

QUENCHING COMBUSTIBLE DUST MIXTURES USING ELECTRIC PARTICULATE SUSPENSIONS (EPS): A NEW TESTING METHOD FOR MICROGRAVITY

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Abstract The Electric Particulate Suspension (EPS) is a combustion ignition system being developed at Iowa State University for evaluating quenching effects of powders in microgravity (quenching distance, ignition energy, flammability limits). Because of the high cloud uniformity possible and its simplicity, the EPS method has potential for 'benchmark' design of quenching flames that would provide NASA and the scientific community with a new fire standard. Microgravity is expected to increase suspension uniformity even further and extend combustion testing to higher concentrations (rich fuel limit) than is possible at normal gravity. Two new combustion parameters are being investigated with this new method: (1) the particle velocity distribution and (2) particle-oxidant slip velocity. Both walls and (inert) particles can be tested as quenching media. The EPS method supports combustion modeling by providing accurate measurement of flame-quenching distance as a parameter in laminar flame theory as it closely relates to characteristic flame thickness and flame structure. Because of its design simplicity, EPS is suitable for testing on the International Space Station (ISS). Laser scans showing stratification effects at 1-g have been studied for different materials, aluminum, glass, and copper. PTV/PIV and a leak hole sampling rig give particle velocity distribution with particle slip velocity evaluated using LDA. Sample quenching and ignition energy curves are given for aluminum powder. Testing is planned for the KC-135 and NASA's two second drop tower. Only 1-g ground-based data have been reported to date.

EPS Design An electric particulate suspension (EPS) utilizes a high voltage electric field to disperse a powder of semi-insulating or conductive material in a cloud of (oppositely) charged particles. The resulting steady state suspension is subsequently ignited by a spark discharge from a stationary (or moving) needle electrode, Fig.1.¹ Particle motion in the direction of the electric field is confined between two parallel plate electrodes with diffusive motion in the horizontal direction confined by a Pyrex cylindrical retainer. High voltage capacitors provide the necessary energy for the spark. Wall quenching tests involve adjusting the height distance between the parallel plate electrodes and testing for flame propagation following the spark. Quenching by inert powders is accomplished by suspending various amounts of copper or glass particles with a combustible powder or gas mixture and igniting the mixture. Acoustic vibration is utilized to aid the suspension of cohesive particle such as coal dust or other fine particles (Fig. 1).¹ The centered spark kernel produces a cylindrically outward propagating flame. Fig. 3 shows a photograph of quench (batch) test of aluminum powder 25-35 μm using the system in Fig. 2.

Powder quenching Powder (wall) quenching studies carried out to date at 1-g 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.² Example quenching and ignition curves for coal dust and aluminum powder are shown in Figs. 3 and 4 respectively, using the setup of Fig. 1. Aluminum powder 25-30 μm in

concentrations of 150-3300 g/m³ was tested in admixtures of oxygen, nitrogen, and carbon dioxide (mole ratio 0.21). These data are then curve fit as in Fig. 4. Flammability curves have been developed for lean to stoichiometric powder mixtures at 1-g. For cohesive particles, 17.5 μm spherical aluminum and 16.7 μm Illinois No. 6 coal, quenching tests are carried out with acoustic assist in Fig. 1. Test results indicate that both the quenching distance and lean flammability limit increase with particle size while the quenching distance of coal is observed to decrease with increasing volatile content.

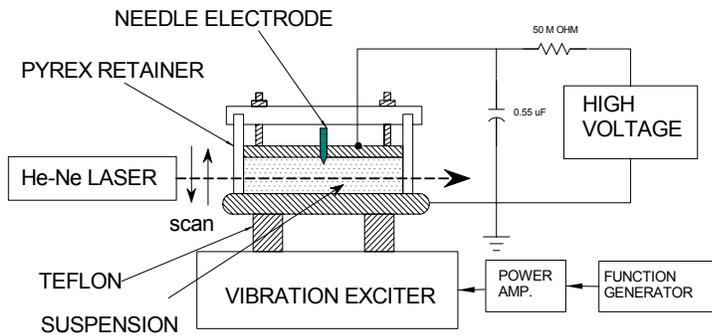


Fig. 1 Batch feed (closed) system with Pyrex cylinder walls: tests of quenching distance, ignition energy, flammability limits.

