Premixed Flame Propagation in an Optically Thick Gas

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Introduction

PRIOR experiments[1,2] on premixed gas flames at microgravity (μg) have shown that radiant heat loss from the burned gases can have an important influence on the flammability limit mechanism and near-limit burning rates. These influences are not observable at Earth gravity because buoyancy-induced natural convection induces heat loss or straining of the flame front that is more significant in promoting extinction than the relatively weak process of radiant loss. However, radiation is probably not a fundamental limit mechanism at μg because emitted radiation can be reabsorbed by the unburned gas, in which case radiation augments conventional heat diffusion, increases the burning velocity S_L, and extends the flammability limits rather than acting as a loss process.[3] Reabsorption can be important only when the Planck mean absorption length l_p is smaller than the combustion chamber size l_s, so that emitted radiation is not lost to the chamber walls. Gas radiation data[4] indicate that typical values of l_p for hydrocarbon-air combustion products are a few meters, and hence only in very large systems could reabsorption be significant.

It is proposed to decrease l_p to values sufficiently low that reabsorption effects might be observable in a laboratory-scale combustion apparatus by seeding combustible gases with inert solid particles. Since solids emit and absorb as blackbodies or greybodies, whereas gases radiate in narrow spectral bands, a seeded gas could emit and absorb much more radiation than a particle-free gas. Neglecting the thermal capacity of the particles, we expect that when the ratio of particle mass to gas mass Y is small, S_L should decrease because $l_p > l_s$, so that reabsorption is negligible (the *optically thin* regime), and thus the particles act primarily as emitters. The increased radiation decreases S_L.[5,6] However, when Y is large, we expect $l_p < l_s$ (the *optically thick* regime), and thus a significant portion of the emitted radiation may be reabsorbed within the gas. This would reduce heat loss and augment preheating of the unburned gas, which acts to increase S_L.[7]

For the proposed method to be viable, at optically thick conditions Y must be small enough that the thermal capacity of the particles does not significantly reduce the adiabatic flame temperature T_{ad}; otherwise the effects of particle radiation and particle mass on S_L cannot easily be separated. In the optically thin limit, l_p is given by[8] $(4\sigma/L)(T^4 - T_0^4)$, where σ is the Stefan-Boltzmann constant, L is the total emissive power per unit volume of mixture, T is the temperature, and T_0 is the background temperature (assumed here to be the same as the ambient gas temperature). In the optically thin limit, for a gas seeded with spherical greybody particles, $L \approx [3\epsilon\sigma Y(T^4 - T_0^4)/r]\,(\rho_g/\rho_p)$, where ϵ is the particle emissivity, r is the particle radius, ρ is the density, and the subscripts g and p refer to gas and particles, respectively. Combining these two relations yields $l_p \approx (4r/3\epsilon Y)\,(\rho_g/\rho_p)$. Then for a typical apparatus with $l_s \approx 25$ cm, to obtain $l_p \approx l_s$ using SiC particles with $r = 0.3$ μm (the particles we employed in our experiments), assuming $\epsilon \approx 1$ would require $Y \approx 0.037$. The ratio of specific heats per unit mass C_p of SiC and air is about 1.05, hence $Y \approx 0.037$ implies a change in T_{ad} of about 4%. This relatively small change in T_{ad} encouraged us to explore the particle-seeding method for studying radiation effects.

Another requirement of the proposed method is that the conductive heat flux per unit area of flame front, q_c $(= \rho_0 S_L Y_f Q_r$, where ρ_0 is the unburned gas density, Y_f is the initial mass fraction of fuel, and Q_r is its heating value), must be significantly less than the blackbody radiant power q_r at T_{ad} $[= \sigma(T_{ad}^4 - T_0^4)]$, so that there is significant potential to increase S_L via radiative augmentation of thermal transport. For lean CH_4-air flames at 1 atm, the measured[1] limit composition at μg is 5.1% (corresponding to $T_{ad} \approx 1500$ K) and at the limit $S_L \approx 1.6$ cm/s; hence $q_c/q_r \approx 0.13$. By comparison, for stoichiometric CH_4-air mixtures ($S_L \approx 40$ cm/s, $T_{ad} \approx 2220$ K), $q_c/q_r \approx 1.0$. Hence, the proposed method is much more viable with slow-burning mixtures near flammability limits.

In summary, these considerations indicate that a viable experiment requires 1) very small particles, so that Y and thus the contribution of the particles to C_p is minimized, 2) mixtures with low S_L, so that radiative fluxes can be larger than conductive fluxes, and 3) μg conditions so that buoyant influences can be avoided even at the low values of S_L required. The results of preliminary experiments satisfying these requirments are described next.

