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EFFECT OF SIMULATED GOB CONDITIONS ON THE BURNING VELOCITY OF PREMIXED METHANE-AIR COMBUSTION

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ABSTRACT

Although it is known that explosive gas zones can form and sustain combustion in a longwall coal mine gob, a complete account of the interaction of the methane flame and gob remains obscure. The goal of this study is to examine the impact of several gob parameters such as packing orientation and void spacing. The impact of ignition location is also detailed. A series of experiments with methane flames were performed in a horizontal cylindrical quartz reactor. The reactor was tested both empty and packed with an obstacle wall consisting of spherical glass beads to investigate the impact of various gob parameters. Results demonstrate that methane burning velocity is sensitive to all parameters investigated, and most sensitive to packing density and ignition location.

INTRODUCTION

The explosion at the Upper Big Branch Mine in 2010 and several other underground longwall coal mine fires and explosions show that explosive gases can mix with fresh ventilation air creating explosive gas zones (EGZs). Investigative reports of these fires have found that EGZs are able to move from the gob and into the active longwall face, endangering workers and equipment [1]. Currently, researchers at the Colorado School of Mines are using computation fluid dynamics (CFD) modeling to predict the location and movement of EGZs in the gob and along the longwall face [2,3]. It is the goal of this work to validate combustion models [4] that include interactions of the flame and the gob for future incorporation into ongoing CFD modeling of EGZs [2,3].

Throughout the years, there has been significant research investigating how flames interact with obstacles and propagate through porous media [4,5,7-11]. Since there is limited access to the gob in a longwall coal mine (Figure 1), the orientation and size of rocks and void spaces within the gob is unknown. Experiments of a simulated gob have been performed in a large scale flame tube in order to investigate the effect of scale (Figure 2) [4,5]. However, the variation in rock spacing, rock orientation, and void location makes it difficult to determine the impact of each of these parameters on methane flame dynamics. This study aims at gaining a stronger fundamental understanding of gob parameters such as spacing, orientation, and ignition location on methane flame propagation. The results from this study will provide a basis for experimentation in larger explosion vessels and will be used to validate methane combustion models for incorporation into longwall ventilation models of EGZ movement [2,3,4].

BACKGROUND

Researchers have been studying flame propagation across obstacles and porous media for many years using various fuels and experimental setups [4,5,7-11]. Experiments have been performed in horizontal chambers with both ends open [7], horizontal chambers that are semi-open [4,11], horizontal chambers with both ends closed [8], and vertical arrangements [9,10]. Due to the variation in experimental setups and methods of characterizing flame dynamics such as flame speed, peak overpressure, or burning velocity it becomes difficult to directly compare results. Flame speed is a property of the mixture and refers to the speed of the unstretched flame front normal to the direction of propagation. This study characterizes the flame by its burning velocity, which is the difference between the flame speed and the speed of the unburned gases just ahead of the flame front. However, some references use the terms flame speed and burning velocity interchangeably. In this study, a semi-open quartz cylindrical reactor was used to determine methane burning velocity, which was used as a basis for comparison to determine the impact of obstacle configuration on methane flame dynamics. The quartz reactor also has the unique ability to allow for flame visualization. These features allow for faster combustion model validation [4].

**Figure 1.** Image of Western U.S. Longwall void [6].

Figure 2. Image of simulated gob used by Fig *et al.* [5].

This research also investigates how the burning velocity is impacted by rock rubble properties such as porosity, void spacing, barrier height, etc. Previous studies of flame propagation through obstacles uses orifice plates or rings [7], while others have used rectangular plates [10] or other shaped obstacles. Qualitative results from these studies show burning velocity increases across obstacles and that in most cases, multiple obstacles continue to increase the burning velocity, sometimes reaching detonation velocities. However, the gob in a longwall coal mine consists of various orientations of rocks with varying porosities. Ciccarelli *et al.* [8] investigated the effect of layers of beads along the length of a horizontal rectangular channel. It was found that bead layer porosity seems to have a larger effect on the flame speed than surface roughness [8]. Mihalik *et al.* [9] studied the effect of porous media size and material on the flammability limits of methane-air mixtures. Results from [9] also found the flame to accelerate across the porous media due to increased resistance from the porous media to the downstream products. Although the various experiments discussed here have similar qualitative results, the different experimental methods make general application of the results difficult, and give little specific insight into flame propagation in a longwall gob. This study aims at taking a more systematic approach by evaluating in turn the effects of gob spacing in addition to geometry, orientation, etc. on the burning velocity of methane flames.

