Comparison of Chemiluminescence, OH PLIF, and NO PLIF for Determination of Flame Response to Acoustic Waves

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Various techniques have been employed by investigators to measure the response of flames to unsteady changes, but there has been no systematic study of the relative benefits and drawbacks of these competing techniques. The goal of this work is to characterize the performance of two different measurement techniques applied in three ways and to examine the differing insights they offer for the response of a flame in a periodic acoustic field. The burner configuration consists of a jet flame in a partial enclosure that stabilizes the flame approximately 8 cm above the jet exit. This burner is installed in an acoustic chamber that has actively-controlled, frequency-selectable, acoustic forcing. Flame response data for different frequencies obtained with chemiluminescence, OH PLIF, and NO PLIF measurement techniques is the basis for this work. Analysis of the data shows the complexity of the measurement required to achieve a given level of understanding of the flame's behavior. The usefulness of these techniques in flame response measurements individually and taken in combination is discussed, with examples.

INTRODUCTION

In the development of combustion systems there has always been a need for diagnostic methodology to assess the combustion process and the behavior of the combustor being designed. The first diagnostics were human senses, temperature determination based on touch and combustion characterization based on sight. Sight, which depends on the natural luminosity of a flame, proved to be quite useful for characterizing the flame in certain ways. Luminescence can be an indicator of whether the flame is laminar or turbulent, steady or unsteady, and even in determining if some change has caused a greater or lesser fraction of the fuel to be consumed (Rijke 1859; Rayleigh 1945). The failing of this methodology tends to be the limitations of human sight. The limitation being that it is very difficult to perceive anything occurring at greater than 20 Hz and that the experimenter must write down any observations as they are witnessed during the progress of the experiment.

Photography greatly enhanced the capabilities of the experimenter by enabling analysis of photographs and with improved film technology, imaging of the chemiluminescence during prescribed periods of time that are significantly shorter than possible by the human eye. With these capabilities, investigators expanded the range of topics that they could study and some of the work progressed into the characterization of flames in an acoustically active environment. Some investigations focused on combined collecting of all or a sizeable portion of the flame luminosity (with a photomultiplier tube) and recording it with very fine temporal resolution (Poinsot et al. 1987; Sterling 1991; Chen et al. 1993; and Kappei et al. 2000). Other investigations have been performed with spatially resolved (CCD type) instruments (Broda et al. 1990; Venkataraman et al. 1999).

A portion of the research community chose to study the research issue involved with a different methodology. These investigators chose to examine only the induced fluorescence of chemical species in the flame rather than the natural luminescence. This methodology is based on employing the finer spatial and chemical species probing capability of Laser Induced Fluorescence (LIF), and later on Planar LIF (PLIF), to better understand flame structure and behavior. In-flame measurements have progressed from LIF (Dyer and Crosley 1982) to OH PLIF (Cadou et al. 1991; McManus et al. 1995; and Shih et al. 1996), to NO PLIF (Cadou et al. 1998), and HCO (Najm et al. 1998). Still, little work has been reported applying temporally and spatially resolved PLIF imaging to acoustically active systems (Pun 2001; Pun et al. 2002; Ratner el at. 2002) and no systematic comparison of the relative benefits of the various techniques has been reported.

The goal of this work is to examine some of the types of data that can be gathered with several different diagnostic techniques when they are applied to the same experimental configuration. In addition, a secondary objective is to compare the derived insights while assessing the increasing difficulty of achieving a particular level of understanding of the flame behavior. In practical terms, chemiluminescence is less expensive and easier to implement than PLIF. These differences are due to the cost of the equipment required and the strengths of the signals involved.

EXPERIMENTAL CONFIGURATION

Detailed descriptions of the experimental configuration, measurement methodologies, and data analysis procedures can be found in Pun (2001), Pun et al. (2002), and Ratner et al. (2002). The description here will be limited to the general system parameters. A schematic of the acoustic chamber is shown in Figure 1. The acoustic chamber consists of a "T" shaped cylindrical (30.5 cm diameter) assembly that is open at the top, acoustically closed at the bottom, and has acoustic drivers (speakers) at the end of the arms of the "T." For driving frequencies between 22 Hz and 55 Hz, the system response is a bulk mode pressure oscillation. To assure uniformity in amplitude and clarity of the driving frequency, the pressure signal is measured near the burner and used for active control of the acoustic drivers. Two burner configurations were used for most of the experiments. Both configurations consisted of a fuel jet, an eductor block, and a quartz flame stabilizing tube. The configurations differed in that the second configuration has small bluff-body tabs placed above the eductor so as to increase flame stability. The fuel jet entrains air, passes through the eductor, and stabilizes in the slower flow region behind the eductor (as illustrated in Figure 1).

