THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

98-GT-304

MEASUREMENT OF AIR-FUEL RATIO FLUCTUATIONS CAUSED BY COMBUSTOR DRIVEN OSCILLATIONS

Rajiv Mongia and Robert Dibble
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, CA

Jeff Lovett
Pratt & Whitney
West Palm Beach, FL

ABSTRACT

Lean premixed combustion has emerged as a method of achieving low pollutant emissions from gas turbines. A common problem of lean premixed combustion is combustion instability. As conditions inside lean premixed combustors approach the lean flammability limit, large pressure variations are encountered. As a consequence, certain desirable gas turbine operating regimes are not approachable. In minimizing these regimes, combustor designers must rely upon trial and error because combustion instabilities are not well understood (and thus difficult to model). When they occur, pressure oscillations in the combustor can induce fluctuations in fuel mole fraction that can augment the pressure oscillations (undesirable) or dampen the pressure oscillations (desirable). In this paper, we demonstrate a method for measuring the fuel mole fraction oscillations which occur in the premixing section during combustion instabilities produced in the combustor that is downstream of the premixer.

The fuel mole fraction in the premixer is measured with kHz resolution by the absorption of light from a 3.39 μm He-Ne laser. A sudden expansion combustor is constructed to demonstrate this fuel mole fraction measurement technique. Under several operating conditions, we measure significant fuel mole fraction fluctuations that are caused by pressure oscillations in the combustion chamber. Since the fuel mole fraction is sampled continuously, a power spectrum is easily generated. The fuel mole fraction power spectrum clearly indicates fuel mole fraction fluctuation frequencies are the same as the pressure fluctuation frequencies under some operating conditions.

INTRODUCTION

Lean premixed (LPM) combustion is the dominant method of meeting increasingly stringent air-quality regulations for nitrogen oxides ($NO + NO_2 \equiv NO_x$) emissions (Bowman, 1992). Unfortunately, a common problem encountered in LPM combustors is unacceptable combustor driven pressure oscillations.

Instabilities in lean premixed combustion

As a result of the nonlinear dependence of NO_x production on temperature, LPM combustors are operated under lean conditions. As conditions inside a LPM combustor approach the lean flammability limit, two types of combustion instabilities are encountered (Richards and Janus, 1997):

Static Instability – Flame extinction caused by slight changes in combustor inlet conditions. These result in unacceptably high levels of CO and of unburned hydrocarbons (UHC). Static instabilities are often avoided by using a non-premixed pilot burner, which contributes significantly to NO_x emissions.

Dynamic Instability – Oscillating combustion inside the combustor results in large pressure variations within the combustor. Dynamic instabilities are commonly solved by trial and error modifications to combustor geometry.

This paper will focus on a diagnostic tool, which aids the combustion engineer in understanding the nature of combustion instabilities.

Dynamic Instabilities

Numerous authors have studied dynamic instabilities in combustion systems; these include but are not limited to: Rayleigh (1878); Putnam (1971); Schadow and Gutmark (1991); Candel (1992); Culick and Yang (1995); Yang and Anderson (1995); and Richards and Janus (1997).

In most cases, the oscillations are characterized by a feedback mechanism between the heat release rate and the acoustic pressure. The Rayleigh criterion (Rayleigh, 1878) states that pressure oscillations are likely to occur if the pressure oscillations are in phase with the local heat release rate. Several mechanisms can cause the feedback such as: changes in mixing, changes in the supply of air and/or fuel, and vortex shedding. The dominant mechanism is strongly dependent on the combustor geometry and

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Stockholm, Sweden — June 2–June 5, 1998

operating conditions. The optical technique described in this paper allows measurement of the fuel mole fraction variations in the premixer of an operating combustor. This mechanism is believed to be an important contributor to dynamic instabilities and is the basis of numerous combustion active control techniques.

