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Experimental Study of Unsteady Laminar and Turbulent Flame Propagation in an Enclosure by Rayleigh Scattering

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Introduction

Unsteady flame propagation in enclosures is one of the classical experimental configurations for I.C. engines and flame propagation studies. Many different designs of enclosed combustion chamber have been developed to produce a wide range of initial temperature, pressure, and turbulence conditions [1 - 9]. Pressure transducers and/or thermocouples mounted to the chambers often serve as the primary diagnostics. Some chambers are fitted with windows providing optical access for flow visualization such as Schlieren. The use of flow visualization coupled with pressure transducers has been applied to address a wide variety of practical and fundamental problems including investigating the effects of ignition sources [1 - 5] and to determining turbulent burning speed [7 - 9]. Spatially and temporally resolved laser diagnostics have been less widely used to investigate the enclosed unsteady flame structures [6]. The difficulty in optimizing the signal-to-noise ratio when transmitting the laser and the light signals into and out of the chamber can be a deterrent. A further reason may be that the majority of the investigations is focused on observing or determining gross properties such as overall flame shape or flame speed which do not require the determination of detailed flame structure.

Knowledge of the flame structures, however, is significant for understanding the physical processes involved in turbulent flame propagation. As the enclosed combustion chamber is one of the most convenient means to investigate flame propagation and flame quenching under intense turbulence, the development and application of laser diagnostics in this configuration is needed. The use of Rayleigh scattering and laser Doppler anemometry (LDA) to open premixed turbulent flame configuration has shown that flame wrinkling due to turbulence is the predominant process in low Reynolds number turbulence flames [10]. The use of these techniques in an enclosed combustion chamber would help to determine the turbulent flame structures under intense turbulence and elucidate the turbulence quenching process.

Rayleigh scattering, an elastic light scattering technique where the incident light and the scattering light have the same wavelength, is a convenient diagnostic to infer time resolved density statistics of premixed combustion [1,6,11]. The Rayleigh scattering intensity of a gaseous mixture is given by:

$$I_R = K I_o N \sum x_i \sigma_{Ri} \quad (1)$$

where K is a constant for the optics, I_o is the incident laser intensity, N is the total number density of the gas, x_i is the mole fraction of species i, and σ_{Ri} is the Rayleigh scattering cross section of species i. σ_{Ri} is given by:

$$\sigma_{Ri} = \frac{4\pi^2}{\lambda^4} \frac{(\eta_i - 1)^2}{N_0^2} \quad (2)$$

where λ is the laser wavelength, η_i is the index of refraction of species i at S.T.P., N_o is the Loschmidt number. In brief the scattering process obeys the relationship:

$$I_R \propto I_o \rho \sigma_{Ri} \quad (3)$$

where ρ is the mixture density and σ the average Rayleigh cross section for the molecules within the sample volume. Thus for a known mixture composition a measurement of Rayleigh scattering signal intensity is a direct measure of the density [11].

Although Rayleigh scattering information cannot be used to determine species concentrations the technique has a much higher signal levels than most other molecular scattering processes. Its application in an enclosure is, however, affected by stray light reflecting off windows and wall surfaces in addition to interference associated with flame and background scattering and Mie scattering from dust. Procedures to minimize these effects include painting the internal walls of the cylinder black, filtering the gas mixture and subtracting the flame and background intensity from the raw Rayleigh signal.

The objective of this paper is to investigate the flame structure of unsteady laminar and turbulent flames using of Rayleigh scattering. Also, given the possible significance of the initial conditions, three different ignition sources have been used to determine their impact on flame structure and the burning rate. As the effects of the ignition source have traditionally been investigated under laminar or quiescent initial conditions, our turbulent results will provide interesting insights into the relative significance of the ignition source and turbulence in enhancing the burning rate.

Experimental System and Apparatus

The enclosed combustion chamber is a cylindrical stainless steel vessel fitted with quartz windows and ports for optical access and instrumentation. It is 90 mm in diameter by 90 mm in length. The circular ends of the cylinder provide mounting sites for windows and other instrumentation. The ignition source is installed in one of the four instrument ports mounted orthogonally at the center of the cylinder. The current

configuration includes of a metal plate covering one of the window openings in which a turbulence generating fan can be installed when necessary.