EXPERIMENTAL SETUP & PROCEDURE

Several horizontal flow reactors from 5 cm to 71 cm in diameter and 1.2 m to 6.1 m in length are currently being used to study the interaction of methane-air flames with a simulated gob [4]. For brevity, only the small-scale horizontal cylindrical quartz flow reactor is presented in this manuscript. A quartz reactor is used to allow full view of the transient flame as it interacts with an obstacle wall to simulate the various physical properties that vary in longwall coal gobs (e.g. porosity, void spacing, barrier length, barrier height, etc.). This provides additional information for improved understanding of flame dynamics for combustion model validation [4] for incorporation into full CFD modeling of EGZ movement in a longwall mine [2,3]. The flame reactor used in these experiments is a horizontal quartz tube that is 12.5 cm in diameter and 150 cm in length as shown in Figure 3. One end of the reactor is open to the atmosphere and the other end is closed. There are 5 flame detector ports equi-laterally spaced 25 apart along the top of the tube.
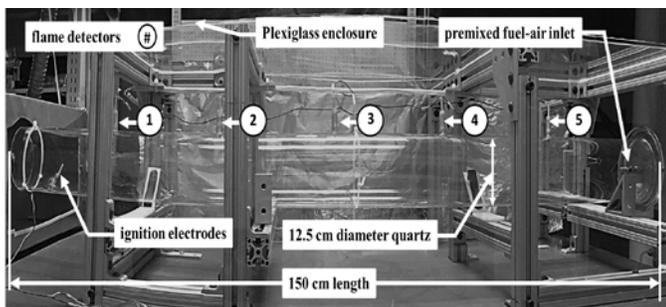
Figure 3. Image of the small-scale experimental horizontal quartz flame tube reactor.

The experimental system consists of compressed methane and zero-grade air cylinders, mass flow controllers, a mixing chamber with turbulence inducing media, and the horizontal quartz flame reactor tube. The experimental process begins by flowing methane and air into the mixing chamber through separate mass flow controllers; a Bronkhorst EL-FLOW® Select (0-50 SLM) controls the air and an Alicat Scientific MC Series (0-5 SLPM) controls the methane. Inside the mixing chamber, turbulence inducing media mixes the methane and air until homogeneity is reached and the desired stoichiometry is satisfied. The reactor is sealed while the methane-air mixture flows into the closed-end of the reactor until the entire reactor is completely saturated; an Infrared Industries IR-6000 gas analyzer is used to confirm homogeneity. After the reactor is filled, flow is stopped and the methane-air mixture is allowed to settle in the reactor to ensure stagnant conditions before ignition. An automotive spark ignition system is used to initiate combustion. Immediately after ignition, the

seal is removed during which there is an initial slight pressure rise of 0.5-1 psig. After each experiment, compressed building air is used to cool down the reactor to room temperature and remove any residual combustion products, ensuring experimental consistency.

In order to measure the burning velocity of the methane flame propagating in the reactor, custom ion sensors were designed and built. The ion sensors are inserted into the flame detector ports. The sensors are connected in series to a DC power source and resistor network so that a large voltage drop is created when the flame front passes across them. The data is recorded by an electronic data acquisition system which uses a NI usb-6008 and usb-6009 DAQ boards capable of sampling at 48,000 samples per second. The system has been tested and proves adequate for this study [4]. Each experiment is run 4-5 times and the DAQ system records 4 average burning velocity measurements along the length of the tube per experimental run. All error bars presented in this work represent the standard deviation of the mean burning velocity.

