Journal of Loss Prevention in the Process Industries 35 (2015) 182–199

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

An analytical model for predicting counterflow flame propagation through premixed dust micro particles with radiative heat loss

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ARTICLE INFO

Article history:
Received 1 January 2015
Received in revised form
19 April 2015
Accepted 19 April 2015
Available online 21 April 2015

Keywords:
Premixed counterflow combustion
Two-phase mathematical modeling
Volatile particle-cloud
Radiative heat loss

ABSTRACT

In this paper, an analytical model has been performed to scrutinize the structure of the flame propagation in counterflow configuration where the mixture of solid fuel particles and air are injected as opposed streams. The structure of counterflow premixed flame in a symmetric configuration, containing uniformly distributed volatile fuel particles, with nonunity Lewis number is examined with considering radiative heat loss effect in counterflow configuration with strain rate issue. The flame structure governing equations, required boundary conditions, and matching conditions are applied for each zone in order to solve the differential equations. The flame position is determined, mass fraction of solid particles and gaseous phases, effect of Lewis number change on the gaseous and solid fuel mass fraction distribution, and the role of strain rate, and different particle diameters are investigated with and without considering thermal radiation effect. In addition, the effect of equivalence ratio on the flame temperature, mixture temperate and non-dimensional flame position is investigated in counterflow flame propagation. According to our finding, the burning velocity of counterflow flame remarkably increases as a function of vaporization Damköhler number as well as non-dimensional vaporization temperature with considering thermal radiation effect in counterflow domain.

1. Introduction

Interactions between solid and gas in combustible mixtures attract particular interest because of its potentials for application in various industrial systems (Markstain, 1963; Seshadri et al., 1992; Zeldovich et al., 1985). To take appropriate measures preventing accidental dust explosions, it is necessary to understand the flame propagation mechanisms in this phenomenon. Recently, some researches focused on the flame propagation process during dust explosions, because dust explosions are the phenomena in which flame propagates through dust clouds in air with increasing degree of subdivision of any combustible solids (Goroshin et al., 1996; Sun et al., 2001). Hence, an accurate knowledge of the origin, development, prevention and mitigation of dust explosions is essential. There are varieties of material such as coal and peat and metals that can cause dust explosions (Eckhoff, 1997; Han et al., 2000).

Basic mechanisms of combustion of two-phase mixtures are yet not well understood because of complexity of the particle-cloud combustion interactions affected by the physical and chemical properties of the fuel, complexity of domain, and the average size, shape and distribution of the particles (Bidabadi et al., 2010; Bidabadi et al., 2013; Cashdollar, 2000; Hanai et al., 2000).

Regarding to the importance of flame propagation through dust particles, Eckhoff (2006) clarified the differences and similarities between dust and gases. It has been concluded that there are two basic differences between dusts and gases, which are of substantially greater significance in design of safety standards than the similarities. Firstly, the physics of generation and up-keeping of dust clouds and premixed gas/vapour clouds are substantially different. Secondly, contrary to premixed gas flame propagation, the propagation of flames in dust/air mixtures is not limited only to the flammable dust concentration range of dynamic clouds.

Liu et al. (2007) researched the flame propagation through hybrid mixture of coal dust and methane in a small-scale chamber. In their studies, flame temperature was detected by a fine thermocouple. The flame propagation speed and maximum flame temperatures of the mixture were investigated. Their results showed that the co-presence of coal dust and methane improves the flame propagation speed and maximum flame temperature dramatically.

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http://dx.doi.org/10.1016/j.jlp.2015.04.015
0950-4230/

Ross et al. (2000) investigated the time required for devolatilization of six different sized coals in a bench scale atmospheric fluidized-bed reactor by measuring the centre temperature response. The effect of coal type and coal moisture content was also investigated at a bed temperature of 850 °C under fluidized-bed combustion conditions.

Proust, (2006a) and (2006b) presented a few fundamental aspects about flame initiation and propagation in dust clouds. These papers that were attempts to contribute to a better understanding of dust explosions, addressed several fundamental questions such as the incidence of thermal radiation and turbulence.

Daou et al. (2002) derived analytical expressions for the burning velocity of a flame propagating in a steady parallel flow whose scale was much smaller than the laminar flame thickness. It was shown that non-unit Lewis number effects become insignificant in the asymptotic limit considered.

Bidabadi and Rahbari (2009a) investigated the effect of the temperature difference between the gas and the particles on propagation of premixed flames in a combustible mixture containing uniformly distributed volatile fuel particles. The analysis was performed in the asymptotic limit, where the value of the characteristic Zeldovich number was large. As result, the variation of the dimensionless temperatures of the gas and the particles, the mass fraction of the particles, the equivalence ratio ϕ_g as a function of ϕ_u, the flame temperature, and the burning velocities of the gas and the particles were obtained in their work.

