Comprehensive Modeling of Superficial Dust Removal via Electrostatic and Dielectrophoretic Forces in Extraterrestrial Exploration Mission

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Abstracts- The Electrostatics and Surface Physics Laboratory (ESPL) at NASA Kennedy Space Center has developed a dust mitigation technology that uses electrostatic and dielectrophoretic (DEP) forces to disperse and remove the dust already deposited on surfaces preventing the accumulation of dust particles approaching or already deposited on those surfaces. Dust removal during lunar and Martian exploration activities is of primary importance for the success of both robotic and human exploration of Mars and the moon. This paper describes a rigorous 3D model developed at the ESPL that uses and couples two physics, electromagnetism and particle tracing, both in transient mode to forecast not only the charging process of the particles (electrostatic and dielectric dipole moment) but also their motion and displacement under an electromagnetic field. The electromagnetic field is generated by supplying a three-phase voltage to an array of parallel conductors embedded in a dielectric substrate. COMSOL Multiphysics®, a general-purpose software platform used for modeling and simulating physics-based problems, was used to model and simulate these two physics that are present in different phases, continuous (electromagnetism) and discreet (particle tracing). The model is aimed at optimizing the implementation of the dust mitigation technology developed at the ESPL in terms of the geometry of the conductor array, power requirements, and particle removal efficiency.

I. Introduction

Future manned and unmanned extraterrestrial missions will face a vast number of challenges that include removal of dust particles from solar panels, thermal radiators, analysis and exploration equipment, astronaut's protection items, such as suit gloves, visors and attached gears. Dust will have a negative impact on the efficiency of solar panels, thermal radiators, and exploration/analysis equipment. ESPL is developing an active dust mitigation technology that has demonstrated to be especially effective in the removal of dust particles from surfaces and in the prevention of the accumulation of those particles on such surfaces [1]. This technology basically creates an Electro-Dynamic Traveling Wave

(EDTW) at the surface using a series of parallel conductors embedded in the surface and connected to an AC source that generates the EDTW on the surface capable of charging particles and polarizing uncharged particles, yielding electrostatic and dielectrophoretic forces on polarized and charged particles respectively, and acting as a contactless conveyor to transport and remove the charged particles.
The authors have built a rigorous 3D-transient model on this dust removal technology by successfully coupling in transient mode the two different physics phases present in this dust removal technology, generation of the electrical-magnetic field and the transportation of charged and polarized particles through the EDTW generated by parallel conductors embedded in the surface. These two modeled phases, that need to be coupled and solved simultaneously in transient mode, are a discrete phase consisting of the dust particles and a continuous phase consisting of the electrical and magnetic fields generated between and above the conductors by a multiphase AC electrical potential applied at the end sides of the conductors.

II. BACKGROUND AND THEORY

The dust removal technology implemented by ESPL is based on the EDTW concept developed by F.B. Tatom in 1967 [2] and implemented later by Masuda in 1970 [3]. This technique has been demonstrated experimentally by lifting and transporting charged and polarized dust particles by electrostatic and dielectrophoretic forces respectively both generated within the EDTW [4,5,6,7,8,9].
To generate the EDTW at the surface a series of parallel conductors are connected to a multiphase electrical potential source to generate a traveling wave acting as a contactless conveyor. The EDTW is generated by a AC voltage applied at the end sides of the conductors having the same amplitude and angular frequency but differing in their phase. The EDTW is generated parallel to the conductors and its direction oscillates back and forth as the polarity of the conductors changes. The change in direction in the electrical field yields a wave that generates forces also in different directions on charged and polarized particles in the region of the electrical field [10].
The dust particles within the EDTW need to be electrically charged or polarized to experience a net force that yields the transportation of the dust particles through the EDTW. If the dust particles are present in a gaseous atmosphere, such as air in earth and CO_2 in Mars the voltage applied to the conductors can yield such a strong electrical field that ionizes the gas (air on earth and CO_2 on Mars) charging the dust particles with ions from the gas by either thermal diffusion or the electrical field itself. The particle charging through the electric field is called field charging. Field charging is more dominant for larger particles ≥ 2 μm, and for smaller particles ≥ 0.2 μm, thermal diffusion charging is more dominant [10]. The charge of a given particle is given by

