A Study of Deflagrations in Stratified Mixtures of Liquefied Petroleum Gas

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ABSTRACT

This paper introduces a laboratory configuration to study deflagrations of stratified mixtures of liquefied petroleum gas (LPG). Stratified deflagrations form an important hazard in industrial safety since leakages of fuel tends to lead to the formation of concentration gradients over the accumulated surface with mine galleries being a classical example. The chamber is made of Perspex walls with an internal square cross-section of 50x50 mm and a height, H = 255 mm giving an overall volume of ~0.63 Liters. The mixture of LPG-air with an equivalence ratio φ_1 is introduced through a porous bronze plate at positioned at the base of the chamber. Stratification is imposed by bursting and igniting a mixture with an equivalence ratio φ_2 through the same porous bronze plate. The duration of the φ_2 burst is critical to ensure that the ignited mixture propagates through a relevant concentration gradient. For a stratification level from $\varphi_1 = 0.85$ to $\varphi_2 = 1.1$, it is found that the flame speed as well as the peak pressure increase to reach the higher level expected for $\varphi_2 = 1.1$ even though the amount of mixture injected at that higher equivalence ratio is small compared to the total volume of the chamber. Additional research is planned to optimize the thickness of the φ_2 layer and hence the stratification level as well as include repeated obstacles in the path of the propagating flames.

KEYWORDS: Deflagration, LPG.

INTRODUCTION

The study of combustion in compositionally stratified mixtures is at least six decades old with early research direct to understand and reduce explosions hazards in coal mines [1-3]. Stratified layers of methane-air mixtures similar to those formed on the ceiling of mine galleries were investigated leading to the first reports on the formation of triple flames [3]. More recent research in stratified combustion was necessitaed by other engineering applications such as direct injection engines where the spray dynamics is controlled to induce mixture stratification at relevant locations to sustain ignition and flame stability while maintaining overall lean combustion [4]. In gas turbines, flames are generally lifted from the base with turbulent partial premixing dominating the stabilization region. Stratification is also induced by the presence of thermo-acoustic instabilities which may be dominant in determining the flame stability characteristics [5, 6].

For the sake of consistency, stratified flames have been defined earlier as a special case of compositionally inhomogeneous combustion where fluid samples are within the flammable limits so that the reaction front propagates through a range of equivalence ratios. Situations where excess heat, transient radicals and possibly combustible species diffuse along the reaction zone to feed the mixture ahead of the propagating flame, are referred to as "back-supported" flames. Recent studies of stratified combustion have spanned both laminar and turbulent configurations and only a brief summary is given here while a more extensive review may be found in [7].

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Earlier investigations of laminar stratified flames have covered a range of burner geometries from counterflow to co-flow. Counterflow burners may be operated in two broad configurations: (i) reactant to products (RTP) [8-17] where reactants of a given equivalence ratio, φ_R counter-flow into combustion products which are at φ_p, and (ii) reactant to reactant (RTR) [14, 18-23] where both streams are non-reacting and have different equivalence ratios (ref. [14] studied both RTP and RTR cases). Reactant to reactant (RTR) studies cover a range of flow configurations and include both numerical [11, 14, 18] as well as experimental [17, 19-23] investigations of back-supported as well as front-supported stratified flames. Conclusions from these studies are that stratified, back-supported flames have higher flame speeds, wider flammability limits, and more resistance to stretch than the homogeneous counterparts.

Turbulent stratified flames span both low and high levels of turbulence and correspondingly, a wide range of flows. The most commonly used flow configuration at low turbulence is the V-flame [24-29] where the stratified mixture issuing towards the stabilising rod is formed. Studies using these burners show some common findings in that the burning velocities and flame propagation rates increase for back-supported flames. Studies in high-turbulence stratified flames have generally focussed on two burner geometries (respectively referred to as the Darmstadt and the Cambridge burners). The Darmstadt burner, [30-32] is axi-symmetric and consists of three streams with the centre providing a pilot while the outer two annular channels supply mixtures at two different equivalence ratios. The Cambridge burner is also axisymmetric but with a bluff-body forming the central part of two-outer concentric streams supplying mixtures of different strength [33-37]. Detailed measurements of temperature and reactive scalar fields were performed in both burners using line Raman-Rayleigh-LIF imaging available both at Sandia and Darmstadt [30, 31, 34, 35]. A key conclusion from these measurements is that stratification leads to values of H_2 and CO within the reaction zone that are higher than those of homogeneously premixed flames [35].

