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Turbulent burning velocity of methane–air–dust premixed flames

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ABSTRACT

Investigation of turbulent burning velocity (S_T) of methane–air–dust premixed flames with different dust types (coal, sand and sodium bicarbonate) and dust concentrations ($\lambda_p = 0\text{–}75\,\mathrm{g/m^3}$) were conducted at three methane–air pre-mixture equivalence ratios ($\phi_g = 0.8$, 1.0 and 1.2) and different turbulent intensities ($u'_{\mathrm{rms}} = 0.65$, 0.72 and 0.88 m/s). Experiments were conducted in a dust Bunsen burner set-up at constant pressure conditions to study stabilized premixed flames. The results indicate that based on the particle type, the variation of turbulent burning velocity with an increase in the particle concentration differs. In general, coal and sodium bicarbonate result in the heterogeneous effect of absorbing heat and releasing volatiles; whereas sand particles just absorb heat from the flame zone. The detailed time scale analysis conducted shows that the presence of particles in the concentration range considered tends to slightly enhance the cold flow turbulence whereas with the presence of flame zone, an increase in the turbulent intensity results in increasing the vaporization rate of the particles. This effects in decreasing the turbulent burning velocity of methane–air mixtures with coal and sodium bicarbonate particles at higher concentrations and turbulent intensities. Out of three dusts examined, sodium bicarbonate addition results in the lowest S_T due to the release of CO_2 and H_2O. Between coal and sand, at fuel lean and stoichiometric conditions, S_T values with coal are greater than sand due to the equivalence ratio promotion with the release of CH_4. But, as the turbulent intensity increases and for $\phi_g = 1.0\text{–}1.2$, S_T values with sand becomes comparable to or greater than that of coal. Model coefficients are generated from the experimental data to estimate the turbulent burning velocity in these conditions and the results show a clear distinction in the model coefficients for gaseous and gas–dust mixtures.

1. Introduction

Combustible gas mixtures and dust clouds present severe threat to process industries and facilities [1]. The explosions resulting from these mixtures are sometimes hybrid in nature, especially when combustible dust particles are entrained into the gaseous flame propagations. Coalmine explosions [2] are one such case where combustible coal dust particles are entrained to methane–air flame propagation resulting in a hybrid mixture combustion. With the development of varied process industries and operations, different types of dusts (e.g., wood, plastic, metal, chemicals etc.) may entrain into the flame propagation [2]. These dusts will have different effect on the flame propagation, based on their thermo-chemical characteristics and concentration.

Burning velocity is one of the most important and fundamental characteristic of a premixed combustible mixture. Most of the dust cloud flame propagation experiments are performed in standard spherical vessels [3,4], where the problem of an increase in turbulent intensity caused by the expanding combustion products in a constant volume vessel has been identified. Benedetto et al. [5] showed that the turbulence generated by the expanding products of combustion needs to be quantified in order to determine the correct turbulent burning velocity. Burner stabilized laminar hybrid flames with coal particles (75–90 μm) were successfully studied by Xie et al. [6] and Lee et al. [7] in fuel lean, stoichiometric and fuel rich pre-mixtures of methane and air. The competing effects of equivalence ratio promotion and the heat sink with the addition of coal particles on the experimentally determined laminar burning velocity was analyzed for different equivalence ratios at various unburnt mixture temperature [7]. Rockwell and Rangwala [8] investigated the influence of coal particles of different sizes (75–90 μm and 106–125 μm) on turbulent methane–air flames in a Bunsen burner type experimental platform. The same

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experimental set-up has been used in the current study. Their results indicated that the smaller particle sizes and larger concentrations ($>50\,\mathrm{g/m^3}$) increase turbulent burning velocity compared with larger particle sizes and lower concentration ranges [8].

Sand and sodium bicarbonate particles were studied extensively as flame extinction agents [9,10]. The difference in their mechanism of inhibition and the critical concentrations for flame inhibition is studied mainly with diffusion flames. Most of the available studies [11,12] on the interaction of inert and dry chemicals in burner stabilized premixed flame conditions are laminar. Chelliah et al. [13] presented a comparison between the extinction effectiveness of silica and $NaHCO_3$ (10–40 µm) in a Bunsen type, stoichiometric premixed laminar methane–air flames and they observed almost negligible effect of inert particles on laminar burning velocity. A mathematical model to predict the laminar flame extinction concentration of inert particles was explained by Ranganathan et al. [14] along with experimental results on the decrease of laminar burning velocity with increase in the sand concentrations of 75–90 µm particle size. Behavior of inert and sodium bicarbonate particles in turbulent premixed flame conditions are less understood, especially in burner stabilized flames. The variation of turbulent burning velocity as a function of concentration and turbulent intensity is also important for understanding their effect on flame propagation. Further, the studies [15–25] on the turbulence modulation due to the interaction of particles and gas in cold flow indicate both attenuation and augmentation of the turbulent intensity with the addition of particles. Factors such as particle size, particle density, particle loading, and Stokes number effect the turbulence modulation. The effect of particle size [18] on turbulent intensity show that smaller particles as compared to the turbulent length scale attenuate turbulence whereas the large particles tend to enhance turbulence.

