Energy 162 (2018) 618–629

Contents lists available at ScienceDirect

Energy

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

Effect of ambient temperature on the ignition and combustion process of single aluminium particles

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A R T I C L E I N F O

Article history:
Received 2 February 2018
Received in revised form
1 August 2018
Accepted 8 August 2018
Available online 11 August 2018

Keywords:
Single aluminium particle
Ambient temperature
Ignition delay time
Combustion time
Ignition probability
Characteristic particle temperature

A B S T R A C T

This experimental work aims to examine the effects of ambient temperature on the ignition and combustion process of single aluminium particles (40–170 μm). Ambient temperatures considerably influence the particle ignition delay time, but the influence on the combustion time is limited. Particle ignition probability is very sensitive to the ambient temperature. The particle ignition probability can be improved by approximately 6.7 times by increasing the ambient temperature by approximately 300 K. As the diameter increases, the ignition probability increases firstly and then decreases in the experimental conditions of Cases 02–06. The diameter ranges for the particle ignition probability of >90% in the experimental conditions of Cases 03–06 can be extended by the high ambient temperature. Moreover, the aluminium particles with high unevenness level can be ignited easily, which should be resulted from the local flame near the raised part. The characteristic particle temperature is measured using the method of two-colour pyrometry. Experimental results show that the aluminium particle in these experimental conditions can barely burn in a pure diffusion-limited regime. The structure and components of the oxide film on the unignited particle show that the oxide film fracture is a key process for particle ignition.

1. Introduction

Aluminium is popularly used as the fuel additive in various propulsion applications, such as solid rocket motors [1], gelled propellant ramjet [2] and powder fuelled ramjet [3]. The advantages of aluminium are its high energy density, relative safety and low cost [4]. In composite solid rocket motors and solid fuel rocket ramjets, the aluminium powders can improve the enthalpy release in the combustion chamber and grants a high specific impulse on a large scale. The particles employed in most solid propellants are usually in the order of, or finer than, 20 μm. However, on the burning surface of solid propellants, several microns-sized aluminium particles will be melted into coarse agglomerations with the diameter of tens to hundreds micron before they are ignited. These phenomena have been observed using high-speed camera [5] and digital in-line holography [6]. These coarse aluminium agglomerations are ignited and burn in a mechanism that is different from that of fine particles. Therefore, exploring the detailed ignition and combustion characteristics of the coarse aluminium particle can provide guidance for evaluating the ignition and combustion model of single aluminium particles, optimizing the formulations of aluminium-based propellant and designing the combustion chamber of solid rocket motor and solid fuel rocket ramjet.

Aluminium ignition [7] and combustion [8] have been studied experimentally over the past decades. The characteristics of aluminium ignition and combustion are recently investigated using several new experimental methods. For aluminium cloud combustion, a stabilised Bunsen-type burner was used to study combustion characteristics of aluminium suspensions in the air [9] and the products of methane flames [10]. To study the combustion regime of the particles and estimate the characteristic combustion time of the suspension, the imaging emission spectroscopy, spatially resolved laser-absorption spectroscopy and particle image velocimetry were applied [11]. Experimental results show that the combustion regimes of aluminium cloud in the air and the post gas of methane-air flame are essentially different. For the combustion of aluminium particles in the air, the individual particles are covered by the vapour-phase micro-diffusion flames, by contrast,

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https://doi.org/10.1016/j.energy.2018.08.066
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Nomenclature

Al	aluminium
C	carbon atom
CO_2	carbon dioxide
H_2O	water vapour
N_2	nitrogen
O	oxygen atom
O_2	oxygen
a	fitting coefficient of ignition time [ms/μm]
b	fitting coefficient of ignition time [ms]
c_1	first constant of radiation [W·m^2]
c_2	second constant of radiation [m·K]
d	diameter of thermocouple contactor [m]
$E_{b\lambda}$	spectral emissive power of black body [W/(m^2·m)]
$E_{\lambda 0}$, $E_{\lambda 1}$, $E_{\lambda 2}$	spectral emissive power [W/(m^2·m)]
h	heat transfer coefficient [W/(m^2·K)]
l_{pixel}	pixel size [μm/pixel]
N	recording time
N_{p}	pixel number occupied by particle
n	number of directions
r_{i}	particle radius in the *i*th direction [μm]
r_{p}	particle equivalent radius [μm]
T	aluminium particle temperature [K]
T_{e}	environmental temperature [K]
T_{g}	corrected gas temperature [K]
T_{m}	temperature measured by thermocouple [K]
V_0, V_1, V_2	response voltage [V]
x_{p}	particle central position in X-direction
y_{p}	particle central position in Y-direction
α	particle unevenness level
α_{c}	fitting coefficient of combustion time [ms/μm]
α_{j}	particle unevenness level in the *j*th image
ε	emissivity of thermocouple
ε_{λ}, $\varepsilon_{\lambda 1}$, $\varepsilon_{\lambda 2}$	emissivity at wavelength λ, λ_1, λ_2
η_{w}	dynamic viscosity near the thermocouple contactor [kg/m·s]
η_{∞}	dynamic viscosity far away the thermocouple contactor [kg/m·s]
λ, λ_1, λ_2	wavelength [m]
λ_{g}	thermal conductivity of hot gas [W/(m·K)]
σ	Stefan-Boltzmann constant [W/(m^2·K^4)]
Pr	Prandtl number
Re	Reynolds number

