Q}_0\delta\left(x-l_g\right) = \overline{\dot{Q}}R_p\frac{p'}{\overline{p}} = \overline{\dot{Q}}R_p\eta_1(t) \tag{B.7}$$

Substitution in (B.5) leads to the linear equation for the pressure amplitude

$$\frac{d^2\eta_1}{dt^2} - 2KR_p\frac{d\eta_1}{dt} + \omega_1^2\eta_1 = 0 \tag{B.8}$$

where $K = \overline{\dot{Q}}R/\overline{\rho}LC_v$ is constant. A solution to η_1 has the familiar form

$$\eta_1(t) = \text{cont.}\, e^{\alpha t}\cos\left(\omega_1 t+\phi\right)$$

where ϕ is an arbitrary phase and $\alpha = KR_p$ is the growth constant for waves; for $\alpha > 0$ (and hence $R_p > 0$) the wave is unstable.

This example is the simplest demonstration of the direct dependence of stability and the response function.

Appendix C — Significance of Combustion Dynamics in Active Control

The general problem of the intrinsic dynamics of a combustor can be most simply represented with the simple block diagram in Figure C-1, a feedback system with possible external inputs f_e. As output, the fluctuating pressure p' is shown because it is easily measured and causes the most trouble in practice. In the forward path, the dynamical properties of the combustion chamber are identified as "combustor dynamics." Those dynamics consist chiefly of compressible waves in the products of combustion but may also include, for example, injector and structural dynamics. This part of the system is essentially an amplifier in the present context. For example, if f_e is a steady sinusoidal pressure input having amplitude $\hat{p}_{in}$ and frequency near a resonant frequency of the chamber, then the output p' will be sinusoidal having amplitude larger than $\hat{p}_{in}$.

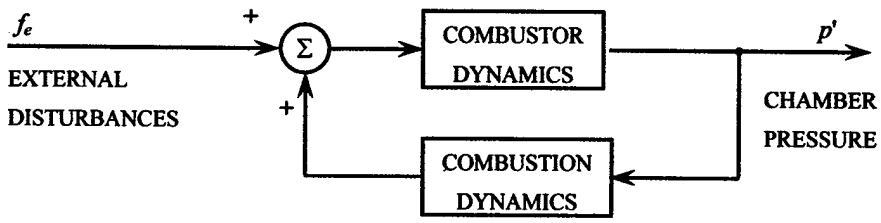

Figure C-1. General Block Diagram for a Combustion System.

Our primary concern in the present work lies with the dynamics in the feedback loop, the combustion dynamics which we represent as response functions. Because the combustion processes are sensitive to pressure, and other flow variables as well, they provide the internal feedback in a combustor. A small increase of pressure will cause a small increase in the reaction rate and hence in the rate at which energy is released. Locally, an increase in the heat release causes local density and volume changes which cause a local change of pressure. If that pressure change augments the initial increase of pressure, then this process is locally destabilizing. Whether or not the combustion dynamics are destabilizing, they generate feedback.

A general block diagram, Figure C-1, contains the basic ideas and if we assume linear behavior we can quantify them in the language of classical control theory. With s the transform variable, we denote Laplace transforms by capital letters and let $G(s)$, $Q(s)$ stand for the transforms (i.e. the transfer functions) for the combustor and combustion dynamics (response function) respectively. Then the diagram in Figure C-1 becomes Figure C-2. That diagram can be solved to give the transfer function for the feedback system:

$$\frac{P(s)}{F_e(s)} = \frac{G}{1-GQ} \tag{C.1}$$

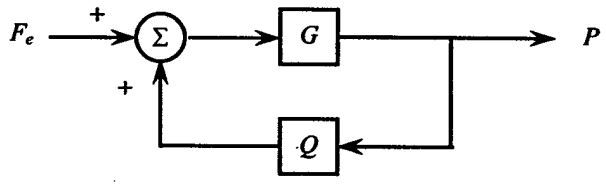

Figure C-2. Block Diagram for a Linear Combustion System: Uncontrolled.