Laser Absorption by Hydrocarbons

The use of laser absorption in combustion systems has been demonstrated by several authors including Schoenung and Hanson (1981) and Nguyen *et al.* (1995) for the measurement of CO and temperature. Several authors have studied the absorption by methane of the infrared He-Ne laser transition at 3.39 µm. Emmerman *et al.* (1980) applied absorption tomography to a methane jet into air and obtained two-dimensional maps of methane concentration. Tsuboi *et al.* (1985) showed that ethane, propane, n-octane, and several other hydrocarbons also strongly absorb light from the 3.39 µm He-Ne laser. More recently, Drallmeier (1994) used the infrared He-Ne laser in conjunction with a visible He-Ne laser to measure the fuel vapor concentration of a fuel spray. The visible laser was used to account for absorption due to droplets in the optical path while the IR laser measured absorption due to droplets and hydrocarbon vapor. Mongia *et al.* (1996) used the 3.39 µm He-Ne laser in conjunction with fiber optics to create a fuel concentration optical probe with 5 mm spatial resolution and kHz temporal resolution.

The Beer-Lambert law relates the transmitted intensity I to the original intensity I_o by

$$\frac{I}{I_o} = \exp(-\alpha \cdot L \cdot P \cdot x_i) \qquad (1)$$

where L is the path length, α is the absorption coefficient, P is the pressure, and X_i is the mole fraction of the hydrocarbon. Greater detail on the spectroscopy of methane in this wavelength regime can be found in the diode laser work of Cline and Varghese (1990) and He-Ne laser work of Perrin and Hartmann (1989).

EXPERIMENTAL

Lean premixed combustor

In order to evaluate the laser absorption technique, the lean premixed, dump combustor operating on methane shown in Fig. 1 was constructed. The injection location is varied changing the degree of air-fuel mixing and the transit time between introduction of fuel and entrance to the combustion chamber. The premixing section has a diameter of 1.5 cm (except at the measurement location) and the combustion chamber has a diameter of 5.2 cm. The flow makes a 90° bend at the exit of the combustion chamber. At the exit bend, a sapphire window is installed so that it is possible to visually monitor the flame. The entire length of the combustion chamber is about 66 cm.

The fuel injector consists of a 6 mm tube with 6 radial holes for the injection of fuel. The holes each have a diameter of 1.4 mm and are spaced evenly around the circumference.

As shown in Fig. 1, 1 type S and 3 type K thermocouples are used to monitor the gas temperature as function of axial distance. The uncorrected thermocouple measurements indicate when steady-state conditions are reached.

Pressure in the premixing section (at the location of the fuel mole fraction measurements) is measured with a pressure transducer (Omega) with 1 msec time response. Figure 2 shows the orientation of the pressure tap with respect to the optical windows.

A mass flow controller (Sierra Instruments) controls the airflow. The air temperature is approximately 21 °C and the pressure is 1 atm. The methane flow was measured by a rotameter (Mattheson).

Infrared absorption technique

A line of sight absorption technique is used to continuously monitor the fuel mole fraction in the premixing tube. A transition piece was constructed to allow laser light to pass through the premixing section. A schematic of the transition piece is shown in Fig. 2. Light from an infrared (3.39 µm) He-Ne laser is passed through the premixer using two sapphire windows. The laser intensity is then measured using a liquid nitrogen cooled InSb detector. The signal from the detector is sampled by a computer data acquisition system that converts the transmission, I/I_o, into a methane concentration.

A low-pass filter with a cut-off frequency of 3 kHz was used before the sampling of the computer data acquisition system. The A/D board sampled at 6 kHz, sufficient to resolve fluctuations on the order of 3 kHz (Nyquist criterion). At each operating condition, four sets of data were recorded. Each set of data was taken over 2.5 seconds yielding 15,000 samples (60,000 points for each trial). During the recording period, the overall equivalence ratio did not change appreciably.

RESULTS AND DISCUSSION

Table 1. summarizes the two flow conditions used in these experiments. The mixing distance (for each condition) was varied between 17 cm and 39 cm.

Table 1. Experiment flow rates

Trial	Air flow (SLM)	Fuel flow (SLM)	Fuel pressure drop (kPa)	X_{fuel}	Φ
1	194	16	20	0.075	0.77
2	194	18	24	0.083	0.86

Measurements during non-reacting conditions

The extent of mixing as a function of mixing distance was measured during non-reacting conditions. Figure 3 shows the percent fluctuations in fuel mole fraction (X'_{rms} / X_{avg} x 100%, X'_{rms} being a temporal quantity) as a function of mixing distance. It should be noted that a finite amount of mixing occurs downstream of the measurement location and before the sudden expansion; therefore, the measurements are a qualitative measure of the extent of mixing into the combustor.

