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# Effect of voltage on multiple particles and collisions in a single Phase Gas Insulated Bus duct

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**ABSTRACT**
20% of failures in Gas Insulated Substations are due to the existence of various metallic contaminations in the form of loose particles. In this paper a single Phase Gas Insulated Bus duct with inner diameter conductor 55mm and diameter of enclosure 150 mm is considered. Three particles of different sizes assumed to be rest at a position, Power frequency voltages of 100 kV, 132 kV ,145 and 200 kV are applied to single Phase GIS bus. The motion of the three particles is simulated for different voltages using MATLAB. Effect of the three particles for power frequency voltage on particle movement are analyzed and time of collisions of the particle at first time is determined for various voltages. And also the horizontal and vertical distances at which the particles collide are determined for Particles of aluminum and copper of 10 mm in length and 0.25 mm radius, 10 mm length and 0.15 mm radius and 7 mm and 0.25 radii. The max displacement of the particles when each particle at a time is considered (without collision) are compared with the max radial displacements of three particles at a time by considering the collisions. The results show that the three particle collide at different points depending on the particles position , the velocity and direction of the particle changes after collisions.. The results show that the max displacement of particles is higher due to collisions as compared with (without collisions) when each particle at a time is considered.
***Keywords -*** Multiple particles , Gas Insulated Substations, Particles Contamination, MATLAB.

## I. INTRODUCTION

Compressed Gas Insulated Substations (GIS) consists basically of a conductor supported by insulator inside an enclosure, filled with SF6 gas. Basic components of the GIS bay are circuit breakers, disconnectors, earthing switches, bus ducts, current and voltage transformers, etc. The inner live parts of GIS are supported by insulators called spacers, which are made of alumina filled epoxy material. The GIS enclosure forms an electrically integrated, rounded enclosure for the entire substation. Even though SF6 exhibits very high dielectric strength, the withstand voltage of SF6 within the GIS is drastically reduced due to the presence of particles or defects like free particles on the inner surface of the enclosure, Protrusion on the high voltage (HV) bus, protrusion on the inner surface of the enclosure and narrow gaps between the spacer and the electrode are due to imperfect casting and imperfect mechanical strength, The presence of contamination can therefore be a problem with gas-insulated substations operating at high fields [1]-[2].

Free conducting particles are most hazardous to GIS. These free conducting particles may have any shape or size, may be spherical or filamentary (wire like) or in the form of fine dust. Particles may be free to move or may be fixed on to the surfaces. wire like particles made of conducting material are more harmful and their effects are more pronounced at higher gas pressures as given by the authors [2-5], the presence of dust containing conducting particles, especially on the cathode, reduces the breakdown voltage The present work deals with considering three different particles on the inner surface of the bus duct at a position, and using the basic equations for the movement of these metallic particles. Power frequency voltages of 100 kV, 132 kV ,145 and 200 kV are applied to single Phase GIS bus. In this paper a 1- Phase Gas Insulated Bus duct with diameter of conductor 55 mm and enclose diameter of 150 mm is considered for analysis . copper and aluminum particles of 10 mm in length and 0.25 mm radius, 10 mm length and 0.15 mm radius and 7 mm and 0.25 radius are considered for simulation with MATLAB.

## II. MODELLING OF GAS INSULATED BUS DUCT.

A typical horizontal single-phase bus duct shown in Figure 1 has been considered for the analysis. It consists of a conductor spaced in a metal enclosure, filled with SF6 gas. Particles are assumed to be rest at some position on the enclosure surface, until a voltage sufficient enough to lift the particles and move in the field is applied. After acquiring an appropriate charge in the field, the particles lift and begin to move in the direction of the field after overcoming the forces due to its own weight and drag. For particles on bare electrodes, several authors have suggested expressions for the estimation of charge on both vertical/horizontal wires and spherical particles. The equations are primarily based on the work of Felici[5].

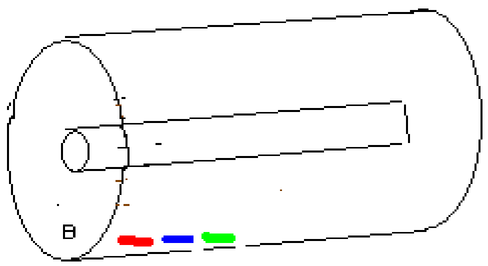


Figure. 1 Typical single phase gas insulated bus

Conducting particles in motion in an external electric field will be subjected to a collective influence of several forces. The forces are : -

- Electrostatic force (Fe)
- Gravitational force (mg)
- Drag force (Fd)

The motion equations for the three particles are given by

$$m_1 \frac{d^2 y_1}{dt^2} = F_{e1} - m_1 g - Fd_1 \quad ----(1a)$$

$$m_2 \frac{d^2 y_2}{dt^2} = F_{e2} - m_2 g - Fd_2 \quad ----(1b)$$

$$m_3 \frac{d^2 y_3}{dt^2} = F_{e3} - m_3 g - Fd_3 \quad ----(1c)$$

where $m_1, m_2, m_3$ = mass of the particles
y = displacement in vertical direction
Fe = Electrostatic force
g = gravitational constant

The charges acquired by a vertical wire particles respectively in contact with a naked enclosure can be expressed as:

$$Q_1 = \frac{\pi \in_0 l_1^2 \, E(t0)}{\left( \ln(\frac{2l_1}{r_1}) - 1 \right)} \ldots\ldots\ldots\ldots 2(a)$$

$$Q_2 = \frac{\pi \in_0 l_2^2 \, E(t0)}{\left( \ln(\frac{2l_2}{r_2}) - 1 \right)} \ldots\ldots\ldots\ldots 2(b)$$

$$Q_3 = \frac{\pi \in_0 l_3^2 \, E(t0)}{\left( \ln(\frac{2l_3}{r_3}) - 1 \right)} \ldots\ldots\ldots\ldots 2(c)$$

where $Q_1, Q_2, Q_3$ are the charges on the particles, $l_1, l_2, l_3$ are the particle length, $r_1, r_2, r_3$ are the particle radii respectively , E(t0) is the ambient electrical field at t = t0. The charge carried by the particles between two impacts has been considered constant in the simulations.

