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Analysis of Particle Movement and Partial Discharge in OFAF Power Transformers Using Computational Fluid Dynamics

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Abstract

This paper deals with movement of particle contaminants in transformer oil and partial discharges (PD) due to the existence of the particle in power transformer. Mineral oil used as coolant and insulation in transformer may have particle contaminations. These particles move along with oil in the gap between transformer discs and pressboard cylinder and between discs. Movements of particle in a power transformer are simulated using Computational Fluid Dynamics (CFD) for directed oil flow in the transformer. Point of contact between conducting particle and transformer disc during the upward movement of particle is identified by using the Computational Fluid Dynamics simulations. Electric stress developed on the particle at the point of contact is theoretically calculated. If the developed stress exceeds the permissible limit, the partial discharge is initiated. Impact of field multiplication (β) factor, which accounts the degradation of oil due to aging and other factors and the flow pattern of transformer oil are also considered for initiation of PD. From the results of simulation, it is observed that particle movement and partial discharge are influenced by type of material, oil velocity, field multiplication factor and starting point of the particle.

Keywords: CFD, Directed oil flow, Field multiplication factor, Partial discharge Particle movement, Power transformer.

INTRODUCTION

Power transformers are very important equipments placed in distribution network. Power transformers have application system in high power. Mineral oil is used as a coolant and liquid insulation in most of the power transformers. This transformer oil may have particle contaminations due to the dust particle left over inside the transformer during its manufacturing process, copper and iron particles formed due to internal sources etc,. Irrespective of filtering, these particles enter in the transformer and move freely along with the insulating oil in the winding space of the transformer. These particles may be made up of conducting materials of different sizes and shapes. Conducting particles when strikes the transformer winding may cause partial discharges. Particles are directed by the flow path of transformer oil. In some transformers, oil is guided in the winding space by placing oil guides in between disc and pressboards of the transformer to ensure the effective cooling of the transformer. In such cases, particle is also constrained to take the path of the oil from bottom entry to top. When conducting particle strikes the energized winding disc, partial discharge may get initiated. Occurrence of partial discharge is one of the major reasons for transformer failure. Many research work show that movement pattern of the particle influences the characteristics of PD. Similar kind of issues are also reported in case of Gas Insulated Substations (GIS).

Irwin et al. [1] presented a UHF based PD monitoring system for Gas Insulated substations. Several discharge patterns were identified depending on the particle movement and location. It is reported that particles in chamber wall can be easily detected by spectrum analyzer. When all the input channels are active, if particles are available at spacer surface it can be detected only by PD monitoring system. Influence of material of gaseous insulation is analyzed by Poonam et al. [2]. It is reported that percentage of SF6 and N2 in the gas mixture determines the movement pattern of particle. It is stated that the higher percentage of N2 in the mixture shows lower movement. The maximum movement is obtained at 20% nitrogen in SF6/N2 mixture and lowest movement is obtained at 90% of nitrogen. Pang et al. [3] analyzed a movement pattern of linear particle for a different lifting voltage in GIS enclosure. It is reported that the lifting voltage is low when the cavity vibrates and high when the shell does not vibrate.

In the latest work by Eslami et al.[4], motion of a conductive particle in dielectric viscous medium influenced by a DC electric field is investigated using CFD model. Up and down motion of spherical particle under DC field is analyzed. The results of the work show that the dielectric liquid ionic conductivity and the wall hydrodynamic effect are main factors in determining the movement of the particle. A work by Carlos [5] suggests that CFD is an appropriate method for analysis and this method can play a major role in design of new geometries thorough information on flow patterns.

Average and hot-spot temperatures of HV and LV winding disc and oil space of oil directed air forced (OFAF) and oil natural air forced (ONAF) cooled transformers are presented by the author. Simulation results are compared with experimental results and corrections are suggested by the authors. Qiao Wen et al. [6] simulated the model of a 720 MVA, 500 kV oil-immersed transformer using CFD software based on Thermal-Fluid Coupled field. Heat transfer pattern of transformer oil is studied from the model. Results of fluid flow analysis show that if the initial velocity is low heat dissipation is poor and also if the initial velocity at the inlet is high, heat dissipation is comparatively more effective.

This paper deals with two dimensional modeling of OFAN cooling transformer winding and analysis of partial discharge due to the movement of particle inside the transformer setup.

