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GOB LOCATION AND THE PROPAGATION OF METHANE FLAMES IN SIMULATED AND EXPERIMENTAL FLAME REACTORS

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ABSTRACT

A knowledge of flame propagation characteristics through and around obstacles is needed to accurately model methane-air longwall coal mine explosions originating or propagating in and around the gob. Researchers at the Colorado School of Mines (CSM) conducted experimental investigations of methane flames in horizontal reactors with simulated gob rock piles. Researchers also carried out coupled, computational fluid dynamics (CFD) and combustion simulations using ANSYS Fluent. Stoichiometric methane-air mixtures were ignited in semi-open experimental reactor vessels of 5cm, 9.5cm and 71cm diameter, all with a fixed length to diameter (L/D) ratio of 8.6. Rock pile length was fixed at 30% of the length of the reactor and rock pile height was fixed at 33% of the diameter of the reactor for direct comparison between reactor vessels across scales. This paper presents results for three reactor configurations: empty reactors, reactors with a rock pile placed at the open end, and reactors with a rock pile at the closed end. Experimental results indicate that flame acceleration depends on pile location and geometry as well as size of the reactor. In the 5cm diameter reactor, the rock pile at the open end of the reactor produced the fastest flame, whereas in the larger reactors, a rock pile at the closed end of the reactor produced the fastest flame. A 2D, CFD combustion model accurately captures the general trends observed in experiments for the smaller reactors but over predicts the magnitude of methane flame front propagation velocity.

INTRODUCTION

Explosions in underground coal mines are among the largest industrial explosions and can release enough energy to cause extensive damage and loss of life [1,2]. The methane gas under pressure in an undisturbed coal bed can be released during the mining process. Under certain ventilation scenarios, this methane can become a hazard, because methane can mix with ventilation air and, if not sufficiently diluted, may form a combustible mixture. An accumulation of combustible gas is an explosive hazard. Recent large coal mine explosions include the 2014 Soma Mine disaster in Turkey that resulted in the 310 fatalities [3] and the 2009 Heilongjiang Mine explosion in China that fatally injured 108 miners [4]. A domestic example is the 2010 disaster at the Upper Big Branch mine in West Virginia, USA, which caused 29 fatalities [5]. A mine explosion may expand into the active mining face or nearby areas, endangering workers and equipment. Mine explosions may transition to detonations [6] – such detonations are suspected to have occurred in the 1992 explosion of the Blacksville No. 1 mine with 4 fatalities and the 2006 explosion at the Sago mine that left 12 miners dead.

The focus of this paper is to develop an understanding of the impact of rock pile obstacle location on the development of high-speed methane gas deflagrations at a variety of experimental scales. Mine explosions often occur in mined-out, caved areas of the mine called gobs. Gob explosions can push into active working faces and fatally injure miners. The experimental and modeling results presented in this paper are part of a research project at the CSM funded by CDC NIOSH and aimed at developing a comprehensive, coupled 3-D CFD and combustion model of a longwall coal mine methane gas explosions. The purpose of this model is to design and assess current mitigation strategies against such disasters in order to develop stronger safety procedures for miners. Since there are few facilities that can perform full mine-scale methane gas explosion experiments, development of numerical models of methane gas explosions in an underground mine is useful. CFD models can be calibrated with experimental input for benchmarking across various, smaller scales. Previous research by [7] has been conducted both experimentally and with CFD investigating the impact of short sections of rock at the open end of flame reactors and results show that methane flame front propagation velocity does not scale linearly. This paper aims at extending this research to include longer piles of rock rubble at the open end and closed end of reactors and presents complimentary CFD, combustion simulations. Reactors of 5cm, 9.5cm and 71cm diameters were used for the experiments presented in this paper. To examine the effects of scaling, the length-to-diameter (L/D) ratio of all reactors was fixed at 8.6, the length of the simulated gob inserts was fixed at 30% of the reactor length and the height of the rock piles were fixed at 33% of the reactor diameter. All experiments were performed with the ignition source at the closed end of the reactor.

