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Quenching Dust Mixtures: A New Microgravity Testing Method Using Electric Particulate Suspensions

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The electric particulate suspension (EPS) is a combustion ignition system under development at Iowa State University for the evaluation of quenching effects of powders in microgravity (quenching distance, ignition energy, and flammability limits). Both walls and (inert) particles can be tested as quenching media. The EPS method has potential as a benchmark design for quenching powder flames that would provide NASA and the scientific community with a new fire safety standard. Because of its simplicity and size, it is also suitable for tests on the International Space Station and the Mars Rover. The EPS method also supports combustion modeling by providing accurate measurement of flame-quenching distance as an important parameter in laminar flame theory because it is closely related to characteristic flame thickness and flame structure. In microgravity, the EPS method is expected to produce dust suspensions that are highly uniform (before ignition) compared to 1-*g*, where gravity can cause stratification of the suspension. Microgravity will also permit increased concentrations of particles to be tested (for a given electric field strength). Several EPS experiments are reviewed, including *X*–*Y* laser scans for cloud stratification, particle velocity distribution evaluation by the use of particle tracking velocimetry/particle image velocimetry and a leak hole sampling rig, and measurement of particle slip velocity by the use of laser Doppler anemometry. Sample quenching and ignition energy curves are presented for aluminum powder and coal dust. Only ground-based data at 1-*g* are reported.

Nomenclature

C	=	particle random speed, m/s
C_0	=	most probable particle speed, m/s
D	=	particle diameter, m
E	=	electric field strength, V/m; ignition energy, J
E_i	=	ignition energy with inert particles mixture, J
E_{i0}	=	ignition energy for particle-free mixture, J
E_{LL}	=	electric field strength, V/m
F	=	fuel (gaseous)/air ratio, mole/mole
F_d	=	drag force on particle, N
F_{LL}	=	minimum lifting force on particle, N
g	=	standard acceleration of gravity, 9.81 m/s^2
L	=	parallel electrode plate separation distance, m
L_x	=	needle electrode point-plane distance at spark breakdown, m
m	=	particle mass, kg
N	=	particle number density, number/m^3
Q	=	electrostatic charge on particle, C
ε_b	=	coefficient of restitution
ε_0	=	permittivity of free space, F/m
λ	=	particle–particle mean free path

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Introduction

THE electric particle suspension (EPS) method developed at Iowa State University is well suited for flame quenching studies in microgravity, as well as for ground-based studies at 1 *g* (Refs. 1–3). Admixtures containing combinations of inert-combustible powders with inert-combustible gases can be studied in this versatile system.[4–9] Both cold walls and inert particles (copper, glass) can be studied as mechanisms for quenching flames in either batch or continuous feed modes.[4,5,7] Two new variables currently being studied as mechanisms in powder flame propagation are the particle velocity distribution (PVD) and particle slip velocity (relative particle–gas velocity).[1] In microgravity, EPS experiments will permit extrapolation of quenching data to near-field-free values ($E = 0$) and broader fuel–oxidant ratios to be tested by the increase of suspension concentration. The rich flammability limit of powders is of particular interest.

An EPS is generated when either semi-insulating (glass, coal) or conducting (copper, aluminum) particles are charged and driven to oscillate between the parallel plates of a capacitor with dc electric field strengths of the order kilovolt per centimeter.[10] The suspension achieves its high uniformity through particle–particle and particle–wall collisions. The energy supplied by the applied electric field in moving charged particles is dissipated under steady-state conditions by inelastic collisions between particles, particles with walls, and through viscous dissipation of particles moving through the ambient (gas) fluid. Both closed systems (batch feed) and open systems (continuous feed) can be tested.[11] To generate electrical suspensions, bulk powder resistivities less than $10^9\ \Omega \cdot \mathrm{m}$ are recommended to maintain a bulk powder charge relaxation time less than about 10 ms at normal temperatures.[10–13] Once formed, the particle cloud can be ignited by the use of a spark discharge or a Yag laser. (Objects such as ignitors cannot be placed inside the test cell due to the high voltage and disturbance on cloud uniformity; however, in micrograċity with reduced voltage, it may even be possible to incorporate igniter wires.) The EPS method provides up to four independent methods for the measurement of particle concentration, including weighing the powder sample (batch feed), laser beam attenuation in the suspension (batch and continuous powder feeds), bleeding particles from the EPS cell, and current measurement in the external circuit associated with particle charge transport.[12] The first method is preferred for accuracy, whereas the latter method requires a calibration procedure. The particle bleed method utilizes measurement of the particle flux, which requires information on the average particle velocity either from calculation or use of laser doppler anemometry (LDA).[12,14] Use of particle tracking/image velocimetry (PTV/PIV) systems can also be used to find particle velocity and concentration.

In addition to being well suited for powder quenching studies, the EPS method has been used to investigate various thermophysical phenomena including electrostatic precipitation,[15] particle–wall heat transfer,[16] pneumatic transport,[14,17] and particle-cloud dynamics such as particle diffusion and concentration calibration.[5,11,18,19]

The present paper presents a review of combustion testing by the use of EPS for ongoing and previous ground-based studies involving quenching and ignition of powder suspensions. The benefits of EPS in microgravity are discussed. Various aspects of EPS are covered, including different feed designs, ignition methods, and particle-cloud dynamics. Quenching experiments in microgravity will be carried out using the NASA John H. Glenn Research Center at Lewis Field drop tower facility and KC-135 aircraft.[1]

Problems in Powder Ignition Testing

Achievement of a uniform dust concentration has been identified as a key problem to be resolved in dust flame studies.[1−3] The flame quenching distance in dusts is one of the important fundamental parameters in laminar flame theory because it is closely related to the characteristic laminar flame thickness and structure. Whereas the EPS method can produce suspensions of high uniformity under specific operating conditions for high field strengths at 1 *g*, the problem of uniform dust concentration will be minimized in microgravity, permitting the use of reduced fields.