The electric field in a coaxial electrode system at position of the particles can be written as:

$$E(t) = \frac{V_m \operatorname{Sin} \omega t}{[r_0 - y(t)] l_n \left[ \frac{r_0}{r_i} \right]} \ldots\ldots\ldots(3)$$

where Vm Sin wt is the supply voltage on the inner electrode, $r_O$ is the enclosure radius, $r_i$ is the inner conductor radius y(t) is the position of the particle which is the vertical distance from the surface of the enclosure towards the inner electrode.

The electrostatic force on each particle is given by

$$F_{e1} = K\, Q_1\, E(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4a)$$

$$F_{e2} = K\, Q_2\, E(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4b)$$

$$F_{e3} = K\, Q_3\, E(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4c)$$

Where K is a corrector and is a factor less than unity. However, for length-to-radius ratios greater than 20 the correction factor, K, is close to unity

The drag forces are given by:

$$F_{d1} = \dot{y}\, \pi r_1 \left( 6\mu K_d (\dot{y}) + 2.656 \left[ \mu \rho_g\, l_1\, \dot{y} \right]^{0.5} \right) \ldots\ldots\ldots (5a)$$

$$F_{d2} = \dot{y}\, \pi r_2 \left( 6\mu K_d (\dot{y}) + 2.656 \left[ \mu \rho_g\, l_2\, \dot{y} \right]^{0.5} \right) \ldots\ldots\ldots (5b)$$

$$F_{d3} = \dot{y}\, \pi r_3 \left( 6\mu K_d (\dot{y}) + 2.656 \left[ \mu \rho_g\, l_2\, \dot{y} \right]^{0.5} \right) \ldots\ldots\ldots (5c)$$

where y is the velocity of the particle, μ is the viscosity of the fluid (SF6 : 15.5_10−6kg/m_s at 200C), $\rho_g$ is the gas density, Kd(y) is a drag coefficient.

The influence of gas pressure on the drag force is given by empirical formula.

$$\rho_g = 7.118 + 6.332P + 0.2032P^2 \ldots\ldots\ldots\ldots (6)$$

where $\rho_g$= density p = Pressure of the gas and 0.1 < p < 1mboxMPa.

The restitution coefficient for copper particles seem to be in the range of 0.7 to 0.95:R = 0.8 implies that 80% of the incoming impulse of the particle is preserved when it leaves the enclosure.

The motion equation (1a) ,(1b),(1c) using all forces can therefore be expressed as

$$m\ddot{y}(t) = \frac{\pi \in_0 l^2 \, E(t_0)}{\ln\left(\frac{2l}{r}\right) - 1} \text{ x } \frac{V_m \operatorname{Sin} \omega t}{[r_0 - y(t)] \ln(\frac{r_0}{r_i})} - mg$$

$$- \dot{y}(t)\, \pi r\, (6\mu K_d (\dot{y}) + 2.656 (\mu r_g\, ly\, (t)^{0.5})$$

In the above equation, the parameters m,l,r can be replaced by $m_1$,$l_1$,$r_1$ and motion of the particle 1 can be obtained, similarly for particles 2 and 3 motions can be obtained. The above equation is a second order non-linear differential equation and in this paper, the equation are solved using MATLAB

In order to determine the random behavior of moving particles, the calculation of movements in axial and radial directions was carried at every time step using random numbers. The above simulation gives the particle movement in the radial and axial directions. The random movement can be adequately simulated by Monte-Carlo technique. It is assumed that the particle emits from its original site at any angle less than φ, where φ/2 is half of the solid angle with the vertical axis.

## III. RESULTS AND DISCUSSIONS

The particle 1 has 10 mm in length and 0.25 mm radius, particle 2 has 10 mm length and 0.15 mm radius and particle 3 has 7 mm and 0.25 radius.

Table 1 shows the radial movement of the aluminum and copper particles in a 1- Phase Gas Insulated Bus duct for voltages of 100kV ,132 kV ,145 kV and 200 kV respectively. Table 2 shows the time at which particle collide for first time Tc and Vertical height of the particle at collisions in mm . velocity of the particle at just before the collision (mm /sec) .

In Table 3 the velocity of the particles at just before the collision and after collision are shown determined by the equation of collision given in appendix at Tc by MATLAB . Figure 2 to Figure 8 shows the movement patterns of copper and aluminum particles in Electric Field for applied voltages of 100KV ,132 kV ,145 KV and 200 KV respectively.

Table.1 Radial movement of aluminum and copper particles with for various voltages assuming one particle at atime (no collisions)
CG: crossing the gap.

| S No | Voltage KV | Time at which particle collide first time Tc (sec ) | Vertical height of the particle at collisions (mm ) | | |
|---|---|---|---|---|---|
| | | | Particle-1 (blue) | Particle-2 (green) | Particle3 (Red) |
| Aluminum particle | 100 | 0.015 | 8.4 | NC | 8.4 |
| | 132 | 0.022 | 12.1 | NC | 12.1 |
| | 145 | 0.015 | 14.2 | NC | 14.2 |
| | 200 | CG | CG | CG | CG |
| Copper particles | 100 | 0.07 | 3.1 | NC | 3.1 |
| | 132 | 0.03 | 5.7 | NC | 5.7 |
| | 145 | 0.06 | 7.2 | NC | 7.2 |
| | 200 | 0.03 | 17 | 17 | NC |

Table.2 height and time of particle collisions for various voltages

| s.No. | Voltage KV | Max. Radial Movement of particle 1 (mm ) | Max. Radial Movement of particle 2 (mm ) | Max. Radial Movement of particle 3 (mm ) |
|---|---|---|---|---|
| Aluminum particle | 100 | 21.44 | 39.3928 | 12.9947 |
| | 132 | 30.536 | 61.4303 | 26.2944 |
| | 145 | 34.28 | 66.2626 | 28.9362 |
| | 200 | 45.79 | CG | 49.5366 |
| Copper particles | 100 | 4.4906 | 14.0571 | 3.4961 |
| | 132 | 9.8475 | 21.4638 | 7.5465 |
| | 145 | 13.73 | 24.0725 | 9.6887 |
| | 200 | 17.807 | 32.2358 | 19.3187 |

It is observed that the three particle are started at same position and the particles collide at different intervals, collision at different points are shown in figures 9 to 15. It is seen that as the voltage varies from 100 kV to 200 kV maximum radial movement also varies as shown in Table1 and also the particles collide at different intervals. At the point of collisions (from fig 9 to 15 ) the particle moves randomly and its direction and velocity also changes. It gives the actual maximum radial displacement more than the maximum radial displacement when only one particle considered at a time (no collision takes place) .