BACKGROUND

Flames have been described as a self-sustaining propagation of a localized combustion zone that will continue to move through a combustible mixture as long as there are no extinguishing conditions such as obstacles or walls [8]. A deflagration flame can be defined by several characteristics; among these is a sharp temperature gradient through the reaction zone. The peak temperatures reached depend on the flow conditions, the fuel, the stoichiometry of the mixture, the unburned mixture temperature, and the pressure at which the reaction occurs. An important characteristic of flames is the laminar flame speed which is the rate at which the reaction zone, or flame, moves perpendicularly through stagnant combustible mixture under ideal conditions [9]. Like the peak flame temperatures, the flame speed is dependent on kinetics, stoichiometry and thermodynamic properties. Examined in this paper is the flame front propagation velocity, which is the rate at which the reaction zone or flame moves through the gas mixture. This is dependent on a given experimental setup, the confining geometry, the fluid flow conditions, and obstacles [7, 8].

There are many different types of obstacles in a longwall coal mining face and in the caved, mined-out area called the gob. The face is characterized by mining equipment while the gob fringes consist of unconsolidated piles of rock rubble. This rubble is comprised of rocks that have caved from the overburden strata and may have different material properties, sizes, packing geometry, height, and void spacing depending on geologic conditions. Unfortunately, the gob is inaccessible, so it is difficult to determine the exact size, geometric configuration and location of rock rubble. However, it is well known that the outer fringes of the gob typically have larger void spaces, as shown in Figure 1. These voids may fill with combustible or explosive gas mixtures when methane from the coal seam is released. Deeper in the gob, the rock rubble is more tightly compacted and has much lower gas permeability. The characterization of methane-air combustion and explosions in longwall gobs requires investigation of how the gob rubble impacts dynamic flame behavior. CSM researchers aim at gaining a fundamental understanding of the relative impact of each of these properties to accurately model methane explosions in coal mines. Experimental results from prior CSM research show that methane flame front propagation velocity is highly sensitive to ignition location and obstacle location [1] across a variety of experimental scales [7]. This paper further explores these effects by increasing the size and location of the rock pile alongside developing CFD, combustion models.

Figure 1. The edge of a longwall gob near the mining face at a western U.S. coal mine [10]. Notice how the size of the rock rubble gets smaller looking further back into the gob.

EXPERIMENTAL SETUPS

CSM researchers used several experimental gas combustion reactors to examine the effects of various parameters on the propagation of methane flames with and without obstacles. Experiments help validate and inform CFD and combustion modeling which will be discussed in the next section of this paper. A detailed description of this experimental equipment is described in [7] and will be briefly described here. The laboratory system consists of methane and air supplied by compressed gas cylinders, two mass flow controllers are used to provide a stoichiometric mixture, a mixing vessel ensures homogeneity, and an array of data acquisition devices and software (Figure 2). The reactors have instrumentation ports fitted with ion sensors as well as pressure transducers to determine the flame front propagation velocity. For all experimental stations, the mixture accuracy was verified by sample analysis with a gas chromatograph thermal conductivity detector.

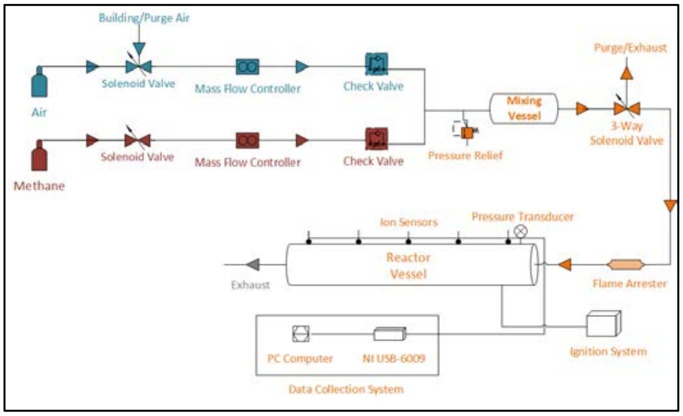

Figure 2. Schematic showing layout of the major components of the experimental flame reactor reactors used for the experimental section.

