Experimental Study of Dielectric Breakdown of Refractory Board Materials for Application in High-temperature Sieving Electrostatic Precipitator

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***Abstract*—This paper presents the results of experiments conducted on the dielectric breakdown of selected number of refractory board materials exposed to high voltage ionizing environment in a hot gas stream. The study looks at the critical parameters such as the gas temperature, physical and composition of refractory materials under study, electric field strength, and identifies breakdown limits of the refractory materials within the given operational range of these parameters. This experimental study provide an insight into the high-temperature characteristics of these electric insulating materials and the necessary experimental data used to select the proper refractory materials for applications that involve high-temperature flue gas particulate clean-up using the Sieving Electrostatic Precipitator (S-ESP) technology.**

I. Introduction

The high voltage electrical insulation at high temperature, especially if it is inside a high-voltage particulate removal device or in the combustor, is a critical aspect for their application. Knowledge of electrical insulating characteristics of a refractory material at high temperature and its properties is needed prior to use this as an electrical insulator for applications where dielectric breakdown plays an important role. This paper examines the behaviour of different refractory board materials and dielectric breakdown at high-temperature. Although, refractory as an insulating material have been subject of numerous investigation, no single theory fully explains the process of breakdown and predict the breakdown stress of given refractory material. The breakdown of refractory material is function of temperature, voltage duration, ambient conditions, and the impurities or defects in the material. There are two major types of electrical breakdown that have been distinguished namely intrinsic and thermal.

Intrinsic breakdown is independent of ambient temperature rise. This type of breakdown is very difficult to identify and usually identified by eliminating all known secon-

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dary causes of breakdown. Thus, intrinsic breakdown can be avoided if the material under test is homogeneous without impurities and the breakdown tests are conducted under controlled temperature and environmental conditions ensuring that there are no external discharges. Thermal breakdown occurs due to disruption of thermal equilibrium in the dielectric. The volume resistivity of the insulating material decreases and dielectric loses increases with the increase of temperature. The critical condition of thermal breakdown are reached when the temperature at the center of the dielectric, Ti = Tcr, reaches the critical temperature at which thermal runaway process sets in. Thus, thermal breakdown of insulating material not only depends on the applied voltage but also ambient temperature and material properties, such as high temperature durability, thermal conductivity.

Dielectric breakdown of refractory material studied at room temperature and at a temperature below 400 ^{0}C, a very little attention has been given to above 400 ^{0}C. This work herein focused on dielectric breakdown of refractory board materials above 400 ^{0}C. This paper focuses on the loss of dielectric strength due to increase of temperature of different refractory materials and compares the results with 98.8% Al_2O_3 ceramic material that shows very good dielectric strength.

II. BACKGROUND

The hot Sieving Electrostatic Precipitator (S-ESP) is a newly developed fine particulate removal technology that is capable of efficiently capturing particulate matter from hot flue gas streams of industrial plants at temperatures exceeding 400 ^{0}C. The hot S-ESP has a unique process involving submicron particles agglomeration and collection mechanism, which leads to a smaller footprint and lower pressure drop compare to the other existing hot flue gas fine particulate clean-up technologies. For efficient operation of the hot S-ESP, proper dielectric insulating material as well as thermal insulator is required that does not change its dielectric properties and hence no breakdown occurs due to applied voltage when exposed to hot flue gas environment inside the S-ESP. Therefore, knowledge of electrical insulating characteristics of refractory materials at high temperatures is essential to avoid their breakdown by excessive sparking inside the S-ESP; which is known to severely degrade the charging functionality and ability of the S-ESP to capture and remove particles from the hot flue gas streams.

The Zero Emission Technologies (ZET) Group of CanmetENERGY has developed a new pilot-scale hot S-ESP prototype as a test platform for studying the capture of very fine particulate matter from flue gases of fossil fuel-fired plants. During the development of the hot S-ESP prototype, it was required to understand the dielectric breakdown of refractory board materials at high temperatures to properly select the materials for the hot S-ESP. A bench scale setup was developed to conduct the study on the dielectric breakdown properties of selected refractory materials when exposed to high-temperature above 400 ^{0}C.

III. TESTING

Total of six refractory board samples were collected from three different suppliers. The composition of these samples reported in the Table 1. All samples were identical having a dimension of 100 x 100 x 25 mm. Since the dielectric breakdown due to temperature rise does not depend on thickness and the hot sieving ESP prototype was built with the provision of 100 mm gap between high voltage and ground source, the test specimen of 100 mm size was chosen. The test results obtained are compared to the base specimen of 99.8% alumina ceramic plate/tube.