These studies, while useful, do not address the issue of structure of stratified flame fronts propagating past repeated obstacles. The effects of stratification on the overpressure in the presence of obstacles are of major concern particularly with respect to explosion safety. A number of recent studies in stratified hydrogen-air mixtures [38-42] have shown that concentration gradients may enhance flame acceleration and speed-up transition to detonation [40]. However, these studies are all focused on hydrogen flames. The objective of this research is to elucidate the effects on concentration gradient in premixed flames of hydrocarbons. A laboratory chamber, used earlier to study homogeneously flames is modified to enable the formation of concentration gradients. No obstacles are employed here, these will be imbedded in subsequent studies. High speed imaging and pressure-time series are employed to provide an initial characterisation of the overpressure and the propagating flame front.

EXPERIMENTAL

A schematic of the experimental is shown in Fig. 1. It is made of Perspex walls with an internal square cross-section of 50x50mm and a height, H = 255 mm giving an overall volume of ~ 0.63 Liters. This design has been used extensively to study premixed flame propagation past repeated solid obstacles [1-4] and now modified to account for stratification while maintaining the same overall features of the design. The mixture of LPG-air (LPG consists of 95% C_3H_8, 4 % C_4H_{10} and 1% C_5+ hydrocarbons by vol.) with an equivalence ratio φ_1 is introduced through a porous bronze plate positioned at the base of the chamber (see inset A in Fig. 1). Stratification is imposed by bursting a mixture with an equivalence ratio φ_2 through the same porous bronze plate.

The equivalence ratio is varied by varying the air flow rate while the fuel flowrate is kept constant. The timing sequence is critical to ensure that two layers of different mixtures (φ_1 and φ_2) are formed in the chamber with φ_2 being close to porous plate and φ_1 further downstream. This is following by ignition which is performed by a focusing an Nd:YAG laser beam with wavelength of 1064 nm and 0.5 mJ/pulse, 2 mm downstream of the centre of the bronze plate. This laser energy is similar to that employed earlier and does not affect the flame propagation rate [43]. Two hinged flaps which are otherwise closed at chamber's exit open up one second before ignition to vent the mixture. The ignited flame kernel initially grows as a hemisphere given that there are further obstructions within the chamber. Provision is made to place a range of obstacles in the chamber and their positions are indicated as 20mm, 50mm and 80mm downstream of the bronze plate. These obstacles are the subject of later research and are not included in the current paper.

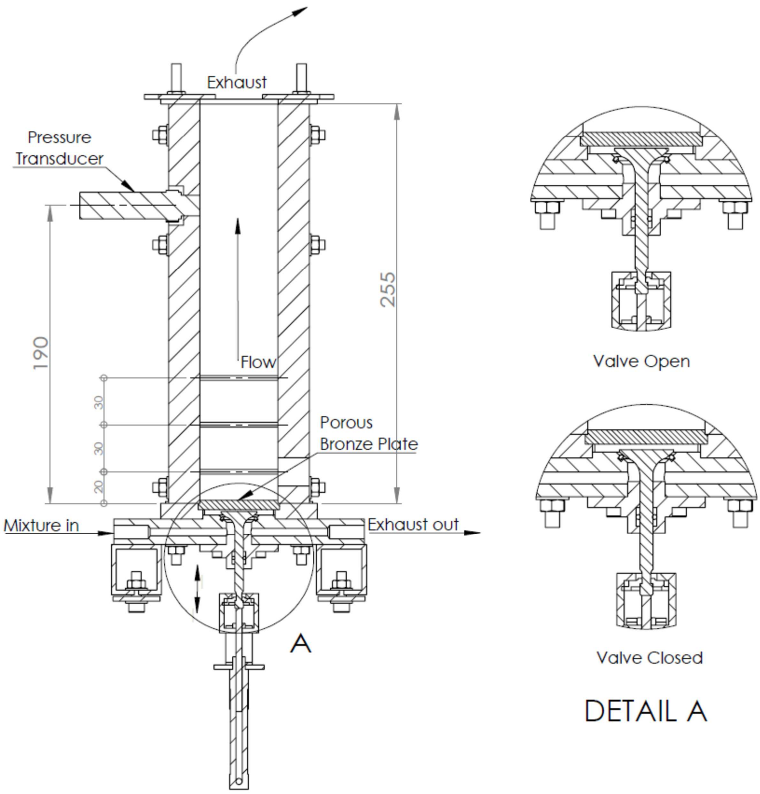

Fig. 1. Schematic of the stratified deflagration chamber. Inset A shows the valve open/close position into the porous bronze plate which just downstream of the valve (dashed).

