The extinction response of strained, atmospheric, premixed methane/air flames was studied experimentally and numerically in the presence of chemically inert particles. The experiments were conducted in normal- and micro-gravity using the opposed-jet configuration and by seeding the particles from the bottom burner. The numerical simulations were conducted by solving the conservation equations of mass, momentum, energy, and species with detailed descriptions of chemical kinetics, molecular transport, and thermal radiation for both phases, along the stagnation streamline of the counter-flow. The experimental data were compared with numerical simulations and insight was provided into the effects of equivalence ratio, strain rate, heat loss, particle size and type, gravity, and flame configuration. It has previously shown experimentally and numerically that for low strain rates larger particles can cool the flames more efficiently compared to smaller particles. Numerical simulations have further shown that this trend is reversed at high strain rates. This prediction was experimentally confirmed in the present study, which also revealed that the crossover point depends not only on the particle size but also on the equivalence ratio of the gas-phase. The micro-gravity experiments, the first ones to be ever conducted for dusty flows, were carried out on board the KC-135 aircraft. The experimental results confirm that the cooling effect of the particles is more profound in the absence of gravity. However, it was found that the effect of gravity on the flame cooling is not caused only by the effect that the gravitational forces have on the particle motion, as one would expect, but also on the effect of those forces on the particle number density distribution. Finally, comparisons between experimental and predicted extinction states were performed for the first time, revealing a close agreement given the various simplified assumptions that are associated with the numerical model. © 2002 by The Combustion Institute

INTRODUCTION

Although there is a wide range of combustion phenomena of interest in which the liquid or solid phase interacts with the gas-phase, much less effort has been devoted to two-phase reacting flows compared to pure gaseous flows. And of those, most of the attention has been paid to sprays and less attention has been given to dusty reacting flows.

The dynamics of dusty flows filled with reacting particles can be very complex, but even inert particles can alter the flammability and extinction limits of combustible mixtures through the dynamic and thermal couplings between the two phases. The presence of Stokes drag, phoretic, and gravitational forces on the particles all affect the dynamic behavior of both phases. At the same time substantial temperature differences between solid and gas phases can develop because of the large difference in the thermal inertias of the two phases.

The understanding of the dynamics and structure of two-phase flows can be ideally attained by using the stagnation flow configuration as it can be conveniently produced in the laboratory and can be simulated with the use of detailed descriptions of all the physico-chemical processes in both phases [e.g., 1–5]. The need for a hybrid Eulerian-Lagrangian approach in numerical studies has been identified by Continillo and Sirignano [1], and has led to the prediction of the phenomenon of droplet flow reversal, which has been observed experimentally [3]. Gomez and Rosner [4] have conducted a detailed study on the particle response in opposed-jet configurations to determine thermophoretic diffusivities. Sung et al. [5] have numerically studied dusty flows in counter-flow configurations, with emphasis on the dynamic coupling. In previous studies on reacting dusty flows [e.g., 4, 5], the thermal coupling between the two phases and the effects on the extinction states were not considered. The effect of gravity on these flows also can be significant.

In Ref. [6] the authors addressed numerically for the first time in the counter-flow configuration the thermal coupling between chemically
inert particles and the gas and also its effects on the dynamic behavior of the two phases, which led to extinction. The effect of gravity was only partially addressed by showing that it can substantially affect the profiles of the particle velocity, number density, mass flux, and temperature. The work reported in Ref. [6] was devoted mainly to the development of a model for reacting dusty flows along the stagnation streamline and the use of the model to provide some insight into the underlying physics. However, several simplifying assumptions were introduced to preserve the one-dimensional nature of the simulations. Clearly these assumptions need to be experimentally tested.

In a subsequent investigation [7] the authors reported on experiments conducted in the counter-flow configuration in which premixed and non-premixed flames were extinguished by inert particles. The experiments included the development of an involved particleSeeder appropriate for use at both normal- (1-g) and micro-gravity (μg). Extinction results were obtained only at 1-g and at low strain rates. Numerical simulations were used to provide physical insight into the observed cooling effect of the particles. It was experimentally and numerically shown that large particles could cool the flame more effectively compared to small particles. Furthermore, numerical simulations showed that at large strain rates this trend can be reversed as small particles were found to cool more effectively compared to large particles. Experimental verification of this observation, however, was not provided. In the same study [7] it was also shown that the complexity of the coupling between the various parameters in such flows does not allow for simple meaningful scaling that can capture all the pertinent physics of the problem.

