

Combustion Time and Ignition Temperature of Iron Particles in Different Oxidizing Environments

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1 Introduction

The burning time and ignition temperature of single particles are important fundamental measurements for many heterogeneous combustion models. One recent development has focused on modeling the combustion of metal dust clouds with a spatially dependent source term [1, 2]. This theory incorporates the discrete nature of localized heat sources. The relevance of this model depends on the dominance of two competing time scales, the reaction time and the heat diffusion time. The reaction time is equivalent to the combustion time of the individual particles, and the heat diffusion time is dependent on particle spacing and thermal diffusivity. In order to facilitate experimental verification of this discrete theory, accurate measurements of the combustion time and ignition temperature of individual particles are critical.

A large body of work exists for the burning times of single particles for certain metals such as aluminum [3, 4] and magnesium [5–9]; however for other metals such as iron, this property is not well documented. The limited experimental data available focuses on the combustion of iron particles in dense clouds [10]. In many cases, previous experimental techniques also have inherent limitations such as overdriving particle ignition [11–14]. The few existing empirical sources focus on a limited range of experimental parameters for particle size and oxidizing environment. Knowing the burning time and ignition temperature in the same environments in which supporting experiments are performed is critical for validating the theory being tested. In order to independently verify these parameters, a single particle burner apparatus was constructed.

2 Theory

Certain properties of iron make it an attractive metal when studying the burning times of particles. It is non-volatile, its adiabatic flame temperature (2250 K in air) is below its boiling temperature (3130 K), and there are no intermediate gaseous sub-oxides produced during the combustion process [15]. Thus, the combustion reaction occurs heterogeneously on the surface of the particle, and produces only condensed-phase oxides. This simplifies the theoretical modeling of the combustion process. It has been shown that the combustion of iron particles can be limited either by the rate of chemical

reaction kinetics, or on the rate of oxygen diffusion to the surface of the particle [16]. In the case of kinetically controlled burning, the burn time is proportional to the particle diameter,

$$t_{b,\text{kin}} = \frac{\rho_s d_0}{2i\rho m_{0\infty} k_s},$$

where ρ_s is the particle density, d_0 is the particle diameter, i is the mass stoichiometric index, $m_{0\infty}$ is the mass fraction of oxygen, and k_s is the kinetic rate constant [17].

For particles that burn in the diffusion-controlled mode, the burn time is proportional to the square of the particle diameter,

$$t_{b,\text{diff}} = \frac{\rho_s d_0^2}{8\rho D \ln(1 + im_{0\infty})},$$

where ρ and D are the density and diffusivity of the gas [17]. Determining what will limit the particle combustion rate depends on the oxidizing environment and the particle size. For the range of parameters being tested in this study, the burning rate should be predominantly diffusion-limited [15]. Figure 1 shows the expected relationship between burning time and particle diameter, for particles that burn in the diffusion-limited mode.

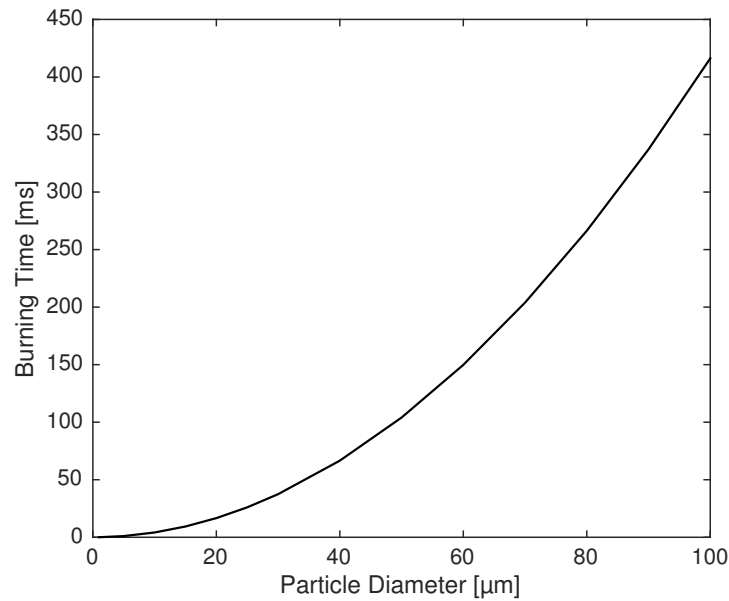


Figure 1: Theoretical burning times for iron in air at 1000 K, demonstrating the d^2 law.

