Combustion and Flame 162 (2015) 1316–1325

Contents lists available at ScienceDirect

Combustion and Flame

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

Combustion of magnesium powders in products of an air/acetylene flame

Song Wang, Amy L. Corcoran, Edward L. Dreizin *

New Jersey Institute of Technology, Newark, NJ 07102, United States

ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form 28 October 2014
Accepted 29 October 2014
Available online 15 November 2014

Keywords:
Metal combustion
Burn rates
Combustion temperature
Particle combustion

ABSTRACT

This paper is aimed at characterizing combustion dynamics of fine magnesium powders. Two spherical, micron-sized Mg powders with different particle size distributions were introduced into an air–acetylene flame. Particles were observed to burn in laminar flames as well as in flames with turbulence induced by an auxiliary swirling air flow. Particle emission was detected above the flame emission background and emission pulses for individual particles were recorded using an array of three filtered photomultiplier tubes. Particle size distributions were correlated with their emission times, interpreted as burn times, for different turbulence levels. Ratios of the recorded filtered emission signals were used to obtain temperatures of the burning particles. Partially burned particles were collected and examined. Particle burn times were approximately proportional to $d^{0.8}$, where d is the particle diameter. The particle spherical shapes were not preserved. For the coarser powder, halos of condensed ultrafine MgO crystals were observed around quenched particles. Presence of slightly greater amounts of MgO on the surface of as received particles of the finer powder resulted in their longer burn times and elevated temperatures. These observations are interpreted assuming that the initial small MgO particles adhered to the metal surface result in the formation of solid MgO islands and inclusions on surface of the burning Mg droplets. Such islands block evaporation of magnesium and thus reduce the burn rates. In addition, they serve as condensation centers for the combustion products and grow rapidly during combustion. As a result, a relatively small number of the initial fine MgO particles can cause substantial disruption in the burning particle shape, surface morphology, and burn rate. Larger MgO inclusions can be heated above the Mg boiling point resulting in an increased measured temperature.

1. Introduction

Research on combustion of Mg has been active for a long time; however, there are relatively few experimental studies quantifying combustion rates and temperatures for Mg particles. Most of the previous experiments [1–8] employed rather coarse Mg particles, with dimensions ranging from hundreds of μm to few mm. In experiments with such individual large particles, the particle size was measured directly in Refs. [1–7]. It was reported that magnesium particles burn according to a well-known d^2 law; i.e., their burn time, τ, is proportional to the square of the initial particle diameter, d: $\tau \sim d^2$. The flame sizes observed for burning Mg particles exceed significantly the particle size [6–8] and the temperatures were reported to be 2630–2800 K [9,10] or even 3400 K [3], close to the predicted adiabatic flame temperatures of 3100–3610 K [10,11].

Based on the published results, it is common to assume that Mg particles burn in the vapor phase, similar to the liquid fuel droplets. However, it was reported that the partially burned and quenched particles, as well as fully burned extinguished particles collected in single particle combustion experiments were not spherical [3,6], which cannot be readily explained considering the classic droplet combustion model [12]. Because MgO produced in combustion is solid at the flame temperatures, its crystals can grow or be deposited on the burning droplet surface. This may locally impede the evaporation of magnesium and alter its combustion regime; the effect may be sensitive to the particle size. Experimental data with fine Mg particles are lacking. Recent experiments on combustion of fine Mg powder in water showed that the exponent, n, in the $\tau \sim d^n$ power law is less than one [13], consistently with recent experiments on fine Al particles [14–16].

The objective of this project is to experimentally characterize combustion of fine Mg particles in an oxidizer comprising combustion products of a hydrocarbon fuel, which is an environment similar to that encountered by the burning metal particles in

* Corresponding author.
E-mail address: dreizin@njit.edu (E.L. Dreizin).

http://dx.doi.org/10.1016/j.combustflame.2014.10.016
0010-2180/

propellants and explosives. Such environments are typically characterized by the mixture of CO_2 and H_2O as primary oxidizing species. In this work, magnesium particles are combusted in the products of an air–acetylene flame. Combustion will be studied in both laminar flame and in the flame with turbulent mixing of the reaction products with surrounding air.

2. Experimental

2.1. Approach

A metal powder is introduced in a premixed air–acetylene flame using a particle seeded coaxial flow of nitrogen. Particles ignite in the hot flame products, and their combustion is examined based on their optical emission. The turbulence in the combustion environment is varied. The experimental setup is schematically shown in Fig. 1. It was described earlier [13,17] and only minor modifications were made for this project.

