Process Safety and Environmental Protection 94 (2015) 517–527

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Thermal radiation from vapour cloud explosions

M.A. Hadjipanayis[a], F. Beyrau[a], R.P. Lindstedt[a,*], G. Atkinson[b], L. Cusco[b]

[a] Department of Mechanical Engineering, Imperial College, Exhibition Road, London SW7 2AZ, United Kingdom
[b] Health & Safety Laboratory, Harpur Hill, Buxton SK17 9JN, United Kingdom

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form 21 October 2014
Accepted 3 November 2014
Available online 18 November 2014

Keywords:
Radiation induced ignition
Vapour cloud explosions
Soot
Cloud size effects
Temperature effects
Impact of mixture composition

ABSTRACT

The current study estimates the radiation flux emitted from hot extended gas clouds characteristic of vapour cloud explosions along with the corresponding level of irradiance posed on particles suspended in the unburnt part of the cloud ahead of an advancing flame front. The data presented permits an assessment of the plausibility of combustion initiation by such particles due to forward thermal radiation. The thermal radiation will depend on the emissivity of the burned volume, which relates to the concentration of gaseous and particulate combustion products. A sensitivity analysis has been carried out to account for variations in the equivalence ratio, mixture pressure and radiative heat losses. The spatial distribution of irradiance ahead of the flame front has been computed by introducing appropriate geometrical factors to explore the impact of cloud size. Using fuel rich ethylene-air mixtures it has been shown that high flame emissivities can be achieved at path lengths of order 1 m even in the presence of very low soot volume fractions. The emissivity of gas-soot mixtures will hence be mainly determined by the soot concentration and to a lesser extent by the mixture temperature. Our analysis suggests that the role of forward thermal radiation as a contributing factor to flame propagation in large scale vapour cloud explosions can not currently be ruled out.

1. Introduction

Radiation often dominates heat transfer process at high temperatures (Hottel, 1958). Consequently, thermal radiation makes a decisive contribution to the overall energy transport in many combustion systems (Nathan et al., 2012). However, the influence of radiative heat transfer in unconfined vapour cloud explosions (UVCE) and on the corresponding rate of flame propagation is not yet fully understood. Particles heated by high levels of radiation can induce ignition of an adjacent explosive charge. Moore and Weinberg (1981, 1983, 1987) have shown that this may become important in vapour cloud explosions (VCE). The emission of strong radiative heat loads, emanating from the hot product cloud, on particles situated in the reactants can be sufficient to ignite the surrounding fuel-air mixture. In order to have a notable effect, ignition centres have to be formed well ahead of the advancing flame, thus relatively long length scales and short time scales are essential. Beyrau et al. (2013) explored the potential of fine particles acting as initiators of combustion in flammable mixtures upon irradiation using a near infrared (NIR) laser source. The experimental investigation featured powders with widely different characteristics (type, size, morphology, etc.) and times to ignition were established. In particular, ignition time scales $\simeq$100 ms were obtained in a stoichiometric butane-air mixture at an irradiance <600 kW/m^2 using substrates coated with a commercially available carbon black powder (acetylene black). In a recent study, Beyrau et al. (2014) quantified the heating process of such irradiated powders using time-resolved emission spectroscopy. The particle surface temperatures necessary to cause ignition of a surrounding charge were also obtained revealing two different ignition regimes based on the reactivity of the powder.

* *Corresponding author*. Tel.: +44 207 594 7039; fax: +44 20 7589 3905.
E-mail address: p.lindstedt@imperial.ac.uk (R.P. Lindstedt).
http://dx.doi.org/10.1016/j.psep.2014.11.004
0957-5820/

Table 1 – Reported radiation heat flux from selected combustion systems.

System	Regime	Remarks	Flux (kW/m^2)	Reference
CH_4-air cloud	Premixed	Scaled	450	Hardee et al. (1978)
C_3H_8-air cloud	Premixed		690	The Steel Construction Institute (2014)
LPG fireball	Non-premixed	Extrapolated	450	Roberts (1981)
LPG fireball	Non-premixed	ASEP	350	Roberts et al. (2000)
LPG fireball	Non-premixed	SEP_{max}	550	Roberts et al. (2000)
GT Combustor	Non-premixed		1500	Lefebvre (1984), Mengüç et al. (1986), Najjar (1985)
Dust explosion	Heterogeneous	ASEP	275	Holbrow et al. (2000)

Fine particles may be raised by an expanding gas cloud and become suspended in the unburnt gas mixture. The dispersion of dusts/particulates ahead of a propagating flame front is a well established phenomenon. According to Klemens et al. (2006), fine dusts can be raised by expansion waves induced from a moderate local explosion. For example, in coal mines the pressure wave of a weak methane explosion can disperse dust deposits leading to the formation of an explosive dust-air cloud. The dust can be ignited by the hot methane-air products causing a (strong) secondary explosion. The phenomenon has been the subject of studies exploring the interaction of deposited dust layers with shockwaves (e.g. Fedorov, 2004; Gerrard, 1963). In addition, the dispersion of coal dust deposits by an advancing methane–air flame has been studied experimentally by Lu et al. (2002) in a laboratory scale flame tube. Hydrogen-air explosions can exhibit visible luminosity due to suspended inert particles while, in hydrogen jet flames, naturally occurring particulates present in the air entrained into the reaction region can also be a source of visible light emission (Shirvill et al., 2012). Finally, inert dust can suppress dust explosions and hence can be employed for the prevention and mitigation of dust explosions in coal mines (Amyotte, 2006).