The current study aims to analyze the turbulent burning velocity of methane–air–dust premixed flames. Coal, sand and sodium bicarbonate dust particles of 75–90 µm mean diameter size at different concentrations ($0–75\,\mathrm{g/m^3}$) are studied in a Bunsen burner stabilized premixed hybrid flames. A characteristic time scale analysis is done to understand the coupling of turbulence, particle interaction, particle vaporization and combustion. An analysis to develop empirical correlation coefficients from experimental results to estimate the turbulent burning velocity as a function of turbulent intensity and laminar burning velocity is also discussed in this study.

2. Experimental set-up

A Bunsen burner type experimental set-up, designed by Rockwell [26] to measure the burning velocity of gaseous, and dust entrained gaseous flames was used in this study. A schematic of this set-up is shown in Fig. 1. The parameters that can be independently controlled include turbulent intensity (u'_{rms}), length scale (l_0), particle size (d_p), and particle concentration (λ_p). The main components of the experimental set-up consist of a combustion chamber with a burner nozzle, dust feeder, shadowgraph optical system, and an exhaust hood. Two mass flow controllers with an uncertainty of 1% of their full scale measurements are used to control the gaseous methane–air flow rates. Methane–air equivalence ratios of $\phi_g = 0.8$, 1.0, and 1.2 are used to replicate fuel lean, stoichiometric, and fuel rich premixed flame conditions. A particle screw feeder injects the dust into the methane–air flow creating a hybrid mixture. The dust feeder screw speed calibration is determined by collecting unburned dust at the end of the nozzle, weighing it and then developing a calibration curve. The instantaneous fluctuations in the feed rate of the dust feeder were not quantified. The standard deviation of volumetric feed rate of dust feeder is ±2% from mean value. The shadowgraph optical system consists of three components, a point source of light, biconvex lens, and a reflective lens high-speed camera with a macro lens. The point source of light, a 480 W projector bulb, is placed at the focal point of a 100 mm diameter biconvex lens (focal length 200 mm). When powered this creates parallel light that travels through the flame in the combustion chamber to a second identical biconvex lens, which reduces the diameter of the image making it narrow enough to fit on the sensor of the high-speed camera. The turbulent burning velocity is calculated by extracting frames from the high-speed video. Other details about the combustion chamber and burner nozzle design of experimental set-up can be found from Rockwell and Rangwala [8]. For brevity, they are not repeated here.

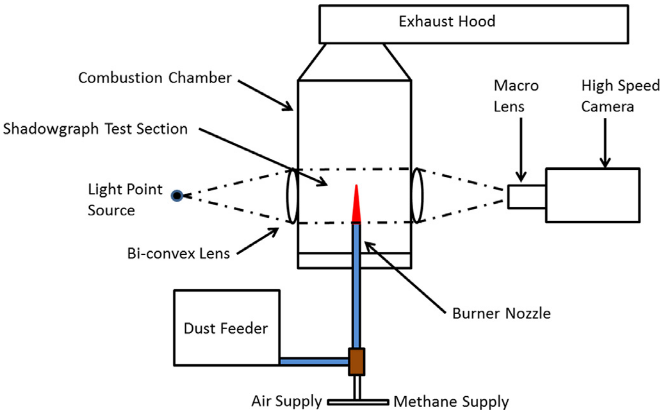

Fig. 1. Experimental set-up.

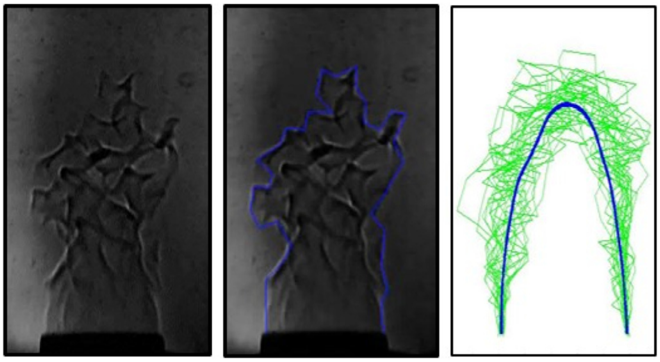

Fig. 2. Shadowgraph flame image and averaged flame image.

Similar to Rockwell and Rangwala [8] and Grover et al. [27] the turbulent burning velocity is determined by averaging the measure flame height of 25 images as shown in Fig. 2. The mean flame height is used to estimate the half cone angle.

$$S_T = \bar{u} \sin \alpha \tag{1}$$

where $\bar{u}$ is the mean flow velocity and α is the half cone angle. Figure 2 shows the sample shadowgraph images and the averaged flame image used for estimating the half cone angle.

The turbulent burner nozzle with inner diameter 14.5 mm consists of a perforated plate to create turbulence, a premixed annular methane–oxygen pilot to anchor the flame, and water cooling lines. The perforated plate used in this study is with hole diameter of 3 mm, with a blockage ratio (area of holes/total area) of 36% is placed at 30 mm from the burner nozzle exit. Turbulence measurements are captured with a hot-wire anemometer in a cold flow at a sampling rate of 100 kHz. The uncertainty of hotwire measurements is a combination of the uncertainties of the individually acquired voltages converted to velocities and the uncertainty of the statistical analysis of the velocities. The standard deviation of the