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RESEARCH ARTICLE

Effect of Copper and Iron Particles on the Dielectric Strength of R410A Gas as an Alternative of SF_6 in GIS

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ABSTRACT The Gas Insulated Switchgears (GIS) used in high voltage transmission and distribution networks are reliable, compact, and maintenance-free. During the manufacturing process, some metal particles remain inside GIS which affects the breakdown strength of insulating gas and hence deteriorates the performance. The breakdown performance of R410A gas in the presence of free metal particles is presented in this paper. Iron and copper particles of various sizes and shapes are used in the research work. The impact of these free particles on the characteristic of R410A gas at various gas pressures and gap distances is elaborated. Power frequency breakdown voltage test in the presence of metal particles and self-recoverability test are performed in a high voltage lab. The effect of various dimensions of metal particles on the dielectric strength of R410A gas under the quasi-uniform field in alternating current is examined. The impact on the breakdown voltage of R410A is analyzed by increasing the pressure and gap distance. Experimental results are discussed in the paper. As metal particles in between them can disrupt the R410A reaction barrier. According to the results of the experiments conducted, the breakdown voltage was affected by 30% by the addition of iron particles and 46.89% by the addition of copper particles, and it is concluded that iron particles perform better at different gaps distances.

INDEX TERMS Gas insulated system, breakdown voltage, dielectric strength, metal particles, SF_6 gas.

I. INTRODUCTION

The metal-enclosed GIS is primarily utilized for power system protection. Due to their flexibility, compactness, and reliability, they have the capability to solve the problems associated with the control, metering, and regulating of the electric power system. Proper insulation is essential for the safety and reliability of GIS. The insulating materials must meet safety requirements, be environment friendly, possess superior dielectric strength, have higher thermal conductivity, lower boiling point, lower Global Warming Potential (GWP), and have negligible ozone depletion potential. The insulating materials should be non-toxic, non-flammable, and non-explosive [1], [2]. Since 1947, the most commonly used insulation gas in the power system for high voltage circuit breakers, switch gears, and other electrical equipment is sulphur hexafluoride (SF_6) [3]. It has an extraordinary mixture of chemical and physical characteristics for high voltage applications. The SF_6 possesses higher dielectric strength, arc quenching capability, thermal conductivity, and thermal stability. It is non-flammable, non-toxic, non-explosive, and less expensive. As an outcome, SF_6-based GIS can be constructed with decreased size, high reliability, and relatively inexpensive [3]–[10].

The dielectric breakdown performance of the gas-insulated medium is affected by various factors, i-e, gas pressure, the temperature of the surroundings, the material of the electrodes, nature of applied voltage, humidity, and the presence of metal particles. During the manufacturing process of GIS, the metal particles are produced, which remain

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inside during assembling. The presence of metal particles affects the breakdown strength of the gases. Free metal particles play a vital role in the disturbance of an electric field which disturbs the motion of partial discharge. The insulation capability of SF_6 is highly affected by free metal particles in a short gap [11]. The breakdown voltage of SF_6 decreases as the number of particles increases. Decomposition of SF_6 occurs with the presence of free metal particles; as a result, SF_6 becomes more electronegative. The size of free particles considerably influences the electric field distribution.

However, SF_6 has the ability to absorb infrared radiations and has an extensive atmospheric lifetime of 3200 years. It is labelled as one of the greenhouse gas [12], [13], has a radioactive effect, is not affected by chemical and photochemical degradation, and attributes to its long lifetime in the environment [9], [10], [14]. The global warming potential of SF_6 is approximately 23,500 times higher than carbondioxide (CO_2); therefore, it is detrimental to the environment [15]. The use of SF_6 in GIS amplifies the greenhouse effects, and approximately more than 15% of greenhouse gas emission is contributed by SF_6 [16]. Since 1970, numerous studies have been conducted to determine a suitable replacement for SF_6. In the literature various potential alternatives SF_6 such as natural gases as CO_2 [17], dry air, nitrogen (N_2), a mixture of SF_6 gas and vacuum [18], [19], trifluoroiodomethane (CF_3I) [20]–[22] are explored. In [23], study of the particle was done in SF_6/N_2 but it shows that the detection of the particle was more difficult in N_2 compared to SF_6. Also, the impulse breakdown voltage is measured in the mixture of SF_6 using buffer gases. The breakdown voltage of CO_2, air and N_2 is relatively low compared to SF_6. A mixture of CO_2 or N_2 and CF_3I were investigated, and it showed that the proposed gas's insulation properties could be an alternative for GIS systems. However, it was discovered that they are hazardous and toxic for recombination and have high boiling temperatures [5].

The mixture of dichlorofluoromethane (R12) with air and carbon dioxide is proposed as an alternative to SF_6 [24]. It has good dielectric strength with a 49%-64% reduced amount of GWP and has a better self–recoverability. However, R12 has a high boiling point; it is chlorofluorocarbon gas and has a high potential for depletion of the ozone layer. The ionization and attachment coefficients are measured for mixtures of heptafluorobutyronitrile (C_4F_7N) with nitrogen (C_4F_7N/N_2) gas to use as an alternative of SF_6 [25]–[27], however, the toxicity level of this gas is too high for GIS systems. The dielectric characteristics of C5-perfluoroketone (C_5-PFK), C_5-PFK-Air and C_5-PFK-CO_2 mixtures are experimentally investigated in order to determine the optimum solution for use as a substitute for SF_6 in power equipment [28]. The proposed gas also has temperature limitations. Hydrofluoroolefin (HFO1234ZEE) was examined as an alternative to SF_6 and found it flammable with high toxicity [29]. In [30], demonstrated fluoronitrile (FN) $Nove^{TM}4710$ and fluoroketone (FK) $Nove^{TM}5110$ and their partial discharge characteristics to replace SF_6 in HVDC and GIS systems, however, fluoronitrile is suitable for medium voltage applications and has slightly high GWP where-as fluroketones have a high boiling point. The thermodynamic characteristics, distribution, and transport coefficients of high-temperature perfluorovaleryl fluoride ($C_5F_{10}O$) mixed with CO_2 and O_2 as a replacement for SF_6 is elaborated in [31] and found high boiling point limitations. Insulation strength of perfluorohexanoyl fluoride ($C_6F_{12}O$) and N_2 gas mixture is analyzed in [32] and found it toxic with a high boiling point. In [33], the authors analyzed the dielectric properties of R410A as a potential alternative of SF_6 gas in high voltage applications. The mixture of tetrafluoroethane (R134) gas with nitrogen and air is presented in [34] and concluded that R134 gas with the addition of buffer gases gives better reliable and sustainable results having a low boiling point and GWP.

