Combustion and Flame 196 (2018) 35–44

Contents lists available at ScienceDirect

Combustion and Flame

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

Ignition and combustion of a single aluminum particle in hot gas flow

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ARTICLE INFO

Article history:
Received 31 August 2017
Revised 3 May 2018
Accepted 7 May 2018

Keywords:
Aluminum particle combustion
Ignition delay time
Combustion time
Single aluminum particle

ABSTRACT

For simulating the aggregated aluminum bulks on the burning surface of solid propellants, large aluminum particles (40–160 μm) are used in this work. The isolated aluminum particles are ignited in hot oxidizing gas. Based on the bright-spot diameter profiles and the known respective reaction mechanisms, the total ignition and combustion process of aluminum particle can be divided into three stages, namely, pre-heating, ignition and combustion. The initial and bright-spot diameters of the aluminum particle are measured directly from the images by using the in-house automated data processing routines. Ignition delay time, t_i, and combustion time, t_c, are also obtained by post-processing the sequential images and can be associated with the particle diameters, D, in the form of $t_i = aD + b$ and $t_c = \alpha D$, respectively. The changing trends of ignition delay time and combustion time with the effective oxidizer mole fraction in the range of 22.8%–49.1% are distinctly different. The oxidizing environments with a high effective oxidizer mole fraction can result in short combustion time but long ignition delay time. For small particles (40–110 μm), the environmental effective oxidizer mole fraction exerts a limited effect on the sum of ignition delay time and combustion time, which indicates total time. By considering the effects of particle sizes and effective oxidizer mole fractions of environments, the percentages of ignition delay time in the total time are analyzed. These results suggest that with the goal of decreasing the total time, suitable methods can be employed for different conditions. Furthermore, we observe and discuss the phenomenon of aluminum particle microexplosion in an environment with high effective oxidizer mole fraction, which decreases particle combustion time by a large margin.

1. Introduction

Aluminum powders are widely used as fuel additives in various solid propellants [1–4] and are also potential fuels for establishing a lunar mission base and exploring Mars [5–7]. The advantages of aluminum are its relatively high volumetric combustion enthalpy, high combustion temperature, nonreactivity during mixing and storage, environmentally benign products, and relatively low cost. The detailed ignition and combustion characteristics of aluminum particle should be explored to optimize the design the formulations of new solid propellants.

The particles employed in most solid propellants are in the order of or finer than 20 μm. However, on the surface of solid propellants, a long ignition delay time of aluminum particle leads to agglomeration of molten particles. Molten particles agglomerate larger aluminum droplets that range in the order of several tens to hundreds of microns in diameter [4,8]. Then, most of the agglomerated aluminum particles will continue to burn in the oxidizing environment after leaving the propellant surface. Thus, the ignition and combustion characteristics of large aluminum particles in the post-combustion zone are worth careful study. Information on ignition delay time and combustion time as functions of particle size becomes increasingly important as the computational models of solid propellants are being developed. Such models critically need the ignition and combustion parameters of single aluminum particles.

Aluminum particles have been investigated experimentally by various methods, such as CO_2 laser [9–15], high temperature gas [16–19], and aluminum dust flame [20–22], or directly as solid propellants [4,23] for investigating the burning characteristics. By using CO_2 laser, the individual aluminum particle can be heated at the preset heating rate in artificially controlled atmospheres. The ignition thresholds [15] of aluminum particles can be measured, and the correlation of burning times related to particles size in different atmospheres has also been established. However, limited by the heating method, aluminum particles are heated by radiant energy only from a fixed direction. In other words, the distribution of heating energy on the particle surface is uneven. The burning characteristics of aluminum particles, including micron-sized particles [16,17] and nanoparticle agglomerates [18,19], are also studied in the post flame of a non-premixed burner. The burner provides high-temperature gas through the combustion of a

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https://doi.org/10.1016/j.combustflame.2018.05.010
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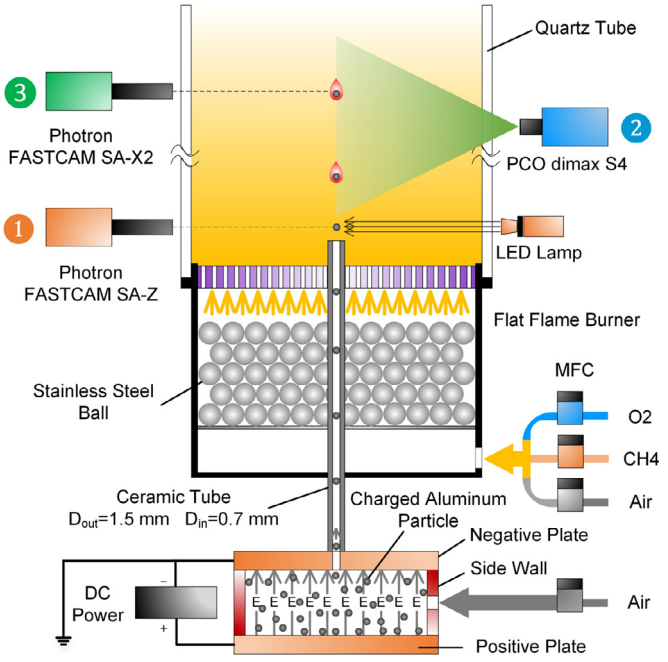

