

REACTION MECHANISMS AND PARTICLE INTERACTION IN BURNING TWO-PHASE SYSTEMS

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INTRODUCTION

The main objective of this research is to understand the mechanisms by which particle interactions affect ignition and combustion in the two-phase systems. Combustion of metal aerosols representing the two-phase systems is carried out in the microgravity environment enabling one to avoid the buoyant flows that mask the particle motion due to the particle-particle interaction effects. In addition, relatively large, e.g., 100 μm diameter particles can be used, that remain aerosolized (i.e., do not fall down as they would at normal gravity) so that their behavior ahead, behind, and within the propagating flame can be resolved optically. An experimental apparatus exploiting this approach has been designed for the 2.2-s drop tower microgravity experiments [1]. A typical experiment includes fluidizing metal particles under microgravity in an acoustic field, turning off the acoustic exciter, and igniting the created aerosol at a constant pressure using a hot wire igniter [1,2]. The flame propagation and details of the individual particle combustion and particle interactions are studied using high-speed movie and video cameras coupled with microscope lenses to resolve individual particles. Recorded flame images are digitized and various image processing techniques including flame position tracking, color separation, and pixel by pixel image comparisons are employed to understand the processes occurring in the burning aerosols. Condensed combustion products are collected after each experiment for the phase, composition, and morphology analyses. New experiments described in this paper address combustion of Ti and Al particle clouds in air and combustion of Mg particle clouds in CO_2 . In addition, microgravity combustion experiments have been conducted with the particles of the newly produced Al-Mg mechanical alloys aerosolized in air.

MAGNESIUM AEROSOL COMBUSTION IN CO_2

Combustion of metal fuels in CO_2 is of interest for the design of atmosphere-breathing propulsion systems for Mars. The experiments were conducted with two size fractions of magnesium powders: particles in the size range of 150 – 180 μm , and particles of -325 mesh (< 44 μm). The combustion chamber and ballast vessel were purged with CO_2 prior to each experiment. For both particle sizes, reference experiments with the clouds of Mg particles burning in air were conducted. The magnesium mass loads were in the range of 0.1 – 0.7 g in the 0.5-liter chamber. The estimated equivalence ratios for the flames in CO_2 were in the range of 0.1 – 0.72 (for the flames in air, the respective equivalence ratios varied from 0.49 to 3.32). The flames readily ignited and propagated in the clouds of Mg particles in CO_2 , the velocities of the flame propagation were much higher than in air, e.g., 0.4 m/s in CO_2 versus 0.1 m/s in air for the 165 μm diameter particles. The products of combustion have been analyzed, only peaks of MgO were detected in addition to the peaks of unreacted Mg. Based on the qualitative comparison of the Mg/MgO peak intensities (cf. Fig. 1) for the products of Mg combustion in air and CO_2 , it could be concluded that the reaction was more complete in CO_2 .

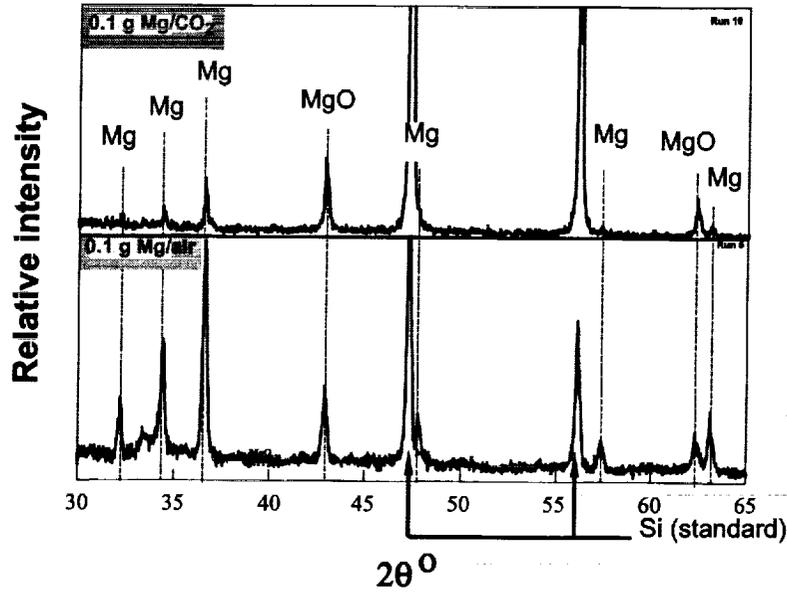


Fig. 1. X-ray diffraction patterns of combustion products of Mg powder in CO₂ and air.