TABLE 1: TEST SPECIMENS AND BASE SPECIMENS MATERIAL COMPOSITION

Sample	Major Compositions	Density kg/m3
1	SiO_2-53.75%; CaO-40.99%; Al_2O_3-0.40%; Fe_2O_3-0.39	832
2	SiO_2-36.04%; CaO-0.67%; Al_2O_3-8.37%; Fe_2O_3-9.28%; P_2O_5-10.33%; MgO-27.19%	724
3	SiO_2-36.41%; CaO-1.06%; Al_2O_3-7.65%; Fe_2O_3-7.99%; P_2O_5-10.59% MgO-24.77%	1218
4	SiO_2-62.03%; CaO-0.09%, Al_2O_3-32.88%; Fe2O3-0.42%	484
5	SiO2-70.13%; CaO-4.38%; Al_2O_3-20.53%; Fe_2O_3-0.37%	1779
6	SiO_2-48.60%; CaO-35.63%; Al_2O_3-2.01%; Fe_2O_3-0.55%	1300
7 & 8	Al_2O_3-99.8%	3920

The test setup is shown in Fig. 1, wherein the heated sample can be placed on 120 mm thick ceramic plate and supported by two blocks of refractory brick. High voltage and grounding cable were connected at the center of two different side of sample. Both cables were sent through ceramic tube to avoid any kind of current leakage, except through the refractory sample. The setup was done in such way that the specimen can be tested at room temperature, at 200 ^{0}C, at 400 ^{0}C, and at 600 ^{0}C and, after 10 days of firing the sample at 600 ^{0}C. An electric furnace close to the setup was installed for this purpose to heat the specimen at required temperature. The test specimen was removed from the furnace and immediately placed on the bench setup. A high voltage test was conducted without any significant delay. Though, the test was conducted in an open space, but for the purpose of comparisons among different refractories, were good enough to draw conclusion about the electrical insulation performance of individual specimen.

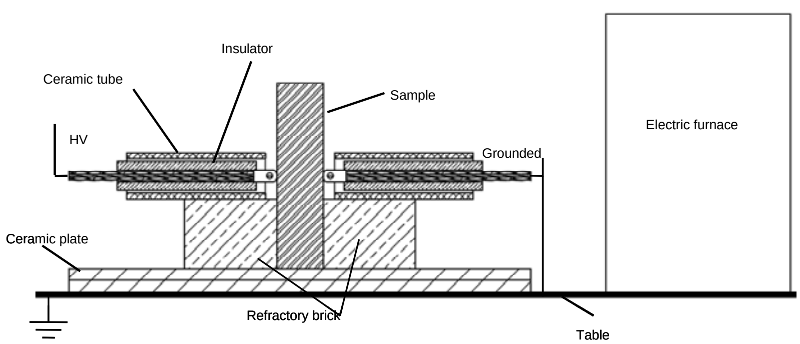

Fig. 1. Refractory board test setup

High voltage was applied from a Transformer Rectifier (TR) set which has a capacity of maximum negative output voltage of 70 kV DC. Voltage was applied with an increment of 3-4 kV up to 58 kV. Though, the maximum applied voltage that could be obtained from the TR set is 70 kV, but for the safety reason maximum voltage was limited to 58 kV.

At each increment, applied voltage and current were recorded. Failure of the specimen had been treated in such a way when sudden increase of current with arcing was observed on the display panel. It was also verified by visual observation of arcing through the board observed from the setup during the test. The sudden increase in the current reading indicated the leakage through the specimen. These tests were repeated two more times to find out the correct breakdown voltage of the specimen and an average breakdown voltage was taken for this purpose.

At first base test was conducted with 99.8% alumina ceramic plate. Four ceramic plates of size 100x100x6 mm combined together to make a specimen about 25 mm thick so that the results can be compared with the same thickness of other specimen. Six specimens were also tested at the same room temperature condition.

Next, all these specimens were heated at 200 ^{0}C for two hours and then dielectric breakdown tests were conducted for each specimen. After that, all specimens were heated for two hours at 400 ^{0}C and dielectric breakdown tests were conducted similar way. Finally, all specimens were heated at 600 ^{0}C for 5 days and dielectric breakdown tests were conducted. Heating of the specimens at 600 ^{0}C continued for 10 days and again dielectric breakdown tests were conducted. The specimen, who showed the dielectric breakdown at certain temperature, was not tested again at the next higher level temperature. During the testing with ceramic plate of 99.8% alumina, at higher temperatures the dielectric breakdown through the air was observed, instead of through the wall of the ceramic plate. Hence, comparison with the same size of ceramic plate could not be done. However, to do the test at high temperature, a ceramic tube of 25 mm OD and 19 mm ID was used (sample#8). The setup is shown in the Fig. 2. Thus, the possibility of breakdown through the air was avoided and the same base specimen material was tested by using ceramic tube.

