Radiation Based Initiation of Vapour Cloud Explosions

M. A. Hadjipanayis, F. Beyrau and R. P. Lindstedt
Department of Mechanical Engineering
Imperial College, Exhibition Road
London SW7 2AZ, UK

1 Introduction

Fast flame propagation modes in large vapour cloud explosions are typically regarded as a consequence of high levels of turbulence. However, there are cases where so far no single propagation mode (detonation, high speed deflagration, deflagration to detonation transition) can fully explain the combination of an apparently episodic event with the severe over-pressures observed. In one such incident, the Buncefield explosion in the UK, the Health and Safety Laboratory (HSL) concluded that a different mode of flame acceleration may be responsible for the observed inconsistencies. The Buncefield site was covered with large quantities of dry leaves and other dead vegetation and a possible mechanism based on premixed explosions in gas clouds seeded with char-forming, porous particulates was formulated by Atkinson [1]. The proposal is based on the pioneering work of Moore and Weinberg [2], but differs in the sense that it assumes an episodic/unstable flame propagation mode. The basis for the suggestion arises partly from evidence obtained using CCTV footage, which suggests an episodic propagation mode with an average flame speed of 150 m/s [3]. The observed timings are such that the radiative ignition mode of propagation is arguably only plausible if flammable pockets can be ignited within 40 ms through radiation from fireballs no further than 6 m away from the point of ignition [1]. Moore and Weinberg [2, 4, 5] studied the ignition of particles made from fibrous materials, such as cotton, packed into spheres and illuminated by a far-infrared (FIR) laser source and visible light from a tungsten-halogen lamp. Ignition times for particles illuminated with visible light were of the order 10^0 s compared to 10^{-1} s for FIR laser illuminated particles when subjected to the same level of radiation flux. The blackening of cotton particles resulted in a significant reduction in ignition times for the former case.

The objective of the current study is to examine if char-forming organic particulates can serve as sufficiently swift initiators of combustion in explosive atmospheres as a result of illumination with radiation levels similar to those experienced in large vapour cloud explosions.

2 Experimental Configuration

A flame tube with a 90 x 60 mm rectangular cross-section and 240 mm in length was used to investigate the ignition behaviour of selected particulates in potentially explosive gas mixtures. Optical access was provided by a 109 x 52 mm fused silica window and one end of the tube was covered in ordinary

Correspondence to: p.lindstedt@imperial.ac.uk

aluminium foil. The arrangement provided sufficient initial sealing/confinement for mixture preparation while, upon ignition, even very small pressure waves ruptured the foil allowing essentially unconfined conditions. The other end of the tube was sealed by a steel plate equipped with fittings for reactant supply, gas recirculation and pressure ports. Different equivalence ratios were achieved using the partial pressure method and mixture homogeneity was ensured by flow circulation using a diaphragm pump. It was found that five minutes of recirculation time, corresponding to 70 flow-through times, provided repeatable results. Several fuels were considered and, in accordance with the hydrocarbons present as a result of the initial leak [6], butane was selected as a sufficiently representative molecule for the current purposes. Candidate particulates were placed at the centre of the flame tube and illuminated using a continuous wave 6 W argon-ion laser that produced emission lines between $454 - 529$ nm. The laser power was measured by a power meter while the magnitude of the radiation flux could be varied by introducing a lens in the path of the laser beam for precise control of the laser spot size. A CCD camera with a sampling rate of 30 fps was used to record ignition events. The experimental configuration can be seen in Fig. 1. Video recordings were initiated while the laser beam was blocked and the time from illumination to ignition was taken from the recordings. The onset of ignition was marked by the appearance of a visible flame and the corresponding time to ignition was regarded as the interval between the time of particle illumination and ignition. The arrangement provided a sufficient, but coarse, time resolution of 33 ms.

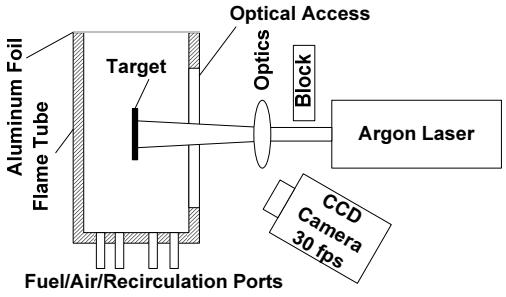

Figure 1: Diagram of flame tube configuration.

