Renewable Energy 92 (2016) 376–384

Contents lists available at ScienceDirect

Renewable Energy

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

Mathematical modeling of premixed counterflow combustion of organic dust cloud

Mehdi Bidabadi [a], Moslem Akbari Vakilabadi [a, *], Alireza Khoeini Poorfar [a], Eliseu Monteiro [d], Abel Rouboa [c, b], Alireza Rahbari [e]

[a] School of Mechanical Engineering, Department of Energy Conversion, Combustion Research Laboratory, Iran University of Science and Technology (IUST), Tehran, Iran
[b] CIENER/INEGI/Engineering Department, School of Science and Technology of University of UTAD, Quinta dos Prados, Vila Real, Portugal
[c] Mechanical Engineering and Applied Mechanics Department, University of Pennsylvania, Philadelphia, PA, United States
[d] C3i-Interdisciplinary Center for Research and Innovation, Polytechnic Institute of Portalegre, Lugar da Abadessa, Apartado 148, 7301-901, Portalegre, Portugal
[e] Research School of Engineering, The Australian National University, Canberra, ACT 2601, Australia

ARTICLE INFO

Article history:
Received 1 April 2015
Received in revised form
15 November 2015
Accepted 2 February 2016
Available online xxx

Keywords:
Counterflow combustion
Organic dust cloud
Mathematical modeling
Flame structure
Asymptotic solution
Heat loss

ABSTRACT

In the present study, a mathematical approach is utilized so as to modeling the flame structure of organic dust particle and air through a two-phase mixture consisting in a counterflow configuration where heat loss is taken into account. Lycopodium is considered as the organic fuel in our research. In order to simulate combustion of organic dust particles, a three-zone flame structure has been considered; preheat-vaporization zone, reaction and post flame zones. The variations of the gaseous phase mass fraction and fuel particle mass fraction as a function of the distance from the stagnation plate are obtained. Subsequently, flame temperature and flame velocity in terms of strain rate are studied. Finally, the effect of heat loss on the non-dimensionalized temperature at different heat loss coefficients is investigated.

1. Introduction

Combustible dusts are fine particles that present an explosion hazard when suspended in air in certain conditions. Dust explosions are common and costly in a wide array of industries such as petrochemical, food, paper and pharmaceutical. Hence, an accurate knowledge of the origin, development, prevention and mitigation of dust explosions is essential. Natural and synthetic organic materials such as coal and peat and metals are the materials that can cause dust explosions [1].

Many studies have been done regarding combustion of organic dust particles within the last few years. Han et al. [2] experimentally investigated the flame propagation mechanism through lycopodium dust cloud in a vertical duct based on dust particles behavior. Liu et al. [3] studied the flame propagation through hybrid mixture of coal dust and methane in a small-scale chamber. But considering the fact that in many practical applications the flow field is appreciably strained and to yield realistic flame prediction under such conditions, counterflow configuration is a proper choice for studying these cases. One of the main applications of counterflow combustion is in aerospace industries, as the weight of equipment is an important factor in aircraft manufacturing, using a counterflow combustion chamber decreases the weight of the plane. Also some of the flame characteristics can be better studied in a counterflow combustion system. Over the last few decades, the counterflow configuration has been extensively adopted in theoretical, experimental and numerical studies as a means of investigating various physical effects on real flames, such as stretch, preferential diffusion, radiation and chemical kinetics [4,5]. Daou [4] analytically investigated the characteristics of strained premixed flames. In his study, he thoroughly studied the effect of heat loss, preferential diffusion and reversibility of reaction. Thatcher and Sarairah [5] modeled steady and unsteady premixed flame propagation in a counterflow configuration and introduced the so-called “twin flame”. But these studies have been conducted for

* Corresponding author.
E-mail address: moslem_akbari@mecheng.iust.ac.ir (M. Akbari Vakilabadi).

http://dx.doi.org/10.1016/j.renene.2016.02.002
0960-1481/

gaseous fuels. The premixed flame stabilized in a stagnation-point flow, or counterflow, has long served as a model for examining the flame response to flow non-uniformities [6]. In 2008, Daou [7] presented an asymptotic study of flame propagation in weakly-strained mixing layers under a reversible chemical reaction in a 2D counterflow configuration.

Bidabadi and Rahbari [8] 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. In another research, Bidabadi and Rahbari [9] 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. Furthermore, Haghiri and Bidabadi [10] investigated the effect of thermal radiation on the flame propagation through organic dust cloud. In these researches [8–10] combustion of organic dust cloud was taken into consideration in a planar configuration.

The counterflow combustion of organic dust cloud is the state of the art topic and there exist very few studies in the literature. In the present study, combustion of organic dust particles in a counterflow configuration is investigated and parameters such as strain rate, flame velocity, flame temperature and gaseous fuel and fuel particle mass fractions, Damköhler number and the amount of heat Loss under various conditions have been studied.