The objective of the present work was to extent the previous studies [6, 7] to provide experimental data on flame extinction by inert particles in microgravity for the first time and confirm previously stated hypotheses based on numerical predictions or simple physical arguments. The latter was achieved by extending the parameter space of the experimental studies compared to previously reported ones. Finally, it also was one of the main objectives of this work to provide a quantitative comparison between experimentally determined and numerically predicted extinction states. Such comparisons would provide evidence on whether the particle model that has been introduced into the gas-phase counter-flow code is a reliable representation of the experiments. As it will be also shown, simulating the extinction conditions can be complicated especially when particle reversal occurs, and this study aimed to resolve this issue as well.

**EXPERIMENTAL APPROACH**

The details of 1-g experimental configuration have been reported in Ref. [7]. It includes the use of two counter-flowing jets issued from two opposing nozzles of diameter D equal to 22 mm, which establishes an axisymmetric stagnation flow. The system was designed so that only the lower jet is seeded with particles. The seeding was achieved through the use of a piston-driven particle feeder similar to that proposed by Goroshin et al. [8]. Figure 1 is a schematic of the stagnation flow conditions in the presence of particles. This approach allows for the establishment of either one or two flat flames (premixed or non-premixed) depending on the chemical composition of the two jets. The presence of the particles has no effect on the flame shape that is always maintained to be planar, similar to gas-phase experiments, to satisfy as closely as possible the assumptions of the numerical model [6]. Two nozzle separation distances, L, were used, that is, L = 9 mm and L = 14 mm, depending on the experiment conditions; the value of L is reported in all figures. The flow rates were measured through the use of calibrated sonic nozzles. The experimental assembly used for the μg measurements is similar to the one used for 1-g tests, but it does not include the laser Doppler velocimetry system and the related computer interface. Thus, the strain rates studied in μg were characterized by their global values, $K_{gh}$, which is defined as the ratio of the nozzle exit gas injection velocity, $u_{g,inj}$, to L/2, which is the distance between the nozzle exit and the stagnation plane. The burner assembly was housed within a sealed experimental rig appropriate for tests on board NASA’s KC-135 airplane.

The burners are 35-cm long straight tubes,
containing honeycomb and 2 layers of steel screen to break up vortices and laminarize the flow. In addition, co-flowing air is introduced around both burners to minimize shear-layer effects. The co-flow also keeps the flames from attaching to the edges of the burners, which may cause overheating. A cooling coil is wrapped around the top burner, which is exposed to the hot combustion products. In 1-g, cold water is constantly run through the coil to keep the top burner cool. In μg, water-cooling was not used as the experimental times are quite short to cause any noticeable heating of the upper burner. Chemically inert aluminum oxide (Al₂O₃) and nickel-alloy (Ni-Cr, 84%Ni per mass) particles were used as test particles. Although Ni-Cr is combustible, it does not ignite at the prevailing temperatures of the fuel-lean flames that were studied in this investigation. The Al₂O₃ particle diameters, d_p, were 25 and 60 microns, while for the Ni-Cr particles d_p = 20 and 37 micron were used. Particle sizes were determined to be within 2 to 5 micron of the nominal size for 90% of the particles.

The calibration procedure for the particle seeder is described in detail in Ref. [7]. Given that the particle pickup can be strongly affected by gravitational forces, calibrations of the system were performed separately in 1-g and in μg on board the KC-135 aircraft. While calibration and experiments in 1-g were performed with both Al₂O₃ and Ni-Cr particles, in μg calibration and experiments were limited to Al₂O₃ particles because safety considerations forbid the use of Ni-Cr particles on board the aircraft.

Flame extinction experiments were con-
ducted in 1-g, by varying the particle-type, size, and mass delivery rate, as well as the gas-phase equivalence ratio, $\phi$, nozzle separation distance, flame configuration, and strain rate. In $\mu$g experiments, the particle-type and nozzle separation distance were not varied. In 1-g, experiments were conducted by seeding $\text{Al}_2\text{O}_3$ and Ni-Cr particles into methane/air flames. In $\mu$g, experiments were limited to $\text{Al}_2\text{O}_3$ particles seeded also into methane/air flames.

