Experimental and Theoretical Advances in the Design of a Prototype Electrostatic Air Filter for Pu Contaminated Soil Excavation

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Motivation & Justification

- When the enamel like top layer of the desert soil is compromised, natural and man-made forces result in airborne dust particles. This is of specific concern in Pu contaminated soil excavation. Conventional water spraying techniques are ineffective for micron and submicron diameter dust particles. Once the micron size dust particles are airborne, the viscous forces of air dominate the gravitational forces. Consequently, the dust particles remain airborne for long periods of time. If these radio-nuclide contaminated dust particles are inhaled, they become trapped in the lungs and may be a health risk. One means of extracting these particles from the air is with an electrostatic air filter.
Purpose and Objectives

• Design a remote cleaning electrostatic air filter which charges, traps, transports, and collects micron diameter radio nuclide dust particles with the aid of electrostatic fields without human intervention.

• Objective
  – Portable
  – Energy efficient
  – Nearly maintenance free
Dust Maker

- Construction
  - Metal box Container (15cm x 20cm x 30.5cm)
  - DC electronic fan (11 cm, 120 V DC)
  - Cardboard air flow director (baffle)
    - sealed on top and sides with tape
    - bottom rests on the surface of the dust base
    - top edge is 8” above dust base
    - bottom edge is 4” from back wall
  - Offset funnel (9 cm dia. to 2.4 cm dia.)
    - bottom edge of funnel is 3” above dust base
  - Dust Base
    - Nevada desert soil sifted with overlapping layers of conventional aluminum screening
    - dust base is roughly 9 cm deep
  - Uniformity in Fan speed is monitored with a strobe-tach for consistency
    - 1420 rpm

- Outlet Air Flow Velocity
  Not measured at present
Dust Maker - Typical Particle Sizes Measured

- Quadruple Baffle Filter Sys. (See fig.)
  - Designed to minimize backflow
  - Filter sys. connected to dust maker outlet
  - Two standard size dixie cups connected at open end
  - Bottom of cups removed
  - Slits placed in cups
  - Filter paper inserted in slits
    - Covers better than half of the cup cross sectional area
    - Whatman 1 Qualitative Filter Paper used (11 µm retention)

- Particle Size Observed (See fig.)
  - Microscope with 500 magn. factor used
  - Most particles smaller than filter mesh
  - Observation Period 5 min.
    - Fan Volt. 80 & 90 V - Part. size < 30 µm
    - Fan Volt. 70 & 75 V - Part. size < 20 µm
Heuristic Theory for Dust Maker - Instan. # of Dust Particles

• The maximum amount of time a single dust particle will spend in a laser beam is
  \[ t_{\text{max}} = \frac{d_l}{v_{\text{ave}}} \]
  – \( d_l \) is the laser beam diameter
  – \( v_{\text{ave}} \) is the average dust particle velocity

• In the time it takes a single dust particle to travel the diameter of the laser beam, there will be \( N_d \) in the beam
  \[ N_d = \psi_d A_l L t_{\text{max}} \]
  – \( \psi_d \) no. of dust particles generated by the dust maker per sec passing through the laser beam interaction region
  – \( L \) is the interaction length of the beam
  – \( A_l \) is the laser beam cross-sectional area

• In a slab thickness \( \Delta z \) of the cylindrical laser beam, it is assumed that there is no dust particle overlap along \( z \)

• The number of photons per sec \( \mathcal{N}_m \) passing through the slab of dust particles of thickness \( L \) without being scattered is
  \[ \mathcal{N}_m = \mathcal{N}_{\text{lo}} \exp(-\psi_d \sigma_{\text{os}} t_{\text{max}} L) \]
  – \( \sigma_{\text{os}} \) optical scattering cross section of the dust particle
  – \( \mathcal{N}_{\text{lo}} \) is the number of photons per sec. generated by the laser in the laser beam

• The number of dust particles in the laser beam at any point in time (S.S.) is
  \[ N_d = \left( \frac{A_l}{\sigma_{\text{os}}} \right) \ln\left( \frac{\mathcal{N}_{\text{lo}}}{\mathcal{N}_m} \right) \]
Dust Maker - Experimental Setup

- Laser mount designed to support laser and photo diode detector - good alignment

- Dust tunnel
  - 4” cube clear Plexiglas container
  - Connects to outlet of dust maker and long plastic bag

- Experimental Procedure
  - 1’ dia., 6 ‘ long bag is initially deflated
  - Experiment is conducted within the time frame when the bag is not fully inflated
  - Steady state voltage reading from diode detector is recorded both before and after the dust maker is turn on
  - About 30 runs were made at each of the following angles 0°, 45°, 90°, 135°
  - The first inch of the dust base was mixed for roughly the first 12 runs, and a full dust base mix was made for the last 18 runs
  - More uniform results were recorded with a
Dust Maker - Angular Dependence in Dust Count

- Dust must be thoroughly mixed after each test (or set of six tests)
- Dust count is reasonable uniform (Refer to Fig.)
- Dust generation reasonably uniform with angle (Refer to Fig.)
- Average count: ~458 dust particles in the beam path at any one instant in time (fan voltage DC - 78 V)
- Figure below shows laser positioned in the 90° position relative to the horizontal
Faraday Tube System

• Application
  – Measure charge on moving dust particles without significantly altering dust dynamics

• Construction of Tube
  – Two copper tubes of different radii sharing the same axis and centrally oriented
  – Separated and held in place by nylon end caps. Except for the ends, the tubes are separated by air.
  – Length of the inner tube is about three to four inner tube diameters shorter that the outer tube
  – Female coaxial connector located off tube stub located on outer tube.

