

Thermal structure and burning velocity of flames in non-volatile fuel suspensions

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Abstract

Flame propagation through a non-volatile solid-fuel suspension is studied using a simplified, time-dependent numerical model that considers the influence of both diffusional and kinetic rates on the particle combustion process. It is assumed that particles react via a single-step, first-order Arrhenius surface reaction with an oxidizer delivered to the particle surface through gas diffusion. Unlike the majority of models previously developed for flames in suspensions, no external parameters are imposed, such as particle ignition temperature, combustion time, or the assumption of either kinetic- or diffusion-limited particle combustion regimes. Instead, it is demonstrated that these parameters are characteristic values of the flame propagation problem that must be solved together with the burning velocity, and that the *a priori* imposition of these parameters from single-particle combustion data may result in erroneous predictions. It is also shown that both diffusive and kinetic reaction regimes can alternate within the same flame and that their interaction may result in non-trivial flame behavior. In fuel-lean mixtures, it is demonstrated that this interaction leads to certain particle size ranges where burning velocity increases with increasing particle size, opposite to the expected trend. For even leaner mixtures, the interplay between kinetic and diffusive reaction rates leads to the appearance of a new type of flame instability where kinetic and diffusive regimes alternate in time, resulting in a pulsating regime of flame propagation.

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1. Introduction

Understanding the mechanisms controlling flame propagation in suspensions of non-volatile particles is crucial to obtaining efficient com-

bustion of metallized propellants, slurry fuels, pulverized coal, and powdered metals as carbon-free chemical energy carriers [1]. It is also necessary for the mitigation of catastrophic explosions in coal mines or in process industries that involve handling metallic dusts and other combustible solid powders.

Like gas flames, flames in particulate suspensions at the laboratory scale are primarily driven

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by molecular heat diffusion and have comparable burning velocities [1]. Nevertheless, they exhibit several significant differences in their structure and behavior from homogeneous flames due to their multiphase nature.

The main distinctive feature of a flame in a solid suspension is the ability of particles to ignite—that is, to transition from a combustion regime limited by reaction kinetics to a regime limited by diffusion of the oxidizing gas towards the particle surface, or in the case of evaporating particles, towards the micro-flame enveloping each individual particle.

After ignition, the temperature of the particle or micro-flame can exceed the gas temperature by several hundred degrees, often surpassing the adiabatic flame temperature for fuel-lean mixtures. The particle combustion rate in the diffusion combustion regime is a weak, non-Arrhenius, function of gas temperature. Unlike gas flames, the width of the flame reaction zone in particle suspensions can span a large temperature range and can be comparable to, or even exceed, that of the preheat zone [2]. The existence of diffusion micro-flames within a global flame-front (in effect, *flames within the flame*), which are insensitive to the bulk gas temperature, makes dust flames resistant to heat loss [1,3–5] and also serves to maintain a constant burning velocity with increasing fuel concentration in fuel-rich mixtures [6]. The ability of particles to ignite, together with low ignition temperatures, may result in much wider flame propagation limits for particle suspensions than for gaseous fuels.

Despite the overall qualitative understanding of the crucial role of the particle combustion regime on burning velocity and thermal structure, the theoretical description of flames in particulate suspensions has been limited to simple semi-empirical models that postulate either purely diffusion or purely kinetic modes of particle combustion [6,7]. The diffusive combustion models presume that particles within the suspension ignite and transit to the diffusion regime instantaneously when they reach the ignition temperature of a single, isolated particle. The common assumption is that, after ignition, the particle within the suspension will have a combustion time equal to that of an isolated single particle. Using this approach, particle ignition temperature and combustion time are considered to be external parameters that are independent of the flame-propagation mechanism. As such, they often are taken from experiments with individual particles or calculated using theoretical models for single particle combustion. These assumptions are useful for estimation, but are, in general, not justified and may lead to erroneous predictions. In reality, the particle ignition temperature, particle reaction time, and the actual regime of particle combustion are all characteristic values of the flame propagation problem directly linked to the burning velocity eigenvalue. Moreover, the particle combustion regime may alternate throughout the

flame. For example, the particle may start to react in a kinetically limited regime, then transit to a diffusion-dominated combustion mode, before returning to a kinetics-dominated mode [3]. As a result, a non-negligible fraction of the particle mass may be consumed during both diffusive and kinetic combustion, leading to a complex dependence of the burning velocity on particle size and concentration, as demonstrated in this study.

In this paper, the thermal structure of a flame in a particulate suspension is investigated using a simplified, transparent model that assumes that non-volatile solid fuel particles react via a single-step Arrhenius surface reaction with gaseous oxidizer delivered to the particle surface by diffusion. Besides incorporating heterogeneous reaction kinetics, the model does not impose the particle combustion mode or any other external combustion parameters. The flame propagation problem is solved numerically in a non-stationary formulation developed by Spalding [8]. This approach avoids the difficulties inherent in a steady-state formulation and permits the investigation of flame stability, which has led to the discovery of a new type of oscillating flame in heterogeneous mixtures.

2. Model formulation

2.1. Combined kinetic-diffusive reaction rate

Following the quasi-stationary approach of Frank-Kamenetskii [4], the overall reaction rate per unit surface area of a particle in an oxidizing gas, accounting for both kinetic and diffusion resistances can be written as

$$\dot{\omega} = \gamma \frac{\kappa \beta}{\kappa + \beta} C_0 \quad (1)$$

where $\dot{\omega}$ is the particle mass consumption per unit surface area, γ is the stoichiometric coefficient, and C_0 is the concentration of oxidizer in the bulk gas far from the particle surface [9]. The kinetic term, κ , is the overall Arrhenius surface reaction rate, $\kappa = k_0 \exp(-E_a/R_u T_s)$, where k_0 is the pre-exponential factor, E_a is the activation energy, and R_u is the universal gas constant. β is the mass transfer coefficient between a particle and the gas.

For simplicity, the contribution of Stefan flow to the heat and mass transfer between the particle and the surrounding gas is assumed to be negligible. Stefan flow is small when the molecular weight of the reaction products is close to that of the consumed oxidizer or when the initial oxidizer concentration is relatively low [4]. In the absence of Stefan flow, the mass transfer coefficient takes the simple form, $\beta = \text{Sh} D_i / 2r$. Here, D_i denotes the oxidizer diffusivity at the particle-gas interface, and r , the particle radius. For a spherical particle that is stationary relative to the gas, the exact solution to the

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