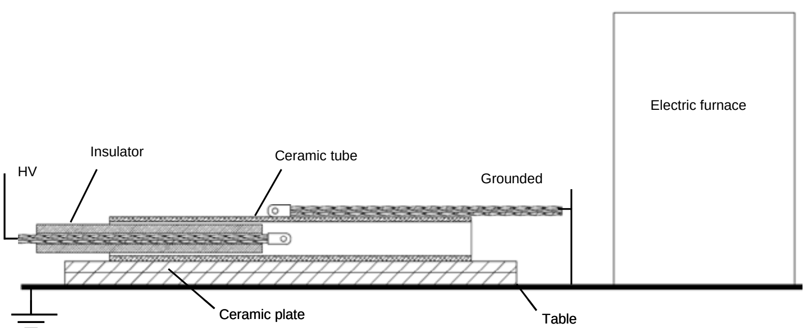

Fig. 2. Test setup with ceramic tube

IV. RESULTS

All samples (sample#1 to sample#7) were tested at the room temperature. Leaking through the refractory was identified when current started to rise at certain applied voltage. This applied voltage considered as the breakdown voltage of the particular specimen at given temperature. Fig. 3 shows the breakdown voltage of all seven samples at room temperature. Sample#7 reached maximum voltage of 58 kV without any indication of breakdown. Breakdown voltages of the sample#1 and sample#3 were found above 55 kV, whereas breakdown voltages for other samples were below 30 kV. High voltage test at room temperature did not show any obvious relation with respect to their composition. At room temperature, high voltage test results mostly depend on the moisture content and the presence of other organic materials in the samples.

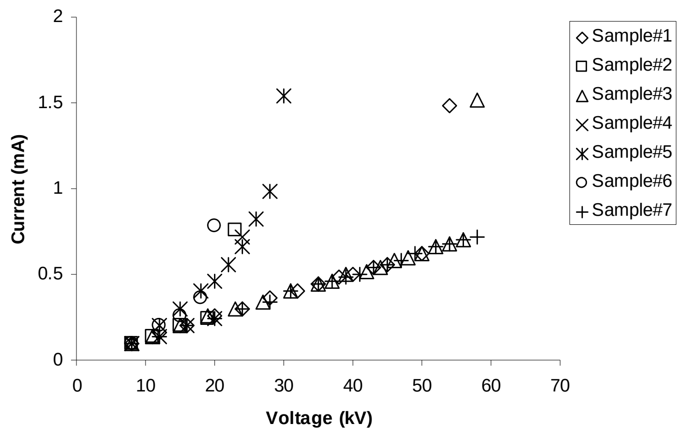

Fig. 3. Dielectric breakdown at room temperature

Samples heated at 200 ^{0}C for two hours were observed that different refractory board materials behaved differently. Breakdown voltage decreased for sample# 2 and sample#4, remained constant for sample#1 and sample#3, while breakdown voltage increased for sample#5 and sample#6. All these data are plotted and shown in Fig. 4. Sample#5 and sample#6 are denser than the other samples, thus higher breakdown voltage was achieved. Sample#3 is also higher dense material but the material composition includes P_2O_5 and MgO, which might acted as a conducting material and lowered the breakdown voltage.

Similarly, samples heated for additional two hours at 400 ^{0}C and tested. The breakdown voltage of sample#2 and sample#4 remained constant, sample#1 and sample#3 decreased, while sample#5 slightly decreased and sample#6 increased. Applied voltage was 54 kV for the sample##7 and at that point spark started through the air without any apparent arcing through the ceramic plate. Due to breakdown of gaseous insulation (in this case air as an insulator) at 400 ^{0}C, the maximum voltage attained was only 48 kV with the ceramic plate due to arcing through the surrounding air. The results for this set of tests are plotted and shown in Fig. 5.