SIMULATION

A 100 MVA, 11 /132 /220 kV, three winding power transformer is considered for analysis. Only HV winding is considered for this analysis as voltage of the winding has higher impact on the initiation of PD. HV winding is divided into two symmetrical half coils. Due to this symmetry, one half of the coil is considered for simulation. The half coil consists of 58 discs placed with assigned gaps. Figure 1 shows the arrangement of transformer winding. Transformer oil is allowed to enter in the gap between bottom winding disc and inner pressboard as shown in Figure 2. Oil flow in the transformer may be either Oil Natural (ON) or Oil Forced (OF). In this analysis Oil Forced (OF) system is considered. In the above mentioned system, oil guides placed near transformer discs in inner and outer radius of the disc alternatively. Due to this oil takes a zigzag path towards top of the transformer.

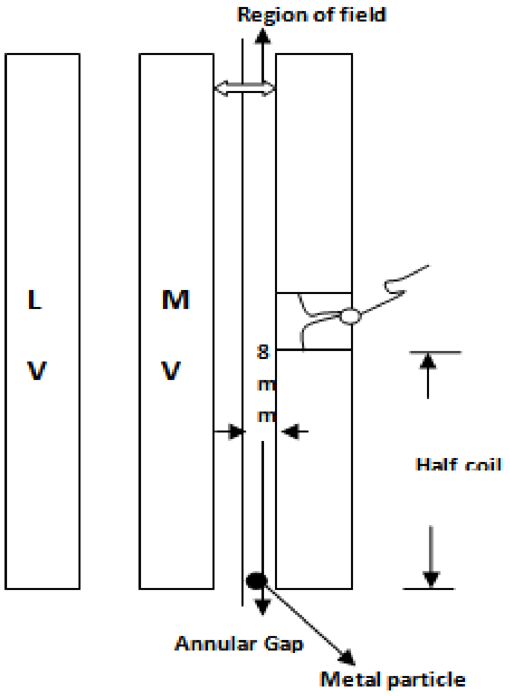

Figure 1 : Arrangement of Transformer Windings

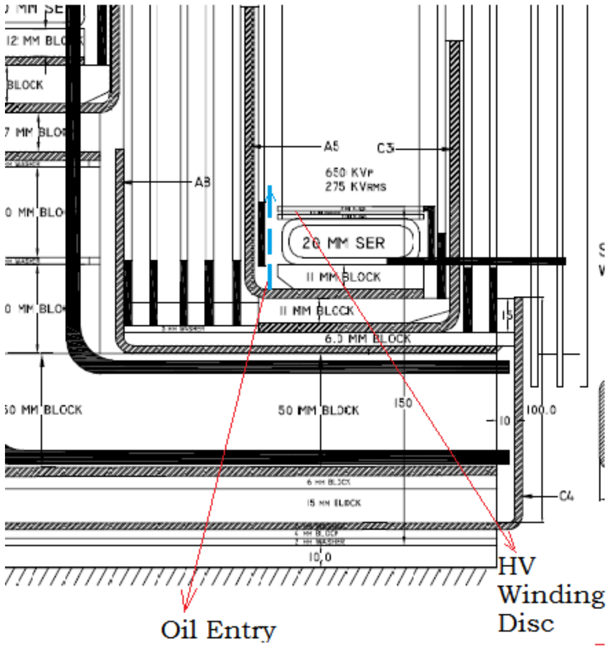

Figure 2 : Part structure of HV winding and oil entry

Transformer oil is assumed to have initial velocity of 1 m/s or 0.5 m/s at the bottom part of the transformer. Figure 3 shows the location of oil flow guides and oil flow lines through the transformer winding at the initial velocity of 1 m/s. Figure 4 shows flow lines of 0.5 m/s. In both the figures, color coding indicates the velocity level of oil flow.