As expected, Fig. 3 shows that the air and fuel are better mixed at the measurement location as the injection distance is increased. Although the reason for the improved mixing, whether it be increased mixing time or some other cause, can not be determined from Fig. 3 alone, the end result is that the air and fuel are better mixed at the measurement location. This is measured for both equivalence ratios. The instrument resolution is also shown on Fig. 3. The limitation is a result of laser, detector, and data acquisition noise.

Measurements during reacting conditions

Figure 4 shows the measured temperature profiles for both equivalence ratios. As previously explained, the measurements are used to determine when the system has reached steady-state. Using the average temperature of 620 °C (for Φ=0.77) and 675 °C (for Φ=0.86), the sound speed is approximately 600 and 617 m/s. Therefore, with a combustor length of 66 cm, a longitudinal mode (1/4 wave) of approximately 250 Hz is expected.

Figure 5a shows the pressure in the premixer (under reacting conditions) as a function of time for Φ=0.86 with a mixing distance of 29.5 cm. Figure 5b is a power spectrum (obtained by a Fourier Transform of the time series measurements) of the pressure data and shows a discrete frequency peak at 285 Hz. This is close to the anticipated longitudinal mode of 250 Hz. When no combustion is present downstream of the premixer (non-reacting), the pressure fluctuations are below the limits of our pressure measurement system.

Figure 6a shows the pressure time series for Φ=0.77 with a mixing distance of 29.5 cm. Figure 6b is the power series of the data. The power spectrum shows a much smaller peak (at the fundamental frequency) than the Φ=0.86 data. As before, the discrete frequency (270 Hz) is close to the anticipated longitudinal mode.

Figure 7 summarizes the pressure measurements. As shown, for Φ=0.86, the pressure oscillations increase as the injection distance increases (pressure oscillations *increase* as fuel-air mixing *improves*). The *opposite* trend is measured for Φ=0.77. Thus, as has been experienced in industry, better air fuel mixing does not guarantee reduced pressure oscillations.

Figure 8a shows the fuel mole fraction in the premixer as a function of time for Φ=0.86 with a 29.5 cm mixing distance during reacting conditions in the combustor downstream of the premixer. Figure 8b is the power series of the fuel mole fraction and shows a discrete frequency at 285 Hz superimposed on the turbulent power spectrum of fuel mole fraction. This is the same frequency as the peak in the pressure power spectrum.

Figures 9a and 9b are the time series and power series of fuel mole fraction for Φ=0.77 with a 29.5 cm mixing distance during reacting conditions. In this case, there is not a discrete frequency in the power spectrum. One possible explanation is that fluctuations in the energy release rate, at Φ=0.77, (the driving force of instabilities) are inadequate to overcome the pressure damping forces and hence pressure oscillations are suppressed (when the air and fuel are relatively well mixed). Consequently, the fuel mole fraction is unaffected. However, Figs. 9a and 9b alone cannot prove this hypothesis; additional information is required.

Figure 10 summarizes the reacting fuel mole fraction measurements for Φ=0.86. Included are the percent fluctuations in fuel mole fraction (reacting), and the percent fluctuations in fuel mole fraction (non-reacting). Figure 10 shows that there are significant mole fraction fluctuations induced by the pressure oscillations during combustion at three discrete injection distances.

Figure 11 summarizes the mole fraction measurements for Φ=0.77. Again, there are significant mole fraction fluctuations induced by the pressure oscillations in the combustion chamber. As noted before, when the air and fuel are well mixed, the oscillations in mole fraction do not occur.

CONCLUSIONS

In this paper, we demonstrate a method for measuring the fuel mole fraction oscillations which occur in the premixing section during combustion instabilities produced in the combustor downstream of the premixer. The fuel mole fraction is measured with kHz resolution by the absorption of light from a 3.39 µm He-Ne laser. A sudden expansion combustor is constructed to test the usefulness of this technique.

