Particle combustion rates in premixed flames of polydisperse metal—air aerosols

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Abstract

A new approach and experimental technique are proposed to determine times of metal particle combustion in flames of polydisperse aerosols. Laminar flames are produced in air at 1 atm, using aerosol jets formed by an electrostatic particulate method. The flame radiation intensities as a function of vertical coordinate are measured and compared with the flame radiation profiles reconstructed using experimental data and simplified models. The experimental data used include particle size distributions, flame velocities, and temperatures of metal ignition and combustion. The simplified models describe the particle ignition delay, combustion time, and particle flame radiation intensity as a function of particle diameter, \(D\). Variable parameters of the models describing particle radiation intensities and combustion times are adjusted to achieve the best fit between the reconstructed and measured flame radiation profiles. A set of parameters providing the best agreement between the reconstructed and measured profiles is selected for several aerosol flames produced by powders of different sizes of the same material. These parameters are assumed to adequately describe particle combustion times and radiation intensities for the chosen material. The experimental radiation profiles for both aluminum and magnesium aerosol flames with particles of different sizes were found to be in very good agreement with the respective reconstructed profiles. For both metals, particle radiation intensities were well described by a \(D^3\)-type expression. The combustion times for magnesium aerosol particles were well described by the traditional \(D^2\)-law with the evaporation constant close to those reported earlier for single particles. Aluminum aerosol particle combustion was better described by a \(D^1\)-law and combustion times of fine (\(<80 \mu m\)) aluminum particles in the aerosol were somewhat longer than the reported earlier combustion times for single aluminum particles. © 2003 The Combustion Institute. All rights reserved.

Keywords: Aluminum combustion; Magnesium combustion; Lifted flame burner; Laminar aerosol flame

Introduction

Metals, such as Al and Mg are widely used as energetic fuel additives in rocket propellants, explosives, pyrotechnics, and incendiaries. Thus, models describing combustion of metals are necessary to design new and control existing propulsion devices and weapon systems. One of the most important characteristics that needs to be predicted by metal combustion models is the burning time of an individual metal particle. Most of the measurements reported in the literature were made for relatively large (>50 \(\mu m\) diameter) single particles, e.g., [1–5]. For practical applications, it is more important to know burning times of finer particles burning in an aerosol cloud. Several estimates were reported for the average combustion time of metal aerosol particles in laminar, relatively large-scale, aerosol flames [1,6,7].
Those estimates used the measured average particle size, flame velocity, and visible flame front thickness. However, because of difficulties in evaluating the flame front thickness and because metal powders usually have wide particle size distribution, that type of estimate could be very inaccurate. In this work, a new approach is proposed to determine times of metal particle combustion in laminar aerosol flames. Small-scale, optically thin laminar metal aerosol flames are produced using a novel aerosol burner [8,9]. The flame images are video-recorded and radiation intensities as a function of vertical coordinate, or radiation profiles of the flames, are measured. These radiation profiles also are theoretically reconstructed using experimental data and simplified single-particle ignition and combustion models. The experimental data used to reconstruct the profiles include particle-size distributions, flame velocities, and temperatures of metal ignition and combustion. The simplified models describe the particle ignition delay, combustion time, and particle flame radiation intensity as functions of particle size. The measured and reconstructed flame radiation intensity profiles are compared to each other. Variable parameters of the models describing particle radiation intensities and combustion times are adjusted to achieve the best fit between the reconstructed and measured profiles. Finally, for aerosol flames produced by the same material but different size powders, a set of parameters providing the best agreement between the reconstructed and measured profiles is selected to describe the particle combustion time and radiation intensity for that material. The paper describes the experimental setup, measurements, and procedure used for reconstruction of the aerosol flame radiation profiles. The description of experiments is focused on the identification of the parameters used for the measurements and reconstruction of the flame radiation profiles. The results are reported for the flames produced by aluminum and magnesium powders burning in air.

**Experimental**

**Production of laminar lifted aerosol flames**

An aerosol burner described in detail elsewhere [8,9] is used to produce flames of Al and Mg powders in air. For completeness of this manuscript, a schematic diagram of the burner is shown in Fig. 1. An electrostatic particulate method [10] is used to produce an aerosol of metal powders. The aerosol is formed between two horizontal electrodes of a high-voltage, parallel plate capacitor. A batch of metal powder is placed on the bottom electrode, and when the voltage is applied, particles acquire an electric charge and repel from the similarly charged bottom electrode surface. The charged particles are attracted to the oppositely charged top electrode and thus move upward. Once they collide with the top electrode, they recharge with the opposite sign and move in the opposite direction (downward) until they reach the bottom electrode. This process repeats itself, and particles continue the round-trip motion producing an aerosol within the capacitor. The edges of the bottom electrode are slightly elevated to make it a convenient reservoir for the powder loading. In addition, the concave shape of the bottom electrode helps to create an electric field component directed toward the capacitor center to prevent the particles from escaping from the interelectrode space. As described elsewhere [8,9], a distributed charge is produced within the capacitor and results in the maximum limit, \( M_{\text{max}} \), on the powder mass that can be aerosolized at the selected DC voltage and distance between electrodes. Thus, when the mass of the powder batch initially loaded into the capacitor exceeds \( M_{\text{max}} \), only a fraction of the loaded powder becomes aerosolized. Therefore, even if an aerosol jet exits from the capacitor, an aerosol with the nearly steady number density can be produced between the electrodes for as long as the powder load on the bottom electrode exceeds \( M_{\text{max}} \).