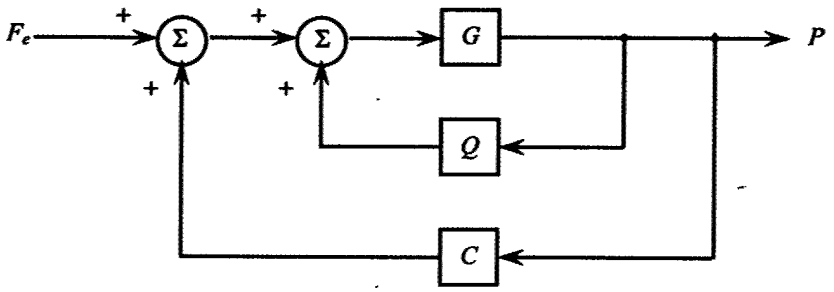

Figure C-3. Block Diagram for a Linear Combustion System: With Feedback Control.

The system has intrinsic or natural motions—that is, there is finite output $P(s)$ even with vanishingly small input ($F_e \rightarrow 0$) —if the denominator vanishes:

$$1 - GQ = 0 \tag{C.2}$$

Equation (C.2) is the familiar condition for instability of an elementary feedback loop. The roots of (C.2) define the frequencies at which the closed loop system is unstable and may exhibit growing oscillations. It's a simple example of the phenomenon that an amplifier (here the combustor dynamics) with feedback (the combustion dynamics) can become an oscillator. The physical behavior is exactly analogous to the shrill screeching occasionally produced by public address systems.

But the chief (and fundamentally important) point here is that condition (2) for instabilities contains the product of G and Q. That is, the ***combustion dynamics*** is just as important as the ***combustor dynamics*** in determining the dynamical behavior of the system—in particular a rocket motor or a gas-turbine combustor.

Now consider the case when active feedback control is used. As shown in Figure C-3, this strategy can be quite generally represented by adding the outer feedback loop containing the controller $C(s)$. The transfer function for the system is now

$$\frac{P(s)}{F_e(s)} = \frac{G}{1 - G(Q + C)} \tag{C.3}$$

and instead of (C.2), the condition for instabilities is

$$1 - G(Q + C) = 0 \tag{C.4}$$

In this context, the purpose of adding the controller is to shift the frequencies at which the natural motions (resonances or normal modes) occur; and especially to ensure that all such motions are stable. That is a problem of control design—choose the controller such that its transfer function, in combination with $Q(s)$ and $G(s)$, guarantees that the system has the desired behavior. Quite clearly that means that both the combustor dynamics and the combustion dynamics must be known if the design problem is to be solved satisfactorily.

In the absence of complete knowledge of the dynamics for an actual system, the problem of control becomes an *ad hoc* matter. And that is characteristic, to some extent at least, of all existing demonstrations of active control of combustion systems, whether they are laboratory or full-scale devices.

That is, based on some knowledge of the combustor dynamics and very limited information about the combustion dynamics, a controller (and actuator) are designed and tried. Then trial and error becomes the standard strategy for improvement. The central purpose of this program is to encourage replacement of trial and error by rational systematic procedures suitable as part of the design of combustion systems.

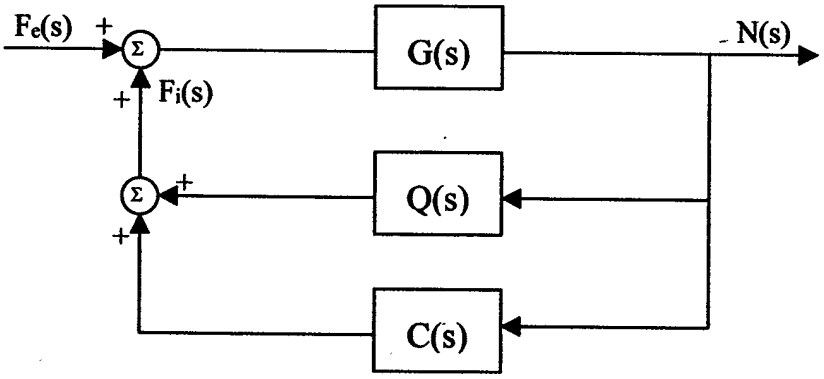

Figure C.4 Combustion System with Feedback Control.

