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Aluminum particle ignition in different oxidizing environments

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ABSTRACT

This paper presents experimental results on ignition of micron-sized spherical Al particles by a CO_2 laser in H_2O/N_2, CO_2, air, H_2O/air and CO_2/O_2 gaseous environments. Al powder with nominal particle sizes in the range of 4.5–7 μm is aerosolized using a parallel plate capacitor by charging particles contacting the electrodes. A thin, laminar aerosol jet is formed using a gas purged through the capacitor and issuing together with aerosolized particles through a small opening in the top electrode. The jet is fed into a focused CO_2 laser beam. A part of the gas mixture is fed as a shroud flow around the central aerosol jet to stabilize and shield the aerosol jet from surrounding air. The velocities of particles in the jet are varied in the range of 0.1–3 m/s. For the H_2O-containing gas mixtures, the gas lines are heated to ~150 °C. A numerical simulation using Fluent CFD code is used to determine the gas composition at the laser focal spot. In experiments, for a given environment and selected particle velocity, the laser power is increased until the particles ignite. The ignition is detected optically using a photomultiplier. The laser power thresholds required for ignition of spherical aluminum particles are measured at varied particle velocities for each environment. The lowest thresholds are found for CO_2/O_2 mixture and the highest for the H_2O/N_2 mixture. Addition of O_2 to H_2O or CO_2 reduces the ignition thresholds. The experimental data are processed to determine the kinetic parameters of a simplified Arrhenius description of the exothermic reaction leading to the particle ignition in different oxidizing environments.

1. Introduction

Aluminum powder is widely used as a fuel additive in solid propellants, explosives, and pyrotechnics. Ignition and combustion of aluminum particles have been extensively studied in the past, e.g., [1–3] with early work reviewed in Ref. [4]. Initial combustion models were developed following the hydrocarbon droplet combustion formalism and then expanded to include condensed reaction products and their transfer between the particle and the flame zone [5–8]. Noticeably less attention was paid to aluminum particle ignition processes which could be equally or even more important for practical applications. Most commonly, ignition is assumed to occur at a specific temperature, varied from 1350 K [9] to 2370 K [10,11] Despite extensive previous research, many of the aluminum ignition and combustion processes are not understood sufficiently well to enable their quantitative modeling. Currently, research of aluminum ignition and combustion in various configurations is very active involving both experimental [12–15] and modeling [16–18] efforts. Quantitative description of particle ignition processes is of specific importance for the practical applications, in which such processes determine ignition delays and bulk burn rates for aluminum. Recently, an ignition model for aluminum particle in oxygen was suggested based on detailed thermo-gravimetric (TG) studies of aluminum powders oxidation [16]. Oxidation was established to occur in several steps, including growth of the initial amorphous oxide layer, a phase change from the amorphous to γ-Al_2O_3 polymorph accompanied by an increase in the oxide density and formation of discontinuities in a thin alumina scale, growth of γ-Al_2O_3 and its transformations into θ- and later α-Al_2O_3 polymorphs. Each alumina polymorph presents a specific diffusion resistance and thus is oxidized at a specific rate. The polymorphic phase transitions result in stepwise changes in the oxidation rate. The rates of mass transfer processes accompanying oxidation of different alumina polymorphs and rates of polymorphic phase changes occurring in alumina were quantified based on the TG measurements [12]. Combining the quantitative description of heterogeneous oxidation processes with the heat transfer analysis for aluminum particles introduced in a hot gas environment or heated by another source (e.g., laser beam) enables one to predict the ignition delay as a function of the particle size and external conditions. The model was validated experimentally for aluminum particles rapidly heated and ignited in air using a CO_2 laser [19].

However, in many practical applications oxygen is not the primary oxidizer available for ignition of aluminum powders. Instead, ignition occurs in CO_2 and H_2O environments [20,21]. This paper describes an experimental study of ignition of aluminum particles

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heated rapidly in well-controlled environments with H_2O and CO_2 being the primary oxidizers. The laser ignition experimental methodology is similar to that for ignition experiments in air as described in Ref. [19]. The experimental setup is modified to enable studies of aluminum ignition in water vapor, carbon dioxide, and mixed oxidizers.

2. Experimental

The experimental approach is similar to the earlier experiments conducted in air [19]. A threshold CO_2 laser power required to ignite a particle is measured for a set of particle jet velocities in different gas environments. A narrow, low number density particle jet is fed through the focal spot of a CO_2 laser. The laser power is increased in steps, until ignition is detected. The minimum ignition threshold indicates that the particles passing through the center of the laser beam are heated sufficiently to transition to the self-sustained combustion, detectable optically. Particles passing through the beam periphery will not be heated as much as those passing through the beam center, so that only a small fraction of the powder particles ignites upon achieving the ignition threshold.

The experimental setup is described in detail elsewhere [19]; its modified version is schematically shown in Fig. 1. It includes an aerosol jet generator, a 125 W CO_2 laser (by Synrad, Evolution 125 series) with a ZnSe convex lens (0.75″ aperture and 4″ focal length), and a modulated green laser (SUWTECH model DPGL-3000 by Photop Technologies, Inc.) operated with a set of a semi-cylindrical and convex glass lenses to produce a laser sheet for the jet visualization. A photomultiplier tube (PMT) by Hamamatsu (model PMT C7247) was used to measure emission traces of the heated and ignited particles.