R410A is the mixture of pentafluoroethane CHF_2CF_3 (50%) and difluoromethane CH_2F_2 (50%). This is the low-cost (around 3 USD per kg) insulating gas among all alternatives of SF_6 discussed in the literature. It is non-flammable, non-toxic and non-corrosive compared to SF_6. The boiling point at 0.1 MPa of R410A is slightly higher than SF_6 but lower than R12 and R134. The atmospheric lifetime of R410A is almost 200 times lower than SF_6, and the GWP of R410A is almost 15 times less than SF_6. From the comparison of alternative gases under a uniform field, it is obvious that the dielectric strength of R410A is slightly less than SF_6 and more than R134, CO_2, N_2 and air [33]. Therefore R410A is a better alternative to SF_6 in GIS.

As a result of inadequate cleanliness during the production process, free metal particles are generated, disrupting the electric field and affecting the insulating characteristics of the gas. Several computational models have been developed by researchers for particle movement in co-axial electrode systems. Researchers have also proposed many experimental techniques to explain the movement of particles. The influence of metallic particles in the gas-insulated switchgear in the triple junction in the presence of air is discussed and found that breakdown voltage and partial discharge are reduced with metal particles compared to without metal particles [35]. The effect of discharge characteristics of the metal particle in DC bushing is presented in [36]. The metal particles were easily adsorbed in areas where the electric field was concentrated, and their presence had an effect on the insulation performance of DC bushings. In [37], the Runge-Kutta method is used to calculate the trajectory of the spherical metal particles between inclined plate electrodes with gas. In coated electrodes, the particle lift-off position drops affectedly; the lift-off electric field rises as SF_6 gas pressure increases. In [38], theoretical and experimental analysis of the particle in GIS in the presence of SF_6 gas was conducted and discovered that in the same metal particles number and same pressure, the large metal particles have a high effect on the SF_6 gas breakdown performance. The influence of particles on AC and DC electrical performance of GIS at high voltage is studied in [39]. The influence of metal particles (Iron, Copper,

FIGURE 1. Control desk.

FIGURE 2. Testing transformer.

FIGURE 3. Hardware setup.

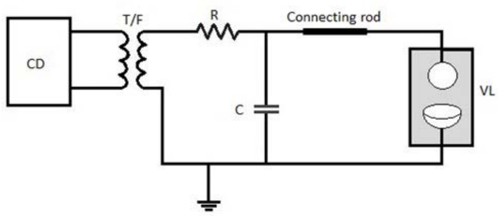


FIGURE 4. Schematic diagram of hardware setup.

and Aluminium) in C-GIS systems in the presence of SF_6 and CF_3I gas is analyzed in [11], [40]. The presence of these metal particles between the electrodes affects the gas insulation performance. Furthermore, copper and aluminium particles have a more significant effect on the breakdown strength as compared to the iron particles. However, SF_6 gas affects the environment and the ozone layer, and CF_3I is toxic and has a high boiling point. The main contribution in this paper is as follows;

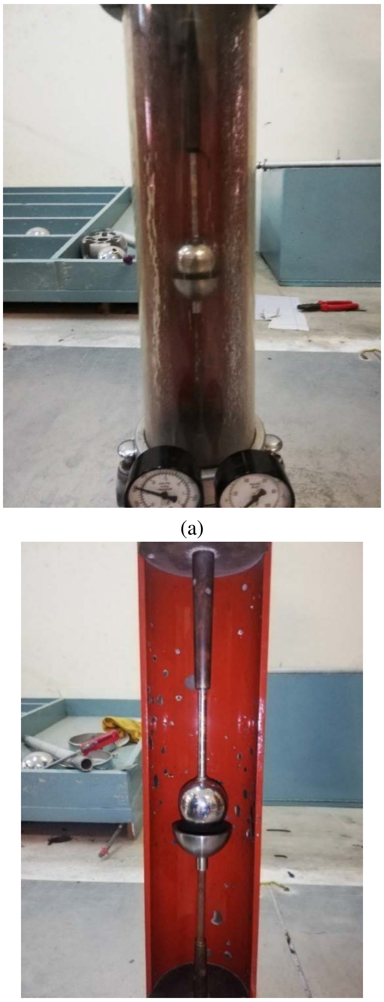
- To replace SF_6 gas with environmentally friendly R410A gas having less GWP.
- To experimentally analyze the influence of metal particles on the dielectric strength of R410A gas.
- To experimentally analyze the influence of metal particles at different gas pressures and distances on the dielectric strength of R410A gas.
- Self-recoverability test of R410A gas experimentally.

II. EXPERIMENTAL SECTION

In this section, the methodology employed in the proposed work is elaborated. The hardware setup of the experiment is discussed in this section. The distribution of electric fields for ball-bowl electrodes in the presence of metal particles in the gap distance is investigated. The experimental arrangements of the equipment and position of electrodes, the effects of metal particles, gas pressure, electrode gap, and gas insulation characteristics are discussed in this section. The procedure and testing methods are explained in the following subsections.

A. EXPERIMENTAL METHOD AND ARRANGEMENTS

The proposed gas testing method is based on the IEC60270 standard13. The console HV 9103 used for measurements and analysis is shown in Fig. 1. It comprises a variable voltage power supply and a built-in peak voltmeter HV 9150. The range of peak voltmeter is from 100 V to 1000 kV, and the output supply voltage varies from 0 to 230 V. The single-stage test transformer HV 9105 used in the experimental setup is shown in Fig. 2. The output voltage range of the test transformer is 220 V to 100 kV. The second stage is connected with a 200 kV resistor to protect the transformer in the breakdown process. The measurement apparatus and voltmeter are calibrated to reduce errors and enhance accuracy by applying a known AC voltage value before the experiment. The experimental setup is shown in Fig. 3. The schematic diagram of the experimental setup is illustrated in Fig. 4.