We find that this technique is capable of measuring the extent of air and fuel mixing in the premixer. Under some flow conditions, significant concentration fluctuations are caused by pressure oscillations in the combustion chamber. We surmise that this is caused by pressure oscillations from the combustion chamber periodically impeding the flow of air and/or fuel. The mole fraction power spectrum clearly indicates that fuel mole fraction fluctuation frequencies are consistent with the pressure power spectrum under some of the conditions studied in this paper.

ACKNOWLEDGEMNTS

This research supported by the National Science Foundation through a graduate fellowship and by the Department of Energy's Advanced Turbine Systems Program through an AGTSR Summer Internship. Equipment purchased through a LACOR grant from Los Alamos National Labs.

REFERENCES

Bowman, C. T., 1992, "Control of Combustion Generated Nitrogen Oxide Emissions: Technology Driven by Regulation," 24th Symposium (International) on Combustion, pp. 859-878.

Candel, S.M., 1992, "Combustion Instabilities Coupled by Pressure Waves and Their Active Control," 24th Symposium (International) on Combustion, pp. 1277-1296.

Cline, D. S. and Varghese, P. L., 1990, "Tunable diode laser measurements of temperature dependent spectral parameters of formaldehyde and methane," 23rd Symposium (International) on Combustion, The Combustion Institute, pages 1861-1868.

Culick, F.E.C. and Yang, V., 1995, "Overview of Combustion Instabilities in Liquid-Propellant Rocket Engines," Liquid *Rocket Combustion Instability*, AIAA, Cambridge, MA, pp. 3-37.

Drallmeier, J. A., 1994, "Hydrocarbon-Vapor Measurements in Pulsed Fuel Sprays, " *J. of Applied Optics*, Vol. 33, No. 33, pp. 7781-7788.

Emmerman, P. J., Goulard, R., Santoro, R.J. and Semerjian, H.G., 1980, "Multiangular Absorption Diagnostics of a Turbulent Argon-Methane Jet," *J. of Energy*, Vol. 4, No. 2, pp. 70-77.

Mongia, R.K., Tomita, E., Hsu, F.K., Talbot, L., and Dibble, R.W., 1996, "Use of and Optical Probe for Time-Resolved In Situ Measurement of Local Air-to-Fuel Ratio and Extent of Fuel Mixing with Applications to Low NO_x Emissions in Premixed Gas Turbines," Twenty-Sixth Symposium (International) on Combustion, The Combustion Institute, 2749-2755.

Nguyen, Q.V., Edgar, B.L., Dibble, R.W. and Gulati, A., 1995, *Combustion and Flame*, 100: 395-406.

Perrin, M. Y. and Hartmann, J.M., 1989, "High temperature absorption of the 3.39 μm He-Ne laser by methane," *Journal of quantitative spectroscopy & radiative transfer*, Vol. 42, pages 459-464.

Putnam, A.A., 1971, *Combustion Driven Oscillations in Industry*, American Elsevier Publishers, New York, NY.

Rayleigh, 1878, "The Explanation of Certain Acoustical Phenomena", *Royal Institute Proceedings*, Vol. VIII, pp. 536-542.

Richards, G.A. and Janus, M.C., 1997, "Characterization of Oscillations During Premix Gas Turbine Combustion," To appear in the *ASME Journal for Gas Turbines & Power.*

Schadow, K.C. and Gutmark, E., 1991, "Combustion Instability Related to Vortex Shedding in Dump Combustors and Their Passive Control," *Progress in Energy and Combustion Science*, Vol. 18, pp. 195-205.

Schoenung, S.M. and Hanson, R.K., 1981, *Combustion Science and Technology*, 24: 227-237.

Tsuboi, T., Arimitsu, N., Ping, D. and Hartmann, J-M, 1985, "Light Absorption by Hydrocarbon Molecules at 3.392 • m of He-Ne Laser, " *Japanese Journal of Applied Physics*, Vol. 24, No. 1, pp. 8-13.