In the twin-flame experiments the flames were positioned symmetrically about the stagnation plane given that identical combustible mixtures were injected from both burners. The particles were added at the bottom burner so that they first reach and, thus, preferentially cool the bottom flame. Subsequently, they may or may not have a chance to directly cool the top flame, depending both on the ability of the particles to penetrate the gas stagnation plane (GSP) and on the particles’ thermal state as they reach the top flame.

The second configuration studied is a single flame established by counter flowing a combustible mixture against an opposing air-jet with the flame being stabilized on the side from which the combustible mixture is injected. Given that the particles are seeded from the bottom burner only, different coupling between particles and flames are expected depending on the side of the GSP in which the flame resides. A single flame is directly cooled by the particles if it is stabilized below the GSP. If the single flame were stabilized above the GSP, only large particles would possess enough inertia to cross the stagnation plane and directly affect the flame. Some limited results on the extinction of flames residing below or above GSP were reported in Ref. [7]. In this study, single flames below the GSP were used to further the investigation on the extinction behavior. Such flames are directly cooled by the particles and other complications associated with the reversal of particles as they cross the GSP [6, 7] are not introduced.

The experiments are performed as follows; the flames are first established at conditions close to their extinction state. Then for the 1-g experiments, the local strain rate, $K$, based on the maximum velocity gradient in the hydrodynamic zone, is measured by using laser Doppler velocimetry. Then the piston seeder is turned on, feeding the particles at a constant rate. The fuel flow rate is then slowly decreased, until the flames are extinguished because of the synergistic effect of the strain rate and the heat loss to the particles. Given that the volume fraction of the fuel is very small compared to the fixed air flow rate throughout this process, the total flow rate and the particle mass delivery rate can be assumed to stay nearly constant throughout the duration of the experiment. To isolate the effect of particle size on flame cooling, the piston speeds were set to deliver equal amounts of mass of different size particles in separate experiments. The accuracy of the data are limited by the 0.5% accuracy of calibration of the sonic nozzles and the $\sim 1$ cm/s accuracy of the LDV. The accuracy of calibration of the particle mass flow rate was found to be within 10%, a value that was determined by repeating the calibration procedure several times.

Note that throughout the text and figures that follow, the local strain rate, $K$, will be used with the 1-g results while the global strain rate, $K_{glb}$, will be used with the $\mu$g results. When 1-g and $\mu$g results are compared the $K_{glb}$ will be used as a measure of the aerodynamic effects.

**NUMERICAL APPROACH**

In an earlier work [6], a set of equations was developed for both phases along the stagnation streamline of the counter-flow configuration. The model includes a quasi-one-dimensional set of equations for the gas-phase similar to those in [9], but including terms describing the dynamic and thermal interactions between the two phases. The solid phase equations were formulated for each particle independently, as the number densities are assumed to be small enough so that particles are unlikely to interact. The axial particle momentum equation includes the Stokes drag, thermophoretic, and gravitational forces acting on the particles (the system configuration is assumed to be vertical so that gravity acts in the axial direction). As the action of gravity and temperature gradients (and thus thermophoretic forces) only exists in the axial direction, the radial particle momentum equation includes only the contribution of the Stokes drag. Similarly, the energy equations for both
the gas and particle phase include terms describing the conductive/convective/radiative heat exchange between the two phases. The model also includes a conservation equation to determine the particle number density. Detailed kinetics [10] were used for the gas-phase, and the code was integrated with the CHEMKIN [11] and Transport [12] subroutine libraries. Solutions were obtained by simultaneously integrating the entire system of equations for both phases. For the integration of the gas-phase equations, an Eulerian frame of reference was used, while the particle equations were integrated in a Lagrangian frame of reference to properly describe particle reversal [1, 6].