(a)

(b)

FIGURE 5. **(a) Testing vessel with plexi glass (b) Testing vessel without plexi.**

FIGURE 6. **Ball-bowl electrodes.**

The steel-made test vessel HV 9134 VL having built-in pressure up to 6 bar used in the experimental setup is illustrated in Fig. 5a. It is used in the setup for gas and vacuum insulation. The nickel-plated aluminium ball-bowl electrodes used in the experiment are shown in Fig. 6. The inner diameter of the bowl electrode is 30 mm, and the outer diameter is

FIGURE 7. **Particles in bowl electrode.**

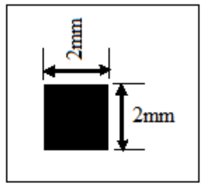


FIGURE 8. **Metal particle size.**

35 mm. The ball-bowl electrodes are placed in a vertical position in an airtight testing vessel, as shown in Fig. 5a and Fig. 5b. There is a gap spacing of 10mm and 15mm between them. Three experiment measurements are taken for each pressure utilized, and their mean is determined.

B. TESTING METHOD

Before performing the vessel test, the inner surface of the electrode and gas tank is cleaned with a silk cloth dipped in alcohol. The main objective of cleaning is to remove impurities and moisture and to eliminate experimental errors. It also decreases the impact of solid particles other than metal particles on the power frequency. After cleaning and drying the test vessel, metal particles are laid down in the ball bowl electrode gap, as shown in Fig. 7. The experiment is carried out in a moisture-free environment at 25°C temperature. After placing the metal partials R410A gas is filled in the test vessel. The gas is then evacuated after 20 minutes from the container to create a high vacuum.

The impact of breakdown voltage on various metal particles such as copper and iron is investigated in this study. Metal particles have flat surfaces, and $2 \times 2mm^2$ flakes are used, as shown in Fig. 8. The metal particles smaller than this size have the possibility to leap out of the region between the sphere and bowl electrodes with the application of an electric field. Hence metal particles having a size smaller than $4mm^2$ are not used in the measurements. The effect of particle number and particle diversity on the R410A breakdown voltage of power frequency is analyzed. Ten particles of each shape are placed in the bowl electrodes, as shown in Fig. 7.

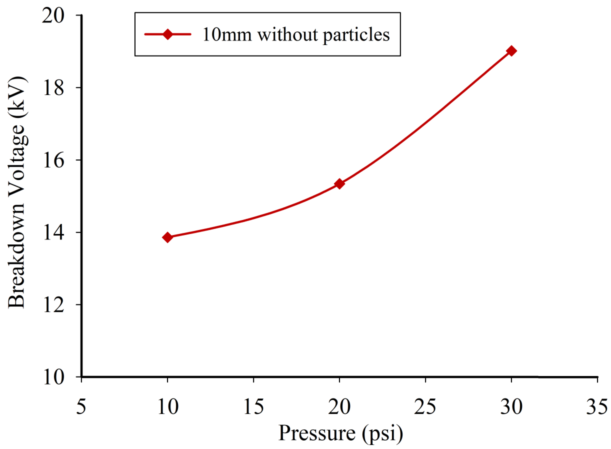


FIGURE 9. Breakdown voltage of R410A gas without metal particles having 10mm gap distance.

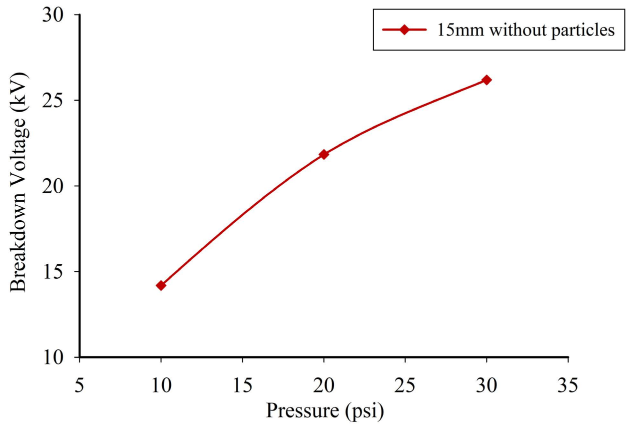


FIGURE 10. Breakdown voltage of R410A gas without metal particles having 15mm gap distance.

III. ANALYSIS AND EXPERIMENTAL RESULTS

The breakdown voltage performance is discussed in this section. R410A gas is used as a dielectric medium, and the effects of metal particles, gas pressure and gas insulation are investigated experimentally.

A. R410A BREAKDOWN PERFORMANCE WITHOUT PARTICLES

The dielectric strength of the medium is affected by the gas pressure, metal particles, and gap distances between the electrode. By increasing the pressure, the breakdown voltage increases, whereas reducing the gap distance between the electrodes lowers the breakdown voltage. The process of ionization in the gaseous medium occurs due to the free ions and by gaining the energy from the free electrons using an electric field. Since R410A is an electro-negative gas, therefore negative ions and positive ions are produced by the attachment and detachment of the electrons with a neutral molecule. This process may occur depending upon the electric field.. Equation (1) gives a relation among dN, N, α, η and dx [34], [41]–[43].

$$dN = N(\alpha - \eta)dx \tag{1}$$

where N is the initial number of electrons, dN is the electron travelled, and dx is the distance. When $\alpha > \eta$ (1) shows exponential growth and hence the breakdown of gas occurs

All the experiments are conducted using 5 and 10 metal particles. The AC breakdown voltage of R410A gas without the metal particles for 10mm and 15mm gap distance between electrodes is illustrated in Fig. 9 and Fig. 10, respectively.

It is observed that increasing the gap distance results in an increase in the breakdown voltage of the R410A gas. Compared to the impact of a small range of pressure levels, the influence of electrode gap distance is more significant in increasing the breakdown voltage of R410A gas at higher pressure levels.