EXPERIMENTAL TEST PARAMETERS

Flame propagation through rock rubble was tested by placing rock inserts near the open and closed ends of each of the reactor vessels. These rock containment inserts were constructed from heavy duty wire mesh hardware cloth for the laboratory reactors and sheet metal for the 71cm diameter reactor. The rock containment inserts are then filled with rock rubble; the rock material used for the laboratory reactors was granite, while gneiss was used in the 71cm diameter reactor. Figure 3, right side, shows views of the 5cm diameter and 9.5cm diameter reactors with granite-filled inserts designed to extend only as high as the rock pile, to avoid any flame quenching or flow interactions with the wire mesh. The rocks used in the 5cm diameter reactor had an average diameter of 1.5cm and the rocks used in the 9.5cm diameter reactor had an average diameter of 3cm. Figure 4 shows the experimental setup for the 71cm diameter reactor located at Edgar Experimental Mine in Idaho Springs, CO. The average size of the rock rubble in the 71cm diameter reactor was 22cm.

Tests were performed in the horizontal reactors to investigate the effects of a constant length of rock rubble near both the open and closed end, from small to large scale. All the reactors were tested 1) empty, 2) with rock inserts at the open end of the reactor, and 3) with rock inserts at the closed end of the reactor. Experiments were performed with stoichiometric methane-air mixtures, 9.5% methane by volume. Ignition location was always at the closed end of the reactors. This simulates an ignition in a confined space representative of an ignition in or around the gob area. The laboratory experiments were performed at 294K and at a local atmospheric pressure of 82kPa which were kept consistent throughout. Experiments performed in the large-scale,71cm in diameter, reactor which is located at Edgar Experimental Mine in Idaho Springs, CO, at 2,400 m, took place at an average absolute pressure of 75±1kPa.

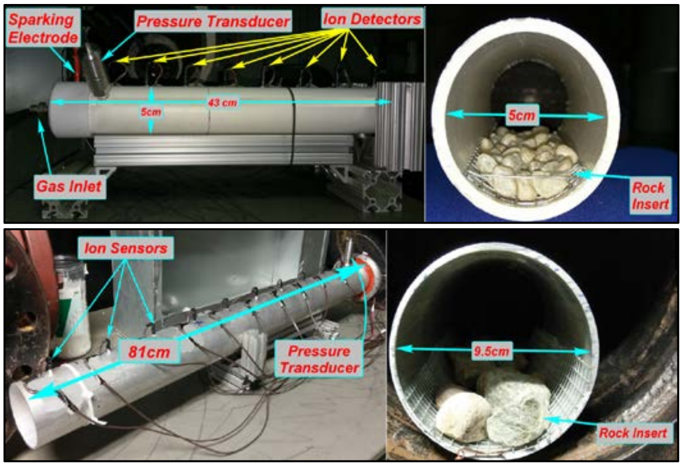

Figure 3. Laboratory scale experimental reactors of diameter 5cm (top) and 9.5cm (bottom). Experiments are performed at 82kPa and 294K with stoichiometric methane-air mixtures. Ignition takes place at the closed end. The rocks used in the 5cm diameter reactor were on average 1.5cm diameter, while the rocks used with the 9.5cm diameter reactor were 3cm.

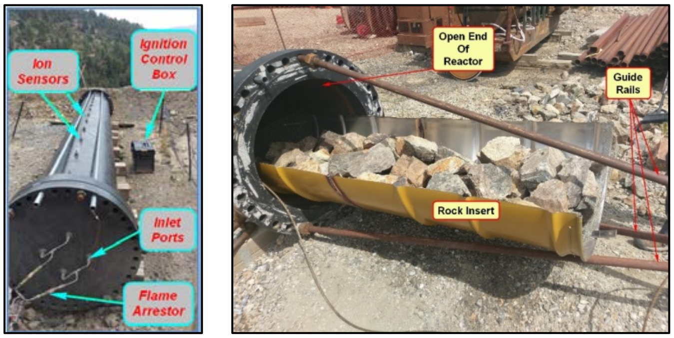

Figure 4. The field scale reactor at Edgar Mine. Tests performed at this location are at 294K and 76kPa due to elevation at 2404m. The 71cm diameter reactor is 6.1m long. The average rock size used here was 22cm.

When the simulated gob rock pile is placed near the open end of the flame tube, and the gas is ignited from the closed end, the flame accelerates linearly along the length of the reactor before encountering any obstacles [11]. No transition past wrinkled turbulence was observed during this initial acceleration, as determined by the measured flame propagation velocities along with inspection of video images of the flame taken from inside the reactor with the use of a SONY FDR-X300 video camera capable of 240 frames per second. Two examples of the flame photographed from inside the large reactor are shown in Figure 5. As the flame passes over the rock pile, it becomes turbulent and accelerates quickly. Researchers also observed a significant increase of the velocity of the unburned gases ahead of the flame both in the empty reactor and when filled with rocks. The flame also becomes more turbulent as it reaches the later stages of acceleration. This feature and its characteristics are important for the model to capture.