Fig. 1. Schematic of the experimental setup.

hydrocarbon mixture, such as carbon monoxide/oxygen [16], acetylene/air [17] and methane/oxygen/air [18,19]. Several key parameters of the burners, such as gas temperature, gas compositions, and even turbulence intensity [17], can be adjusted to the levels that approximate the practical levels to imitate several practical applications. Ignition temperature and burning time of aluminum particles (less than 40 μm) were measured with the help of thermocouples and high-speed cameras. Moreover, the microexplosion phenomenon of nanoparticle agglomerates [18,19], which is caused by the vaporization of unreacted aluminum core, and the large stress for tearing the Al/Al_2O_3 particle into numerous smaller clusters, is also observed in the oxidizing environment, which contains an oxygen concentration exceeds 3.5 mol/m^3.

The combustion regime of aluminum particles is crucial for investigating the combustion process and developing a combustion model [24]. In Ref. [5], the combustion regimes of aluminum particle in various atmospheres were reviewed and discussed. With the help of advanced optical investigative techniques, the combustion regimes of aluminum suspensions were studied in a Bunsen-type burner [21,25] and counterflow dust burner [26]. The combustion regimes of aluminum particles (arithmetic mean diameter, 4.2 μm) in air and the post gas of methane-air flame are different. For the combustion of aluminum particles in air, individual particles are covered by the lifted vapor-phase micro-diffusion flames and burn in a diffusion-controlled combustion regime. In aluminum-methane-air flames, the absence of vapor-phase micro-diffusion flames indicates that particle combustion is likely kinetically-controlled. For evaluating the role of heterogeneous reaction in aluminum combustion, a model that considered detailed gas-phase and surface kinetic mechanisms was developed [27]. Simulation results show that under certain conditions (small-sized particles and/or oxidizing atmosphere), heterogeneous reaction probably plays an important role and should be taken into account in simulations. In addition, the ignition and combustion characteristics of nano- and micro-sized aluminum particles were summarized extensively in Ref. [24]. According to the analysis of experimental details, the ignition and combustion process is divided into several stages, and a general theory of ignition and combustion of aluminum particles is proposed.

The goals of current work are to directly measure the sizes of single aluminum particles (40–160 μm) and their ignition delay times and combustion times. For simulating the aggregated aluminum bulks on the burning surface of propellants, the particles used in this work are relatively large. Single aluminum particles are aerosolized and injected into the hot gas region by using the particle generator. The premixed flat flame burner can provide a relatively high temperature and oxygen-rich environment for particle ignition and combustion. As soon as the particles appear in the hot gas region, their original shapes and ignition and combustion behaviors are recorded by high-speed cameras. By analyzing image sequences, the ignition delay time, combustion time, and total time of aluminum particles in several effective oxidizer mole fraction environments can be obtained. Meanwhile, the ignition delay times and combustion times are fitted as functions of particle sizes under each given experimental condition. Certain detailed experimental phenomena, such as oxide cap, asymmetric gaseous flame, and microexplosion, are also presented in this article.

Table 1
Experimental conditions. The effective oxidizer mole fraction of post-combustion gas were calculated by assuming that the premixed gases burn completely.

Case	Air/L/min	CH_4/L/min	O_2/L/min	Effective oxidizer mole fraction of post-combustion gas, X_{eff} (%)
Case01	30.0	7.0	8.0	22.8
Case02	27.0	7.0	11.0	28.0
Case03	24.0	7.0	14.0	33.3
Case04	21.0	7.0	17.0	38.6
Case05	18.0	7.0	20.0	43.8
Case06	15.0	7.0	23.0	49.1

2. Experimental apparatus

2.1. Flat flame burner

A premixed flat flame burner is employed to provide a series of high-temperature environments for the ignition and combustion of aluminum particles. As shown in Fig. 1, air, methane, and oxygen are supplied through needle valves, and their flows are measured by three mass flow-meters (Alicat Scientific; Model M50SLPM) to ±1% accuracy, respectively. Then, fresh gases are mixed in the burner when passing through the stainless steel balls zone. According to the combustion characteristics of CH_4 in the air-oxygen mixtures, a molybdenum alloys back-flame preventer is designed. A total of 1400 micro holes with diameters of 0.5 mm are bored in the center area of the back-flame preventer. A 90×90 mm^2 square quartz tube with thickness of 3.0 mm isolates the combustion product gas from the surrounding atmosphere and allows optical access into the test region. In post-combustion gas, the effective oxidizer mole fraction can be adjusted in the range of 22.8%–49.1% by changing air and oxygen flow rate (Table 1). In this work, the effective oxidizer mole fraction, proposed by Beckstead [28], was used to correlate the ignition and combustion characteristics of aluminum particles. The effective oxidizer mole fraction is defined by

$$X_{\text{eff}} = X_{o2} + 0.6X_{H_2O} + 0.22X_{CO_2}, \quad (1)$$

where X is the mole fraction of the oxidizing chemical species for the aluminum particle. The mole fractions of the three major oxidizers were determined under the assumption of complete burning of the premixed gases:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O. \quad (2)$$

In the measurement of gas temperature, one of the four quartz glasses is replaced by a stainless plate. Temperature distributions