The regions of particle reversal have to be dealt with special care, as the particle number density is singular at those points (although the singularity is integrable). Each point of reversal can be thought of as a Particle Stagnation Plane (PSP). These will surround and eventually converge onto the GSP [6]. It was also noticed that in the vicinity of each PSP, the particle velocities are small so that, at equal time steps, the Lagrangian spatial resolution is substantially greater than the Eulerian one. Thus, convergence may not be possible if singular values of particle number densities are mapped from the Lagrangian grid onto a more coarsely resolved Eulerian grid, causing discontinuities in property values and particularly in the phase interaction terms of the gas-phase momentum and energy equations. This problem could be resolved by further refining the Eulerian grid around the PSPs, beyond the level that is required by the gas-phase. To aid convergence, the phase interaction terms, which are discontinuous at particle reversals, were smoothed in the Eulerian grid over a distance of about one twentieth of a flame thickness around the reversal points. Comparisons of the solutions with the previously obtained solutions without smoothing revealed that the smoothing has a negligible effect on the overall flame and particle response, but greatly enhances the efficiency of the computations.

It should be noted that particle reversal did not cause convergence difficulties in our previous studies [6, 7] as only low and moderate particle number densities were considered. However, to simulate extinction conditions, large number densities must be considered and the magnitude of the discontinuity, as imposed by the coupling terms between the two phases, increases significantly making thus, in most cases, the convergence of the gas-phase nearly impossible.

RESULTS AND DISCUSSION

It should be noted that the experimental results derived from this study are the only such available in the literature and constitute a reliable set of archival data against which models can be tested. Thus, the majority of these data are reported in graphical form rather than simply referenced in the text.

Normal Gravity Studies

Flame extinction experiments and numerical simulations were conducted to quantify the extinction of single premixed methane/air flames stabilized below the GSP. In all numerical simulations presented below the gas and particle velocities at the nozzle exits were considered to be equal.

Single-Flames Stabilized below the GSP

In Ref. [7] it was predicted numerically and verified experimentally by using Ni-Cr particles and twin flames that for the same injected solid mass, larger particles could result in better cooling and more effective extinction of the flames as compared to smaller particles below a certain strain-rate value. However, it also was predicted, but not verified experimentally, that smaller particles result in more efficient cooling at higher strain rates. Since then, experiments were conducted by using Al₂O₃ particles at high strain rates. To verify that the same effect could be expected for this new material and for single flames, a computational study was performed.

Figure 2 depicts the variation of the numerically predicted maximum flame temperature (a marker of cooling efficiency) as function of \(K_{ trab} \) for a methane/air flame with \( \phi = 0.75 \) seeded by 25-, 60-, 70-, and 120-micron Al₂O₃ particles. All results shown in Fig. 2 were derived for a constant particle mass delivery rate PMDR = 21.0467 \( \times 10^{-3} \) gm/cm²-s, to isolate the effect of
particle size on cooling. Note that PMDR = \( u_{p,inj} * m_p * n_{p,inj} \), where \( u_{p,inj} \) is the particle velocity, \( m_p \) the particle mass that scales with \((d_p)^3\), and \( n_{p,inj} \) is the number density at the exit of the nozzle. Thus, for the same \( u_{g,inj} \) (recall that in all simulations \( u_{g,inj} = u_{p,inj} \)) \( n_{p,inj} \) was reduced inversely proportional to \((d_p)^3\) as \( d_p \) increased. Thus, for the same strain rate (i.e., \( u_{g,inj} \)) the simulations of the small particles involve larger \( n_{p,inj} \) values, compared to the large particles. Similarly, for the same \( d_p \), \( n_{p,inj} \) was reduced inversely proportional to \( u_{g,inj} \) so that for higher strain rates lower \( n_{p,inj} \) values were involved. Comparing the results for the 25- and 60-micron cases first, it can be seen that at large strain rates (i.e., above 140 \( s^{-1} \)), smaller particles exhibit greater cooling efficiency while the larger particles cool more effectively at low strain rates. The results of Fig. 2 also show that the crossover point also depends on the particle size. For example, as \( d_p \) increases from 60- to 70-micron the crossing point with the 25-micron curve shifts toward a lower strain rate value (about 120 \( s^{-1} \)). For the 120-micron particles there exist no point at which the cooling trend shifts for the range of strain rates reported in Fig. 2.

The numerical predictions shown in Fig. 2 were experimentally confirmed by conducting extinction experiments for strain rates well above the crossover values shown in Fig. 2.