Figure 5. Left - The stoichiometric methane flame in the initial run up inside the empty 71cm diameter reactor. Right - The flame accelerates dramatically when the rocks are encountered. This image shows the flame over the first part of the rock insert in the 71cm reactor. Tests performed at a mean of 76kPa and 294K.

CFD COMBUSTION MODEL SETTINGS

The experimental setups were modeled using CFD with ANSYS Fluent. For the laboratory reactors, a 2D symmetry model was employed that used a k-ϵ turbulence model with initial velocity of 0.01m/s used for calculating the initialization of the turbulent parameters for the quiescent mixture. A stoichiometric mixture of methane was used, and a simple two-step kinetics mechanism was assumed for the flame chemistry. The reduced mechanism is a simplification of the GRI 1.2 mechanism [12]. The mixture was ignited with a small energy source amounting to 5 mJ release over 1ms. The walls of the vessels were assumed rough with a roughness height of 0.5mm. Initial pressure and temperature was set to 82kPa and 294K. The mesh used in the laboratory reactors was limited to a maximum size of 1mm to ensure accurate resolution of the flame. An adaptive mesh refinement method that adapted on the temperature gradient was also used to ensure the movement of the flame was captured accurately. 2D models have been found to produce different magnitudes with respect to velocity and accelerations than 3D models [13]; however, here the goal is to minimize the computational time while still accurately capturing the impact of the rock pile on the flame front propagation velocity. The basic CFD model was previously validated for much shorter rock half-walls placed in the flame tubes with an open-end ignition [14] and with closed end ignition [15,16]. The results presented below extend the base model to larger obstructions. Using a more detailed chemical reaction mechanism achieves more realistic flame front propagation velocities.

RESULTS & DISCUSSION

The experiments performed in the 5cm diameter reactor show the impact of the rock pile on flame front propagation velocity (Figure 6). In the empty reactor, the flame front propagation velocity has a nearly linear acceleration as it propagates from the closed end to the open end of the reactor, which agrees with what has been observed previously [11]. This acceleration is mainly driven by the expansion of the exhaust gases in the confined space behind the flame. The model captures the main flame front acceleration, but overpredicts the magnitude for most of the length of the reactor. Also, the model can capture the slow down observed in experiments as the flame reaches the open end of the reactor and exhausts to the atmosphere.

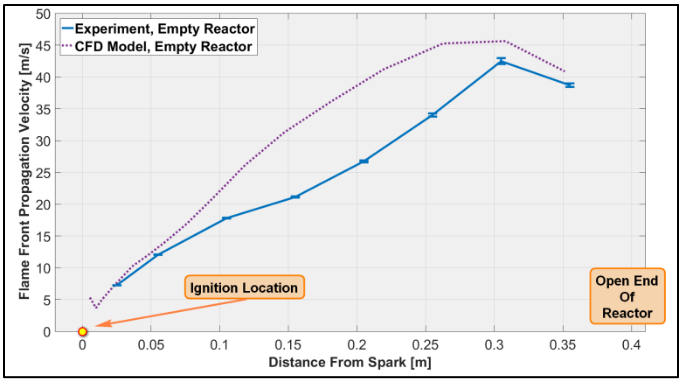

Figure 6. The 5cm diameter, empty reactor with stoichiometric methane-air. Experiments and simulations carried out at 82kPa and 294K. Mean relative error between experiment and model is 24% and maximum relative error is 50%.

Figure 7 shows the impact of placing a rock insert at the closed end of the 5cm diameter reactor and Figure 8 shows the impact of placing a rock insert at the open end of the 5cm diameter reactor. When placed at the closed end, the rock insert leads to significant flame acceleration along the entire length of the reactor. This is due to the increased local turbulence that is introduced into the unburned gases ahead of the flame. This turbulent flow increases mixing of the unburned gases to the reaction zone, and since it starts early in the flame development, it leads to faster burning rates early in the flame development which further increases the expansion rate of the flame front. When the rock insert is placed at the open end, the flame is seen to initially expand with about the same velocity as in the empty case. When the flame reaches the rock pile, the flame accelerates across it. Here the main flame acceleration mechanism is a combination of a Bernoulli-type effect whereby decreased void space increases mass flow, and increased turbulent mixing encountered over the rock insert which results in a turbulent boundary layer. The model captures the behavioral trend of the flame well, showing the increase in flame front propagation velocity due to the rock pile.