Yang, V. and Anderson, W., eds., 1995, *Liquid Rocket Combustion Instability*, AIAA, Cambridge, MA.

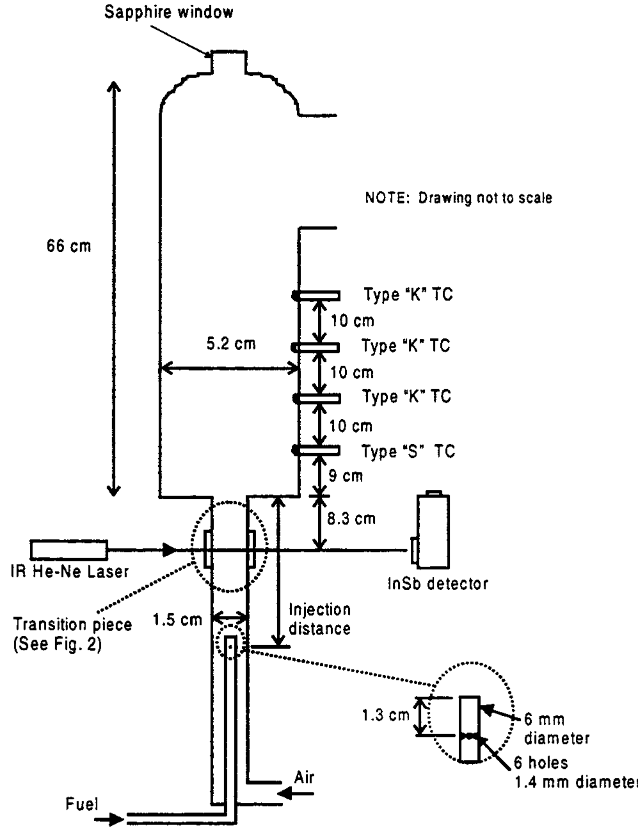


Figure 1. Schematic of sudden expansion combustor

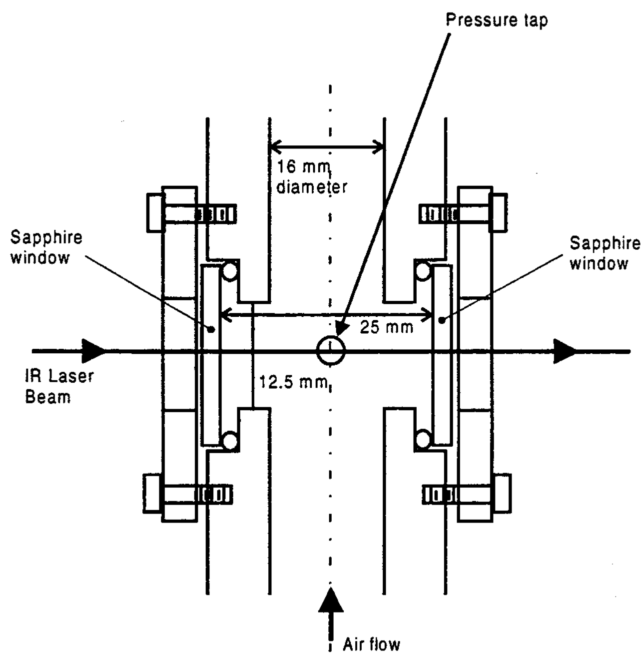


Figure 2. Schematic of transition piece in premix duct

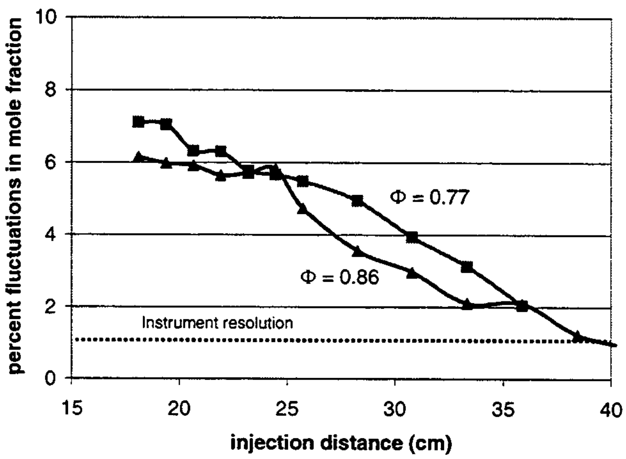
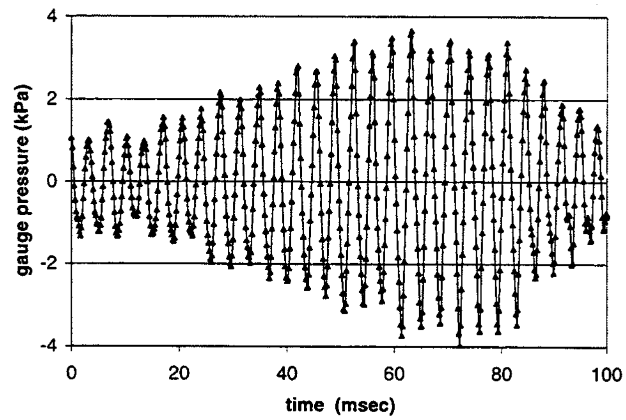