9 Personnel Supported

F.E.C. Culick joined the faculty of the California Institute of Technology after receiving his Ph.D. in Aeronautics and Astronautics from MIT in 1961. He is currently Richard L. and Dorothy M. Hayman Professor of Mechanical Engineering and Professor of Jet Propulsion. Dr. Culick's Ph.D. dissertation was on the subject of combustion instabilities in liquid rockets and much of his research since then has been concerned with problems of unsteady motions in combustion chambers generally. He began working on solid rocket combustion instabilities in 1965, and since 1979 has been addressing the problem in air-breathing systems, including combustors and afterburners for gas turbines. He currently teaches the introductory course on control of physical systems, and, on alternate years, an introductory course on combustion or a course on performance, stability, and feedback control of aircraft. Dr. Culick is a Fellow of the American Institute of Aeronautics and Astronautics and a member of the International Academy of Astronautics. In 1981, he received the AIAA Pendray Aerospace Literature Award and in 1988 the JANNAF Combustion Subcommittee Recognition Award. From January to June 1992, he was appointed Professor Associate at École Central in Paris. From 1977–1986, Dr. Culick was a member of the AGARD Propulsion and Energetics Panel, and resumed that position in 1994. He has been a consultant to all of the major US rocket companies as well as to various government organizations. For nine years until 1995 he was a member of the Technical Advisory Council for Sverdrup Technology, Inc., primarily concerned with operation of the propulsion test facilities at AEDC, Tullahoma, Tennessee. He is a member of the Pratt and Whitney Technical Advisory Council.

Dr. A. Ratner received his Bachelor of Science in Engineering and Applied Science from Caltech in June 1995. While there, he worked on a student run space experiment that proved both educational and yielded interesting data. From fall of 1995–2000 he was at the University of Michigan, Department of Aerospace Engineering, working for Prof. James Driscoll. At U of M, he was supported by a 5-year FXB Association Fellowship. This fellowship allowed him to focus on research and academic work. He received Masters degrees in both Aerospace Engineering and Mathematics. In his research, he was first to perform PIV in several regimes: highly turbulent flames, high swirl flames, and supersonic flames. In addition, he performed simultaneous CH and OH PLIF, as well as simultaneous OH PLIF and PIV. He also obtained fuel efficiencies by gas sampling. From October 2000 to July 2003, Dr. Ratner was a Postdoctoral Research Scholar at Caltech. He is presently an assistant professor of mechanical engineering at the University of Iowa, Iowa city. He is a member of the AIAA and the Combustion Institute.

Dal Mo Kang graduated from the department of Mechanical and Aerospace engineering, Seoul National University in Republic of Korea with Bachelor of Science in October, 2000. From July 2000 to August 2001 he served as a research scientist at Korea Institute of Science and Technology (KIST) for reliability problems arising in manufacturing processes. Having joined the Jet Propulsion Center (JPC), California Institute of Technology in October 2001, he received his Master of Science in engineering in June 2002, and was admitted to the doctoral candidacy in 2003. Since joining the group, he has performed experimental research dedicated to the study of unsteady combustion dynamics with intensive use of laser-based diagnostic techniques.

Carlos Pinedo was an undergrad student in Aeronautical Engineering, at the Massachusetts Institute of Technology, who joined the group (JPC) briefly for the summer 2003 as a part of the Minority Undergraduate Research Fellowships Program (MURF). He is a member in the Air Force ROTC program in MIT and will commission as an officer June 2005. Carlos Pinedo is currently in Master's program in Aeronautical Engineering, at MIT. He contributed to the construction of the experimental configuration in setting up the acetone-PLIF system, and the data acquisition system.

Steven L. Palm is officially on leave but is carrying out research in his own laboratory located near San Diego, approximately 125 miles from Caltech.

10 Interactions

United Technologies Research Laboratory

Common research interests in combustion instabilities; a continuing interaction.

Pratt and Whitney

Professor Culick is a member of the P&W Technical Advisory Council and has made several private visits, mainly to deal with problems of combustion instabilities.

