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A correlation function method of recovering the combustion law parameters for particles burning in optically thin dust flames

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Abstract

To determine the law describing how the rate of combustion of a particle depends on its diameter, we propose a correlation function (CF) method of measuring a particle's combustion time in a polydisperse dust flame. The method is based on observing the light intensity, $I(t)$, emitted by the flame, whose fluctuations are mostly governed by the random ignition and extinction of the particles. For an optically thin stationary dust flame, the CF for the intensity, $I(t)$, consists of correlation functions of radiation traces from each burning particle. To establish the relation between the CF for the intensity and the combustion law for a particle, the radiation trace was considered to be a pulse function, whose magnitude depends on the initial particle diameter, d_0, according to αd_0^δ and whose duration depends on kd_0^γ. This model provides a measure for the linear decay of the CF with time (an effective correlation time, τ_c), which is experimentally accessible. It is found that the effective correlation time depends on moments of the initial size distribution, $\tau_c = k\langle d_0^{2\delta+2\gamma-1}\rangle/\langle d_0^{2\delta+\gamma-1}\rangle$, and can be used to evaluate the combustion law. The CF method has been applied both to single particles of Mg burning in air and to a self-sustained flame of polydisperse Mg dust particles with sizes in the range 30 μm $\lesssim d_0 \lesssim$ 240 μm. The values of δ, γ, and the combustion constant k were estimated from experimentally measured values of τ_c and the moments of the initial size distribution. For single burning particles, the CF method resulted in $k = 0.51(\pm 0.05) \times 10^2$ s/cm^2, which was confirmed by direct measurement of the combustion time. For the self-sustained dust flame of particles with $d_0 \lesssim$ 120 μm, k was found to equal $1.27(\pm 0.08) \times 10^2$ s/cm^2. For dusts of larger particles, $d_0 \gtrsim$ 120 μm, the value of k decreases with increasing d_0 towards the value for the single burning particle.

Keywords: Mg particle; Dust flame; Combustion time; Emitted light; Intensity fluctuations; Correlation function

1. Introduction

The propagation of a combustion front through a cloud of solid or liquid fuel particles suspended in a gaseous oxidizer is a subject of much interest in combustion science [1–5]. It is evident that the conditions for a particle burning in a suspension differ from those

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Nomenclature

d_0	initial diameter of a particle
F	function describing the shape of the radiation trace from a burning particle
$I(t)$	intensity of the radiation emitted by a dust flame
$I_\nu(t)$	intensity of the radiation emitted by a particle
k	combustion law prefactor (combustion constant)
m	ratio of exponents, δ/γ
n	number of particles
$P(n)$	probability distribution function for the number of ignitions within T
t	time
T	sampling time
α	constant in the radiation law
β	burning rate constant, $1/k$
γ	combustion law exponent
δ	radiation law exponent
θ	dimensionless time
ϑ	combustion time of a particle
$\rho(d_0)$	initial size distribution function
$\rho(\vartheta)$	combustion time distribution function
τ	delay time
$\Psi(\tau)$	correlation function
$\tilde{\Psi}(\tau)$	normalized correlation function, $\Psi(\tau)/\Psi(0)$

Indices

b	denotes the combustion
c	denotes the correlation time
t	denotes the trace duration
ν	denotes the moment of ignition

for a single particle burning in an environment of an oxidizer. The mutual thermal interaction between particles in a dust flame and the susceptibility of the fuel to reacting with an oxidizer not only result in the establishment of a combustion front, but provide control of the combustion time of suspended particles [6,7], as well as the structure, thickness, and velocity of a dust flame [8–11]. To understand the mechanism of flame propagation and to predict the evolution of such systems, the combustion time of a particle has to be known.

There are two conceptually different experimental approaches to measuring the combustion time of particles in a dust flame. The first is classical and consists in direct video monitoring of the intensity of light emitted by the burning particles [11,12]. This method needs much effort to recognize a particle's trace and also good statistics and laborious work to explain the measurements. The analysis is even more complicated for polydisperse aerosols, which can be affected by agglomeration, and common flames surrounding clusters of particles [11–13]. Specifically, to identify the relationship between the combustion time of a particle and its initial diameter, $\vartheta = kd_0^\gamma$ (i.e., the combustion law), is the ultimate goal of these investigations. The number of particles in the combustion front, the shape of the microflames, and the distribution of the radiated intensity can be also obtained from direct observations [11,12,14,15].

The second approach demands the time-averaged characteristics of the combustion front [16], one of which is a profile of the intensity of the light emitted by a dust flame. In this case, the adjustable parameters of the combustion law (the exponent, γ, and the constant, k) are derived from matching the measured intensity profile with a modeled profile. This method has been successfully applied to obtain combustion times for magnesium and aluminum particles in laminar flames [4,5]. The small deviation of k for particles in a dust flame from the value corresponding to a single particle burning in air has been explained by the mutual interactions between particles [4].

The method developed below is closer to the second experimental approach. However, instead of the time-averaged intensity profile, we consider fluctuations of the integrated intensity of a laminar dust flame (intensity integrated over the volume of a flame, but not over time). For optically thin polydisperse dust flames, these fluctuations are caused by random ignition and extinction of particles and also by the change in emission during a particle's combustion. The statistics of when ignition occurs are related to when particles arrive to the flame; the statistics of when extinction occurs are governed by the variety of combustion times and the accidental moments of ignition. The fluctuations of a flame's intensity on a timescale smaller than the combustion time are associated with details of the combustion process itself, together with jetting and the spinning of burning particles [14,15].

To understand the essence of the method, consider an optically thin stationary flame, where particles ignite independent of each other and randomly with time. The integrated intensity of the radiation emitted by a flame is simply the sum of the intensities from each burning particle and therefore is proportional to their number; i.e., $I(t) \propto n(t)$. The statistical independence of when ignition occurs and the optical transparency of the flame allow one to construct the