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Effects of radiation on propagating spherical flames of dust–air mixtures

Mehdi Bidabadi [1], Abazar Vahdat Azad *

School of Mechanical Engineering, Iran University of Science and Technology, Narmak, Tehran 16846, Iran

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ABSTRACT

A new analytical model has been presented for spherical flame propagation in organic dust–air mixtures. This method assumes a quasi-steady state flame propagation. The flame structure consists of a preheat zone, a reaction zone, and a post-flame zone for lean mixture. Radiation, conduction, and convection are the three flame propagation mechanisms considered in this model. Flame speed and temperature are calculated; and by adding the radiation term, it is observed that the flame temperature in the preheat zone and the flame speed both increase. This phenomenon may be attributed to the radiative heat transfer from the flame zone to the preheat zone. The flame temperature in the reaction zone increases with the reduction of particle size and the increase of dust concentration. Also, the increase of flame radius results in the increase of flame speed.

1. Introduction

The combustion of heterogeneous mixtures consisting of fine particles and an oxidizer is an important subject in many areas of engineering. The risk of ignition and explosion of organic particle clouds has always raised a critical challenge in agricultural, chemical and food industries and in grain storage, coal mining, etc. Scientists have been trying to develop methods for modeling the combustion of organic particles and the prevention of their explosion in the mentioned industries. Bio powders and organic particles are suitable options for the production of alternative fuel. Biomass combustion is the main technology route for bioenergy production, providing over 90% of the globally produced bioenergy [1]. Using the biomass as fuel to generate electricity and heat has gained renewed interest in many parts of the world. Biomass is an indigenous, often cheap, and above all, a renewable fuel source [2]. The knowledge of the physical and chemical processes involved in the combustion of organic particles can be applied to the design of energy production components such as boilers, large-scale furnaces, advanced spark ignition engines, and gas-turbine systems used for electricity generation. The combustion process of organic particles has been simulated and modeled by many researchers.

Bidabadi et al. presented a mathematical model for the structure of an upward-propagating flame containing uniformly distributed volatile fuel particles in an oxidizing gas mixture [3].

Bidabadi et al. [4] also studied flame propagation in particle clouds according to the temperature difference between particles and gas in planar flames. In another study, Bidabadi et al. [5] investigated the effect of Lewis number and heat loss on the combustion of organic particles. Eckhoff emphasized the importance of being familiar with powder science and technology when striving to design safer processes for industries with dust explosion hazards [6]. An illustrative and comprehensive list of dust explosions, cases, causes, consequences and control methods has been presented in [7]. The effect of radiation on the combustion of organic particle cloud was analyzed by Bidabadi [8,9]. In all of these studies, the flame is considered to be planar and without any stretch. The dominant process in flame propagation through dust clouds is often the radiative heat transfer, which produces a condition of excess enthalpy in the combustion field. Lipinskia et al. [10] numerically solved the problem of unsteady radiative heat transfer in a chemically reacting medium for a suspension of ZnO particles directly exposed to concentrated solar radiation and undergoing thermal dissociation.

The thermal theory was used to study the spherical flames for the first time [11,12]. More detailed models were presented by Zeldovich for describing the spherical flames on the basis of adiabatic flame balls [13] and for controlling the initiation of spherical flames [14,15]. Chen et al. [16,17] demonstrated that the initiation of a spherical flame of gaseous fuel is affected by the Lewis number and radiation loss of the fuel. Frankel and

* Corresponding author. Tel.: +98 21 77491228 9.
E-mail addresses: bidabadi@iust.ac.ir (M. Bidabadi), abazar.vahdat@gmail.com (A.V. Azad).
[1] Tel.: +98 21 77491228 9.

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Sivashinsky [18] investigated the effects of thermal expansion and Lewis number on the propagation of spherical flames by using asymptotic techniques. An integral analysis was applied by Chung and Law [19] to the study of spherical flames. Bechtold et al. [20–23] examined the hydrodynamic and thermal instabilities and Ronney and Sivashisky [24] studied the expansion of spherical flames by using the Slowly Varying Flame (SVF) theory. Chen et al. [25] investigated the effects of radiation on the propagation speed of spherical flames.

In our study, the outward propagation of a spherical flame in a cloud of organic particles, with and without the consideration of thermal radiation, was analytically investigated. Here, a spherical shape was chosen for the flame, because a steady flame in an unbounded space can exist only as a spherical combustion [26]. Mills and Matalon [27] suggested a thermal diffusion model for spherical flames with a single-stage reaction. By matching the asymptotic expansions [26–28] an approximate solution was found for the problem of steady-state spherical flame diffusion. The above-mentioned studies of spherical flames investigated gaseous fuels.

The main motivation of this study is to further develop the previous spherical flame models by adding the effect of thermal radiation on the combustion of dust/air mixtures. The radiation heat-transfer equation is employed to describe the thermal radiation exchanged between the burn and the preheat zones. Hence, in the present paper, we have tried to investigate the thermal radiation effect on both the temperature profile and flame propagation speed.

