Effect of Coal Particles on Turbulent Burning Velocity of Methane – Air Premixed Flames

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Abstract
The effect of 75-90 µm coal particles on turbulent premixed methane – air flames is studied using a shadowgraph. The methane air flame has an equivalence ratio of 0.8 and the coal particles have a concentration of 100 g/m^3. The results show that addition of coal particles cause the turbulent burning velocity to increase by up to 3%.

1. Introduction
In industrial coal mining explosions are a continuous hazard. A recent example occurred in West Virginia on April 5, 2010. This incident caused 29 fatalities and is considered one of the most disastrous mining accidents in US history. Many coal mine explosions begin with a methane-air deflagration which then combines with fugitive coal dust. The interaction of the coal dust with a laminar methane –air flame has been analyzed by Xie et al. [1]. Expansion of the combustion products in a confined environment such as a coal mining tunnel causes the flame to quickly become turbulent in nature. The coal particles can also cause instabilities which can induce turbulence. For example, Greenberg et al. [2] have shown that the addition of combustible micron sized liquid droplets can increase the burning velocity of a gas-air flame under certain conditions. The effect of solid particles on turbulent gas-air flames has not been thoroughly investigated in literature and is the focus of the current study.

2. Experimental Apparatus
Experiments are conducted in a Bunsen burner type of setup with a similar design to the one used by Kobayashi et al. [3]. Flame burning velocities were calculated using the area method. The flame edge was captured using a shadowgraph captured on a Nikon D90 with a Macro lens using a shutter speed of 1/4000 s, aperture setting of 4.2, and an International Organization of Standards (ISO) of 100. The images were then processed using an image algorithm programmed in MATLAB. Methane and air flow rates were controlled with flow-meters ,for this study, the equivalence ratio of the methane –air mixture was kept fixed at 1.28.
Figure 2 shows visual images of a premixed methane - air flame (a) and a premixed methane – air flame including 100 g/m^3 of 75-90 µm coal dust. It is shown that the luminous flame produced by the coal particles makes it difficult to determine the outline of the gaseous methane – air flame exists, which is why the shadowgraph images proved extremely useful.

Figure 3 shows an example image of the shadowgraph of a turbulent flame with and without dust. It is shown that the methane-air flame can be distinguished from the background caused by the illumination of the coal particle combustion. The flame was held on the burner using an annular pilot as shown in figure 1. The area ratio of the annular pilot flame was 10% of the Bunsen burner nozzle area. Turbulence was generated using a perforated plate with 2.38 mm diameter holes and a blockage ratio of approximately 50%.

The turbulent burning velocity (S_T) of the flame is calculated in a using the area method [4]

$$S_T = \frac{V}{A}, \tag{1}$$

where V (m^3/s) is the volume of air going through the burner and A (m^2) is the surface area of the flame. To handle the uncertainty and random shape of the turbulent flames 50 images were analyzed to determine an average turbulent burning velocity for a given turbulent intensity. The surface area of the flame was found by using

$$A = \pi \frac{D}{4} L \,, \tag{2}$$

where D (m) is the diameter of the nozzle exit and L (m) is the overall length of the flame edge shown in the shadowgraph. Similar to Smallwood et al [5], the overall length of the flame is used rather than a flame edge angle. The flame edge was selected manually using an image processing algorithm developed in MATLAB. Turbulent intensity was measured using a hot wire anemometer placed at the center of the nozzle exit at a distance of 0.5 cm from the rim, and is given by

$$u'_{rms} = \sqrt{\frac{(u'_1 + u'_2 + ... + u'_n)^2}{n}} \,, \tag{3}$$

where u' is the difference between the instantaneous value of the flow velocity (measured by the hot-wire anemometer) and the mean flow velocity. "n" represents the number of data points which is equal to 180000 (velocity data was collected for 3 min).

3. Results and Discussion

Table 1 shows the measured burning velocity for two flow rates with and without dust. The addition of coal tends to increase the burning velocity of methane.

Table 1: Burning velocity of methane with and without the addition of coal dust.

Flow rate air (lpm)	Flow rate methane (lpm)	Turbulent Intensity (m/s)	S_L without Dust (cm/s)	S_L with Dust (cm/s)
10	1.35	0.0064	24.4	26.2
15	2.0	0.0072	34.2	34.5

The increase in burning velocity due to the addition of coal particles is likely due to the radiation feedback from the coal particles combustion. This radiation preheats the methane air mixture which allows it to burn faster. The coal may also increase the local turbulent intensity which increases burning velocity.