The axial movements of particles and are shown in figures 16 and 17 for the applied voltages of 100 kV aluminum and copper respectively.

The time of collisions , vertical velocity of the particles are calculated by simulation results by the equation given in appendix , the velocity of the particles 1, 2 and 3 after collisions are calculated as given in Appendix.

Table. 3 Time of collisions and velocities of the particles before and after the collision..( CG:crossing the Gap)

| S.No | Voltage KV | Time at which particle collide first time Tc (sec ) | Velocity of the particle at just before the collision (mm /sec) | | | Velocity of the particle after the collision (mm /sec) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Particle1 (blue) | Particle2 (green) | Particle3 (Red) | Particle1 (blue) | Particle2 (green) | Particle3 (Red) |
| Aluminium particle | 100 | 0.015 | **362.1** | 812.7 | **268.2** | 284.7703 | **NC** | **378.6703** |
| | 132 | 0.065 | **-386.6** | 1450.3 | **-285.0** | -302.9291 | **NC** | -404.5291 |
| | 145 | 0.05 | **567.0** | 878.4 | **449.0** | 469.8232 | **NC** | 587.8232 |
| | 200 | CG | **CG** | CG | **CG** | CG | **CG** | CG |
| Copper particles | 100 | 0.07 | 384.2 | **274.0** | 177.2 | 110.8000 | **NC** | 317.8000 |
| | 132 | 0.03 | **582.9** | 1399.7 | **394.2** | 333.6701 | **NC** | 522.3701 |
| | 145 | 0.06 | **-846.9** | -1709.2 | **-729.4** | -691.7092 | **NC** | -809.2092 |
| | 200 | 0.03 | **1116.1** | 2247.1 | **807.7** | 708.7736 | **NC** | 1017.2 |

Table. 4 Max Radial displacements with and without collision. CG: crossing the gap

| S.No | Voltage KV | Max. Radial movement of particle 1 ( mm ) | | Max. Radial movement of particle 2 ( mm ) | | Max. Radial movement of particle 3( mm ) | |
|---|---|---|---|---|---|---|---|
| | | without collisions | with collisions | without collisions | with collisions | without collisions | with collisions |
| Aluminum particle | 100 | 21.4465 | 21.9538 | 39.3928 | NC | 12.9947 | 17.6209 |
| | 132 | 30.5296 | 29.4974 | 61.4303 | NC | 26.2944 | 27 |
| | 145 | 34.2775 | 33.6727 | 66.2626 | NC | 28.9362 | 29.8350 |
| | 200 | CG | **CG** | **CG** | CG | CG | **CG** |
| Copper particles | 100 | 4.4906 | 4.6719 | 14.0571 | NC | 3.4961 | 11.3931 |
| | 132 | 9.8475 | 10.6898 | 21.4638 | NC | 7.5465 | 7.8136 |
| | 145 | 13.7259 | 14.1039 | 24.0725 | NC | 9.6887 | 9.0872 |
| | 200 | 17.8027 | **20.1111** | 32.2358 | NC | 19.3187 | 20.4977 |