$$Q(t) = Q_s \frac{\frac{1}{\tau}}{1+\frac{1}{\tau}} \qquad 1)$$

$$Q_s = \pi\epsilon_o \frac{3\epsilon_s}{\epsilon_s+2} {d_p}^2 E \qquad 2)$$

$$\tau = \frac{4\epsilon_o}{J} E \qquad 3)$$

Where
$Q(t)$ = Electrical charge at time t (s)
Q_s = Saturation charge (C)
t = Charging time (s)
τ = Time constant of the field charging (-)
ϵ_o = Permittivity of vacuum 8.85×10^{-12} F/m
ϵ_s = Specific permittivity of the particle (F/m)
d_p = Particle diameter (m)
E = Electrical field (V/m)
J = Current density (A/m^2)

The dust particle charged $Q(t)$ will experience an electrostatic force proportional to the electrical field:

$$F_e = Q(t)E \qquad 4)$$

Where
F_e = Electrostatic force (N)

Coupled with the electric field E the magnetic field B is generated wrapping the conductor and yielding a magnetic force on the charged particles in motion:

$$F_m = Q(t)Bv_p \qquad 5)$$

Where
F_m = Magnetic force (N)
B = Magnetic field (Teslas)
v_p = particle velocity (m/s)

Additionally an uncharged particle can experience a force from the fact that particles possess an extrinsic electric dipole moment. If this dipole moment is exposed to a spatially non-uniform electric field, the particle experiences a dipole-based force known as dielectrophoretic force [10]. In contrast with the charging source stated above that happens by ionization of the gas surrounding the particles, this additional force source may occur in vacuum and could be the main dust particle polarizing source on the moon. Assuming the dust particle as a spherical dielectric particle with a (small) radius in an electric field, the electric dipole moment can be expressed as:

$$P = 4\pi\epsilon_s {r_p}^3 f_{CM} E \qquad 6)$$

$$f_{CM} = \frac{\epsilon_p{}^* - \epsilon_m{}^*}{\epsilon_p{}^* + 2\epsilon_m{}^*} \quad 7)$$

$$\epsilon_p{}^* = \epsilon_p - \frac{i\sigma_p}{\omega} \quad 8)$$

$$\epsilon_m{}^* = \epsilon_m - \frac{i\sigma_m}{\omega} \quad 9)$$

Where
P = Electric dipole moment on the particle (C.m)
ϵ_s = Permittivity of the medium (F/m)
r_p = Particle radius (m)
f_{CM} = Mossotti-Clausius factor (-)
$\epsilon_m{}^*$ = Complex permittivity of the medium (F/m)
$\epsilon_p{}^*$ = Complex permittivity of the particle (F/m)
σ_m = Electrical conductivity of the medium (S/m)
σ_p = Electrical conductivity of the particle (S/m)
ω = Angular frequency

The dielectrophoretic force has a vector-valued relationship with the electric dipole and is expressed as:

$$F_d = P.\nabla E \quad 10)$$

Where
F_d = Dielectrophoretic force

Replacing (6) into (10) F_d becomes:

$$F_d = 4\pi r_p{}^3 kE.\nabla E = 2\pi r_p{}^3 k\nabla|E|^2 \quad 11)$$

As indicated in equation 10 only dust particles yielding an electric dipole moment under a electrical field (equation 6) within non-uniform electrical field are subject to dielectrophoretic force. Since the dust particle is small, its dipole moment is considered a constant. Equation 11 shows the dependency of the electric-dipole induced force on the gradient of the square of the magnitude of the electric field.
Non-electric forces on the dust particles, such as gravitational, buoyant, and drag forces need to be added to compute the net force generated on charged and polarized dust particles. The more relevant of these forces are:

$$F_g = \frac{4}{3}\pi r_p{}^3 \rho_p g \quad 12)$$

$$F_f = 6\pi\eta_f r_p v_p \quad 13)$$

$$F_b = \frac{4}{3}\pi r_p{}^3\rho_f g \quad 14)$$

Where

F_g = Gravitational force (N)