1.1. Modeling

The role of radiation as a mechanism of dust flame propagation has not yet been completely elucidated. Two mechanisms can equally affect the flame propagation process. In the first mechanism, the radiative heat transfer tends to preheat the unburned mixtures, and in doing so, it accelerates the flame. In the second mechanism, the radiation heat loss from the surfaces near the reaction zone lowers the flame temperature. An analytical study has been conducted to investigate the effect of radiation heat loss on spherical flame propagation in coal-dust clouds [9]. This study assumes heat to be lost from the flame zone to a zone far from the flame, regardless of the radiation absorbed by the particles in the preheat zone. But here, the effect of radiation absorption in the preheat zone has been considered. For a more accurate calculation of temperature in the reaction zone, we use a method which defines the reaction rate in terms of the reaction time and burning velocity. The reaction rate, which is considered to have an average and constant value, is expressed as m_s/τ_c (where m_s is the particle mass and τ_c is the burning time) [29,30].

Here, the investigation has been focused on flame propagation in highly volatile dusts such as coal dust. Coal particles are assumed to be spherical. Temperature within all these particles is supposed to be uniform because of the particles' small size and large thermal conductivity. The involved chemical processes could include the evaporation of volatiles from particle surfaces and the homogeneous combustion of volatiles following their premixing with oxidizer in the gas phase. The propagation of flame in this kind of mixture, in the presence of a considerable amount of excess oxygen, has been examined. Three separate zones can be distinguished in flame propagation: the preheat zone, the reaction zone, and the post-flame zone (Fig. 1). The first zone is the preheat zone ($R_f < R$), where the temperature of mixture is lower than the ignition temperature and the rate of reaction is equal to zero. The second zone is the reaction zone ($R_f < R < R_f + 1$,), where the gaseous fuel burns. The third zone is the post-flame zone ($R < R_f$), where the temperature of the combustion products is constant. Because of the excess oxygen, the reduction of oxygen concentration in the flame is small, and the combustion time (τ_c) in the reaction zone is constant.

The thickness of the reaction zone is non-zero. By using the burning velocity v and combustion time τ_c, the reaction zone thickness will be obtained as:

$$\delta = v.\tau_c. \tag{1}$$

It is assumed that the dust cloud consists of uniformly distributed, equal-size coal particles and air. In the performed analysis, the gradients of all the dependent variables including the temperature and concentration in the direction parallel to the flame front are ignored. It is also assumed that particle velocity is equal to gas velocity. Collisions and interactions between burning particles are disregarded. The Biot number is very small, suggesting a uniform temperature distribution within each particle. Also, gas and particle temperatures are considered to be equal. The thermal conductivity of the gas is a linear function of temperature: $\lambda = \lambda_u(T/T_u)$ (here, index u denotes an unburned mixture) [31–34]. The ignition point, T_{ign}, occurs when the temperature of a mixture is close to the auto-ignition temperature of a Vaporized fuel (methane). The concentration and the initial

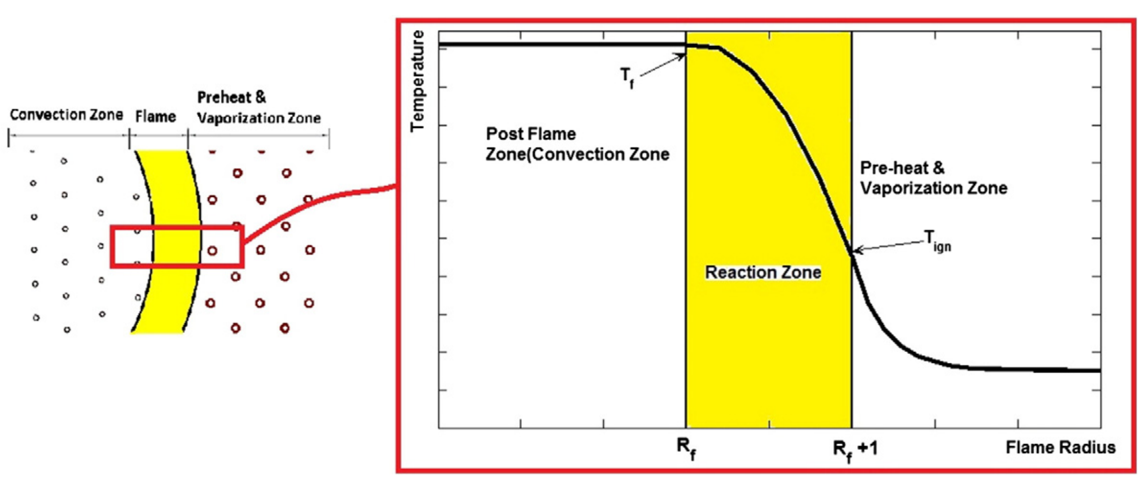

Fig. 1. Schematic shape of the flame structure.