EXPERIMENTAL TEST PARAMETERS

To evaluate the effect of rock orientation and ignition location on the burning velocity of methane flames, the quartz flame reactor was used to measure methane burning velocities with and without an obstacle wall. The obstacle wall consisted of 6.35 mm diameter, smooth, solid glass spheres in various orientations and at different locations along the length of the quartz reactor. The obstacle wall was contained in a metal cage having a length of 2.54 cm and inserted into the reactor at different locations. Studies were conducted with an empty tube and with an empty cage inside the tube to determine a base case to gain insight into the effects of the cage on burning velocity and to isolate the impact of the obstacle wall. All experiments were performed at atmospheric pressure and temperature, 83 kPa and $24^{o}C$ respectively. The lower pressure is due to the lower barometric pressures at this altitude – Denver, CO. Note the metal cage has a spacing of 6.35 mm, which is larger than the quenching distance of methane flames at the pressure and temperature investigated.

Obstacle wall material

The obstacle wall used in this study consisted of 6.35 mm diameter, smooth, solid glass spheres configured in various geometries. Glass was used because it has similar thermal properties to that of actual rocks found in a longwall gob; the thermal conductivity of glass is approximately 1.05 W/m-K which is similar to clay (1.1 W/m-K), sandstone (1.7 W/m-K), and limestone (1.3 W/m-K). Spheres were used because it removes the impact of irregular shaped rock and rock geometry, which is also under investigation in this study. Additionally, spheres allows for easier comparison in future and ongoing computational fluid dynamics and combustion models [4]. Note that in the future, this research will also be investigating spheres of different sizes and materials.

Variation in obstacle wall geometry

In order to capture the two main characteristics in a longwall gob, porosity and void spacing, two obstacle configurations were chosen for this study (Figure 4): a wall barrier with varying void spacing and a checkerboard pattern with varying porosity. A wall configuration was used to investigate how the methane flame interacts with a solid obstacle. Experiments were performed varying the wall height and length which translates to changing gob void spacing. A checkerboard pattern was used in order to investigate effects of porosity by varying the spacing between the spheres. For example, in Figure 4, the spheres are 6.35 mm in diameter and are spaced 6.35 mm from each other. Adding or removing spheres from the checkerboard pattern allows the porosity of the geometry to be changed, but the void spacing to remain the same.

Variation in ignition location

The obstacle wall and metal cage insert were tested at different locations along the length of the quartz reactor to investigate the effect of ignition location relative to the obstacle wall. The obstacle wall was tested 37 cm from the open-end hallway between sensors 1 and 2 and 62 cm from the open-end halfway between sensors 2 and 3 (Figure 2). For all of the obstacle wall experiments the ignition source was in the center of the reactor in the radial direction 11 cm from the open-end.

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Additional experiments were performed in an empty reactor with ignition 11 cm from the closed-end, centered in the radial direction.
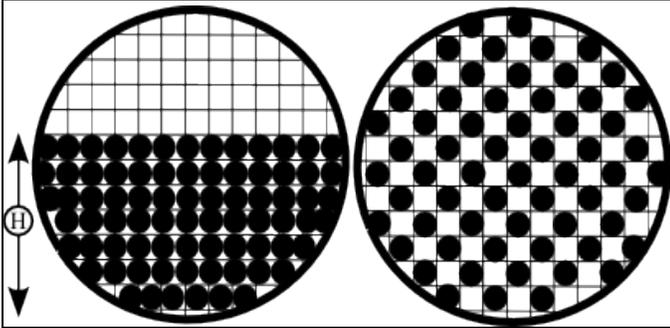

Figure 4. Sketch of wall geometry (left) and checkerboard geometry (right). Not to scale.