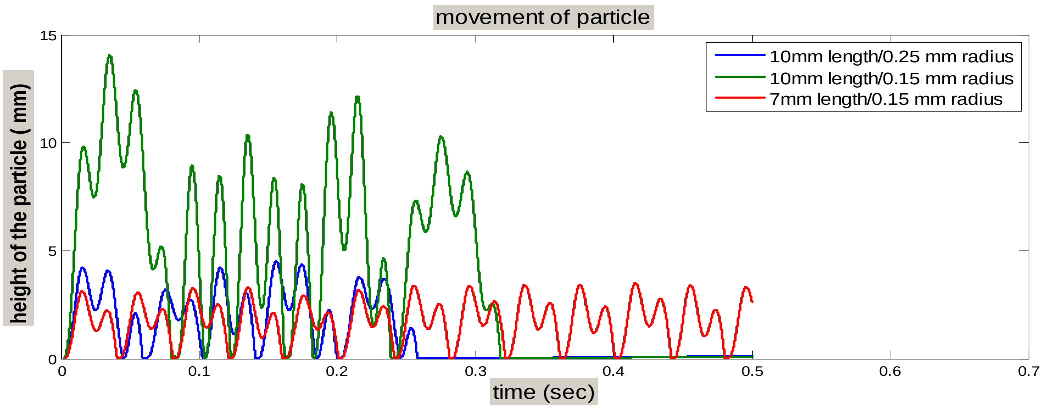


Figure. 2 Radial Movement Cu particles / 100KV / 55mm - 150mm Enclosure

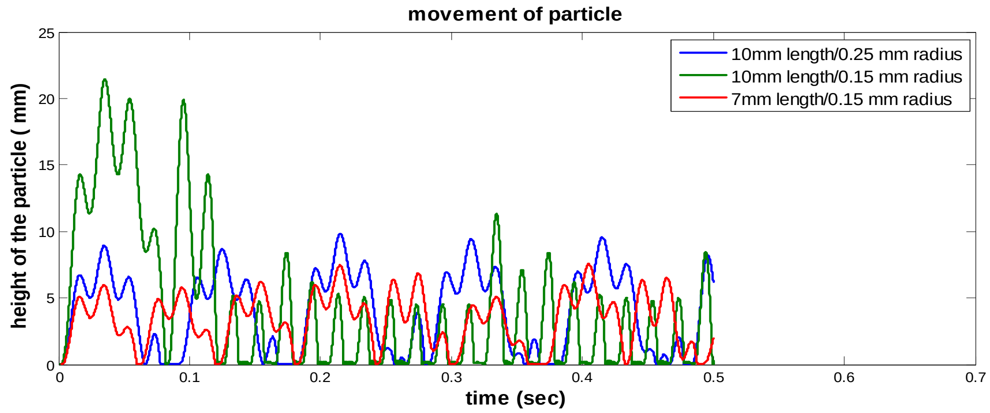


Figure. 3 Radial Movement Cu particles / 132KV / 55mm - 150mm Enclosure

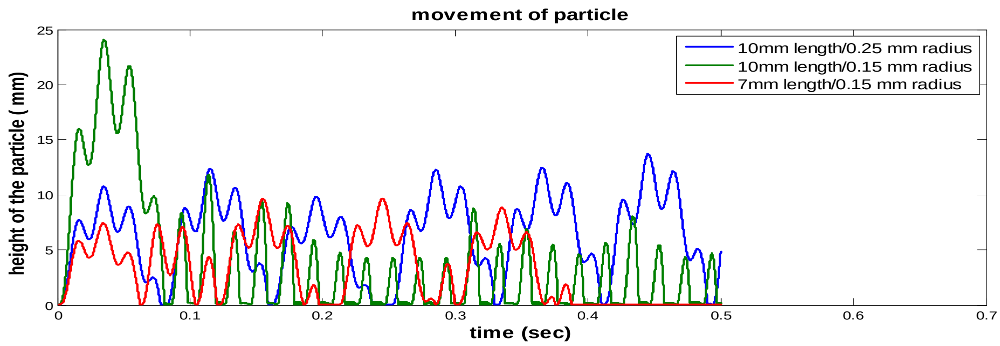


Figure. 4 Radial Movement Cu particles / 145KV / 55mm - 150mm Enclosure

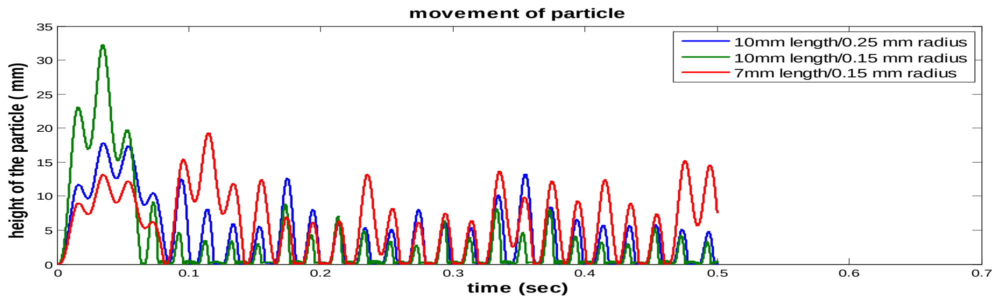


Figure.5 Radial Movement Cu particles / 200KV / 55mm - 150mm Enclosure

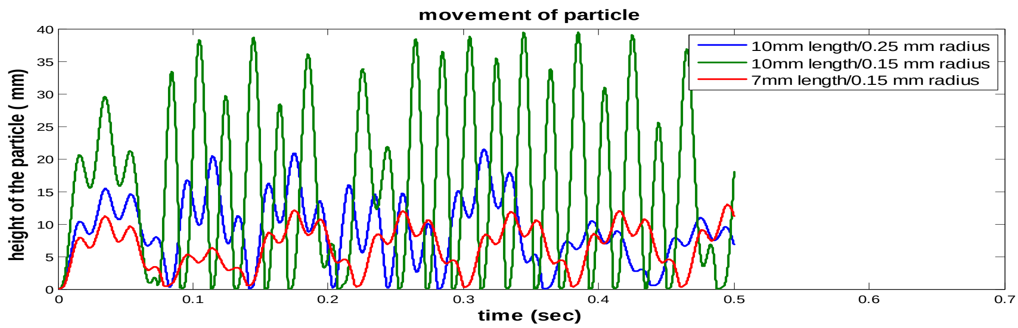


Figure.6 Radial Movement Al particles / 132KV / 55mm - 150mm Enclosure

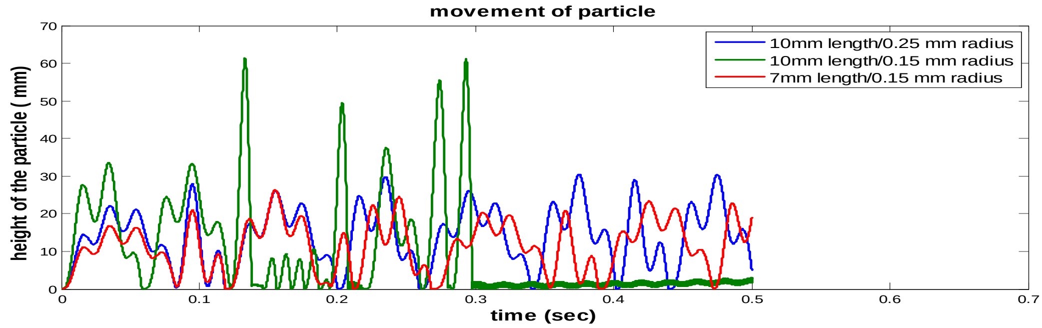


Figure.7 Radial Movement Al particles / 132KV / 55mm - 150mm Enclosure