The levels of flame surface flux reported in literature from various combustion systems can be seen in Table 1. There is a notable absence of data on the premixed systems considered in the current study. However, Holbrow et al. (2000) examined the radiative power densities from fireballs produced from vented dust explosions. Average surface emissive power (ASEP) of up to 275 kW/m^2 have been measured with coal dust and up to 2900 kW/m^2 with aluminium. In heterogeneous combustion systems, reaction takes place at the surface of the condensed fuel, hence, dust explosions emit continuous Planck's radiation which is a function of the particle temperature. This can explain the discrepancy between results obtained with aluminium and coal dust. Thermal radiation from fireballs produced in Boiling Liquid Expanding Vapour Explosion (BLEVE) have also been examined. These turbulent flames emit non-luminous infrared radiation emanating from the emission bands of gaseous combustion products and luminous continuous radiation by soot particles in the visible and infrared (Tien and Lee, 1982; Viskanta and Mengüç, 1987). High emissivities can be achieved due to the high soot concentration and large burnt gas volume. Measurements by Roberts et al. (2000) indicate SEP_{max} up to 550 kW/m^2 while extrapolated results from Roberts (1981) suggest that SEP_{max} up to 450 kW/m^2 can be achieved. Average SEPs from optically thick diffusion flames can typically be expected to be of the order 200–300 kW/m^2 with maximum spot values of 350–450 kW/m^2 as shown in Table 1. Similarly, radiation emanating from gaseous products and soot is a well known design consideration in gas turbine burners. Theoretical results, obtained from spray-stabilised flames in pressurised enclosures, suggest that flame surface flux around 1500 kW/m^2 can be achieved (Lefebvre, 1984; Mengüç et al., 1986; Najjar, 1985).

Experiments by Hardee et al. (1978) involving fireballs, produced by non-premixed as well as premixed stoichiometric methane–air mixtures (1.5 and 10 kg of CH_4), showed that premixed clouds, although appearing less luminous and relatively more transparent than the corresponding non-premixed case, emit higher flame surface fluxes due to the increased temperature of the gas. Scaled results suggest that maximum flame surface fluxes up to 450 kW/m^2 could be expected from a premixed cloud. The argument is corroborated by considering results from Dorofeev et al. (1996) who collected light from stoichiometric and fuel rich propane-air detonations. Measurements showed that significantly more light is emitted during the premixed burning phase than at any subsequent excess fuel burnout. In a detonation wave, both the temperature and pressure are much higher than in conventional deflagration, which will ultimately induce increased gas emissivities. Radiation measurement obtained from premixed propane-air clouds suggest spot values of approximately 700 kW/m^2 (The Steel Construction Institute, 2014). In these particular tests, carbon based dusts were laid on the floor of the explosion chamber to examine if they would cause secondary ignition due to forward thermal radiation. While no acceleration that could be attributed to radiative heating was observed, previous work has shown (Beyrau et al., 2013) that ignition timescales can vary by orders of magnitude for different carbon black powders. Explosions often deviate from stable deflagrations or detonations occurring under ideal conditions and in unimpeded geometries (Oran and Williams, 2012). Accordingly, in a real incident local gas pockets may achieve high pressure and temperature without subsequently developing into a detonation. Hence, radiative properties obtained from local events may still be important for an unsuccessful deflagration-to-detonation transition (DDT).

There is an obvious lack of radiation measurements in large scale premixed systems related to explosions and the actual level of thermal radiation emitted from a VCE remains conjectural. Radiation emanates from both gaseous and particulate combustion products, which are at higher temperatures for premixed flames and hence higher radiation levels are expected. Moore and Weinberg (1981) reported theoretical values of blackbody radiation up to 1 MW/m^2 assuming a burnt gas temperature (T_b) at 2050 K as representative of a stoichiometric mixture and unit emissivity. Although laboratory premixed flames vary from the blackbody condition, in vapour cloud explosions, the shear size of combustion product cloud is believed to yield higher emissivities (Finkelnburg, 1949). Additionally, soot can be generated as a result of local inhomogeneities in the equivalence ratio or in fuel rich regions. The presence of a large number of very small unburned carbon particles, initially expected to be in thermal equilibrium with the