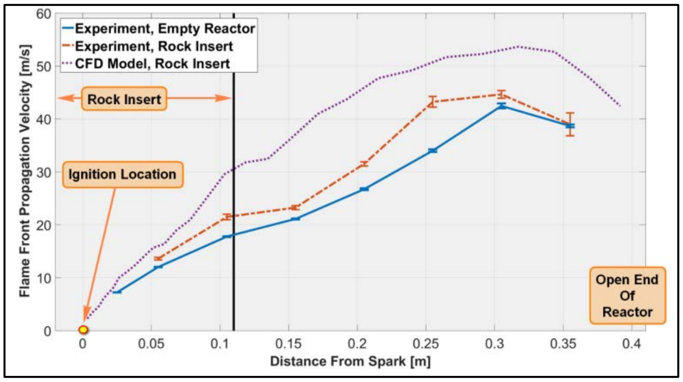

Figure 7. The 5cm reactor with rock insert at the closed end with stoichiometric methane-air. Experiments carried out at 82kPa and 294K. Mean relative error between experiment and model is 30% and the maximum is 60%.

When these same experiments were repeated with the larger, 9.5cm diameter laboratory reactor, a similar effect was observed, as shown in Figure 9. Similar to the 5cm diameter reactor, the methane flame in the 9.5cm diameter reactor is observed to accelerate linearly along the length of the vessel until it exhausts at the open end of the reactor. Unlike the 5cm diameter reactor, the 9.5cm diameter reactor did not exhibit the same slowdown near the open end. The slowdown exhibited by the smaller reactor at the open end is thought to be due to acoustic coupling.

Experimental results of rock inserts at both the open and closed ends of the 9.5cm diameter reactor show an increase in flame front propagation velocity, shown in Figures 10 and 11, which agrees with trends observed in the 5cm diameter reactor. Once again, the presence of the rocks at either end accelerates the flame within the reactor. However, for the 9.5cm diameter reactor rocks at the closed end has a larger impact on methane flame front propagation velocity than rocks at the open end. This is, likely since the rocks take up a smaller fraction of the cross-sectional area and so the turbulent boundary layer that forms above the rock pile has less of an overall effect. The model for these reactors captures the impact of the rocks on flame behavior but continues to overpredict the flame front propagation velocity.

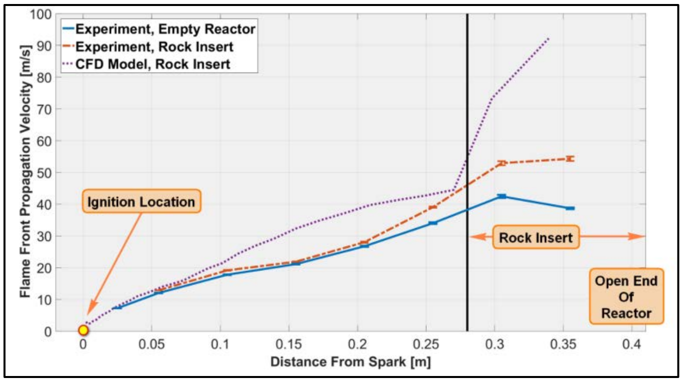

Figure 8. The 5cm empty reactor with rock insert at the open end stoichiometric methane-air. Experiments carried out at 82kPa and 294K. Mean relative error between experiment and model is 32% and the maximum error 63%

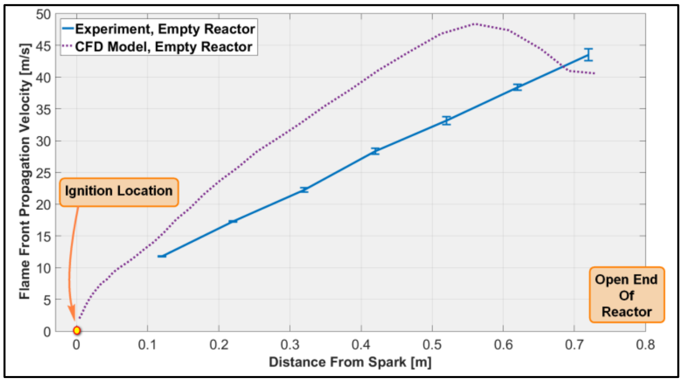

Figure 9. The 9.5cm empty reactor with stoichiometric methane-air. Experiments carried out at 82kPa and 294K. Mean relative error between experiment and model is 34% and maximum is 49%