Figure 3 depicts experimental extinction data obtained by seeding with both 25- and 60-micron Al\(_2\)O\(_3\) particles in single premixed methane/air flames stabilized below the GSP. The local strain rate for all cases was measured to be about 216 \( s^{-1} \). In accordance with the numerical predictions, these results indicate that small particles extinguish stronger flames for the same PMDR. As it has been reported in Ref. [7], this trend reversal is because of the fact that at high strain rates, the large mass inertia of the large particles rapidly transports them through the flame leaving little time to remove much heat from the flames. However, small particles have less inertia and effectively decelerate as they approach the stagnation plane. Thus, they reside longer within the flame region and cool the flame more effectively. The shift of the crossover point of the curves shown in Fig. 2 toward lower strain rates for larger particles can be also explained. The larger are the particles the larger is their mass inertia and they do not readily decelerate. Thus, their residence time within the flame zone can be significantly reduced even at low strain rates. For example, the 120-micron particles possess enough inertia and they do not noticeably decelerate as they approach the stagnation plane even at the lowest strain rates considered in Fig. 2.

An important finding of this work was the dependence of the cooling efficiency of the
particles on the equivalence ratio, $\phi$, of the gas-phase. Numerical simulations were conducted for single methane/air flames with different $\phi$ stabilized below the GSP in 1-g, and seeded by 20- and 37-micron diameter Ni-Cr particles. Similarly to the simulations presented in Fig. 2, the strain rate was increased while keeping $\text{PMDR} = 18.19 \times 10^{-3}$ gm/cm$^2$-s. Figs. 4 and 5 depict the cooling effect of the particles for two different flames with $\phi = 0.74$ and 0.85, respectively. The results of Fig. 4 reveal that the 37-micron particles cool more effectively the $\phi = 0.74$ flame relative to the 20-micron particles. However, the opposite is observed for the $\phi = 0.85$ flame as it is shown in Fig. 5. Analysis of the flame structures revealed that in the $\phi = 0.85$ case the 20-micron particles maintain a significant temperature difference between themselves and the gas-phase even within the reaction zone. This is contrary to the $\phi = 0.74$ case for which the temperature of the 20-micron particles closely follows the gas temperature and thus transfer less heat within the reaction zone compared to the 37-micron particles. For both the $\phi = 0.74$ and $\phi = 0.85$ cases the 37-micron particles manage to maintain a large temperature difference with the gas-phase within the main reaction zone. For the $\phi = 0.85$ flame case, the flame temperature and the corresponding thermal expansion of the gas-phase are greater than the $\phi = 0.74$ case within the transport (i.e., preheat) zone that precedes the reaction zone. Thus, the resulting temperature and velocity gradients are higher compared to the $\phi = 0.74$ case. Under these circumstances, the 20-micron particles do not have time to adjust themselves both thermally and dynamically and follow the gas-phase, as they are able to do in the $\phi = 0.74$ case. An indication of this is that in the $\phi = 0.85$ case the gas-particle temperature differences (which drive the gas-particle heat transfer) for both the 37-micron and 20-micron particles are about the same, contrary to the $\phi = 0.74$ case. Given the larger total surface area of the small particles, they cause more effective heat transfer within the reaction region for the $\phi = 0.85$ flame. For the $\phi = 0.74$ flame, the larger particles transfer more heat as they establish a larger temperature difference within the reaction zone, despite their lower total surface area.

Figure 6 depicts a comparison of the experimentally determined and the numerically predicted extinction states for single methane/air flames stabilized below the GSP and seeded with 37-micron chemically inert Ni-Cr particles in 1-g. The predictions of the numerical simulations differ from the experimental results by less than 20%. Given the simplifying assumptions used in the quasi-one dimensional model [6] this agreement is satisfactory. It is also of
interest to note that the simulations systematically overpredict the experimental data. This may result from the fact that the code is quasi-one dimensional and only provides solutions along the stagnation streamline, while the actual flow field may not exactly conform to the assumptions invoked around the centerline. However, the level of agreement realized in Fig. 6 is encouraging in terms of validating the basic assumptions pertaining to gas-particle interactions and which are invoked in the numerical model.

