Journal of Loss Prevention in the Process Industries 41 (2016) 241–251

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Experimental and numerical investigation of methane ignition and flame propagation in cylindrical tubes ranging from 5 to 71 cm – Part I: Effects of scaling from laboratory to large-scale field studies

Matt K. Fig, Gregory E. Bogin Jr. *, Jürgen F. Brune, John W. Grubb

Colorado School of Mines, United States

ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form
29 January 2016
Accepted 16 March 2016
Available online 30 March 2016

Keywords:
Methane combustion
Computational fluid dynamics
Longwall coal mining
Flame characteristics
Tube diameter

ABSTRACT

A firmer understanding of the dependence of flame characteristics as a function of scale is needed to describe methane driven longwall coal mine explosions, which are among the largest industrial explosions. Toward this goal, experimental and numerical investigations of methane combustion and flame propagation in horizontal cylindrical tubes as a function of stoichiometry and tube diameter were carried out. The effect of ignition location was also investigated for stoichiometric air-fuel conditions with ignition at the closed–end of the reactor producing a significant increase in burning velocities on the order of 2–4 times faster as the diameter of the reactor was increased. In the experimental section, horizontal tubes were used with one end allowed to vent to the atmosphere, and the other end a solid wall. Tubes with diameters ranging from 5 to 71 cm were used. It is found that maximum laminar flame propagation velocity increases with tube diameter. 2-D numerical simulations for these tubes were carried out with ANSYS Fluent. A hot-wall was used as an ignition source, with burning velocity trends consistent with experimental data. A functional relationship between stoichiometric uniform burning velocity and tube diameter is presented.

1. Introduction

The study of flame propagation in tubes has a long history, dating back to the late 1800s with the work of Le Chatelier and others. This early work focused on producing detailed experimental data which were compared with simplified theoretical descriptions of the underlying physical processes (Le Chatelier, 1908). Modern studies focus on the use of computational fluid dynamics (CFD) coupled to chemical mechanisms with the goal of predicting experimental findings such as flame-speed, temperature, and pressure profiles (Hawkes and Chen, 2004, 2006; Kozubkov et al., 2014). We seek to extend this understanding to include the effects of scale. This study was undertaken as the first step in a larger project aimed at understanding flame movement through the gob, or rock rubble, found behind the shields in longwall coal mines. Several reaction vessels of various sizes were used to measure the average burning velocities of methane flames without obstacles. This experimentation was carried out to validate a CFD model and establish a baseline for later comparison when obstacles are added to the vessels.

When an explosion happens in a mine, the resulting pressure and temperature increases are enough to endanger both personnel and equipment. This type of explosion in a methane rich, confined space has taken many lives over the years (Brune, 2013). In order to mitigate these dangers, a fundamental understanding of the mechanisms involved is needed. Once the initial flame studies and model validations are concluded, further enhancements to both the model and the experimental setup will be introduced. These will include the placement of rock rubble in the path of the flame within small and large tubes, simulating the passage of a methane flame through the gob, which is currently being prepared as part II of this manuscript. The combustion model will also be incorporated into another, larger model of longwall coal mines concurrently developed.

The two-fold modeling and experimental approach is based on the conviction that a fundamental understanding of combustion behavior can be acquired through a rigorous modeling analysis alongside complimentary experimentation. For the present study, ANSYS Fluent was used to simulate combustion methane-air

---

* Corresponding author. 1500 Illinois st., Golden, CO, 80401, United States.
E-mail address: gbogin@mines.edu (G.E. Bogin).

http://dx.doi.org/10.1016/j.jlp.2016.03.018

mixtures inside small, smooth walled tubes. The modeling reported here focused on gaining an understanding of the computation of deflagration in geometry corresponding to several bench-top experiments.

ANSYS Fluent is widely used to model complex fluid flows, both in industry and in academic research. The inclusion of chemistry solvers in the suite of capabilities offered by ANSYS extends its usefulness into many other areas of scientific interest. The use in this work of a global, one-step mechanism to model the combustion reaction barely exposes the capabilities of this software package. Such a simple mechanism is not without merits, however. These mechanisms are designed to capture prominent feature(s) of the reaction (Westbrook and Dryer, 1981), foremost among these is the flame speed, which is the feature of interest for these investigations.

2. Background

A flame is described as a “self-sustaining propagation of a localized combustion zone” (Turns, 2012). Thus the combustion reaction itself moves, in the current consideration along the axis of a tube, and continues to do so as long as there is an appropriate fuel-air mixture and no quenching obstacles. Flames have several defining characteristics. Among these is a sharp temperature gradient through the reaction zone. The peak temperatures reached depend strongly on the fuel used, the ratio of fuel to air (stoichiometry), and the unburned fuel temperature, among other factors. Another characteristic is the flame speed. By this we mean the rate at which the reaction zone is observed to move through the combustible mixture in a direction perpendicular to the flame surface. Like the peak temperature, the speed of the flame depends on several factors, including the fuel and stoichiometry, the local and induced pressure differences across the flame, and whether the flame is laminar or turbulent.