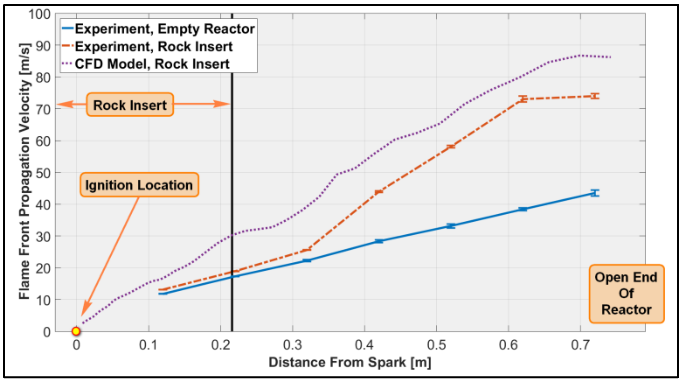

Figure 10. The 9.5cm empty reactor with rock insert at closed end with stoichiometric methane-air. Experiments carried out at 82kPa and 294K. Mean relative error between experiment and model is 31% and maximum is 62%

Experiments matching those performed in the laboratory were also performed in the 71cm diameter reactor located at Edgar Experimental Mine in Idaho Springs, CO. Though the reactor is larger, the geometric scaling is preserved such that there is similarity between this reactor and the laboratory reactors. The empty reactor results show the familiar pattern of a linear flame acceleration along the length of the reactor.

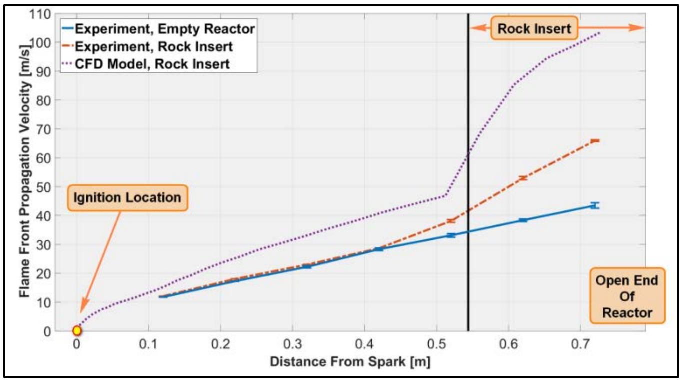

Figure 11. 9.5cm empty reactor with rock insert at open end stoichiometric methane-air. Experiments carried out at 82kPa and 294K. Mean relative error between experiment and model is 43% and maximum is 66%.

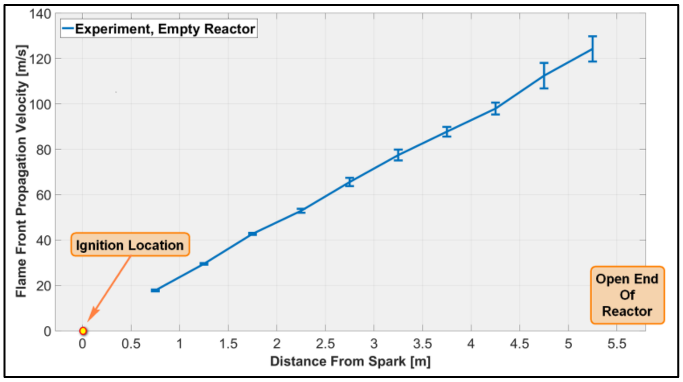

Figure 12. The 71cm empty reactor with stoichiometric methane-air. Experiments carried out at 78kPa and 300K.

The experimental results for the 71cm diameter reactor with rock obstacles are shown in Figures 13 and 14. When the rock pile is placed at the closed end, the flame accelerates faster than when the rocks are placed at the open end, which agrees with the laboratory scale experiments. This bolsters the hypothesis that even though the rocks are the same relative depth when placed at front of the reactor, the ratio of the cross-sectional area occupied by the turbulent boundary layer compared to the total cross-sectional area is smaller with the larger reactors than in the smaller reactors, and thus has less of an effect on the main flame front.