F_f = Friction force (N)

F_b = Buoyant force (N)

ρ_p = Particle density (kg/m^3)

ρ_f = Surrounding gas density (kg/m^3)

η_f = Surrounding gas dynamic viscosity (N-s/m^2)

v_p = Particle velocity (m/s)

g = Terrestrial gravitational acceleration (9.8 m/s^2)

Current density J, electrical and magnetic fields E and B included in the expressions above are found by solving Maxwell's equations subject to certain boundary conditions. Maxwell's equations are a set of equations, written in differential or integral form, stating the relationships between the fundamental electromagnetic quantities, Electric field intensity E, Electric displacement or electric flux density D, Magnetic field intensity H, Magnetic flux density B, Current density J, and Electric charge density ρ.

The Maxwell's equations can be formulated in differential form or integral form. The differential form is used in the model because it leads to differential equations that the finite element method can handle. For general time-varying fields, Maxwell's equations can be written as:

$$\nabla \text{x} H = J + \frac{\partial D}{\partial t} \quad 15)$$

$$\nabla \text{x} E = -\frac{\partial B}{\partial t} \quad 16)$$

$$\nabla . \mathrm{D} = \rho \quad 17)$$

$$\nabla . \mathrm{B} = 0 \quad 18)$$

Where

E = Electric field intensity (N/C)

D = Electric displacement or electric flux density (C/m^2)

H = Magnetic field intensity (Teslas)
B = Magnetic flux density (Wb)
J = Current density (A/m^2)
ρ = Electric charge density ρ (C/m^3)

Equation (15) is known as Maxwell-Ampere law and equation (16) is known as Faraday's law. Equations (17) and (18) are two forms of Gauss' law: the electric and magnetic form, respectively. Another fundamental equation is the equation of continuity

$$\nabla . J = -\frac{\partial \rho}{\partial t} \qquad 19$$

Out of the five equations (15) through (19), only three are independent. The first two combined with either the electric form of Gauss' law or the equation of continuity form such an independent system.
To build a comprehensive model for the removal of superficial dust in extraterrestrial exploration mission via electrostatic, magnetic, and dielectrophoretic forces we need to solve coupled equations (1) through (19) that describe a two-phase system, a discrete phase consisting of the dust particles (equations 1 through 14), and a continuous phase that surrounds the dust particles (equations 15 through 19). COMSOL Multiphysics®, a general-purpose software platform used for modeling and simulating physics-based problems, was used to model these interconnected two dissimilar phases and simulate in transient mode dust particles removal on extraterrestrial surfaces. The problem of tracking the Particles (discrete phase) and yielding the electrical and magnetic fields (continuous phase) were formulated using two COMSOL's modules, the *Mathematical Particle Tracing (pt)* and *Electrical Currents (ec)* modules respectively. The discrete phase (the particles) is assumed to be a volume fraction of the continuous phase, the domain where the particles are located and exposed to the electrical and magnetic fields. The mayor challenging in modeling this coupled discrete and continuous phases is the fact that both phases need to be solved simultaneously in transient mode as the state of the continuous phase is time-dependent having boundary conditions at the outer end side of each conductor yielding transient multiphase electrical potential. The state of the discrete phase (the particles) is intrinsically time dependent.
For the discrete phase (dust particles), COMSOL's *Mathematical Particle Tracing (pt)* module solves an ordinary differential equation for each component of the particle's position vector. This means that three ordinary differential equations are solved for each particle in 3D, and two in 2D. At each time step, the forces acting on each particle are queried from the computed fields at the current particle position. If particle-particle interaction forces are included in the model, they are added to the total force. The particle position is then updated, and the process repeats until the specified end time for the simulation is reached.
For the continuous phase (electrical-magnetic field), COMSOL's *Electrical Currents (ec)* module solves Maxwell's equations together with material properties and boundary conditions. The equations are solved using finite element method with numerically stable edge element discretization in along with state-of-the-art solvers.

