EFFECTS OF COMBUSTIBLE DUST CLOUDS ON THE EXTINCTION BEHAVIOR OF STRAINED, LAMINAR PREMIXED FLAMES IN NORMAL GRAVITY

M. GURHAN ANDAC, FOKION N. EGOLFOPOULOS AND CHARLES S. CAMPBELL
Department of Aerospace and Mechanical Engineering
University of Southern California
Los Angeles, CA 90089-1453, USA

An experimental and numerical study was performed on the interaction of combustible solid particles with atmospheric, strained, laminar premixed methane/air and propane/air flames in normal gravity. The study was conducted in the opposed-jet configuration in which a single flame was stabilized below the gas stagnation plane by counterflowing a mixture against an air jet. Into the flame were seeded spherical 50 µm, combustible glassy-carbon particles. Flame extinction data were analyzed to provide insight into the effects of fuel type, gas-phase composition and temperature, flame thickness, strain rate, and particle number density. It was found that at low strain rates, the particles could effectively burn within the gaseous flame zone and thus enhance the overall reactivity of the system and resistance to extinction. At high strain rates, however, the particles are rapidly transported through the flame and their ignition is delayed until they are well downstream of the flame and so have no effect or at best a minor one on the gaseous flame. If no ignition occurs, the combustible particles act simply as heat sinks, promoting extinction. The effects of Lewis number and flame thickness were also studied. It was found that the enhancement of the gas-phase reactivity by the particles is more profound for $Le/H_1 > 1$ and for thick flames. Finally, at the same flame temperature, fuel-lean flames were determined to be more resistant to extinction compared to fuel-rich flames in the presence of combustible particles. This was attributed to the higher concentrations of $O_2$, $O$, and $OH$ species, which are largely responsible for the consumption of carbon.

Introduction

The behavior of reacting dusty flows is complicated by the numerous dynamic, thermal, and/or chemical interactions between the particles and the gas phase. The dynamic and thermal interactions can be rigorously addressed for dilute dust clouds in which the average distance between particles is much greater than their diameter. Understanding the solid-phase kinetics is a challenging task even in studies of single particle burning [e.g., Refs. 1–5], in which the condition are at least spatially symmetric. In dusty flows, fluid mechanics and phoretic, and long-range forces can complicate the dynamic and thermal states of the individual particles. Thus, asymmetric and/or non-uniform distributions of (gaseous) species concentrations could form around each particle and have a strong effect on the chemical processes between the gas and the solid phases.

Given this level of complexity, the fundamentals of reacting dusty flows can be best investigated in simple configurations such as the stagnation flow, in which the mechanical, thermal, and chemical parameters can be varied nearly independently. Stagnation flows have been previously used for many studies of two-phase flows, for example, dilute sprays and dusts [e.g., Refs. 6–8].

The authors have previously adopted such an approach [9–11] to study flame extinction by chemically inert particles. Many fundamental issues associated with the dynamic and thermal response of even inert particles must be understood before the reactivity of combustible particles can be considered. After all, reacting particles are inert until their ignition temperature is reached. Thus, the thermal evolution of particles, while still inert, has a strong effect on the chemical processes that lead to their subsequent ignition and burning. Both experimental and numerical results [9–11] have revealed that the response of inert particles to gravity and the gas-phase conditions is complex to the point that meaningful universal scaling is not possible. For example, the effects of thermophoresis, gravity, gas-phase dilatation, and particle flow reversal can have a major effect on the particle trajectory and thermal state, yet have no immediately apparent scaling arguments.