Researchers conducted experimental flame propagation tests in several laboratory and large-scale reactors and compared observations to complimentary CFD combustion models. Rock inserts placed in the reactors increase flame front propagation velocity in all cases investigated. The larger reactors showed that the placement of the insert near the closed end more dramatically increases the flame front propagation velocity along the reactor, while rocks at the open end led to the largest flame acceleration in the smallest reactor. The reason the rock insert at the closed end generally has a larger effect is because it introduces turbulent mixing into the flow earlier, and this increase in mixing of the unburned mixture to the reaction zone increases the burn rate, which expands the exhaust gases faster. When rocks are placed at the open end, the flame does not accelerate due to the turbulent mixing until it is over the rocks near the end of its expansion. The flame does, however, benefit from the narrowing of the flow area over the rocks which leads to increased flow velocity of the unburned gases. The buildup of turbulence intensity over the rocks ahead of the flame is illustrated in Figure 15.

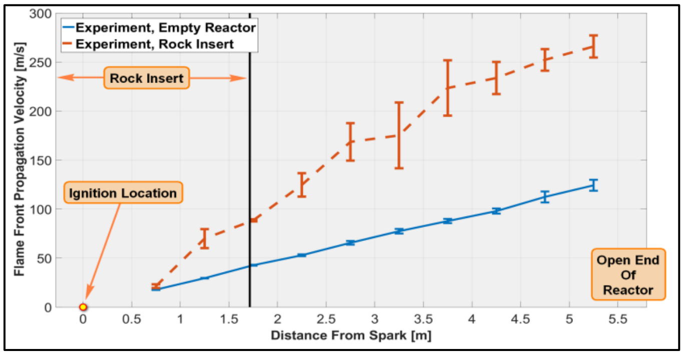

Figure 13. The 71cm empty reactor with rock insert at closed end with stoichiometric methane-air. Experiments carried out at an average of 78kPa and 300K.

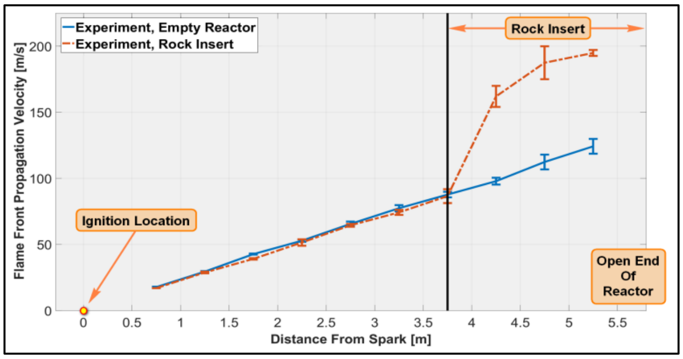

Figure 14. The 71cm reactor with rock insert at closed end with stoichiometric methane-air. Experiments carried out at an average of 78kPa and 300K.