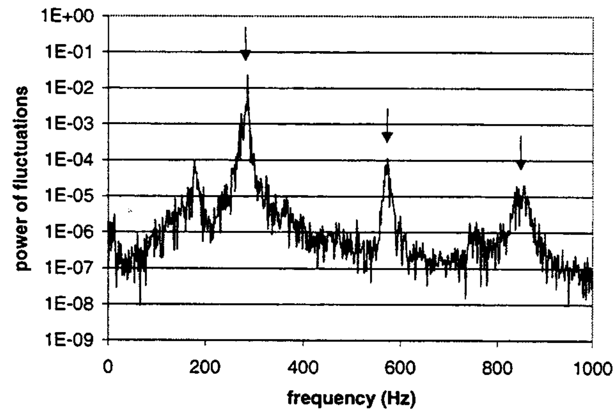


Figure 3. Extent of fuel mixing as a function of mixing distance



(a) time series of pressure



(b) power spectrum of pressure

Figure 5. Pressure fluctuations for Φ=0.86 and mixing distance of 29.5 cm (Note: peaks near 300, 600, and 900 Hz)

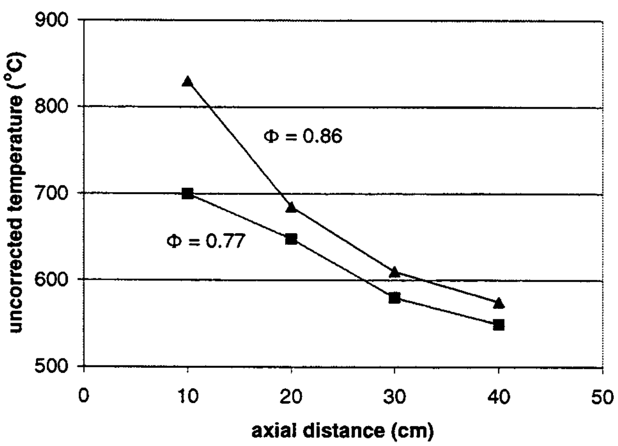
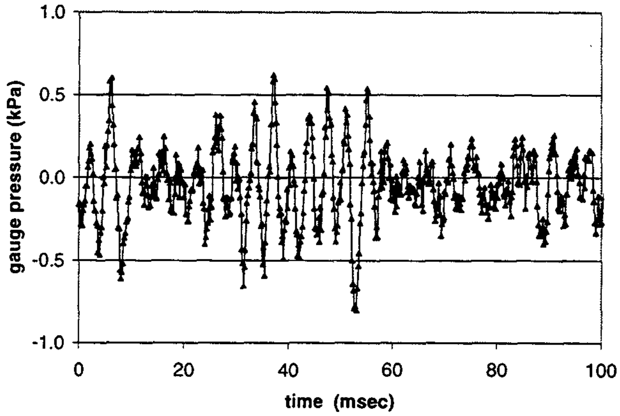
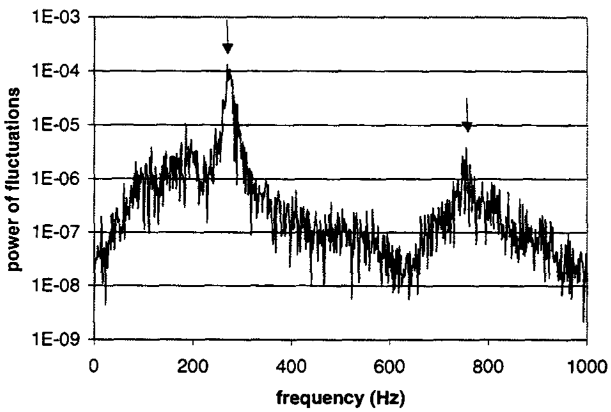