This study also investigated the effect of in-gob ignition since fires and explosions in a longwall coal mine can occur within the gob. For these experiments, the ignition electrodes were centered in the middle of the cage inserts under sensor port 1, 25 cm from the open-end as shown in Figure 5. A baseline test was run with an empty cage with metal grid backings on either end spaced 15.24 cm apart. Next, 6.35 mm glass spheres were arranged in a checkerboard pattern and spaced 15.24 cm and 30.48 cm apart.
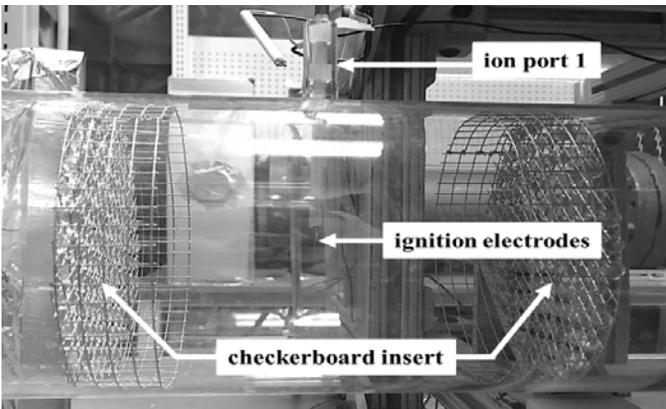
Figure 5. Image of in-gob ignition.

RESULTS AND DISCUSSION

All experiments in this study were performed at atmospheric pressure and temperature, 83 kPa and 24°C respectively. The burning velocity reported in these results is an average burning velocity over 25 cm based on the spacing of the ion sensors. The dotted lines in all figures represent the location of the 5 ion sensors and the gray bar represents the location of the obstacle wall. Note that methane content was within ± 0.2% reported in this study.

In order to establish a base case for an empty tube, experiments were run at various methane volume fractions. Figure 6 shows that a stoichiometric mixture of methane and air, 9.5%, has the highest burning velocity. A lean mixture, 7.5%, is slower than the stoichiometric mixture, but faster than the rich mixture, 11.5%. From a fundamental understanding of methane flame speed, a rich mixture produces faster burning velocities than the lean mixture [12]. However, visually the rich mixture flame front is significantly different than the lean and stoichiometric cases (Figure 7). The lean and stoichiometric cases have a forward leaning flame due to the buoyancy effect of hot exhaust gases preferentially accelerating the top of the flame. However, the rich flame is not as accelerated by the exhaust gases and in some instances a secondary diffusion flame appears. Since the flame front of the rich case is near the bottom of the tube and the ion sensors are at the top of the tube, it is possible that the ion sensors are not accurately measuring the burning velocity of the methane rich flame.

To isolate the impact of the obstacle wall on methane burning velocity, the empty cage was inserted into the tube to help determine a base case (Figure 8).
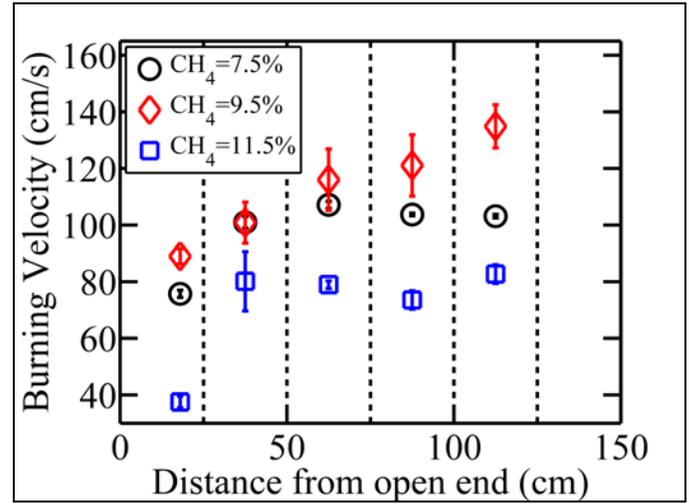