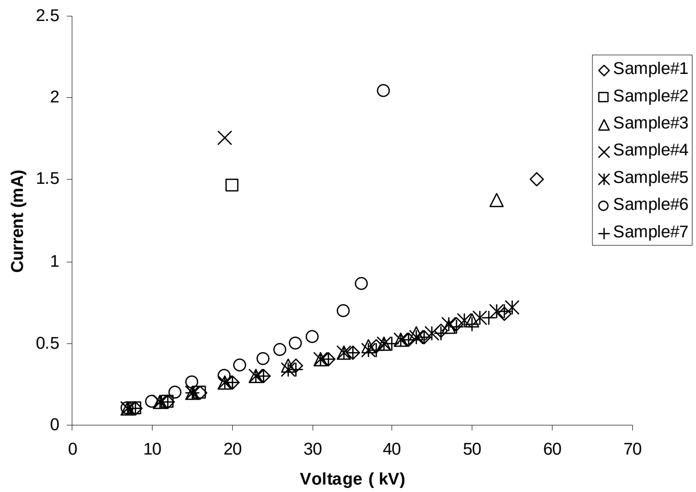

Fig. 4. Dielectric breakdown test after heating at 200 ^{0}C for two hours

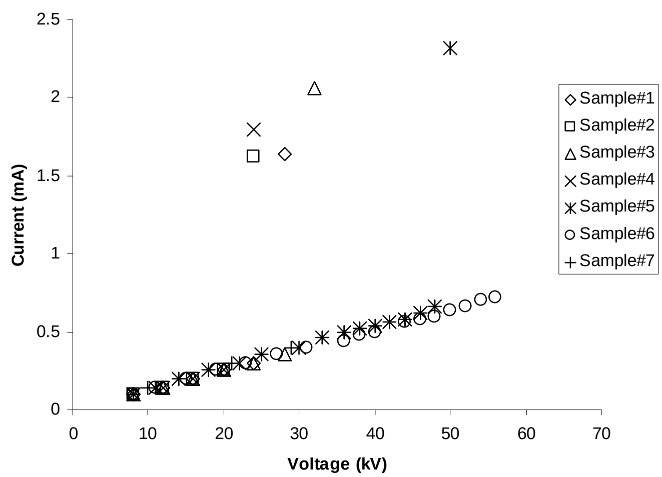

Fig. 5. Dielectric breakdown test after heating at 400 ^{0}C for two hours

Samples heated again to 600 ^{0}C for additional 20 hours. Most of the refractories under study, the breakdown voltage reduced to less than 20 kV, except for sample#6 which showed higher breakdown voltage with heating to higher temperatures. Fig. 6 shows that rate of current leaking through the wall for the sample#2, sample#4 and sample#5 is higher compare to the other samples.

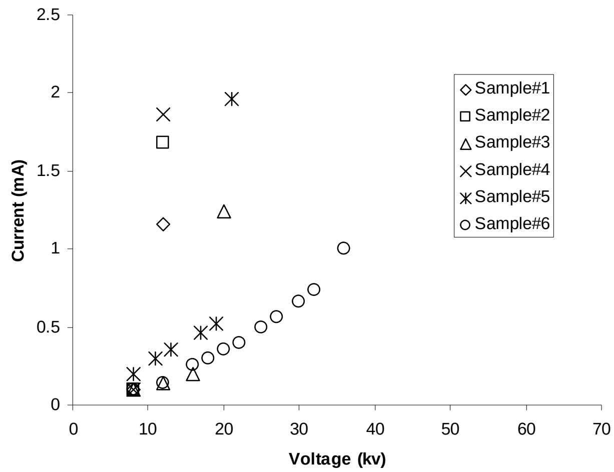

Fig. 6. Dielectric breakdown test after heating at 600^0 C for twenty hours

The next dielectric breakdown test was performed at 600 ^{0}C after 240 hours of heating. Since no other samples were survived at a temperature 600 ^{0}C for long time, this test was done only with sample#6 and the results were compared with ceramic tube of 25 mm OD and 19 mm ID. High voltage cable was inserted inside the ceramic tube and grounded cable was placed outside the tube; thus avoiding the gaseous breakdown. The results are depicted in Fig. 7. Breakdown voltage for the sample#6 was 33 kV.

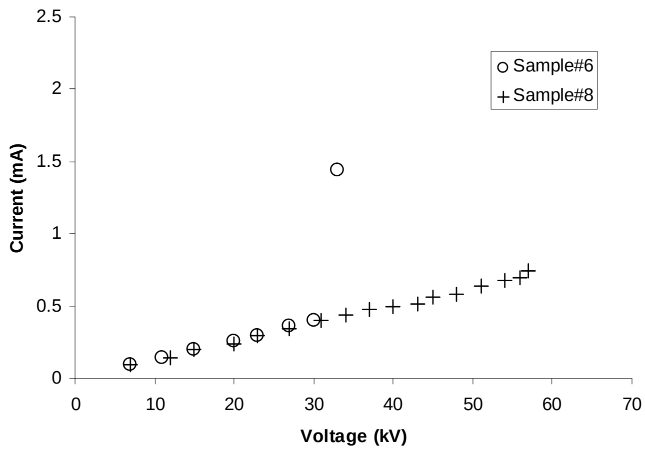

Fig. 7. Dielectric breakdown test after heating at 600 ^{0}C for 240 hours

The effect of temperature on dielectric breakdown of different refractory boards are plotted and shown in Fig. 8. In less denser refractory boards with higher porosity the dielectric breakdown voltage decayed with temperature exponentially. Breakdown voltage decreased for sample#3 and at certain point it reached a plateau. However, only for samples#5 and sample#6, dielectric breakdown voltage initially increased with the increase of temperature; after heating the samples for a longer time the breakdown voltage decreased. Sample#2 and sample#3 did not show any good dielectric strength. The amount of Fe_2O_3 is higher in these two samples which stopped them from achieving a higher breakdown voltage.

