Journal of Loss Prevention in the Process Industries 26 (2013) 295–301

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Methane–air detonation experiments at NIOSH Lake Lynn Laboratory

R.K. Zipf Jr. [a,*], V.N. Gamezo [b], M.J. Sapko [a], W.P. Marchewka [a], K.M. Mohamed [a], E.S. Oran [b], D.A. Kessler [b], E.S. Weiss [a], J.D. Addis [a], F.A. Karnack [a], D.D. Sellers [a]

[a] Office of Mine Safety and Health Research (OMSHR), National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA 15236, USA
[b] Laboratory for Computational Physics and Fluid Dynamics (LCPFD), Naval Research Laboratory (NRL), Washington, DC 20375, USA

ARTICLE INFO

Article history:
Received 29 November 2010
Received in revised form
8 March 2011
Accepted 9 May 2011

Keywords:
Detonation
Methane
Experiments
Limits

ABSTRACT

The methane–air detonation experiments are performed to characterize high pressure explosion processes that may occur in sealed areas of underground coal mines. The detonation tube used for these studies is 73 m long, 105 cm internal diameter, and closed at one end. The test gas is 97.5% methane with about 1.5% ethane, and the methane–air test mixtures varied between 4% and 19% methane by volume. Detonations were successfully initiated for mixtures containing between 5.3% and 15.5% methane. The detonations propagated with an average velocity between 1512 and 1863 m/s. Average overpressures recorded behind the first shock pressure peak varied between 1.2 and 1.7 MPa. The measured detonation velocities and pressures are close to their corresponding theoretical Chapman-Jouguet (CJ) detonation velocity (D_{CJ}) and detonation pressure (P_{CJ}). Outside of these detonability limits, failed detonations produced decaying detached shocks and flames propagating with velocities of approximately 1/2 D_{CJ}. Cell patterns on smokefoils during detonations were very irregular and showed secondary cell structures inside primary cells. The measured width of primary cells varied between 20 cm near the stoichiometry and 105 cm (tube diameter) near the limits. The largest detonation cell (105 cm wide and 170 cm long) was recorded for the mixture containing 15.3% methane.

Published by Elsevier Ltd.

1. Introduction

Explosions caused by natural gas and coal dust accumulations continue to occur in underground coal mines in the USA. Since 1976, a total of 185 coal miners were killed and many were seriously injured as a result of underground coal mine explosions. Between 1976 and 2010, at least 25 explosions involving methane and coal dust occurred in the active areas of coal mines, resulting in at least 1 and up to 29 fatalities in each explosion. From 1986 to 2006, at least 12 known explosions involving methane alone occurred in the abandoned and sealed areas of coal mines (Zipf, Jr., Sapko, & Brune, 2007) including Sago Mine in West Virginia in 2006 with 12 miners killed, Darby Mine in Kentucky in 2006 with 5 miners killed, and Blacksville Mine in West Virginia in 1992 with 4 miners killed.

Researchers from the National Institute for Occupational Safety and Health (NIOSH) and the Naval Research Laboratory (NRL) are engaged in fundamental experimental and computational research on explosion processes involving mixtures of methane and air. Explosive mixtures that form in coal mines are essentially mixtures of air and natural gas composed primarily of methane with small amounts of ethane and other alkanes. Though most accidental gas explosions in coal mines are deflagrations, the worst-case scenario involves detonations that can be extremely destructive and can generate explosion pressures up to 10 MPa on reflections. It is therefore important to know the conditions in which natural gas-air mixtures can or cannot detonate. This research is aimed at understanding explosion pressures that can develop in coal mines and the factors that lead to high explosion pressure and possible transition to detonation.

To carry out large-scale experiments with test mixtures of methane and air, researchers constructed an explosion tube measuring 105 cm in diameter and 73 m long located at the NIOSH Lake Lynn Laboratory (LLL) and about 60 km south of Pittsburgh. The methane used in these experiments is natural gas containing about 97.5% methane, about 1.5–1.7% ethane, less than about 0.05% other higher hydrocarbons, and the balance air and carbon dioxide. The experiments are being conducted in two phases. In the first phase, reported herein, detonations in test mixtures of methane and air are created by a direct initiation process that uses a near-stoichiometric, detonable mixture of methane and oxygen as

* Corresponding author. P.O. Box 18070, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA. Tel.: +1 412 386 4097; fax: +1 412 386 6595.
E-mail address: rzipf@cdc.gov (R.K. Zipf).

0950-4230/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.jlp.2011.05.003

a strong ignition source. In the second phase of the work to be reported later, researchers will examine detonations created through a deflagration-to-detonation transition (DDT) using weak spark ignition sources.

2. Previous experiments and methane–air detonations

Existing experimental data from methane and air explosion tests does not definitively answer this question: Given a flammable mixture of methane and air of sufficient volume and lateral extent that may exist in coal mine tunnels or entries, can the mixtures develop into a detonation from a weak spark ignition source? Laboratory-scale experiments examined three different methane–air explosion problems: 1) explosions of methane–air that are confined in pipes, 2) explosions of methane–air that are unconfined and in free space, and 3) explosions of methane–air that are partially confined by congested spaces, such as a process facility. The conclusion regarding the ability of methane–air to either detonate or develop high explosion pressures depended, in part, on the problem geometries under consideration.