3 Results & Discussion

During the combustion of a vapour cloud large quantities of soot can be formed in fuel-rich regions. Soot particles can be expected to be in thermal equilibrium with the surrounding gas, at least initially, resulting in a strong emission of blackbody radiation. Assuming a typical flame temperature of 2000 K, blackbody radiation levels of up to 1 MW/m^2 can be expected [2]. Experimental evidence from vapour cloud explosions [7] indicate radiation flux levels of 1.25 MW/m^2 during the first 10 ms of the event with a subsequent reduction to 250 - 300 kW/m^2 over several hundred milliseconds. A simple calculation was performed in order to assess how a leaf fragment can be heated up by radiation from hot combustion products resulting from an explosion front. Both flame and leaf were considered as co-axial disks with view factors obtained from Hottel [8]. The analysis showed that for large flames ($d > 10$ m), providing a heat flux of 900 kW/m^2, the magnitude of radiation received by the leaf remained fairly constant up to a distance of 6 m, while it was reduced to 200 kW/m^2 and 60 kW/m^2 at distances of 10 m and 20 m respectively. Considering that the heat flux remains high up to a distance of 6 m and taking into account the length and time scales proposed by Atkinson [1], the potential temperature rise for a leaf initially

located 6 m away from an approaching flame traveling at 150 m/s was investigated. Assuming typical leaf properties (a density 175 kg/m^3, a specific heat capacity of 2.4 kJ/Kg·K and a penetration depth of light of 50 μm) surface temperatures of 800 K can be expected within 20-30 ms. Glowing combustion or smoldering is initiated at around 800 K [9]. Thus basic considerations suggest that it is possible for a rapidly propagating flame front to ignite leaf fragments. It may also be noted that 800 K is above the auto-ignition temperature of butane.

In order to study the principle, specimens of 200 μm thick black paper were initially illuminated in stoichiometric butane/air mixtures. Black paper was preferred because of difficulties encountered in obtaining reproducible results using dry dead leaves. Different areas of the same leaf may have lighter or darker spots, which will alter the absorption characteristics. The matter is not important if the illuminated area is large as would be expected in practice. Black paper has a similar flake-like shape and its colour ensured that significant portion of the visible laser radiation was absorbed. Reproducible ignition of the adjacent flammable mixture was achieved by illuminating 200 μm black paper at different spot size/radiation flux combinations. Selected results are shown in Fig. 2. The time to ignition was shorter for a smaller spot size/higher radiation flux. No ignition occurred at spot sizes above 1.7 mm due to the low power densities achievable with the available laser power. The behaviour of particulates coated with soot collected from a butane/propane flame was also investigated. The presence of the additional layer of soot led to a dramatic reduction in the time to ignition to below the current time-resolution (within 33 ms) as shown in Fig. 3. Moreover, the inconsistencies observed in the times to ignition can be expected to at least partly relate to soot layer inhomogeneities arising from the coating technique. The currently required laser power densities are high as compared to the radiation heat flux expected in a vapour cloud explosion such as Buncefield. This is believed to be caused by the small spot sizes ($d < 1.7$ mm) achievable with the laser power available initially. In the present investigation, a strong coupling was observed between the spot size and radiation flux and it is expected that a more powerful radiation source that will enable the illumination of larger areas will remove or reduce the need for excessive heat fluxes.

The effect of mixture composition on the time to ignition is shown in Fig. 4. Richer butane mixtures resulted to longer ignition times under identical radiation levels as compared to stoichiometric conditions, while for leaner mixtures the results were similar to the latter. The impact of soot layer inhomogeneities is apparent - especially for fuel rich mixtures. In addition, Fig. 5 shows that ignition times shorter than 40 ms are plausible for stoichiometric and lean mixtures. Ignition times < 100 ms were observed across the whole flammability range indicating that ignition is not limited to a specific stoichiometry. From the perspective of the proposed radiative propagation mechanism, the above observation does not prove the hypothesis. However, the findings suggest that a wide range of compositions within an actual vapour cloud are susceptible to radiative ignition. The observation is interesting as Moore and Weinberg [2] found that cotton particles were incapable of igniting fuel rich propane mixtures.