the absence of vapour-phase micro-diffusion flames in the aluminium-methane-air flames indicates that the particle combustion is likely kinetically-controlled. The ignition [12] and combustion [13] processes of individual aluminium particles were investigated using a CO_2 laser. Their sizes were measured by the scattered light pulses from a low-power laser and burning times were obtained from the particle emission signal [14]. Thus, the combustion characteristics can be directly correlated with the size of each particle. By analysing the particle flame temperature and the AlO emission, the combustion regimes for differently sized particles were obtained. The combustion processes of aluminium particles burning in the air can be separated into two stages [15]. In the first stage, the reaction is controlled by the vapour-phase combustion. However, in the following reaction stage, the vapour-phase flame is suggested to approach the particle surface, and the reaction continues with an increased contribution from surface oxidation. The larger aluminium droplets (>200 μm), which were produced by fusing aluminium wire, were also heated using CO_2 laser in the air [16]. During steady combustion, the flame spectra markedly contain the wave peaks of Al and AlO, and the aluminium droplets are surrounded with a film of stand-off gaseous flame. Therefore, it is believed that the combustion of the coarser aluminium droplet in the air should be controlled by vapour diffusion. The ignition and combustion characteristics of nano- and micron-sized aluminium powders in different oxygen content environments have also been experimentally investigated in Ref. [17]. Small sized samples in high oxygen content environments can achieve a good ignition and combustion characteristic. An empirical correlation has been established to predict the ignition temperature T_{i} of aluminium particle with diameter of d in different oxygen ratios c: $T_{\mathrm{i}} = 578.454 + 0.896\ \mathrm{d} - 35.75\ c$.

The locations of the heterogeneous reactions have been studied experimentally [18]. Aluminium particles were heated at a low rate in oxygen-containing environments by using the method of thermogravimetric measurements. Supported by the scanning electron microscopy (SEM) images of samples that were quenched at various temperatures during oxidation [18], the heterogeneous oxidation should occur at the outer surface of the growing rigid oxide layer. The heterogeneous oxidation is controlled by the outward diffusion of aluminium ions for a broad range of temperatures from 400 °C to 1500 °C. The growing oxide shell can barely be broken up once its thickness reaches approximately 100 nm. The nano-sized aluminium particles have been regarded as an effective burning rate enhancer for solid propellants [19] due to their high reactivity, low ignition temperature and short burning time [20]. However, the natural defect of agglomeration diminishes their performance. Thus, the combustion characteristics of aluminium nanoparticle agglomerates were investigated using a Hencken burner [21]. When the oxygen concentration exceeds 3.5 mol/m^3, the microexplosion phenomenon occurs and should be driven by the vaporisation of unreacted aluminium core. The improved melt/vapour dispersion mechanism based on the melt dispersion mechanism has been proposed to cover the phenomenon of microexplosion.

The numerical codes are being developed to simulate the combustion of aluminium-based propellants. Such codes critically need the ignition and combustion parameters of the aggregated aluminium particle. These parameters are also important for optimizing the formulations of the aluminium-based propellant and designing the combustion chamber of solid rocket motor and solid-fuel rocket ramjet. However, the investigations on the effect of ambient temperature on the ignition and combustion process of a single aluminium particle are limited. The morphological structure of the raw aluminium particle is also an important factor for the particle ignition probability, but this factor is usually neglected in previous works. Considering these research gaps, this paper introduces an experimental study on the ignition and combustion of individual aluminium particles (40–170 μm) by exposing to the hot mixtures of oxygen, water, and carbon dioxide, produced by the methane-air-oxygen flame. Using a high-resolution camera, the diameter and unevenness level of the single aluminium particle can be obtained directly. With the help of another high-speed camera, the entire ignition and combustion process along with the ignition delay and combustion times can be recorded. In particular, the change trends of particle ignition probability relating to particle shape and ambient temperature are also proposed for the first time. Characteristic particle temperatures are also measured using the method of two-colour pyrometry. Moreover, the morphology and