Many methods of determining the flame speed and propagation velocity for various hydrocarbon fuels have been tried, and there is no agreed-upon standard technique. (Andrews and Bradley, 1972a). Both stationary and moving flame techniques have been used to some degree of success. Andrews and Bradley (Andrews and Bradley, 1972b) use a horizontal tube with two ignition kernels to measure flame speed. They argue that the symmetries inherent in this setup avoid some of the common pitfalls found in open ended flame-tube studies. When evaluating single-kernel tube methods, many investigators (Andrews and Bradley, 1972b; Rallis and Garforth, 2001) have found the inclusion of an orifice on the closed end of the tube also can stabilize flame motion. This method was used for the larger quartz vessel, while for the steel vessels a solid wall was used.

3. Experimental procedure

3.1. Laboratory scale

Alongside the modeling effort, a laboratory scale flame tube was designed and built for investigation of methane ignition and flame propagation. The laboratory scale experimental setup is utilized to validate the modeling efforts and provide several data points from which to extrapolate to larger combustion geometries where modeling is more time consuming and less exact. An overall schematic of the experimental setup is shown in Fig. 1.

The system consists of compressed methane and zero-grade air cylinders and accompanying controls, a mixing vessel, several reactor tubes of different dimensions housed in a Plexiglas chamber for safety and visual inspection, and data acquisition equipment. The tubes have instrumentation ports along the outside wall, which can be fitted with flame detectors and pressure transducers. The Plexiglas shield, along with a 5 cm diameter steel tube and a 13.6 cm diameter custom fabricated quartz tube, are shown in Fig. 2.

Another, larger, flame tube was also constructed of a 1.2 m section of 30.5 cm diameter pipe. This tube has a large enough gas volume to be treated as a large-scale tube, which was used to predict the behavior of methane flames in larger tubes. It too was outfitted with sensors for the detection of flames. This tube is shown in Fig. 3.

The experimental process with all tubes begins by allowing streams of both the methane and air to pass through mass flow controllers or flow meters and then to enter a mixing vessel, which consists of a large diameter chamber filled with turbulence-inducing media. Once mixed to the desired stoichiometry, the fuel-air mixture flows past a ball valve and flashback arrestor into the reactor tube. When the tube is saturated with the methane-air mixture, the combustion reaction is initiated by a piezoelectric sparking mechanism. The flame then propagates down the length of the tube, passing the ports containing the sensors along the way.

The electronic data acquisition is done through a NI usb-6008 and usb-6009 DAQ boards, which allow for up to 48,000 samples per second - high enough to capture the passing of the flame. This ensemble provides more than enough acquisition and control hardware.

Custom built flame detectors were made from stock spark plugs, in the case of the 5 cm steel tube, and ceramic welding rod feeds for the quartz tube, shown in Fig. 4. This allows accurate flame detection and ease of installation and replacement. In addition, thermocouples were used to measure the flame speed on a smaller glass tube which has no sensor ports.

This device has been tested and found reliable. Several tests confirmed that the sensor can pick up a passing flame and also a steady flame. The operating principle is the same as with the spark plug sensors, but the form is slimmer. These sensors are made of various lengths so that the flame can be probed beyond the tube wall into the centerline.

An example signal from these smaller sensors is shown in Fig. 5. The black peak indicates the flame is near the open end of the tube, which is where the leading sensor is placed. Further spikes are made as the flame travels to the closed end.

For the larger tubes, a different sparking system was used. This consisted of a relatively low-voltage automotive coil hooked to a relay circuit which produces sparks at the frequency of the switch inside the relay. This system was tested on the large quartz tube and found to be effective and produce no noticeable difference in flame velocities from those produced by the single piezo-electric sparker, in agreement with the findings of others (Agnew and Graiff, 1960; Frendi and Sibulkin, 1990).

Between experimental runs, the tube was allowed to cool for 10 min while a volume of air equivalent to 8 tube-volumes flushed the system of exhaust products. After the tube was filled with a flammable mixture, the flow was stopped and the tube was allowed to settle for 30 s before the spark. This settling time ensures near stagnant conditions inside the vessel, which helps to eliminate the influence of currents on flame velocity values.

3.2. Edgar Mine gas explosion test facility (GETF)

In addition to the bench-top experimental setup, a larger scale flame tube (GETF) was installed at the CSM Edgar Mine above the town of Idaho Springs. The CSM Methane GETF is an experimental apparatus designed to permit safe combustion and flame studies for mining and other industrial applications. The GETF consists of four subsystems, which are the large flame tube, the fuel and air