A second problem, the collapse of the suspension during ignition is essentially eliminated in microgravity. This is an important consideration for particle quenching and burning velocity measurements. By contrast, at 1 *g* the collapse of the powder suspension must be designed so that the passage of the flame front is complete before the particles fall through a significant fraction of the height of the test cell. The relevant time constants for spark ignition and EPS formation dynamics (statistical time lag, first and second pulses for sparking, flame front passage, particle–particle collisions, and particle–wall collisions) have been discussed prevously.[5,9]

Additional problems of nonuniformity and transient distributions are encountered in standard techniques used for testing the explosion–ignition characteristics of powders, (for example, tumbling and pneumatic entrainment. The well-known Hartmann-type bomb relies on the dispersion of a charge of dust by the use of an injected gas, whereas the tumbling and open-tube methods of ignition testing depend on gravity-fed dispersions.[20−22] Most transient dust clouds tested at 1 *g* or in microgravity must be measured optically or assumed to have a uniform distribution of particles over the test volume, so that particle concentration can be determined.[23−25] The EPS method in microgravity should overcome the transient problem and offer the possibility of achieving both high uniformity and increased dust concentrations for the investigation of the rich flammability limit of powders.[26]

Electric field effects in microgravity gas flames have also been studied to eliminate buoyancy effects, to investigate chemi-ionized gas pumping by electric fields, and for electrostatic spraying.[27,28]

Field-Free Quenching

Lewis and von Elbe[29] give various references for quenching gas flames with salts. They discuss the importance of a critical surface area to volume ratio of the dust in turbulent flames.[29] Lower melting point salts proved more effective than those with higher melting points for quenching. They note that detonations can also be quenched by particles.

Field-free studies involving quenching and flame propagation mechanisms in dust suspensions have been conducted in microgravity and also in ground-based studies that use open and closed systems.[30−32] Researchers at McGill University use a flow dispersal system in which a powder flame burns from one end of a tube (80 cm in length by 5-cm diam) through a series of parallel plates having variable separation distance in which quenching takes place. The powder dispersion system features acoustic flame damping and a unique powder dispersal method developed from McGill University's current NASA and CSA research programs.[1,33]

EPS Designs

Roesgen studied an electrical confinement technique using charged particles in microgravity.[34] Figures 1–5 show basic EPS configurations used by Colver et al. for studies involving quenching distance, ignition energy, flame burning velocity, and flammability limits.[35,36] A suspension is generated by the application of an electric field between the parallel wall electrodes, followed by ignition of the cloud by a spark discharge from either a moving or stationary needle electrode.[8,9] High voltage (adjustable or fixed) capacitors provide the necessary magnitude of stored energy for the spark. A quenching test is carried out by adjustment of the distance between the electrodes and by checking for flame propagation (go/no-go) after the spark. Quenching by inert powders is accomplished similarly, by suspension of various amounts of copper or glass particles, together with a combustible powder or gas mixture and ignition of the mixture.[4] Figure 2 shows the use of acoustic vibration as an aid in forming more difficult suspensions consisting of small or cohesive particles such as coal dust.[6,7]

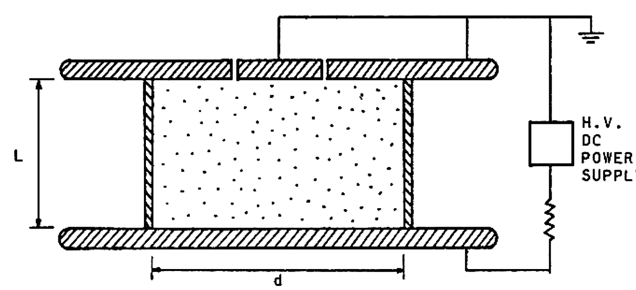

Fig. 1a Batch feed, closed system with Pyrex cylinder walls.[6,7]

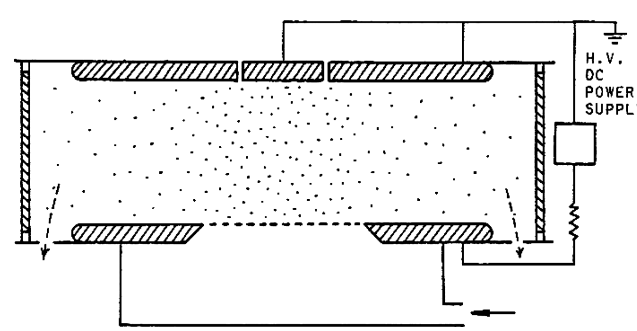

Fig. 1b Continuous feed, open system.[6,7]

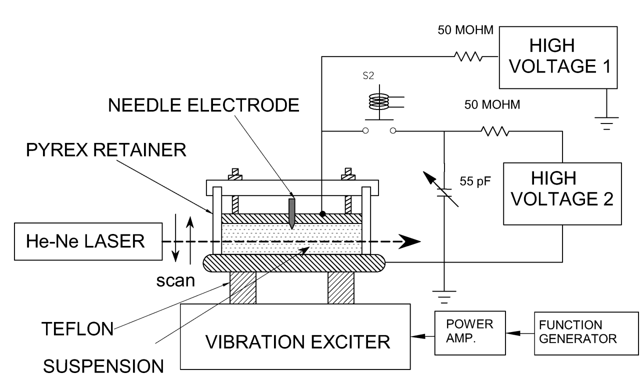

Fig. 2 Batch feed, closed system with Pyrex cylinder walls: tests for quenching, ignition energy, and flammability limits.[6,7]

The continuous and batch feed systems shown in Figs. 1a, 1b, and 2 have been used for detailed combustion studies. The special high-voltage relay switch in Fig. 2 triggers a spark kernel and outward propagating cylindrical flame. The external fixed or adjustable high-voltage capacitor (~55 pF) provides the necessary stored energy 1–10 J to ignite typical powders at voltages of 10–20 kV, even with radiation and shock losses associated with sparks. Particle motion (speed) in the vertical direction is controlled independently by a second high-voltage power supply shown in Fig. 2. The particles are confined and oscillate between the parallel plate electrodes or can be (optionally) retained by a Pyrex or quartz cylindrical retainer. Figure 3 shows a photograph of a quench (batch) test of aluminum powder, 25–35 μm, that resulted from the use of the system in Fig. 2 (Refs. 6 and 7).

