Combustion of Supersonic Metallic Spheres

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Introduction

If a supersonic projectile ignites, there is a possibility that the projectile may have lower aerodynamic drag due to this combustion. For example, the "base bleed" effect, in which a small pyrotechnic charge at the base of an artillery shell fills the wake region with gaseous combustion products, is known to increase the range of projectiles by up to 30% (Kuo, 1991). This effect is attributed to the gas which fills the low-pressure wake, creating a "virtual tail cone" and reducing the "suction" drag on the base. While a burning sphere cannot be expected to burn only in the wake region, as in the base bleed effect, there is reason to believe that burning on the entire sphere surface could still reduce drag. In experiments investigating spheres fired into combustible gas (hydrogen/air) at Mach 4.3, Ruegg and Dorsey (1962) reported a reduction in drag coefficient of approximately 50%, reducing C_D from 0.92 to 0.4 ± 0.3. While the problem of combustion and detonation initiation by supersonic projectiles has been extensively studied in the nearly 40 years since Ruegg and Dorsey, this drag reduction effect has not been definitively established. Although a projectile of combustible material traveling through an oxidizing environment is considerably different than a nonreacting projectile traveling through a combustible gas, it is possible that surface burning can contribute to drag reduction or possibly even thrust. A ram accelerator experiment conducted at the University of Washington in 1994 with an aluminum projectile fired at 1.8 km/s into pure oxygen at 25 bar resulted in a brief, intense acceleration of the projectile before the projectile was destroyed (Knowlen et al., 1996). Recently, Hohlfeld (1996) has reportedly performed experiments using magnesium-fueled projectiles at 1 km/s with external combustion and measured projectile acceleration of the order of 100 g's in an atmospheric range, although no details of these experiments have yet been published. All of these results suggest that supersonic projectiles made from a combustible metal may not only ignite in air, but may also have reduced drag or possibly even thrust.

A metal sphere, accelerated to supersonic speed, represents a simple, aerodynamically stable system for investigating the effect of combustion on the aeroballistics of a projectile. The present experiments were carried out to address the following two questions: i) under what conditions will a sphere of combustible metal ignite due to aerodynamic heating alone, and ii) once ignited, will the sphere have lower aerodynamic drag? These experiments used a light gas

gun to fire spheres 1.27 cm in diameter at velocities between 1.3 km/s and 2 km/s into air and oxygen at pressures between 1 and 10 bar. Spheres machined from aluminum, magnesium, and zirconium were used, while copper, steel, and brass spheres were used for control experiments without combustion. Ignition was determined by observing the sphere with photodiodes. The aerodynamic drag was measured by tracking the bow shock of the sphere with pressure transducers.

Theoretical Considerations

In general, the ignition conditions for a metal particle are a complex function of particle size, oxidizing environment, melting point and solubility of the metal oxide and the metal itself. A general guideline, however, is that the temperature should exceed the melting temperature of metal for ignition to occur. If the theoretical adiabatic flame temperature is greater than the boiling point of the metal, then self-sustained combustion is a likely possibility, since the vapor phase of metal is extremely reactive. This guideline does not hold for some "nonvolatile" metals, such as zirconium, which can ignite at temperature below the melting point (1852°C) and undergo heterogeneous combustion at a temperature below the boiling point of the metal (3580°C). Nonetheless, the general guideline that the temperature must exceed the melting or boiling point of the metal can provide some indication of the regimes of projectile flight in which combustion might be encountered.



Fig. 1 Comparison of shock and stagnation temperatures and the melting and boiling points of aluminum, magnesium, and zirconium.

In Fig. 1, the stagnation temperature (T_o) and the normal shock temperature (T_{shock}) are plotted as a function of Mach number, assuming perfect gas behavior (= 1.4). Also shown on the graph are the melting points and boiling points of the metals of interest (aluminum, magnesium, and zirconium). Note that shock and stagnation temperatures are nearly identical over this range. Not until the flow exceeds Mach 3 (or about 1 km/s in air) do the shock and stagnation temperatures reach the melting point of aluminum and magnesium. At shock Mach numbers greater than 7, the shock and stagnation temperatures become very large (> 3000°C), eventually exceeding the adiabatic flame temperature of metal-air combustion, which is in turn

determined by the boiling point of the oxide products. Under such conditions, exothermic metal combustion is not possible; the high temperatures prevent recombination of metal oxides and thus there is no energy release. At such high Mach numbers, the phenomenon simply becomes ablation, where the flow enthalpy will completely dominate over any possible energy addition by combustion of the particle material. Thus, there exists a relatively narrow range of Mach number (3 < M < 6) in which particle ignition and combustion could be expected to occur and have some influence on the flow field.

It is also of interest to estimate the degree of penetration of the thermal boundary layer into the sphere during a test. The one-dimensional spherical heat equation was solved, assuming the surface of the sphere was at the stagnation temperature of the flow. Thus, the supersonic flow is assumed to act as a constant temperature "bath" into which the projectile is immersed. The results of this calculation show that, for a characteristic residence time of the sphere in the test section of 1 ms, the thermal boundary layer is only about 1 mm thick, so the heating and combustion of the sphere is restricted to a thin surface layer.

Experimental Details

The experiments were conducted within the 38-mm-bore University of Washington (Seattle) ram accelerator facility. The first 18 m of the facility functioned as an extended gas gun, accelerating the projectile (supported in a sabot) up to the desired test velocity. The next 4 m were used to strip the sabot via a high molecular weight inert gas (SF₆). The final 4 m of the facility functioned as the aeroballistic test section, filled with air or oxygen at pressures between 1 bar and 10 bar. In certain experiments , an oxygen 2-m long "igniter" stage was inserted between the sabot stripper and test section. This stage (at either 1 or 5 bar initial pressure) was an attempt to see if, once ignited, the sphere would continue to burn in air under conditions in which it had been previously observed to not ignite in air. The sabot velocity was measured by EM probes that tracked a magnet embedded in the sabot. The sabot stripping and sphere trajectory through the test section were followed with pressure transducers. A "ring" of 3 pressure transducers at the same axial location also gave a measure of how well centered the sphere was. Luminosity measurements made using fiber optic probes determined the presence of combustion and gave a qualitative measure of its intensity and location relative to the sphere.