Gravity Effects

Twin Premixed Flames

Micro- and normal-gravity flame extinction experiments were performed for twin premixed methane/air flames seeded with 60-micron Al$_2$O$_3$. To augment the gravity effect, the present experiments were conducted for strain rates that are lower compared to previously reported ones [7] for twin flame extinction at 1-g. The $\mu g$ experiments were conducted for the same $K_{glb}$ and PMDR compared to 1-g. The $K_{glb}$ was kept the same by using the same $u_{g,inj}$ in both $\mu g$ and 1-g. The PMDR was kept the same by adjusting the piston speed of the calibrated particle seeder to match the PMDR achieved in 1-g. Recall that for the same gas flow rate and feed piston speed the PMDR in $\mu g$ is greater compared to 1-g [7].

Figure 7 depicts the variation of PMDR with the extinction equivalence ratio, $\phi_{ext}$, for a fixed $K_{glb} = 48 \text{ s}^{-1}$. It can be seen that for the same PMDR the particles extinguish stronger flames in $\mu g$ compared to 1-g. The results also reveal that the slope of the 1-g curve is less than the slope of the $\mu g$ curve. This means that while there is a strong effect of gravity for the smaller PMDR, gravity effects become increasingly less important for larger PMDR. To understand the reasons behind these observations, numerical simulations of the experimental conditions reported in Fig. 7 were carried out and are presented next.

Figs. 8a and 8b depict the velocity profiles of the gas and the particle phases along the stagnation streamline for the two 1-g and $\mu g$ points that are labeled as (a) and (b), respectively in Fig. 7. In these two figures, the $\phi$ values are the same as the experimental values but the PMDR is slightly smaller than the experimental extinction value of $50 \times 10^{-3} \text{ gm/s}$. This was done intentionally to observe the conditions just before extinction and to reveal the underlying physics. It is seen that particles can barely reach and cross the GSP in 1-g. The Stokes drag that pushes the particles upwards (i.e., to the right in Fig. 8) is opposed by gravity (which exerts a force to the left in Fig. 8). Thus, while these
particles cool the bottom flame directly, they do not reach the top flame, which is therefore only indirectly affected by the particles. In the μg case, however, particles can penetrate deep into the opposing jet and remove heat from the top flame directly. This readily explains why the same particle mass delivery rate extinguishes stronger flames in μg. It should also be realized that in one of our previous studies [6] it was shown that gravity might also have a strong effect on the particle mass distribution in the flow field. This effect will be discussed in more detail in a later section.

Similar numerical simulations were performed for larger PMDR and $\phi$ values corresponding to the two data points labeled as (c) and (d) in Fig. 7. These results are shown in Figs. 8c and 8d, respectively. Again it is apparent that particles can penetrate deeper into the opposing jet and cool the top flame directly in μg compared to 1-g, leading thus to more effective cooling in μg. While the fact that particles extinguish stronger flames in μg can be readily understood, the physical mechanisms affecting the change in slope between the 1-g and μg curves is more elusive.

Fig. 8. Numerically determined spatial variation of gas and particle phase velocities at low and high equivalence ratios in 1-g and μg, and for $L = 14$ mm.

Comparing the 1-g results in Figs. 8a and 8c [data points (a) and (c)], it can be seen that in Fig. 8a (low $\phi$ and PMDR) the maximum reach of the particles is just past the GSP. On the other hand Fig. 8c (high $\phi$ and PMDR) depicts that the particles penetrate significantly beyond the GSP compared to Fig. 8a and thus, approach closer to the top flame. This is a result of the stronger thermal expansion resulting from the higher flame temperature that corresponds to the higher $\phi$. The stronger thermal expansion generates a zone of larger acceleration in the gas-phase, which through the action of Stokes drag accelerates the particles to the point that they cross the GSP with higher inertia, reaching deeper into the opposing jet.