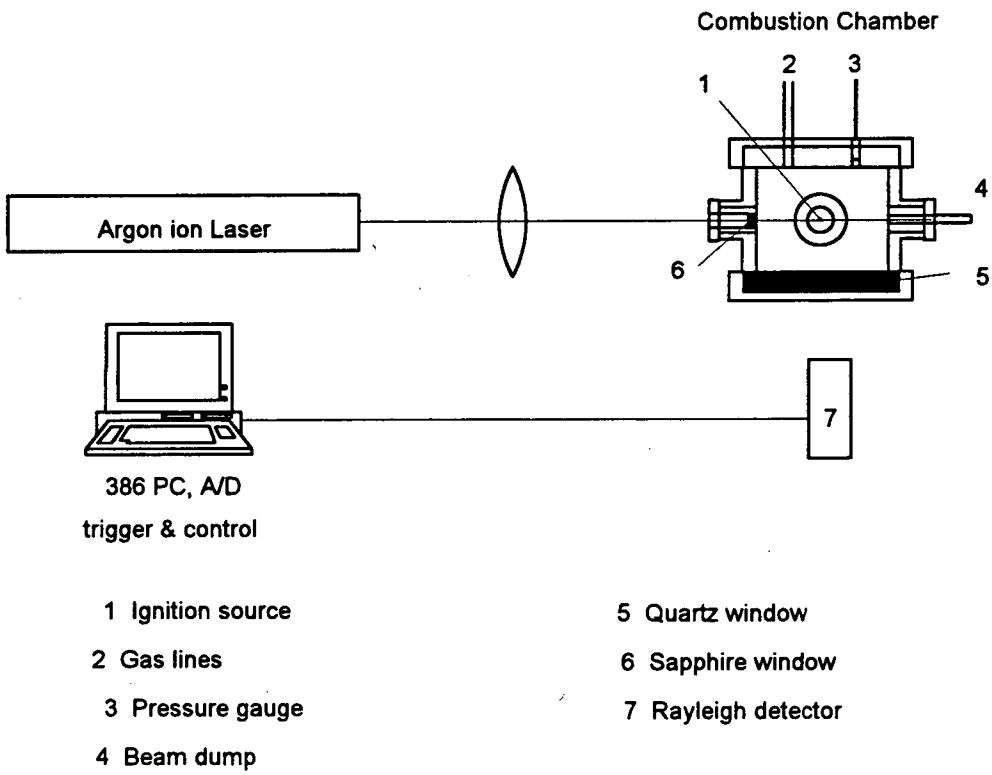

Figure 1 Schematic of the apparatus and diagnostics systems.

The Rayleigh scattering system is shown schematically in Figure 1. The 4 watt argon ion laser beam enters the vessel through a small sapphire window mounted on one of the side ports and exits through a beam dump on the opposite port. A lens and photomultiplier assembly monitor the Rayleigh scattering intensity at the beam waist though a quartz window mounted on the remaining large circular opening. The beam waist is positioned at the geometric center of the vessel. The combustion chamber is also fitted with a Kistler Mod. 613B piezoelectric pressure transducer with its diaphragm coated with vacuum grease to reduce thermal strain during combustion operation. The pressure transducer was calibrated statically and dynamically and the linearity of the instrument was checked using a dead weight meter. Sampling of the Rayleigh scattering and pressure transducer signals is interfaced with a data acquisition system based on a 386 PC.

Three ignition sources were used : i) a conventional spark plug, ii) a Pulsed Jet Combustion (PJC) and iii) Pre-Chamber Ignition (PCI). PJC and PCI are generated within a 0.5 cm^3 cavity with a 2mm diameter discharge orifice[1,4,5] fitted at the top of a 14 mm ignition plug. A high voltage electrode tube place in the center of the cavity admits the charge into the cavity. To operate in the PJC mode, the cavity is filled with a

rich propane/air mixture (ϕ = 1.5). PCI is generated with the cavity filled with the test mixture in the main chamber. Ignition for all modes is achieved by an electric spark using a standard automobile coil delivering about 60 mJ in 3.5 msec.