The spheres of reactive metal (aluminum, magnesium, zirconium) were CNC machined from rod stock of pure metal available from Alpha Æsar and had a smooth surface finish and good sphericity. The steel, copper, and brass spheres used for control experiments were commercially available balls.

Results

Ignition. In 23 experiments, the spheres entered the test section at an accurately measured velocity and were observed to decelerate via pressure transducers. Either intense luminosity was observed centered around the sphere at each axial location of the photodiodes, or no luminosity was observed. Thus, ignition of the sphere appeared to be a "Go" or "No Go" phenomenon, without delayed ignition or extinction of combustion once initiated in a particular gas. In some experiments in which combustion was initiated in an igniter stage of pure oxygen, however, combustion was observed to extinguish once the sphere transitioned to air. The ignition characteristics of aluminum and magnesium spheres is summarized in Fig. 2. In this plot, the solid symbols represent successful ignition and the open symbols failed ignition. Spheres that

did ignite continued to burn as they decelerated through the test section. Qualitative envelopes for the ignition conditions are shown as thick, dark lines. Both aluminum and magnesium spheres failed to ignite in air at 1 bar. If the aluminum or magnesium spheres were ignited in an "oxygen-ignition" section, the combustion was quenched once the sphere entered air. In the case of zirconium spheres at about 1.95 km/s, ignition was observed for both 1 and 5 bar oxygen, but not in air. However, when ignition was triggered with a 2-m section of oxygen at 1 bar, combustion was sustained when the sphere traveled through 1 bar air.



Fig. 2 Envelope of ignition for aluminum and magnesium spheres, along with zirconium combustion in air.

Drag Measurements. For all the experiments, the projectile velocity was measured by tracking the bow shock of the projectile via pressure transducers down the tube test section. By curve fitting an exponential to the velocity-position data, the drag coefficient of the projectile could be measured. For about half of the experiments, the diagnostics resolution was sufficient to provide two independent measurements of projectile drag, one based from transducers along the top of the tube, the other using transducers on the right side of the tube. The results are summarized in the table below.

Shot	Material	Gas	Pres.	V_0	Ignition	C_D	C_D	Error Bar	Error Bar Outside
			(bar)	(km/s)		(top)	(right)	(±)	$0.9 < C_D < 0.95$
BS06	Mg	O ₂	1	2.02	No	0.969	0.915	0.054	No
BS08	Zr	Air	1	1.93	No	0.704	0.920	0.216	No
BS10	Al	Air	1	2.01	No	0.867	1.201	0.333	No
BS12	Al	O_2	1	1.54	No	0.990	1.020	0.030	No
BS13	Al	O ₂	5	1.55	No	0.967	0.990	0.023	No
BS16	Zr	Air	1	1.93	No	1.008	0.977	0.031	No
BS21	Cu	O ₂	10	1.94	No	0.934	0.969	0.035	No
BS07	Zr	O ₂	1	1.93	Yes	0.818	0.799	0.019	Yes
BS09	Al	O_2	1	2.00	Yes	0.898	0.838	0.060	No
BS11	Mg	O2	5	1.42	Yes	0.756	0.768	0.012	Yes
BS19	Zr	Air	1	1.93/1.89	Yes	0.864	1.064	0.200	No
BS22	Zr	O ₂	10	1.90	Yes	0.898	0.923	0.025	No

The difference in the two independent drag measurements is a measure of the error in the experimental results. All the drag results fall in the range between about 0.9 and 1.0, with the exception of the two experiments shaded in the table. Although these results are suggestive of a reduction in drag, considering that the error in C_D can range as large as 0.3, they cannot be taken as definitive proof.

Discussion

All the spheres made of combustible material could be ignited in pure oxygen at 5 bar initial pressure if they entered the test section at 1.9 km/s and above. Note (from Fig. 2) that magnesium would continue to ignite in 5 bar oxygen as its velocity was lowered to 1.4 km/s, while aluminum would not ignite at 1.6 km/s in 5 bar oxygen. This difference might reflect magnesium's low boiling point, which corresponds to the stagnation temperature at 1.4 km/s. In fact, the lower velocity limits for both magnesium and aluminum ignition roughly correspond to their boiling temperatures (see Fig. 1).

The results of the drag measurements show that there is no significant reduction in drag. At hypersonic speeds (M > 2 for a blunt object like a sphere), wave drag dominates over all other forms of drag. Simple Newtonian impact theory for a hemispheric forebody predicts a drag coefficient of $C_D = 1.0$ (Anderson, 1989). The fact that the experimentally observed drag coefficient of a sphere in hypersonic flight is well established at $C_D = 0.92$ implies that the other sources of drag (viscous, base, etc.) are of minor significance. Thus, it is not too surprising that no reduction in drag was observed in these hypersonic experiments (4 < M < 6). It is interesting to note that the one experiment that appeared to show the greatest reduction in drag was also the lowest velocity experiment (0.8-1.4 km/s or Mach 2–4). Future experiments might check for a reduction in drag for burning projectiles at lower (transonic) Mach numbers. An additional interesting possibility would be to investigate the effect of combustion on the drag (thrust) of projectiles with elongated tails comprised of reactive metal, to increase the surface area available for thrust.

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