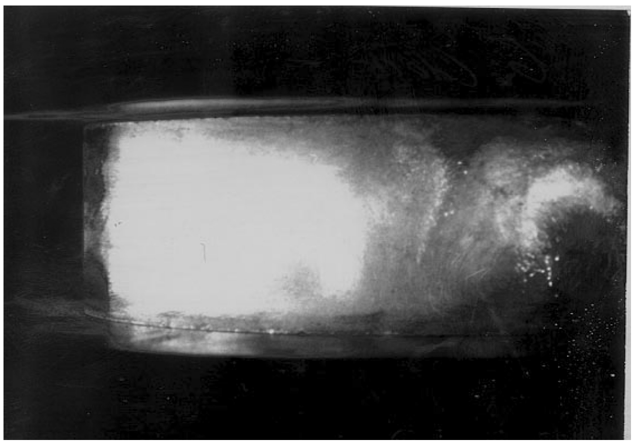

Fig. 3 Flame quenching test (batch feed); aluminum powder 25–35 μm.[6,7]

The unconfined (approximately one-dimensional) continuous open-flame systems in Figs. 4 and 5 have proven difficult to stabilize and also to quantify.[6,7] The system in Fig. 4 incorporates an auger makeup of particles and "open" flame stabilizing (no wire mesh), whereas Fig. 5 uses a piston reservoir makeup of particles and a wire mesh to help stabilize the flame.[6,7] In both systems, particles are driven from the surface of a packed bed by the electric field upward into the flame front together with gas flow. The particle and air (or oxidant) flows are adjusted independently, which offers the possibility of controll of the relative velocity between the particles and oxidant. This feature of controlled relative motion between particle and oxidant can also be exploited in confined system ESP designs (Figs. 1 and 2) and is one aspect of our present research effort. Shoshin and Dreizin have successfully stabilized various metal powder flames 3–5 cm above the upper plate of an open EPS system, similar to that in Fig. 4, by introducing secondary airflow around the outside of the powder jet and making adjustments in primary (inner) airflow and powder feed rate.[37]

A one-dimensional unconfined theory for feeding particles is given by Colver.[11] Unconfined EPS flows have been successfully utilized in various noncombustion applications including electrostatic precipitation for the capture fly ash with charged particles and

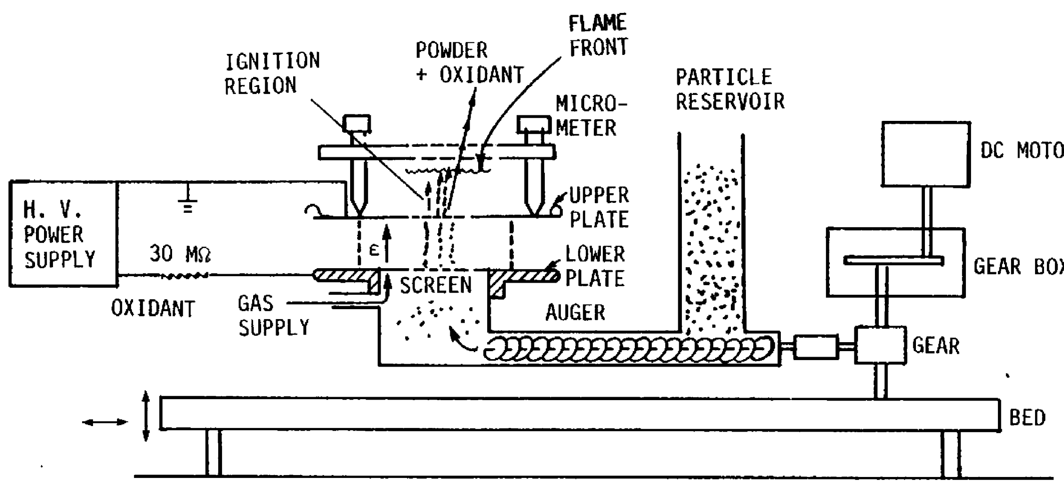

Fig. 4 Continuous (auger) feed, open-flame system; steady-state flame produced.[6,7]

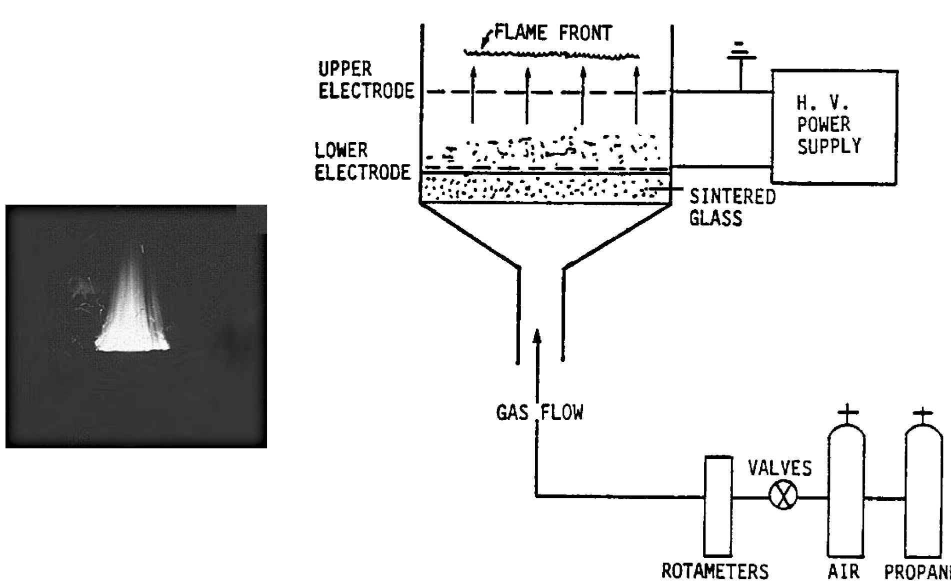

Fig. 5 Continuous (piston) feed, aluminum–air, open flame system.[6,7]

the measurement of PVD in which particles are leaked from the EPS test cell.[11,12,15]

Combustion Experiments at 1 *g*

Powder Quenching

Our powder (wall) quenching studies to date include the measurement of quenching and ignition energy curves for aluminum powder and coal dust in various admixtures of oxygen, nitrogen, and carbon dioxide at ambient conditions of temperature and pressure. Typical quenching and ignition curves for coal dust and aluminum powder are shown in Figs. 6 and 7, respectively, by the use of the setups of Figs. 2 and 8 (Refs. 6–9). For example, aluminum powder, 25–30 μm, in concentrations of 150–3300 g/m^3 was tested in admixtures of oxygen, nitrogen, and carbon dioxide (mole ratio 0.21). These data are curve fitted in Fig. 6. Such flammability curves have been developed for lean to stoichiometric powder mixtures.[7,9] For smaller cohesive particles, 17.5-μm spherical aluminum particles and 16.7-μm Illinois-6 coal, the quenching tests were conducted in the acoustic system shown in Fig. 2. Results from such tests indicate that both the quenching distance and lean flammability limit increase with particle size, whereas the quenching distance of coal is observed to decrease with increasing volatile content. Figure 8 shows the actual ignition of 17.5-μm spherical aluminum powder at a plate separation distance of about 15 mm. In this rig, the voltage is varied from 7 to 18 kV ($\sim$0.8 kV/cm) to disperse the aluminum particles at 1 *g* (Ref. 7).

