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Influence of the reactant temperature on particle entrained laminar methane–air premixed flames

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Abstract

This study investigates the laminar burning velocity of premixed methane–air mixtures, entrained with micron-sized (75–90 μm) coal dust particles over a range of gas phase equivalence ratios (0.9–1.2), dust concentrations (0–250 g/m^3) and reactant temperatures (297, 350, 400 K) using a novel Bunsen-burner type experimental design. The experimental results show that, the laminar burning velocity is enhanced by the increase in the reactant temperature, irrespective of the equivalence ratio of the mixture. Addition of coal particles in fuel lean ($\phi < 1$) mixtures increases the laminar burning velocity initially, but after a certain concentration of dust addition this trend is altered. The dust concentration value, where this variation is observed, increases with increase in reactant temperature. In other words, the reactant temperature plays a significant role in the trend of increase in laminar burning velocity with dust addition. For $\phi \geqslant 1$, at a given reactant temperature, a linear decay of burning velocity with dust addition is observed. When a combustible dust particle interacts with the flame zone, it extracts energy from the flame and releases volatiles, thereby changing the equivalence ratio. This local increase in the equivalence ratio and the heat sink effect, are found to be influenced by the reactant temperature. A mathematical model including these effects is developed and the model predictions are compared with the experimental results. The results are in a good agreement for fuel lean and stoichiometric mixtures; whereas the model is found to under predict results for fuel rich cases.

Keywords: Burning velocity; Particle; Premixed flame; Volatilization; Coal

1. Introduction

Dusts or fine particles (<100 μm) generated in industries during machining, mining, manufacturing, and other processes can produce an explosive environment when dispersed in the form of a cloud. For instance, the Imperial Sugar Refinery in Savannah, Georgia, had a huge explosion due to the dispersion and consequent ignition of accumulated sugar dust throughout the building [1]. Another example is in the recent increase in accidental coal mine explosions in different incidents at Tallmansville [2] and Montcoal [3]. Such explosions are usually hybrid in nature whereby the deflagration comprise of both methane mixed with coal dust particles.

An earlier study by Xie et al. [4] investigated laminar premixed methane–air flames with coal particles of different sizes. The reactant

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Nomenclature

A	parameter characterizing rate of vaporization of particles, Eq. (2)
B	frequency factor characterizing rate of gas phase oxidation of gaseous fuel
b	Burner base width
C_p	heat capacity of air
C_s	heat capacity of solid particle
C_{total}	heat capacity of particle–gas mixture
c	concentration
E	activation energy characterizing the gas phase reaction
h	height of the flame cone
k	thermal conductivity
L_v	latent heat of vaporization
M	molecular mass
m_i'''	mass of species per unit volume
n	temperature exponent characterizing rate of vaporization of coal particles in Eq. (2)
$n_{product}$	number of moles of products
n_s	number of particles
$\dot{n}_{air}$	number of moles of air per unit time

Greek symbols

α	flame cone angle
ε	$=1/Z_e$, expansion parameter
ρ	density of the solid–gas mixture
ρ_s	density of the particle
δ	thickness of devolatilization zone
ϕ	original gaseous mixture equivalence ratio
$\dot{Q}$	heat release rate

$\dot{q}''$	heat flux to particles
R	universal gas constant
r	mean radius of particles
S_u	laminar burning velocity
T_b	flame temperature based on original mixture and unburnt gas temperature
T_f	flame temperature with particles
T'_f	promoted flame temperature due to locally increased equivalence ratio
T''_f	reduced flame temperature due to heat sink effect of particles
T_u	temperature of unburned gas
t_r	residence time of gas in devolatilization zone
U	average flow velocity at burner nozzle
$\dot{V}_{air}$	volumetric flow rate of air
$\dot{V}_{CH_4}$	volumetric flow rate of methane
V	volume
$\dot{w}_v'''$	rate of vaporization of fuel particles
χ	spatial coordinate
Z_e	Zeldovich number

Subscripts

a	ambient condition
b	adiabatic condition
d	devolatilization zone
f	flame
g	gas phase
s	solid particle
u	conditions in the controlled reactant temperature condition.
v	vapor

temperature was kept constant at 297 K. In various situations of flame propagation, especially through lean mixtures, as a result of coal dust addition, partial volatilization causes the mixture to become richer. The volatilization of coal particles also extracts energy from the flame. The influence of these competing effects on the experimentally determined laminar burning velocity was analyzed for several equivalence ratios less than 0.85 by Xie et al. [4]. To further explore the particle–flame interaction, experiments were conducted in the present study with higher equivalence ratios 0.9 to 1.2 higher than that reported in Xie et al. [4]. Also the influence of higher reactant temperature (up to 400 K) is explored in the present study. The mathematical model to predict the burning velocity including the effect of higher unburned mixture temperature is developed. The results are compared with that obtained from experiments.

2. Experimental set-up and procedure

Bunsen burner flame approach is the simplest, lab-scale, and feasible option to conduct experiments in the presence of dust particles. This method has been adopted previously for many studies that are involved with particle entrained premixed flames such as Xie et al. [4], Goroshin et al. [5], and Rockwell and Rangwala [6]. For this reason, a lab-scale experimental set-up capable of precisely controlling the dust concentration, gas-phase equivalence ratio, and reactant temperature has been designed and constructed.

A schematic diagram of the experimental set-up is shown in Fig. 1. The burner consists of an insulated steel tube with connections from a gas heater and dust feeder. Air supplied to the gas heater is heated, while methane is supplied along with the coal particles from the dust feeder so as to maintain a constant flow of dust to the burner.

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