All the experiments were performed using lean propane air mixtures at an initial pressure of 5 atmosphere. At this elevated pressure, the Rayleigh scattering intensity is high and the effects of flame and background scattering are significantly reduced. Turbulence inside the enclosure is generated by a 2" diameter fan running at 7200 rpm for 1 minute before each test. The fan is turned off prior to ignition. Hot-wire measurement of the turbulent field indicates that while relatively high turbulence is generated, the fan also creates flow circulation with mean velocity ranging from 4 to 6 m/s. The turbulence intensity is 10% relative to the mean flow circulation. Even though the flow circulation would have some effect on the turbulent burning rate, it is not very significant for investigating the effects of the different ignition sources.

Results and Discussion

The equivalence ratio of the air/propane mixture in the test chamber was varied from ϕ=0.5 to ϕ=1.0. A series of tests was carried out to determine the low misfire limit (LML) for the three. The LML for conventional spark plug (referred to from here on as FTC -"Flame Traversing the Charge" according the nomenclature of Oppenheim) is ϕ=0.65. The LML for PJC and PCI are lower at ϕ=0.55.

The normalized Rayleigh scattering intensities and pressure records obtained for quiescent and turbulent cases with ϕ=0.65 are compared in Figure 2. The time origin is the time when the spark is fired. For PJC and PCI, this corresponds to 15 msec after the injection of the cavity mixture. Beginning with the quiescent FTC (top left), it can be seen that the Rayleigh scattering signal shows a slight increase in density prior to the sharp decrease due to the passage of the flame at 63.5 msec. The density increase due to the isentropic compression of the reactants is confirmed by the thin broken line which shows the relationship $p.v^{\gamma}$ = constant with γ=1.35. An increase in the product density after the flame has passed indicates the continuing compression and is predicted by the lower broken line using γ = 1.21 corresponding to the adiabatic flame temperature of the test mixture. The products compression is observed until 125 ms when the signal is overwhelmed by Mie scattering from water condensation on the windows and flame luminosity. The pressure trace shows that the peak pressure attained during the process is about 26 atm. At the time when the flame crosses the Rayleigh probe (i.e. the geometric center of the chamber) only 5% of the mass of the test mixture is burned and the Rayleigh signal is overwhelmed when 62% is burned.