Von Karman and Millan [11] were amongst the first who investigated the effect of heat loss in combustion. Bidabadi et al. [12] used a novel thermal model employing discrete heat sources in order to study the propagation and extinction of dust flames in narrow channels. In their research, the burned and burning dust particles are considered as heat sources and the channel walls as heat sinks and it is concluded that wall temperature affects the heat loss to the walls. Hou [13] utilized activation energy asymptotic to examine the effects of inert spray, non-unity Lewis number and internal and external heat losses on the extinction characteristics of propane/air flames. Alliche et al. [14] determined the extinction conditions of a premixed flame in a channel. The influence of heat losses at the wall through thermal conductivity of the wall has been investigated.

In dust flame concept, we have a new term, representative of vaporization of organic particles which should be included in the governing equations unlike the gas flame structure. In addition, the heat capacity involved in the governing equations is a function of heat capacities of gas and particle.

In the present paper, a mathematical method is employed to analyze the flame structure in counterflow combustion of organic dust cloud when heat loss is present. In order to simulate the dust combustion phenomenon, it is presumed that flame structure consists of three zones: a broad preheat-vaporization, reaction and convection (post flame). An asymptotic solution has been performed where Zeldovich number is considered to be large. According to the obtained results, mass fraction of volatile fuel particles and gaseous fuel are affected by the value of strain rate. In addition, variations of flame temperature and flame velocity in terms of strain rate have been shown. Also, it is demonstrated that heat loss plays an important role in the changes of non-dimensionalized temperature where for high values of heat loss coefficient, the rate at which θ decelerates, rises.

2. Governing equations

A model is considered to describe steady, one-dimensional and counterflow flame in a combustible mixture consisting of uniformly distributed volatile fuel particles in air. The structure of the flame is supposed to consist of a broad preheat-vaporization zone in which the rate of chemical reaction between the fuel and oxidizer is considered negligent, a reaction zone, where convection and the rate of vaporization of the fuel particles are regarded small and a convective zone, where diffusion term in the conservation equations are presumed small. In the asymptotic limit, it is assumed that the characteristic Zeldovich number based on the gas-phase oxidation of gaseous fuel is large and is defined as [15]:

$$\mathrm{Ze} = \frac{\mathrm{E}\left(\mathrm{T_f} - \mathrm{T_u}\right)}{\mathrm{RT_f^2}} \tag{1}$$

where E, R, T_f and T_u are the activation energy of the reaction, the universal gas constant, flame temperature and fresh mixture temperature, respectively.

It is presumed that the number density of particles n_u (which is defined as the number of particles per unit volume in ambient reactant stream), and their initial diameter, r_u, are known. Table 1 presents the summary of thermophysical properties of lycopodium solid fuel particles used in this study.

In this analysis, it is assumed that the fuel particles vaporize to form a known gaseous compound which is then oxidized. In other words particles do not participate in the reaction. Furthermore, the main assumptions made are: (1) there is no temperature difference between particles and the gaseous phase, (2) heterogeneous combustion (surface burning) is not possible and we are dealing with a homogenous flame front, (3) constant properties, (4) diffusion coefficient is proportional to temperature squared, and (6) only conductive heat loss has been taken into consideration. The configuration of the problem is as follows (Fig. 1):

The velocity field has components in the Cartesian directions, where a is the (dimensional) strain rate. For small values of strain rate, one can consider the problem to be one dimensional.

Also, as mentioned earlier, the combustion process is represented by a two-step reversible reaction of the form of

$$\nu_F[F] + \nu_{O_2}[O_2] = \nu_{product}[P].$$

where the symbols *F*, O_2 and *P* denote the fuel, oxygen and product, respectively, and the quantities ν_f, ν_{O_2}, and $\nu_{product}$ denote their respective stoichiometric coefficients.

Mass conservation equation

$$\rho v = \text{constant} \tag{2}$$

Energy conservation equation

$$-aY\frac{dT}{dY} = D_T\frac{d^2T}{dY^2} + \omega_F\frac{Q}{\rho c} - \omega_{vap}\frac{Q_{vap}}{\rho c} - H(T - T_u) \tag{3}$$

In Eq. 3, "*a*" stands for dimensional strain rate, D_T is thermal diffusion coefficient, Q is the heat released from the unit mass of fuel burned and the quantity Q_{vap} represents the heat associated with vaporization of the unit mass of fuel. The heat capacity *C* appearing in Eq. (3) is the combined heat capacity of the gas, C_p, and

Table 1
Properties of the solid fuel studied.

Property	Value	Ref.
E [kcal/mole]	23	[16]
T_u [K]	400	[assumed]
ρ_u [g/cm^3]	$1.135 * 10^{-3}$	[16]
ρ_s [g/cm^3]	1.0	[16]
A [$[g]_F/[cm^2]_s$ K.s]	$3.4 * 10^{-6}$	[16]
n_u [1/cm^3]	3900	[16]
B [mol^{-1} s^{-1}]	$3.5 * 10^6$	[16]
λ [cal/(cm.s.K)]	$3.5 * 10^{-4}$	[16]