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A review on understanding explosions from methane–air mixture

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ABSTRACT

This review examines existing knowledge on the genesis and flame acceleration of explosions from methane–air mixtures. Explosion phases including deflagration and detonation and the transition from deflagration to detonation have been discussed. The influence of various obstacles and geometries on explosions in an underground mine and duct have been examined. The discussion, presented here, leads the readers to understand the considerations which must be accounted for in order to obviate and/or mitigate any accidental explosion originating from methane–air systems.

1. Introduction

Methane– air systems are life-threatening mixtures particularly in underground coal mines. Explosions initiated by these mixtures have destroyed infrastructure in the mines and taken thousands of lives in the past. The explosion which occurred in Mount Kembla Mine in 1902 was the worst mining tragedy in Australian history, killing 96 people (Radford, 2014). The second worst disaster, according to the lives lost, occurred earlier in 1887 which took the lives of 81 miners from the Bulli Mine (Brown, 2010; Dingsdag, 1993). Methane from coal mines initiated explosions in these disasters and the explosions are later escalated by coal dust. The deadliest coal mine explosion in human history occurred in 1942 at the Benxihu Colliery, China killing 1549 people (Dhillon, 2010a). A number of other coal mine explosions are reported in literature (Dhillon, 2010a,b; Tu, 2011). In each explosion disaster, lives were lost and resulted in immense financial loss to the mining companies. The severity of these disasters motivated a number of researchers to initiate research on methane–air systems.

Explosions cannot be initiated for every concentration of combustible gas in air. The concentration range of a combustible gas for which explosions can originate is known as explosion limit/range or flammability limit/range. While a combustible-air mixture within the flammability range can develop into explosion, such explosions may be deflagration, detonation or may transit from deflagration to detonation. When the combustion wave propagates at a speed lower than the speed of sound, the explosion is termed deflagration (Fig. 1) (Suzuki et al., 2005). The temperature of combustion products is much higher than room temperature. As the speed of sound increases with increasing temperature, the explosion sound, travelling in combustion products becomes very high. As a consequence, the limit of deflagrated flame speed for combustion products is much higher than the speed of sound in air at room temperature. In contrast, a combustion wave that propagates much faster than the speed of sound at the specific temperature is termed detonation. The pressure rise in detonation is much higher than deflagration and can be calculated by correlations for the Chapman-Jouguet condition (Chapman, 1899; Jouguet, 1905). Mathematically, detonation refers to the pressure and flame speeds equal to and higher than those estimated by Chapman-Jouguet correlations. Compared to original pressure, the pressure may rise up to eight times in deflagration (King, 1990). In detonation, the peak pressure may reach twenty times or more (James; King, 1990). In addition, shock waves generated in detonation are very ruinous (King, 1990). Briefly, detonation is much more detrimental

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Abbreviations: DDT, deflagration to detonation transition; LEL, lower explosive limit; LFL, lower flammability limit; UEL, upper explosive limit; UFL, upper flammability limit; BR, blockage ratio; CJ, Chapman-Jouguet; LPG, liquefied petroleum gas; *L/D*, length-to-diameter ratio.

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Nomenclature

Symbols

Φ	equivalence ratio of fuel (dimensionless)
M	Mach number (dimensionless)
ϕ	degree of confinement (dimensionless)
φ	width or height of a square cross-section of mine gallery (m)
λ	detonation cell size (cm)
P_f	pressure of hydrogen–oxygen mixture in the initiator tube (atm)
E_c	total chemical energy of the stoichiometric hydrogen–oxygen mixture per unit volume at atmospheric pressure (J m^{-3})
V_i	volume to the initiator tube (m^3)
Q_{H_2}	heat of combustion of hydrogen (J m^{-3})
d	orifice plate bore diameter (m)
D	inner diameter of the explosion tube (m)
L	length of the explosion tube (m)
A_o	the largest cross-sectional area blocked by an obstacle (m^2)
A_d	inner cross-sectional area of the explosion duct (m^2)
l	length of an obstacle bar (m)
x	diameter of the circular area for an cylindrical obstacle bar or a side for triangular or square obstacle bar (m)
E_g	generation of thermal energy due to combustion of the flammable gas (J)
E_l	loss of energy due to the sharp rise of local temperature to final flame temperature (J)
U_{obs}	measured flame speed (m s^{-1})
U_{cj}	flame speed at Chapman-Jouguet condition (m s^{-1})
C_f	wall drag coefficient (dimensionless)
R	radius of a tube (m)