Figure 4. Steady state temperature profile (uncorrected)



(a) time series of pressure



(b) power spectrum of pressure

Figure 6. Pressure fluctuations for Φ=0.77 and mixing distance of 29.5 cm (Note: Peaks are less than that of Fig. 5b.)

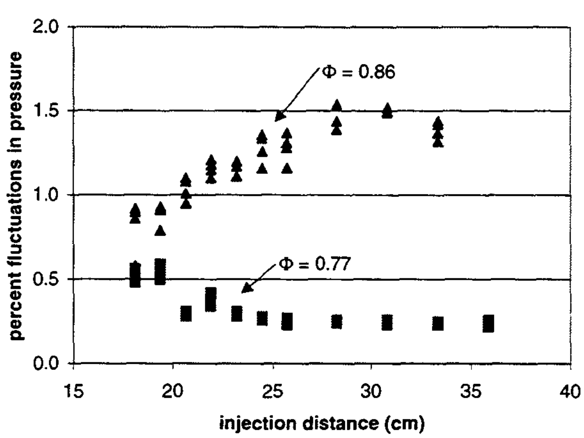
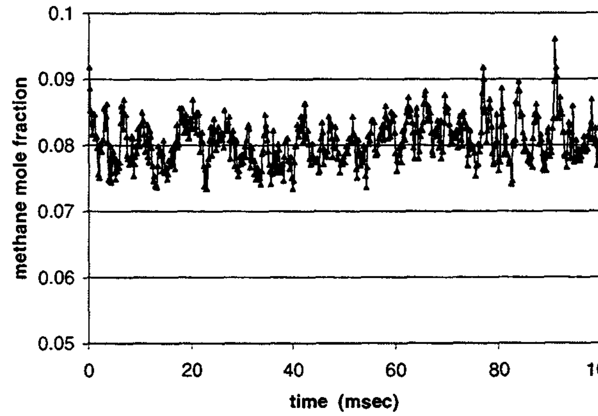
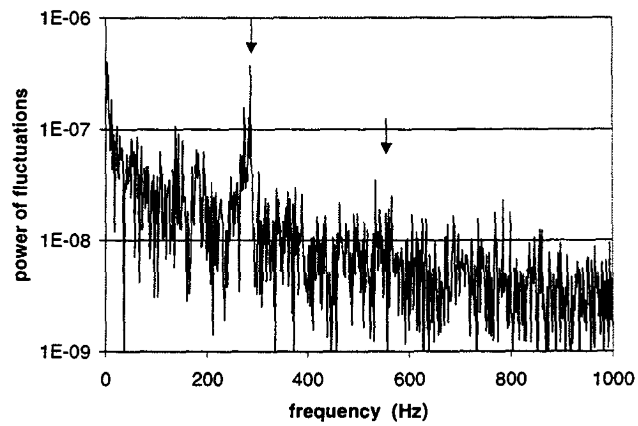