The first problem involves explosive mixtures of methane–air confined within pipelines used for gas distribution or in process industries. In these experiments, the explosion spreads in one direction along the length of the tube. Using direct initiation of detonation, Kogarko (1958) and Wolanski, Kauffman, Sichel, and Nicholls (1981), p. 1651 found that the lower concentration limit (LCL) needed to sustain detonation ranged from about 6.3 to 8% methane in air, while the upper concentration limit (UCL) ranged from 13.5 to 14.5%. Recent work by Matsui (2002) found similar values for the LCL (7.5%) but a lower value for the UCL (11.5%). Bartknecht (1981), using a turbulent flame jet for ignition, shows that the tube length-to-diameter needed for a detonation to develop ranged from 75 to 125 depending on the tube diameter. In a review paper of detonation research in tubes, Lee (1984) summarized that on the order of 50–100 tube diameters are required for DDT to develop, starting with a weak ignition source in a smooth tube. The early work on methane–air detonation was conducted within smooth tubes less than 61 cm in diameter. Results showed that test mixtures of methane–air could sustain a detonation if it was initiated by an external, strong ignition source, and several researchers, such as Gerstein, Carlson, and Hill (1954) and Bartknecht (1981), were able to achieve detonation by DDT in smooth tubes. Some of the earlier work may have contributed to the perception that methane–air mixtures can only detonate under extraordinary circumstances not seen in the practical world. However, Lindstedt and Michels (1989) observed DDT with stoichiometric methane–air in 5 cm diameter tubes using Shchelkin spirals to create varying surface roughness of the tube.

In the 1970s and early 1980s, numerous research groups (Bull, Elsworth, Hooper, & Quinn, 1976; Nicholls, Sichel, Gabrijel, Oza, & Van Der Molen, 1978; and Parnarouskis, Lind, Raj, & Cece, 1980) examined the second problem—explosions of unconfined methane–air—which could develop from the catastrophic release of liquid natural gas during transport or storage. Unlike the prior discussion with explosions in tubes, the explosion in this case develops freely in all three spatial dimensions. These research groups used large volumes of methane–air or methane-oxygen-nitrogen mixtures and tried to sustain detonation in the test mixture using a high explosive charge as the initiator. None of the experiments produced sustained detonation in a stoichiometric methane–air mixture. Bull et al. (1976) supported by Nicholls et al. (1978) suggested that 22 kg of solid explosive is required to produce detonation in an unconfined stoichiometric methane–air cloud, which is a highly unlikely occurrence. No experiments with large volumes of unconfined methane–air mixtures produced detonation either by direct initiation or DDT, and researchers concluded that detonation with unconfined methane–air is unlikely. This early work with unconfined methane–air mixtures also contributes to the impression that methane–air mixtures are very unlikely to detonate. However, work by Kuhl et al. (1972) and Strehlow and Baker (1975) shows that devastating overpressures can develop with an accelerating flame or a rapid deflagration, and that detonation is not necessary to achieve high dangerous overpressures.

Recent studies have focused on the third problem—explosions of methane–air that is partially confined in congested spaces. This kind of explosion could occur if a methane–air mixture develops within a process facility, which contains obstacles such as pipes, tanks, reaction vessels, support structures, and other equipment. The obstacles both confine the flow, which acts to accelerate the flame, and interrupt the flow path. This leads to turbulence and additional flame acceleration. The increased flame speed leads to the development of blast and shock waves, which in turn may lead to detonation in the explosive mixture. Ciccarelli and Dorofeev (2008) summarize recent studies of criteria for the onset of detonations in obstructed channels based on cell size, tube diameter, blockage ratio (BR), and other geometric factors. The minimum diameter to observe the onset of detonations is $d>\lambda$ where d is the unobstructed passage diameter and λ is the detonation cell size (Peraldi, Knystautas, & Lee, 1986; Ciccarelli & Dorofeev, 2008).

Moen, Funk, Ward, and Rude (1983) reported the first measurements of the detonation cell size for stoichiometric methane–air at about 28 cm. Lee (1984) and Bartknecht (1993) report a detonation cell size of about 30 cm, while Shepherd (2006) gives a range from 25 to 35 cm for stoichiometric methane–air. Kuznetsov et al. (2002) provided cell size data for a range of methane in air compositions. At 8.5% methane, the measured cell size is 44 cm; at 9.5% it is 19 cm, and at 12%, it is 33 cm.

Early research on gaseous detonation considered the "run-up length", i.e. the distance required to develop a supersonic flame with respect to the combustion products which then undergoes DDT. For smooth tubes, empirical observations show that the run-up length may range from 50 to 100 times the tube diameter (Lee, 1984; Bartknecht, 1993; van Wingerden et al., 1999; Kolbe & Baker, 2005). Based on theoretical models, Ciccarelli and Dorofeev (2008) provided relationships for the length required by a flame to reach supersonic velocity with respect to the combustion products, but not DDT. For methane–air in a smooth tube, this length is about 80 tube diameters. In obstructed channels with a BR of 0.3, this length decreases to about 20 diameters, and for a BR of 0.6, it decreases to about 10 diameters.

Recent research developed a geometrical criterion for the development of detonation in obstructed tubes. The characteristic geometrical size, L, necessary to sustain detonations is:

$$L>7\lambda$$

where λ is the detonation cell size (Dorofeev, Sidorov, Kuznetsov, Matsukov, & Alekseev, 2000; Dorofeev, 2002; Ciccarelli & Dorofeev, 2008). Here, L is computed as:

$$L = D/(1 - d/D)$$

where D is the tube diameter and d is the unobstructed tube diameter.

Kuznetsov et al. (2002) conducted the most recent detonation experiments with stoichiometric methane–air in 17.4- and 52.0-cm diameter tubes with BRs of 0.3 and 0.6, respectively. In some experiments, a sustainable detonation developed by DDT. In other cases, the detonation could not be sustained. This ambiguity has caused many people in the US coal mining industry to question