Kayal, and Chakravarty (2007) examined the numerical analysis of combustion of submicron carbon particles inside an inert porous medium where the particles in form of suspension in air enter the porous medium. The effects of emissivity of medium, absorption coefficient, flame position and reaction enthalpy flux on radiative energy output efficiency had been presented. It was observed that in porous medium the combustion of suspended carbon particles is similar to premixed single phase gaseous fuel combustion except the former has shorter preheating temperature zone length.

Bidabadi and Rahbari (2009b) presented an analytical model for predicting the effects of the temperature difference between gas and particles, different Lewis numbers and heat loss on the combustion of lycopodium particles. The obtained results illustrated the effects of the combustion parameters on the variations of the dimensionless temperature, particle mass fraction, flame temperature, and burning velocity for gas and particle.

Although recently some researches focused on the flame propagation process during dust explosions (Dobashi and Senda, 2006; Proust, 2006a), as yet no unified theory exists covering the counterflow combustion of particles. However, in many practical applications the flow field is appreciably strained. Over the last few decades, the counterflow configuration has been extensively adopted in theoretical, experimental and numerical studies as a mean to investigate various physical effects on real flames, such as stretch, preferential diffusion, radiation and chemical kinetics (Daou, 2011; Thatcher and AlSarairah, 2007), but these studies are done for gaseous fuels. So far, the most common fuels in the counterflow configuration studies have been done for gaseous fuels such as methane, H_2 and so on. Hence, it is important to investigate the behavior of particle-cloud from pre-flame reaction to the final state of the combustion products.

Wang et al. (2007) investigated the structure and extinction characteristics of counterflow diffusion flames with flame radiation and nonunity Lewis numbers of the gaseous fuel and oxidant in gaseous fuel. The influence of radiative loss on the extinction Damköhler numbers was found to be through its effects on the flame temperature, the excess enthalpy, and the reduced extinction Damköhler number.

Liu et al. (2000) analyzed the effects of radiation heat loss and variation in near-unity Lewis numbers on the structure and extinction of counterflow diffusion flame established near the stagnation plane of two opposed free streams of gaseous fuel and oxidizer using the asymptotic method of large activation energy. This analysis was able to predict the existence of inflammable limits of counterflow diffusion flames in terms of the near-unity Lewis numbers and concentrations of the fuel and oxidizer streams.

It is important to mention that the works stated above, (Wang et al., 2007; Liu et al., 2000), are done for gaseous fuel in counterflow configuration without considering combustible solid particle. However, with considering particle clouds combustion in counterflow configuration (strained flow), it would be needed to take radiation into account in the combustion of dust clouds, because the mixture of gas and particles is gray. For a gray, the effects of absorption coefficient, emissivity of medium, flame position and reaction enthalpy flux on radiative energy output efficiency should be considered. Radiation behavior in particle-cloud combustion is so complicated. Beside the complexity of the governing mathematics, the lack of certain knowledge on the radiation properties of the existing materials in the system also adds to the difficulty of solving this problem. On the other hand, these properties themselves change in the course of the chemical process and during the making of products. The complete solution of Maxwell's equations in Mie theory can only be achieved for spherical particles. Obviously, many assumptions will be needed to take radiation into account in the combustion of dust clouds (Bidabadi, 1995).

Lipiński et al. (2006) formulated the unsteady energy equation that links the rate of radiative heat transfer to the rate of the chemical reaction and numerically solved unsteady radiation heat transfer problem by the finite volume technique and the explicit Euler time-integration scheme in a chemically reacting medium for a suspension of ZnO particles directly exposed to concentrated solar radiation and undergoing thermal dissociation. They found that the chemical conversion increases with decreasing initial particle diameter and volume fraction due to the efficient radiative absorption.

The objective of this study is to investigate mathematically the flame propagation of dust micro particles in premixed counterflow configuration with considering strain rate and thermal radiation effects. It is presumed that the fuel particles are heated firstly to reach to the onset of vaporization temperature, and then vaporize to yield a gaseous fuel, which is oxidized in the gas phase. In order to simulate the combustion process, the flame structure, which is symmetric about the plane $X = 0$, is composed of four zones: preheat, vaporization, reaction and finally a post flame zone. Then, the governing equations are applied for each zone and the Standard Asymptotic Method (SAM), where the value of the characteristic Zeldovich (Ze) number is large, is used for solving these differential equations. Consequently, the burning velocity as a function of equivalence ratio is plotted. The variation of the flame position with the initial radius, the equivalence ratio, the flame temperature and the Lewis number effects are investigated. In addition, distribution of the mass fraction of the particles and the gaseous fuel are plotted. Simultaneously effects of strain arte and thermal radiation are taken into consideration, which has not been attempted before in counterflow combustion of particles. This paper is structured in the following manner. Section 2 outlining the model formulation, mathematical method and simulation conditions, Section 3 discussing the mathematical results, and finally, in Section 4, a summary of the main conclusions are presented.

2. Mathematical modeling

2.1. Governing equations

The study is carried out in the counterflow configuration, shown