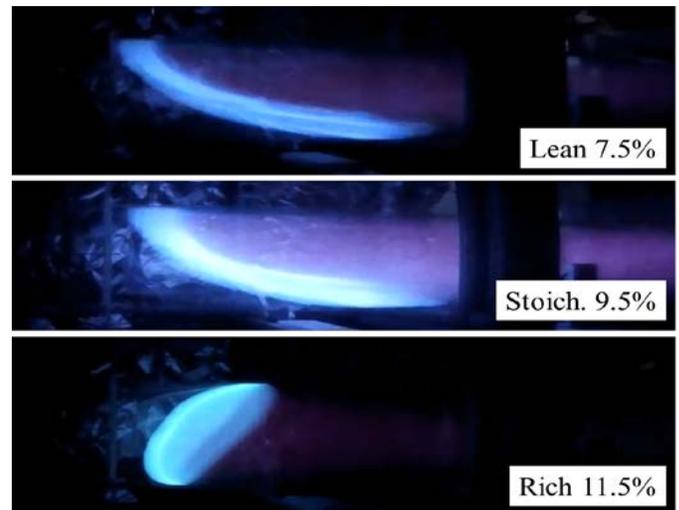**Figure 6.** Impact of stoichiometry on methane burning velocity. Ignition 11 cm from open end.

Figure 7. Images of a lean, stoichiometric, and rich flame propagating right to left in the quartz reactor.

Figure 8 shows that for an open-end ignition, the empty cage does not have a significant impact on the methane burning velocity.
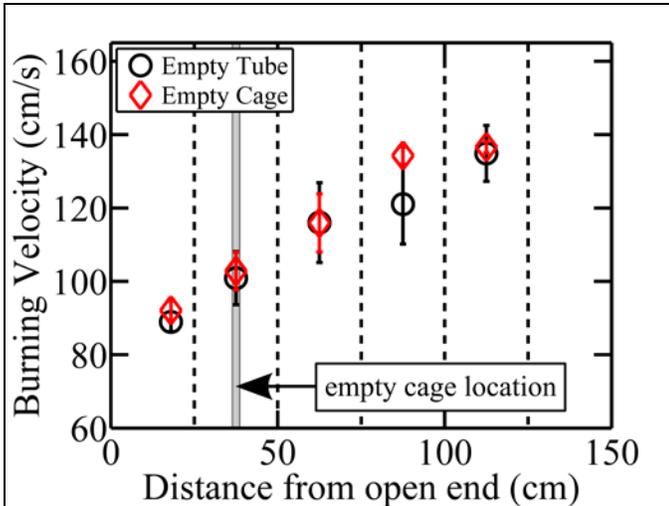
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Figure 8. Impact of metal cage insert on methane burning velocity. Ignition 11 cm from open end. CH_4=9.5%.

Results – Effect of obstacle wall height

In this experiment, 6.35 mm glass spheres were arranged in a wall pattern as shown in Figure 4 with the void located at the top of the tube. The length of the gob is constant at 12.7 mm while the height of the wall is increased from 3.81 cm to 9.84 cm (Figure 9). Results show that adding an obstacle wall into the quartz reactor enhanced flow and gas transport and thus accelerated the flame across the obstacle wall, which is in agreement qualitatively with previous studies [7-10]. Increasing the obstacle wall height from 3.81 cm, void fraction 73%, to 7.62 cm, void fraction 33%, did not have a large effect on the burning velocity. However, when the obstacle wall height was increased to 9.84 cm, void fraction 12%, the amount of void space in which the flame could propagate decreased and the flame further accelerated across the obstacle wall.
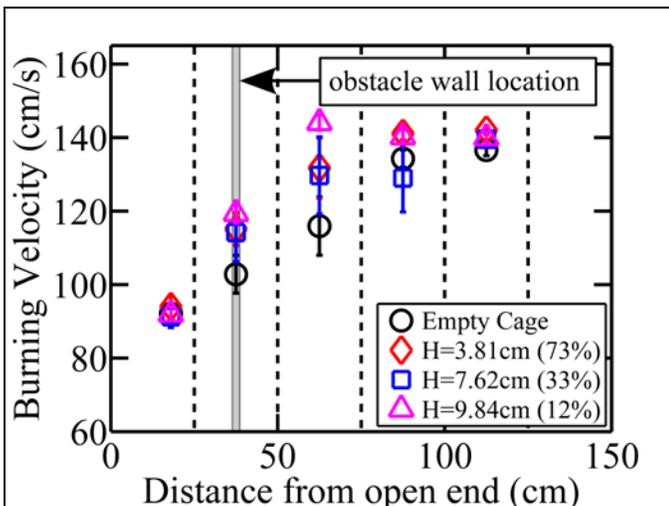