• System
  – Faraday Tube (connected to electrometer input)
  – Oscilloscope (connected to electrometer analog output)
  – Electrometer with analog outputs
  – Amplifier circuit in figure not required
Faraday Tube Calibration - Simple Theory for Bead of Charge

- **Model**
  - Metal spherical ball bearing with small hole through diameter is charged by a set of parallel plates
  - Metal ball slides along nonconducting fish line passing through Faraday tube
  - The charged ball forces the outer surface of the inner tube to support the same charge that exists on the sphere. The grounded outer tube becomes oppositely charged.
  - Faraday tube acts as a capacitor
  - The voltage across the cylindrical tubes is monitored
  - Knowing the tube cap, the meas. charge is $Q = CV$

- **Simple Theory - Bead Calibration**
  - Charge placed on a metallic sphere in-between two parallel plates of infinite extent but touching one of the plates is (Laplace Eq. with various coordinate transformations)
    
    $$ Q_r = -4\pi\varepsilon_0 \frac{R_o^2 V_o}{D} \left[ \frac{\left( \frac{b}{R_o} - 1 \right)^2 + 1}{\left( \frac{b}{R_o} - 1 \right) \left( \frac{b}{R_o} - 2 \right)} \right] $$

    - Faraday tube treated as a simple infinite in extent coaxial capacitor
    - Meas. Volt.
      
      $$ V_{\text{meas}} = 2 \frac{R_o^2 V_o}{LD} \ln \left( \frac{b}{a} \right) \left[ \frac{\left( \frac{b}{R_o} - 1 \right)^2 + 1}{\left( \frac{b}{R_o} - 1 \right) \left( \frac{b}{R_o} - 2 \right)} \right] $$
Faraday Tube Calibration - Complex Theory for Bead of Charge

Model

- Metallic sphere of radius $R_0$ position anywhere on the $z$ axis
- Inner tube of radius $b$ and finite length $L$ with tube axis aligned with $z$ axis
- Outer tube of radius $a$ and infinite in extent length with tube axis aligned with $z$ axis
- Total charge on sphere known. Distribution of charge over surface of sphere is unknown.
- Outer tube is grounded and inner tube is floating

Method of Solution

- Laplace’s Equation with various coordinate transformations
- Boundary conditions handled using the dual integral equation technique

Solution for Charge - (Form provided; all functions NOT defined here)

$$Q = -\frac{2}{3} \pi \epsilon_0 V_f R_0^3 \int_0^\infty \frac{v^2 \cos(vz)}{I_0(va)} A_i(v) dv$$

where,

$$A_i(v) = \frac{1}{v} \left[ N(v) + 1 \right] \left[ J_0 \left( \frac{L}{2} \right) v J_1(v) - K_0(t) J_0 \left( \frac{L}{2} \right) \right]$$

and

$$\Phi(t) = \frac{\Phi_0(t)}{\epsilon_0} + \frac{1}{\epsilon_0} \int_0^L \Phi(y) K(y,t) \left[ R_0 \left( \frac{L}{2} \right) \right] dy$$

[Fredholm Equation of Second Kind]
Faraday Tube Calibration - Numerical Solution of Complex Theory

- **Key Numerical Programs Employed**
  - **DIESIMP**
    - automated double precision numerical program for Fredholm integration equations
    - based on Nostrom method with Simpson rule
  - **DQAWF and DQAGI and HKBESSEL**
    - QUADPACK numerical integration routines evaluating a function over a interval $(a, \infty)$
  - **DFZERO**
    - zero finding routine from SLATEC library
  - **DDERIV**
    - Double precision IMSL routine to compute a derivative
  - **DBSJ0, DBSJ1, DBSI0, DBSI1**
    - Double precision IMSL Bessel functions of the first kind and the modified Bessel function of the first kind

- **Platform**
  - Personal Computer
  - Using Digital Visual Fortran

- **Numerical Results Currently Being Debugged**
Faraday Tube System- Experimental Results With Bead

- **Charging Potential - 2.4 kV**
  - Top Fig. - Bead Neg. Charged - -340 mV meas.
  - Bot. Fig. - Bead Pos. Charged - +380 mV meas.