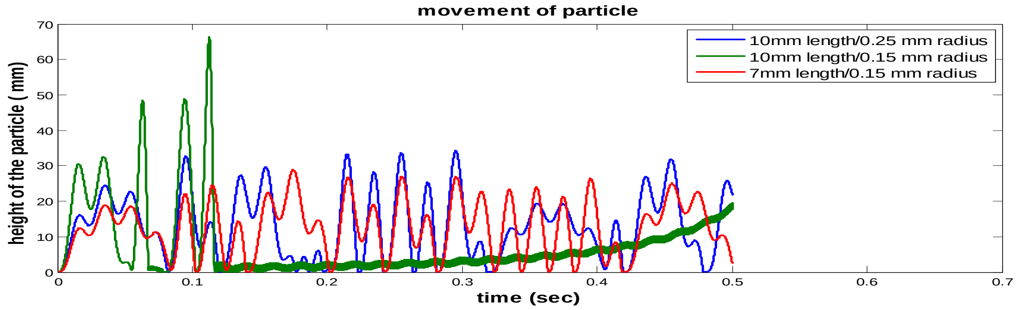


Figure.8 Radial Movement Al particles / 145KV / 55mm - 150mm Enclosure

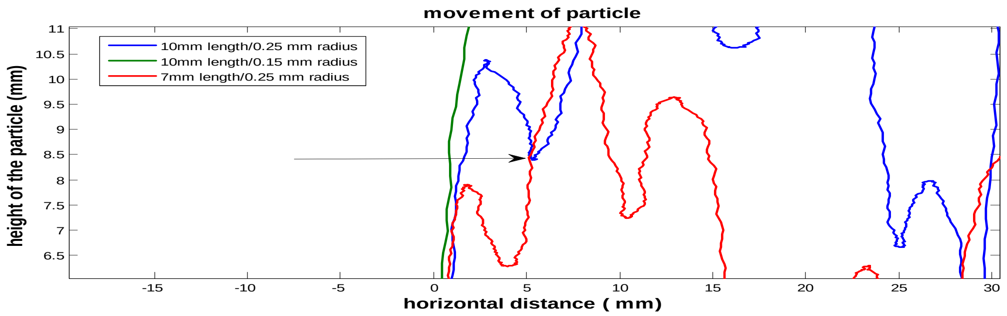


Figure.9 Particle collisions for Al / 100 kV / 55mm - 150mm Enclosure

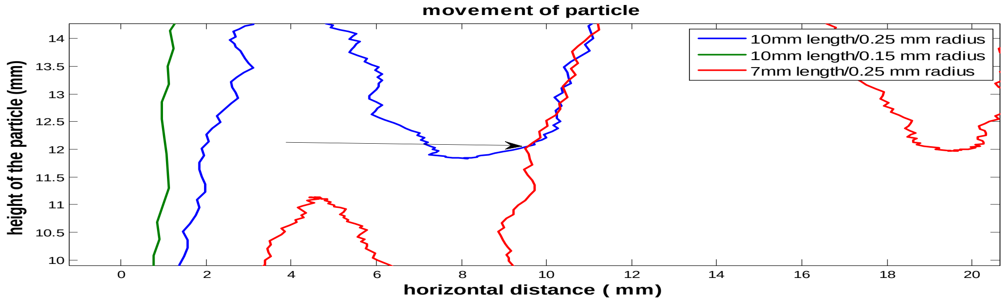


Figure.10 Particle collisions for Al / 132 kV / 55mm - 150mm Enclosure

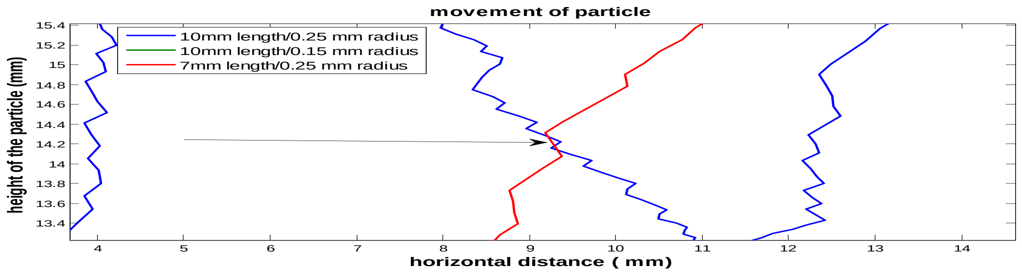


Figure.11 Particle collisions for Al / 145 kV / 55mm - 150mm Enclosure

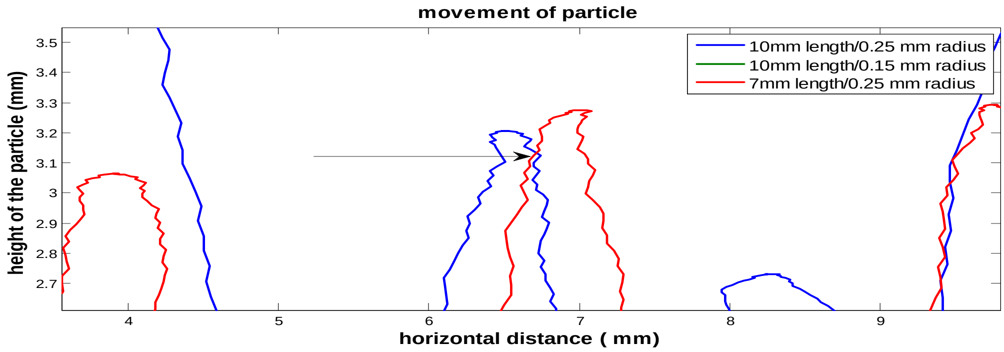


Figure.12 Particle collisions for Cu/100 kV/55mm -150mm Enclosure

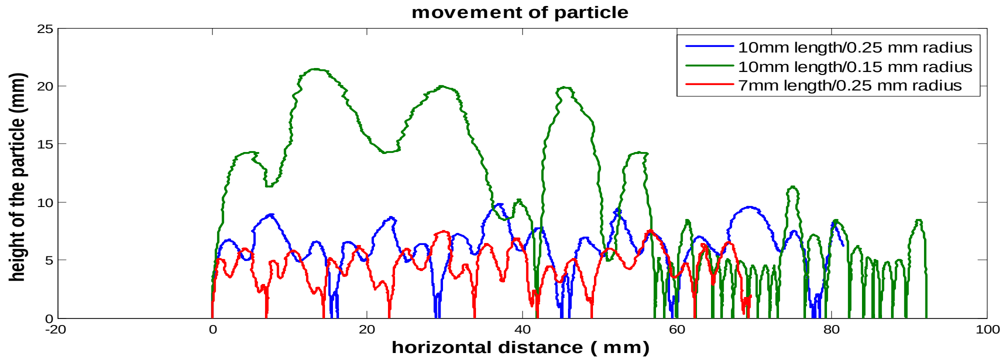