3 Experimental Apparatus

The apparatus used consists of two high temperature tube furnaces connected inline with a ceramic tube running the full length of each. The gas inlet is situated at the entrance to the first furnace and creates an adjustable flow of gas through the ceramic tube. The gas inlet allows for control of the oxidizing environment. The outlet of the second furnace is connected to a transparent fused silica tube with a metal connecting sleeve. A semi-circular heater covers one half of the silica tube to maintain a high temperature. The particle dispersion system allows single particles to be injected into the sleeve connector, where the hot gas flowing at around 4 m/s pushes the particles into the silica tube where they ignite. The injection is achieved by pressurizing a fluidized bed in a vibrating plastic sphere to

force single particles through a thin tube into the connecting sleeve. K-type thermocouples measure the temperature at the particle inlet and along the silica tube. The temperature is maintained at around 1000 K throughout the silica tube.

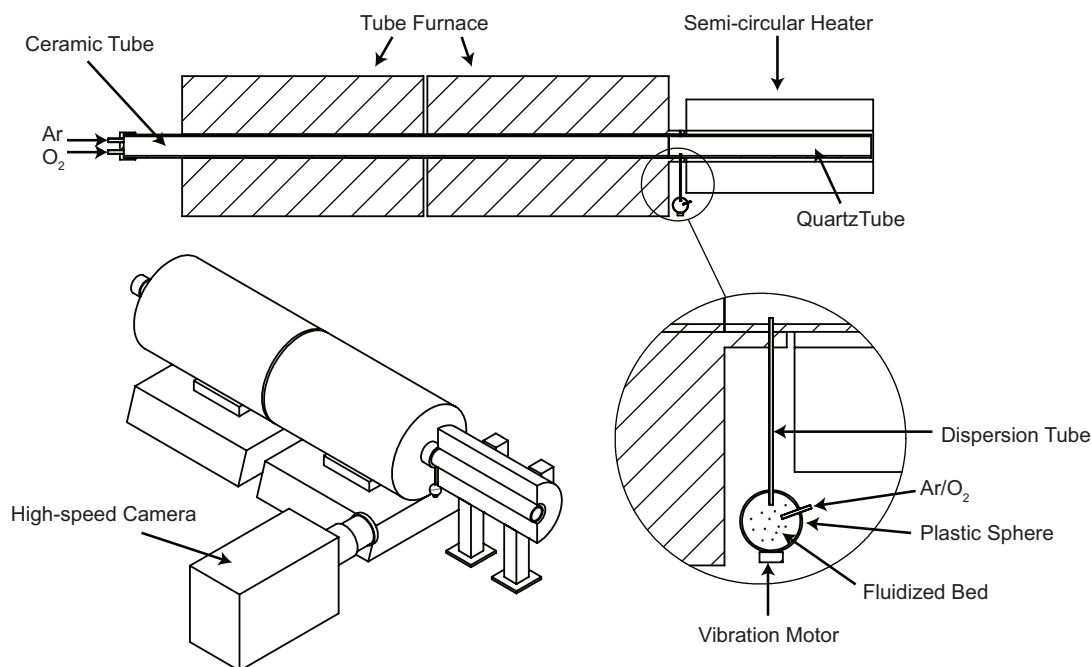


Figure 2: Top: Cross section view of single particle ignition experiment with two tube furnaces on the left and the silica tube with semi-circular heater on the right. Right: Isometric view of full apparatus and detailed view of dispersion system.

In order to measure the burning times of the particles, a high-speed camera visually captures the ignition events. A DSLR camera is also used for long exposure photographs of the single particle streaks.

The iron particles being tested are sieved through a series of standard sieves in order to obtain narrow particle size distributions. An automated particle sizing technique was developed in order to obtain the exact size distributions of these cohorts. This allows for the correlation of burning time and ignition temperature with particle size. Iron particles are placed on a microscope slide, and a series of photographs are taken with a camera mounted to the microscope. A MATLAB script automatically parses a statistically significant number of these images, and measures the diameter of each visible particle. The sizing method works best for spherical particles, and scanning electron microscopy confirms that the particles used are appropriate. Hundreds of particles are analyzed for each cohort, and fitting one term Gaussian functions to each gives adjusted R^2 values of over 98%.