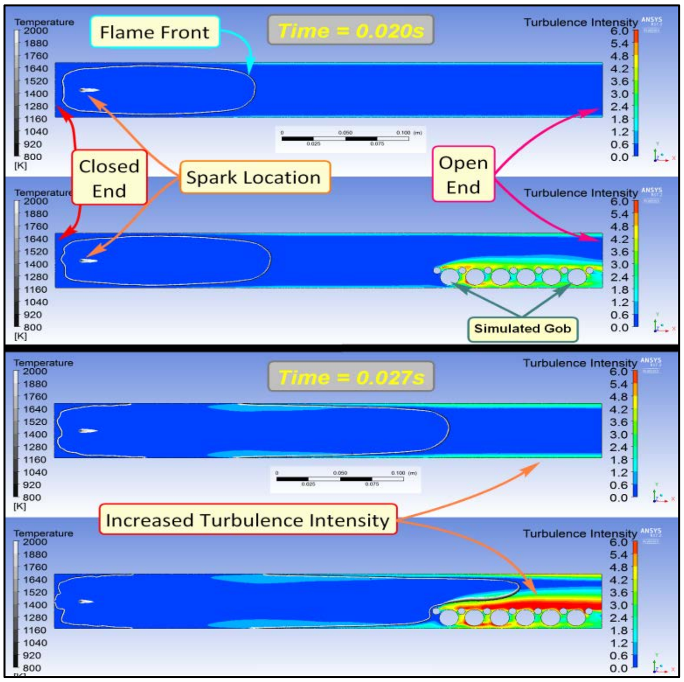

Figure 15. Simulated stoichiometric methane-air in a 2D, 5cm diameter reactor at two separate time steps. Both the empty reactor and the reactor with simulated rocks near the open end are shown. Evident is the buildup of turbulence over the rock insert, and the impact it is having on accelerating the flame over the pile. Simulation conditions are 82kPa and 294K.

Thus far, the 2-D, CFD combustion models accurately predict the trends, but overpredict the values of the flame front propagation velocities in all cases. The relative errors of the models when compared to the experimental findings are tabulated below. Performance of the model decreases with increasing reactor size. It is expected that a model with the same setting would perform similarly for the 71cm reactor. Both the flame front propagation velocities and the corresponding model shapes found in Figure 6 and Figure 9 suggest a physical scaling similarity is present, and the model captures that. A plot of the experimental results all together shows how the slope of the curve decreases with reactor size, as shown in Figure 16. The inset in Figure 16 shows the normalized velocities plotted against the normalized propagation distance. The curves are nearly colinear, which confirms the scaling similarity and helps explain the similarity of the modeling results shown in Figure 6 and Figure 9.

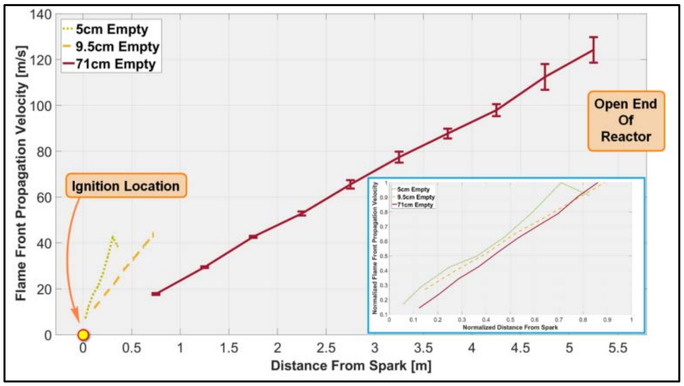

Figure 16. Experimental results from the 5cm, 9.5cm and 71cm empty reactors with stoichiometric methane-air. The inset shows these same curves normalized by their maximum velocities and plotted against a normalized propagation distance. This reveals an underlying scaling similarity present in this set of experiments.

CONCLUSIONS

The ability to model and simulate a methane explosion inside a realistic longwall mine model is important to the development of effective prevention and mitigation strategies and can inform future mine designs. Researchers paired experimental and CFD modeling efforts to characterize methane explosions that interact with rock rubble in longwall gobs. Experiments across scales in laboratory and field reactors are used to benchmark CFD combustion models. Researchers demonstrated the effectiveness of the model by matching several key features of flame acceleration through a confined space with and without rock obstacles. By modeling and experimenting with fixed L/D ratios, researchers confirmed the trends observed based on the physics of fluid flow and combustion chemistry. The CFD model is sufficiently refined to capture these trends.

The research presented in this paper provides insight into the effects of rock pile placement on methane flame dynamics in horizontal, cylindrical combustion reactors across a wide range of scales. Results show the presence of rock piles, such as those found in a mine, dramatically increases the flame front propagation velocity for all reactors, and this trend is confirmed with the models. The prediction of the trends for all cases indicates that the model has been correctly developed thus far and invites comparison with different configurations of the rock piles, such as variations in the height and length of the piles. Across scales, the results indicate that even a relatively simple model that uses 2-step chemistry in 2D to approximate the 3D reality can be used to predict trends in complex methane flame phenomena. The CSM research group will continue testing the combustion models with the goal of producing a single 3D, CFD combustion model of methane flame front propagation capable of capture key methane flame physics and trends across scales. In the future, the combustion model will be incorporated into a full-scale longwall coal mine ventilation model so that researchers can study these large-scale methane gas explosions and have confidence in the predicted methane deflagration physics since the model was developed across a wide range of scales.

ACKNOWLEDGEMENTS

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