The device used to produce the aerosol jet was described in detail elsewhere [22,23]. Its main part is a parallel plate capacitor with a conductive (e.g., metal) powder placed onto the bottom electrode. The bottom electrode has a concave shape and the top electrode has a small hole in its center. A DC voltage in a range of 1–15 kV is applied and conductive particles acquire electric charge. They are repelled from the bottom electrode and attracted to the top electrode, at which they re-charge upon collision. The motion of the charging and re-charging particles continues so that an aerosol is produced in the space between the capacitor's electrodes [22]. The applied voltage is used to control the particle number density in the produced aerosol. The space between the capacitor's electrodes was enclosed in a chamber. A controlled gas flow measured by a gas mass flow meter (M-200SCCM-D by Alicat Scientific Inc.) and fed into the space between the electrodes exits through the opening in the top electrode. Thus, an aerosol jet issues from the capacitor. In these experiments, as in Ref. [19], a low number density of the produced aerosol was maintained so that the number of particles fed into the aerosol jet was of the order of 1000 per second. The carrier gas flow rate was adjusted to control the aerosol jet speed in the range of 0.1–3 m/s. An additional plate with a built-in electric heater is placed above the top electrode. The space between the electrode and the plate is enclosed, and the plate has an opening coaxial with that of the nozzle in the top electrode. The size of the opening is greater than the electrode nozzle, as illustrated in Fig. 1. A separate gas mixture is fed between this plate and the top electrode to generate a shroud gas jet around the central aerosol jet, as shown in Fig. 1. The shroud gas jet stabilizes the central aerosol jet as well as shields it from the room environment. For experiments with the only oxidizer being H_2O, the central jet comprised of N_2 while the shroud jet was a mixture of N_2 and superheated steam. For the mixed H_2O/O_2 oxidizing environments, the steam mixture with air and/or air as the central jet carrying gas could be used. Note that argon could not be used as the central jet carrier gas because of its low electric breakdown potential, further reduced at elevated temperatures [24]. The steam gas flow tubes as well as the space between the top electrode and the additional plate were heated to about 150 °C to eliminate water condensation.

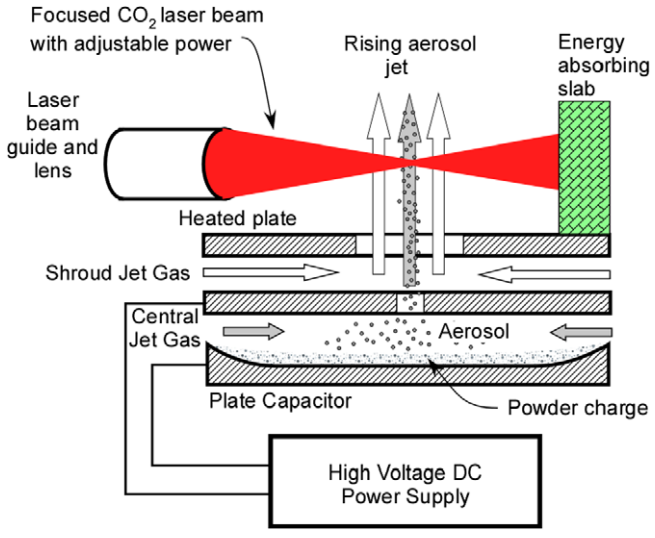

Fig. 1. Schematic diagram of the experimental setup.

In experiments involving H_2O, superheated steam was generated using a customized steam generator. A peristaltic pump (Variable Speed Pump by Control Company) supplied a metered amount of liquid water (typically, 0.1 ml/min) into a steel tube (3.1 mm diameter, 5 m overall length) coiled inside a tube furnace (Tube Furnace 21100 by ThermoLyne). Prior to entering the furnace, the tube was connected to a tee and a second tube to which a metered nitrogen (or air) flow was supplied. Both the carrier gas (nitrogen or air) and water were pumped through the furnace. The furnace was pre-heated to 400 °C so that a superheated steam, mixed with the carrier gas at a controlled ratio, issued from the coiled tube exiting the furnace. The steam/carrier gas mixture was fed through a heated hose maintained at about 150 °C, to the aerosol jet generator (with its respective components also pre-heated). The shroud jet and the main particle carrying gas mixed rapidly as discussed in more detail below, so that a well-controlled gas environment was generated in the area where the particles entered the laser beam.

For experiments with CO_2 serving as an oxidizer, the shroud gas was pure CO_2 and the heaters for hoses and components of the aerosol generator were turned off. CO_2 was also used as the central jet carrier gas. For mixed CO_2/O_2 environments, a premixed CO_2/O_2 mixture was used for both shroud and central gas flows.

Threshold CO_2 laser power required for particle ignition was measured for three different jet velocities for each environment, similar to the experiments in air [19]. The variation in the jet velocity is equivalent to changing the particle heating rate in the laser beam, which is useful for identification and/or validation of the ignition kinetics. The aerosol jet velocity was measured using particle image velocimetry. A vertical green laser sheet modulated with a frequency in the range of 300–3000 Hz illuminated the aerosol jet, with the higher frequencies selected for higher jet speeds. Produced particle streaks were recorded using a digital camera and the streak lengths were measured to determine the jet velocity.

For each experiment, a stable aerosol jet was established and the CO_2 laser was fired continuously for 8 s, at a preset power level. Visible radiation generated by heating and/or ignition of particles was monitored using a PMT connected to a PC-based data acquisition system. The experiment was repeated with the laser powers