Figure 9 shows the ignition of a propane–air mixture by the use of 96-μm copper particles as quenching media in a spark ignition energy study (plate separation distance about 1 cm).[4,9] The high-speed moving electrode system in Fig. 10 was used. A high-speed "injected" moving needle is also visible at upper plate, and the Pyrex® glass and copper electrodes give reflections from the spark. Streaks of particles are apparent following ignition from the spark between the high-voltage electrodes. Once breakdown occurs, the suspension collapses with the field. However, the particle motion persists over times needed (typically meter seconds) for passage of the flame front.[5] As noted earlier, the problem of collapse of the suspension following the spark is eliminated in microgravity.

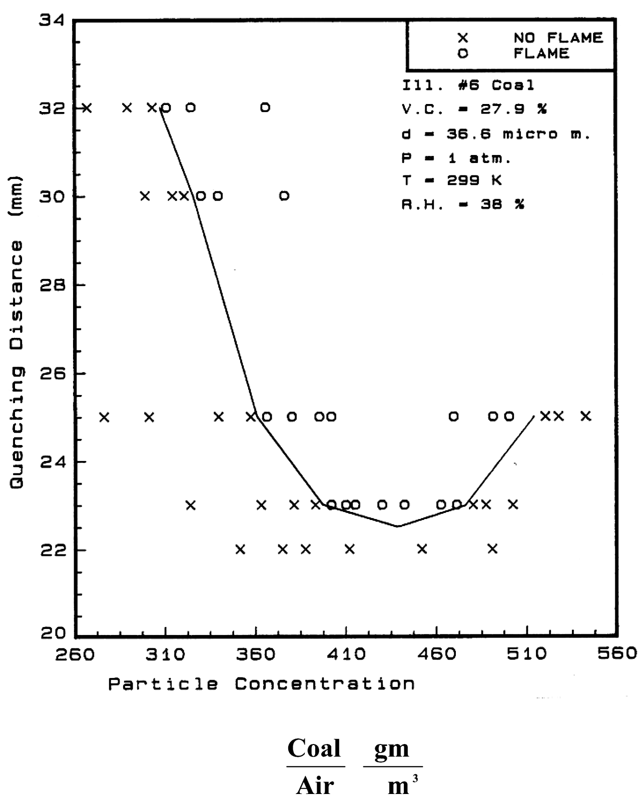

Fig. 6 Quenching distance (millimeters) vs fuel–air ratio 36.6-μm Illinois-6 coal.[7]

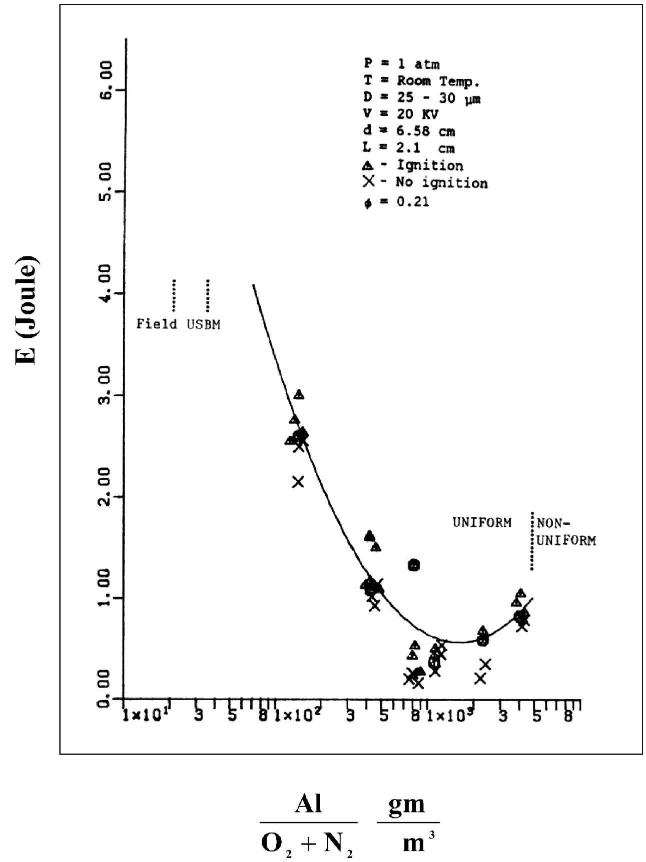

Fig. 7 Spark ignition energy (joules) vs fuel–air ratio, 27.5-μm aluminum.[7]

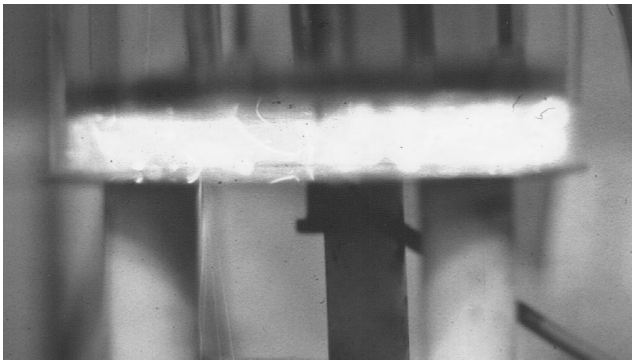

Fig. 8 EPS quenching test cell, ignition of 17.5-μm spherical aluminum powder (spark at center) at plate separation of 15 mm.[7]

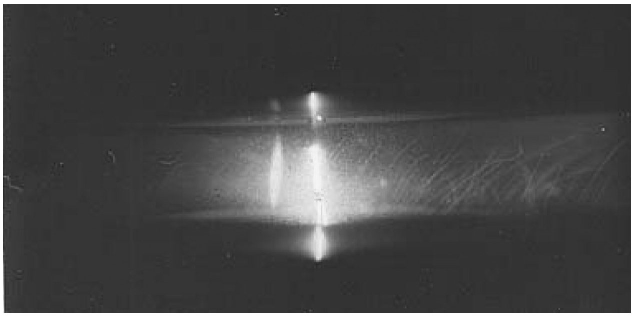

Fig. 9 EPS method: Quenching mixtures of propane–air with 96-μm copper particles in spark ignition energy study with trails of copper particles clearly visible.[4]

