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Effect of flow conditions on burn rates of metal particles

Song Wang[a], Salil Mohan[b], Edward L. Dreizin[a,*]

[a] New Jersey Institute of Technology, Newark, NJ 07102, United States
[b] Naval Surface Warfare Center, Indian Head Division, Indian Head, MD 20640, United States

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ABSTRACT

Micron-sized aluminum and titanium powder particles were carried by an air flow into a focal point of a CO_2 laser beam, where they were ignited. The ignited particles continued to burn in room temperature air. The air flow pattern was varied in different experiments to produce both laminar and turbulent flow conditions. The flow pattern was described using a computational fluid dynamics model; characteristics of the turbulent flow were established and correlated with the particle combustion characteristics. Particle burn times and temperatures were measured optically. Effect of turbulent flow conditions was observed on combustion characteristics for both aluminum and titanium powders. For both powders, luminous combustion streaks became shorter. For aluminum, the brightness of the streak and the optically measured temperature were also substantially reduced in the turbulent flow conditions. For titanium, reduction in both streak brightness and temperature were minor for different flow conditions. The burn rates of aluminum were observed to increase more than 4 times in the turbulent flows compared to the burn rates measured for the same powder in laminar flow. For titanium, the burn rates in turbulent flows were approximately twice as fast as in the laminar flow. Simple empirical correlations are proposed for both metals enabling one to predict the increase in the metal particle mass burn rate for turbulent flow conditions taking into account the particle size and such flow characteristics as Kolmogorov length scale and average kinetic energy.

1. Introduction

Due to their high combustion enthalpy, metal powders are widely used as fuel additives to increase the energy density of propellants, explosives and pyrotechnics [1–4]. For all applications, particle burn times represent one of the most important characteristics of metal fuels. Respectively, multiple experiments aimed to determine such burn times are described in the literature [5–13]. Quiescent or laminar flow environments were employed in nearly all reported experiments, whereas turbulent flow conditions exist in most practical configurations involving metal particle combustion. Particle velocity relative to gas, in particular, was shown to affect its burn time substantially [14]. It is further expected that the burn times of metal particles are affected by turbulence in the flow pattern, and this effect needs to be better quantified. Recently, effect of turbulent flow conditions on combustion of aluminum [15] and magnesium [16] powders was explored experimentally. Metal powders were injected into a hydrocarbon flame; turbulent flow patterns were generated using an auxiliary swirling flow. Particle burn times in turbulent flows became markedly shorter compared to those measured for the same powders in the laminar flow. However, in addition to an altered flow pattern, the particle burn times in experiments reported in Refs. [15,16] were affected by mixing of the combustion products of the hydrocarbon flame with surrounding air. That mixing was also enhanced when turbulent flows were produced, which could have additionally accelerated metal particle burn rates. This work is aimed to separate the effect of turbulent flow pattern on the metal particle burn time from the effects that might be caused by mixing different oxidizers. Experiments are performed with metals burning predominantly at the surface (Ti) and in the vapor phase (Al). Particles are ignited in air and enter a turbulent air flow pattern. Their burn times and temperatures are determined optically.

2. Experimental

2.1. Materials

Two metal powders were used in experiments. Spherical aluminum powder was provided by Alfa Aesar, nominal particle size 17–30 µm, purity 99%. Titanium powder by Alfa Aesar was also 99% pure, and the nominal particle size was characterized as −325 Mesh (less than 44 µm). Particle size distributions for both powders were measured using a Beckman-Coulter LS320 Enhanced

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

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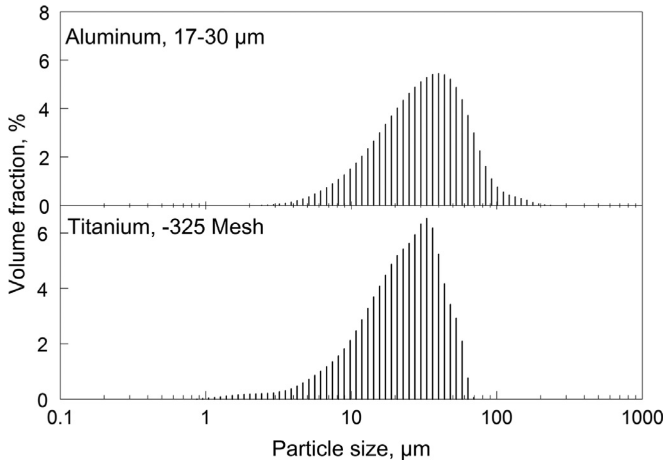

Fig. 1. Particle size distributions for aluminum and titanium powders used in experiments.