III. MODEL CASE STUDY

A dust particle removal system consisting of three parallel spiral-shape conductors designed and used by technology developers at ESPL was modeled initially in 2D and then extended to 3D. The model uses the same dimensions and materials of the actual dust particle removal system used at ESPL and depicted in Figure 1.

Fig 1.Particle removal system consisting of three parallel spiral-shape conductors designed at ESPL

Each one of the three spiral conductors made of indium tin oxide is 0.25-mm thick, and 0.05-mm high. The clearance between parallel spiral conductors is 0.27 mm. The indium tin oxide conductor is embedded in a glass substrate shelling the conductor's surface with a microscopic layer of glass. The electrical conductivity values used in the model for the indium tin oxide and glass are 1.4×10^{6} and 5.6×10^{-4} S/m respectively. At the end side of each one of the three spiral-shaped conductor a AC potential is applied having the same angular frequency and amplitude for all three conductors but different phase for each conductor. As the other side end of the conductors is not grounded, minor potential gradient as well as low electrical current along the conductor is expected

A. 2D Model Approach

The mayor assumption in the 2D model approach is the fact that electrical field is generated only between conductors due to the fact that the electrical potential gradient along the conductor is negligible as the end side is not grounded.
A 2D model on the multiphase dust removal system depicted in Figure 1 was initially built utilizing actual AC potential profile set at the outer side ends of the three spiral-shape connectors, 1000-V AC potential amplitud and 64-Hz angular frquency for all three connectors and individual phases of 0, $2\pi/3$, and $4\pi/3$ respectively. Figure 2 illustrates the squarewave function used in the model to set these AC potential conditions as boundary conditions at the outer side end of each one of the three spiral-shape connectors.

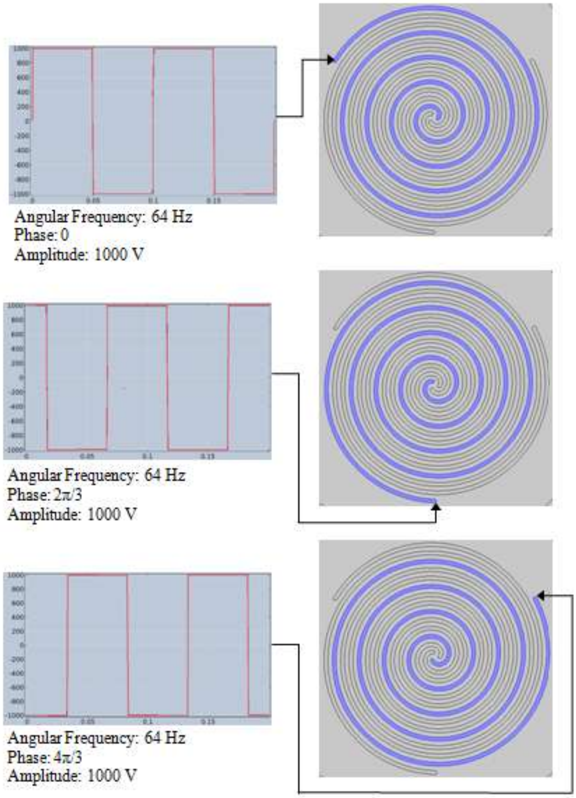

Fig 2. Multiphased dust removal system via three spiral conductors bearing phases of 0, 2π/3, and 4π/3 respectively at 1000-V amplitude and 64-Hz angular frquency.