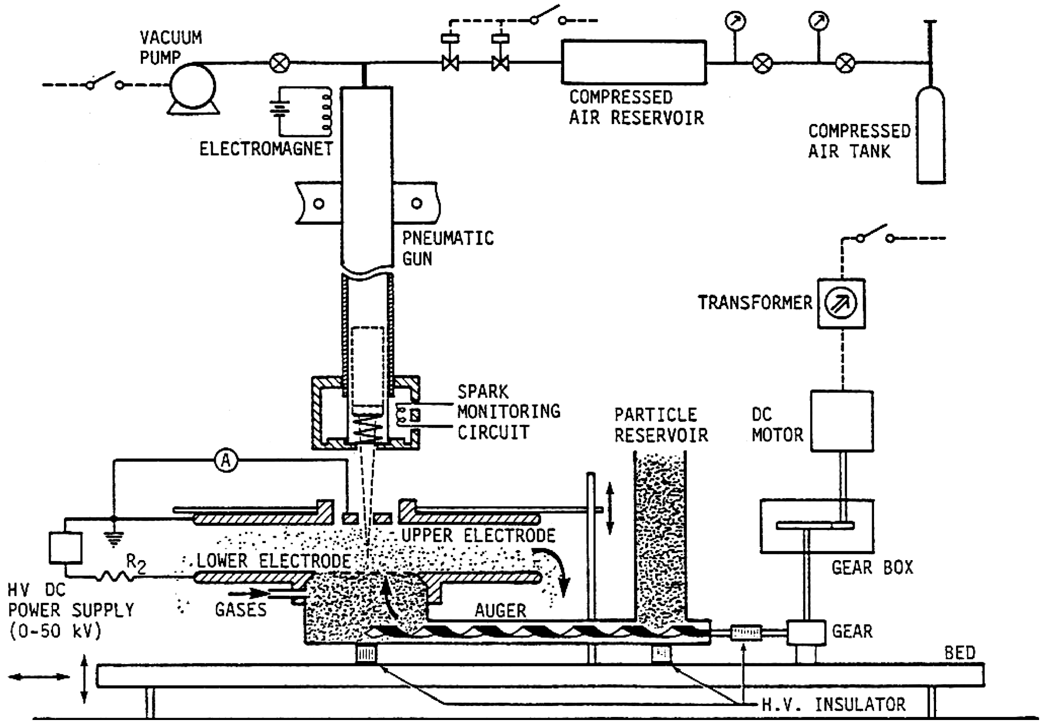

Fig. 10 Batch (with Pyrex glass cylinder) or continuous feed: test spark voltage breakdown, ignition energy, flammability limits with inert copper particles.[4,5]

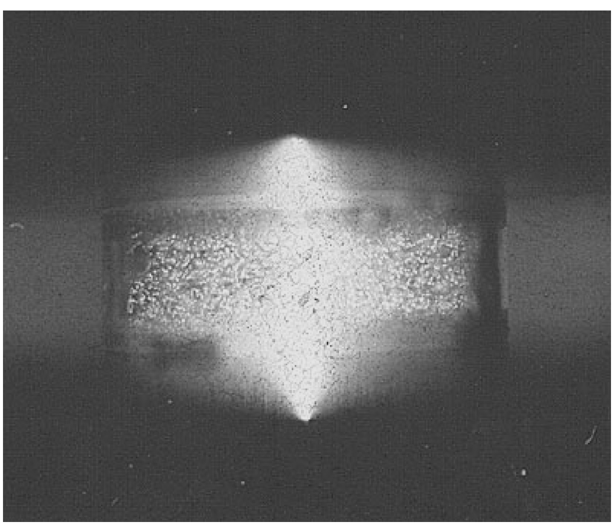

Fig. 11 Spark breakdown in copper–air mixture (batch feed).[4]

Spark Ignition Energy

The EPS experiment shown in Fig. 10 is used to investigate spark ignition energy and quenching of propane–air mixtures in the presence of copper particles.[4,5,9] Figure 11 shows spark breakdown in a copper–air mixture (batch feed).[4] This unique system utilizes a high-speed moving electrode ($\sim$10 m/s) to trigger the spark to preserve the uniformity of the suspension before breakdown. Yu found for copper particles that the parameter ND^2 (N, particle number density, and D, particle diameter) was important for gas ignition.[4] The quenching effect of particles is clearly shown in Fig. 12 for propane–air mixtures because greater ignition energy is needed for either higher values of particle concentration N or particle diameter D. (E_{i0} is the energy required to ignite a particle-free propane–air mixture for the same fuel–air ratio.

Suspension Dynamics

PVD

The PVD in Fig. 13 associated with randomized motion from particle–particle and particle–wall collisions was investigated by

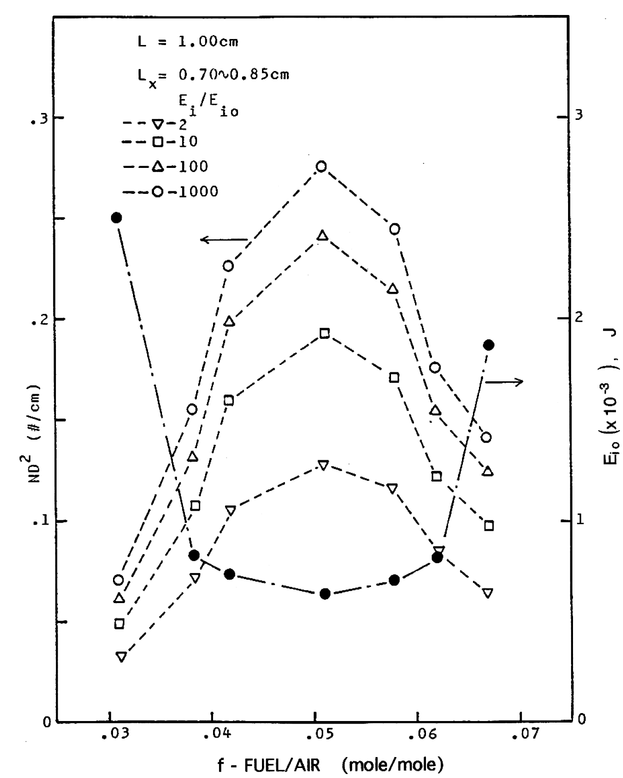

Fig. 12 Ignition energy and ND^2 parameter for quenching copper–propane–air mixtures.[4]

Colver and Ehlinger.[12] Particles were leaked from a 1.61-mm hole located in the top of the test cell (Fig. 14a). Their data shown in Fig. 14b give a reasonably good fit to an assumed Maxwellian speed distribution, Eq. (1):

$$\frac{\mathrm{d}N}{\mathrm{d}C} = \frac{4N}{C_0\sqrt{\pi}}\left(\frac{C}{C_0}\right)^2 \exp\left[-\left(\frac{C}{C_0}\right)^2\right] \tag{1}$$