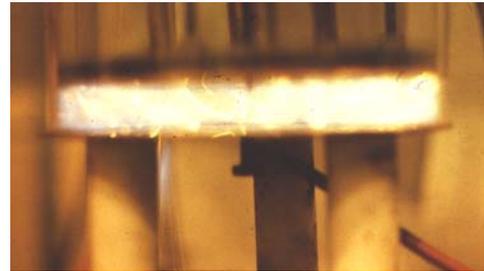


Fig. 2 EPS method: Ignition of 17.5 μm (avg) spherical aluminum powder.

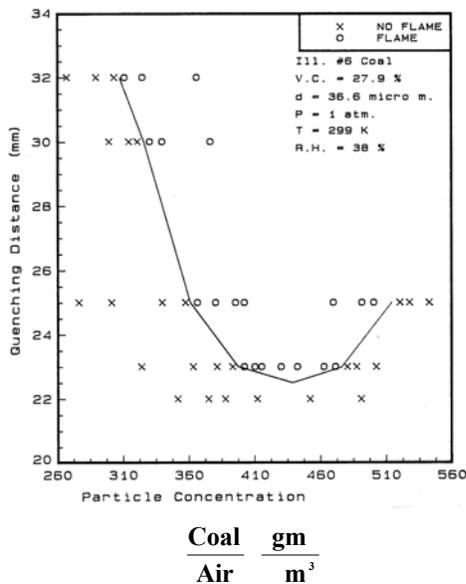


Fig. 3 Quenching distance (mm) vs fuel-air ratio 36.6 μm Illinois #6 coal.

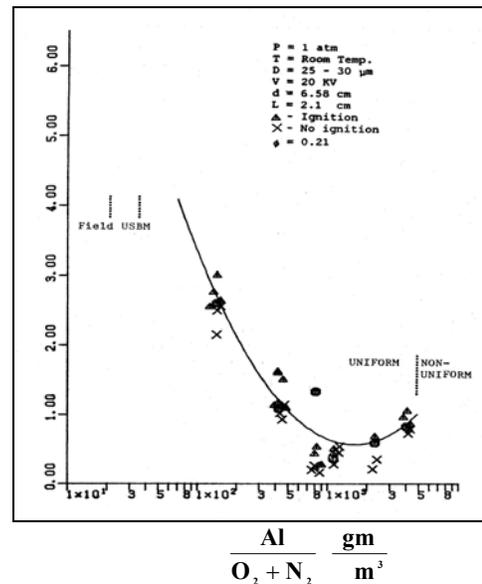


Fig. 4 Spark ignition energy (J) vs. fuel-air ratio, 27.5 μm aluminum.

Fig. 5 shows the ignition of a propane-air mixture using copper particles as quenching media. 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 motion of the particles persists over times needed for passage of the flame front, usually ms. The problem of suspension collapse is expected to be reduced in microgravity.

Spark ignition energy The EPS experiment in Fig 5 is used to investigate spark ignition energy and quenching of propane-air mixtures in the presence of copper particles. This particular EPS system utilizes a high speed moving electrode (~10 m/s) to trigger the spark so as to preserve the uniformity of the suspension prior to breakdown.³ For copper particles the parameter Nd^2 (N = particle number density, d = particle diameter) is found to be important for gas ignition (Fig. 5). The quenching effect of particles in Fig. 6 for propane-air mixtures shows that a greater ignition energy is needed for either higher values of particle concentration N or particle diameter D (E_{i0} is the energy to ignite a particle free propane-air mixture for the same fuel-air ratio).

