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Brief Communication

Energy balance and global characteristics of metal dust flames

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A B S T R A C T

Recently demonstrated high values of radiative loss during metal combustion require a new approach to describing dust flames. In particular, given strong light emission, the adiabatic flame temperature (AFT) concept is not applicable due to high radiative losses. Accordingly, global flame characteristics such as an expansion factor become unrelated to the AFT. That expansion factor can be directly inferred from the flame geometry, and therefore, its analysis offers a simple path to justify the need for a detailed energy balance in metal dust combustion. The analysis can also provide insight into peculiarities of the temperature distribution within the flame. In the current paper, previously published data on flow velocities in a metal dust flame are used for the expansion factor analysis. A relatively low value of the obtained expansion factor is reconciled with the advanced comprehension of metal particle combustion.

1. Introduction

A detailed comprehension of energy transfer in a flame is required for accurate modeling. Temperature measurements are commonly considered a tool to inform modeling. In the case of homogeneous gas flames, temperatures that enter model equations can be similar to measured values. Commonly, those temperatures are also compared with adiabatic flame temperatures (AFT) calculated based on conservation of energy. This concept is historically transferred to metal combustion without sufficient grounding. Heterogeneous metal dust flames are completely different systems and include processes which cannot be generalized by an analogy to pure gaseous systems.

The major disparity is related to strong radiation emitted by the condensed phase present in metal flames [1,2]. The corresponding emitted energy is lost in the system heat balance [3]. Therefore, the AFT, which is obtained without accounting for radiative loss, is a significant overestimate and not representative of the system behavior. At the same time, numerous publications report measured temperatures similar to AFTs [4–6].

The reason of the inconsistencies between energy lost and measured temperatures can be realized with an appreciation for the varied temperature distributions around burning metal particles. In other words, the maximum local temperature in the metal particle combustion zone is not distinguished from the average value in the burning particle vicinity. That average temperature is obviously lower than the measured temperature that reconciles the inconsistency with the erroneous interpretation of the AFT. At the same time, the average temperature is responsible for the global characteristic of the metal dust flame such as an expansion factor (EF). The EF is the ratio of cold (before the flame front) and hot (after the flame front) gas densities, and, therefore, is a direct measure of the heat transferred from a reaction to gas. Thus, a direct experimental estimation of the EF is an essential step in justifying the above comprehension and advancing a description of metal flames.

In the current paper, we infer the EF of an aluminum dust flame based on previously published data on measured flow velocities in the system [6]. A relatively low value obtained for the EF is evidence that the AFT is not a relevant metric for a metal flame. A brief thermal analysis that considers peculiarities of metal combustion addresses the important puzzles plaguing metal dust flames.

2. Combustion of metal particles in dust flames

A combustion regime of metal particles in a flame can be characterized by a parameter, ξ, that is the ratio of the average distance between particles, L, to the particle diameter, D_0. In the cold dust mixture that enters the flame, ξ can be expressed as Eq. (1), where ρ is the metal density and c is the dust concentration.

$$\xi = \left(\frac{\rho}{c}\right)^{\frac{1}{3}} \tag{1}$$

In an aluminum ($\rho = 2700$ kg/m^3) flame at $c = 250$ g/m^3, $\xi = 22$. It is understandable that within the hot flame, this parameter increases due to thermal expansion. In the case of single metal particle combustion, the ratio, η, of the reaction zone diameter, D_c, to the particle diameter is on the order of 3 [7,8]. Since $\xi >> \eta$, the concept of individual particle flames is a representative assumption for metal dust combustion. Those

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individual flames create temperature distributions around burning particles. Based on the analysis presented in Supplementary Information, it can be concluded that the average temperature around the burning particle is noticeably lower than the reaction zone temperature. It is a consequence of the existence of the conductive heat flow from the reaction zone toward the periphery [9]. The temperature profile around a burning particle can be quantified by interferometry [10].

Thus, common spectral measurements in the system used to infer temperature cannot provide insight into global flame characteristics important for applications. The measured temperature is a useful characteristic for an analysis of the reaction zone kinetics, but it has nothing to do with the average temperature that determines the EF. In the literature, the measured temperatures are often reported to be close to the AFTs [4–6]. But coincidence is neither evidence nor correctness of measurements. As demonstrated in Supplementary Information, the combustion zone temperature, which is the output of measurements, is significantly higher compared to the average temperature. Thus, in the case of the measured value being close to the AFT, a more detailed interpretation of the AFT relevance is further required.