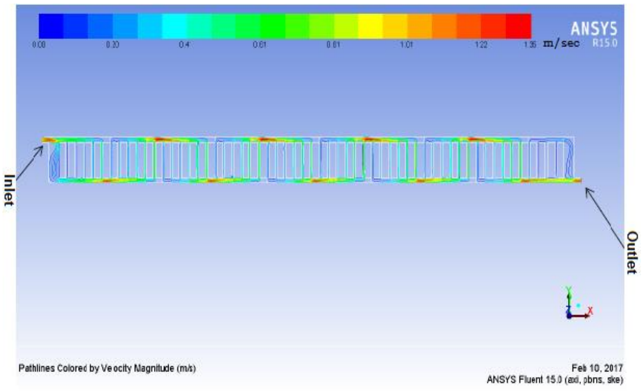

Figure 3 : Directed oil flow lines at initial velocity of 1 m/s

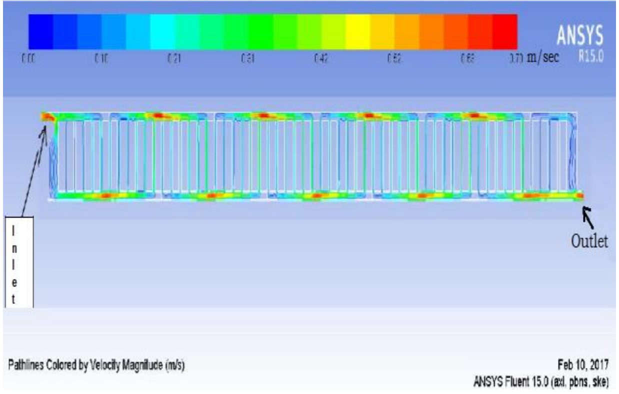

Figure 4 : Directed oil flow lines at initial velocity of 0.5 m/s

Transformer structure is generated by using ANSYS software. By using FLUENT fluid flow simulation has been carried out. Particle of copper and aluminum materials are assumed to be present at the bottom of the transformer. Movement pattern of spherical and cylindrical shaped particles are simulated. Spherical particle is assumed to have 0.5 mm radius and cylindrical particle having 0.5 mm radius and 1 mm length. Particles are assumed to be present in their initial positions Viz, 1 mm, 4 mm and 7 mm gap from inner pressboard. Final settling point of particle at each case is noted and stress at that point is theoretically calculated as,

$$E_S = \frac{V}{d} \qquad --(1)$$

Where,

Es = Electrical stress on the particle

V = Voltage of the disc which particle strikes

D = Distance between two electrodes

Results and discussion

CFD simulations are carried out for tracking of copper and aluminum particles of spherical and cylindrical shape. Each particle is traced individually for its initial position of 1, 4 and 7 mm gap.

Initial velocity of 1 m/s

Figure 5 shows the tracking of copper spherical particle with initial position 1 mm at the bottom of transformer winding with initial velocity of 1 m/s. Particle is found to strike at many places and finally exits through the top of the winding.

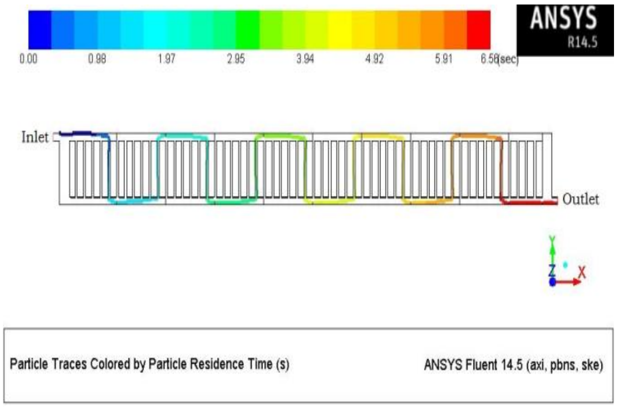

Figure 5 : Trajectory of copper spherical particle starting from 1 mm gap with velocity of 1 m/s

Similarly, particle trajectory for initial position of 4 mm and 7 mm are simulated and shown in figure 6 and 7 respectively. From figure 6 it is observed that copper particle with initial position of 4 mm takes almost similar path as 1 mm. But when the particle starts from initial position of 7 mm it strikes the bottom disc of the winding and settling in the bottom of the tank. This variation is due to the lift and drag forces resulting from oil properties like viscosity, density etc,. Further, properties of material of the particle contribute to the flow pattern. Movement of copper cylindrical particle for initial position of 1, 4 and 7 mm gap resembles the trajectory of copper spherical particle only. Figure 8, shows the trajectory of aluminum particle with initial position of 7 mm. Aluminum particle shows different trajectories for the above cases of simulation.