The 2D model setting shown in Figure 2, three square AC potential waveform applied at the outer edge ends of three spiral conductors, generates a linear gradient electrical potential around the conductor's edges starting with a maximum electrical potential value at the conductor's edge and vanishing as the distance to the conductor's edge increases to eventually reaches zero value. Figure 3 shows the electrical potential and the respective electrical field in one particular instant. Figure 4 shows the electrical field generated at four different instances (0, 0.025, 0.05, and 0.1 seconds respectively).

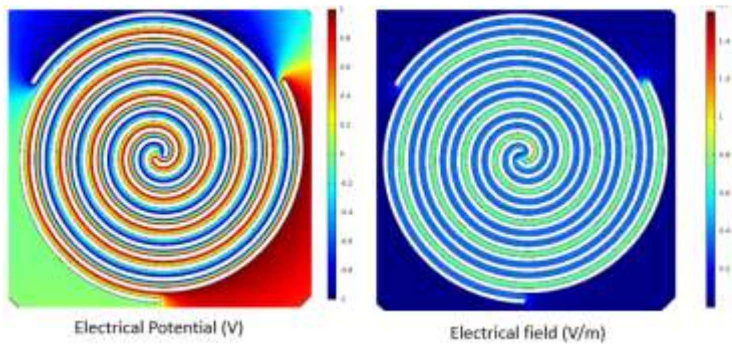

Figure 3. 2D electrical potential profile and its derived electrical field.

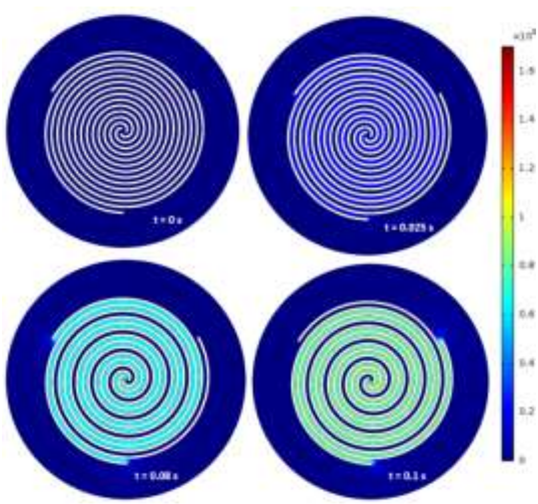

Fig 4. 2D electrical field profile generated during four instances, 0, 0.025, 0.08, and 0.1 seconds respectvily.

As stated above and corroborated in Figures 3 and 4, the electrical field generated at all instants within the separation area between parallel conductors is uniformed as the respective gradient of the electrical potential is linear. As stated in equation (10), dielectrophoretic force generation is only feasible at non-uniform electrical fields allowing electrostatic force to be the only electric-based force to be considered in this 2D model approach. Magnetic force is neglected in this 2D model approach as it is actually relevant in 3D domains.

Electrostatic force outcome on dust particles is basically dictated by the charging time as illustrated in Figures 5a and 5b. The trajectory and velocity of a 25-µm dust particle with two different charging time τ, one as stated in equation 3 (Figure 5a) and the other one equal to zero (Figure 5b) differ substantially as charging time determines how fast or slow the particle gets full charge (saturation charge). When charging time is not assumed to be zero but a function of the electrical field and the current density (equation 3) the particle takes a shorter path but at slower velocity leading to a longer removal time, 0.115 against 0.07 seconds as shown in Figure 5. Assuming instantaneous saturation charge on the particle (Figure 5b) leads to higher particle's velocity and shorter removal time even though the particle takes longer path that the particle with charging time (Figure 5a).