ACRI

This is a continuing collaboration with the founder, Dr. Akshai Runchal of this small software company. Beginning in October 2003, Professor Seungbae Lee, from Korea, spent his sabbatical year at Caltech working with Prof. Culick and Dr. Runchal on a problem of common interest. Professor Lee returned to Korea in August 2004.

11 Papers & Posters — Abstracts

1. Central State Section meeting of Combustion Institute (CSSCI), 2004

Imaging of Fuel Mixture Fraction Oscillations in a Driven System using Acetone PLIF

D.M. Kang[1], C. Pinedo[1], A. Ratner[2], F.E.C. Culick[1]

[1]Jet Propulsion Center and Mechanical Engineering, California Institute of Technology, Pasadena, California, USA

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Measurements of fuel mixture fraction are made for a jet flame in an acoustic chamber. Acoustic forcing creates a spatially uniform, temporally varying pressure field which results in oscillatory behavior in the flame. Forcing is at 22, 27, 32, 37, and 55 Hz. To asses the oscillatory behavior, previous work included chemiluminescence, OH PLIF, nitric oxide PLIF imaging, and fuel mixture fraction measurements by infrared laser absorption. While these results illuminated what was happening to the flame chemistry, they did not provide a complete explanation as to why these things were happening. In this work, the fuel mixture fraction is measured through PLIF of acetone, which is introduced into the fuel stream as a marker. This technique enables a high degree of spatial resolution of fuel/air mixture value. Both non-reacting and reacting cases were measured and comparisons are drawn with the results from the previous work. It is found that structure in the mixture fraction oscillations is a major contributor to the magnitude of the flame oscillations.

2. Poster presentation, 4F5-09, 30th International Symposium on Combustion, University of Illinois at Chicago, Chicago, IL, July 25–30, 2004

Imaging of Fuel Mixture Fraction Oscillations in an Acoustically Driven System using Acetone PLIF

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Combustion instabilities, caused by a coupling between thermo-acoustic and fluid-dynamic conditions present during the combustion processes, are combustion chamber pressure oscillations that are standing waves. Interfering with proper operation, these instabilities may cause catastrophic structural damage by excessive stresses or by localized combustion near surfaces. Because of these issues and the lack of accurate methods of analysis, great interest exists to establish a general approach for evaluating and actively controlling combustion.

The purpose of this work is to study the impact of acoustic oscillations on the fuel/air mixing and to characterize the link between this effect and the resulting flame behavior. The acoustic forcing is imposed on the flame by placing the burner arrangement in an acoustic enclosure and driving chamber pressure modes at selected frequencies. The acoustic standing waves then interact with the flame and cause oscillations of the flame and the heat release. Both reacting and non-reacting cases are studied to examine and isolate the effects of modifying direct flame chemistry versus destabilization of the fuel-air mixing layer by the imposed acoustic field.

Acetone planar laser induced fluorescence (PLIF) is used to image the distribution of fuel in the mixing region upstream of a non-premixed jet flame. Acetone is seeded into the methane fuel stream so as to use it as a marker of evolving fuel mixture fraction. This technique is non-intrusive, a critical property for studying on instability, produces spatially and temporally resolved images, and is repeatable. Acoustic waves at frequencies of 22–55Hz are applied to the system and PLIF images are captured at many values of acoustic phase. The images are then sorted according to phase, grouped, and averaged to give the phase-resolved responses of mixing behavior. The unmixedness is then calculated for these averages to provide a measure of the degree of fuel/air mixture variations in both time and spatial location.

The results show that the flame behavior depends strongly on the acoustic excitation frequency; this is largely due to the induction of mixture fraction oscillations at the driving frequency upstream of the flame front. These induced modes of oscillations are clearly visible in the phase-resolved spatial unmixedness. The temporal unmixedness pattern reveals fuel core breakdown slower in the reacting flow cases, likely because the jet velocities induced by the buoyancy of the hot product gases are higher than in the non-reacting cases.