To produce an aerosol jet, the entire capacitor is placed in a sealed chamber and the top electrode serves as the chamber’s top flange. A gas (air was used in this work) is introduced into the chamber via a feedthrough and exits through a small nozzle made in the center of the top electrode. Thus, a laminar, constant-number density, aerosol jet is produced above the chamber and can be maintained until the mass of the powder on the bottom electrode is greater than \( M_{\text{max}} \). A vertical transparent duct made of polycarbonate sheet is placed on top of the chamber to protect the aerosol jet from minor air drafts. To avoid effects of natural convection and gas recirculation within the enclosure, an additional, slow shroud airflow is formed around the central aerosol jet that provides consistent environment ensured by forced convection. The jet is ignited by a small torch with natural gas-oxygen diffusion flame. The torch is immediately removed upon ignition so that a self-sustained, lifted, laminar aerosol flame is produced. The mechanism of stabilization of the aerosol flame is similar to that of a gaseous lifted flame. The velocity of the central aerosol jet is much higher than the velocity of the shroud flow. Therefore, the aerosol jet is decelerated by the shroud flow, so that the flame stabilizes at a height where the flame propagation velocity equals to the velocity of the aerosol jet. The nozzle used in these experiments had a diameter of...
0.8 mm, and because of the gas jet expansion, the diameter of the produced flame was around 1.5 mm. The flames were stabilized at the heights of 5–25 mm above the nozzle. The total mass of the metal powder loaded in the capacitor was in the range of 0.5–1.5 g and stable flames were produced for periods of 3–5 minutes.

The metal powders used in these experiments were spherical aluminum: 10–14 μm nominal sizes, 98% pure, and 17–30 μm nominal sizes, 99% pure; and magnesium: −325 Mesh size (less than 44 μm); 99.8% pure, all by Alfa Aesar. For some experiments, powders were additionally size-classified using a 400 Mesh sieve (38 μm opening size). Aerosol flames were produced using “as received” −325 Mesh Mg and 10–14 μm Al powders and narrow size fractions: Al and Mg −400 Mesh (less than 38 μm), and Mg −325 + 400 Mesh (between 38 and 44 μm). Note that the size ranges listed for “as received” Al powders are given by the supplier as “nominal sizes” and do not reflect the actual particle size distributions. For example, about 30 mass percentage of the “17–30 μm” Al powder remained on the 400 Mesh sieve after its sifting during 5 hours.

Flame radiation profiles

A 3-CCD digital video camera Panasonic AG-EZ30P was used to record the flame images. The video camera was equipped with two close-up lenses with a common focal length of 10 cm and with a 8X gray filter. Time-averaged images were made at the exposure time of 1/60 s and typical flame images for aluminum and magnesium aerosols are shown in Fig. 2. The flame radiation intensity profiles were obtained using image processing software “Tracker” version 3 developed by NASA researchers [11]. The profiles corresponding to the red, green, and blue components of the video signal as well as to the integral radiation intensity were obtained. Figure 3 shows respective flame radiation profiles determined for the Mg flame shown in Fig. 2.

As shown in Fig. 3, profiles obtained for different spectral ranges coincide almost exactly (after normalization by the maximum intensity level). A similar observation was made for aluminum aerosol flames, and several important conclusions could be made based on these observations. One practical conclusion is that for both Al and Mg aerosol flames, the flame temperature did not change significantly within

![Fig. 1. Schematic diagram of laminar lifted flame aerosol burner](image-url)
the visible flame zone. Thus, it was not important which radiation profile was used for the analysis. In this work, red radiation profiles were selected and analyzed as described below. Another conclusion is that the scattering of the radiation produced by the flame zone is insignificant within the flame itself. Indeed, the ultrafine oxide particles, which mainly cause radiation scattering, have sizes much less than the visible light wavelength, and their scattering cross-section is a strong function of the light wavelength. Typical sizes of ultrafine oxide particles formed during Al or Mg combustion in air at 1 atm are \( \sim 0.1 \mu m \). The scattering intensity for the dielectric particles of this size is approximately proportional to the fourth power of the radiation wavelength, even though these particles are too large to scatter visible light in the strict accordance with the Rayleigh formula [12]. For the light wavelengths of 0.47 \( \mu m \) and 0.65 \( \mu m \), which roughly correspond to the middles of the blue and red spectral ranges, respectively, the scattering intensities should differ by about a factor of four. Therefore, noticeable scattering would have caused very significant distortions, different for different color flame radiation profiles. No such distortions were observed indicating that the flame’s scattering of its own radiation is negligible.