TITANIUM AEROSOL COMBUSTION IN AIR

Titanium clouds in air were produced and ignited in microgravity. Two types of powder, 160 μm average diameter (by Wah Chang Company) and -325 Mesh ($< 44 \mu\text{m}$, by Alfa Aesar) were used. The flame velocity for the coarse particles varied in the range of 0.02 – 0.1 m/s, at equivalence ratios in the range of $4.8 < \phi < 6$. The fine particle flames propagated at a velocity of 0.3 m/s at $\phi = 2.2$ and 1.8 m/s at a higher particle loading, $\phi = 3.1$. The appearance of flames of clouds of titanium particles was qualitatively similar to those of zirconium. Individual particle flames could be clearly visible in all the runs. Particle explosions were observed in only one experiment with the fine particles and lower mass load (equivalence ratio of 2.2, cf. Fig. 2). The experiments have shown that the titanium combustion products do not agglomerate as much as the products of zirconium combustion as was observed in the earlier tests [3]. Instead, a large number of very fine particles were observed in the combustion products, indicative of significant vapor-phase reaction followed by the product condensation. The phase compositions of combustion products formed in experiments with finer Ti particles were analyzed and the results of these analyses are illustrated in Fig. 3. It is interesting that significant amounts of TiN are found in the products in addition to rutile and anatase, two modifications of Ti₂O₃. It can be noted that based on the relative peak intensities, more of the TiN (and less of Ti₂O₃) was formed in a run with the higher Ti powder load ($\phi = 3.1$), in which no particle explosions were observed. These observations are consistent with the earlier results [4] describing the process of Ti particle combustion. It has been suggested that during the initial combustion period, both oxygen and nitrogen are dissolved in molten titanium, with the initial rate of

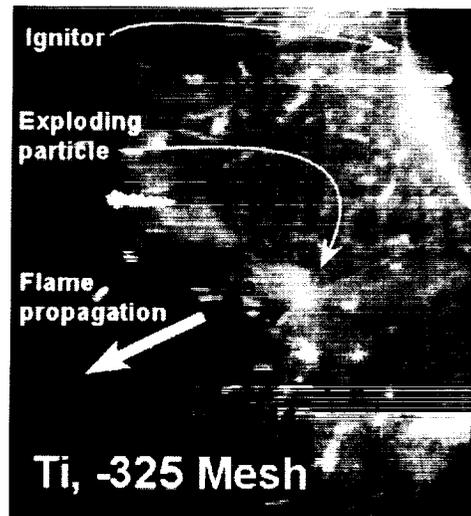


Fig. 2. Appearance of Ti flame in air (a high speed movie frame)

nitrogen dissolution being higher than that of oxygen. At the later stages of combustion, the rate of nitrogen dissolution decreases. At the end of combustion, when the particle temperature decreases, the solution becomes supersaturated, and nitrogen is released from the particles causing their explosions. Therefore, the interpretation of the current experiments is that in a fuel-rich mixture, the amount of oxygen available was not sufficient to produce the supersaturated solution and thus no explosions were observed. When the particles with large amounts of dissolved nitrogen cooled (relatively slowly in a cloud as compared to single particles), the phase of TiN formed.

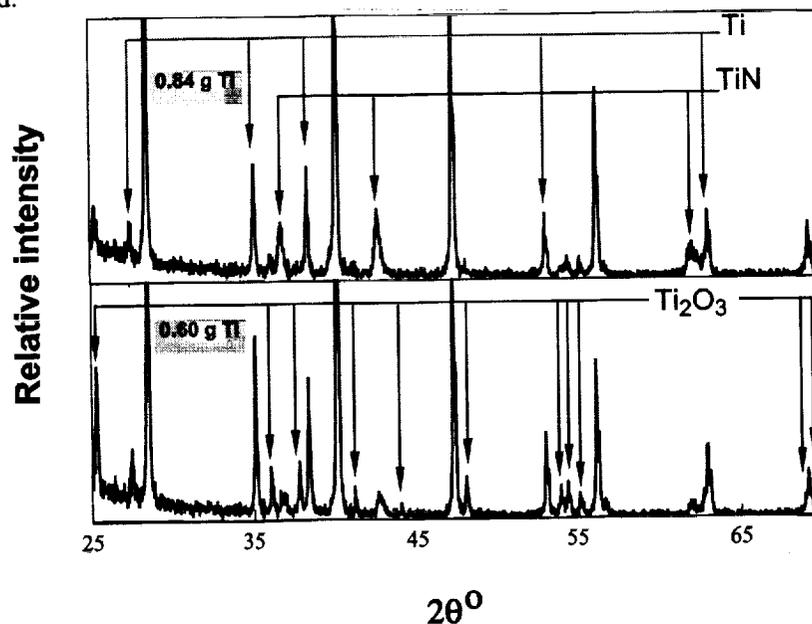


Fig. 3. X-ray diffraction patterns of Ti combustion products. Unmarked peaks are those of Si, used as an internal standard.