Experimental Apparatus and Procedures

The apparatus we employed has been described previously[1]; hence only a brief description is given here. An aluminum pipe of 25-cm diam and 25-cm length with transparent end windows served as the combustion chamber. Initial gas compositions were determined by partial pressures. The mixtures were ignited, after the μg period began, at the center of the chamber by an electric spark of ≈ 1 J energy release. The 2.2-s drop tower at the NASA Lewis Research Center was employed to obtain μg conditions. As a consequence of the centrally located ignition source and μg environment, freely propagating, spherical, expanding flames were obtained. Burning velocities, chamber pressures, and gas temperatures were measured in the same manner as in our previous study.[2]

We chose SiC particles because of their high melting point (≈ 3000 K),[9] because they are practically inert in oxidizing atmospheres at temperatures below 1800 K[9] (which is well above the maximum flame temperatures of interest, about 1400 K), and because our preliminary studies suggested that ϵ is significantly higher in SiC than other common refractory powders such as SiO_2 or ZrO. The advertised mean particle radius was 0.3 μm. To minimize agglomeration, the particles were dried in an oven and stored in a desiccant jar until use.

The particles were dispersed into the mixture by the following method. Just before the drop test, a set of four small electric fans inside the combustion chamber was started. The fans were stopped a few seconds before the drop began, and a valve connecting a gas jet to a 25-cm^3 gas bottle that was filled to a pressure of ≈ 2 atm with the same combustible mixture that was in the main chamber was opened. This jet was aimed at a small cup filled with particles located inside the combustion chamber. The shear layer at the jet boundary dispersed the particles into the nearby gas. The cloud of particles thus formed was dispersed throughout the chamber by the decaying turbulent eddies generated by the fans. Stopping the fans before activating the jet reduced the number of particles that collided with the chamber walls and fell to the bottom of the chamber. After allowing the eddies to decay, the drop test was started. The settling rate of 0.3-μm particles is ≈ 0.005 cm/s; thus settling effects in the few seconds before the drop test were negligible.

Visual observations indicated that at high particle loadings the mixtures were optically thick, at least at visible wavelengths, since under these conditions objects inside the chamber that were more than a few centimeters from the window were completely obscured by the particulate "fog." Since the optical properties of the particle-laden mixtures were not measured in this preliminary study, we cannot make quantitative comparisons with theoretical predictions. However, we can make qualitative comparisons, since the particle concentration in the gas increases with increasing mass of particles in the cup. Also, although no direct measurements of optical uniformity were made, the spherical symmetry of

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the resulting flames led us to conclude that the particle dispersion was sufficiently uniform.

Results and Discussion

It was found that all mixtures propagated unsteadily at first but reached quasisteady burning while the flame radius was still small compared with the chamber radius. The initial propagation rate is larger than the quasisteady value, which is probably due to both the ignition energy deposition and Lewis number (*Le*) effects,[1,10] where *Le* is the ratio of gas thermal diffusivity α to scarce reactant mass diffusivity. For 5.25% CH_4-air mixtures, as the particle loading (i.e., the mass of particles in the cup) was increased, S_L decreased at first and then increased. The values of S_L were 2.28, 1.68, 2.07, 2.03, 2.29, and 2.41 cm/s for particle loadings of 0.0, 0.25, 0.50, 0.75, 2.0, and 7.5 g, respectively. This trend is consistent with the hypotheses advanced in the Introduction. In a leaner mixture (5.15% CH_4) at particle loadings of 0.00 and 0.75 g, the burning velocities were 1.70 and 1.30 cm/s, respectively. The latter value is noteworthy because it is lower (by about 15%) than any value attainable in particle-free lean CH_4-air mixtures at 1 atm.[1] This suggests that the addition of sufficient quantities of particles reduces the radiative loss to values below those attainable in particle-free mixtures (since the lower the radiative loss rate, the lower is the steady burning velocity at the flammability limit[5,6]). This in turn suggests that the addition of particles might extend the flammability limit of this mixture family.

Figure 1 shows chamber pressure histories for selected particle loadings. The peak pressure decreases and then increases as the loading increases. The decrease in peak pressure at low loadings is consistent with an increasing radiative loss with increasing loading. The increase at high loadings suggests that some of the emitted radiation is reabsorbed within the gas rather than lost at the walls and indicates that the effect of the thermal capacity of the particles at high loadings does not dominate the effect of additional absorption. Figure 1 also shows that the maximum rate of pressure rise decreases and then increases as loading increases, which is consistent with the trend in S_L.