To address the effect of possible temporal flame size and shape fluctuations on the measured radiation profiles, several images were analyzed for each flame. The overall profile shapes were repeatable, and for more detailed comparisons, the peak half-width, \( \Delta h \), (i.e., the difference in the flame height between the levels where radiation is at a half of its maximum intensity) was measured for each profile. It was found that for each flame, \( \Delta h \) was changing within about 10\% of its average value. For each flame with a specific material and particle size distribution, a profile with the peak half-width most close to the average value for that flame was then selected for the following analyses. It should be noted that for one case, a flame produced by the coarse fraction of Mg (Mg-325 + 400), the shapes of the radiation intensity profiles fluctuated significantly for different images. For this flame, the experimental radiation profile for further analyses was generated as an average of five consecutive images.

**Burning particle velocities**

The velocities of burning metal particles in the flame were determined using video images taken at short exposure times (1/1000 and 1/2000 s) in which individual particle streaks in the flame region could be identified (see Fig. 4a). The same exposures but with wide-open lens aperture settings were used to film the streaks of particles illuminated by flame radiation in the preheat zone under the flame, cf. Fig. 4b. These images were used to determine the particle
velocities in the preheat zone. In addition, a 0.5-mW, 635-nm laser diode was used to produce a thin, vertical laser sheet projected on the aerosol jet without the flame. A typical example of the image of an aerosol jet illuminated by the laser sheet (without the flame) is shown in Fig. 4c. It was observed that particle velocities under the flame, in the preheat zone, coincided (within the experimental scatter of ±5%) with the particle velocities measured for the cold aerosol jet at the same locations. Only relatively weak particle acceleration was observed within the flame, e.g., the particle velocities at the top region of the flame were about 10% higher than those measured at the bottom of the flame. Therefore, the flame velocities used to reconstruct the flame radiation profiles below were assumed to be equal (with the opposite sign) to the average values between the measured particle velocities in the preheat zone and in the flame. The aerosol flame velocities obtained for different fractions of Mg and Al powders are shown in Table 1.

**Flame temperature**

A three-color pyrometer coupled with a data acquisition system [13,14] was used to measure flame radiation temperature. The pyrometer included three photomultipliers, three interference filters, and a trifurcated optical fiber bundle. The interference filters used were for 500-, 568-, and 610-nm light wavelengths, and were selected to minimize the emissions of the Al, Mg, AlO, and MgO bands on the temperature measurement. The pyrometer was calibrated using a NIST-certified strip lamp. Measured flame temperatures were found to be repeatable for the flames of different size aerosols of the same materials and were 3000 ± 200 K for Mg aerosol flames and 2800 ± 200 K for Al aerosol flames.

**Particle size distribution**

The particle size distributions for the Al and Mg powders used in the combustion experiments were measured using an LS230 Beckman-Coulter Particle Counter. This instrument uses low angle laser light scattering (LALLS) technique. Preliminary calculations used the measured Mg particles size distributions and produced flame radiation profiles, which were much longer than the experimental ones. In addition, it was observed that based on the estimated rate of heat transfer, a large fraction of the powder (larger particle sizes) would not even ignite during the time the aerosol jet was estimated to pass through the entire flame zone. Analyses of those preliminary estimates showed that the particle size distributions determined by the LALLS technique included very

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**Table 1**

Experimental aerosol flame velocities for different powders

<table>
<thead>
<tr>
<th>Powder</th>
<th>Mg</th>
<th>Mg</th>
<th>Mg</th>
<th>Al</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−400 Mesh</td>
<td>−325 Mesh</td>
<td>−325 + 400 Mesh</td>
<td>10–14 μm</td>
<td>−400 Mesh</td>
</tr>
<tr>
<td>Flame velocity, m/s</td>
<td>1.00</td>
<td>0.75</td>
<td>0.43</td>
<td>0.36</td>
<td>0.30</td>
</tr>
</tbody>
</table>

