Investigation of Supersonic Combustion of Bulk Metal Via Spectroscopy

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1 Introduction

The ability of reactive metals (e.g., aluminum, magnesium, titanium, and zirconium) to burn in bulk form in supersonic flow of an oxidizing gas is an unusual mode of combustion in that the combustion occurs in the large Biot number regime, wherein the interior of the metal remains cold while extensive exothermic reaction occurs on the surface exposed to the high-speed flow. This feature distinguishes it from the more familiar type of metal combustion, in which the metal is burned in fine particulate form with the particle at a nearly uniform temperature ($\mathrm{Bi} < 0.1$). This model of combustion may be encountered in aerospace applications, particularly since some of the alloys listed above are widely used in aerospace. For example, it has been speculated that combustion of the exposed aluminum structure may have contributed to the demise of the Space Shuttle Columbia in 2003 [1]. This type of combustion may even find application in airbreathing hypersonic propulsion (metal-fueled ramjets and scramjets) and drag reduction technologies for projectiles, as well as in high explosives.

Prior studies, using either aeroballistic testing of metal projectiles launched into oxidizing atmospheres or expanding shock-accelerated oxidizing flows over stationary metal samples, have shown that titanium and zirconium may be more reactive than aluminum and magnesium, with both Ti and Zr burning at lower flow velocities and exhibiting significantly more mass removal than Al and Mg [2–4]. These prior studies also suggested that air at ambient conditions (1 bar, 300 K) is outside the ignition envelope of these metals, but they are capable of igniting in pure oxygen at elevated pressure and may continue to burn in air once ignited. The data from prior studies was relatively sparse in its measurement of the oxygen partial pressure and flow (or projectile) velocity required to observe bulk metal combustion. The present study focuses on the analysis of spectroscopic measurements collected while performing a systematic investigation of the envelope of projectile velocities and oxygen pressures for which exothermic reaction is observed to occur for titanium projectiles. Projectiles, consisting of spheres 3.175 mm (0.125 in.) in diameter, were launched at speeds of 0.7 to 1.8 km/s (Mach 2.0 to 5.4) using a single-stage light-gas gun into a test section of oxygen with pressure varying between 1 and 5.5 bar in order to determine the conditions necessary to observe combustion. The projectile is observed using a combination of high speed photography, photodetectors, and spectrometers to quantify the luminosity emitted. The results are correlated with the melting and boiling points of titanium, the adiabatic flame temperature, and the stagnation conditions of the supersonic flow.

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2 Experimental Facility

2.1 Gas-Driven Launcher

A velocity calibrated single-stage light-gas gun was used to launch projectiles to velocities in the range of 0.7 to 1.8 km/s. The gas gun operated using helium gas at high initial pressures, up to 400 bar. The launcher itself consisted of a 1.48-cm-internal diameter stainless steel driver tube (34.3 cm long), a double-diaphragm firing mechanism, a 2.1-m-long hardened steel launch tube with an internal diameter of 7.1 mm (0.280 in.), and a sabot stripping section.

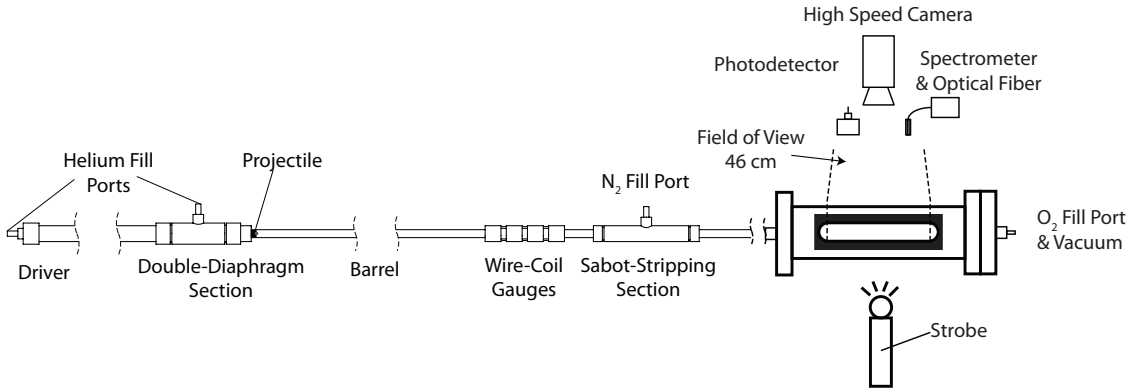

Figure 1: Experimental facility schematic (not to scale)