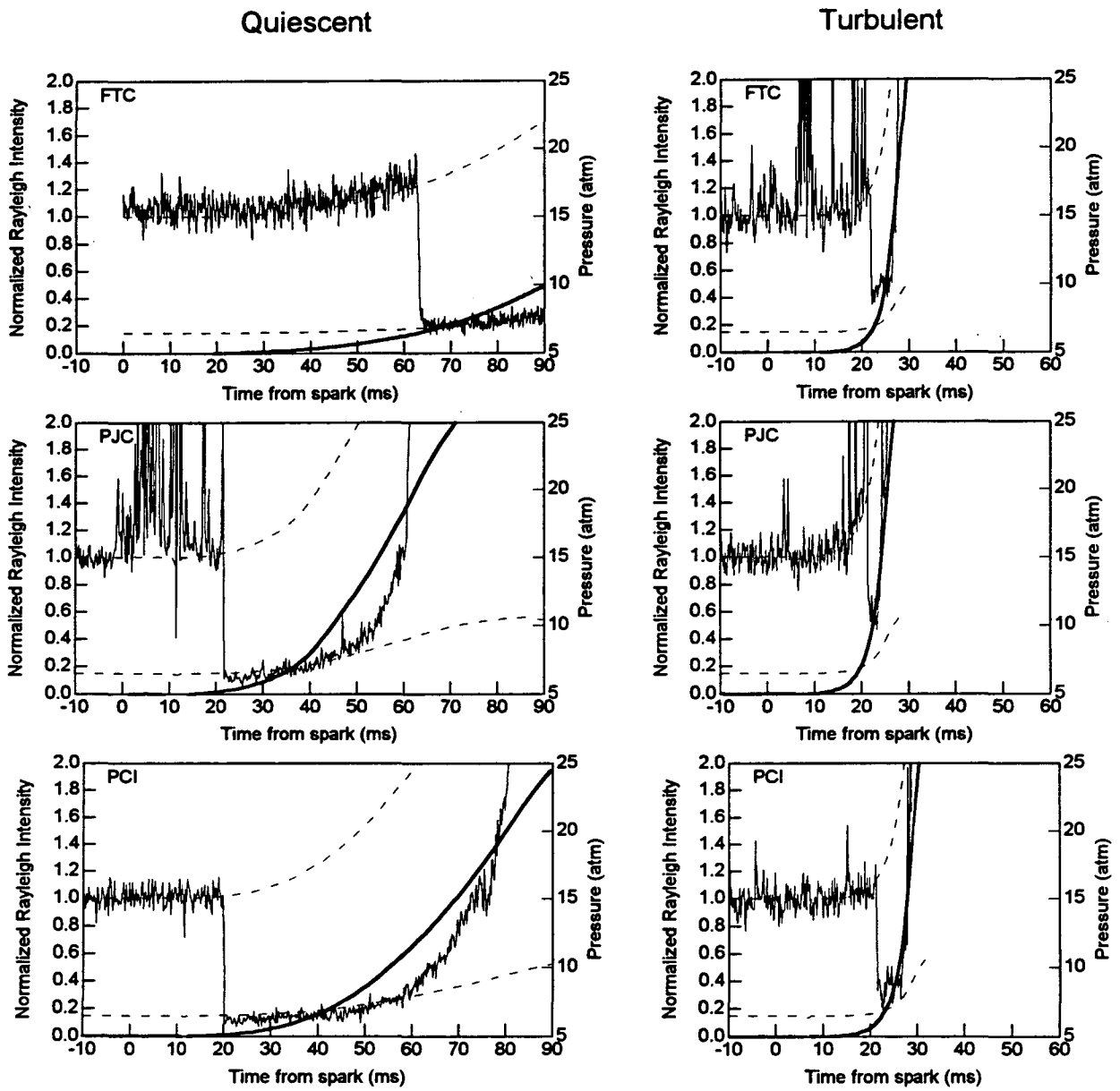

Figure 2 Comparison of Rayleigh scattering signals and pressure traces obtained for unsteady flame propagation in propane-air mixtures of ϕ = 0.65 at 5 atm. initiated by three ignition sources under quiescent (left) and turbulent (right) conditions. Pressure traces are shown by the heavy solid line.

Similar features occur in the quiescent PJC and PCI cases (Fig. 2 center left and bottom left respectively). The wrinkled flamelet model, therefore, should provide a valid description of the flame structures for these flames. With PJC, however, the compression of the reactants is not as clearly shown due to the Rayleigh signal ahead of the flame contaminated by noise spikes and by the fact that the flame reaches the probe volume much sooner than for the FTC. The noise spikes are probably associated with the injection of oil droplets or particles from the pumping action. The

flame for PJC and PCI both reach the chamber center at about 20 msec (t_f in Table 1). Compression of the burnt gases can be observed until about 50 msec when the signal begins to show signs of corruption due to condensation. Both PJC and PCI have a more rapid pressure rise than FTC indicating a significant increase in the burning rate. However, flame passage occur at 7% of the total mass burned which is comparable to that observed in FTC. Relevant pressure parameters and t_f for these quiescent cases are shown in Table 1.