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Fig. 4. Examples of short exposure images of the aerosol particles streaks used to determine the particle velocities:

a. Burning magnesium particle streaks within the flame. Arrows show the streak lengths that could be determined from the image.
b. Aluminum aerosol particle streaks under the flame illuminated by the flame radiation.
c. Streaks of magnesium particles in a cold aerosol jet illuminated by a laser sheet.
large particle sizes that were not observed on the scanning electron microscope (SEM) images of the same powders. Therefore, it was identified that a systematic error was being made in the LALLS-produced size distributions and it was suggested that the error was caused by nonspherical shapes of the powders. The LALLS technique is based on the Fraunhofer diffraction theory [12] and is developed for spherical particles. When non-spherical particles are being analyzed and each particle can be characterized by the minimum and maximum dimensions, \( D_{\text{min}} \) and \( D_{\text{max}} \), respectively, the LALLS measured particle size distribution varies from the minimum dimension of the smallest particle, \( D'_{\text{min}} \), to the maximum dimension of the largest particle, \( D'_{\text{max}} \). For powders for which \( D_{\text{max}} \) and \( D_{\text{min}} \) are relatively close, e.g., \( D_{\text{max}} - D_{\text{min}} / D_{\text{max}} + D_{\text{min}} < 1/3 \), this error may be insignificant for many applications of the LALLS technique. However, the error becomes important for the analyses of the particle combustion time. Indeed, a 20% error in the particle size results in more than 70% error in the particle volume and mass, that is important for estimating the time of chemical reaction consuming the entire particle.

Particle imaging could be more informative in defining the adequate particle size distribution for nonspherical powders; however, the routine use of image analysis to determine size distribution is undesirable because the process is lengthy and cumbersome. Therefore, a procedure for correction of LALLS data is developed that can use only a small number of particle images. A mathematically accurate correction procedure for irregularly shaped particles would be quite complicated; therefore a simplified correction method is suggested and described below.

The method uses so-called Feret diameter, \( D_F \), found by the image-processing software, “UTHSCSA ImageTool,” from the particle images and defined as the diameter of a circle with the same area as the image of a non-spherical particle. It is assumed that Feret diameter is equal (or very close) to the size of interest for combustion time estimates, i.e., the diameter of a spherical particle with the volume equal to that of a nonspherical particle. Thus, the goal of the correction procedure is to make a transform that would compress the LALLS-determined particle size range, \( (D'_{\text{min}} - D'_{\text{max}}) \), to the range of Feret diameters found from the image analysis, i.e., \( (D_F_{\text{min}} - D_F_{\text{max}}) \).

The approach is to find the shape factors, \( S_{\text{min}} \) and \( S_{\text{max}} \) that would connect the values of \( D_F_{\text{min}} \) with \( D'_{\text{min}} \) and \( D_F_{\text{max}} \) with \( D'_{\text{max}} \), respectively, and then use a shape factor \( S(D) \) continuously adjusted for different particle sizes between \( S_{\text{max}} \) and \( S_{\text{min}} \) to correct all the LALLS particle diameters changing from \( D'_{\text{min}} \) to \( D'_{\text{max}} \).

To establish the procedure, more than 1000 particle images per powder sample were analyzed for several powders, and particle size distributions using Feret diameters were found. Powders were imaged using an optical microscope, and the UTHSCSA ImageTool software determined \( D_F \) as well as the maximum and minimum particle dimensions (or lengths of major and minor axes, respectively), \( D_{\text{max}} \) and \( D_{\text{min}} \), for each particle. The particle size distributions for the Feret diameters were compared with the LALLS size distribution as illustrated in Fig. 5a and 5b, respectively. To determine the shape factors needed for correction, the maximum and minimum particle sizes for each particle were plotted against the Feret diameter, as shown in an example in Fig. 6. The correlations of \( D_{\text{max}}(D_F) \) and \( D_{\text{max}}(D_F) \) were interpolated by straight lines: \( D_F = S_{\text{max}} \cdot D_F \), where the shape factors \( S_{\text{max}} \) and \( S_{\text{min}} \) are different for different powders. With the found shape factors, the limits of the LALLS size distribution should be adjusted from \( D_{\text{min}} \) to \( D_{\text{max}} \) to \( D_{\text{min}} / S_{\text{min}} \) and \( D_{\text{max}} / S_{\text{max}} \), respectively. The simplest linear transform that corrects the LALLS data accordingly is:

\[
D_{\text{corrected}} = \frac{D_{\text{LALLS}} - D'_{\text{min}}}{D'_{\text{max}} - D'_{\text{min}}} \left( \frac{D'_{\text{max}} - D'_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \right) + \frac{D'_{\text{min}}}{S_{\text{min}}}
\]

(1)

where \( D_{\text{LALLS}} \) is the particle size measured by LALLS method and \( D'_{\text{min}} \) and \( D'_{\text{max}} \) are, respectively, the minimum and maximum particle sizes of the LALLS-produced size distribution. For example, the LALLS size distribution shown in Fig. 5b was corrected as shown in Fig. 5c. It is observed that for the corrected size distribution, the range of diameters becomes closer to the range of Feret diameters de-
determined from the image processing. As mentioned above, large numbers of particles were imaged to establish this procedure; however, in order to use it in practice, only $S_{\text{min}}$ and $S_{\text{max}}$ need to be found, and there is no need to determine the entire particle size distribution using Feret diameters. Thus, for all the powders used in this work, only one image with 30–50 particles was needed to determine $S_{\text{min}}$ and $S_{\text{max}}$ with sufficient accuracy. The corrected LALLS size distributions were determined for each powder using Eq. (1) and employed to reconstruct the flame radiation profiles as described below.