The study of reacting particles can be further complicated when they are the principal fuel interacting with a gaseous oxidizer. Extensive experiments in the authors’ laboratory with aluminum and magnesium particles burning in air have shown that the large
were separated by a distance were used to create a stagnation flow. The burners nal diameter perspherical glassy-carbon particles with a nomi-
be found in Ref. [10]
experimental setup and the particle-seeding unit can
Schematics and more complete descriptions of the
which allows for particle seeding at a controlled rate.
similar to that proposed by Goroshin et al. [13],
through the use of a piston-driven particle feeder
was seeded with particles. The seeding was achieved
experiments and simulations. Only the lower burner
flame zone.
turn increases the particle residence time within the
mixtures to increase the flame thickness, which in
turn increases the particle residence time within the
flame zone.
The flame extinction experiments were conducted
in two different ways. In the first, a flame close to
its extinction state was established and then particles
were fed into the flow at a predetermined constant
rate. Subsequently the fuel flow rate was decreased
until the flame was extinguished. The final composi-
tion was recorded as the extinction equivalence ra-
tio, \( \phi_{\text{ext}} \), for the corresponding conditions (\( n_p, L/D \),
etc.). In the second approach, extinction was
achieved by increasing the global strain rate, \( K_{gb} =
\frac{u_{\text{exit}}}{(L/2)} \), where \( u_{\text{exit}} \) is the gas-phase velocity at the
nozzle exit. The accuracy of the data is limited by
the 0.5% accuracy of the of the sonic nozzle calib-
trations.

Experimental Approach

Two opposing burners with diameter \( D = 22 \text{ mm} \)
were used to create a stagnation flow. The burners
were separated by a distance \( L = 14 \text{ mm} \) for all
experiments and simulations. Only the lower burner
was seeded with particles. The seeding was achieved
through the use of a piston-driven particle feeder
similar to that proposed by Goroshin et al. [13],
which allows for particle seeding at a controlled rate.
Schematics and more complete descriptions of the
experimental setup and the particle-seeding unit can
be calibrated by seeding particles into the airflow
for a certain time period and collecting the particles
in ultralight plastic bags at the burner exit. The
PMDR was calculated by measuring the mass of the
bag on a precise scale before and after the test and
dividing by the particle collection time. Subse-
sequently, the particle number density, \( n_p \), in particles
per cubic centimeter units, was calculated by divid-
ing PMDR by the volumetric gas flow rate, in cen-
timeter per second units, and the mass of an indi-
vidual particle, in milligram units. The accuracy of
the particle seeder calibration was found to be better
than 8%.

Experiments assessed the effects of reacting par-
ticles on premixed CH\(_4\)/air and C\(_3\)H\(_8\)/air flame
extinction. Parameters varied included the particle
number density, gas-phase composition, fuel type,
flame temperature, and strain rate. The particles
were always seeded from the bottom burner and
both gases and particles were injected at ambient
temperature.

In all studies, a single flame was established below
the gas-phase stagnation plane (GSP) by injecting
the combustible mixture from the bottom burner
along with the particles against an air jet issuing from
the top burner. Stabilizing the flames on the particle
injection side was intentional for two reasons. First,
the particles would enter the flame region from up-
stream thus establishing more direct thermal and
chemical interactions between the two phases. Sec-
ond, the particles have a chance to pass through and
interact with the flame; for downstream injection the
particles might not penetrate the GSP far enough to
reach the reaction and/or the preheat zone of the
flame [e.g., Refs. 9–11].

To gain further insight into the thermochemical
interactions between the two phases, the fuel/air
mixtures were diluted by inert gases. Various
amounts of N\(_2\) were used to keep the flame tem-
perature constant as the equivalence ratio, \( \phi \), was
varied, thus decoupling concentration and thermal
effects. Helium was also added to the fuel/air
mixtures to increase the flame thickness, which in
turn increases the particle residence time within the
flame zone.

Numerical Approach

A detailed modeling of the experiments should
ideally include a rigorous description of all pertinent
processes that affect the two phases and their inter-
actions. But this is not always possible. The authors
have already developed a numerical code [9], for
the simulation of stagnation flows of reacting gas phase
seeded with chemically inert particles, in the region
along the stagnation streamline. This code was used
[9–11] to investigate the effects of inert particles on
both the extinction and ignition of gaseous flames.
The code includes comprehensive models describ-
ing the dynamic and thermal response of both
phases, as well as the kinetics of the gas phase.

Implementing solid-phase chemistry into the code
to properly simulate the present experiments could
introduce various uncertainties that could compre-
mise the value of the simulations. The uncertainties
include the solid-phase kinetics, physical processes
at the surface such as product condensation and fuel
The gas-phase modeling is similar to that in Ref. [14] but also includes terms describing the dynamic and thermal interactions with the particle phase at the dilute dust limit. The momentum equations consider Stokes drag, thermophoretic, and gravitational forces on the particles. The energy equations include terms for the conductive/convective/radiative interphasial heat exchange. Mass conservation is enforced for both phases.