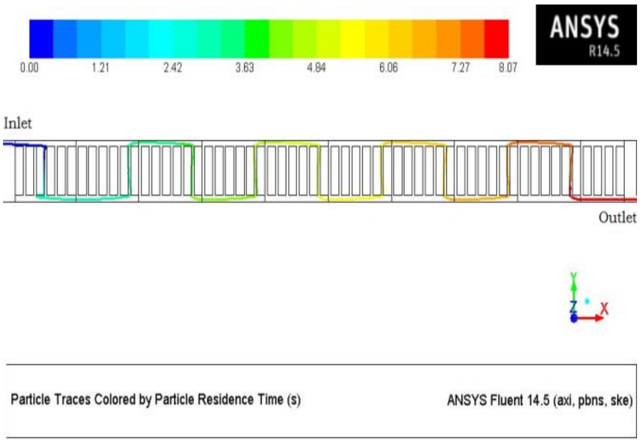

Figure 6 : Trajectory of copper spherical particle starting from 4 mm gap with velocity of 1 m/s

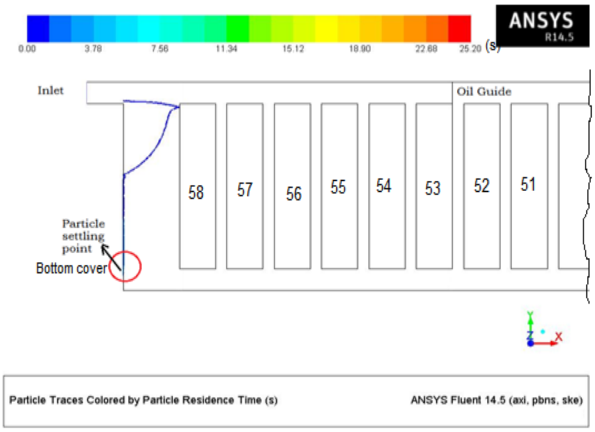

Figure 7 : Trajectory of copper spherical particle starting from 7 mm gap with velocity of 1 m/s

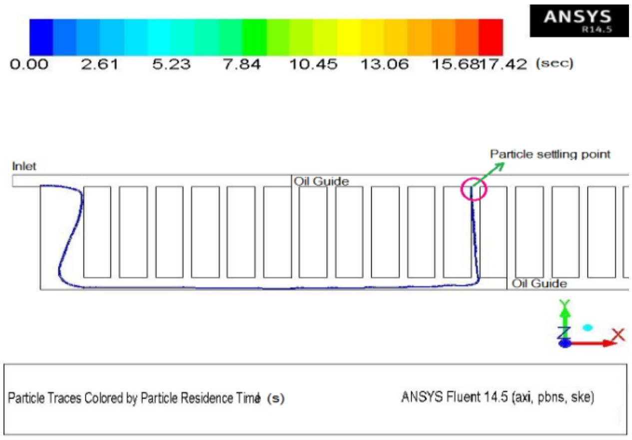

Figure 8 : Trajectory of aluminum spherical particle starting from 7 mm gap with velocity of 1 m/s

Final settling point of aluminum particles are noted as disc 54, 56 and 48 for gap of 1, 4 and 7 mm respectively. Similar simulation is carried out for aluminum cylindrical particle and trajectories found similar to the trajectory of aluminum spherical particle. Table. 1 indicates point of strike in each case and stress developed due the corresponding disc voltage. Effect of field multiplication factor β at which PD can be initiates is also mentioned in Table 1. Copper cylindrical particle when starting from 4 mm gap strikes discs 53 and 54 (in case of Cu spherical it is 55 and 56). Remaining trajectory is similar to copper spherical particle. Similarly, aluminum spherical and cylindrical particles have shown exactly similar trajectories for all initial positions.