In order to obtain consistent launcher performance, a double-diaphragm technique was employed, using either Mylar or brass diaphragms. The sabot-supported projectile used in the experiments consisted of a polycarbonate sabot, a rare earth magnet, and a sphere made of titanium. The projectile was supported by a sabot for several reasons: (i) use of a sabot lowers the areal density of the projectile, increasing the velocity that can be obtained (ii) the sabot prevents blow-by of propellant gas by using a Bridgman-type seal, and (iii) the sabot prevented mechanical contact between the sphere material and the launch tube wall that could have resulted in friction-induced ignition and an undesirable spray of sparks into the test section. The coil gage section consisted of a polycarbonate tube whose internal diameter matched the internal diameter of the launch tube. Tightly-wound sections of transformer wire (gage 30) resulted in a distinct current pulse that could be recorded via a high-speed oscilloscope, which was used to both determine the sabot/projectile velocity and in order to trigger the data acquisition, strobe, high-speed camera, and spectrometer. Before it reached the windowed test section, the sabot was removed (stripped) from the sphere via a combination of gasdynamic and mechanical sabot stripping techniques. An inert gas (N_2) was used in the gasdynamic section at a pressure of 20 bar.

2.2 Diagnostic Equipment

In order to visualize the flight of the projectile, a high speed camera recording at 100,000 frames-per-second was used in conjunction with a bright strobe that back-illuminated the projectile during flight through the windowed test section. This strobe is a common commercial model used in professional photography. The camera was also used as the primary means to determine projectile combustion, the velocity of the projectile, and to verify the intensity readings obtained by the photodetectors. The f-number of the lens was varied and neutral density filters were applied as required to avoid pixel saturation. The exposure time was held fixed across all experiments at 0.4 μs.

Photodetectors were placed against the test section window and near the camera and were used to monitor the intensity of the emitted light of both the strobe and the projectile upon ignition. Due to the extremely high intensities of luminosity emitted in the experiment, neutral density filters with optical densities ranging from 2 to 4, corresponding to signal intensity attenuations of 100 to 10000 times respectively, were mounted on the photodetectors to avoid saturation.

A modified SLR camera was used in combination with a fiber-optic-based spectrometer to collect the emission intensity as a function of wavelength for the burning projectiles. A fiber optic cable was mounted on the film-plane of the SLR camera to facilitate collecting luminosity from the region of interest in the test section. This fiber was then inputted into an Ocean Optics HR-4000 spectrometer with an integration time of 30 ms with 0.27 nm wavelength resolution over the range from 200 nm to 1100 nm. A long integration time ensured that the event was consistently captured and, given the substantial intensity difference between the projectile and the trailing wake, the authors believed that the collected spectra were representative of the projectile. Spectra of both the strobe and the ambient light were collected before each experiment and subtracted from the burning projectile spectrum. The projectile temperature was obtained via poly-chromatic fitting of the continuum part of the spectra to Plancks law of blackbody radiation. The emissivity was assumed to be constant over the wavelength range of the spectrometer (grey body assumption).

3 Experimental Results

The facility described above was used to launch 100 sabot-supported titanium spheres (3.175 mm diameter, 0.2 g each) into a pure oxygen environment. All spheres were procured from the same supplier and originated from the same lot. The results of these trials can be seen in figure 2. The spheres were roughened with 100C grit aluminum oxide coated sandpaper immediately prior to the experiment that resulted in uniform surface asperities on the order of 100 μm on the entire projectile surface.

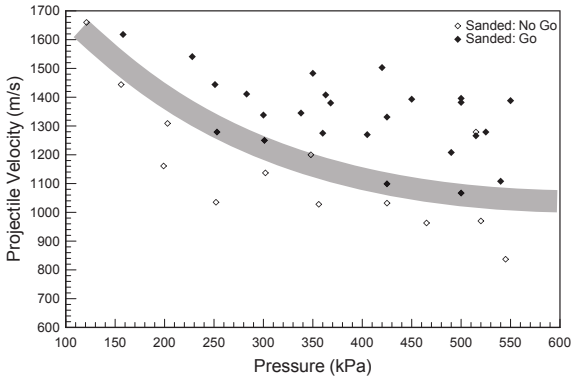

Figure 2: Ignition envelope for titanium spheres

The results of experiments conducted with these spheres are reported in figure 2. Experiments at high velocity and oxygen pressure resulted in combustion, while low velocity and oxygen pressure did not result in any observable reaction. The boundary between the two results is sharply defined, with only one no combustion case being obtained above the boundary that has been drawn in figure 2. The boundary has been drawn to span the region between consistent ignition and consistent "no combustion" cases and its thickness was set to the uncertainty in velocity measurements. The roughened spheres exhibited combustion at low projectile velocities, as low as 1070 m/s, and low oxygen pressures, as low as 150 kPa.

