Acta Astronautica 115 (2015) 82–93

Contents lists available at ScienceDirect

Acta Astronautica

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

Radiation heat transfer in particle-laden gaseous flame: Flame acceleration and triggering detonation

M.A. Liberman [a,*], M.F. Ivanov [b], A.D. Kiverin [b]

[a] NORDITA, KTH Royal Institute of Technology and Stockholm University, Stockholm, Sweden
[b] Joint Institute for High Temperatures of RAS, Moscow, Russia

ARTICLE INFO

Article history:
Received 28 March 2015
Received in revised form
9 May 2015
Accepted 12 May 2015
Available online 21 May 2015

Keywords:
Flame
Radiation
Detonation
Particles
Ignition
Gradient

ABSTRACT

In this study we examine influence of the radiation heat transfer on the combustion regimes in the mixture, formed by suspension of fine inert particles in hydrogen gas. The gaseous phase is assumed to be transparent for the thermal radiation, while the radiant heat absorbed by the particles is then lost by conduction to the surrounding gas. The particles and gas ahead of the flame is assumed to be heated by radiation from the original flame. It is shown that the maximum temperature increase due to the radiation preheating becomes larger for a flame with lower velocity. For a flame with small enough velocity temperature of the radiation preheating may exceed the crossover temperature, so that the radiation heat transfer may become a dominant mechanism of the flame propagation. In the case of non-uniform distribution of particles, the temperature gradient formed due to the radiation preheating can initiate either deflagration or detonation ahead of the original flame via the Zel'dovich's gradient mechanism. The initiated combustion regime ignited in the preheat zone ahead of the flame depends on the radiation absorption length and on the steepness of the formed temperature gradient. Scenario of the detonation triggering via the temperature gradient mechanism formed due to the radiation preheating is plausible explanation of the transition to detonation in Supernovae Type Ia explosion.

1. Introduction

Notoriously, while studying combustion in gaseous mixture, the radiation of hot combustion products is usually not important, as the radiation absorption length in a gaseous mixture is very large, so that the gaseous mixture is almost fully transparent for the radiation and therefore the radiation heat transfer does not influence the flame dynamics. For example, the photon mean free path in the atmosphere at pressure $P = 1atm$ is about tens meters because of very small $(10^{-24} \div 10^{-25})cm^2$ values of the Thompson scattering and “bremsstrahlung” cross section processes. Therefore the contribution of radiation to the heat transfer is negligibly small. If the flame propagates in a tube out from the closed to the open end, the radiation heat losses of the hot combustion products cause a relatively modest cooling of the burned products resulting in a modest decrease of pressure behind the flame front, which is negligible compared to the thermal conduction heat losses to the tube walls. In the traditional theoretical combustion the heat is transferred by the molecular gaseous thermal conduction and/or convection while the radiation heat transfer is negligible because the energy transferred by the radiant heat flux contributes far too small to the mechanism of combustion wave propagation and does not influence the flame velocity.

The situation changes drastically if the gaseous mixture is seeded with fine inert particles, which absorbed and heated by thermal radiation and then transfer the heat by

---

[*] Corresponding author. Tel.: +46 855378444.
E-mail address: mliber@nordita.org (M.A. Liberman).

http://dx.doi.org/10.1016/j.actaastro.2015.05.019
0094-5765/

conduction to the surrounding gas. In this case the gas temperature ahead of the flame lags that of the particles and the radiation preheating causes either acceleration of the flame or non-uniform temperature distribution with a proper temperature gradient, formed ahead of the flame, trigger either new deflagration or detonation via the Zel'dovich gradient mechanism. In the present paper we investigate the influence of the radiation preheating for the particle-laden hydrogen-oxygen and hydrogen/air flames. Scenario of the radiation preheating resulting in the triggering detonation can be plausible mechanism explaining deflagration-to-detonation transition in the thermonuclear Type Ia supernovae (SN Ia), which still remains the least understood aspect of the SN Ia explosion phenomenon. In the case of non-uniform distribution of particles, which is typical e.g. for dust deposits layers ("methane-air detonation" in coal dust), the time of the radiative heating is longer. If time of the flame arrival to the boundary of denser particles layer, where the radiation is noticeably absorbed, is long enough, the maximum temperature within the temperature gradient established due to the radiative preheating may exceed the crossover value. In this case either new deflagration or detonation can be ignited via the Zel'dovich's gradient mechanism [1,2]. What kind of combustion regime is ignited in the "distant" particle seeded cloud depends on the radiation absorption length and on the steepness of the formed temperature gradient.

