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Deflagration-to-detonation transition in natural gas–air mixtures

Richard K. Zipf Jr. [a,*], Vadim N. Gamezo [b], Khaled M. Mohamed [a], Elaine S. Oran [c], David A. Kessler [b]

[a] Office of Mine Safety and Health Research, National Institute for Occupational Safety and Health, Pittsburgh, PA 15236, USA
[b] Laboratory for Computational Physics and Fluid Dynamics, Naval Research Laboratory, Washington, DC 20375, USA
[c] University of Maryland, College Park, MD 20742, USA

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ABSTRACT

The gas explosion test facility (GETF) previously used to study detonability of natural gas (NG)–air mixtures was modified for studies of flame acceleration and deflagration-to-detonation transition (DDT). The 73-m-long by 1.05-m-diameter tube was equipped with 15 baffles of varying blockage ratio (BR) = 0.13, 0.25, or 0.50, placed near the closed end of the tube and spaced 1.52-m apart. The remaining part of the tube was smooth. Experiments used mixtures between 5.1% and 15.0% NG–air.

Ignition was achieved in NG–air mixtures over the composition range 6.1–14.1%. After passing the 15 baffles, both flame and pressure wave velocity were more than 300 m/s over this range. Flame velocity was increasing over the range 6.2–12.8% NG–air, and it reached the sound speed in the burned gases (800–1000 m/s) over the composition range 8.0–10.8% NG–air. Pressure wave velocity was increasing over the composition range 6.1–14.1% NG–air and had reached sonic velocity over the composition range 6.2–12.6% NG–air. Shock waves with magnitude greater than 1 MPa were measured in all tests over the composition range 6.5–12.4%. DDT within the baffled section of the tube and sustained detonations beyond the baffles in the smooth part of the tube were observed over the composition range 8.0–10.8% NG–air. The observed run-up length to sonic flame velocity normalized by the tube diameter, X_{ru}/D, ranges from 16 to 23 at BR = 0.13, 10 to 21 for BR = 0.25, and 13 to 21 for BR = 0.50. The observed run-up length to DDT normalized by the tube diameter, X_{DDT}/D, ranges from 19 to 23 at BR = 0.13, and 16 to 23 for BR = 0.25 and 0.50.

Coal mine safety regulations in the US require mine seals to resist an explosion pressure–time curve that rises instantaneously to 0.8 MPa and remains at that level for 4 s. Pressure–time curves measured in these experiments show that shock waves with near-instantaneous rise time and magnitude greater than 1 MPa can develop from weak spark ignition after passing 15 turbulence-generating obstacles in test mixtures ranging from 6.5% to 12.4% NG–air.

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1. Introduction

Between 1976 and 2010, explosions caused by natural gas (NG) and coal dust accumulations in underground coal mines in the USA killed 186 coal miners and seriously injured many others. A total of 25 explosions involving NG and coal dust occurred in the active areas of coal mines, resulting in 165 deaths. The Scotia Mine disaster in 1976 killed 26 coal miners and rescuers, and most recently, the Upper Big Branch disaster in 2010 killed 29 miners. Another 12 explosions involving NG alone occurred between 1986 and 2006 in the abandoned and sealed areas of coal mines [1], resulting in 21 more fatalities. The Sago mine disaster in 2006 killed 12 miners; the Darby mine disaster also in 2006 killed 5 more miners, and the Blacksville mine explosion in 1992 killed 4 miners.

Completely eliminating the possibility of an NG–air explosion in underground coal mines may not be possible, since NG seeps continuously into most underground coal mines. Some of the gas emanates from the mined coal seam itself, and some flows from fissures in the surrounding rock. The mine ventilation system is designed to dilute and transport the gas out of the mine before a flammable mixture accumulates anywhere in the active mine workings. However, situations can arise where flammable mixtures of NG might develop, due to sealing of abandoned mined-out areas or to ventilation problems in active mining areas.

When mining is completed in some part of a mine, it may be partitioned off from the rest of the mine with seals that are sturdy walls or plugs designed to stop airflow into the sealed area and resist explosion pressures that could develop. The atmospheric

* Corresponding author. Fax: +1 412 386 6891.
E-mail addresses: rzipf@cdc.gov, rkarlzipfjr@gmail.com (R.K. Zipf Jr.).

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composition within a sealed area starts as normal air, and as NG seeps in, a flammable mixture could form in the sealed area and exist for some period of time. Eventually, the NG concentration rises above the upper flammability limit and approaches 100%. These rich mixtures are not flammable; however, when the atmospheric pressure decreases due to a passing weather system, NG in the mined-out areas can expand into surrounding coal mine openings and possibly form a flammable mixture.

Once a flammable mixture forms, it can be ignited by a variety of uncontrolled means. The destructive power of the resulting explosion depends on the volume of the reactive mixture, its composition, and the mine geometry. Typical coal mine tunnels measure 6-m-wide and range from 1- to 4-m-high, depending on the coal seam geology. Usually, anywhere from 3 to 10 or more tunnels are excavated in parallel to mine a coal seam. The main tunnels can be several kilometers long, and they are connected every 30–60 m by additional tunnels excavated at right angles. The roof, floor, and walls of these tunnels are rough with asperities on the order of 1- to 10-cm high. Many kinds of obstructions might fill the coal mine tunnels such as mining machinery or rock supports. From a fluid mechanics perspective, coal mine tunnels have a characteristic "diameter" of about 2 m and many possibilities exist for generating turbulent flow such as wall roughness, obstructions, and intersecting flow paths.