	P_{max} atm.	t at P_{max} msec.	$(dP/dt)_{max}$ atm/msec	t at $(dP/dt)_{max}$ msec	t_f msec	n_v
FTC	26.1	196.0	0.275	114.0	63.0	0.61
PJC	30.0	91.0	0.64	60.5	21.6	0.23
PCI	28.4	115.0	0.48	78.5	20.0	0.23

Table 1

The Rayleigh scattering signals and pressure traces observed for the three turbulent cases shown on the right are very similar. The Rayleigh scattering noise levels prior to flame arrival are generally higher. This may be due to the fan churning up dust particles inside the chamber. The sharp drop in density as the flame crosses the Rayleigh probe is also shown though it is not as easily to discern as in the quiescent cases due to the noise. The density in the products is higher than predicted by assuming adiabatic heat release. Whether or not this is an artifact of the reduced signal-to-noise ratio needs further study. But it is clear that the structure of the flame is independent of the ignition source and the turbulent conditions.

	P_{max} atm.	t at P_{max} msec.	$(dP/dt)_{max}$ atm/msec	t at $(dP/dt)_{max}$ msec	t_f msec	n_v
FTC	33.8	35.8	3.56	28.0	21.8	0.34
PJC	33.4	32.0	3.72	25.5	21.3	0.34
PCI	33.3	37.2	3.78	29.0	21.3	0.18

Table 2

As shown in Table 2 the flame crosses the Rayleigh probe at about 21 msec for all three cases. These results are quite different from the quiescent cases where flame arrival of FTC lags far behind that of PJC and PCI. The reason for the significant difference in the quiescent cases can be explained by the difference in the flame shape as shown in high speed schlieren movies [4]. For FTC, the shape of the unsteady flame is hemispherical while the plume generated by PJC and PCI is elongated and projected much faster towards the chamber center. Using the schlieren silhouette as an indicator of the volume burned, Maxson and Oppenheim [4] have compared the fraction burned deduced from pressure record with that derived from schlieren. The discrepancy shown for the PJC cases lead them to conclude that for PJC burning may not take place in thin flamelets. Although high speed schlieren movies for the turbulent cases are not yet available, the fact that the flame arrival time for quiescent and

turbulent PJC and PCI are about the same time suggests that turbulence and/or convection may have significantly disrupted the development of the plume to account for the difference in the corresponding pressure rise.