The simplified models used in the computations are described below.

**Ignition delay**

It was assumed that each particle ignited when it was heated up to an ignition temperature, $T_i$, specified for each material. The ignition temperatures for Mg and Al were taken from the published experimental results for single particles. Specific temperatures of $T_i = 1000$ K for magnesium [15] and $T_i = 2300$ K for aluminum [16] were used in the calculations.

The ignition delay was computed as a time required to heat a particle from room temperature, $T_0$, to the ignition temperature, $T_i$. The particle was considered to follow the gas in the preheat zone in which the gas temperature was assumed to change linearly from $T_0$ to the experimental flame temperature $T_f$. The distance over which the temperature changed was found according to a well-known estimate for the laminar flame preheat zone, $\delta_i$ [17] as $\delta_i \approx a/v_f$, where $a$ is the average thermal diffusivity of the gas and $v_f$ is the velocity of the flame propagation (determined from the experimental particle velocities). Therefore, the gas temperature profile was defined as:

$$\text{Reconstruction of the aerosol flame radiation profile}

**General profile description**

The flame profile was assumed to be formed as a sum of the radiation intensities produced by the streaks of all the burning particles. Several simplifying assumptions were made:

1. Each particle emits a constant intensity radiation during its combustion and does not radiate before ignition and after extinction.
2. The length of the radiation streak produced by each particle is defined by the particle combustion time and particle velocity. Particle combustion time is defined from the simplified combustion model (see below). Particle velocity is the same for all particles and equal to the experimentally found average particle velocity in the flame.
3. Ignition occurred at a constant temperature specified for each material. The ignition delay is computed using a simplified model described below.
4. Radiation interaction with the flame and combustion products is neglected.
5. The particle radiation intensity and burning time are functions of the particle initial diameter, as specified by the radiation and combustion models below.

Obviously, the above assumptions are extremely crude and cannot be used to describe the aerosol combustion mechanism. However, the objectives of this work were to determine whether a reasonable agreement between a simplified model and experiment can be obtained, and if so, what are the parameters of the simplified models that describe the particle radiation and burning time as a function of the initial particle diameter. Clearly, the answers to these questions would only indicate the starting point for the in-depth research on the mechanisms of aerosol combustion. At the same time, these results could produce valuable simple estimates for the aerosol combustion parameters that could be used as building blocks of larger scale engineering codes.

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\[ T_g = T_0 + \frac{v_f^2}{a} \cdot (T_f - T_0) \cdot t \]  

(2)

Considering the convective heat transfer from the gas to the particle and treating the particle as a sphere with diameter, \( D \), equal to the measured particle size, the rate of the particle heating was described as:

\[ \frac{c_p \rho D^2}{6 Nu \cdot \lambda} \frac{dT_p}{dt} = T_g - T_p \]  

(3)

where \( c_p, \rho \), and \( T_p \) are the specific heat, density, and temperature of the particle, respectively; \( Nu \) is the Nusselt number assumed to be equal to 2, and \( \lambda \) is the gas thermal conductivity. Introducing a particle characteristic thermal relaxation time

\[ t_p = \frac{(c_p \rho \rho D^2)}{(6 Nu \cdot \lambda)} \]

and substituting the gas temperature from Eq. (2) into Eq. (3), we obtain a differential equation for the particle temperature \( T_p \) as a function of time \( t \):

\[ t_p \cdot \frac{dT_p}{dt} = T_0 + \frac{v_f^2}{a} \cdot (T_f - T_0) \cdot t - T_p \]  

(4)

The solution for Eq. (4) is:

\[ T_p = T_0 + (T_f - T_0) \cdot \frac{t_p a}{v_f^2} \cdot \left( e^{-\frac{a t_p}{v_f^2}} + \frac{t}{t_p} - 1 \right) \]  

(5)

This equation was used to determine the ignition time, \( t_i \), when the particles of different sizes reached the ignition temperature, \( T_r \). Tabulated values of the air thermal diffusivities and thermal conductivities (e.g., see ref. [18]) were used at the average preheat zone gas temperature \( (T_f - T_0)/2 \). Because the particles were assumed to move with the gas with a constant velocity (equal to \( -v_f \)), the ignition delay time, \( t_i \), determined the location where the particles ignited, \( h_i = v_f \cdot t_i \).