TABLE 1. Stress calculation for copper spherical/cylindrical particle for initial velocity of 1 m/**s**

Disc of impact (Numbered From Top)	Voltage of disc kV	Stress kV/cm	β for PD	Disc of impact (Numbered From Top)	Voltage of disc kV	Stress kV/cm	β for PD
Initial Position 1 mm gap				Initial Position 4 mm gap			
5	123.4	4.59	15.25	5	123.45	4.59	15.25
6	122.5	2.22	31.46	6	122.56	2.22	31.46
11	118.1	19.2	3.65	11	118.10	19.20	3.65
12	117.2	0.25	31.52	12	117.21	0.25	31.52
17	112.7	3.40	20.58	17	112.75	3.40	20.58
18	111.8	2.22	31.58	18	111.86	2.22	31.58
23	107.4	17.4	4.01	23	107.41	17.46	4.01
24	106.5	2.24	31.28	24	106.51	2.24	31.28
29	102.0	2.21	31.63	29	102.06	2.21	31.63
30	101.1	2.51	31.34	30	101.17	2.51	31.34
35	96.71	15.7	4.45	35	96.71	15.73	4.45
36	95.82	2.23	31.41	36	95.82	2.23	31.41
41	91.36	1.02	68.32	41	91.36	1.02	68.32
42	90.47	2.23	31.41	42	90.47	2.23	31.41
47	86.01	13.9	5.01	47	86.01	13.99	5.01
48	85.12	2.22	31.41	48	85.12	2.22	31.41
53	84.23	0.23	301.4	55	78.88	0.36	193.3
54	83.34	2.23	31.41	56	77.99	2.23	31.41
Initial Position 7 mm gap							
58	76.21	8.47	8.27				

Table 2. Stress calculation for aluminum spherical / cylindrical particle for initial velocity of 1 m/s

Disc of impact (Numbered From Top)	Voltage of disc kV	Stress kV/cm	β For PD
Initial Position 1 mm gap			
54	79.77	12.97	5.39
Initial Position 4 mm gap			
55	78.81	0.36	193.3
56	77.99	12.68	5.52
Initial Position 7 mm gap			
47	86.01	13.99	106.2
48	85.12	2.23	31.39
58	76.21	0.66	31.4

Initial velocity of 0.5 m/s

Similar analysis is carried out for initial oil velocity of 0.5 m/s. Trajectories of spherical and cylindrical particles made up of copper and aluminum are simulated with initial position of 1, 4 and 7 mm gap. Figure 9 shows the tracking of copper spherical particle with initial position 1 mm at the bottom of transformer winding with initial velocity of 0.5 m/s. It is seen that particle follow the same trend of trajectory as 1 m/s with different disc. A swing in movement of the particle at the edge of discs is seen in places where oil takes diversion. This may be due to insufficient lift force on the particle. This similarity is found in trajectories for 4 mm and 7 mm gap. Figure 10 and 11 show the trajectory for particle initial position of 4 mm and 7 mm gaps.

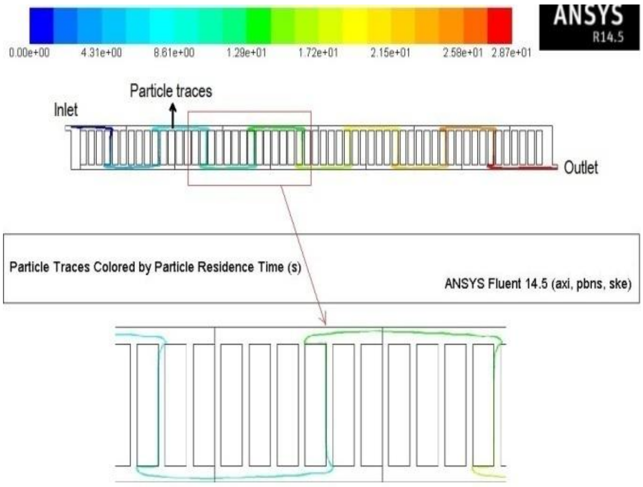

Figure 9 : Trajectory of copper spherical particle starting from 1 mm gap with velocity of 0.5 m/s

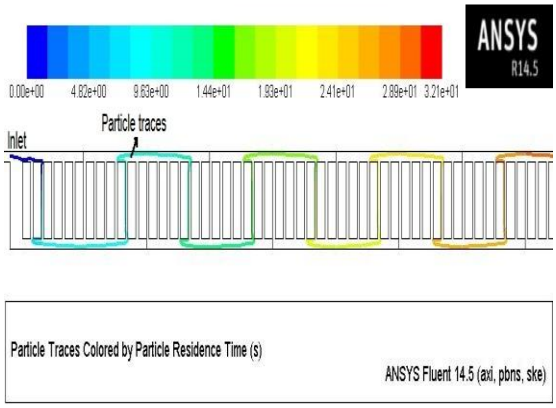

Figure 10 : Trajectory of copper spherical particle starting from 4 mm gap with velocity of 0.5 m/s