It is known, that uncontrolled development of detonation poses significant threats to chemical storage and processing facilities, mining operations, etc. [3–5], while controlled detonation initiation can be a potential application for propulsion and power devices [6,7]. Detonations may or may not develop depending on the ability of a particular mixture composition to sustain detonations, and on the ability of flames to accelerate and produce shocks that are strong enough to ignite detonation. Study of the premixed flames and detonations arising and propagating in the particle-laden gaseous combustible mixture is important for the understanding of unconfined vapor cloud explosions and accidental explosions in many industrial processes associated with the risk of dust explosions, and for better performance of rocket engines using fluid or solid fuels, see e.g. [8,9]. Majority of the previous studies used a one-step chemical reaction model and were mainly focused on the deflagration-to-detonation transition (DDT) in a gaseous combustible mixtures in attempt to understand nature of the detonation formation. Although significant progress has been made in the understanding of the flame dynamics, the nature of the transition to detonation still remained highly uncertain because a one-step chemical model allows ignition at any temperatures, so that the results of such studies were often remained questionable. In the 1980–1990s, several groups used a one-step Arrhenius chemical model and asymptotic methods for high activation energy to examine effects of the radiation on the flames propagating in a gas mixture seeded by solid particles [10,11]. The flame propagating in the presence of the uniformly dispersed inert solid particles has been considered with and without account of radiative heat transfer [12–18]. Coal combustion research has been focused mainly on two aspects of practical interest: the production of volatiles due to thermal decomposition of coal dust and char combustion [19–21]. The combustible volatiles can react and release energy, which in turn may contribute to the heat-up of the particles, enhance the combustion energy release due to energy feedback mechanism resulting in an explosion. For the coal-dust suspension air filling the coal-fired burners and for rocket engines using the solid or fluid fuels as well as for coal-fire mining safety both the ignition and combustion evolution are of paramount importance. Effect of radiation transfer on a spray combustion can be of interest for practical cases such as diesel engines, gas turbine combustors etc.

A combustible mixture can be ignited by electrical sparks, or by thermal heating. The ignition capability of an electrical spark varies with fuel concentration, humidity, oxygen content of the atmosphere, temperature, and turbulence, requiring about 0.01–0.03 mJ depending on the mixture reactivity. In contrast, radiation-induced ignition typically requires much larger amounts of energy to be released in the mixture. Direct thermal ignition of gaseous combustible mixture by absorption of radiation causing a rapid increase in temperature at least up to 1000 K is possible by focusing a high power laser radiation and has been demonstrated both theoretically and experimentally [22,23]. However, ignition at low power levels is unlikely because of a very large length of absorption of the combustible gases at normal conditions.

In the present study effects of thermal radiative preheating is considered for the flames propagating in a two phases composite comprising of gaseous combustible mixture and inert particles. Recent experiments have shown that the dust cloud flame propagation is strongly influenced by the thermal radiation [24–27]. The effects of the radiation preheating is investigated for the hydrogen-oxygen and hydrogen-air flame. The gaseous phase is assumed to be transparent for the radiation, while solid particles absorb and reemit the radiation. Different scenarios are considered depending on spatial distribution of the suspended particles and the laminar flame velocity in a pure gaseous mixture. It the case of uniform spatial distribution of the particles the thermal radiation emitted from the hot combustion products is absorbed by the particles ahead of the flame resulting in the radiation preheating, which in turn causes the increase of the flame velocity. It is shown also that the radiative heat flux from the primary particle-laden flame may generate secondary explosion ahead of the flame in the distant particle cloud. This phenomenon is demonstrated for the non-uniform spatial distribution of particles, when the radiation absorbed far ahead of the flame creates a nonuniform temperature distribution in the unburned mixture. If maximum temperature ahead of the flame rises up to the crossover value before the flame arrival to this location, then either new deflagration or detonation can be ignited via the Zeldovich gradient mechanism.

The paper is organized as follows. In Section 2 we present the mathematical model used to study the problem in question. A simple model explaining the principal features of the radiation preheating, and numerical study of the influence of the radiative preheating on combustion wave velocity for a uniform spatial distribution of the particles is