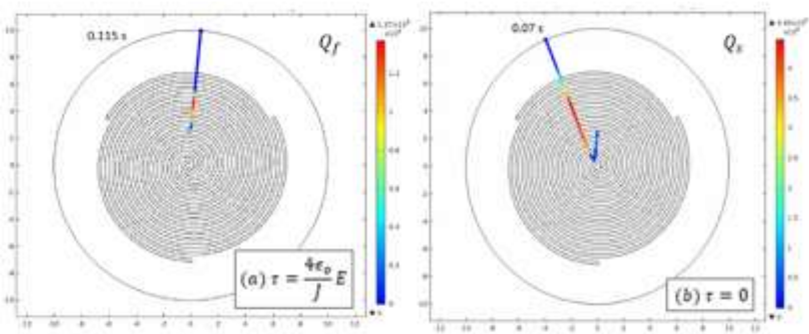

Fig 5. Trajectory and velocity of a dust particle modeled with two charging times: a) according to equation 3, b) 0,

Figure 6 depicts a total of 8,690 1-µm-size particles evenly distributed underneath a 2D multiphase spiral-shape conductors, as those shown in Figure 2, to remove them. The model was solved to estimate the trajectory of each particle and the final particle distribution within the 2D domain.

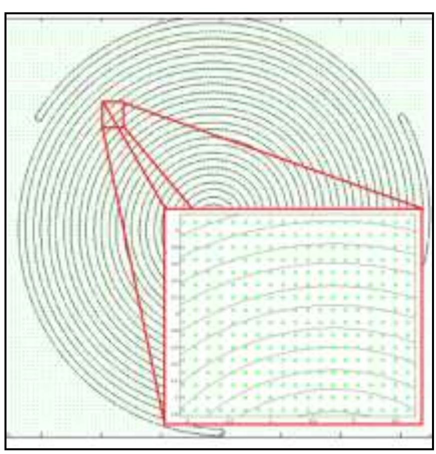

Fig 6. Initial distribution of 8,690 particles evenly dispersed throughout the spiral-shape-conductor removal system.

Figure 7 depicts the particle removal outcome generated by the model during four different instants, 0.0025, 0.01, 0.02, 0.05, 0.1, and 1 second respectively.

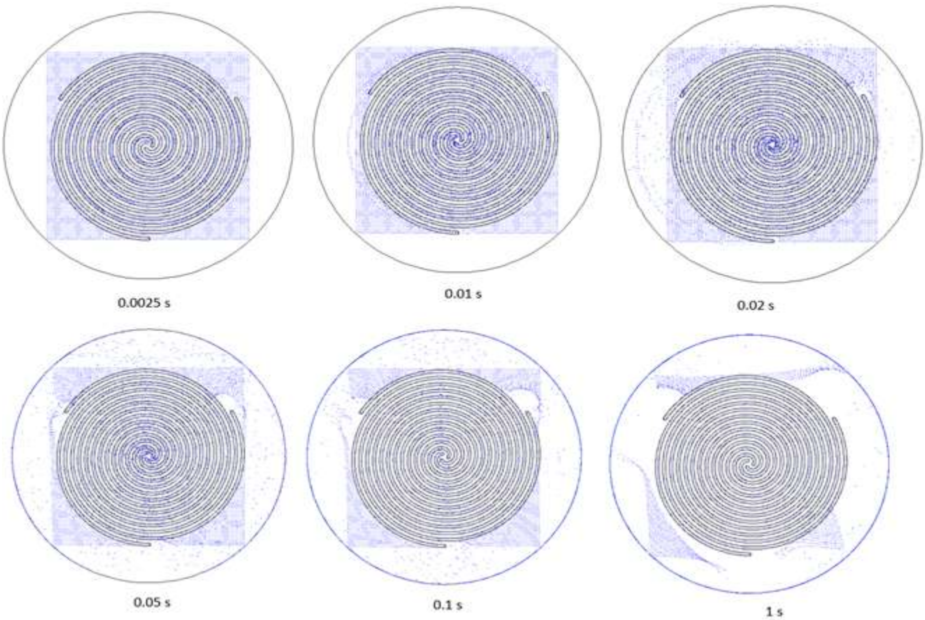

Fig 7. Model transient outcome on electrotastic removal of 8.690 particles initially dispersed evenly as shown in Figure 6.