4 Experimental Results

Early trials revealed that the burning of single iron particles terminates with a micro-explosion of the particle, rather than a gradual burnout. The particle breaks up into smaller pieces which quickly burnout. This is similar to the behavior of burning titanium particles [18, 19]. For titanium particles, the mechanism behind the explosion is thought to be due to dissolved gases in the particles expanding as they are heated, until they violently force the particle apart. Attempts at degassing the iron particles under high temperature vacuum conditions did not affect the behavior of the particle combustion. Figure 3 shows a trace for an iron particle burning in air.

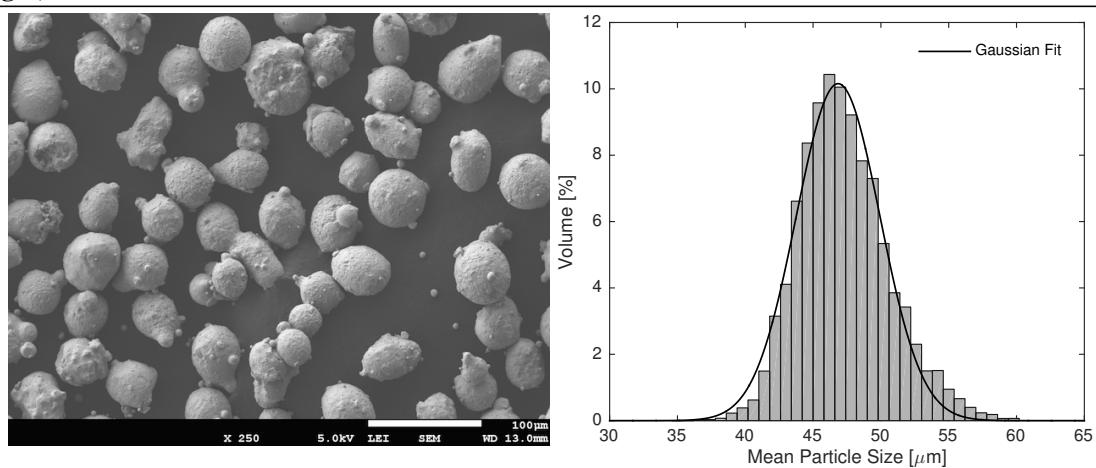


Figure 3: SEM and size distribution for 38-45 μm cohort tested



Figure 4: Long exposure photograph of iron particle exploding in oxygen/argon environment

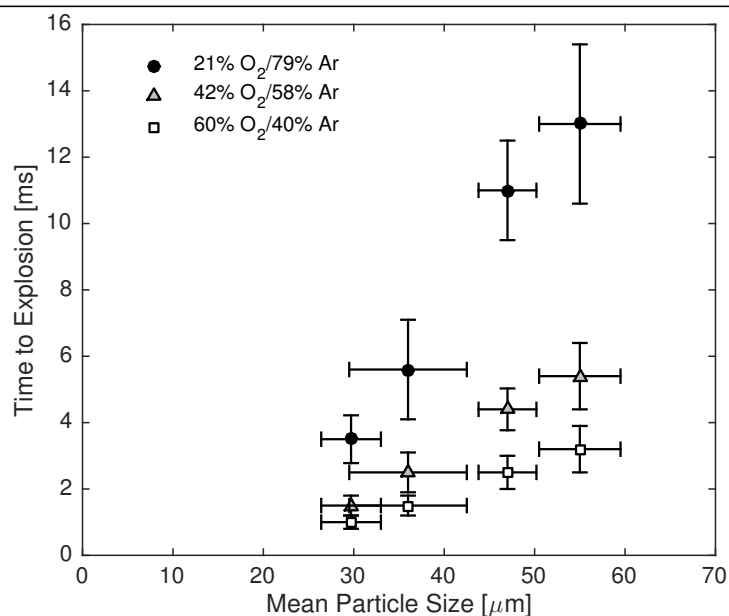


Figure 5: The error bars represent one standard deviation from the mean for both particle size and time to explosion.

As the burning of the particles terminates with an explosion rather than a gradual burnout, the influence of the d^2 law is uncertain. The times to explosion are much less than what is predicted with the d^2 law, likely because only a fraction of the iron has been consumed before the particle explodes. The results however show the qualitatively expected behavior. The time to explosion increases with increasing particle size, and decreasing oxygen concentration. The times to explosion for an average of 60 particles were tested for each size distribution, and are reported in Figure 5.

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