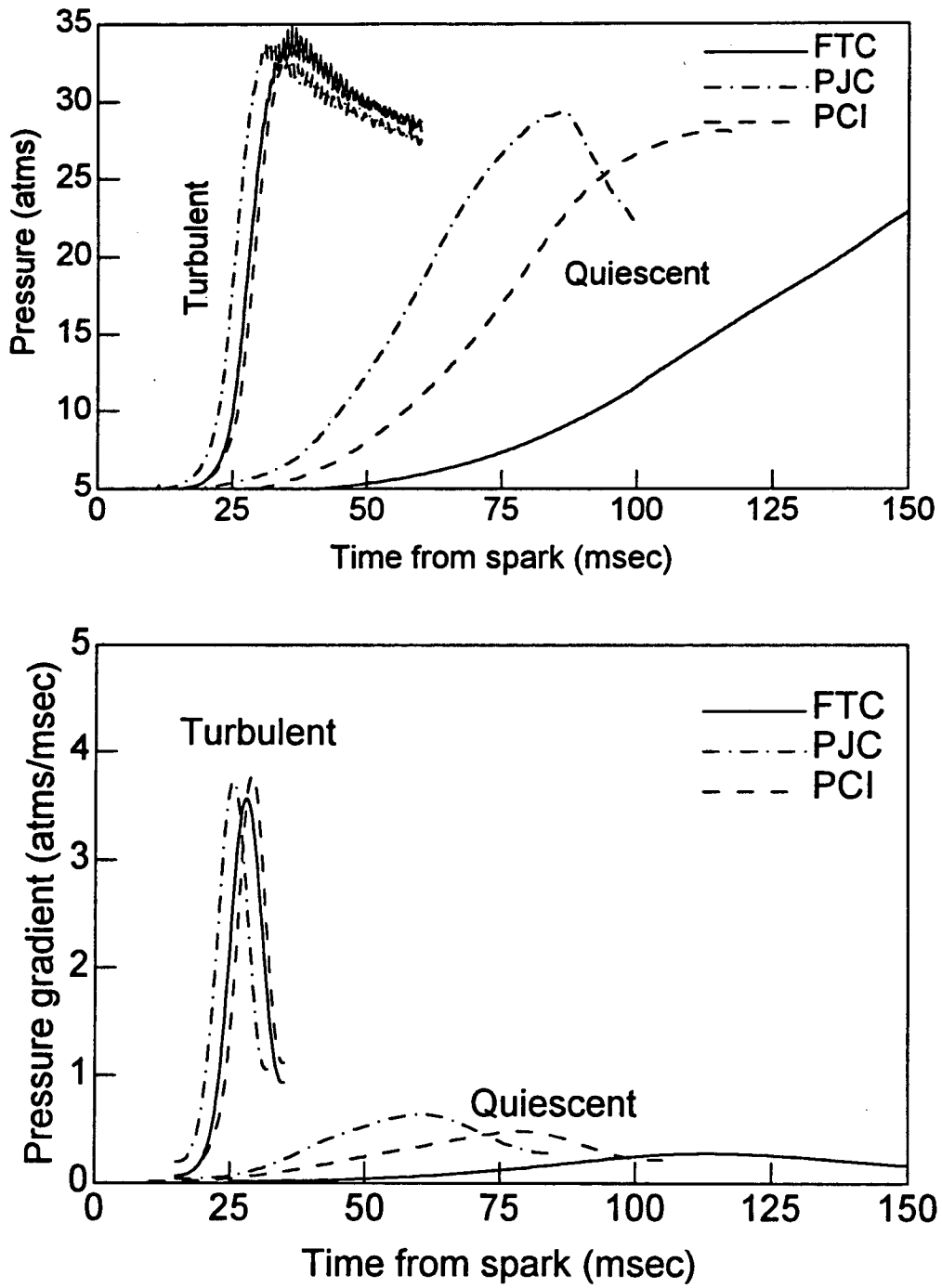

Figure 3 Pressure records obtained for propane/air flames with $\phi = 0.65$

Shown in Figure 3(a) are the pressure traces for the cases given in Figure 2. The turbulent pressure traces are almost identical while the quiescent cases show larger differences in both the peak pressure and time to attain peak pressure. The turbulent pressure traces have significantly higher compression rates as compared to the quiescent cases. The time rate of change in pressure, dP/dt, is directly proportional to the burning rate and it would be useful to determine the peak pressure gradient, $(dP/dt)_{max}$ to quantify the relative significance of turbulence and ignition source in enhancing the burning rate. The pressure gradients shown in Fig 3(b) are obtained by cubic splines of the pressure traces. The significant differences in the $(dP/dt)_{max}$ between the quiescent and turbulent cases are apparent.