4 Conclusion

An experimental investigation of the behaviour of organic particulates under intense radiation has been presented and the possibility of such materials acting as combustion initiators in flammable atmospheres has been assessed in the context of plausible time scales for vapour cloud explosions. The constructed experimental configuration was found to be adequate for the current proof of concept study. Ignition characterisation was performed by means of a CCD camera and the ignition time was determined as the interval between laser illumination and the appearance of a visible flame. Illumination of black paper specimens in butane/air mixtures were found to lead to ignition. The laser beam size and the radiation flux was varied resulting in shorter ignition times for higher levels of the radiation flux. Coating black

paper with soot resulted to a significant reduction in ignition times - in some cases below the measuring accuracy of the current experimental configuration. Furthermore, ignition was found to be plausible across the flammability range for butane. The currently required laser radiation intensities are high. However, the use of near-infrared (NIR) lasers that are more representative of the radiation wave lengths of a practical situation can be expected to reduce the power requirement substantially.

5 Outlook

Overall, the findings presented above have firmly established the principle of radiation induced ignition on plausible time scales albeit at high fluxes. The argon laser has been recently replaced with a NIR laser diode (λ = 808 nm, 50 W) and the time resolution has been improved to around 1 ms. The detection of ignition is now performed with a photodiode, fitted with a filter to block the laser light, which is focused at a point near the illuminated area. The precise time of illumination is defined by a voltage send to the oscilloscope from the laser power supply and the time to ignition is taken as the difference between this time of illumination and the rise of the photodiode signal. The use of the more powerful radiation source enables the variation of the radiation flux at a constant irradiated area and we are now in the process of investigating the coupling between the spot size and power density at larger spot sizes than previously explored. Furthermore, the NIR wave length much better resembles the peak in emissions of an explosion, as compared to the previous green argon light, and will therefore provide a much better assessment of the required radiation intensities. Given the propensity of organic materials to absorb in the NIR region, we expect that lower energies can be used and that these can be much more accurately determined. We are confident that all items mentioned in the current outlook will be ready for presentation at the meeting in July.

6 Acknowledgements

The authors are grateful to the Health & Safety Laboratory of the Health and Safety Executive for providing financial support for the current study. Helpful discussions with Graham Atkinson, Laurence Cusco, Hans Michels and Bob Simpson are also gratefully acknowledged.

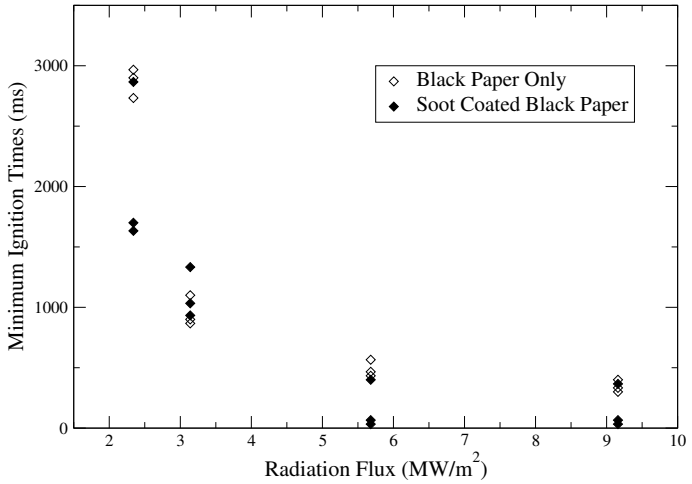

Figure 2: Time to ignition for black paper in a butane/air mixture (ϕ = 1.0). Shorter ignition time can be seen for higher levels of radiation flux. Longer ignition times are attributed to variations in the soot coating.

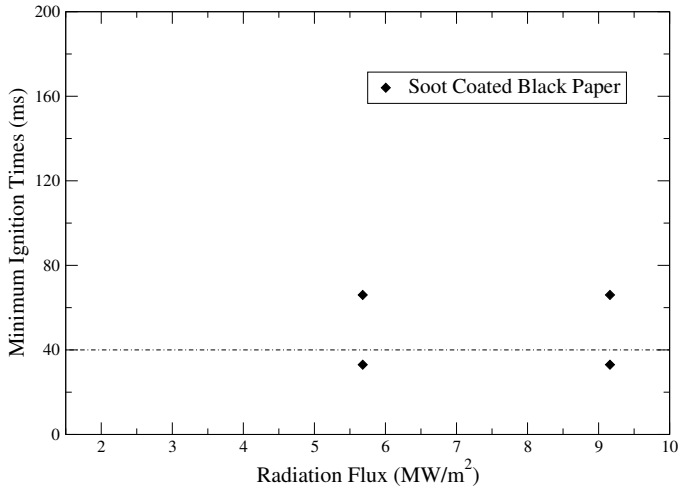

Figure 3: Time to ignition for soot coated black paper in a butane/air mixture (ϕ = 1.0). Ignition times below 40 ms could be observed.