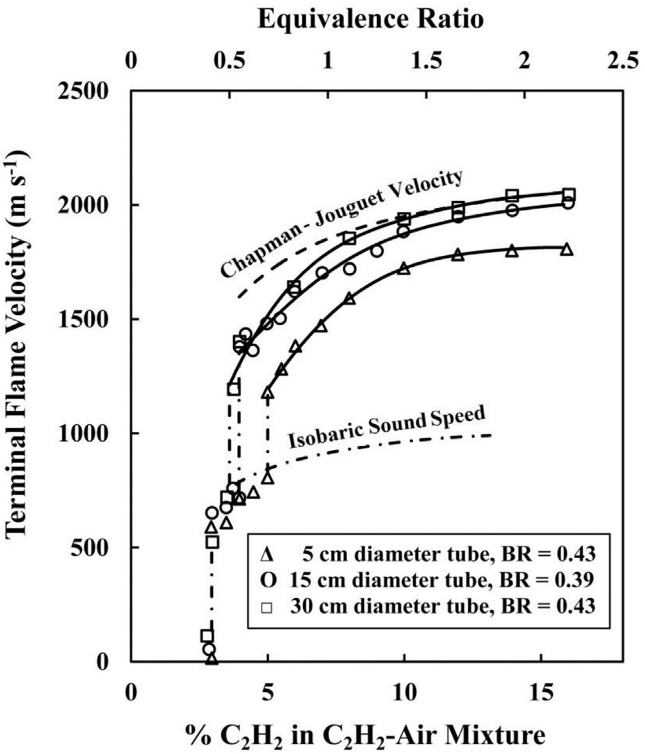

Figure 1. Illustration of deflagration and detonation limits as presented by isobaric speed of sound and speed at Chapman-Jouguet condition lines constructed from experiments conducted for the acetylene–air mixtures (Peraldi et al., 1986).

compared to deflagration.

Interestingly, there is no particular name for the flame of an explosion within the limits of isobaric sound speed and speed at Chapman-Jouguet condition (Fig. 1). However, explosions with flame velocities lower than but close to speed at Chapman-Jouguet condition are often termed as quasi-detonation. When a transition occurs for a low speed deflagrated flame, it reaches quasi-detonation or detonation. The phenomenon of the transformation of a low speed deflagrated flame to a catastrophic detonation explosion is known as Deflagration to Detonation Transition or DDT.

A deflagration flame transition to quasi-detonation or detonation was found to occur in the presence of a number of factors including obstacles and particular geometries of explosion galleries. The shapes of obstacles are important in accelerating flame propagation. Orifice plates and Shchelkin spirals are commonly employed obstacles in experimental investigations; however, the obstacles present in the real world are diverse. The geometries of explosion galleries, briefly confined, semi-confined and unconfined, are also important in flame acceleration. The analyses of various investigations found in literature are presented in this article with the aim of providing an understanding of explosions originating from methane–air systems.

2. Explosion limits of methane–air mixtures

When methane build-up in an underground coal mine reaches a certain concentration range, explosion can be initiated by the presence of a small heat source. The minimum concentration of methane (in air) of this explosive concentration range is its Lower Flammability Limit (LFL) or Lower Explosive Limit (LEL). In contrast, the maximum concentration of this range is the Upper Flammability Limit (UFL) or Upper Explosive Limit (UEL) of methane in air (Gharagheizi, 2008). When methane concentration falls below LEL, the amount of methane becomes too low to ignite. Similarly, the amount of oxygen becomes too low when the methane concentration reaches above UEL and no ignition occurs. The LEL is limited by the fuel source (methane concentration) while the UEL is limited by the oxidant (oxygen concentration).

Several researchers investigated the flammability range of methane (Bartknecht, 1993; Bunev et al., 2013; Checkel et al., 1995; Chen et al., 2011; Claessen et al., 1986; Gieras et al., 2006; Vanderstraeten et al., 1997). The outcome of these researches concludes that the LEL of methane is 4.6 ± 0.3% (the concentrations presented in this article are in volume basis) while the UEL of methane is 15.8 ± 0.4% when methane is ignited in air at 20 °C and 100 kPa (relates to ambient temperature and pressure) as presented in Fig. 2 (Vanderstraeten et al., 1997). In addition, the maximum pressure rise occurs at a methane concentration of ~9.5%.

The explosion parameters depend largely on initial temperature and pressure. As can be seen in Fig. 3, the UEL value of methane increases, shifts towards the right, at elevated initial pressures. In addition, a couple of zones are observed for methane–air mixture