Figure 7. Summary of pressure fluctuations as a function of injection distance

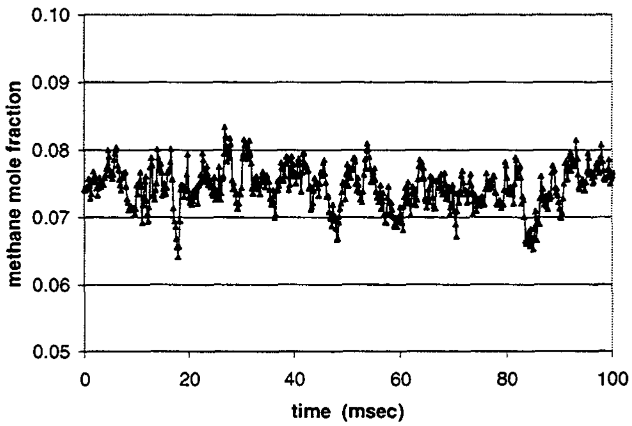


(a) time series of methane mole fraction

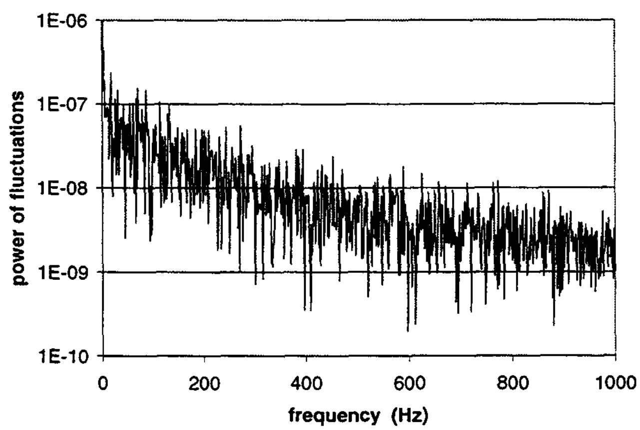


(b) power spectrum of methane mole fraction

Figure 8. Mole fraction fluctuations for Φ=0.86 and mixing distance of 29.5 cm



(a) time series of methane mole fraction



(b) power spectrum of methane mole fraction

Figure 9. Pressure fluctuations for Φ=0.77 and mixing distance of 29.5 cm

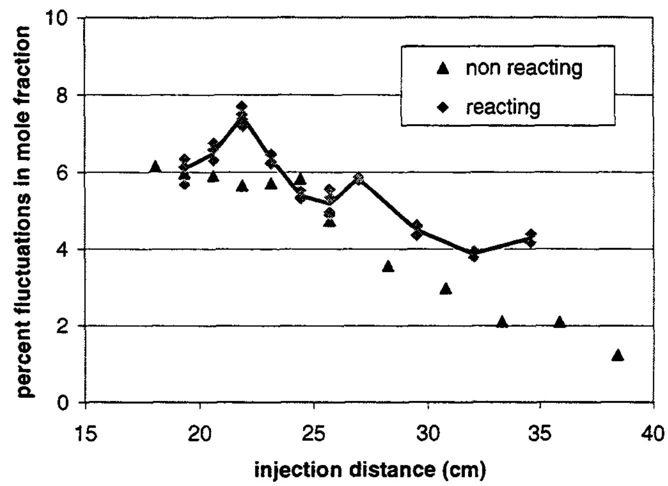


Figure 10. Summary of mole fraction fluctuations for Φ=0.86

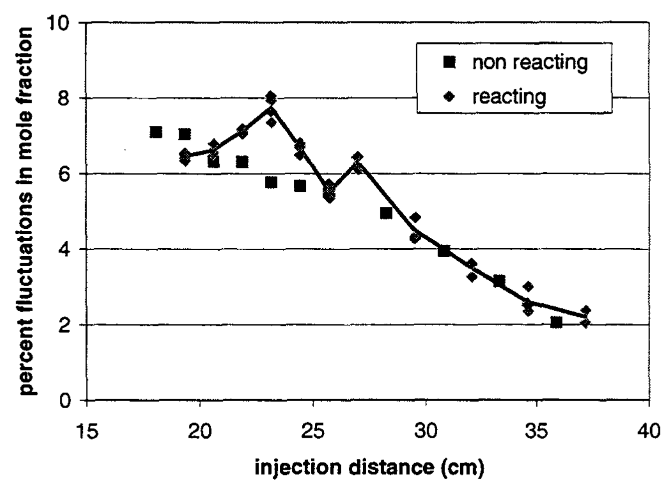


Figure 11. Summary of mole fraction fluctuations for Φ=0.77