There are many critical parameters in this experiment and these are explained here along with a description of the sequence of events followed during a typical experiment. The stratification factor, S is defined as the concentration gradient over a physical distance Δx, such as $S = (\varphi_1 - \varphi_2)/\Delta x$. The relevant time scales are: (i) $\tau_{\varphi 1}$, $\tau_{\varphi 2}$, the time over which mixtures φ_1 and φ_2 are injected into the chamber, (ii) τ_{flush}, the time taken to flush the lines from φ1 and transition to φ_2 (the valve is closed during this time), (iii) τ_f, $\tau_{f,\ open}$ the time delay for the flap to open after injection and the time over which the flap stays open, (iv) τig, the time delay after the flap opens at which is the laser ignitor is triggered. For these experiments, only $\tau_{\varphi 2}$ and τ_{ig} are varied while the other parameters are kept constant as follows: $\tau_{\varphi 1}$ = 10 s, τ_{flush} = 2 s, τ_f = 0 s, and $\tau_{f,\ open}$ = 2 s. These times are dictated by the necessity to fill the chamber homogeneously with mixture φ_1 initially before the φ_2 pulse is introduced. Also, it is important to have vented chamber when ignition has taken place.

The initial pressure in the chamber is atmospheric and the initial temperature is ambient at about

21°C. Pressure in the chamber is recorded at 10 kHz using a Keller type PR21-SR piezo-electric pressure transducer with a range of 0-1 Bar and a total error < 0.5 %. The exact location of the transducer is indicated in Figure 1. High-speed imaging is obtained for the propagating flame front using a CMOS high-speed star 6 (HSS6) camera with a resolution of 768x768 pixel and a repetition rate of 10 kHz. The leading edge of the flame front is employed here to report flame speed while the peaks of the pressure-time traces are used to compare between the various cases reported here. The cases investigated here are reported in Table 1.

Table 1. List of relevant parameters for the Liquefied Petroleum Gas (LPG) conditions studied

Case	Fuel (l/min)	Air for φ_1 (l/min)	Air for φ_2 (l/min)	φ_1	φ_2	$\tau_{\varphi 2}$ (s)	τ_{ig} (s)
1	0.97	28.7	28.7	0.8	0.8	-	1
2	0.97	20.9	20.9	1.1	1.1	-	1
3	0.97	28.7	20.9	0.8	1.1	0.3	1.0
4	0.97	28.7	20.9	0.8	1.1	0.5	1.0
5	0.97	28.7	20.9	0.8	1.1	0.9	1.0
6	0.97	28.7	20.9	0.8	1.1	0.5	0.5

RESULTS

Figure 2 shows sample images of the flame front propagating along the chamber at various times for Case 3 (φ_1 = 0.8, φ_2 = 1.1). While the stratification here span an equivalence ratio range of 0.3, the flame structure remains smooth and not different from that of a homogeneous flame (not shown). Note that the horizontal traces are due to the slits which will house a range of repeated obstacles intended for future research.

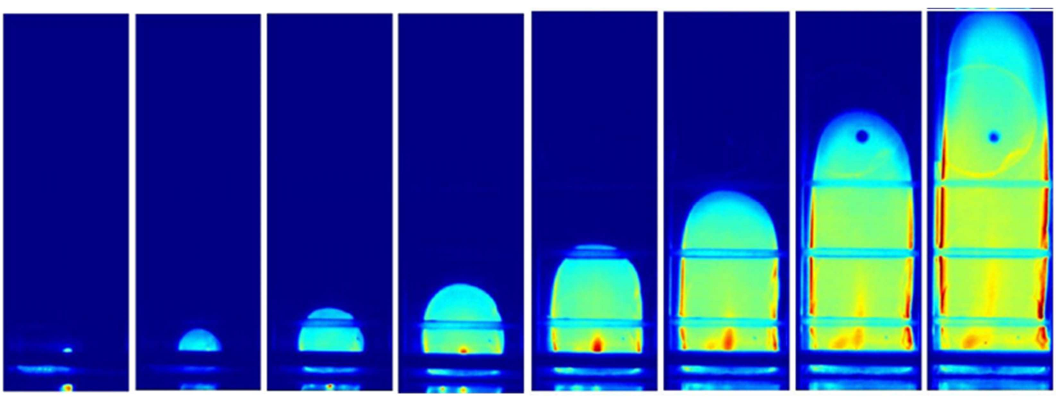

Fig. 2. Flame front evolution for Case 3 (φ_1 = 0.8, φ_1 = 1.1). Time difference between images is 2 ms.