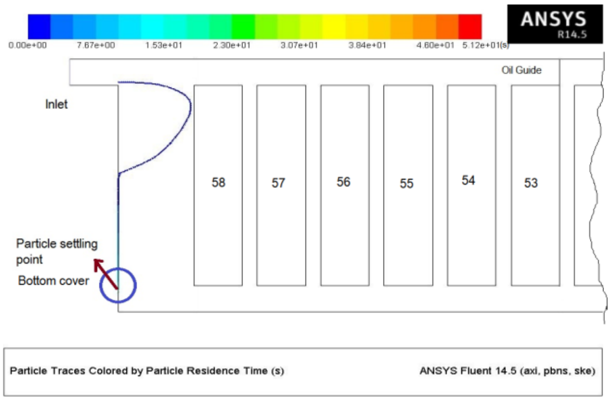

Figure 11 : Trajectory of copper spherical particle starting from 7 mm gap with velocity of 0.5 m/s

Trajectory of aluminum particle for initial position of 1, 4 and 7 mm gap are shown in figure 12, 13 and 14 respectively. Trajectory for 1 mm and 7 mm gaps are similar to that of spherical particle and particle settles at disc 57. Table 3 shows the complete detail of trajectory and stress calculation due to copper particle.

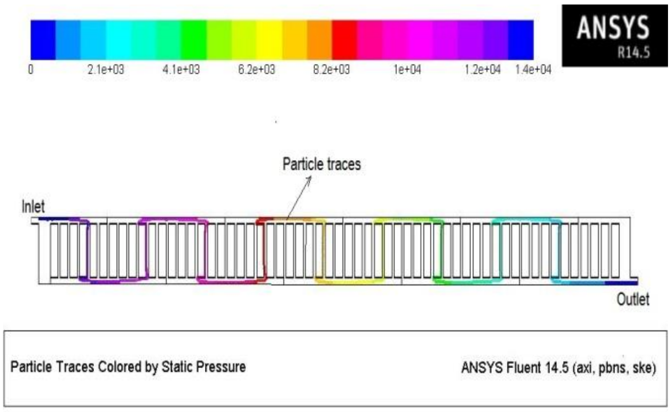

Figure 12 : Trajectory of copper cylindrical particle starting from 1 mm gap with velocity of 0.5 m/s

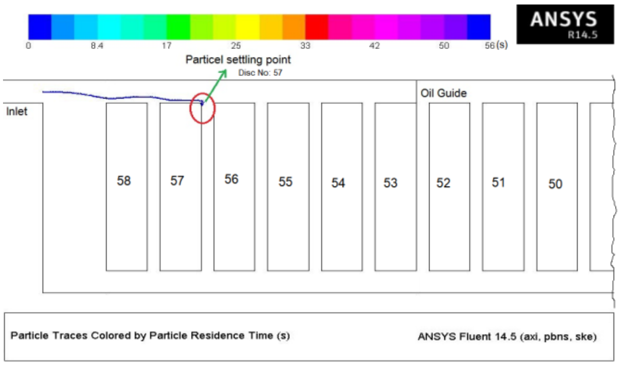

Figure 13 : Trajectory of copper cylindrical particle starting from 4 mm gap with velocity of 0.5 m/s

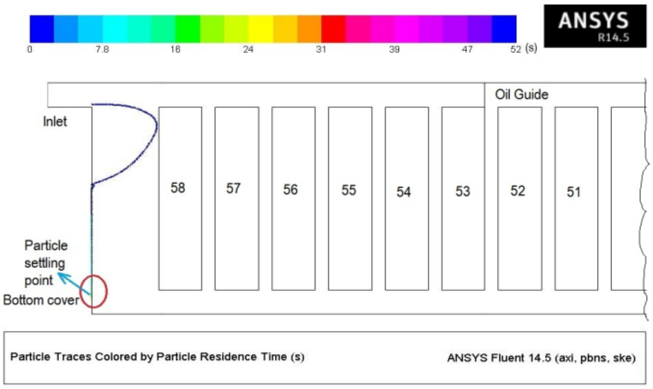

Figure 14 : Trajectory of copper cylindrical particle starting from 7 mm gap with velocity of 0.5 m/s