**Combustion time**

A dependence of the burning time, \( t_b \), of the single particle on its initial size, \( D \), is often described by a power law (e.g., refs. [19–21])

\[ t_b = K_i \cdot D^{n_1} \]  

(6)

For the diffusion-controlled combustion typical for larger particles, theoretical models predict the value of the exponent \( n_1 \approx 2 \). The diffusion rate becomes relatively high for smaller particles, and it is usually expected that the kinetic rate of reaction on the particle surface starts to control the combustion time for very fine particles. For the case of the kinetic control of the combustion rate, the theoretical value of the exponent \( n_1 = 1 \). Clearly, most of the practically interesting cases fall in the range of conditions when \( 1 < n_1 < 2 \). The modeling becomes more difficult for aerosol combustion, and the derivation of a theoretical expression for \( t_b(D) \) is not straightforward. In this work, we used Eq. (6) to determine the particle combustion time with the exponent being the adjustable parameter. To simplify the process of adjusting the value of \( n_1 \), the selection was made from only three fixed values, 1, 1.5, and 2. The parameter, \( K_i \), was also adjusted for each \( n_1 \) to obtain the best match with the experimental data.

**Radiation intensity**

The intensities of radiation, \( I \), produced by each burning particle should be evaluated and added together in order to reconstruct the flame radiation profile. Because a detailed mechanism of metal particle combustion describing the condensation and coagulation processes is not available, an approach for estimation of the flame radiation is not generally established. Different processes in the flame zone could result in different dependencies of the overall flame radiation intensity on the particle size. For example, in earlier theoretical models of Mg combustion [22], the oxide particles condensing within the flame were assumed to be the main radiators. An optically thick flame was considered with the radiation intensity defined by its overall surface area. Assuming the flame size to be proportional to the particle size, \( D \), it could be suggested that:

\[ I = K_{rad} \cdot D^2 \]  

(7)

For the optically thin flames, the radiation is expected to be affected by the ultrafine oxide particles that can be accumulated within the flame zone. If the oxide accumulation occurs but the flame remains optically thin (e.g., for relatively large flames), the average radiation power of the burning particles would be proportional to the total volume of the ultrafine oxide formed. Because the total volume of the generated oxide is proportional to the initial particle mass, or cube of the initial particle size, one could expect that

\[ I = K_{rad} \cdot D^3 \]  

(8)

In addition, recent experiments [5], showed that for large (1–3 mm) Mg particles burning in air, the total radiation power of the particle flame was proportional to the initial particle size, e.g.,

\[ I = K_{rad} \cdot D \]  

(9)

Thus, it appeared that it was impossible to determine an a priori dependence for the radiation inten-
sity as a function of the particle size. Therefore, it was suggested to use a generic expression of
\[ I = K_2 \cdot D^{n_2} \]  
(10)
where the exponent \( n_2 \) was varied from 1 to 3 to determine the best match with the experimental data and determine which trend better describes the radiation of the aerosol flame. For simplicity, only the integer numbers of 1, 2, and 3 were considered.

### Profile computation algorithm

The reconstruction of the radiation profile (radiation intensity as a function of vertical coordinate, or height) was conducted using the experimental data, the simplified models described above, and the following algorithm:

1. The particle combustion model defining the burning time as a function of particle diameter, \( t_b(D) = K_1 \cdot D^{n_1} \), the radiation model defining the radiation intensity as a function of particle diameter, \( I(D) = K_2 \cdot D^{n_2} \), and the ignition temperature, \( T_i \), are selected.

2. Experimental (corrected and normalized LALLS) particle size distribution is entered as reference table with the fixed number of bin sizes containing different numbers of particles, \( N_j(D_j) \).

3. For each bin size \( D_i \):
   - the height of ignition \( h_i^{\text{ign}} \) is determined using the ignition model
   - the height of extinction \( h_i^{\text{ext}} \) is determined using the combustion model

4. The range of vertical coordinates considered is digitized (nodal points are selected with a constant interval) and for each height nodal point \( h_j \):
   - the sizes \( D_k \) of the particles burning at that height are found
   - the radiation intensities \( I(h_j) = \sum I(D_i)N_k \) are found

As a result of these computations, a step-like radiation intensity profile was produced and its shape was smoothed. The smoothing procedure used random variations of the computed ignition and extinction heights for each particle bin size in the range limited by the ignition and extinction heights for the adjacent bin sizes. Finally, to reduce the “digital noise” effect, each calculation was repeated 250 times and an average profile was found. Calculated profiles were normalized by the peak radiation intensity and compared versus the similarly normalized experimental radiation profiles. The adjustable parameters in the particle radiation and combustion models were selected as described below to achieve the best match between the calculated and experimental profiles.