Chemiluminescence imaging of both burners was performed with a CMOS-based camera capable of recording 1000 images per second. For both OH and NO PLIF, an intensified CCD camera was employed to capture the fluorescence signal. Over 1000 consecutive images were acquired for each frequency. Both cameras have 512x512 pixel resolution, although the NO PLIF required binning the pixels 2x2. The laser system employed for PLIF imaging was the same for both NO and OH measurements, consisting of an Nd:YAG pumped dye laser whose output was frequency doubled (for both OH and NO) and wavelength mixed (for NO only). Saturated fluorescence was achieved for both species, which required restricting the size of the imaging region. As a result, several image heights were combined in post-processing.

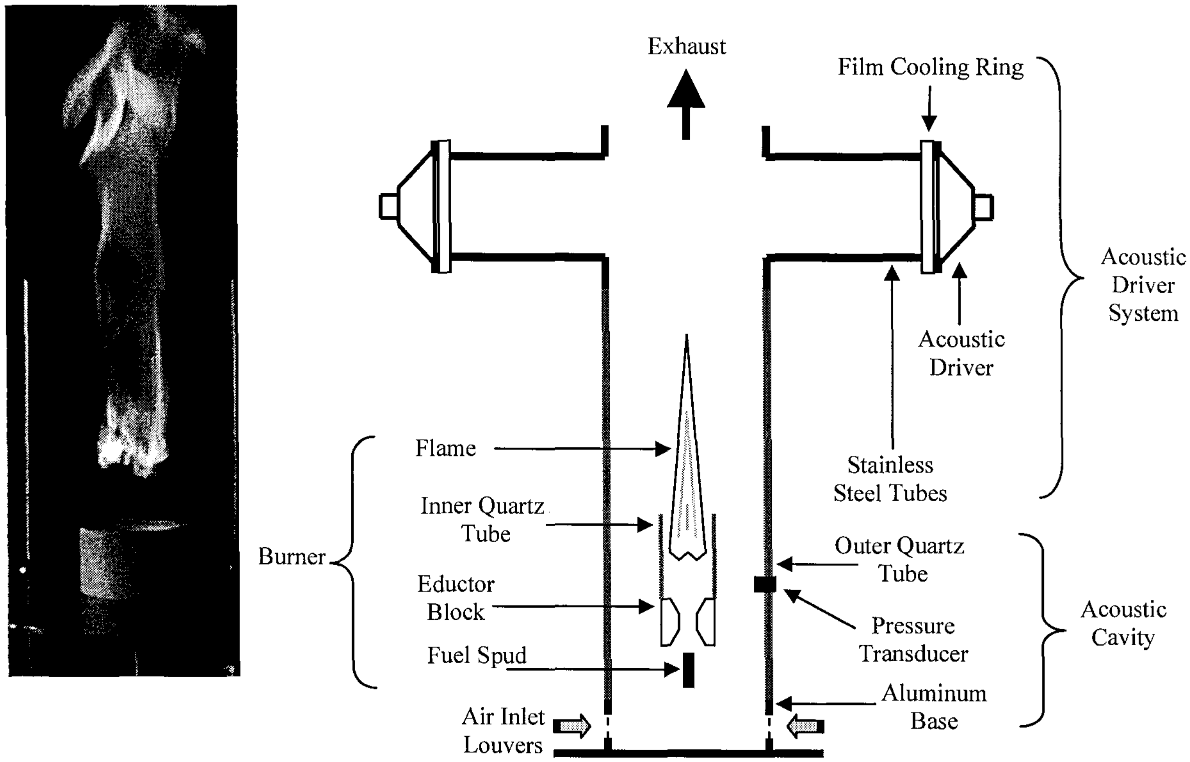

Figure 1. Schematic of acoustic chamber showing the flame and burner assembly. A photograph of the flame and eductor block is on the left.

For chemiluminescence, images were phase-locked to the pressure signal while for PLIF they were phase-averages. To determine the pressure phase dependent behavior of the system, images were separated or sorted into bins spanning 10° degrees of phase. The images in each bin were then averaged to produce a single image per 10° degrees of phase. From this, it is possible to determine the portion of each image that varies with the phase change and to correlate that variation to the sinusoidal pressure variation.