4. Conclusions

Experiments using a turbulent premixed burner were conducted to observe the effect of adding coal dust (75 – 90 µm) to a methane air flame. The particles tend to slightly increase the burning velocity. It is hypothesized that the increase in burning velocity may be due to the radiative feedback caused by the combusting coal, preheating the unburned gasses. This influence is currently being quantified. Future work will also include obtaining turbulent burning velocity at lower equivalence ratios with higher turbulent intensities.

5. Figures

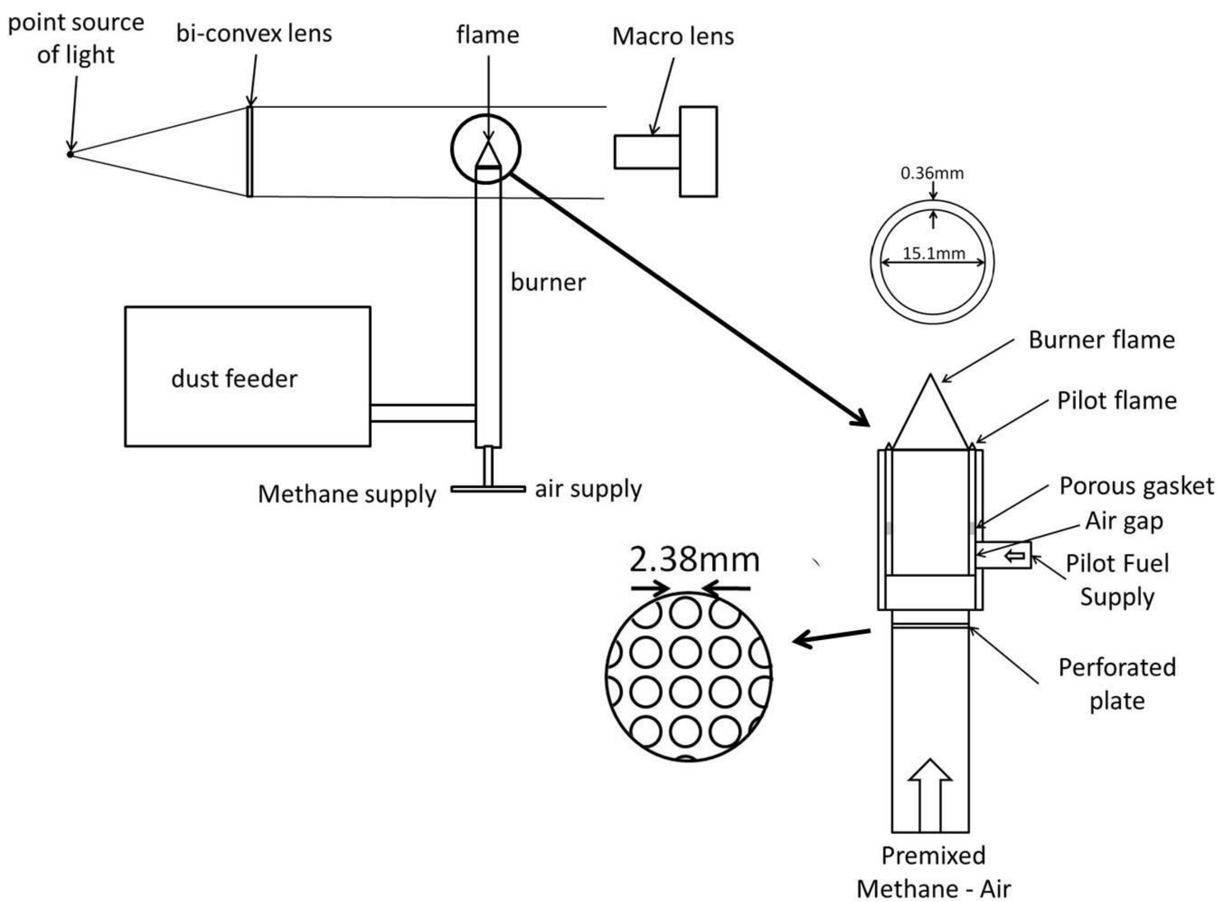