The equations for both phases were simultaneously integrated, but in different frames of reference. While the gas phase was integrated in Eulerian coordinates, the particle phase used a Lagrangian frame. Detailed chemical kinetics [15] and transport were incorporated, through the CHEMKIN [16] and Transport [17] subroutine libraries, respectively.

**Results and Discussion**

Flame extinction experiments were conducted for single premixed CH₄/air and C₃H₈/air flames stabilized below the GSP. In earlier studies, [10,11], the strain rate was fixed, which determined the gas flow rate. Then, there is no difference between fixing PMDR or \( n_p \), as varying either changes the particle mass delivery per unit volume. As a result, the previous results were presented as functions of PMDR. In the current studies, the strain rate is varied and, consequently, the PMDR changes even at fixed \( n_p \). Hence, the current data are presented as functions of \( n_p \) rather than PMDR.

Representative calibration results for the 50 µm size glassy-carbon particles are shown in Fig. 1. It can be seen that PMDR varies fairly linearly with flow rate, at least for the lower gas flow rates but the slope decreases at high flow rates. As might be expected, PMDR also increases with the particle seeder speed. On the other hand, \( n_p \) exhibits a local maximum within the range of flow rates studied. The rate of increase in PMDR is smaller than the gas volume flow rate. This explains why at high flow rates, \( n_p \) decreases slightly while PMDR continues to increase. Note also that the higher the particle seeder speed, the higher is the flow rate at which the maximum \( n_p \) is reached.

Figure 2 depicts the variation of experimentally determined \( \phi_{\text{ext}} \) with \( K_{\text{gb}} \) for unseeded (\( n_{p,\text{inj}} = 0 \) parts/cm³) and seeded (\( n_{p,\text{inj}} = 4000 \) parts/cm³) (a) CH₄/air and (b) C₃H₈/air flames. The data comparison reveals that, contrary to the inert particle result, the presence of reacting particles augments the resistance to extinction. This is apparent from the correspondingly lower \( \phi_{\text{ext}} \) values implying that weaker gas-phase reactant concentrations can be sustained.
At the same $K_{gh}$ when particles are present. This behavior is even more profound at the lower values of $K_{gh}$ and indicates that the particles have started reacting and releasing heat, enhancing the gas-phase kinetics.

However, it should be realized that the particles play a dual role. In addition to the heat that is released by their reactions, the particles also act as inert heat sinks before they ignite. The absorbed heat is essential to initiate solid fuel vaporization (e.g., for aluminum) or surface reactions (e.g., for carbon) that only become fully activated at high temperatures. The results of Fig. 2a reveal that for high $K_{gh}$s the observed difference between the $\phi_{act}$s obtained with and without particles nearly disappears. This implies either that the particles do not ignite or that even if they do, the ignition occurs well downstream of the gaseous flame. In such regions, the gas is still hot enough to ignite the particles but little of the released heat can effectively diffuse upstream and affect the flame kinetics. At high $K_{gh}$s, the corresponding large particle velocity transports them rapidly through the flame and they do not receive sufficient heat to ignite. Thus, the result of adding reacting particles to flames is a tradeoff between the particle cooling before ignition and the heat release following ignition. For the conditions at the highest reported $K_{gh}$ in Fig. 2a, the heat release effect just marginally exceeds the cooling effect.

Figure 2b depicts similar results as in Fig. 2a but for $C_3H_8$/air flames. Similar to the CH$_4$ flames, particles appear to resist extinction at the lower $K_{gh}$s. But at higher strain rates, the two curves merge and cross each other. For large $K_{gh}$s, beyond the crossing point, stronger flames are extinguished when particles are present indicating that their cooling effect exceeds the heat released by the carbon reactivity. Comparing the results of Fig. 2a and b, one extrapolates that a similar crossing point would appear for CH$_4$/air at still higher $K_{gh}$s.