The EF can be directly obtained by an analysis of the streamline behavior in the Bunsen flame as sketched in Fig. 1.

The constancy of the velocity components tangential to the oblique flame front in cold and hot mixtures allows for expressing the gas expansion factor, ε, in Eq. (2).

$$\varepsilon = \left[\frac{\left(\frac{v_b}{v_u}\right)^2 - \cos^2(\alpha)}{\sin^2(\alpha)}\right]^{\frac{1}{2}} \tag{2}$$

In Eq. (2), α is the Bunsen cone angle, and v_u and v_b are the flow velocities of cold and hot mixtures, respectively.

Alternatively, the EF can be obtained using the streamline angle in the hot mixture, β, according to Eq. (3).

$$\varepsilon = \frac{\tan(\beta)}{\tan(\alpha)} \tag{3}$$

The flow velocity map in the premixed aluminum dust flame measured in Ref. [6] provides all necessary data to calculate the EF using either Eq. (2) or Eq. (3). Note that the reported [6] flows were characterized by particle image velocimetry. Under operational conditions, the Stoke's number associated with the particles was small enough (i.e., 10^{-3}) implying that particles closely follow the air streamlines and are stationary with respect to the gaseous phase.

From Ref. [6], we obtained $v_u = 1.0$ m/s; $v_b = 2.2$ m/s; $\alpha = 21^\circ$; $\beta = 65^\circ$ Then, the expansion factor calculated using either Eq. (2) or Eq. (3) is about 5.5. That value is noticeably lower than the ratio of the AFT (~3600 K [6]) to the initial system temperature (~300 K), i.e., ~ 12. It should be noted that the EF value of ~ 12 would correspond to the case of the average gas temperature around burning particle being equal to the AFT. Thus, the experiment demonstrates that the actual EF is not determined by the AFT value in accordance with the above concept. It should be emphasized that the actual EF, which is about half of what could be expected based on the AFT, is in agreement with ~50 % radiative loss reported in aluminum flames [11,12]. The energy transferred from the burning metal particles to gas constitutes about 50 % of the theoretical combustion heat that results in gas heating to the temperature of ~ 50 % of the AFT.

It is worth adding that the relatively high fraction (~50 %) of radiative loss, which results in the discussed effect, originates from the condense-luminescent nature of light-emission in metal flames [13]. Condense-luminescence also explains why emission characteristics of alumina inferred based on the equilibrium assumptions [14] have a huge scatter. The phenomenon of condense-luminescence is why equilibrium characteristics of nano-alumina cannot be used to quantify radiative fluxes in the system.

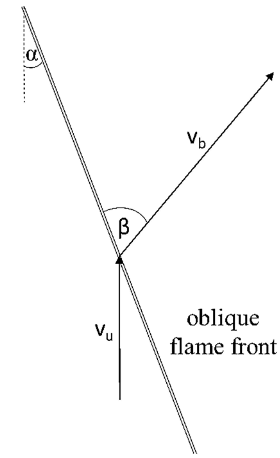

Fig. 1. Schematic illustrating the evolution of flow velocities in the Bunsen flame. Directions of velocities of cold, v_u, and hot, v_b, mixtures are determined by angles α and β.

3. Concluding remarks

The individual character of metal particle combustion in dust flames leads to a need to revisit the purpose and significance of temperature measurements in the global system. While temperature provides insight into reaction kinetics, the measured temperature does not characterize global flame behavior. The average temperature, and, correspondingly, the expansion factor are more important metrics to elucidate accurate physical modeling of metal particle flames.

The irrelevance of the AFT to the global flame characteristics such as the expansion factor is an important result that should be considered in applications of metal dust combustion. Radiative energy loss explains why the average temperature in the system is noticeably lower compared to the AFT. Accurate process modeling requires consideration of the significant radiative loss during metal combustion.

4. Novelty and significance

The paper highlights a need of detailed comprehension of energy transfer in metal dust flames and emphasizes that ignoring significant radiative loss will lead to a misinterpretation of temperature measurements in the system. This analysis of the expansion factor in the aluminum flame is the first-time direct demonstration of the problem related to the global behavior of the system. Results ultimately justify the importance of radiative loss for accurate modeling in metal dust flames.

Author's contributions

The authors contributed equally to this work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.combustflame.2024.113310.

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