COMPARISON OF TECHNIQUES AND EXAMINATION OF MEASUREMENTS

When performing chemiluminescence, correlation with the pressure variation tends to highlight changes at the exterior boundaries of the flame due to the spatial smearing inherent in chemiluminescence. This smearing renders interior structures indistinguishable; hence fine variations in structures can not be measured. Conversely, PLIF is an ideal method for probing the internal flame structure since it images only the spatial regions illuminated by the laser. Flame base height and oscillation amplitude are indicators of flame stability and can be used to determine the impact of burner modification on stability. Chemiluminescence can measure these parameters and provide a description of the flame behavior. Figure 2 depicts plots of the mean flame base height and the amplitude of the flame base oscillation. The data, derived from chemiluminescence measurements, demonstrates the type of information that this diagnostic provides. The plots show that the peak responsiveness of the burner shifted from approximately 32 Hz to 38 Hz with the addition of the bluff-body tabs, evident in the peak locations.

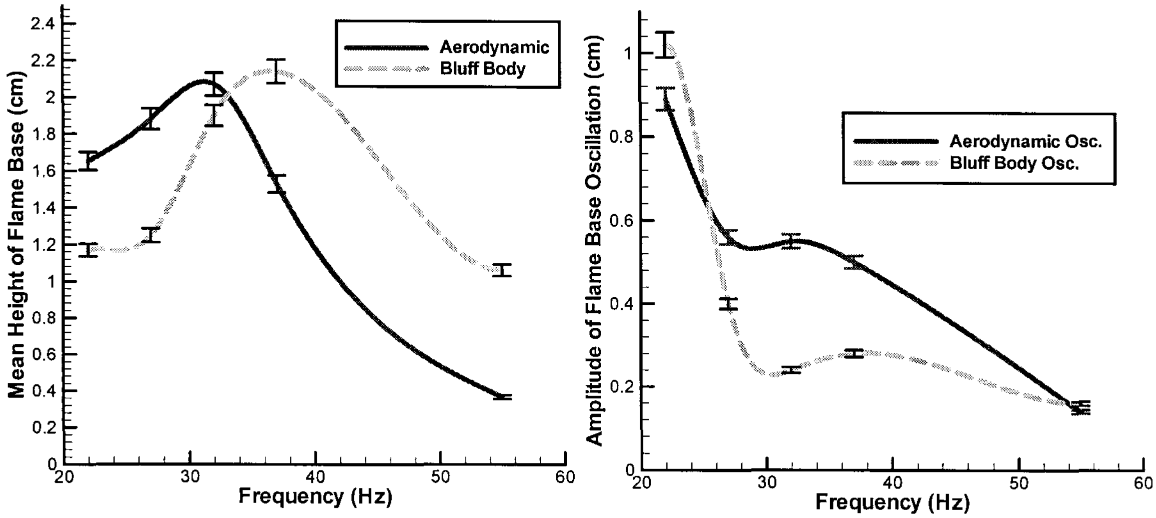

Figure 2. Mean height of flame base (left) and amplitude of flame base oscillations (right) for both the aerodynamically and bluff-body stabilized burner configurations. The experimental values are at the center of each error bar and the curves are splines fitted to those values.

Chemiluminescence data showed that the bluff-body tabs reduce the amplitude of the oscillation by approximately half over the 25 Hz to 50 Hz range. This indicates that for measurements of flame response with a measurable translation component, chemiluminescence can be a sufficiently detailed diagnostic to reveal the desired information. In this burner configuration, chemiluminescence shows that the flame stabilization zone above the quartz tube is affected by the acoustic field. The imaging also shows that the resonant frequencies induced a "puffing" mode, which likely has a strong impact on the height of the flame base oscillations. This could be an important mechanism to understand if modifications of the flame base oscillation behavior are to be attempted.

In some circumstances, chemiluminescence is either insufficient or does not measure the desired property. OH PLIF measures the OH concentration which is an approximate measure of local temperature in flame reaction product regions, and because of this, is useful as a relative indicator of heat release. For internal regions of the flame that experience flow or chemical structural changes, OH PLIF can provide a window into these processes. Similarly, NO PLIF measures the NO species concentration at each location, and consequently is a useful indicator of NO production. So to examine the responsiveness of the flame internal structure, it is useful to study some of the information derived from the OH and NO PLIF imaging.