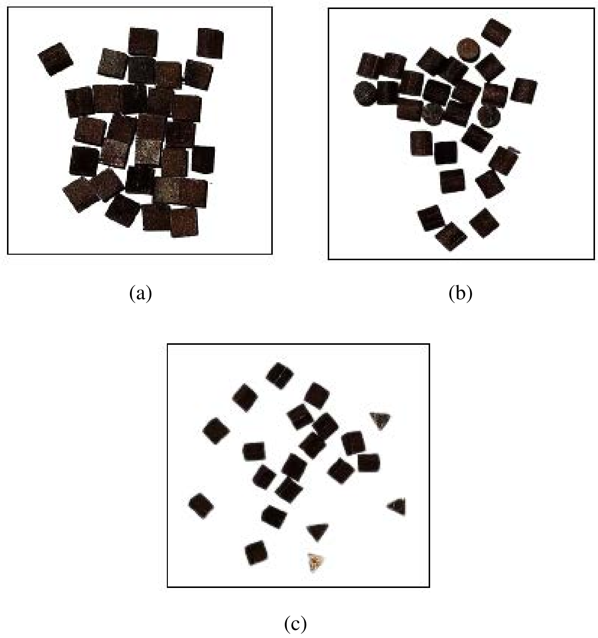


FIGURE 11. (a) Cube copper metal particles (b) Cylindrical copper metal particles (c) Triangle copper metal particles.

B. R410A BREAKDOWN PERFORMANCE WITH PARTICLES

The effect of metal particles on breakdown voltage with varying gap distances is discussed in this section.

1) R410A BREAKDOWN PERFORMANCE WITH COPPER PARTICLES

The copper metal particles with various shapes used in the experiment are depicted in Fig. 11.

The breakdown voltage of R410A in the presence of 5 and 10 copper metal particles of various shapes with 10 mm gap distances is illustrated in Fig. 12 and Fig. 13, respectively.

It is observed that breakdown voltage decreases by increasing the number of particles with a constant gap distance. The breakdown voltage increases almost linearly in both gap

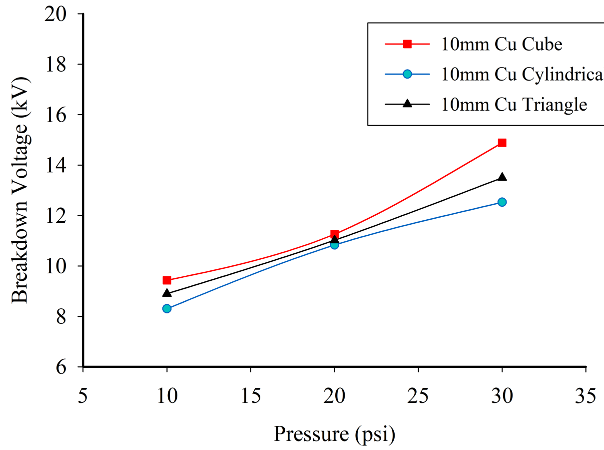


FIGURE 12. Breakdown voltage of R410A gas with 5 copper metal particles having 10mm gap distance.

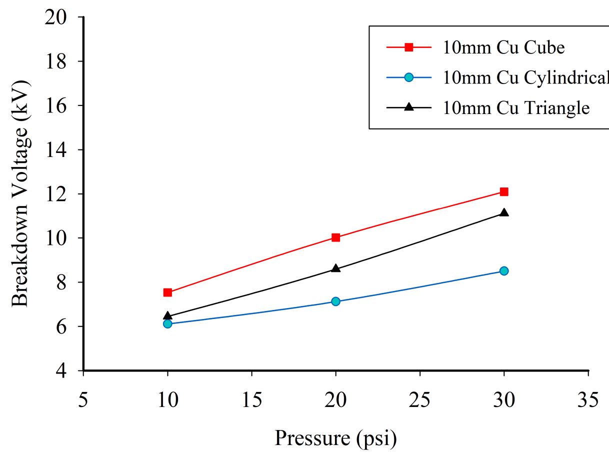


FIGURE 13. Breakdown voltage of R410A gas with 10 copper metal particles having 10mm gap distance.

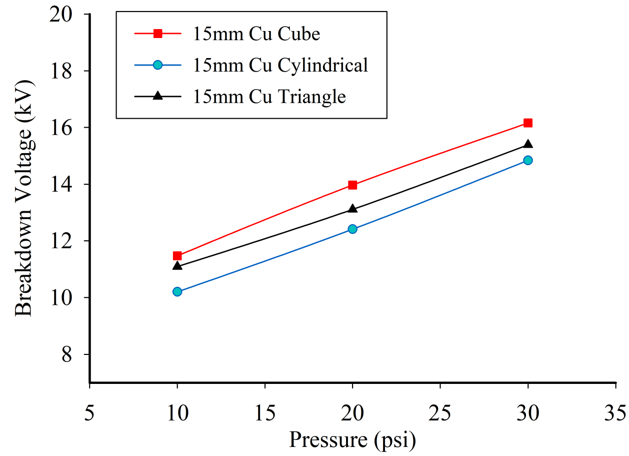


FIGURE 14. Breakdown voltage of R410A gas with 5 copper metal particles having 15mm gap distance.

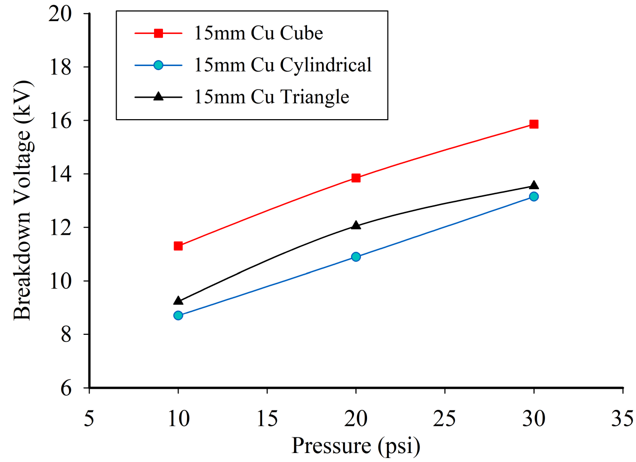


FIGURE 15. Breakdown voltage of R410A gas with 10 copper metal particles having 15mm gap distance.

distances by increasing the vessel pressure. In both the gap distances, the cube-shaped copper particles outperform the triangle and cylindrical-shaped copper particles. Masanori Hara's study indicated that metal particles remarkably reduce the initial voltage of a partial discharge between two gaps, hence accelerating the formation of negative and positive streamers [44]. The electric field between the ball-bowl electrodes is distorted because of free metal particles. The breakdown voltage decreases as the uniformity of the electric field decreases. Furthermore, the existence of additional metal particles enhances the electric field's inhomogeneity. Sarathi's study specified that the random jitter of particles between electrodes significantly affects the insulating property of gas when a discharge occurs [45].