Collision forces, which occur when charged particles collide with other particles and the background gas are not included in the model results illustrated in Figure 7. COMSOL's *Mathematical Particle Tracing (pt)* module allows the inclusion of these forces, they will be included in further studies.

B. 3D Model Approach

The 2D domain bearing the three multiphase spiral-shape conductors used above was extruded to create an equivalent 3D domain. The boundary conditions remain basically the same but applied to areas (for 3D domain) rather than edges (for 2D domain). The entire 3D domain is depicted in Figure 8 and includes the basic domains, the surrounding (air/CO_2/vacuum), the spiral conductors, and the substrate that holds the spiral conductors. All the outer faces are appropriately assumed to be electrical and magnetically insulated as they are away enough from the spiral-shape connectors. The current and voltage are considered to be present in all domains while the dust particles are reduced to be present in the two upper domains above the domain containing the conductors embedded in the substrate.

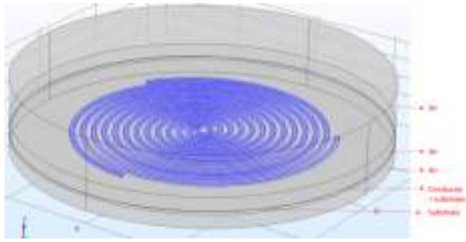

Fig 8. 3D domains built to model removal of particles via spiral-shape conductors

Figure 9 depicts the electric potential, the electric field, and the magnetic field generated in a given instance by the three 3D spiral-shape depicted in Figure 8. Multiphase potentials are applied at the outer ends of the 3D spiral-shape conductors as illustrated in Figure 2 for 2D spiral-shaped conductors with the difference that the AC potential are set as boundary conditions on the area ends (3D model) rather than the edge ends (2D model) of the spiral conductors.

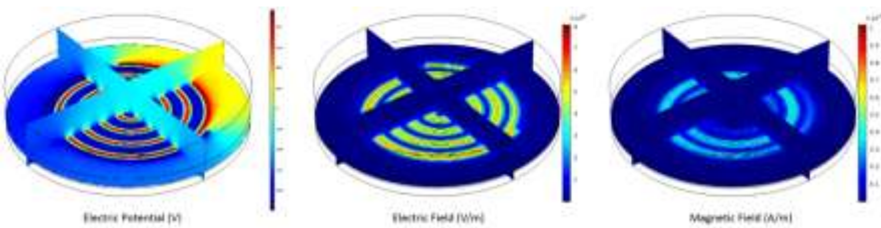

Fig 9. Electric potential, electric field, and magnetic field yielded by particle removal system shown in Figure 8.

3D model yields an electrical potential gradient above the surface of the conductor generating the EDTW as depicted in Figure 10. The EDTW induces a dipole moment on the dust particle (equation 6) that leads to the generation of a dielectrophoretic force (equation 10) applied to the particle as a gradient on the electrical field is present as illustrated in Figure 10.

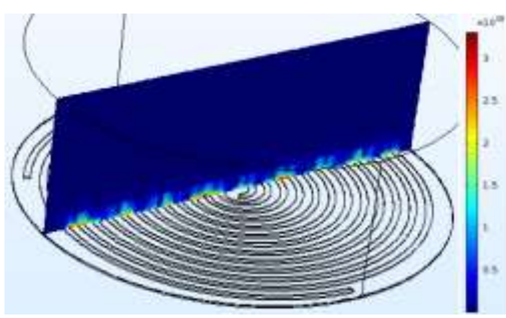

Fig 10. Modeled electric field gradient profile within the EDTW at the conductor surfaces.