Figure.13 Particle collisions for Cu / 132 kV / 55mm - 150mm Enclosure

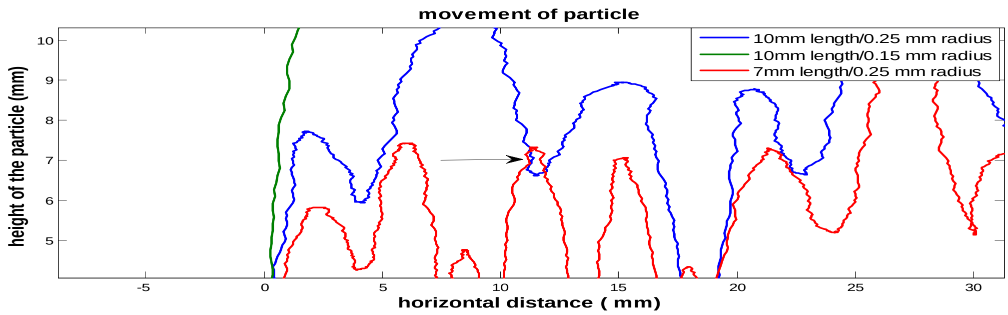


Figure.14 Particle collisions for Cu / 145 kV / 55mm - 150mm Enclosure

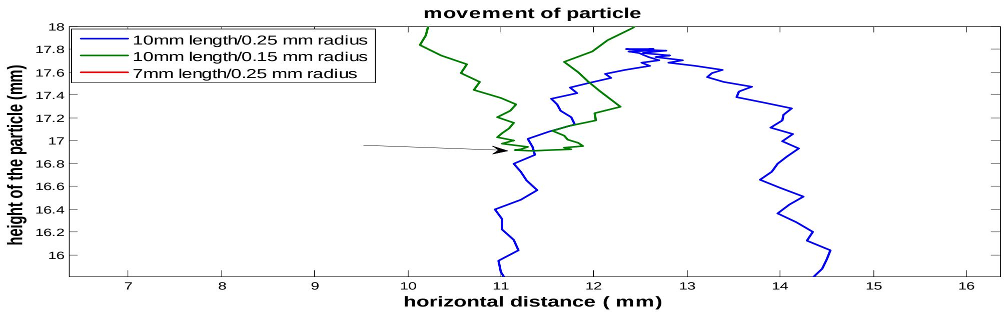


Figure.15 Particle collisions for Cu / 200 kV / 55mm - 150mm Enclosure

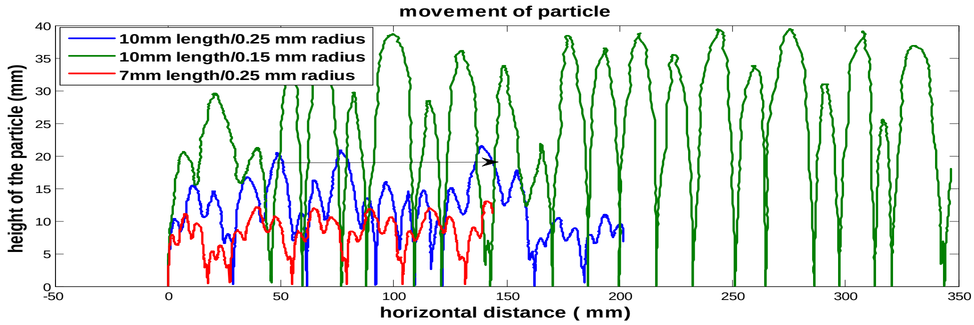


Figure.16 Axial Movement Al particles/100 kV/55mm -150mm Enclosure

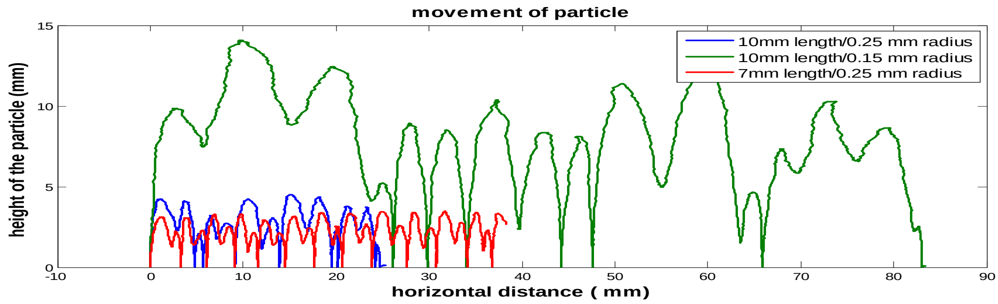


Figure.17 Axial Movement Cu particles / 100 kV / 55mm - 150mm Enclosure

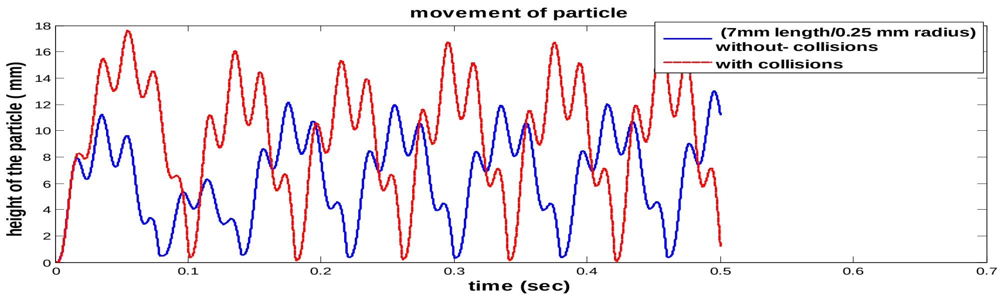


Figure.18 Radial movement of Al particle-3with and without collisions/ 100 kV / 55mm - 150mm Enclosure