3. Poster presentation, 4F3-11, 30th International Symposium on Combustion, University of Illinois at Chicago, Chicago, IL, July 25–30, 2004

On Non-Intrusive Measurement of NO in Premixed Flames

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Combustion processes for propulsion, energy conversion, manufacturing and heating are vital to modern day civilization. However, the utilization of combustion engenders a numbers of serious concerns in regard to fuel resource availability, environmental impact, human health effects and climatic shifts, for both the short and long terms. Despite the controlled use of combustion for several hundreds years, there are many areas of combustion science and technology that are still not fully understood. Increased knowledge and understanding of combustion are clearly necessary to increase the efficiency and cleanliness of current processes and to evolve and develop new approaches with capabilities previously unavailable.

Many of the current limitations in the knowledge base of combustion can be attributed to the inability to experimentally probe these processes to the extent necessary for both empirical and theoretical advances. These limitations arise for two primary reasons, which at first may sound contradictory, namely the hostility and delicacy of combustion processes. The high temperatures and heat transfer rates make these systems difficult to probe physically with desired spatial and temporal resolutions that are consistent with probe survivability. Also combustion processes are delicately stabilized and, thus, easily altered by physical intrusion. A large number of laser diagnostic techniques have been developed in the last twenty years for use in combustion and have become extremely valuable tools to study many aspects of the combustion process.

Significant research emphasis has been placed on nitric oxide (NO) detection during the past decade. In fact, NO is an atmospheric pollutant whose output has become strictly regulated, and therefore needs to be monitored in real combustion systems.

Laser Induced Fluorescence (LIF) has been demonstrated as a fairly reliable technique for the detection of minor species concentrations such as OH, CO, CH and NO in many combustion environments. However LIF is predicted to lose accuracy due to collisional quenching and absorption. These issues are critical when a quantitative measurement of NO are to be performed in post-flame regions where the

presence of oxides of carbon and water enhances collisional quenching and absorption and therefore lowers the measured LIF signal.

In this study, a steady premixed, rich (σ =1.25 or σ =1.35), methane/air flat flame at atmospheric pressure with dilution is used to compare LIF under different regimes (linear/saturated) corresponding to different laser power and evaluate the response of the rotational lines probed to collisional quenching. The dilution is either pure nitrogen or pure carbon dioxide and is chosen so that the NO levels and temperature are the same for each stoichiometric ratio in the probed zone, while concentrations of quenching species change significantly. Carbon dioxide and nitrogen are respectively a strong and mild quencher.

Our data clearly show that for a given NO level and temperature but different quenching environments, the LIF lineshape in the vicinity of the $Q_2(27)$ transition depends on laser power and electronic quenching. This is caused by the different responses of excited rotational lines ($Q_2(27)$ and $Q_1(23)$) to quenching and by laser line-width effects. In addition, laser detuning can have significant impact on the accuracy of LIF. A 2 pm detuning of the exciting laser source can lead to a 20% error in a sub-saturated LIF regime for highly collisional environments.

Some numerical computations, obtained using the kinetic mechanism GRI 3.0, are illustrated and compared to the experimental results. Our data show that the GRI 3.0 mechanism over-predicts NO levels in rich flames. This result suggests that research effort should be focused on correcting the deficiencies in the reaction mechanism for fuel rich flame conditions.

4. (In progress) to be submitted to *Experiments in Fluids*

Combined Acetone PLIF and IR Laser Absorption Probe Measurements of Fuel Mixture Fraction Oscillaitons

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Measurements of fuel mixture fraction are made for a non-premixed jet flame in a combustion chamber with imposed acoustic oscillations at frequencies of 22–55 Hz. As part of studies on combustion instabilities and the dynamical behavior of combustion systems, this work is intended to provide a better understanding of mixing characteristics and a link between responses in the mixing zone and the flame zone. Infrared laser absorption and phase-resolved acetone PLIF are used to measure the fuel mixture fraction throughout the flow field. The degree of fuel/air mixing is then calculated in terms of unmixedness factor based on these measurements in both temporal and spatial respects. Results show that the acoustic excitation causes oscillations in fuel/air mixing at the driving frequency, which results in inhomogeneous burning in the flame region and thus affecting the flame behavior. Also, the presence of the flame affects the mixing in that mixture fraction fluctuations at higher driving frequencies exhibit greater overall magnitudes than in corresponding cold flow mixing cases.