### Selection of adjustable parameters

Initially, a radiation profile was reconstructed for an aerosol flame of one size fraction of one material (Al or Mg) and the adjustable parameters were found that provided the best fit with the measured profiles. Calculations were conducted for all the combinations of the exponents of \( n_1 \) and \( n_2 \) (\( n_1 = 1, 1.5, \) and \( 2; n_2 = 1, 2, \) and \( 3 \)). When the exponents \( n_1 \) and \( n_2 \) were fixed, the pre-exponent \( K_2 \) in the particle radiation law was selected so that the peak radiation intensity of the reconstructed profile matched exactly to the peak intensity for the experimental radiation profile. The values of \( K_2 \) depended on specific experimental and diagnostics details (e.g., video-camera sensitivity and setting) and thus of no practical significance. These values could be adjusted for each computed profile as a normalization of the computed and experimental data. As a final step, the pre-exponent \( K_1 \) in the particle combustion law was varied to achieve the minimum deviation between the calculated and experimental radiation profiles. The goodness of the obtained profile fit was evaluated using a Sum of Squares Error, \( SSE \), determined as

\[ SSE = \sum_{j=1}^{n} (I_{j,\text{experim}} - I_{j,\text{fit}})^2 \]

after \( n \) equidistant nodal points, \( j \), were selected over the entire profile height and the radiation intensity values for both experimental and reconstructed profiles, \( I_{j,\text{experim}} \) and \( I_{j,\text{fit}} \), respectively, were determined at the same nodal points. For example, Fig. 7, shows reconstructed flame radiation profiles for a Mg aerosol (Mg - 400 Mesh) at different values of the exponents, \( n_1 \) and \( n_2 \), and pre-exponents, \( K_1 \) and \( K_2 \), adjusted as described above. The reconstructed profiles are overlapped with the respective experimental flame radiation profile. Respective values of the \( SSE \) are given in Table 2. As illustrated in Fig. 7 and Table II, the best agreement with the experimental profile was observed with \( n_2 = 3 \). It was also observed (cf. Fig. 7) that the value of the exponent \( n_1 \) in the “combustion law” almost did not affect the shape of the reconstructed profiles for the radiation law exponents of \( n_2 = 2 \) and \( n_2 = 3 \).

Similar computations and comparisons were repeated for the same material aerosols with different particle sizes, and a set of \( K_1, n_1, \) and \( n_2 \) was identified, providing the best fits for the reconstructed and experimental profiles for all size fractions simultaneously. It was assumed that if one set of adjustable
parameters provided good match between the experimental and computed profiles for several size fractions of the same material powders, the selected $n_1$ and $n_2$ were adequate to describe the trends of the aerosol combustion and radiation behaviors, respectively.

**Results and Discussion**

*Magnesium Aerosol Flame*

Magnesium powder Mg - 325 Mesh “as received” and size-classified fractions of this powder Mg -400 Mesh and Mg -325 + 400 Mesh were used. The size distributions of these powders determined by the LALLS technique (uncorrected) are shown in Fig. 8. The best match between the reconstructed and experimental radiation profiles produced by magnesium aerosols was achieved with the following set of parameters:

$n_1 = 2$

$K_1 = 1.0 \cdot 10^6 \text{ s/m}^2$

$n_2 = 3$

The resulting reconstructed profiles and respective experimental flame radiation profiles for different size Mg aerosols are shown in Fig. 9. The agreement between the experimental and reconstructed flame radiation profiles is remarkable considering the number of simplifications made to produce the reconstructed profiles.

The identified set of adjustable parameters signifies that the combustion times of Mg particles in the small scale aerosol flames produced in our experi-

<table>
<thead>
<tr>
<th>$n_2$</th>
<th>$n_1 = 1$</th>
<th>$n_1 = 1.5$</th>
<th>$n_1 = 2$</th>
<th>$n_1 = 1$</th>
<th>$n_1 = 1.5$</th>
<th>$n_1 = 2$</th>
<th>$n_1 = 1$</th>
<th>$n_1 = 1.5$</th>
<th>$n_1 = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSE</td>
<td>19.00</td>
<td>16.16</td>
<td>50.54</td>
<td>3.54</td>
<td>2.73</td>
<td>1.91</td>
<td>2.39</td>
<td>2.22</td>
<td>1.73</td>
</tr>
</tbody>
</table>
The values of diameter Mg particles in air were reported in Ref. [3].

Diameter 250 constant found in that work for particles with initial
tion in air were measured in [4]. The evaporation
combustion. The combustion times were measured
determined and reported earlier for single Mg particle

This is agreement with most of the earlier descrip-

tions of magnesium particle combustion time as a
function of its size. It is interesting to compare the
evaporation constant varied in the range of 0.69 \cdot

10^{-6} < \beta < 0.92 \cdot 10^{-6} m^2/s.

The comparison shows that the evaporation con-
stant for magnesium aerosol combustion found in this
work, 1 \cdot 10^{-6} m^2/s, is in good agreement with the
earlier results on combustion of single magnesium
particles. Thus, a conclusion can be made that com-
bustion of magnesium powders in laminar aerosol
flames can be satisfactorily described by the “D^2
law” with approximately the same evaporation con-
stant as that found for 50–3000 \mu m diameter single
Mg particles.

The finding that the particle radiation can be de-
scribed by a D^3 law is interesting and can serve as an
indicator that the produced radiation is proportional
to the volume of the produced condensed oxide, as
discussed above.