For the constants in Eq. (1), they give $C_0 = 68$, 76, and 149 cm/s, respectively, for 44–53-, 63–75-, and 105–125-μm copper spherical

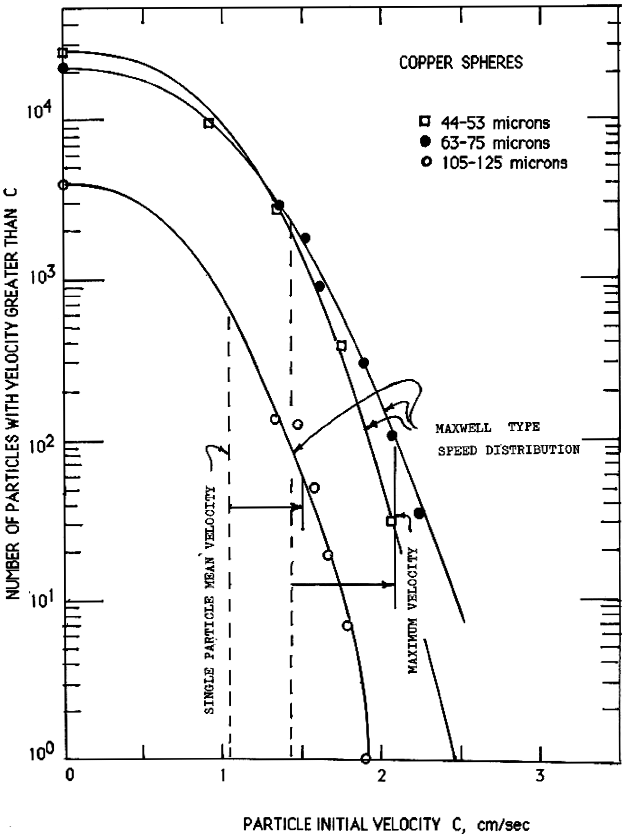

Fig. 13 Particle speed distribution in EPS approximates fitted to Maxwellian curve at 1 g (Ref. 12).

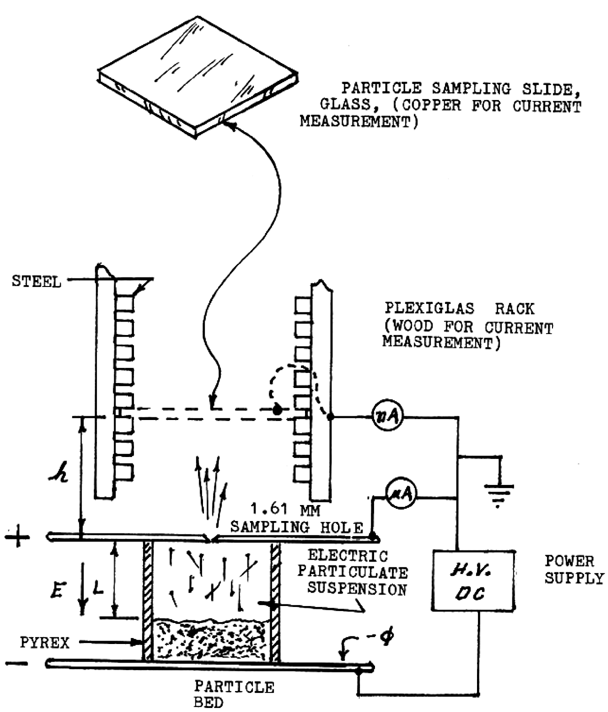

Fig. 14a Particle sampling rig.

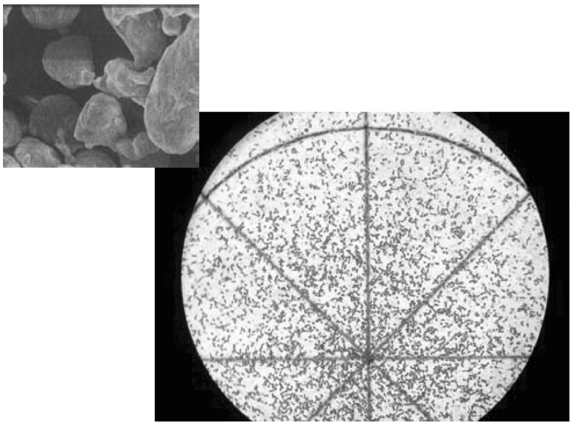

Fig. 14b Aluminum particles, 63–74 μm, under microscope for hand counting.[12]

Fig. 15a PTV velocity vectors from 20–25-μm aluminum particles calculated by software.

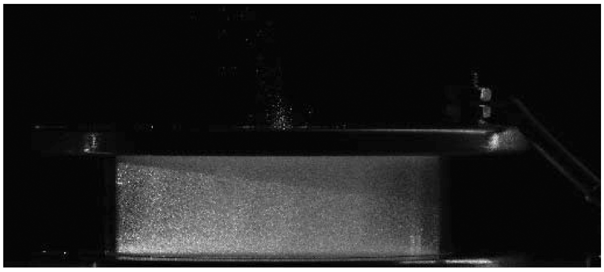

Fig. 15b PTV–charge-coupled device image of 20–25-μm aluminum particles leaked (top plate center) from 1.92-mm-hole EPS test cell.[38]

particles at electric field strengths of about 12 kV/cm. A recent study by Eimers expanded on this study.[38]

Figures 15a and 15b show the EPS system and velocity vectors from 100-μm copper spheres leaked from an EPS cell by the use of PTV and a LaVision Flowmaster System. The test is similar to the PVD experiment just described, in which particles are leaked from a 1.92-mm hole. The PTV/PIV pulsed laser sheet is formed from the laser beam by an imaging cylindrical lens and directed as a plane above the leak hole. The DaVis5.2 (LaVision) software computes the velocities of the particles exiting the hole using the distance traveled between successive laser pulses.