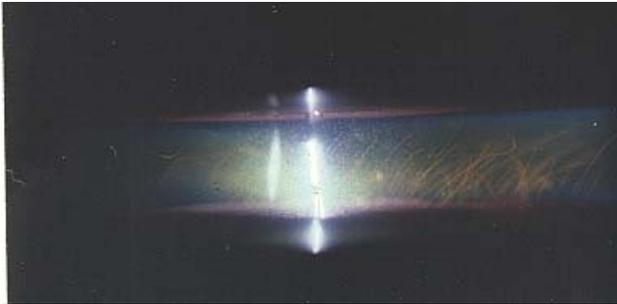


Fig. 5 EPS method: Quenching mixtures of propane air with 96 μm copper particles.

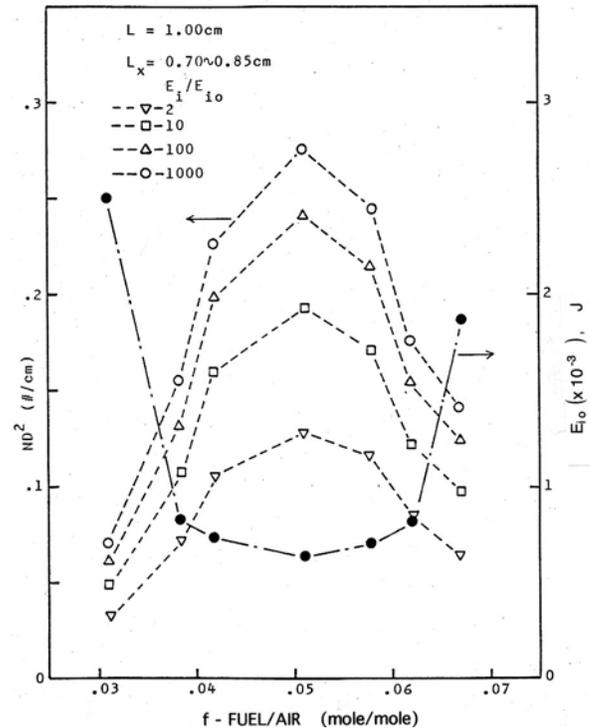
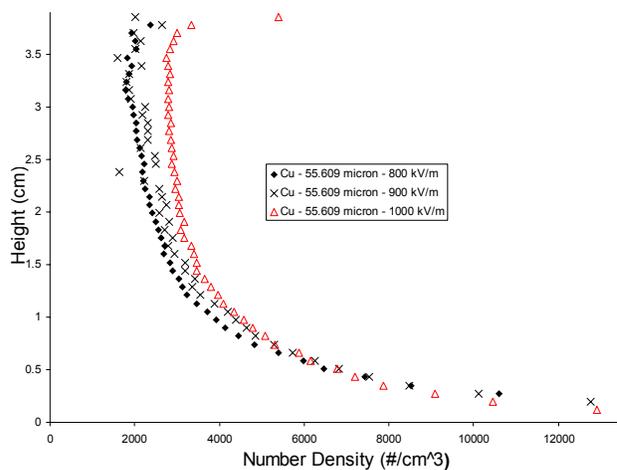
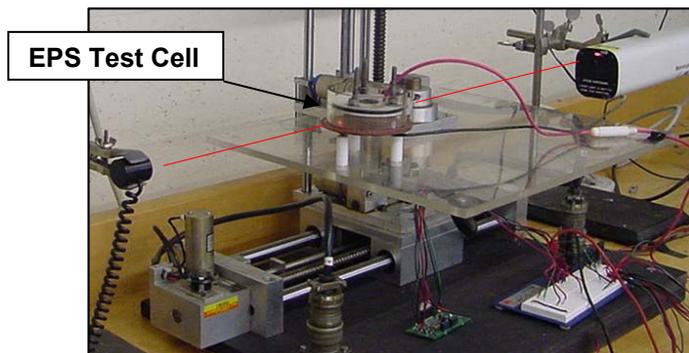


Fig. 6 Ignition energy and ND^2 parameter for quenching copper-propane-air mixtures.