The breakdown voltage of R410A in the presence of 5 and 10 copper metal particles of various shapes with 15mm gap distances is illustrated in Fig. 14 and Fig. 15, respectively.

From the experimental results, it can be inferred that the smaller gap distance causes more electric field distortion due to free metal particles. Particle size significantly affects the electric field distribution when the particle is near the gap distance. Furthermore, for the same voltage, when the gap distance reduces, the electric field intensity increases. The spacing between the electrodes has a significant influence on the dielectric strength. An increase in the gap distance between the electrodes results in an increase in the breakdown voltage, as expressed in equation (2). As a result, the breakdown voltage of particles under 10mm gap distance is lower than that of the breakdown voltage of particles under 15mm gap distance. Existing research has shown that the breakdown voltage and gap distance of metal particles are positively correlated [46].

$$E = V/D \tag{2}$$

where E is the electric field, V is the breakdown voltage and D is the gap distance between the electrodes

2) R410A BREAKDOWN PERFORMANCE WITH IRON PARTICLES

The iron metal particles with various shapes used in the experiment are shown in Fig. 16 shows the iron metal particles with various shapes.

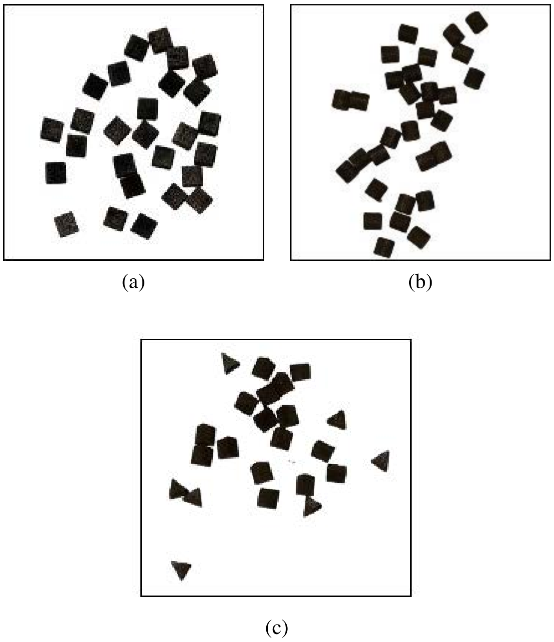


FIGURE 16. (a) Cube iron metal particles (b) Cylindrical iron metal particles (c) Triangle iron metal particles.

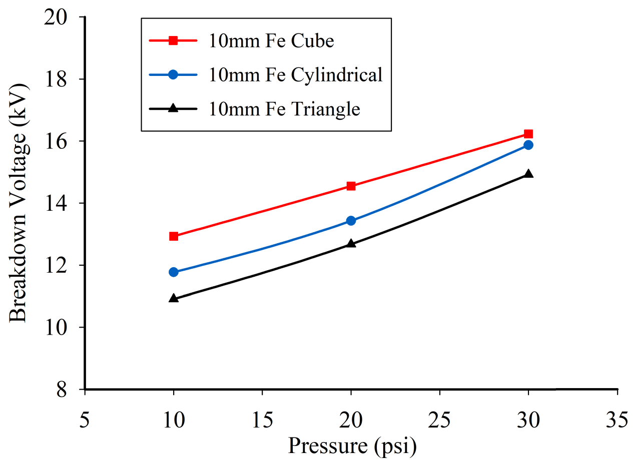


FIGURE 17. Breakdown voltage of R410A gas with 5 iron metal particles having 10mm gap distance.

The breakdown voltage of R410A in the presence of 5 and 10 iron metal particles of various shapes with 10mm gap distances is shown in Fig. 17 and Fig. 18, respectively.

The observed results demonstrate that the breakdown voltage decreases by increasing the number of particles with a constant gap spacing. Also, by increasing the pressure of the vessel, the breakdown voltage increases. The breakdown voltage is higher in the case of cube-shaped iron particles compared to triangle and cylindrical-shaped copper particles. When metal particles are added to a gaseous medium, they behave as an impurity, and the breakdown voltage tends to drop as the presence of impurity distorts the electric field.

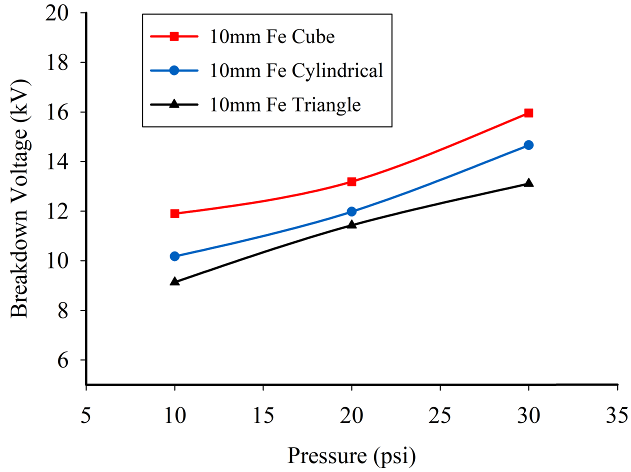


FIGURE 18. Breakdown voltage of R410A gas with 10 iron metal particles having 10mm gap distance.