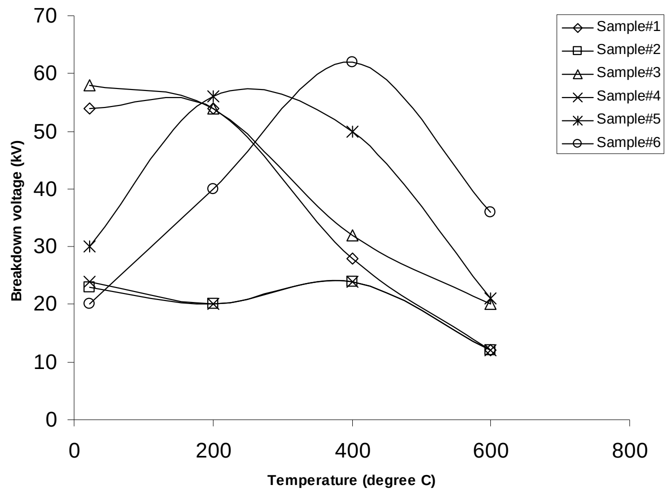

Fig. 8. Breakdown voltage of refractory boards at different temperature

V. Conclusion

The composition and the density of material are important for selecting a good dielectric strength refractory board material. The existence of Fe_2O_3 in the composition affects the dielectric breakdown of the refractory board. Increasing the density by adding more SiO_2 was not helpful to increase the dielectric breakdown voltage. Dielectric properties of SiO_2 degrade with temperature. The higher percentage of Al_2O_3 in the material helps to increase the dielectric strength. However, high Al_2O_3 ceramic is very expensive and not a good for thermal insulator. The percentage of CaO in the refractory material also plays an important role for electrical insulation. The higher percentage of CaO in conjunction with $Al_2O_{3,}$ will help to lowering the material cost down for applications that involve operation at high temperature and high voltage up to 35 kV.

VI. Acknowledgements

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REFERENCES

[1] Z. H. Khan, “Bench- and pilot testing of sieving electrostatic precipitator” Ph.D. dissertation, Dept. of Mech. Eng., Ohio Univ., Athens, OH, 2007.

[2] H. Ismailoglu and O. Kalenderli, “An investigation on electrical properties of meerschaum” IEEE International Conference on Conduction and Breakdown in Solid Dielectrics, Vasteras, Sweden, June 22-25, 1998.

[3] J. M. Bunch and F. W. Clinard, “Dielectric breakdown of potential RTPR first wall insulator materials,” Proceedings, First Topical Meeting on the Technology of Controlled Nuclear Fusion, San Diego, CA, April 16-18, 1974.

[4] Z. H. Khan and H. Pasic, “Capturing fine particulates with sieving electrostatic precipitator,” ESA Annual Meeting 2005, Alberta, Canada, June 21-24, 2005.

[5] K. Zanganeh, Z. H. Khan, C. Salvador, and J. Jackson, “ Hot sieving electrostatic precipitator,” WIPO Patent, WO 2001/006262 A1, January 20, 2011.

[6] J. J. O’Dwyer, “Theory of dielectric breakdown in solids,” *Journal of Electrochemical Society: Solid States Science*, vol. 116 no. 2.

[7] L. Vouyovitch et al., “Dielectric breakdown of epoxy-based composites: relative influence of physical and chemical aging,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 13 no. 2; April 2006.

[8] L. Tao et al., “How to eliminate ESP insulator thermal breakdown and insulation aging,” ICESP IX, Mpumalanga, South Africa, May 17-21, 2004.

[9] D. L. Lin, “ESD sensitivity and VLSI technology trends: thermal breakdown and dielectric breakdown,” *Journal of Electrostatics* vol. 33 pp. 251-271.

[10] D. Tommasini. (2010, April09). “Dielectric insulation and high voltage issues,” Presentation [Online]. Available: http://cas.web.cern.ch/cas/Belgium-2009/Lectures/PDFs/Tommasini.pdf