Figure 1: Diagram of dual phase fuel burner experiment

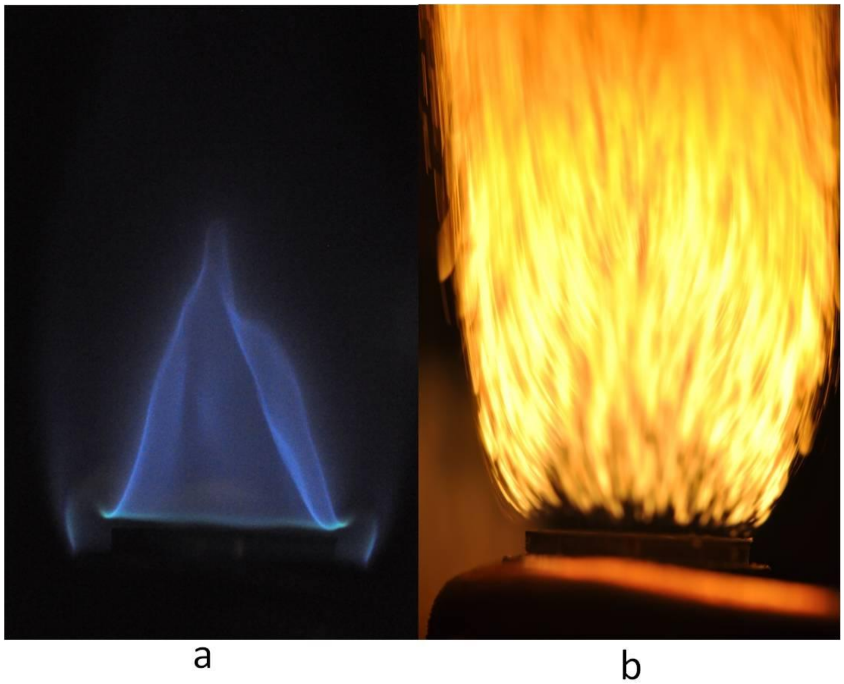

Figure 2: Images of a turbulent burner flame using annular pilot with and without dust (flowing 10 lpm air). (a) methane – air flame (b) methane – air flame including 100 g/m^3 of coal particles

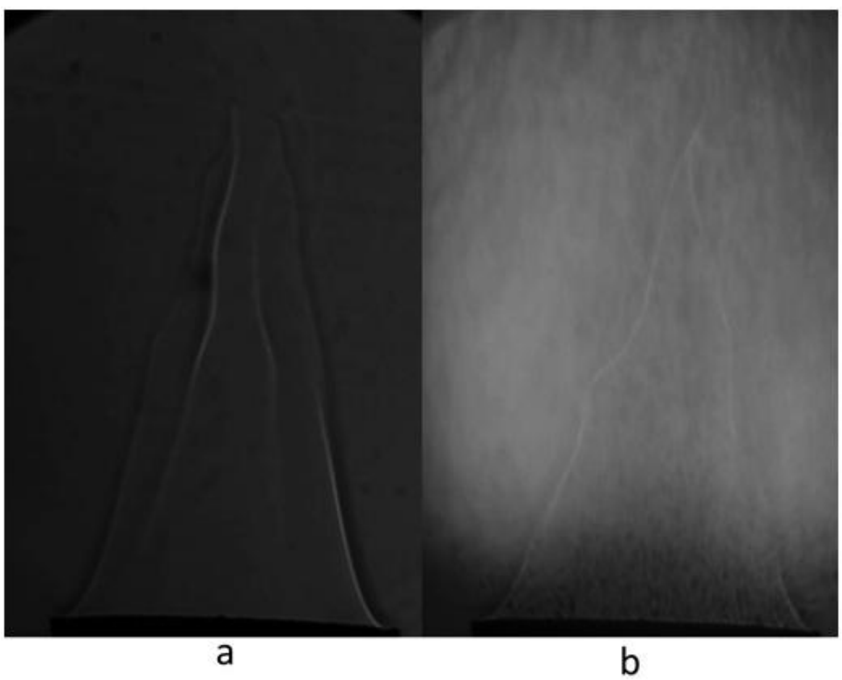

Figure 3: Shadowgraph images of flames with and without dust (flowing 15 lpm air). (a) methane – air flame (b) methane – air flame including 100 g/m^3 of coal particles

6. References

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