- **Geometrical Configuration**
  - Bead - 1.625 mm radius
  - Charging electrodes separated by 2.7 cm
  - Faraday tube
    - Outside radius of inner tube 3.1 mm
    - Inside radius of outer tube 7.0 mm
    - Length of inner tube 0.15 m

- **Loading Effect of Faraday Tube**
  - $1.1 \, \Omega$ ($1.1 \times 10^{12} \, \Omega$)

- **6517A Electrometer Properties**
  - Input resistance > $200 \, \Omega$ ($2 \times 10^{14} \, \Omega$)

- **Estimated Max. Volt.**
  - Calculated 2.77 V
  - a factor of 7.25 to 8.13 larger than measured experimental values
First Corona Charging System - Electrode Configuration

- Electrode Configuration
  - Top electrode with three ridges angled at 45 deg.- all corners replaced with large radius fillets
  - Bottom electrode flat - large radius bend on front and back edges - all corners replaced with large radius fillets
  - Plexiglas separates electrodes (side walls)
  - To obtain a sharp edge on the three ridges, slits are incorporated along the ridges and razor blades are inserted.
  - Photo on the right shows six razor blades inserted well beyond the position where the natural edge should be. Distance between edge of razor blade and the bottom plate is ~ 1/2 inch

- High DC Voltage Source - 18 kV
  - Ave. current drawn over a 10 hrs is 1.25 mA
First Corona Charging System - Experimental Observations

• Corona
  • Intense Purplish - blue beacons of light scattered over the razor blade edges
  • Below this intense light, a cloud of bluish light exists as observed in the photo
  • Ozone generation very apparent
  • 10 hr operation; the current varied between 1.1 mA to 1.5 mA

• Edge Effects of Plates
  • Virtually eliminated for this plate geometry

• Aluminum Plates - (without razor blades)
  • Oxidized
  • Glow not consistent

• Razor Blade Edge (magnetic material)
  • Rusted - typical when ferromagnetic materials oxidize
  • Glow very consistent
First Corona Charging System - Theoretical Calculation

- **Model & Theory**
  - 2-D Problem with the side walls of the plate configuration being metal separated by a very thin insulator
  - Plexiglas sidewalls are used in experiment because:
    - Significant arcing resulted
    - Although good dielectric insulators are used at the plate junctions, arcing occurred along the outside of the dielectric and could not be suppressed
  - Combination of two conformal mapping techniques
    - Schwartz-Christoffel Transformation
    - Inverse Cosine transformation
  - Numerical study employed the following key programs:
    - QAWS from Quadpack - subroutine package for automatic integration
    - BROYDEN from Numerical Recipes - globally convergent method for solving a nonlinear system of equations
    - RAN2 from Numerical Recipes - a random number generator
  - Equations too complicated to be displayed
    - A numerical result presented on the next slide
First Corona Charging System - Theoretical Calculation cont.

• Results
  – Can only predict the region of *intense* light
    • when breakdown results, one may think of the breakdown region as an extension of the metal surface (becomes more valid when arcing results)
    • Figure below shows one region where breakdown is most likely to occur
  – Theoretical and experimental results are currently being compared
Second Corona Charging System - Electrode Configuration

- **Motivation**
  - Charge more dust particles at any one time
  - Air flow through the corona slab instead of parallel to the slab
  - Minimize turbulence

- **Electrode Configuration** (See figs.)
  - Both top and bottom plates are parallel
  - Razor blade edges are inserted in the upper plate extending slightly beyond the inside surface. Less than one sixth of the distance of separation of the upper and lower plates. The razor blades are inserted at an angle in the direction of the air flow.
  - Stainless steel blades used. If possible, use Stainless Steel No. 316 or 17-4-Ph.. These contain minimal amounts of iron. Rusting due to oxidation is minimized.

- **Potential Difference**
  - Less than 16 kV required
Water Charging System

- Mechanical water atomization with conventional spray head (Orifice dia. .016”)
  - at 20 psi (cap. 0.035 gpm)- ~220 µm dia. droplet
  - at 40 psi (cap. 0.05 gpm)- ~210 µm dia. droplet
  - droplets are heavy enough to be influenced by gravity

- Positive flow pump draws water from a reservoir and maintains the desired pressure at the spray head

- Spray head and circulating system is held at a high potential

- A grounding electrode with rubber insulation is located near the spray nozzle for charging to occur

- Experimentation NOT conducted as of yet
  - Pump needs to be electrically isolated from the motor
Initial Dust Charging Test

• Procedure
  – Sifted dirt in plastic bag
  – Tube suspended in center of bag
  – Bag is inflated, shook, and squeezed
  – Grounded plate in plastic bag below electrodes - positioned outside of free fall path of dust
  – Electrode potential roughly 16 kV (S.S.)

• Observations
  – As dust passed through ionized slab regions between plates significant arcing was visually observed and heard
  – Significant dust collected on plate - observed visually
Alternative Novel Design

• Corona charging results in ozone and the degradation of the charging electrodes. An alternative to corona charging is charging by photo-ionization. An ultraviolet laser source is required. Such a source is at the edge of the state of the art and therefore is costly. Details of this design may be found in the literature cited below.

• Alternative Novel Design - Publications
Conclusions

- Designed - dust maker, charging electrodes, dust charging diagnostic
- Design underway - water droplet charging
- Comparison between theory and experiment for charging electrodes and dust charging diagnostic is currently underway
- Complicated analysis characterizing the dust charging diagnostic is in the programming stage
- Future - combine each element of the electrostatic air filter into a single system