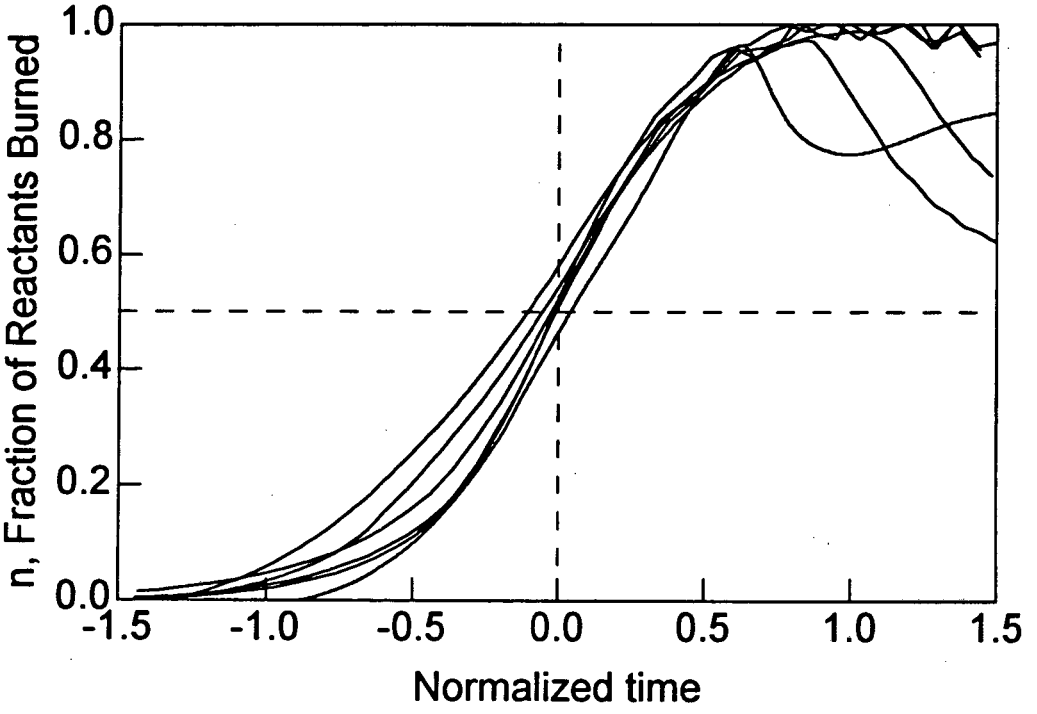

Figure 4 Normalized pressure traces to shown fraction of reactants burned for $\phi = 0.65$ cases.

To demonstrate that the $(dP/dt)_{max}$ results provide a consistent means for comparing the peak burning rates, the pressure traces are plotted in terms of the fraction burned, n [12] and the normalized time t^*. The fraction burned is defined by $n = (P - P_0)/(P_{max} - P_0)$ where P_{max} is the peak pressure attained and P_0 is the initial pressure, and the normalized time is defined by ; $t^* = (t - t_1)/(t_2 - t_1)$ where t_1 and t_2 are respectively the time when $(dP/dt)_{max}$ and P_{max} are attained. As shown by the results in Figure 4, the $(dP/dt)_{max}$ points all occur near $n = 0.5$. Comparison of the peak burning rate deduced for all cases are shown in Figures 5 and 6.

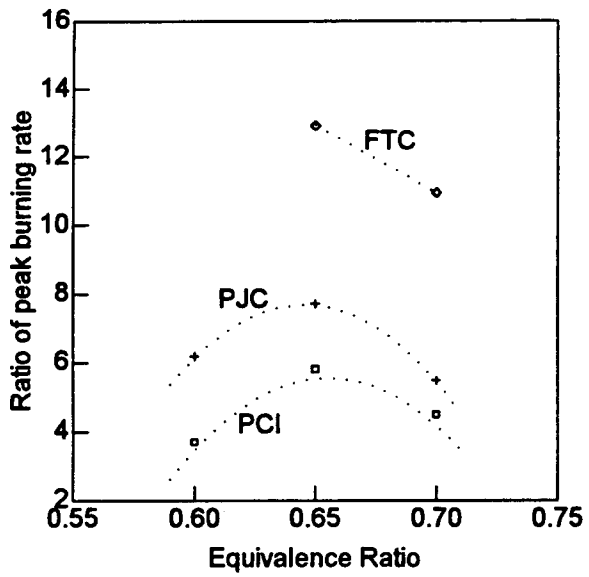

Figure 5 Comparison of the peak burning rate between turbulent and quiescent cases.

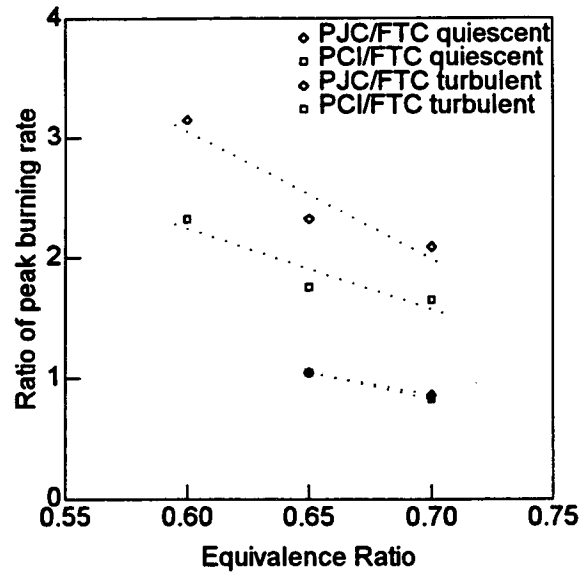

Figure 6 Ratios of the peak burning rate generated by different ignition sources.