Although ignition of the roughened spheres was consistently observed above the boundary in figure 2, a gradient in the intensity of luminosity was observed as either the pressure or velocity was varied within

the regime. This result is illustrated by a series of images from different experiments in figure 3, all of which were taken using the same filters and camera settings. The trials were performed at a fixed pressure of 5.5 bar and the velocity was decreased until combustion was not achieved. Combustion at the highest sphere velocity (1430 m/s), figure 3(a), is characterized by an intense comet-like plume surrounding the entire sphere and extending significantly downstream, while at lower velocity (1280 m/s), figure 3(b), only minor exothermic centers are seen on the surface. The luminosity can be unambiguously attributed to exothermic reaction, since the same projectile launched at even the highest velocities used into high pressure nitrogen does not exhibit any luminosity at all. This series of experiments reported in figure 3, although only qualitative in nature, indicates that the phenomenon is not a classical particle ignition-type combustion event which, when initiated, reacts largely independently of the surrounding environment. Rather, the intensity of the exothermic reaction appears to be sensitively coupled to the flowfield conditions around the projectile.

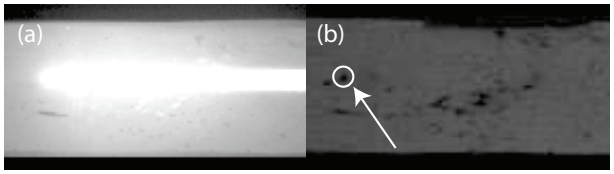

Figure 3: Series of images illustrating the gradient in the intensity of luminosity at 5.5 bar O_2 with the following projectile velocities: (a) 1430 m/s (b) 1200 m/s

As an attempt to better quantify the regime of combustion occurring around the projectile, spectra were collected for several different experiments in which the sphere velocity was held constant at approximately 1400 m/s and the pressure was varied from 3 to 5 bar. The field of view of the spectrometer was also shifted between experiments in order to collect spectra from both the projectile and the trailing luminous wake. In figure 4(a) below, the spectrum emitted by the trailing wake was characterized by several molecular lines and did not allow for a reasonable estimate of the reaction temperature. However, the spectrum emitted by observing the titanium sphere directly at 5 bar, shown below in figure 4(b), was a continuous spectrum with a peak at approximately 560 nm. Due to its continuous nature, it was possible to estimate the temperature of the reacting sphere by fitting the spectrum to Planck's radiation law for a grey body. The derived temperature, approximately equal to 5900 K for this particular experiment, was then compared to both the post-shock temperature in pure oxygen and the adiabatic flame temperature for a stoichiometric titanium-oxygen reaction (see Section 4.0). As is evidenced by figure 5, there is a good agreement between the experimental temperatures obtained and the theoretical adiabatic flame temperature calculated using the NASA CEA code. Although only preliminary spectroscopy work has been performed so far, the temperatures encountered are far higher than typical post-shock temperatures for Mach numbers above 5. This leads to the presumption that what is being observed in these experiments is better classified as combustion rather than decoupled reaction of material that has been ablated from the projectile.

4 Analysis

The NASA ideal gas equilibrium code (CEA) [5] was used to estimate several properties of the flow fields encountered experimentally. The analysis began by assuming a reservoir of quiescent oxygen at 4 bar initial pressure and 300 K, typical values found in experimental trials. A shock wave of varying strength (Mach numbers ranging from 1.25 to 7) was applied to the reservoir and the pressure and temperature of the shocked gas were calculated by CEA. This post-shock pressure, which is representative of the conditions behind the bow shock on the projectile, was then used as the initial pressure for a

