Journal of Loss Prevention in the Process Industries 35 (2015) 46–51

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Suppression of premixed flames with inert particles

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ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form
9 March 2015
Accepted 9 March 2015
Available online 17 March 2015

Keywords:
Burning velocity
Heat sink
Premixed flame
Inert
Sand

ABSTRACT

Dispersal of inert particles on a flame front is one of the techniques employed to suppress explosions. The current study investigates the influence of micron-sized (75–90 μm) inert (sand) particles on the laminar burning velocity of methane-air premixtures of different equivalence ratios (0.9–1.2) and reactant temperatures (297, 350, 400 K) using a Bunsen-burner type experimental apparatus. When an inert particle interacts with the flame zone, it extracts energy from the flame, thereby acting like a heat sink and hence reducing the flame temperature. Results show that for sand particle size in the range of 75–90 μm, a concentration of 380–520 g/m^3 is necessary for extinction of a methane-air flame at ambient temperature. An increase in reactant temperature reduces the heat-sink effect necessitating a higher concentration of sand to extinguish the flame. A mathematical model is developed to generalize the results and make them applicable to a wide range of parameters.

1. Introduction

1.1. Background and scope of work

Prevention of explosions by using inert gases such as nitrogen is well known and is one of the most commonly used methods. The usage of chemically inert dusts such as sand, rock dust, limestone is another way to protect against explosions (Dewitte et al. 1964; Harris et al., 2010) and the practice of rock-dusting in coal mines has been adopted since very old days (Haswell Colliery explosion and Faraday and Lyell report (Faraday and Lyell) in 1845). It is important to scrutinize the influence of particle interaction on the rate at which a flame propagates to evaluate the hazardousness of any explosion. Fundamentally, this requires an investigation of the impact of inert particles on the laminar burning velocity of a gas-air premixture. The present study is focused on the experimental investigation of the effect of different concentrations of sand particles on the laminar burning velocity of premixed methane-air flames for a range of equivalence ratios and reactant temperatures.

1.2. Prior studies relevant to the topic

Prior studies on suppression of flames using dust particles are divided into that devoted to inert and chemically reacting particles. The suppression mechanisms of the two types of particles are different (Chelliah, 2007; Fleming, 1999; Rumminger and Linteris, 2000). Specifically, while, inert particles in a reacting gas flow can suppress the flame through cooling, reacting particles produce inert gasses, which locally dilute the fuel or oxidizer levels thereby suppressing the flame. For example, chemically reacting particles such as sodium bicarbonate, potassium chromate and metal salts are found to decompose and produce CO_2 to extinguish the flame (Birchall, 1970; Linteris et al., 2008; Mitani and Niioka, 1984; Rosser et al., 1963; Trees and Seshadri, 1997) whereas the thermal inhibitors like silica, alumina etc. reduce the flame temperature significantly (Amyotte, 2006; Andac et al., 2000; Dong et al., 2005; Harris et al., 2010; Mitani, 1981). As explained in Amyotte (2006) (Amyotte), the chemical inhibitors terminate the chain branching reactions by capturing the free radicals thereby inhibiting the chain reactions. An extensive literature review about the influence of solid inert-particles in mitigating and preventing explosions can be found in (Amyotte, 2006; Kosinski, 2008; Qiao et al., 2005). The current study is focused on suppression mechanisms using inert particles and hence the remainder of the literature review is focused on understanding the controlling parameters related to this type of suppression.

In general, when a particle enters the flame zone, it absorbs some energy from the flame, thereby acting like a heat sink. The extinction mechanism is controlled mainly by thermal energy balance, where in the particle size, concentration and thermal

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http://dx.doi.org/10.1016/j.jlp.2015.03.009
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Nomenclature

B	Frequency factor characterizing rate of gas phase oxidation of gaseous fuel
C_p	Heat capacity of air
C_s	Heat capacity of solid particle
c	Concentration
E	Activation energy characterizing the gas phase reaction
k	Thermal conductivity
$n_{product}$	Number of moles of products
n_s	Number of particles
$\dot{n}_s$	Number of particles per unit volume per unit time passing through the flame
$\dot{n}_{air}$	Number of moles of air per unit time
$\dot{Q}$	Heat release rate
$\dot{q}''$	Heat flux absorbed by particles
R	Universal gas constant
S_u	Laminar burning velocity
T_b	Flame temperature based on gaseous mixture and unburnt gas temperature
T_f	Flame temperature
T_f''	Reduced flame temperature due to heat sink effect of particles
T_u	Temperature of unburned gas
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
Z_e	Zeldovich number