Contour plots of Rayleigh index are shown in Figure 3. Rayleigh index is the correlation of heat release fluctuations with pressure oscillations; it, and its application to this data, is described in Pun et al (2002). This flame has a hollow core, which is evident in figure 3, plots C and D, but can not be ascertained from plots A and B. As a result of the same spatial smearing process, the calculated chemiluminescence-based Rayleigh index is not correct. Correspondingly, a global Rayleigh index would also be incorrect. The smearing effect has a similar impact on other global quantities that are structure dependent, and necessitates the use of PLIF to produce accurate results. Also, the ability to separate the responses of individual species can be useful.

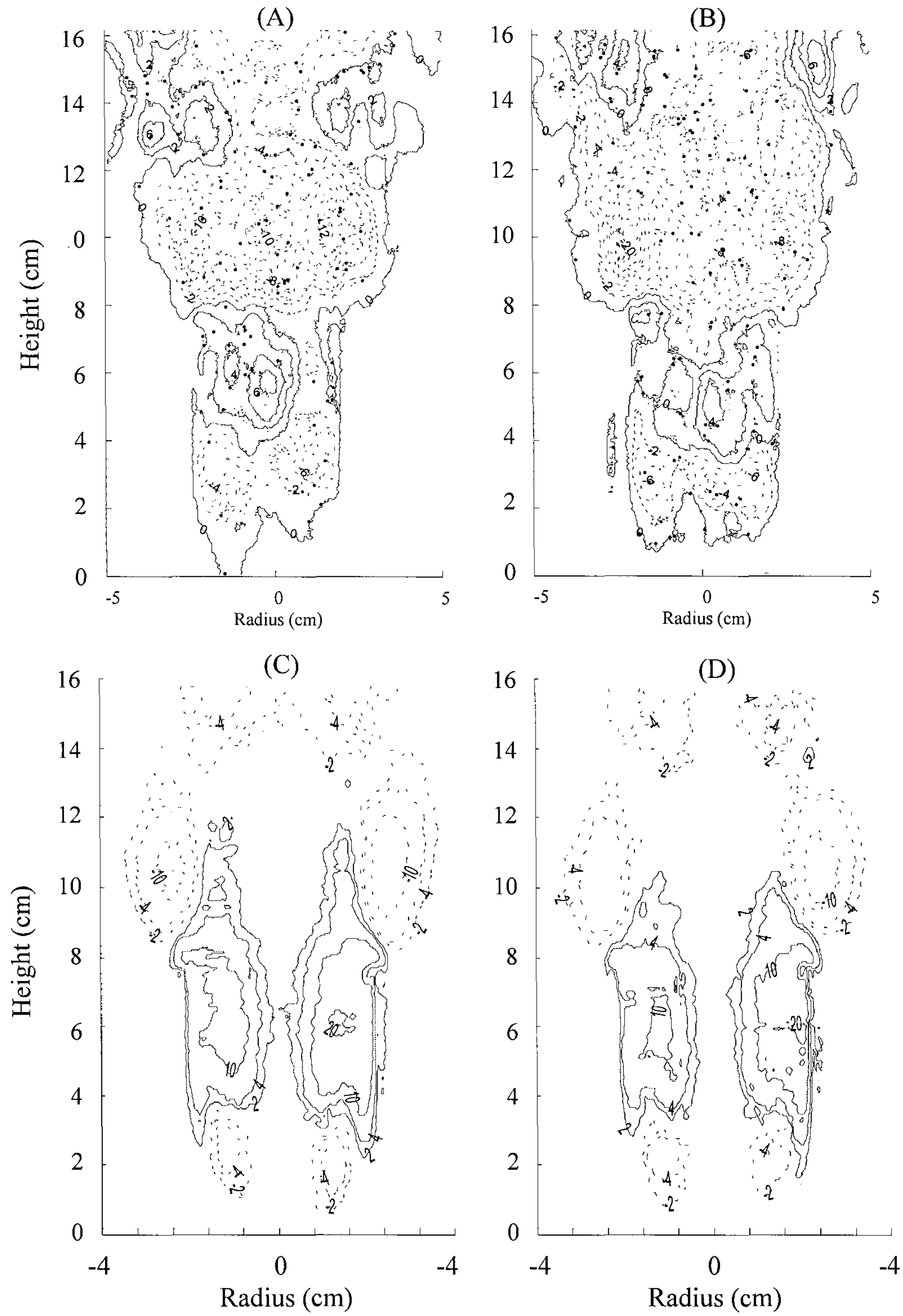

Figure 3. Contour plot of Rayleigh Index for 32 Hz driving frequency: chemiluminescence of (A) the aerodynamically stabilized burner and (B) the bluff-body stabilized burner, OH PLIF of (C) the aerodynamically stabilized burner and (D) the bluff-body stabilized burner (Pun 2001). Dashed contour lines indicate negative index values.