To provide further insight into the strain-rate effect shown in Fig. 2a and b, numerical simulations were carried out by seeding glassy-carbon particles, treated as inert, into CH$_4$/air flames with $\phi = 0.6$ and 1.0 at $K_{gh} = 35$ and 165 s$^{-1}$ respectively. The goal of these simulations was to analyze the evolution of the particles’ temperature as they approach the flame and draw conclusions about the ignition response by monitoring the spatial location of a characteristic particle-ignition temperature, $T_{p, ign}$. It should be emphasized that a single temperature value can not be assigned to $T_{p, ign}$ as particle-ignition depends on the local conditions. In addition to O$_2$, the presence of radicals such as O and OH can accelerate the surface chemistry of carbon. For example, in a flame environment that is rich in radicals, particle ignition may occur at a lower temperature than a single carbon particle burning in air (e.g., Refs. 5, 12, 18).

The results of the simulations are shown in Fig. 3. It can be seen that at low $K_{gh}$s, the particle temperature more closely follows the gas-phase temperature than at higher $K_{gh}$s. Previous studies [12, 18] of graphite suggest that the consumption rate of graphite becomes finite around 1000 K. Assuming a kinetically similar behavior between graphite and glassy-carbon, a $T_{p, ign} = 1000$ K is assigned. This serves only as a reference ignition temperature to facilitate comparisons between the various simulations.

In Fig. 3 a narrow temperature range around the $T_{p, ign} = 1000$ K value is used as the (particle) ignition zone. It can be seen that at low $K_{gh}$s, the ignition zone is located well before the main gas-phase reaction zone (marked at the location of maximum temperature curvature). Thus, the particles burn as they approach the (gas-phase) reaction zone and thus augment the overall reactivity of the system. At high $K_{gh}$s, however, the particles are transported rapidly through the flame, their temperature rise is delayed as a result of the reduced residence time, and the location of the ignition zone lies downstream of the reaction zone. This diminishes the effect of particle heat release on the overall reactivity. For even higher $K_{gh}$s, particle-ignition conditions are not observed within the finite domain of the counterflow and the particles act only as heat sinks. It is also of interest to note from Fig. 3 that the particle temperature is very sensitive to the strain rate and less sensitive to the flame temperature. For example, particle ignition is achieved more readily for the colder $\phi = 0.6$ flame with a lower $K_{gh}$ compared to a hotter $\phi = 1.0$ flame with a higher $K_{gh}$.
Fig. 4. Variation of experimentally determined $\phi_{\text{ext}}$ and numerically determined adiabatic flame temperatures as functions of He dilution for CH$_4$/air/He flames. The $\phi_{\text{ext}}$ was determined with $n_{\text{p,inj}} \simeq 3650$ parts/cm$^3$.

Fig. 5. Numerically determined gas-phase and particle temperatures of undiluted and He-diluted CH$_4$/air flames with $K_{\text{glb}} = 0.982$ and $K_{\text{glb}} = 71$ s$^{-1}$.

A careful examination of the results shown in Fig. 2a and b reveals that for the same $K_{\text{glb}}$, $\phi_{\text{ext}}$'s are higher in C$_3$H$_8$/air flames compared to the CH$_4$/air flames. This is a Lewis number ($Le$) effect, as $Le > 1$ for lean C$_3$H$_8$/air flames making them more sensitive to strain rate and heat losses. Thus, C$_3$H$_8$/air flames are extinguished more readily, which explains why the crossing between the two curves is observed in Fig. 2b but not in Fig. 2a within the same $K_{\text{glb}}$ range.

The effect of the flame thickness on flame extinction was also assessed by adding He to a CH$_4$/air flame at a constant $K_{\text{glb}} = 71$ s$^{-1}$. The thicker the flame is, the larger the particle residence time is and the greater the likelihood is that the particles are heated to ignition before leaving the flame zone. Fig. 4 depicts the variation of $\phi_{\text{ext}}$ with the He mole fraction for $n_{\text{p,inj}} \approx 3650$ parts/cm$^3$. As He is added, weaker gaseous flames can be sustained, indicating additional heat release resulting from the particle reactivity. There are several points to be made here. Adding He to a flame increases the flame thickness and the mixture’s thermal conductivity while it decreases the flame temperature. For the case considered in Fig. 5, the ratio of conductivities of mixtures with and without He addition was found to be 1.46 while the corresponding flame thickness ratio is 1.80. The effect of He addition on the adiabatic flame temperature, $T_{\text{ad}}$, is also shown in Fig. 4. Thus, in the absence of particle reactivity, He addition weakens the gas-phase kinetics and should result in larger $\phi_{\text{ext}}$ values at the same $K_{\text{glb}}$. But seeding reacting particles into these thicker and more thermally conductive flames results in additional heat release within the preheat and/or reaction zones of the gas phase, augmenting thus the overall reactivity and, consequently, should result in lower $\phi_{\text{ext}}$ values at the same $K_{\text{glb}}$. The results of Fig. 4 indicate that the particle heat release effect dominates that of $T_{\text{ad}}$ reduction with He dilution.