The flame evolution in complex mine geometries can result in substantial flame acceleration. Although most accidental explosions in coal mines are deflagrations, in the worst-case scenario, the flame acceleration can lead to deflagration-to-detonation transition (DDT). The resulting detonations are extremely destructive and can induce pressures above 3 MPa. Detonations may or may not develop depending on the ability of a particular mixture composition to sustain detonations, and on the ability of flames to accelerate and produce shocks that are strong enough to ignite detonations. Even if detonations do not develop, the pressures, up to 1 MPa, generated by fast deflagrations can also be very dangerous.

The ability of NG–air mixtures to sustain detonations on large scales has been studied previously [2,3] using the Gas Explosion Test Facility (GETF) at NIOSH Lake Lynn Laboratory. In these experiments, the detonations were directly initiated in test mixtures confined in a 1.05 m diameter tube using a strong ignition source – 3–6 m^3 of stoichiometric methane–oxygen mixture. Self-supporting detonations with velocities and pressures close to theoretical values were observed for mixtures containing between 5.3% and 15.6% of NG. These detonability limits are wider than previously measured on smaller scales. The detonation cell sizes varied from about 20 cm for 10% NG to 1 m or more near the limits.

In this work, we use GETF to study the ability of flames in NG–air mixtures to accelerate and produce strong shock and detonations. Flames in test mixtures are ignited using weak sparks from an electric match and propagate in a 1.05 m diameter tube fitted with baffles. The experiments aim to answer several critical questions pertinent to underground coal mine safety:

(1) Can a weak spark ignition of a NG–air mixture develop into a detonation?
(2) What physical conditions contribute to the flame acceleration and possible DDT?
(3) What explosion pressures can develop in NG–air mixtures during deflagrations and detonations?

In common coal mining terminology, the gas that seeps into underground coal mines is called "methane" or "coal bed methane." In this paper, we call this coal bed gas "natural gas" (NG), and usually use the word methane to mean chemically pure methane denoted by the formula CH_4. The composition of typical coal bed gas ranges from 82% to 99% CH_4 by volume depending on the coal bed. It can also contain several percent nitrogen, 15% or more CO_2, and usually less than 2% ethane and other higher hydrocarbons, again, depending on the coal bed [4,5]. The NG used in these experiments came from the community NG distribution system and is similar in composition to the NG found in many coal mines. Typically, it contained about 97.5% methane, from 1.5% to 1.7% ethane, about 1% nitrogen, and trace amounts of higher hydrocarbons.

2. Prior studies of DDT in natural gas–air mixtures

Early studies of deflagrations and detonations in methane–air and NG–air mixtures produced seemingly contradictory conclusions about their ability to sustain detonation or undergo DDT. Using stoichiometric test mixtures in 2.5- and 30.5-cm-diameter tubes and ignition sources ranging from electrical discharges to 50 g of high explosive, Payman and Shepherd [6] failed to produce a sustained detonation, and concluded that methane–air seemed unlikely to support detonation. Working with test mixtures at less than atmospheric pressure (0.2–0.4 atm) and using a magnesium flare for ignition, Gerstein et al. [7] observed DDT and sustained detonation in a 61-cm-diameter tube. Using a 70 g high explosive charge for ignition in a 30.5-cm-diameter tube, Kogarko [8] observed detonation in NG–air test mixtures over a range from 6.3% to 13.5%.

In the 1970s, several research groups examined spherical detonation in unconfined NG–air clouds that could develop after a large spill of liquefied natural gas (LNG) during transport. Using various methane, oxygen, and nitrogen mixtures ignited by 2.5–520 g high explosive charges, Bull et al. [9] failed to produce detonation and concluded that at least 22 kg of high explosive would be required to initiate detonation in an unconfined cloud of stoichiometric methane–air mixture. Using a sectored shock tube to simulate spherical detonation, Nicholls et al. [10] also examined various methane–air mixtures ignited by high explosive charges and concluded that about 500 g of high explosive are required to initiate detonation in an unconfined methane–air mixture. Using 5- and 10-m-diameter hemispheres of stoichiometric methane–air ignited by a spark or up to 2050 g high explosive charge, Parnarouskis et al. [11] also failed to initiate detonation and concluded that "transition from deflagration to detonation in unconfined vapor clouds does not appear to occur" and that "LNG is extremely difficult to detonate."

Wolanski et al. [12] observed detonation over the range 8.0–14.5% methane–air in a 6.35-cm-square tube using a stoichiometric hydrogen–oxygen mixture as the ignition source. Bartknecht [13], working with stoichiometric methane–air test mixtures ignited by a flame jet, observed flame acceleration in various diameter smooth pipes. DDT was observed after 12.5 m in a 10 cm pipe, and after 18.5 m in a 20 cm pipe, but DDT was not observed in a 40 cm pipe after 30 m – the maximum length of the pipe used in these experiments. Bartknecht concluded that "the tendency to reach detonation velocity decreases with increasing pipe diameter." Citing Payman and Shepherd [6], Bartknecht [13] stated that methane–air mixtures normally cannot be made to detonate except through the use of very powerful ignition sources. However, re-examination of Bartknecht's data shows that the normalized distance to detonation (X_D/D) decreases from 125 to at least 75 as pipe diameter increases. This means that detonations are likely to appear in pipes of any diameter, if the pipe is long enough. Lindstedt and Michels [14] observed DDT in stoichiometric methane–air mixtures using a 5-cm-diameter tube equipped with Shchelkin spiral obstacles of BR = 0.44 and varying length at the ignition end. DDT occurred at a distance X_D of about 8 m corresponding to an X_D/D ratio of about 160.