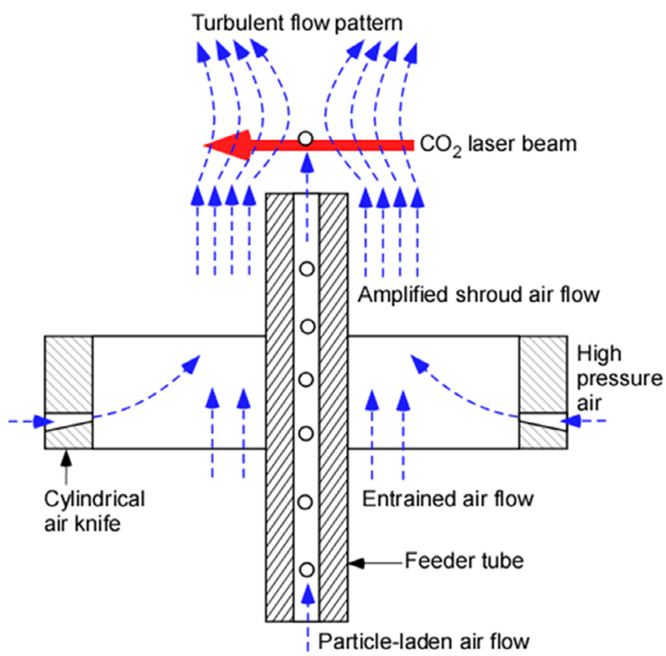

Fig. 2. Schematic diagram of the gas flow configuration in the experiments.

Particle Analyzer exploiting low-angle laser light scattering. Obtained particle size distributions are shown in Fig. 1. These size distributions were used explicitly to process the burn time measurements and obtain the effect of particle sizes on their burn times for both metals exposed to different air flow patterns.

2.2. Gas flow configuration

Metal powders were fed by a laminar airflow into a CO_2 laser beam as illustrated in Fig. 2. Using the laminar flow initially enabled us to ignite particles reproducibly, which would be difficult to achieve in a turbulent flow. In each experiment, powder was loaded into a custom-made screw-feeder described in detail elsewhere [16–18]. The particle feed rates were approximately 2.3 and 1.5 mg/min for aluminum and titanium, respectively. Considering their volume-based average particle sizes, these feed rates respectively translate to approximately 415 and 300 particles per second for aluminum and titanium. The number of particles crossing the focal area of the laser beam was substantially smaller, however, because the diameter of the powder-laden air jet was much greater than the size of the laser focal spot (see dimensions below). The velocity of the powder-laden air flow exiting the tube was 3.3 m/s. This velocity was obtained by particle image velocimetry, with the jet illuminated by a pulsed laser sheet produced by a 70 mW, 785 nm laser diode. Spherical aluminum powder used in combustion experiments also served as a tracer material for these measurements. Particles were carried by the gas through a 10-cm long, 2.4-mm internal diameter tube, where the gas velocity was constant. Therefore, the slip between the particle and gas velocities was expected to be minimized at the exit from the nozzle.

Table 1
Flow settings used in different experiments. Flow rate for the powder-laden flow is 1.1×10^{-5} m^3/s.

Flow condition		Compressed air flow rate for air knife, $\times 10^{-4}$ m^3/s	Used for powders
Laminar		0	Al,Ti
Turbulent	1	1.18	Al
	2	2.36	Al,Ti
	3	3.93	Ti

The powder exited from a brass tube with internal diameter of 1.1 mm and wall thickness of 0.2 mm and crossed the laser beam about 2 mm above the tube's end. A Synrad Evolution 125 sealed laser was used; the beam was focused to about 250 μm diameter using a ZnSe lens. The laser power was set at 70% of its maximum power (125 W) in order to reliably ignite metal particles crossing the beam.

Ignited particles continued to move vertically up and were entrained into a turbulent air flow produced by mixing the powder-laden air jet with a much faster shroud air flow. The shroud air flow was generated using a cylindrical air knife placed around the tube feeding the powder, as shown in Fig. 2. A compressed air was fed into the air knife; additional room air was entrained into the flow, amplifying the produced shroud air flowrate. Within a few millimeters above the tube's end (or the nozzle), the wall of the feeder tube shielded the powder-laden air jet from the shroud flow. The laser beam crossed the powder-laden jet within that shielded volume, so that particles ignited by the laser while still moving in a laminar air flow. After ignition, they were entrained into a turbulent flow nearly instantaneously.

Experiments were performed at four different flow settings listed in Table 1. One setting generated a laminar flow pattern. Different levels of turbulence were achieved with three additional flow settings. Each flow condition is described below using respective numerical model.

2.3. Optical diagnostics

Particle emission signals were recorded using an array of three filtered photomultiplier tubes (PMTs). Particle emission was split to the PMTs using a three-furcated fiber optics cable. Two Hamamatsu R3896-03 PMTs were equipped with 700 and 800-nm interference filters, and the third, Hamamatsu R636-10 PMT was equipped with a 900-nm interference filter. Signals recorded by the 700 nm-filtered PMT were the strongest and these signals were processed to obtain the particle burn times. The pulse duration measured while the signal exceeded the noise level measured in the baseline signal was treated as the burn time. The signals from PMTs were fed at a rate of 100,000 samples per second to a 16-bit PCI-6123 data acquisition board by National Instruments. Signals were saved and processed using LabVIEW software. Characteristic sequences of pulses produced by ignited particles are shown in Fig. 3 for both aluminum and titanium powders. Time zero represents the beginning of a data acquisition run; multiple runs were saved for each experimental configuration. Particle emission pulses