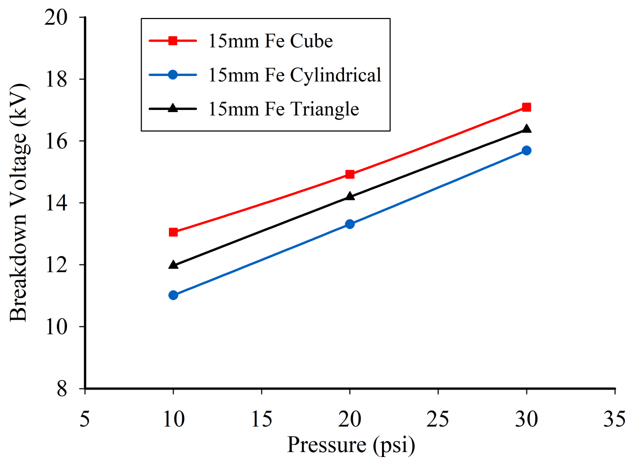


FIGURE 19. Breakdown voltage of R410A gas with 5 iron metal particles having 15mm gap distance.

By increasing the gas pressure increases, the breakdown voltage increases.

The breakdown voltage of R410A in the presence of 5 and 10 iron metal particles of various shapes with 15mm gap distances is shown in Fig. 19 and Fig. 20, respectively. According to Fig. 19 and Fig. 20, the electric field distortion reduces when the gap distance between the electrodes is increased.

IV. R410A BREAKDOWN PERFORMANCE IN PCF RATIO

The particle contamination factor (PCF) is the ratio of the particle effect breakdown voltage to the clean gap breakdown voltage [47]. This ratio characterizes the reduction in gas insulation performance in the presence of a metal particle in GIS. The breakdown voltage performance of R410A is investigated when the gap distance is 10mm and 15mm, respectively, as well as by varying the pressure. Through this ratio, the performance of the metal particles is known.

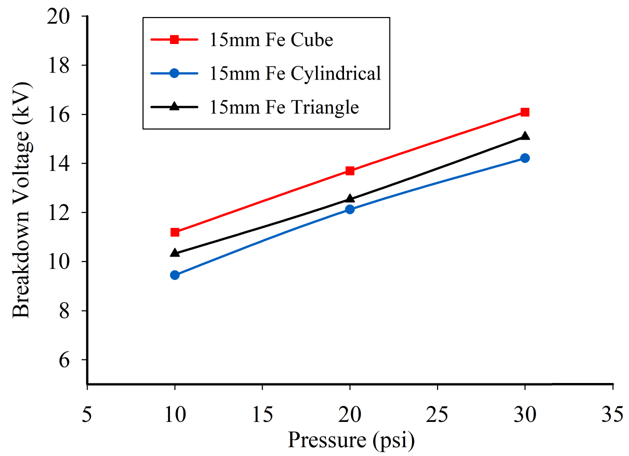


FIGURE 20. Breakdown voltage of R410A gas with 10 iron metal particles having 15mm gap distance.

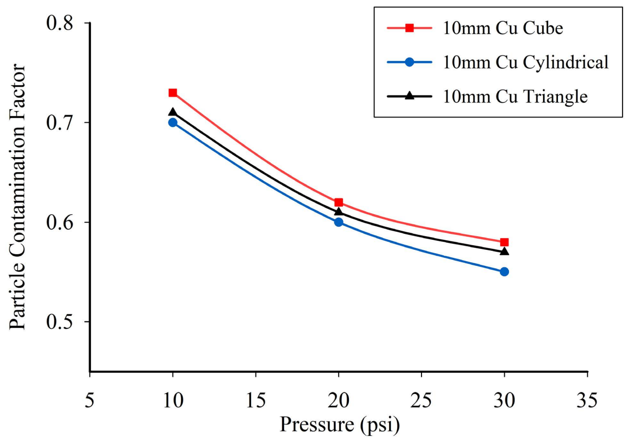


FIGURE 21. R410A PCF with 5 copper metal particles gas 10mm gap distance.

The ratio value near the unity is considered to have better performance.

A. PCF OF COPPER PARTICLES

The PCF ratio of 5 and 10 number of various shapes of copper particles with electrodes gap distances of 10mm is shown in Fig. 21 and Fig. 22, respectively.

The PCF ratio of 5 and 10 number of various shapes of copper particles with electrodes gap distances of 15mm is shown in Fig. 23 and Fig. 24, respectively.

The measured results of PCF indicate the sensitivity of the breakdown voltage to copper particle contamination when the gap distance is 10mm and 15mm, respectively. It is observed that R410A gas is less susceptible to electric field distortion when the gap distance is 15mm, and the PCF decreases as the gas pressure increases. The sensitivity of the dielectric gas is affected by the gas pressure [47].

B. PCF OF IRON PARTICLES

The PCF ratio of 5 and 10 number of various shapes of iron particles with electrodes gap distances of 10mm is shown in Fig. 25 and Fig. 26, respectively.

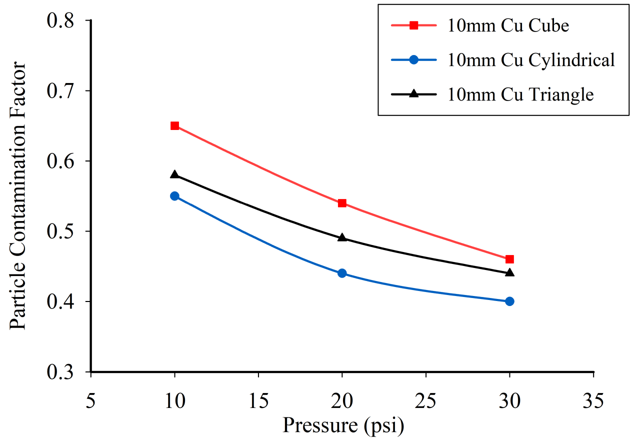


FIGURE 22. R410A PCF with 10 copper metal particles gas 10mm gap distance.

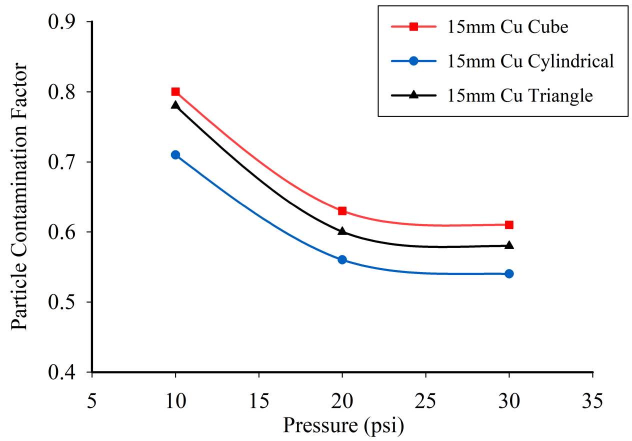


FIGURE 23. R410A PCF with 5 copper metal particles gas 15mm gap distance.