FLAMES OF ALUMINUM AND ALUMINUM-MAGNESIUM MECHANICAL ALLOY AEROSOLS

In an effort to develop new aluminum-based energetic materials for advanced metallized propellants, metastable Al-Mg mechanical alloys have been recently prepared and characterized [5]. In this work, the experimental setup and microgravity environment have been exploited to compare the flame propagation in the pure Al versus Al-Mg mechanical alloy aerosols. Two size fractions of the pure Al particles were used with the size ranges of 3 – 4.5 and 10 – 14 μm . The average sizes of the mechanical alloy particles were measured to be in the 7 – 10 μm range. Three compositions of the mechanical alloys with 10, 30, and 50 weight % of Mg were tested. It was found that the flame propagation velocities through the clouds of the alloy particles (around 0.5 m/s) exceeded noticeably the flame velocities in the same density aluminum particle cloud (~ 0.15 – 0.2 m/s). The flame structures of the alloy and aluminum particles are remarkably different, as illustrated in Fig. 4. The individual particles are well distinguished in the alloy flame but not in the aluminum flame, where only several large agglomerates are visible. The radiation intensity profiles measured across the flame zone are shown in Fig. 5. The flame front of the alloy aerosol flame is noticeably sharper as compared to the aluminum flame indicating a very narrow preheat zone. Such a difference has been expected based on the hypothesized mechanism of the alloy particle ignition at a specific phase transition temperature that is significantly lower than the Al_2O_3 melting point.

Combustion products have been collected after each microgravity experiment and the phase and elemental compositions of the products are being analyzed using electron microscopy coupled with the energy dispersive spectroscopy, and the x-ray diffraction.

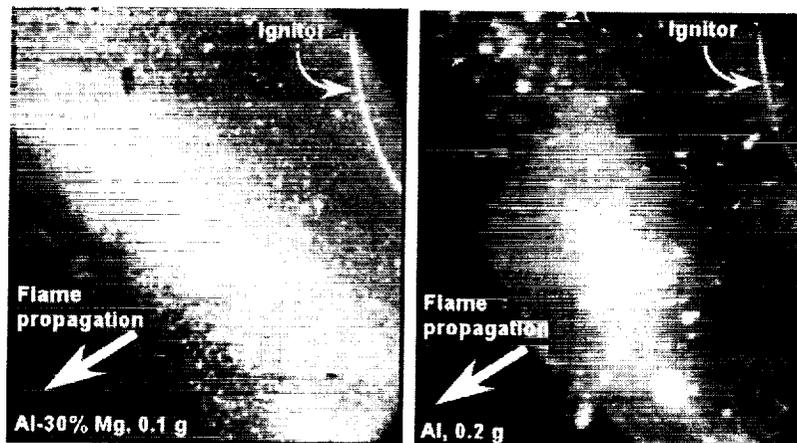


Fig. 4. High-speed movie images of flames propagating in the Al-30% Mg mechanical alloy and pure Al - air aerosols.

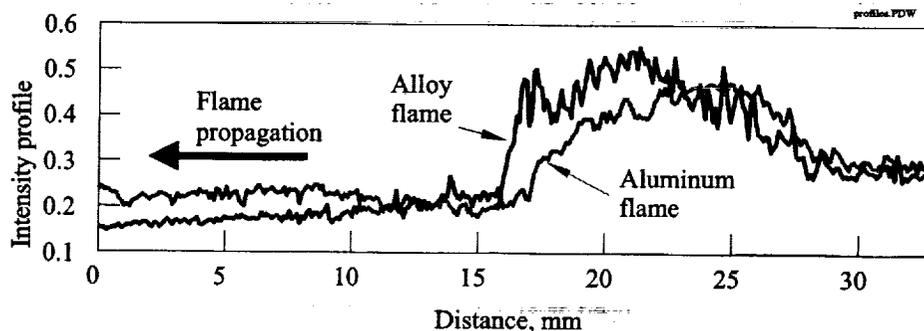


Fig. 5. Brightness profiles across images of the flames propagating in the Al-30% Mg mechanical alloy and pure Al - air aerosols.

ACKNOWLEDGEMENT

This research was supported by NASA Glenn Research Center, Cooperative Agreement NCC3-746. The help of Dr. Kurt Sacksteder in organizing the microgravity experiments is greatly appreciated. We also thank Mr. Hugh Aylward of NASA GRC for the assistance in image processing.

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