Stratification of Dust Clouds at 1 g

An advantage of microgravity is the expected formation of highly uniform suspensions. Particle forces from gravity at the lower electric field strengths will induce stratification in the cloud as noted earlier. Cloud stratification is similar to the decrease in gas density observed with elevation in a normal atmosphere. Microgravity is also expected to extend the range of combustion testing to near $E = 0$ values. Figures 16a–16d show an automated X–Y laser scanning facility for measuring particle concentration. At 1 g, a laser attenuation scan (Fig. 16d) shows significant gravitational stratification in particle concentration with height, although the cloud

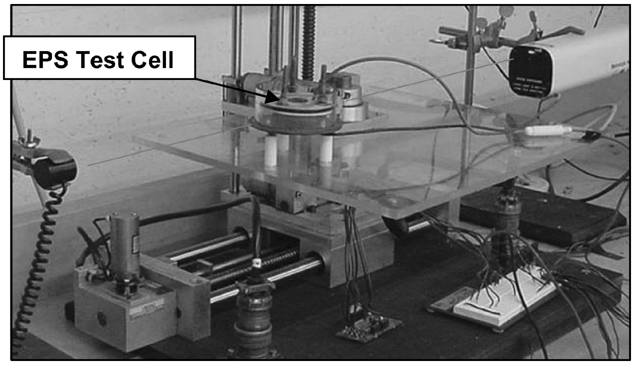

Fig. 16a ***X–Y*** **automated scan experiment for measuring particle concentration using laser attenuation.**

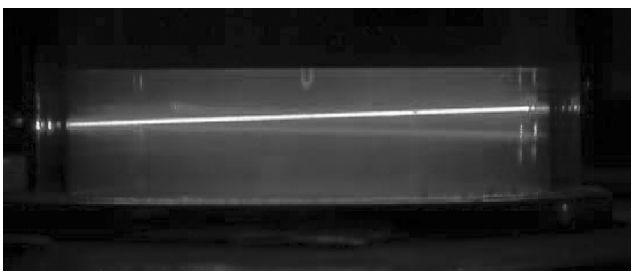

Fig. 16b Laser traverse of 55.6-μm copper spheres.

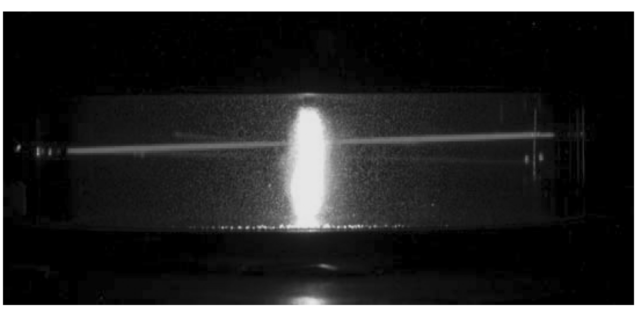

Fig. 16c Spark discharge, ∼ 1–10 J for powders.

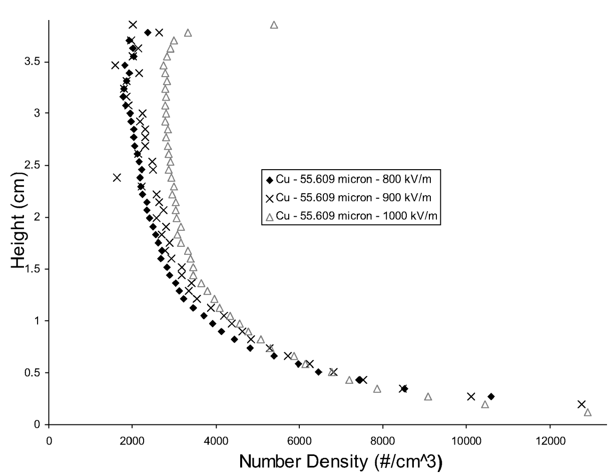

Fig. 16d Stratification scan at 1 ***g*****, number particles per cubic centimeter vs height.**

remains visually uniform and steady.[18] The test data were collected by the use of a low value of electric field strength to bring out the maximum stratification effect for 55.6-μm spherical copper powder (size distribution in Fig. 16e). The sparking in Fig. 16c is produced when the applied voltage is raised until breakdown occurs, compared to the improved pulse voltage method discussed in Fig. 2. As noted earlier, the external capacitor (Fig. 2) can readily deliver the 1–10 J necessary to ignite most powders.

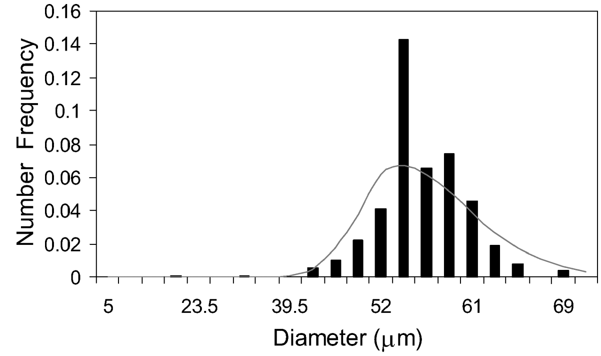

Fig. 16e Particle size distribution for 55.6-μm copper powder compared to log-normal distribution (Hiac-Royco particle size analyzer).

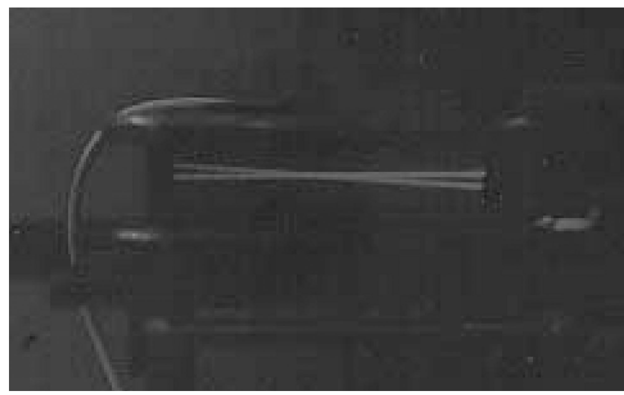

Fig. 17 EPS measurement of particle (slip) velocity using LDA for 96-μm copper spheres at 1 ***g*** **(Ref. 14).**

Particle Slip Velocity

The authors are not aware of any quenching or related combustion studies in which the particle–gas slip (relative) velocity was studied as a control variable, as is possible with EPS. Lewis and von Elbe, in a discussion of droplet burning, note the importance of particle size (coarse and fine) and the ability of coarse particles to move with respect to ambient air.[29] The flame around larger particles becomes unsymmetrical from gas currents producing droplet distortion. For coarse particles, the critical separation distance is larger (relative to their particle diameter) and the fuel–air ratio becomes correspondingly smaller compared to fine aerosols. In many combustion systems, a slip velocity between particles and gas is expected under conditions of large particles flowing near walls or vertical transport against gravity, or with accelerating flows such as burners. In a pulverized coal combustor, the minimum scale of microturbulence is 10–100 times the diameter of a pulverized-coal particle and is also the scale of particle separation, so that the gas within this distance from the surface of the particle is nonturbulent relative to the particle.[39] For large particles (>50 μm), diffusion and heat transfer to the surface of the particle can be important during particle combustion. Both the Sherwood (mass transfer) and Nusselt (heat transfer) numbers are increased by the particle–gas relative velocity. For example, increasing the particle Reynolds number from 1 to 10 doubles both Sherwood and Nusselt numbers for a spherical particle.[39] Inertial effects cause particle motion to persist relative to the gas in accelerating flows, as in the pulsating combustor.[40] Hahn et al. gave theoretical predictions for electromagnetic effects for a droplet in microgravity.[41] Inculet et al. studied the dynamics of breakup of large (1.5-cm) water droplets in microgravity.[42] An electrodynamically fluidized bed was investigated by Bologa et al. in weightlessness for heat transfer and its fluid mechanical characteristics.[43] In field-free powder flames, the particle–gas slip effect is anticipated for larger particles, although the effect is not simple to isolate.