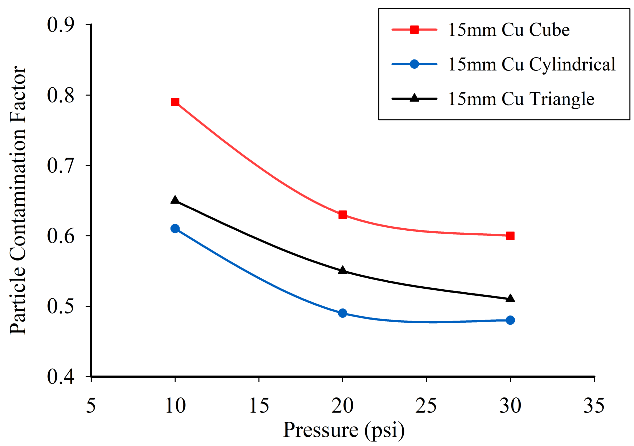


FIGURE 24. R410A PCF with 10 copper metal particles gas 10mm gap distance.

The PCF ratio of 5 and 10 number of various shapes of iron particles with electrodes gap distances of 15mm is shown in Fig. 27 and Fig. 28, respectively.

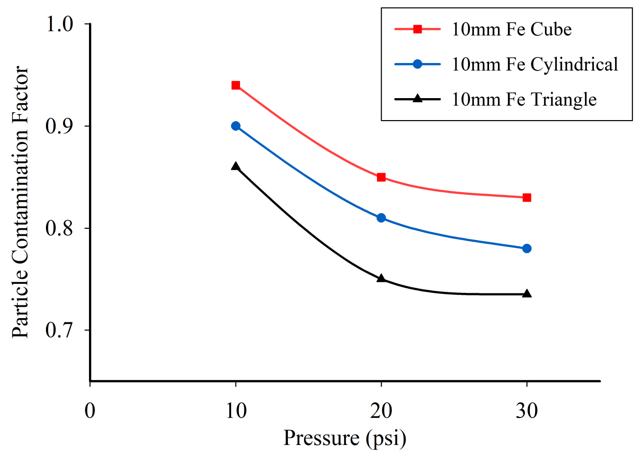


FIGURE 25. R410A PCF with 5 iron metal particles gas 10mm gap distance.

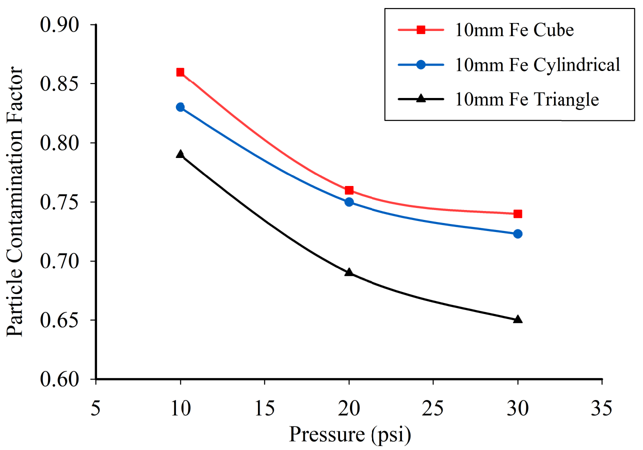


FIGURE 26. R410A PCF with 10 iron metal particles gas 10mm gap distance.

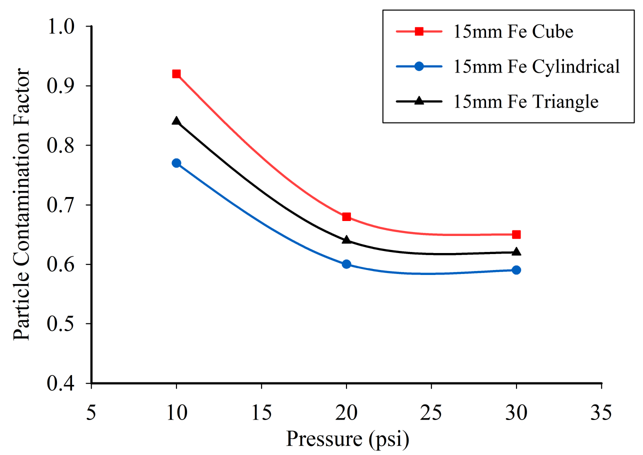


FIGURE 27. R410A PCF with 5 iron metal particles gas 15mm gap distance.

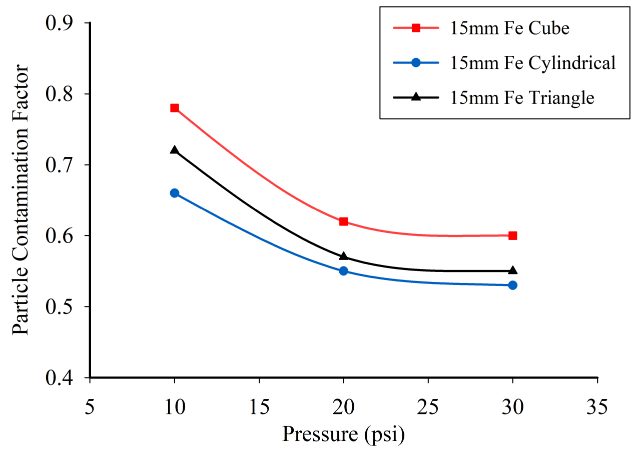


FIGURE 28. R410A PCF with 10 iron metal particles gas 15mm gap distance.