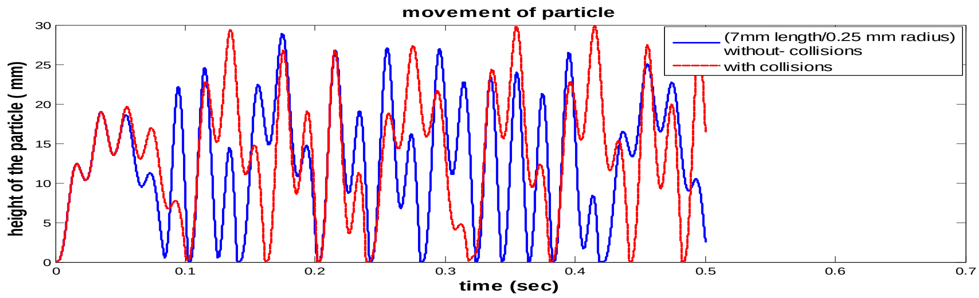


Figure.19 Radial movement of Al particle-3with and without collisions/ 145 kV / 55mm - 150mm Enclosure

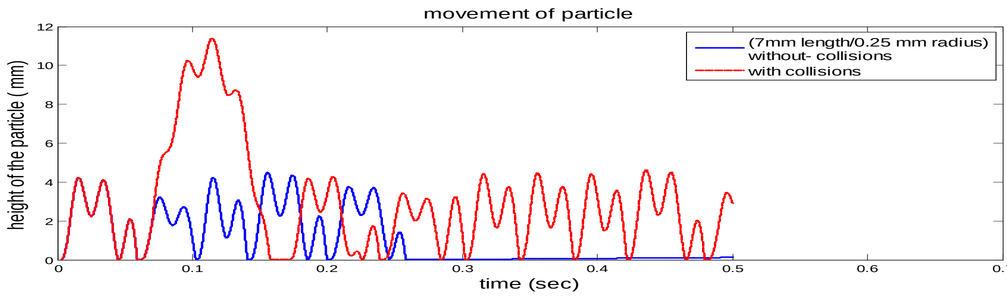


Figure.20 Radial movement of Cu particle-3 with and without collisions/ 100 kV / 55mm - 150mm Enclosure

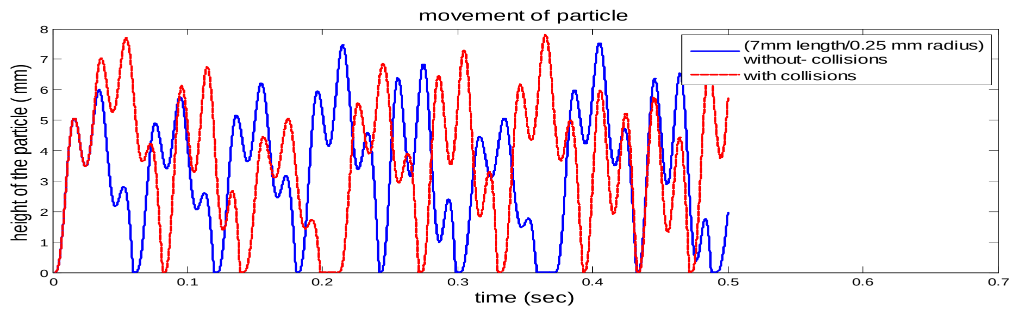


Figure.21 Radial movement of Cu particle-3 with and without collisions/ 132 kV / 55mm - 150mm Enclosure

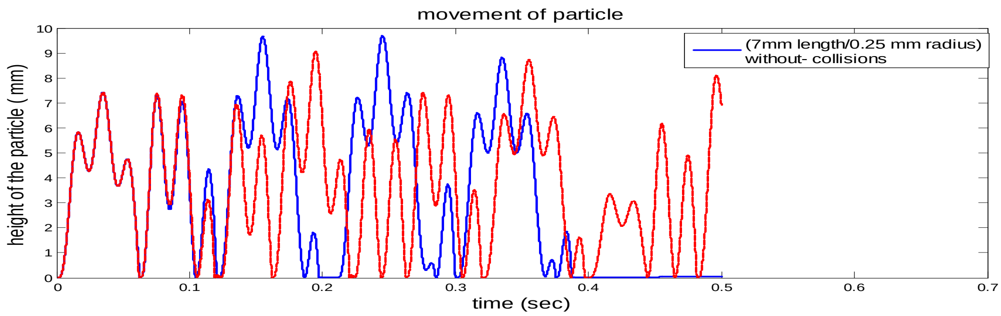


Figure.22 Radial movement of Cu particle-3 with and without collisions/ 145kV / 55mm - 150mm Enclosure

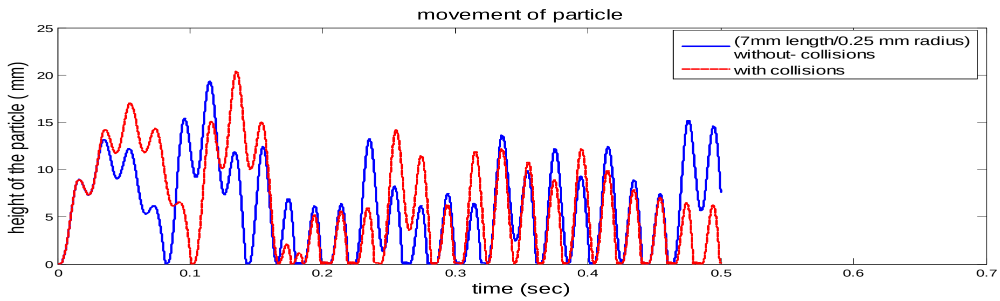


Figure.23 Radial movement of Cu particle-3 with and without collisions/ 200kV / 55mm - 150mm Enclosure