This argument was confirmed by numerical simulations conducted by injecting particles into two flames with $\phi = 0.982$ and $K_{\text{glb}} = 71$ s$^{-1}$: (1) a CH$_4$/air flame and (2) a CH$_4$/air/He flame with a 17% He mole fraction (corresponding to the first data point in Fig. 4). The results of Fig. 5 reveal that the flame thickness increases about 80% as a result of the He addition, allowing thus more time for effective particle heating to its ignition temperature synergistically with the augmented interphasial heat transfer enhancement due to the higher conductivity. Thus, in the case of He-diluted flame, the particle temperature rises to its ignition temperature (~1000 K) in the vicinity of the reaction zone. In the case of undiluted CH$_4$/air flame, however, this temperature is reached well downstream of the reaction zone, and the flame receives no significant feedback from the particle burning. For higher He additions, the flame thickness and gas conductivity increase even further, shifting the particle ignition into the preheat region to the left of the reaction zone. This allows further particle consumption, introducing more energy to the flame prior to the reaction zone.

Additional experiments were performed, in which the extinction global strain rate, $K_{\text{glb,ext}}$, was determined at various $\phi$'s keeping $T_{\text{ad}}$ constant by modifying the relative concentration of O$_2$ and N$_2$ in the oxidizer through N$_2$ dilution. This eliminates thermal effects, so that the effects of the gas- and solid-phase chemistry may be independently studied. Fig. 6 depicts the variation of $K_{\text{glb,ext}}$ with $\phi$ at $T_{\text{ad}} = 1870$ and 1970 K, for unseeded ($n_{\text{p,inj}} = 0$ parts/cm$^3$) and seeded ($n_{\text{p,inj}} \simeq 3500$ parts/cm$^3$) flows. The
Fig. 6. Variation of experimentally determined $K_{glb,ext}$ with $\phi$ for unseeded ($n_{p,inj} = 0$ parts/cm$^3$) and seeded ($n_{p,inj} = 3500$ parts/cm$^3$) CH$_4$/air/N$_2$ flames with constant $T_{ad} = 1870$ and 1970 K.

Fig. 7. Numerically determined $H$, $O$, and OH mass fractions and particle temperatures for $\phi = 0.8$ and $\phi = 1.2$ CH$_4$/air/N$_2$ flames, with $T_{ad} = 1970$ K.

experiments were conducted for lean ($\phi = 0.8$), stoichiometric ($\phi = 1.0$), and rich ($\phi = 1.2$) mixtures. Extinction was achieved by gradually increasing $K_{glb}$. Comparing seeded and unseeded flames, it is seen that for the same $\phi$, the seeded flames are more resistant to extinction (higher $K_{glb,ext}$) indicating that the particles are reacting. For the same $\phi$, $K_{glb,ext}$ is higher for the higher $T_{ad}$, as expected. Also note that the effect of $T_{ad}$ on $K_{glb,ext}$ is more profound for the $\phi = 0.8$ flame. For the same $T_{ad}$, however, it can be seen that $K_{glb,ext}$ decreases as $\phi$ increases, indicating that lean flames are more resistant to extinction.