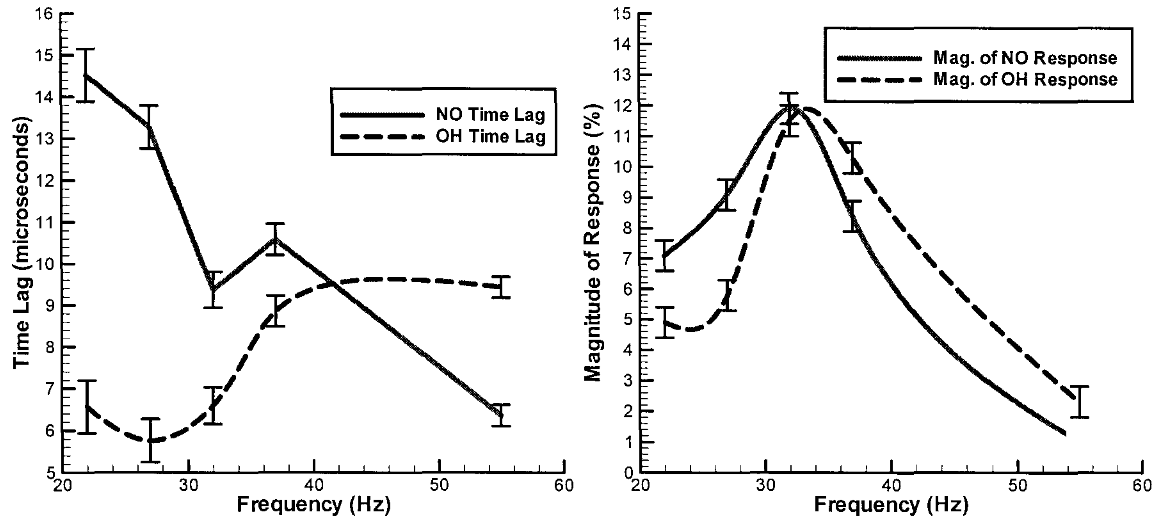

Figure 4. Time lag in microseconds of species concentration oscillation to pressure oscillation (left) and the magnitude in percent of the chemical species concentration oscillation versus its respective mean value (right).

Figure 4 plots the time lag between the pressure fluctuation and the chemical species concentration, and the magnitude of the response of the changes in species concentrations to the acoustic signal. The NO time lag is approximately linear with a resonance dip at 32 Hz. The NO time lag changes with frequency (and acoustic wavelength) such that if the wavelength doubles, the time lag doubles. The resonance dip in the NO time lag is at the same frequency as that where the whole flame experiences resonance (figure 4 shows data for the aerodynamically stabilized flame only). The magnitude of the response also shows the resonant nature of the flame, and that the OH has a slightly higher resonant frequency. A different mechanism appears to be responsible for the behavior of the OH time lag then is responsible for the behavior of NO.

It is known that NO (Paul et al. 1994) has significantly slower chemistry than OH (Paul 1994). OH should respond faster than NO and not show acoustic sensitivity, and thus exhibiting a uniform time lag. The plot indicates that the OH resonance dip appears to be much broader than that of the NO. Also, since the magnitude of the OH response drops-off at low frequencies in a fashion similar to the NO, the enlarged resonance dip is more likely due to a chemistry or reaction zone structure effects rather than general flame susceptibility to oscillations.

CONCLUDING REMARKS

Chemiluminescence, OH PLIF, and NO PLIF provide different types of information about different aspects of flame response to acoustic forcing. Chemiluminescence imaging can accurately measure flame oscillatory movement and be used to determine the impact on resonance of flame flow-field or chemical field modifications. As a low cost method that can be quickly implemented, chemiluminescence imaging is a useful tool for both industrial and research use.

OH and NO PLIF provide spatial localization and determination of flame chemical structure motion that chemiluminescence can not. PLIF imaging can be used to identify internal flame structure and its response to acoustic forcing, including Rayleigh index. This information is beneficial when the research goal is the examination of physical processes or the designing of new burners whose performance is to be optimized and susceptibility to acoustic fields is to be reduced.