Figure 17 shows an EPS steady-state suspension of 96-μm copper spheres suspended at 1 g by the use of an LDA to measure average

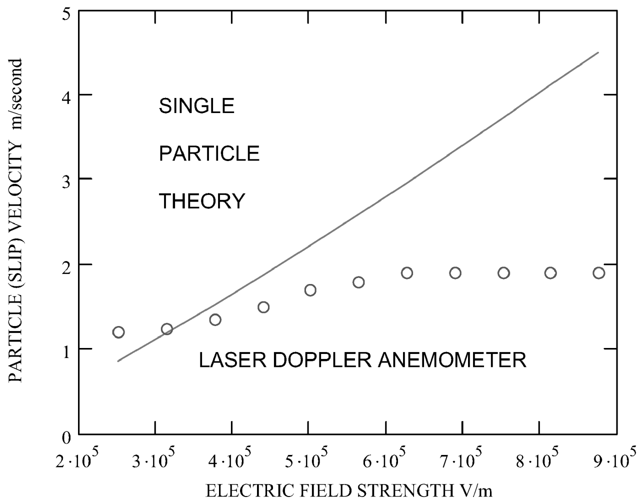

Fig. 18 Calculated particle slip velocity vs measured velocity (LDA) at 1 g for 80-μm glass spheres (coefficient of restitution 0.9 assumed).[14,18]

particle (slip) velocity.[16] The plate separation distance is about 2.0 cm, with a plate voltage of 8 kV. Crossing of the LDA beams is made visible by scattering from the suspended particles. An electric field strength of about 3.4 kV/cm is needed to disperse the copper particles for 1 g. Sarhan found that the average particle velocity for the upper concentration limit of an EPS at 1 g increases with a dc electric field up to a limiting value for both glass and copper particles and then levels off before electrical breakdown occurs, as shown in Fig. 18 (Ref. 14). The slip velocities were measured over a range of 0.70–1.9 m/s for particle size, material, and electric field strength. As noted earlier, this range can be expanded to smaller velocities under microgravity conditions.

Figure 18 also shows the calculated (ideal) single particle slip velocity at 1 g for 80-μm glass spheres and an assumed coefficient of restitution 0.9 and plate separation of 1.6 cm (Ref. 18). The single-particle theory overpredicts the average particle speed compared to the measured average particle speed as a result of charge relaxation with walls, as well as multiple-particle effects resulting from collisions, charge neutralization, and charge shielding.[10,14]

EPS Formation Criteria

In a 1-g environment, the EPS electric field must be of sufficient magnitude ($E \sim 2$–5 kV/cm) to lift the particles against gravitational forces such that $F_{\mathrm{LL}} = mg = QE$, in which m is the particle mass, g is gravity, Q is the induced charge (ignoring triboelectric charging), and E is the electric field strength. Because of particle momentum, once particle motion is initiated, the required lower limit electric field strength E_{LL} to sustain the suspension is reduced below that required to lift the particle against gravity.[18,37] This lower limit criteria is given by[18]

$$E_{\mathrm{LL}} = \left(\left\{\left[\left(1-\varepsilon_b^2\right)\big/\left(1+\varepsilon_b^2\right)\right]mg + F_d\right\}\left(6\big/\pi^3\varepsilon_0 D^2\right)\right)^{\frac{1}{2}} \tag{2}$$

to oscillate a single particle, where ε_b is the coefficient of restitution for the particle–wall encounter, ε_0 is the permittivity of the gas (usually space), F_d is the particle drag force (an empirical equation is used), m is the particle mass, and g is gravity. When F_d and ε_b are both zero, one recovers the lifting field against gravity alone. In microgravity, $g \to 0$, giving $E_{\mathrm{LL}} \to 0$ in Eq. (2), so that quenching distance measurements from a series of tests need to be extrapolated to the (near) field-free limit. For the case of multiple particles, E_{LL} in Eq. (2) is increased because of the average decrease in particle velocity resulting from collisions, charge neutralization, and dispersion of the particles. Under conditions that the particle mean free path λ is much larger than the parallel plate spacing $L(\lambda/L \gg 1)$, single-particle theory may be considered an approximate representation of the particle dynamics for the suspension.

In multiparticle combustion systems the additional effects of charge shielding, particle collisions, and charge transfer becomes important in sustaining the suspension. A review of characteristic times for EPS is given by Colver.[11] Triboelectric charging may or may not contribute to the charge on the particles. As a first approximation, the triboelectric charge is superimposed on the induced charge.[44] The required suspension power (<1 W), current density (<10^{-3} A/m^2, based on plate area), and particle charge (<10^{-13} C) are small quantities depending on electric field strength, particle diameter, and other parameters (gravity, particle material density, coefficient of restitution, etc.). Typical particle concentrations at 1 g are 10^3–10^4 cm^{-3} for $E \sim 5$ kV/cm.

Summary

The EPS test method can produce steady-state clouds of high uniformity (before ignition testing) while providing up to four alternative methods for the measurement of particle concentration. Reduced gravity (microgravity) is expected to reduce cloud stratification and electric field requirements. If electric field strengths are increased to high values, the particles themselves will trigger electrical breakdown between the parallel electrodes. Consequently, at 1 g, there are practical operating limits for EPS from the lowest values of electric field strength of typically 2–5 kV/cm, as determined by gravitational forces, to limiting values of 6–20 kV/cm where spontaneous sparking occurs. Small, irregular-shaped particles such as coal dust (<5 μm) can be difficult to suspend, in which case acoustic excitation is used to first break up the particles before lifting. Generally, both spherical and irregular conducting particles (copper and aluminum) are found to produce well-formed suspensions. Suspension dynamics for the EPS method are covered more fully by Colver.[10,11,18]

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