Initial flows of both premixed air–acetylene and nitrogen carrying particles are directed vertically. Turbulence is introduced by air fed through three auxiliary nozzles placed horizontally around the flame and directed tangentially within a short cylindrical enclosure. The auxiliary nozzles generate a swirling flow around the flame. The flow rate of the auxiliary air jets is adjusted to alter the level of the achieved turbulence. The generated flow pattern inducing the flame turbulence is cylindrically symmetric. It does not noticeably affect the premixed air–acetylene flame cone, but changes substantially the flow pattern of its combustion products and of the gas in the extended diffusion flame envelope. In addition to the new flow pattern, this approach enhances mixing of the flame and burning particles with the surrounding air. The effects of a turbulent flow pattern and of an enhanced mixing with surrounding air cannot be separated from each other in the present experiment.

Particle emission signatures were recorded using an array of three filtered photomultiplier tubes (PMTs). Assuming that larger particles burn longer, the measured statistical distribution of particle burn times was correlated with the distribution of their sizes. This correlation produced a trend for the particle burn times as a function of their diameters. Further, emission intensity ratios measured at different wavelengths were used to evaluate the burning particle temperatures.

Note that most particles ignite while being injected into a laminar flame zone and continue burning passing through the turbulent regions. The measured burn times do not discriminate between these, possibly different combustion regimes. Different particles arrive into the flow regions affected by turbulent mixing at different stages of their combustion. Thus, the present experiments are only meaningful when a statistically significant number of particle emission pulses is collected and analyzed. Results characterize the gross effect of turbulence on the statistically distributed burn times and temperatures of magnesium particles.

The flow configuration achieved in the experiment is a simplified laboratory representation of the environment in a fireball produced by a metalized explosive and expanding in air [18]: turbulent mixing of reaction products of an explosive with surrounding air affects both flow pattern and gas composition to which the metal particles are subjected. The gross effect of this turbulent mixing on the particle combustion rate is of interest.

2.2. Material

Two spherical, 99.8% pure magnesium powders provided by Hart Metals, Inc., were used. One of the powders was described by the manufacturer as magnesium −325 Mesh, and the other nominally contained particles with sizes in the range of 1–11 μm. Powders were characterized using a LEO 1530 Field Emission Scanning Electron Microscope (SEM).

Particle SEM images for both 1–11 μm powders and −325 Mesh powders are shown in Fig. 2. Nano-sized oxide particles are observed to adhere to the Mg surface for both powders, more such particles appear to cover the surface of the finer, 1–11 μm particles compared with the coarser, −325 Mesh powder. For coarse powder, almost all particles are spherical. For fine particle, most particles are also spherical; however, coalesced spheres and non-spherical particles are observed.

Particle size distributions were measured using a Beckman-Coulter LS230 Enhanced Particle Analyzer. Results are shown in Fig. 3. A distribution "tail" representing ultrafine particles, less than 1 μm, was appearing in the measurements for the 1–11 μm powder, shown as broad gray bars in Fig. 3. Such Mg particles were unexpected based on the manufacturer's specification. It was suspected that the submicron sized particles could represent separated nano-sized oxide particles adhering to the surface of spherical Mg, as seen in Fig. 2, which could be knocked off the surface by ultrasonic agitation used during the measurement. An additional microscopic analysis of the powder was performed showing no particles with diameters smaller than 1.2 μm, in agreement with the manufacturer's specification. Diameters of all particles observed in microscopic images fell in the size range implied by the main peak in the measured size distribution, Fig. 3. Respectively, the measured particle size distributions were corrected by removing the "tail" representing the ultrafine particles. The remaining particle size distribution was re-normalized to

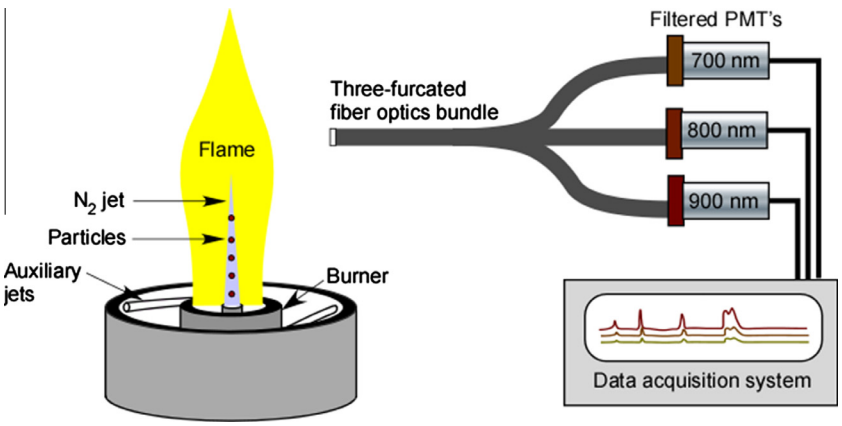

Fig. 1. Schematic of the experimental apparatus.