Comparing the μg results of Figs. 8b and 8d, it can be seen that there is an additional effect that causes gravity to have a weaker effect on extinction as PMDR increases. It is seen that the behavior of the particles is almost the same despite the significant differences in PMDR and $\phi$. Furthermore, the distance that the particles reach into the opposing flow is the same regardless of the different strengths of the thermal expansion in these two flames. In this case, the particle reversal is caused by the opposing jet flow that the particles encounter as they cross the GSP. Also note that the velocity fields of the gas-phase are not affected directly by gravity. The particle reversals seen in Figs. 8b and 8d occur in the post-flame region between the two flames. Given that the particle dynamic response is rather sensitive to the gas-phase velocity gradients, a distinction must be made between the response of the particles within the thermal expansion zone (i.e., preheat zone) and the decelerating zone as a fluid element approaches the stagnation plane in the post-flame region. The dynamic response of the particles around the PSP’s in Figs. 8b and 8d is controlled by the gas deceleration in the post-flame region that is not affected to the first order by the augmented thermal expansion as $\phi$ increases. Analysis of the flame structures indeed reveals that there is a minor change in the gas velocity gradient in the post-flame region for both the low and large $\phi$ shown in Fig. 8. This is because at higher $\phi$’s, the flame temperature increases, while the flame speed increases, thus displacing the flame further away from the stagnation plane. The combination of these two factors result in a second order effect on the velocity gradients in the post-flame regions. Furthermore, at μg the motion of the particles is not opposed by gravity. As a result they possess more momentum, they do not decelerate noticeably as they approach the preheat zone, and
their dynamic response is less affected by the expansion zone of the first flame that is encountered below the GSP. This is contrary to the 1-g case in which particles do decelerate as they approach the preheat zone, thus making them more susceptible to the effect of thermal expansion of the first flame below the GSP.

The effect of particle size was also assessed by conducting experiments at μg and 1-g using 25-micron size Al₂O₃ particles at \( K_{glb} = 48 \text{ s}^{-1} \). The PMDR values were once again adjusted through the calibrated particle seeder to match the conditions of 1-g, resulting in sets of data obtained in 1-g and μg under the same strain rate and PMDR. The results are presented in Fig. 9. It is clear that for the same values of PMDR and strain rate (i.e., nozzle exit velocity), stronger flames are extinguished in μg compared to 1-g. A comparison with the results obtained for 60-micron particles that were shown in Fig. 7 reveals that the effect of gravity is reduced for 25-micron particles. This behavior is anticipated as the 25-micron particles are lighter and their response is mostly affected by the Stokes drag and less by gravity compared to the 60-micron particles.

Figure 10 depicts the results of flame extinction experiments conducted in μg for twin flames seeded with 25- and 60-micron Al₂O₃ particles at \( K_{glb} = 48 \text{ s}^{-1} \). The particle seeder speeds were adjusted using the calibration curves to obtain sets of data with the same values of PMDR for the two different size particles. This was intentionally done to isolate the effect of particle size. It is observed that larger particles have stronger cooling effect on the flames compared to smaller particles as they extinguish stronger flames for the same PMDR and strain rate. The explanation for this behavior is similar to the one reported earlier in the discussion pertaining to Fig. 2 as well as to similar observations reported in Ref. [7].

Figure 11 depicts results of flame extinction
experiments that are similar to the ones presented in Fig. 10, but at a lower $K_{glb} = 37 \text{ s}^{-1}$. In fact this strain rate is so low that it is not possible to conduct the corresponding 1-g experiments simply because such small flow rates cannot effectively entrain particles into the flow against gravity. Again, it is seen that larger size particles cool the flames more effectively. Comparisons of these results with the relatively higher strain rate experiments presented in Fig. 10 reveal that the particle size effect on $\phi_{ex}$ is more profound at the lower strain rates shown in Fig. 11. Physically this happens for two reasons. First, the burning velocity of lean methane/air flames decreases as the strain rate is reduced [13], since the effective Lewis number is less than unity. The second and most important reason is that decreasing the strain rate increases the particle residence time within the flame zone, allowing for more effective cooling by the particles. Note that the thickness of the flame zone is not affected to the first order by the strain rate.