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REFERENCES

Broda, J.C., Seo, S., Santoro, R.J., Shirhattikar, and Yang, V. (1998) "An Experimental Study of Combustion Dynamics of a Premixed Swirl Injector", *Proceedings of the Combustion Institute*, Vol. 27.

Cadou, C.P., Logan, P., Karagozian, A.R., and Smith, O.I. (1998) "Laser diagnostic techniques in a resonant incinerator", *Environmental Sensing and Combustion Diagnostics*, SPIE, Vol. 1434, pp. 67-77.

Cadou, C.P., Smith, O.I., and Karagozian, A.R. (1998) "Transport Enhancement in Acoustically Excited Cavity Flows, Part 2: Reactive Flow Diagnostics", *AIAA Journal*, Vol. 36, No. 9, pp. 1568-1574.

Chen, T.Y., Hegde, U.G., Daniel, B.R., and Zinn, B.T. (1993) "Flame Radiation and Acoustic Intensity Measurements in Acoustically Excited Diffusion Flames", *AIAA Journal of Propulsion and Power*, Vol. 9, No. 2.

Kappei, F., Lee, J.Y., Johnson, C.E., Lubarsky, E., Neumeier, Y., and Zinn, B.T. (2000) "Investigation of Oscillatory Combustion Processes in Actively Controlled Liquid Fuel Combustor", presented at the 36th Joint Prop. Conf., Huntsville, Al, AIAA 2000-3348.

McManus, K., Yip, B., and Candel, S., (1995) "Emission and Laser-Induced Fluorescence Imaging Methods in Experimental Combustion", *Experimental Thermal and Fluid Science*, Vol. 10, pp. 486-502.

Najm, H.N., Paul, P.H., Mueller, C. J., and Wyckoff, P.S., (1998) "On the Adequacy of Certain Experimental Observables as Measurements of Flame Burning Rate", *Combustion and Flame*, Vol. 113, pp. 312-332.

Poinsot, T.J., Trouve, A.C., Veynante, D.P., Candel, S.M., and Esposito, E.J., (1987) "Vortex-Driven Acoustically Coupled Combustion Instabilities", J. Fluid Mech., Vol. 177, pp. 265-292.

Paul, P.H. (1994) "A Model for Temperature Dependent Collisional Quenching of OH A2 Σ+", *Journal of Quantitative Spectroscopic Radiation Transfer*, Vol. 51, No. 3, pp. 511-524.

Paul, P.H., Gray, J.A., Durant, J.L., and Thoman, J.R. (1994) "Collisional Quenching Corrections for Laser-Induced Fluorescence Measurements of NO A2 Σ+", *AIAA Journal*, Vol. 32, No. 8.

Pun, W., (2001) "Measurements of Thermo-Acoustic Coupling", Ph.D. Thesis, California Institute of Technology, Pasadena, CA.

Pun, W., Palm, S.L., and Culick, F.E.C., (2002) "Combustion Dynamics of an Acoustically Forced Flame", submitted to *Combustion Science and Technology*.

Ratner, A., Pun, W., Palm, S.L., and Culick, F.E.C., (2002) "Phase-Resolved NO Planar Laser-Induced Fluorescence of a Jet Flame in an Acoustic Chamber with Excitation at Frequencies <60 Hz", submitted to the 29^{th} Symposium (International) on Combustion, Sapporo, Japan, July 21-26.

Rayleigh, J.W.S. (1945) **The Theory of Sound**, Vol. II, Dover Publications, New York.
Rijke, P. (1859) "Notiz über eine neie Art, die Luft in einer an beiden Enden offenen Röhre in Schwingungen zu versetzen", *Annal der Physik*, Vol. 107, pp. 339-343.
Shih, W.P, Lee, J.G., and Santavicca, D.A., (1996) "Stability and Emissions Characteristics of a Lean Premixed Gas Turbine Combustor", Twenty-Sixth Symposium (International) on Combustion, The Combustion Institute.
Sterling, J.D. and Zukoski, E.E., (1991) "Nonlinear Dynamics of Laboratory Combustor Pressure Oscillations", *Combustion Science and Technology*, Vol. 77, pp. 225-238.
Venkataraman, K.K., Preston, L.H., Simons, D.W., Lee, B.J., Lee, J.G., and Santavicca, D.A. (1999) "Mechanism of Combustion Instability in a Lean Premixed Dump Combustor", *AIAA Journal of Propulsion and Power*, Vol. 15, Iss. 6, pp. 909-918.