Figure 9. Impact of obstacle wall height using 6.35 mm glass spheres in a wall pattern. Ignition 11 cm from open end. CH_4=9.5%.

Results – Effect of obstacle wall length

To investigate the effect of obstacle wall length, 6.35 mm glass spheres were arranged in a wall pattern as shown in Figure 4. The height of the obstacle wall is constant at 7.62 cm while the length is increased from 6.35 mm to 12.7 mm (Figure 10). Results show as the obstacle wall length increases the burning velocity of the methane flame also increases. Since the flame must pass through the void for a longer distance, the burning velocity of the flame increases in order to maintain mass flow. However, Chapman and Wheeler [7] found that for a brass ring, as the thickness of the ring increased, the mean speed of the flame decreased. Since brass has a high thermal conductivity

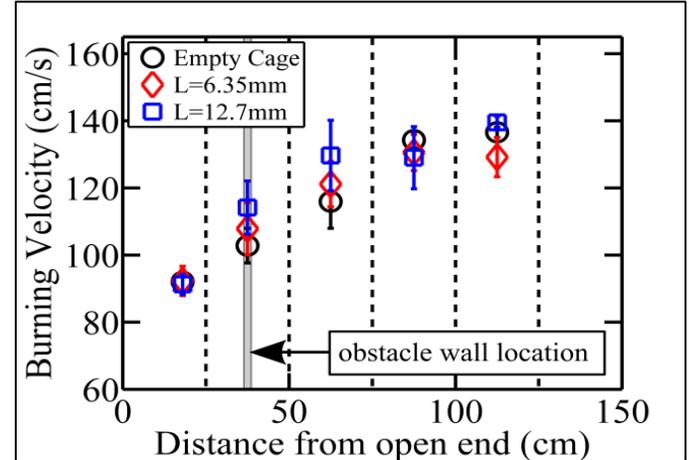compared to glass, most likely the brass absorbed heat from the flame thereby decreasing the velocity of the flame.

Figure 10. Impact of obstacle wall length using 6.35 mm glass spheres in a wall pattern. Ignition 11 cm from open end. CH_4=9.5%.

Results – Effect of obstacle wall geometry

In Figure 11, the effect of geometry is investigated by comparing a wall of height 7.62 cm and length of 6.35 mm with a porosity of 50%, and checkerboard geometry of length 6.35 mm with an approximate porosity of 75%.
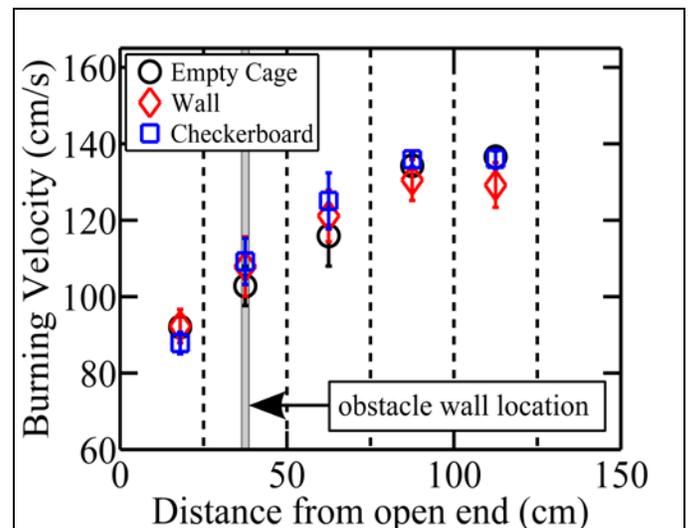

Figure 11. Impact of obstacle wall geometry using 6.35 mm glass spheres. Ignition 11 cm from open end. CH_4=9.5%.