Figure 2 shows temperature histories at one thermocouple location for varying particle loadings. For each trace, there is a rapid rise in T as the flame front passes the thermocouple junction, followed by thermal decay in the burned gas and finally a slow rise in T as the pressure rise in the chamber compresses the burned gas. Here the rate of thermal decay behind the front is the most important feature, since this decay is closely related to the degree of reabsorption and the nonadiabatic S_L.[5–7] Figure 2 shows that the peak decay rate increases at first and then decreases with increasing loading, these values being about 680, 1070, 930, and 630 K/s for loadings of 0, 0.25, 0.75, and 2.0 g, respectively. The changes in trends occur near the same loadings as those corresponding to the changes in S_L, peak pressure, and rate of pressure rise. The

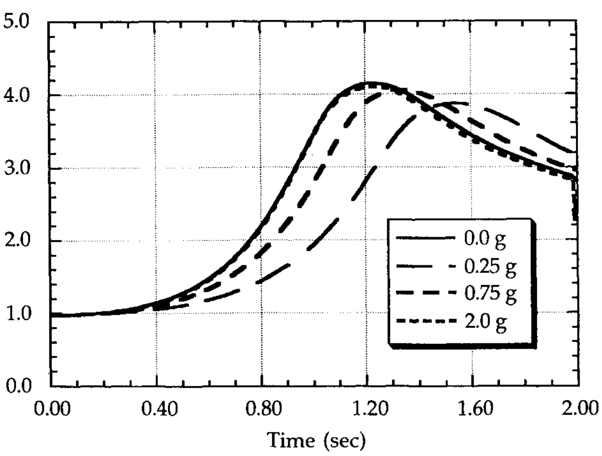

Fig. 1 Measured chamber pressure histories for various particle loadings in 5.25% CH_4-air mixtures at 1 atm initial pressure.

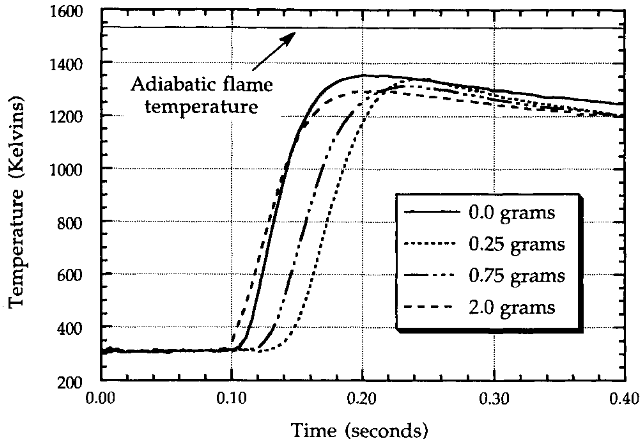

Fig. 2 Measured temperature histories at 2.2 cm from the ignition source for various particle loadings in 5.25% CH_4-air mixtures at 1 atm initial pressure.

increase in decay rate with increasing loading at small loadings is consistent with the hypothesis of increased radiative loss under these conditions. The decrease in decay rate with increasing loading at larger loading is consistent with the hypothesis that the optically thick regime has been reached and the net radiative loss is decreasing.

Figure 2 shows that the flame in the mixture laden with 2.0 g of particles was thicker (by about 50%) than the particle-free flame, although the values of S_L are almost the same (2.3 cm/s) in the two cases. Since theory[10] shows that the flame thickness is proportional to α/S_L, it would appear that α is larger by 50% in the particle-laden mixture. This is further support for the notion that radiant heat transport augments thermal conduction in the optically thick limit.

Although the effects of particle loading on S_L, pressure histories, and temperature characteristics are consistent with theoretical predictions,[7] there are two theoretical predictions that were not observed. First, we did not observe superadiabatic temperatures at the flame front due to radiative preheating of the reactants; all peak temperatures T^* were below T_{ad}. Second, the ratio m of S_L to the burning velocity of the adiabatic, particle-free mixture S_{L0} in the optically thick limit is predicted to be given by[7]

$$m = \exp(B/m); \qquad B \equiv \frac{\sigma(T_{ad}^4 - T_0^4)}{\rho_0 S_{L0} C_p T_{ad}} \frac{E}{RT_{ad}} \frac{\sqrt{1-\omega}}{\gamma} \tag{1}$$

where the symbols E, R, ω, and γ indicate, respectively, activation energy, gas constant, albedo (scattering to attenuation ratio), and a constant ($\sqrt{3} < \gamma < 2$, depending on ω). Using $S_{L0} = 2.3$ cm/s and $E = 44{,}000$ cal/mole for the 5.25% CH_4-air mixture,[1] with other properties calculated from thermodynamics, we estimate $B \approx 89 \sqrt{1-\omega}/\gamma$. For the limiting case $\omega = 0$ (no scattering), $m \approx 16$, i.e., a factor of 16 increase in S_L is possible according to Eq. (1). Even for the unrealistically high value of $\omega = 0.99$, $m \approx 3.8$. These predicted increases in S_L are much larger than those observed experimentally.