The dependence of $K_{glb,ext}$ on $\phi$ at fixed $T_{ad}$ can be explained by considering the detailed kinetics of carbon. It has been shown [5,12] that, in addition to O$_2$, carbon can also react with O and OH radicals and to a smaller degree, with H radicals. Fig. 6 supports this argument as O$_2$, O, and OH are more abundant for lean flames especially for the same $T_{ad}$. Fig. 7 depicts numerically determined spatial profiles of $H$, $O$, and OH radicals for $\phi = 0.8$ and 1.2 flames with $T_{ad} = 1970$ K. It can be seen that the O and OH concentrations are significantly higher for the $\phi = 0.8$ flame while the H radical concentration is higher for the $\phi = 1.2$ flame. The particle temperature evolution is also shown in Fig. 7. It is of interest to note that the ignition temperature of 1000 K is reached by the particles close to the vicinity of the maximum O and OH radicals. The increased extinction resistance of the $\phi = 0.8$ flame compared to $\phi = 1.2$ flame can be attributed to the higher concentrations of O$_2$ as well as O and OH radicals that also contribute to the carbon consumption. The more profound effect of $T_{ad}$ on $K_{glb,ext}$ for lean flames can be expected as increasing the flame temperature accelerates the carbon reactions with O$_2$, and O and OH radicals. In rich flames, these species would be preferentially consumed in the gas phase so that they are not available for the carbon consumption. The increased H-radical pool in rich flames has a relatively minor contribution on carbon consumption.

Concluding Remarks

The effects of combustible dust on the extinction of strained, laminar, premixed flames were investigated experimentally and numerically in an opposed-flow configuration at atmospheric pressure and normal gravity. The effects of fuel type, gas-phase composition and temperature, flame thickness, strain rate, and particle number density were assessed. CH$_4$ and C$_3$H$_8$ were used as fuels, while the gas phase was seeded with spherical glassy-carbon particles.

The results revealed that the effect of combustible particles on gaseous flames is controlled by the competition between the cooling effect that the particles can exert on the gas phase while inert, and the heat that the particles can release upon burning. It was found that this competition is critically affected by the fluid mechanics. At low strain rates the solid-phase chemistry is activated before the gaseous reaction zone, and the attendant heat release augments the gas-phase reactivity compared to the particle-free flames. However, as the strain rate progressively increases, the location at which the solid-phase chemistry is activated shifts further downstream as the particle residence time is reduced which delays the particle heating. Thus, under high-strain-rate conditions, the particles behave largely as inert with at best minor feedback from the particle burning that takes place downstream of the flame.
It was also determined that increasing the flame thickness increases the particle residence time permitting ignition within the flame region. Thus, the resulting heat release strengthens the flame.

The effect of gas-phase $Le$ number was also investigated. It was found that the enhancement of the gas phase reactivity by burning particles is more apparent for $Le < 1$ flames, given that $Le > 1$ flames are more sensitive to the cooling effect of the particles which moderates the effect of the subsequent heat release.

The effect of gas-phase composition on the solid-phase chemistry was investigated by performing extinction experiments of lean, stoichiometric, and rich flames at the same adiabatic flame temperature. It was found that lean flames are more resistant to extinction due to the larger concentrations of $O_2$, $O$, and $OH$ that readily consume carbon.

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REFERENCES


COMMENTS

Chih-Jen Sung, Case Western Reserve University, USA
The dust concentration was not varied over a wide range in the present study. Please comment on its effect. Additionally, the present results demonstrate which flame strength could be affected by the combustible droplets. Please elaborate on the implications for the diagnostics (e.g., LDV, PIV) that use this type of particles.

Author’s Reply. The dust concentration has indeed a significant effect on the flame response, and this has been shown both experimentally and numerically in our previous studies on inert particles (Refs. [1–4] in paper). In the present investigation, a limited variation of the dust concentration was considered as the emphasis was on the effects of gas-phase composition and strain rate. In these experiments the dust concentration was kept constant in order to isolate other mechanisms of interest. The effect of extensively varying the dust composition is being currently addressed by our group and will be reported in an upcoming publication.

This is a very interesting point, as it is possible that the presence of reacting droplets in DPIV or LDV studies can influence the gas-phase reactivity. Our investigations focus on solid particle rather than droplets, but our experimental apparatus can be used to assess the effect of reacting droplets. We plan to perform such studies in order to map the regimes of gas-phase equivalence ratio and condensed-phase number density for which the reactivity of the condensed phase does not alter the characteristics of the gaseous flame.