There are several previous studies that investigated the effect of restriction amount on flame burning velocity. Chapman *et al.* [7] found that as the size of the restriction decreases, the flame acceleration across the obstacle increases. Though results in Figure 9 agree with [7], results from Figure 11 show when the two geometries are close to the ignition source, the checkerboard geometry further increases the initial downstream burning velocity due to the increased pressure resistance.

Results – Effect of ignition location

Figure 12 shows that obstacle wall location relative to the ignition source has a significant effect on the burning velocity of methane flames. For the case of the checkerboard pattern, as the obstacle moves further from the ignition source, the upstream burning velocity is slightly retarded initially and then the flame accelerates across the obstacle, which is consistent with previous results [7, 10]. This initial slow-down of the flame is likely due to pressure resistance from the obstacle wall. This pressure build up likely slows the flame while simultaneously inducing turbulence in the unburned gas mixture,

helping to accelerate the flame across the obstacle wall. Additionally, the relative increase in burning velocity of the methane flame across the obstacle wall located 37 cm from the open end is less than the relative increase in burning velocity when the obstacle is moved 62 cm from the open end of the reactor. Interestingly, when the obstacle wall is located 62 cm from the ignition source, the burning velocity across the empty cage is greater than the checkerboard pattern. When the obstacle wall was 37 cm from the ignition source, the checkerboard pattern produced faster burning velocities. This difference could be due to the competition between induced turbulence of the obstacle and pressure resistance of the obstacle. Further from the ignition source, the pressure resistance of the checkerboard pattern may have a larger effect than the induced turbulence.

Figure 13 shows that ignition within the empty cage increases the burning velocity due to the enhanced turbulence. However, ignition within the gob consisting of the checkerboard geometry shows a decrease in burning velocity which is likely due to the increased pressure resistance. The pressure resistance of the checkerboard geometry slows the initial flame kernel growth therefore decreasing the burning velocity of the flame. When the checkerboard geometries are located further from each other, Figure 13, the flame does not accelerate as quickly across the obstacle, but the downstream burning velocities are not significantly affected.
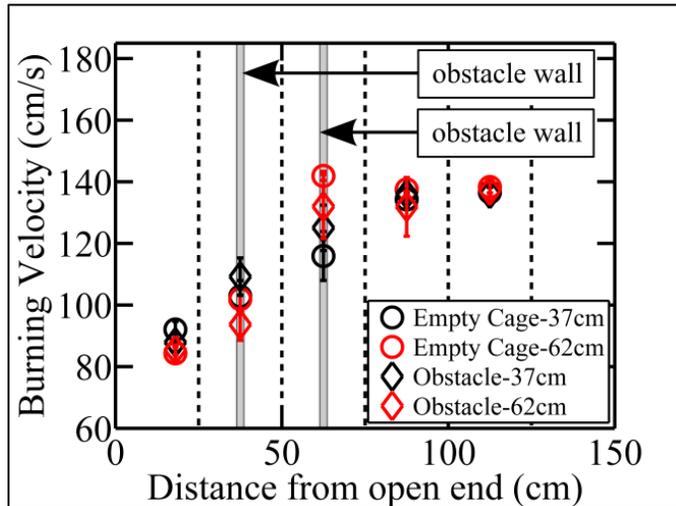