Figure 3 shows a profile of peak overpressure versus equivalence ratio confirming that the peak occurs at stoichiometric mixtures. The crosses refer to multiple realizations and the solid curve is a best fit. These results are consistent with earlier finding and provide confirmation of the validity of the current measurements.

Figure 4 plots the peak overpressure for the stratified cases 3 to 5 (see Table 1) versus $\tau_{\varphi 2}$ which ranges from $\tau_{\varphi 2}$ = 0.3 to 0.9 s. Also shown on Figure 4 are the peak overpressures measured for the two homogeneous limiting cases of $\varphi_1 = 0.8$ and $\varphi_2 = 1.1$ and these correspond to $\tau_{\varphi 2} = 0.0$. The experiments are repeated multiple times as shown on the plot. It is interesting to note here that for the stratified cases, the peak pressure is closer to that of $\varphi_2 = 1.1$ while the chamber is initially full of mixture at $\varphi_1 = 0.8$. While additional work is needed to demonstrate this, the implication is that the back support provided by the richer mixture seems to push the pressure to its higher level.

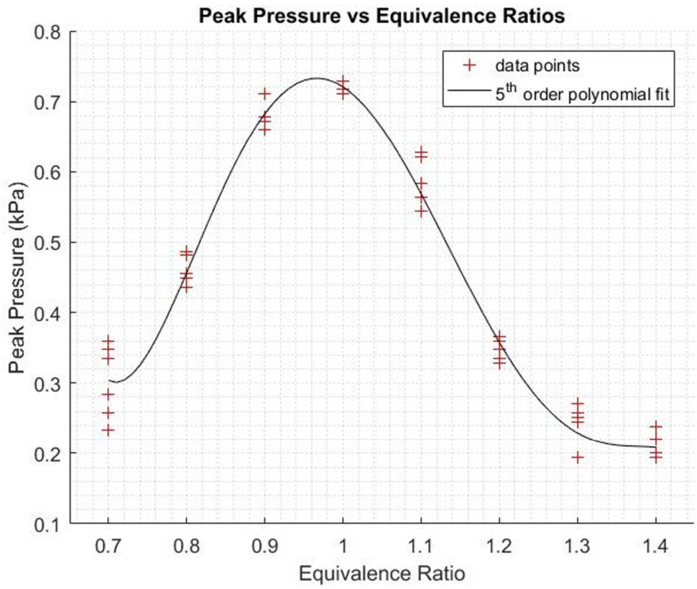

Fig. 3. Peak overpressure versus equivalence ratio.

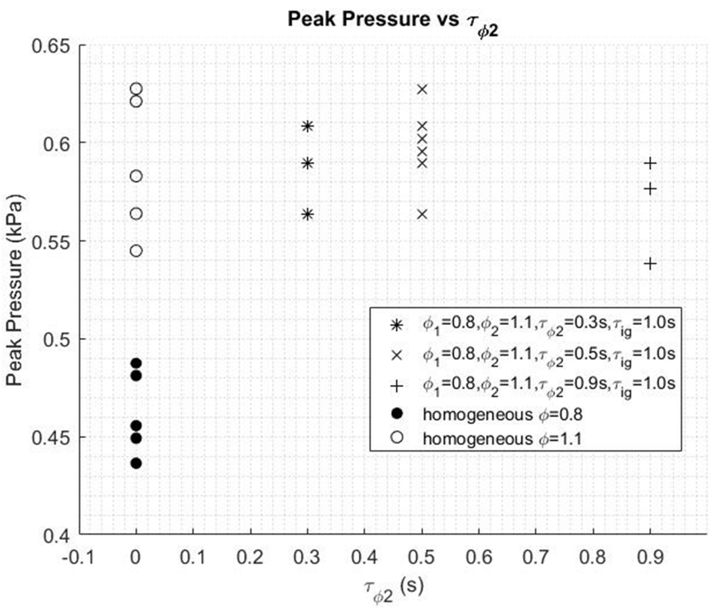

Fig. 4. Peak overpressures for Cases 1 to 5 versus $\tau_{\varphi 2}$.

CONCLUDING REMARKS

The modified chamber enables a controlled laboratory study of the effects of stratification on the overpressure and flame structure of vented deflagrations. This initial work shows that with back-supported stratification from φ_1 = 0.8 to φ_2 = 1.1, the peak overpressure increases quickly to the level of φ_2 even when the amount of φ_2 mixture injected is small. Additional work is planned to optimize the level of stratification and timing parameter as well as study the effects of repeated obstacles on the overpressure and flame structure.

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