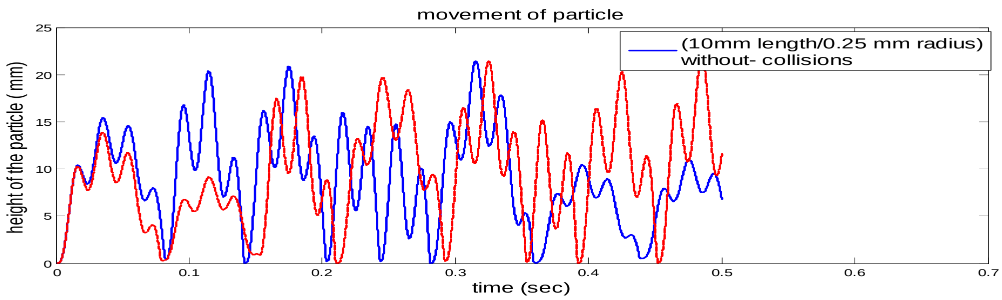


Figure.24 Radial movement of Al particle-1 with and without collisions/ 100kV / 55mm - 150mm Enclosure

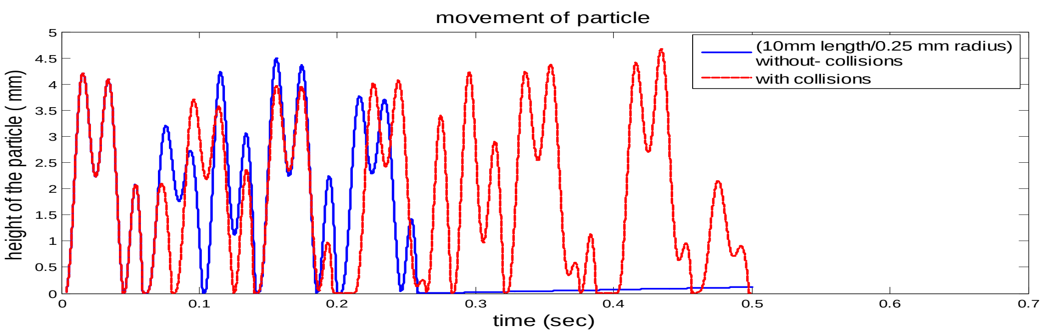


Figure.25 Radial movement of Cu particle-1 with and without collisions/ 100kV / 55mm - 150mm Enclosure

In the table 3 ,the velocity of the particles just the instant after collision for different voltages is given. It is seen from the table 3 that the particles 1 and 3 are collide and their velocities are ( Blue and red colors in the plot) abruptly changes after collision. Whereas for particle 2 , no significant collisions are detected hence there is no change in the velocity of particle-2

Sample calculation for a voltage of 100 KV

The velocity before collision at Tc for particle 1 (blue) u1 =362.1 mm/sec.

The velocity before collision at Tc for particle 3(blue) u2 =268.2 mm/sec.

Mass of the particle1= m1 = 5.3014e-006

Mass of the particle 3= m2 =3.7110e-006

the velocity after collision at $T_C$ for particle 1 and 3

$$v_1 = \frac{u_1(m_1 - m_2) + 2m_1u_2}{m_1 + m_2}$$

$$v_2 = \frac{u_2(m_2 - m_1) + 2m_1u_1}{m_1 + m_2}$$

$V_1$=284.7703 mm/sec

$V_2$= 378.6703 mm/sec

The movement patterns of copper and aluminum particles with collisions and without collisions ( when each particle considered separately) are compared and are shown in Figure 18 to Figure 25. It is seen that the particle 1 and particle 3 collide and there are no collisions takes place to the particle 2 (green) . The maximum radial displacements of the particles 1 and 3 are higher due to the collision of the particles . In figure 18 and 19 , aluminum particle -3 for a voltages of 100 kV and 145 kV are shown it is seen that the max height of the particles due to simultaneous movement is higher than the movement of particle when single particle alone is considered( no-collisions). From fig. 20 to 23 , movement of copper particle-3 are shown ,compared with collisions and without collisions i.e when single particle alone is considered. From fig 24 and 25 , movement of copper particle-1 and aluminum particle-1 are shown ,compared with collisions and without collisions i.e when single particle alone is considered.

## IV. CONCLUSION

The Maximum radial displacements of the particles both aluminum and copper for the voltages of 100 kV 132 kV and 145 kV and 200 kV are calculated (simulated) when each particle is considered one at a time. When the three particles are simultaneously considered then three particles move and collide, their velocities after collision changes abruptly. Hence the maximum radial displacements of the particles are higher as compared to when particles are considered individually. As the density of aluminum is low hence the max heights of the aluminum particles as compared to copper particle is high.

Hence the calculations, as described above, are performed by considering a single particle at a time as no collisions takes place, max height of the particle and chances of flash over would be low. The results obtained from the simulation show that due to collision of particle the maximum radial displacements are high and lead to high flash over chances. However the collision of the particles in the gap will increase the chances of flashover.

**Appendix One- dimensional Collision of particles**

Consider two particles, denoted by subscripts 1 and 2. Let $m_1$ and $m_2$ be the masses, $u_1$ and $u_2$ the velocities before collision, and $v_1$ and $v_2$ the velocities after collision.

The conservation of the total momentum demands that the total momentum before the collision is the same as the total momentum after the collision, and is expressed by the equation.

$$m_1u_1 + m_2u_2 = m_2v_2 + m_1v_1$$

Likewise, the conservation of the total kinetic energy is expressed by the equation.

$$\frac{m_1u_1^2}{2} + \frac{m_2u_2^2}{2} = \frac{m_1v_1^2}{2} + \frac{m_2v_2^2}{2}$$

These equations may be solved directly to find $v_i$ when $u_i$ are known or vice versa. An alternative solution is to first change the frame of reference such that one of the known velocities is zero. The unknown velocities in the new frame of reference can then be determined and followed by a conversion back to the original frame of reference to reach the same result. Once one of the unknown velocities is determined, the other can be found by symmetry.

Solving these simultaneous equations for $v_i$ we get:

$$v_1 = \frac{u_1(m_1 - m_2) + 2m_1u_2}{m_1 + m_2}$$

$$v_2 = \frac{u_2(m_2 - m_1) + 2m_1u_1}{m_1 + m_2}$$

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