**Aluminum aerosol flame**

The size distributions of the aluminum powders
used in the experiments determined by the LALLS
technique (uncorrected) are shown in Fig. 10. The
comparison of experimental and reconstructed flame
radiation profiles for Al aerosol flames showed that
the best match was observed at:

\[ n_1 = 1 \]

\[ K_1 = 200 \text{ s/m} \]

\[ n_2 = 3 \]

Respective experimental and reconstructed pro-
files for different size aluminum powders burning in
air are shown in Fig. 11. Once again, it is interesting
to point out a remarkable match between the exper-
imental flame radiation profiles and the profiles re-
constructed using a set of very crude assumptions and
simplified models.

Also interesting, similar to the magnesium flame
radiation above, the aluminum aerosol radiation is
observed to be best described by the D^3 law, but
unlike magnesium, the burning time of aluminum
aerosol particles is better described by the “D^1-laws”.

Different “combustion laws” were suggested in
the literature to describe the experimental results for
single Al particles [20]. Many experimental results
were found to fit well the D^2 trend with the evapo-
ration constant \beta in the range of (1.4–4.0) \cdot 10^{-7}
m^2/s identified in Ref. [2]. Thin dashed lines in Fig.
12 show the boundaries of this range. A bold line
shows the “D^1-law” found to fit best the experimental
and reconstructed flame radiation profiles in this
work. The bold line is shown as solid for the range of
particle sizes corresponding to the used Al powders,
and it is dashed for the extrapolation for larger par-

Fig. 9. Experimental and calculated aerosol flame radiation
profiles for different magnesium powders.
The best fit is achieved with the “D^2” combustion law and
“D^3” radiation law.

\[
\begin{align*}
\text{Mg -400 Mesh} & \quad \text{experimental} \quad \text{reconstructed} \\
\text{Mg -325 Mesh} & \\
\text{Mg -325+400 Mesh} & 
\end{align*}
\]
particle sizes. Figure 12 indicates that for Al particles less than 80 μm, the particle combustion times in aerosol flames are somewhat longer than for the same-size single particles.

Experimental results for single Al particle combustion under variety of conditions reported by different authors were recently summarized in Ref. [20]. It was suggested that the “$D^2$” particle combustion law (more precisely, $t_b = 3.0 \times 10^6 D^{1.99}$, where $t_b$ is in seconds and $D$ is in meters, so that $\beta \approx 3.33 \cdot 10^{-7} \text{ m}^2/\text{s}$) provides the best fit for a wide range of published results. Even though in our experiments the “$D^1$ combustion law” was found to work better in restoring the flame radiation profiles for different size aluminum powders, the pre-exponents for the “$D^2$ law” were also identified that provided the best fits between the experimental and reconstructed profiles for each powder. These pre-exponents could be readily compared with the value in Ref. [20], and they were $3.6 \times 10^6 \text{ m}^2/\text{s}$ and $3.0 \times 10^6 \text{ m}^2/\text{s}$ for the “Al 10−14 μm” and “Al -400 Mesh” powders, respectively. Thus, there is a very good agreement between the pre-exponent (and evaporation constant) for the “$D^2$ combustion law” identified in Ref. [20] and in this work.

**Conclusions**

A new experimental technique is developed to investigate laminar flames of metal aerosols. The technique includes measurements of the flame velocity, temperature, radiation profile, and burning aerosol particle velocities.

A method for the reconstruction of the aerosol flame radiation profiles is suggested using very simple models for particle ignition, combustion, radiation, and experimental particle size distribution. The
matching between the experimental and reconstructed profiles is achieved varying the exponents in the $D^2$-type expressions for the combustion time and radiation intensity as a function of the initial particle size, $D$. The reconstructed flame radiation profiles for both aluminum and magnesium aerosols with particles of different sizes are found to be in very good agreement with the respective experimental profiles, a somewhat surprising result considering simplified ignition, combustion, and radiation models used in the computations. For both metals, particle radiation intensities are observed to be best described by a $D^3$-type expression.

The combustion times for magnesium aerosol particles are found to be well described by the traditional $D^2$-law, with the evaporation constant close to those reported earlier for single particles. Aluminum aerosol particle combustion time is found to be better described by the $D^1$-law, and combustion times of fine ($<80 \mu m$) aluminum particles in the aerosol are found to be somewhat longer than the single aluminum particle combustion times reported earlier.

It is suggested that the developed technique can be used to assess parameters of simplified metal combustion models applicable to combustion of aerosols with different particle sizes. Such an assessment can serve as an initial step for further development of the detailed metal combustion models. It can also be useful in development of large-scale practical codes in which metal combustion represents only an intermediate step and should be modeled using simplified algorithms.

Finally, it is suggested that the developed technique can be useful in comparison and evaluation of combustion parameters of aerosols of different materials. For this application, the main advantage of this technique is in its unique ability to deal with the powders with different size distributions.

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