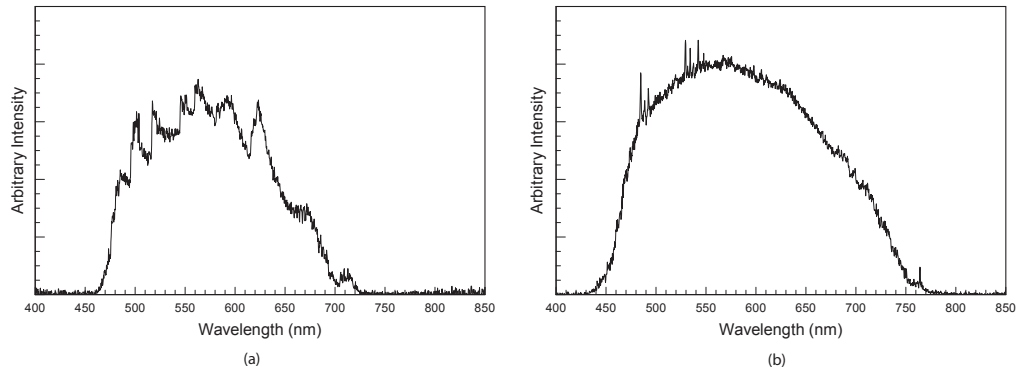

Figure 4: Spectra collected from trials performed at 4.5 bar O_2 with a projectile velocity of 1400 m/s: (a) luminous wake spectrum (b) projectile spectrum

stoichiometric titanium-oxygen constant pressure combustion reaction. The CEA code performed the equilibrium calculation, taking all possible products into account, and the adiabatic flame temperature for the range of post-shock pressures calculated above was extracted. Both the post-shock and adiabatic flame temperatures were then plotted as a function of the Mach number of the flow and compared to the melting and boiling temperatures of titanium, as shown in figure 5. To account for the pressure dependence of the boiling point, a correlation for the vapor pressure of liquid titanium developed by Paradis et al. was used and extrapolated to the range of post-shock pressures present in this study [6]. As can be seen in figure 5, a minimum Mach number of 5.75 would be required for the post-shock temperature to reach the melting point of titanium. All of the experiments in which combustion was observed occurred at Mach numbers below this speed. Hence, it can be presumed that the sphere was neither melting nor vaporizing due solely to the temperature increase in the shocked gas. Rather, it is believed that the high temperatures that were observed spectroscopically, more than triple the post-shock temperatures, can be attributed to combustion effects. Indeed, the preliminary spectroscopic analysis reported above appears to agree well with the equilibrium predictions of the adiabatic flame temperature.

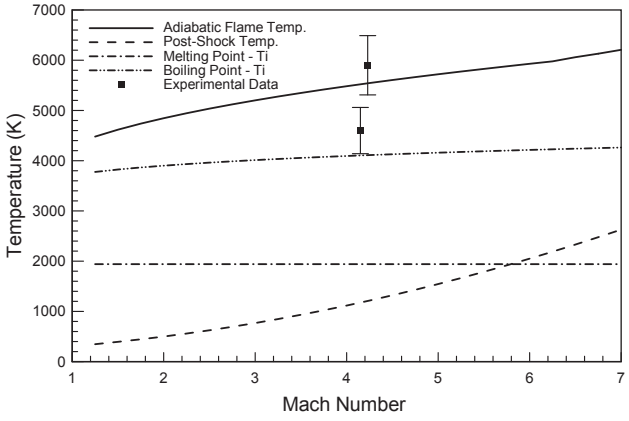

Figure 5: Comparison of adiabatic flame temperature with post-shock, melting point, and boiling point temperatures of titanium

5 Conclusion

The ignition envelope for supersonic titanium spheres in a pure oxygen environment was determined using a single-stage light-gas gun facility. The spheres, roughened with 100C grit aluminum oxide coated sandpaper, were launched at velocities of 0.8 to 1.7 km/s into a windowed reservoir pressurized to 1 to 5.5 bar of pure oxygen. The flight of the sphere was recorded by a high speed camera and light intensity data was collected using a combination of photodetectors and a spectrometer. Preliminary spectroscopy has resulted in experimental temperatures on the order of the adiabatic flame temperature for a stoichiometric titanium-oxygen reaction (upwards of 5000 K at elevated pressures) which lead the authors to believe the observed phenomenon could be attributed to combustion effects and not merely reactive ablation. Currently, there are efforts being made to collect spectra at various different projectile velocities and flow pressures in order to obtain a more complete and meaningful data set.

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