Figure 12. Impact of ignition location using 6.35 mm glass spheres in a checkerboard pattern. Ignition 11 cm from open end. CH_4=9.5%.
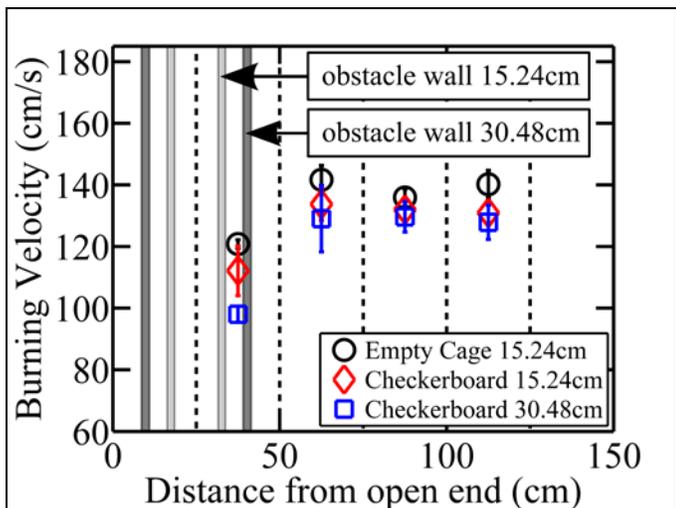

Figure 13. Impact of in-gob ignition on methane burning velocity. Ignition 25 cm from open end. CH_4=9.5%.

When ignited from the closed-end (Figure 14), the methane burning velocity increases by two orders of magnitude compared to ignition from the open-end (Figure 6). This increase in burning velocity from the closed-end is likely due to the increase in pressure of the exhaust products and simultaneous reduction in upstream pressure accelerating the flame.

CONCLUSIONS

These studies provide valuable insight into the relative impact of gob parameters (e.g. porosity, barrier length, barrier height, void spacing, etc.) on methane flame burning velocities: 1) Open-end ignition upstream of the obstacle wall accelerates the flame across the obstacle wall due to enhanced flow and transport. 2) Densely packed spheres allow for higher velocities in void spaces as well as an increase in exhaust back pressure, further increasing the downstream burning velocity. 4) Increased spacing between the spheres reduces the pressure ahead of the flame while simultaneously enhancing fluid motion and increasing transport, resulting in an increased burning velocity. 5) As the obstacle wall moves downstream from the ignition source, the burning velocity across the obstacle increases due to the enhanced flow. 6) Closed-end ignition results in an increase in exhaust product pressure and simultaneous decrease in upstream pressure resulting in a two order of magnitude increase in the burning velocity of the methane flame.
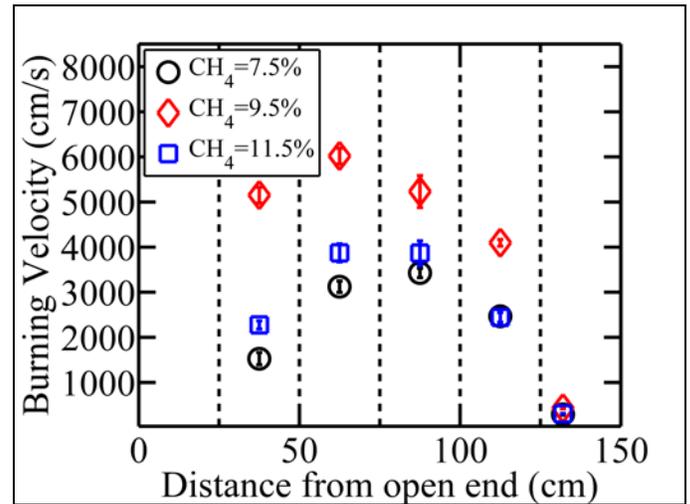

Figure 14. Impact of stoichiometry on methane burning velocity. Ignition 11 cm from closed end.

The results from this study are important for validating methane explosions models [4] for incorporation into full-scale longwall ventilation models [2,3] in order to help better predict the movement and explosion risk of EGZs. Based on the results from this study, ignition near the face of a longwall coal mine may result in higher burning velocities, potentially endanger workers. Obstacles, including mining equipment and workers, in the path of the flame could accelerate the flame resulting in greater damage. Overall, these results provide valuable insight to the complex interaction of fluid dynamics, heat transfer, and methane flame dynamics in rock rubble. The systematic approach taken in this study allows the effect of various gob parameters to be evaluated so that researchers may understand the combination of these effects.

ACKNOWLEDGEMENT

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