**Single-Flame below the GSP**

Figure 12 depicts experimental extinction results for single flames stabilized below the GSP in $\mu$g and 1-g, with 25-micron and 60-micron $\text{Al}_2\text{O}_3$ particles, and for $K_{glb} = 48 \text{ s}^{-1}$. It is observed that stronger flames are extinguished in $\mu$g than at 1-g for the same particle mass delivery rate. Similar observations were reported in the twin-flame section and the explanation was based on the fact that in $\mu$g particles can cross the GSP and penetrate further into the opposing flow. This results in a more effective cooling of the flame that resides above the GSP. However, this argument is not applicable to the case of a single flame residing below the GSP. The physical mechanism behind such behavior is explained by an observation reported in Ref. [6]. Gravity can affect the particle number density distribution within the flame. Figure 13 depicts the spatial distribution of the scaled particle number density ($n_p/n_{p,inj}$) for 60-micron $\text{Al}_2\text{O}_3$ particles. It can be seen that in $\mu$g the particle number density is larger (by 20 to 25%) within the reaction region than at 1-g, thus leading to more effective cooling. Physically this happens because in the absence of gravity the particles possess large momentum as they approach the stagnation plane and they decelerate at a lower rate compared to 1-g. Thus, in $\mu$g the particles are less responsive to the thermal expansion within the flame, which tends to reduce the particle number density [6]. This is because the closer the velocities of the two phases follow each other, the more similar is the variation of the gas density and particle number density. In 1-g, the particles decelerate more effectively and they are more responsive to the thermal expansion that results in a reduction in both the particle number density and the gas density.
Figure 14 depicts experimental flame extinction results conducted in μg for single flames stabilized below the GSP as well as for twin flames seeded with 25- and 60-micron Al₂O₃ particles. It can be seen that the same PMDR values lead to the extinction of stronger flames in the single flame configuration as was also shown in Ref. [7]. This is anticipated because the twin flames are adiabatic while the single flames experience downstream heat loss to the counter-flowing air stream. However, it is noticeable that the particle size does not have as strong an effect in single flames as they do in twin flames. It should be realized that in the single flame configurations, the competition of the total particle surface area and the temperature difference between gas and particle phases within the flame largely determines which size cools more effectively. On the other hand, in twin-flame configurations the ability of the particles to reach the top flame is an important parameter, and while the 60-micron particles indeed reach the top flame the 25-micron particles do not. Thus, the effect of particle size is more apparent in twin-flame configurations.

**CONCLUDING REMARKS**

A comprehensive study was conducted to quantify the extinction of strained premixed methane/air flames by inert particles in the counter-flow configuration. The study was both experimental and numerical in nature and it describes the effects of varying the equivalence ratio, flame configuration, strain rate, and gravity, as well as the particle type, size, and mass delivery rate.

The results were obtained for conditions that are distinctly different than previous investigations. In particular, the micro-gravity experimental data are the first to ever be reported in the literature and constitute an important archival set of data for validating models and for deriving physical insight in two-phase reacting flows.

In the present investigation it was convincingly shown that while large particles cool a flame more effectively than small particles at low strain rates, at high strain rates this trend is reversed. Numerical simulations previously have predicted this reversal, but the present study provided experimental confirmation. Furthermore, it was shown that the strain rate crossover point at which this reversal occurs depends not only on the particle size but also on the equivalence ratio. This behavior was explained based on the effect of particle residence time within the flame zone as well as on the effect of the gas-phase thermal expansion on the particle dynamic response.

Comparisons between flame extinction data obtained in 1-g and μg revealed that in the absence of gravity the particles cooling efficiency is larger than at 1-g, for both twin and single flames. However, the physics controlling the cooling efficiency in these two flame configurations was found to be different. In the twin flame configuration the effect of gravity on the particle momentum was found to be responsible for the augmented cooling efficiency. However, in the single flame configuration the effect of gravity on the spatial distribution of the particle number density within the reaction zone was found be the pertinent mechanism.

Experimental results showed that the difference in the extinction behavior between μg and 1-g is less significant for smaller particles because their dynamic response is primarily affected by the Stokes drag rather than gravity. Comparisons of high and low strain rate experimental results revealed that the particle size has a more profound effect on extinction at low strain rates because of Lewis number and residence time effects. It was also found that in-
creasing the particle mass delivery rate has a more profound effect on the extinction equivalence ratio in 1-g than in μg.

It was found that particle size does not have as strong an effect in single flames as it does in twin-flames. This is because in single flame configurations, the competition of the total particle surface area and the temperature difference between phases in the flame region primarily determines the particle size that cools more effectively. In twin-flame configurations, however, the ability of the particles to reach the top flame is more important.

Finally, the experimentally and numerically predicted flame extinction results agree to within 20%. This is remarkable, given the simplifying assumptions that are included in the independently-developed numerical model. Such comparisons are the first ones to be reported in the literature.

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REFERENCES