Figure 5 shows that turbulence has the most significant enhancement of the burning rate for the FTC. The 12 to 14 times increase is much higher than those measured in open premixed turbulent flame systems with comparable turbulence levels. However, it should be noted that the fan generates a circulating flow as well as turbulence. The increase in burning rate shown here is therefore a combined effect. The use of more than one fan to reduced the amount of circulation may be necessary. Though the increase in the PJC and PCI peak burning rates by turbulence are smaller, the results demonstrate that turbulence is the dominating process in controlling the burning rate.

The effect of the ignition source on the burning rate is shown in Figure 6. For the quiescent cases, the increase in burning rate by PJC and PCI over FTC is between 2 to 3 times. In open flame systems, this size of increase can be achieved by introducing 5% turbulence in the incident flow. The results also imply that the mechanism responsible for the increase in burning rate by PJC and PCI is most likely associated with the wrinkling of the initial flame kernel during the injection of the cavity fluid into the main chamber of the vessel. For the turbulent cases, the results show that the burning rates for all ignition sources to be equal indicating that the unsteady turbulent flame propagation rate is independent of the ignition source.

Although our study has demonstrated that the Rayleigh scattering technique can be applied successfully to investigate unsteady flame structures, it will be observed that the measurements can only be obtained during the early stages of flame propagation. This is due in part to the physical constraints of the chamber such that the Rayleigh scattering probe volume can only be located near the geometric center of the chamber. As shown by n_V in Tables 1 and 2 which is the fraction of reactants burned at time when the Rayleigh signal is corrupted, except for the quiescent FTC, the values are all

less than 0.35. These results show that interrogating the flame structures at or during peak burning period is not possible. This constitutes a significant limitation for the use of this technique for the investigation of the entire burning to determine if the flame structure retain its flamelet character.

Clouding of the windows and flame luminosity will also affect the use of other diagnostics for determining the burning speed. In the past, the burning speed has been derived from the rate of growth of the flame kernel shown by high-speed schlieren movies. A better method is the use of tomographic technique will show the cross-sectional geometry of the flame kernel. Tomography requires an unimpeded field of view. Therefore, useful results can be obtained only for a short time after ignition during which time relatively little mass is burned. The main drawback is that the pressure records which does not change significantly in the early stage cannot be used to provide a reference for the burning rate derived from the flame wrinkle geometry.

Conclusion

The Rayleigh scattering technique has been used to investigate the flame structure of unsteady propane/air flames propogating under quiescent and turbulent conditions initiated by three ignition methods: (1) conventional spark plug (2) pulse jet combustion (PJC) and (3) Pre-Chamber ignition (PCI). The Rayleigh signal obtained for the laminar cases are all characterized by a sharp transition associated with the large density change which occurs as leading flame front of the expanding flame kernel crosses the measurement point. This indicates that the local flame structures are independent of the ignition source and may be characterized as flamelets. The maximum burning rates deduced from the pressure records show that PJC and PCI increases the burning rate from two to three times above that of conventional spark ignition.

The Rayleigh scattering signal obtained for the turbulent cases are also characterized by sharp transition. The wrinkled laminar flamelet model, therefore, provides a valid description of the flame structures for all these unsteady flames. For a given equivalence ratio, the maximum turbulent burning rate deduced for the three turbulent cases with different ignition sources are similar. This suggests that while PJC and PCI enhances burning rate when conditions in the chamber are quiescent, the enhancement is not significant when turbulence fluctuations are present. The PJC and PCI, however, are capable of igniting leaner conditions than the spark plug. This may be due to the injection process which initially disperses ignition sites to a larger volume at a faster rate.

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