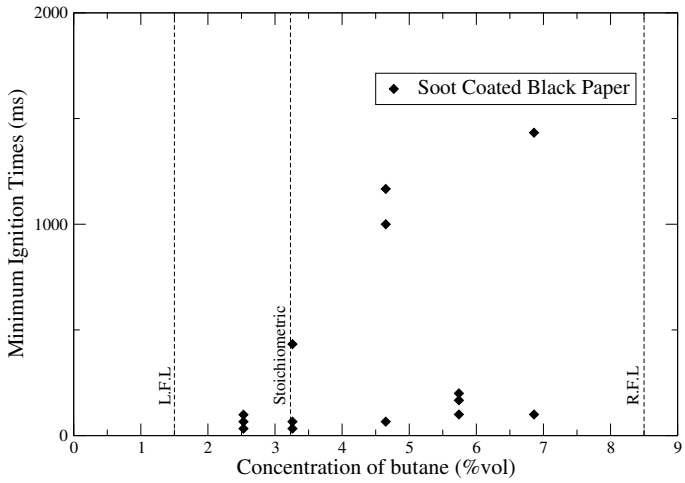

Figure 4: Time to ignition for soot coated black paper for different mixture composition (flux = 5.5 MW/m^2). Longer ignition times are attributed to variations in the soot coating.

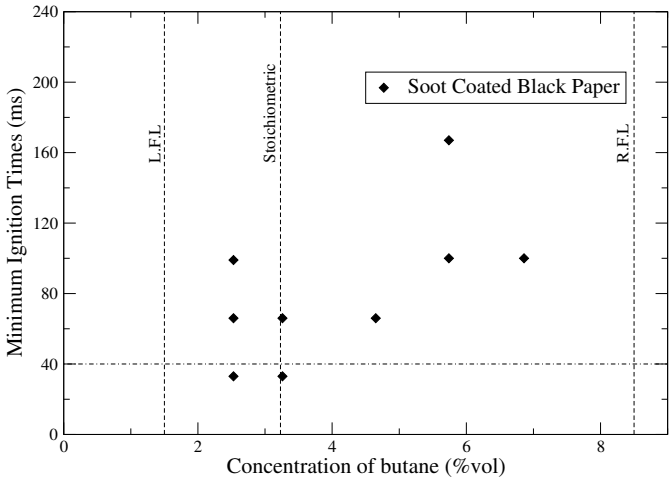

Figure 5: Time to ignition for soot coated black paper for different mixture composition (flux = 5.5 MW/m^2). Ignition times lower than 100 ms were found plausible across all equivalence ratios while ignition times reduced under 40 ms in stoichiometric and leaner mixtures.

References

[1] G. Atkinson. The Buncefield explosion mechanism, Technical report FP/09/02, Health and Safety Laboratory, 2009.

[2] S. R. Moore and F. J. Weinberg. High propagation rates of explosions in large volumes of gaseous mixtures. *Nature*, 290(5801):39–40, 1981.

[3] Buncefield Major Incident Investigation Board, Final Technical Report, Volume 1, 2008.

[4] S. R. Moore and F. J. Weinberg. A study of the role of radiative ignition in the propagation of large explosions. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 385(1789):373–387, 1983.

[5] S. R. Moore and F. J. Weinberg. Further studies of the role of radiative ignition in the propagation of large explosions. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 409(1836):1–20, 1987.

[6] G. Atkinson, S. Gant, D. Painter, L. Shirvill and A. Ungut. Liquid dispersal and vapour production during overfilling incidents. *Institution of Chemical Engineers Symposium Series*, 154:552–536, 2008.

[7] S. Dorofeev, V. Sidorov, M. Kuznetsov, A. Dvoinishnikov, V. Alekseev, and A. Efimenko. Air blast and heat radiation from fuel-rich mixture detonations. *Shock Waves*, 6:21-28, 1996.

[8] H. C. Hottel. Radiant heat transmission between surfaces separated by non-absorbing media. *ASME Transactions*, 53, FPS-53-196:265–273, 1931.

[9] P. J. Crutzen and J. G. Goldammer. *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires.* John Wiley & Sons, Ltd., 1993.