These discrepancies might result from the thermal capacity of the particles. At higher loadings, the particles will decrease T_{ad} at least slightly (see Introduction), whereas Eq. (1) was derived assuming zero particle thermal capacity. Evidence of this can be seen in Fig. 2, where T^* decreases monotonically with increasing loading even though at high loadings S_L, peak pressure, and rate of pressure rise increase and the thermal decay rate decreases, all of which would indicate more robust burning. The decreased T^* with increasing loading in the presence of increasingly robust burning suggests a combination of lower loss rates (as discussed previously) and lower T_{ad}. Lowering T_{ad} would lower S_{L0} and thus reduce the maximum (radiation-enhanced) S_L, which would be consistent with the observation of less increase in S_L than theoretically predicted. Detailed measurements of Y and l_p are required to resolve this issue.

Finally, we noticed that the flame fronts appeared to be smoother when particles were added. Lean CH_4-air mixtures have $Le \approx 0.8$ (temperature averaged), which is low enough that they may exhibit diffusive-thermal instabilities[10] that cause flame front wrinkling when Le is sufficiently low. An increase in Le with increasing particle loading might be expected since the radiative transport in the optically thick regime would increase α but would not increase mass diffusivity. The observed trend is consistent with the notion of a higher "effective" Le in particle-laden mixtures.

Conclusions

Experiments in particle-laden gas mixtures were conducted to study flame propagation in both the optically thin and the optically thick regime of radiative transport. Data on flame shapes, propagation rates, peak pressure, maximum rate of pressure rise, and thermal decay in the burned gases were consistent with the hypothesis that at low particle loadings the particles act to increase the radiative loss from the gases, whereas at higher loadings reabsorption of emitted radiation becomes significant. This reabsorption acts to decrease the net radiative loss and augment conductive heat transport. Away from flammability limits, these effects will usually be small because the burning velocities are sufficiently high that the conductive heat flux per unit area of flame front is larger than the blackbody radiant power at the adiabatic flame temperature. In fact, very slow burning flames near flammability limits, using low-gravity conditions to suppress buoyancy effects, were required to observe these effects. Comparison with theory[7] indicated a smaller effect on burning velocity than anticipated, possibly due to the effects of the thermal capacity of the particles. Based on these results, we speculate that in sufficiently large systems, in which the absorption length is much smaller than the system size, flammability limits might not exist at μg conditions because emitted radiation would not constitute a loss mechanism.

Acknowledgment

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Reliability Analysis of Laminated Ceramic Matrix Composites Using Shell Subelement Techniques

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Introduction

An updated version of the composite ceramics analysis and reliability evaluation of structures (C/CARES)[1] integrated design program was developed to use laminated shell elements in the reliability evaluation of ceramic matrix composites (CMCs). In this version of C/CARES, a subelement technique is implemented to improve the modeling of stress gradients within an element to be taken into account. The noninteractive reliability function (see Refs. 2 and 3) is now evaluated at each Gaussian integration point instead of using averaging techniques. As a result of the increased number of stress evaluation points, considerable improvements in the accuracy of reliability analyses have been realized.

Because of the relatively small thickness in comparison to the overall dimensions of typical laminated CMC material systems, components fabricated from this material are conveniently modeled using shell elements. In the formulation of standard shell elements, classical lamination theory is usually adopted to describe the mechanical behavior. Finite element algorithms exactly determine the stresses at the Gaussian integration points of a shell element where the local stiffness matrix is evaluated. For this reason the concept of subelements is introduced in the new version of C/CARES, whereby the risk of rupture intensity is evaluated at each Gaussian integration point instead of using averaging techniques. This method defines a corresponding subelement for each Gaussian integration point. The subelement volume is defined as the contribution of the integration point to the element volume and is determined by the numerical integration procedure associated with the shell element. Thus, each ply in the laminate is divided into subelements, and the risk of rupture intensity function ψ is evaluated for the corresponding stress tensor at each integration point. The number of subelements in each element depends on the element type and on the order of integration chosen. By using the subelement technique, as opposed to averaging the stresses across the element, stress variations within a component can be better modeled. As a

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