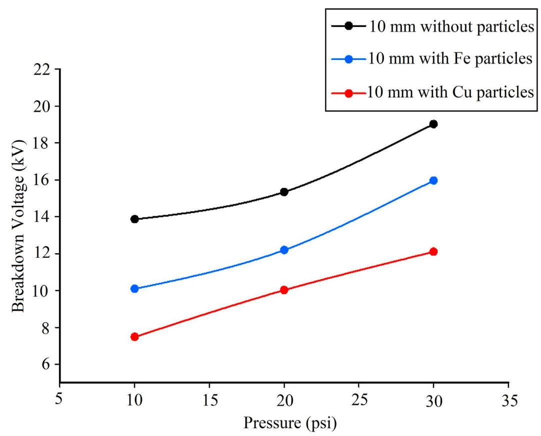


FIGURE 29. R410A breakdown voltage without and with metal particles having distance of 10mm.

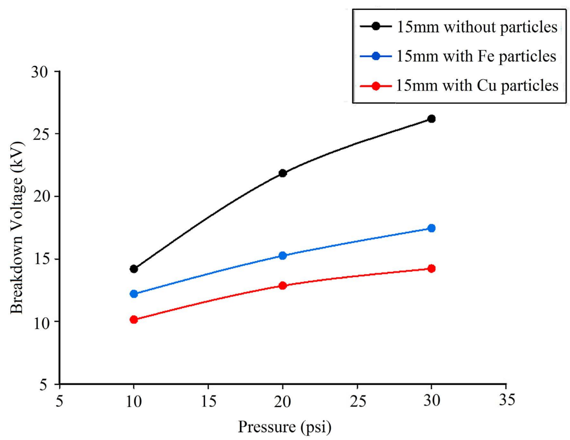


FIGURE 30. R410A breakdown voltage without and with metal particles having distance of 15mm.

The analysis shows that raising the pressure in both gap lengths causes the PCF to drop. Furthermore, cube-shaped iron particles exhibit reduced susceptibility to the breakdown voltage compared to cylindrical and triangular-shaped iron particles.

V. COMPARISON OF R410A BREAKDOWN VOLTAGE

Fig. 29 and Fig. 30 illustrate a comparison of the breakdown voltage of R410A with and without particles when the gap distance is 10mm and 15mm.

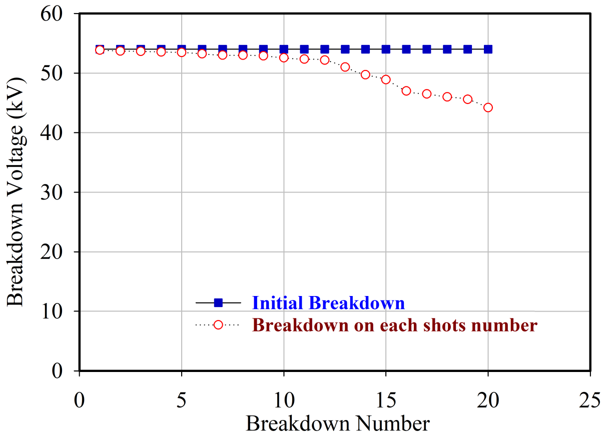


FIGURE 31. R410A self-recoverability test.

From Fig. 29 and Fig. 30, it is clear that the breakdown voltage of R410A gas in the absence of metal particles is found to be greater than the breakdown voltage of R410A gas containing metal particles. Iron particles have a less negative influence on the breakdown voltage than copper particles do under the same circumstances. Masanori Hara discovered that metal particles might considerably diminish the breakdown voltage of a gas and its onset corona; however, the effect of metal particles on the breakdown voltage is yet unclear [44]. Metal particles between the electrodes may potentially alter the initial electric field's uniform distribution, resulting in electric field distortion.

VI. COMPARISON OF R410A AND BREAKDOWN VOLTAGE WITH SF_6

SF_6 and R410A are compared in terms of PCF and breakdown voltage. Since the dielectric strength of R410A gas is 0.75 and that of SF_6 gas is 1, the breakdown voltage of R410A is lower than that of SF_6, but the PCF of R410A is better and approaches unity at the same pressure and particle number. Copper and iron particles with triangular shapes have a stronger negative effect on the breakdown voltage than cubic particles. Iron particles with a cubic shape perform better in both gap distances. Copper particles have a stronger effect on the breakdown strength of both (R410A and SF_6) gases.

VII. INSULATION OF SELF-RECOVERABILITY OF R410A GAS

In order to analyze the self-recoverability and dielectric properties of R410A, the breakdown voltage or temperature is exceeded beyond its limit. The test is performed in order to examine the self-recoverability of a gas. For this purpose, 10 to 20 shots of breakdown are applied to the gas. After 8 to 9 shots are applied, the insulation of the gas starts to decay due to the occurrence of carbon deposit in the insulation gas and the electrodes, as shown in Fig. 7. The presence of carbon deposits affects the breakdown performance and distorts the electric field as carbon is a good conductor of electricity. The presence of carbon deposit is an obstacle for using R410A as an insulation medium in high voltage applications. This drawback can be removed by certain methods of preventing carbonization [48]. Fig. 31 shows the self-recoverability of R410A gas and is compared with SF_6 [49].

VIII. CONCLUSION

The characteristics of R410A gas as an efficient, ecologically acceptable substitute for SF_6 are analyzed in this paper. The effect of R410A's dielectric strength is examined in the presence of free metal particles of various shapes using ball-bowl electrodes. From experimental results, it was observed that the electric field disturbance is lower as the gap distance is increased. Furthermore, the insulation performance is degraded by increasing the metal particles as a result, the breakdown voltage drops. Under the same conditions, breakdown voltage drops to 30% of its original value when iron particles are utilized, while it drops to 46.89% when copper particles are used. Therefore, copper particles have a greater impact on the R410A gas reaction barrier than iron particles. Iron particles with a cubic shape perform better in both gap distances evaluated in the experiment. Copper particles in both gap distances contribute significantly to the reduction of the breakdown voltage. Based on the experiments conducted, it is concluded that R410A gas is a better insulation medium than SF_6. A future study might include nitrogen and carbon dioxide to test their insulating strength against metal particles. A moderate mixing ratio of nitrogen or other buffer gases may be utilized to increase the liquefaction temperature of R410A gas and study the effects of metal particles in R410A gas.

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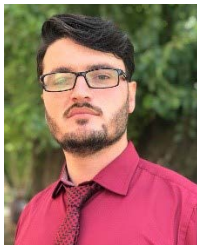

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