Figure 11 depicts the 3D model outcome at three different instances on the trajectory of a 5-µm dust particle subject to electrostatic forces (equation 4) generated within the EDTW and viewed from xyz volumetric and xy planar perspectives.
As all models shown above, here the multiphase AC potential conditions are the same as those illustrated in Figure 2. Figure 11a is at the starting instant (t=0) having the particle idle and in its initial position, In Figure 11b, a snapshot at 0.005-second instant, the particle is slighted levitated floating on the EDTW and moving away from the its initial conditions. In Figure 11c, a snapshot at 0.01-second instant, the particle jumped from the EDTW and completed removed from the zone where the set of the three multiphase spiral conductors are. As stated above the model is set to stick the particles that hit the lateral walls that serve as geometric domain boundaries.

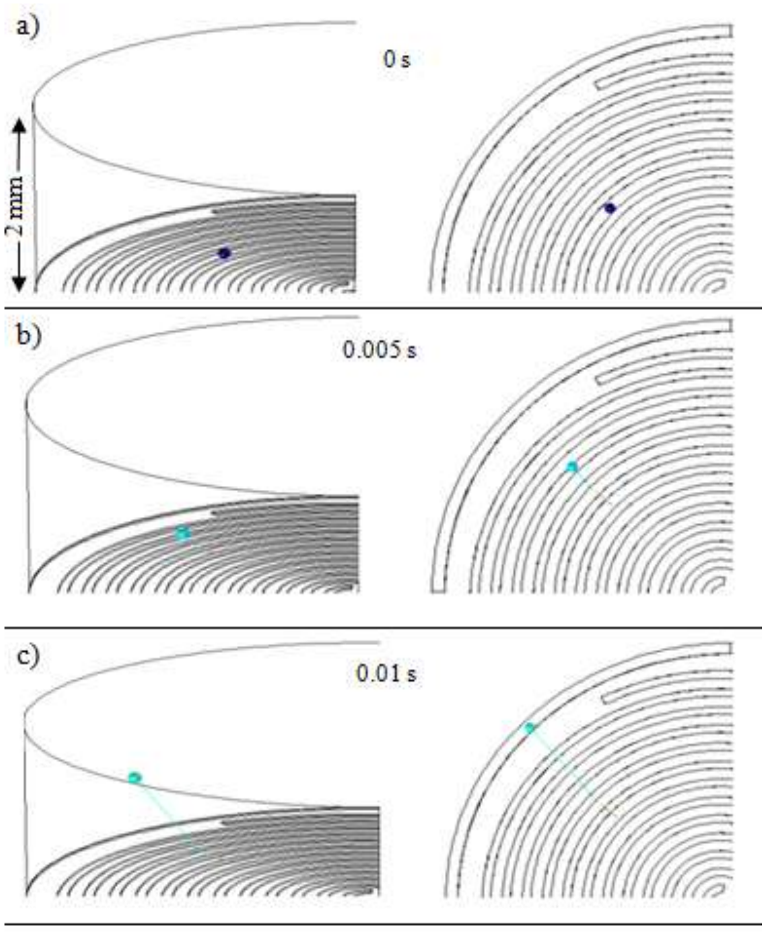

Fig 11. Modeled 5-µm dust particle trajectory viewed from xyz volumetric and xy planar perspectives. The particle is subject to an electrostatic force.

IV. Conclusion

NASA ESPL at Kennedy Space Center has built a comprehensive 3D modeling on superficial dust removal via electrostatic and dielectrophoretic forces for extraterrestrial exploration mission. The model is intended to optimize the implementation of the dust mitigation technology developed at the ESPL in terms of the geometry of the conductor array, power requirements, and particle removal efficiency.

The next step on the development of this NASA ESPL model is its validation using different experimental conditions under gaseous atmosphere (air/CO_2) and vacuum as well as different conductor geometries and conductor-array setups. The validation process will be conducted by recording the trajectory of known-size Simulant Martian particles via a high-speed high-resolution camera to not only track the trajectory of the particle but also estimate its velocity through all the trajectory.

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