Greek Symbols

α	Flame half cone angle
ε	$=1/Z_e$, expansion parameter
ρ	Density of the solid–gas mixture
ρ_s	Density of the particle
ϕ	Gaseous mixture equivalence ratio

Subscripts

a	Ambient condition
f	Flame
g	Gas phase
s	Solid particle
u	Conditions in the controlled reactant temperature condition.
s	Solid particle

properties such as k, ρ, C_p are the important controlling parameters. Dewitte et al. (1964) (Dewitte et al.) conducted one of the earliest experimental studies on the inhibition and extinction of premixed flames by different dust particles based on the variation of the mean flame temperature and flame propagation velocity with respect to the concentration of dust particles. Specifically, a limiting value of the mean kinetic flame temperature (1500–1600 K) below which flame cannot self-sustain was identified and subsequently used to predict the critical dust concentration for the thermal inhibitors (Dewitte et al., 1964). Mitani (Mitani, 1981) developed a flame inhibition theory for 'thermal' inhibitors alone, based on two non-dimensional parameters – one related to the heat capacity of the particle; and the other related to the rate of heat of absorption by dust particle. On a large scale, the ability of the inert particles to suppress an explosion was investigated, experimentally and computationally, by Dong et al. 2005 (Dong et al.). An increase in the particle cloud density and the decrease in the particle size, facilitates explosion suppression because of an increase in the inhibition surface area of a contact with the gaseous flame front (Dong et al., 2005).

The current study is a step towards improving our understanding of suppression of flames by inert particles, using an experimental platform with a simple flow geometry which can be conveniently reproduced in the laboratory. The influence of different concentrations of inert particles (sand particles of diameter 75–90 μm) are investigated using a laminar Bunsen burner type burner capable of handling dusty flows (Xie et al., 2012)). A mathematical model is also developed to generalize the experimental results and make them applicable to a wide range of parameters.

2. Experimental set-up and procedure

The experimental set-up used in this study, shown in Fig. 1. Specifically, an insulated steel tube of 1 cm diameter with inlets from methane, air and particle feeder has been used as the burner. Air supplied to the burner is preheated using a gas heater and the inert particles are fed using a screw feeder, which is pre-calibrated for different feed rates ensuring continuous supply of particles to the burner (Fig. 2). The methane-air gas flow is controlled through a mass flow controller and the particles used in the experiments are in the size range of 75–90 μm. To ensure that the desired reactant temperature is achieved, a K-type thermocouple is located at the exit of the burner to measure the temperature of the reactants both before and after the experiments. During the experiments, the thermocouple is removed. The difference between the temperatures measured before and after the experiment, as compared to the mean desired temperature, did not exceed 3 K. For image acquisition, the presence of particles in the flame makes shadowgraph technique a mandatory requirement to clearly capture the flame edges (Fig. 3). The significance of this can also be referred from the previous studies of Xie et al. (Xie et al., 2012), Lee et al. (Lee et al., 2014), and Rockwell & Rangwala (Rockwell and Rangwala, 2013). Since the above mentioned literature goes over the accuracy of the flow controllers and the specifications with respect to shadowgraph system used in detail, for brevity these details are not repeated here.

From a processed shadowgraph image of the flame zone as shown in Fig. 2d, the cone half angle α is measured for each sloping line detected and the values are averaged. The sloping line is detected from the middle portion of the Bunsen flame cone, in order to eliminate the stretch effects due to curvature at the flame tip and flame region close to the exit of the burner. These are the two regions which are susceptible to stretch effects in a Bunsen flame, due to the maximum local burning velocity at the flame tip and the minimum local burning velocity as a result of heat loss to the burner rim (Law, 2006). This half cone angle α, measured, is employed to calculate the laminar burning velocity using:

$$S_u = U \cdot \sin(\alpha), \quad (1)$$

where U is the unburned gaseous mixture velocity at the exit of the burner, which is obtained by $U = U_a(T_u/T_a)$. Though the total