Table 3. Stress calculation for copper spherical particle for initial velocity of 0.5 m/s

Disc of impact (Numbered From top)	**Voltage of disc kV**	**Stress KV/cm**	**β For PD**	**Disc of impact (Numbered From top)**	**Voltage of disc kV**	**Stress kV/cm**	**β for PD**
Initial Position 1 mm gap				Initial Position 4 mm gap			
6	122.56	4.49	15.59	6	122.56	4.49	15.59
7	121.67	2.23	31.41	7	121.67	2.23	31.41
12	117.21	19.06	3.67	12	117.21	19.06	3.67
13	116.32	2.23	31.41	13	116.32	2.23	31.41
18	115.43	3.70	18.93	18	115.43	3.70	18.93
19	114.54	2.23	31.41	19	114.54	2.23	31.41
24	106.51	17.32	4.04	24	106.51	17.32	4.04
25	105.62	2.23	31.41	25	105.62	2.23	31.41
30	101.17	2.11	33.11	30	101.17	2.11	33.11
31	100.28	2.23	31.41	31	100.28	2.23	31.41

Disc of impact (Numbered From top)	**Voltage of disc kV**	**Stress KV/cm**	**β For PD**	**Disc of impact (Numbered From top)**	**Voltage of disc kV**	**Stress kV/cm**	**β for PD**
36	95.82	15.58	4.49	36	95.82	15.58	4.49
37	94.93	2.23	31.41	37	94.93	2.23	31.41
42	90.47	0.93	75.63	42	90.47	0.93	75.63
43	89.58	2.23	31.41	43	89.58	2.23	31.41
48	85.12	13.84	5.06	48	85.12	13.84	5.06
49	84.23	2.23	31.41	49	84.23	2.23	31.41
54	79.77	0.26	266.14	56	77.99	0.46	151.8
55	78.88	2.23	31.41	57	77.10	2.23	31.41
Initial Position 7 mm gap							
58	76.21	0.66	106.19				

Continued Table 3.....

Table 4 gives the details of trajectory of copper cylindrical particle and stress analysis of the particle.

Table 4. Stress calculation for copper cylindrical particle for initial velocity of 0.5 m/s

Disc of impact (Numbered From Top)	Voltage of disc kV	Stress kV/cm	β For PD
Initial Position 1 mm gap			
6	122.56	4.49	15.59
7	121.67	2.23	31.41
12	117.21	19.06	3.67
13	116.32	2.23	31.41
18	115.43	3.70	18.93
19	114.54	2.23	31.41
24	106.51	17.32	4.04
25	105.62	2.23	31.41
30	101.17	2.11	33.11
31	100.28	2.23	31.41
36	95.82	15.58	4.49
37	94.93	2.23	31.41
42	90.47	0.93	75.63
43	89.58	2.23	31.41
48	85.12	13.84	5.06
49	84.23	2.23	31.41
54	79.77	0.26	266.14
55	78.88	2.23	31.41
Initial Position 4 mm gap			
57	77.10	0.56	124.9
Initial Position 7 mm gap			
58	76.21	0.66	31.4

Trajectory of aluminum spherical particle is shown in figure 15, 16 and 17. For the initial position of 1 mm gap the aluminum spherical particle touches disc 54 and settles on the other side of the disc. This particle strikes and settle on disc 56 when made to start with the initial position of 4 mm. For the gap of 7 mm from pressboard the particle move closer to disc 58 but without touching the disc it settles at the bottom of the tank. Aluminum cylindrical particle also shows the same trajectories of aluminum spherical particle for 1 mm, 4 mm and 7 mm gap. Table 5 gives the information of trajectory and stress on the aluminum particle.

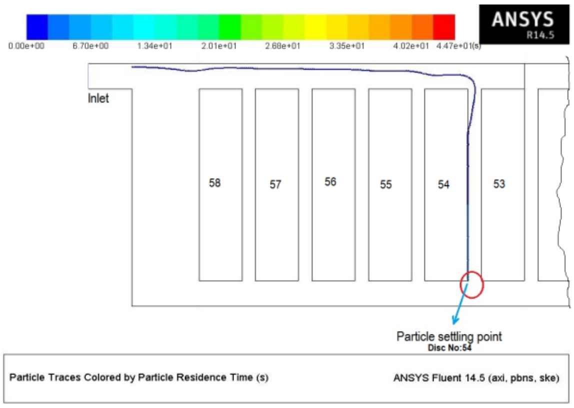

Figure 15 : Trajectory of aluminum spherical particle starting from 1 mm gap with velocity of 0.5 m/s