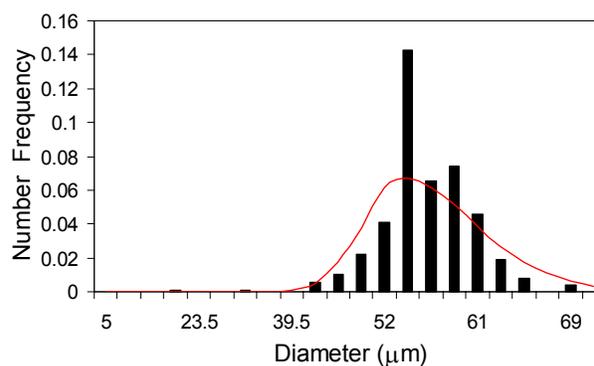
Particle velocity distribution & particle-oxidant slip velocity The Particle Velocity Distribution (PVD) associated with randomized motion from particle-particle and particle-wall collisions is being investigated in this study. Particles are leaked from a 1.61 mm hole located in the top of an EPS test section and their velocity vectors determined by the height attained. Particle Tracking Velocimetry (PTV/PIV, LaVision Flowmaster System) has also been utilized to compute particle velocities between successive pulses. A laser sheet is formed by imaging the beam with a cylinder lens that is directed just above the EPS leak hole. A second combustion variable, the **particle-oxidant slip velocity**, can be computed or measured using LDA and studied with the electric field. The slip velocity can affect heat and mass transfer in flames for large particles and high temperatures. For example, increasing the particle Reynolds number from 1 to 10 doubles both Sherwood and Nusselt numbers for a spherical particle.

Stratification of dust clouds at 1-g Particle forces resulting from gravity induce stratification in the cloud similar to the decrease in gas density observed with elevation in normal atmosphere. Microgravity is expected to extend the range of combustion testing to near $E = 0$ values while also reducing cloud stratification. Figs. 7 show an automated X-Y laser scanning facility for measuring particle concentration. At 1-g, laser attenuation scans show that gravitational stratification occurs in particle concentration of copper spheres with height (Fig. 7 top right). The test data were collected at different values of electric field strength and a large electrode separation distance (3.9 cm) to bring out the stratification effect. The completely automated data acquisition system (LabView) samples the power meter at 10-80 readings per “window” with a

tolerance up to ± 0.01 cm (each data point in Fig. 7-top right). The user can specify multiple scans of the motorized system and automatic reversals (up-down traverses).



Figs. 7 (top) EPS X-Y automated scan rig for measuring of particle concentration by laser attenuation; (top-right) Effect of electric field strength brings out stratification at 1-g and large electrode separations (3.9 cm) using 55.6 μm copper powder (60 readings per data point at ± 0.01 cm); (right) Size distribution for 55.6 μm copper powder compared to log-normal distribution.



Summary and Limitations using EPS The EPS combustion test method can produce steady-state clouds of high uniformity while providing alternative methods for measuring particle concentration. Reduced gravity (microgravity) is expected to further reduce cloud stratification and electric field requirements while extending the concentration range of powders. Spark breakdown at 1-g limits present fields between 2-5 kV/cm, as determined by gravitational forces, and the highest values of 6-20 kV/cm where sparkover can occur. For cohesive particles ($< 5 \mu\text{m}$) acoustic excitation can be helpful in the EPS method for breaking up the particle clusters.

Acknowledgment This is a NASA-CSA joint sponsored study between Iowa State University and McGill University under (NASA) Microgravity Combustion Science Grant NCC3-846. The authors appreciate the helpful input from their grant advisor Dr. Peter Sunderland at NASA Glenn. Thanks also to ISU undergraduate Joel Smeby for his shop skills.

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