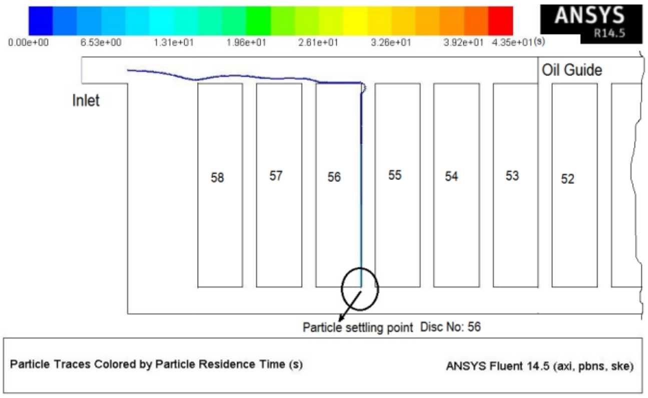

Figure 16 : Trajectory of aluminum spherical particle starting from 4 mm gap with velocity of 0.5 m/s

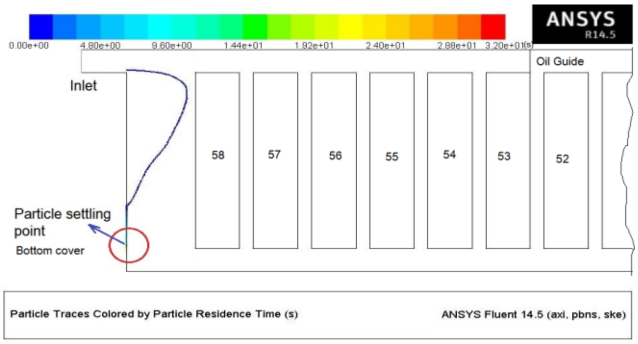

Figure 17 : Trajectory of aluminum spherical particle starting from 7 mm gap with velocity of 0.5 m/s

Table 1 : Stress calculation for aluminum spherical / cylindrical particle for initial velocity of 0.5 m/s

Disc of impact (Numbered From Top)	Voltage of disc kV	Stress kV/cm	β For PD
Initial Position 1 mm gap			
54	79.77	12.97	5.3
Initial Position 4 mm gap			
56	77.10	0.46	151.8
Initial Position 7 mm gap			
Not touching	-	-	-

From the above results it is noted that, copper spherical and cylindrical particles show similar trajectories for oil velocity of 1 m/s. Similarly aluminum spherical and cylindrical particles show similar flow patterns for 0.5 m/s. Among all the cases, highest stress formed is 19.20 kV/cm. This stress is formed corresponding to disc 11 by copper spherical or cylindrical particles. It is also seen that scope of particle to move to the outer radius side of the winding is high in case of copper particle for starting point of 1 mm from inner pressboard. This is due to the directed oil flow. In this case particle completes its travel from bottom to top without settling anywhere in between bottom and top. It is to be mentioned that a level of 70kV/cm could be reached only in condition of higher β as shown in table 1 – 5. Smallest value of field multiplication factor required to initiate PD is 3.65 for copper spherical or cylindrical particle as shown in Table 1. In case of aluminum particle the least value of field multiplication factor required to initiate PD is found to be 5.3as shown in Table 5.

CONCLUSION

Movement patterns of copper and aluminum particles are simulated for spherical and cylindrical shapes with initial velocity of 0.5 m/s and 1 m/s with respect to their initial positions 1, 4 and 7 mm from inner pressboard.

It can be concluded that directed flow pattern provides chance of particle striking discs from inner and outer radius of the winding.

It is observed that, copper particle completes its travel till outlet at the top in higher number of cases when compared to aluminum particle. Aluminum particle settles inside the disc space in most of the cases.

Particles move upward along with the oil at the velocity of 1 m/s, but in case of 0.5 m/s it shows the downward movement.

The lowest and highest values of field multiplication factor required to initiate PD are 3.65 and 266.1 respectively.

Copper particle shows the higher chance of initiating PD than that of the aluminum particle for the given size of the particle.

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