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FABRICATION AND SIMULATION TECHNIQUES OF PERMITTIVITY GRADED MATERIALS FOR GAS INSULATED POWER EQUIPMENT

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Abstract: For the relaxation and optimization of the electric field stress in electric power equipment, the application of FGM (Functionally Graded Materials) with spatial distribution of dielectric permittivity can be an effective solution. We investigated the applicability of FGM with various relative permittivity distributions to gas insulated power equipment. Firstly, we investigated the application effect of FGM to GIS spacers by electric field calculation. Next, we investigated the simulation technique for fabrication of FGM with different types of relative permittivity distribution and compared it with fabricated samples. Consequently, we developed the effective techniques for FGM fabrication and simulation, and verified the applicability of FGM to GIS spacers.

1 INTRODUCTION

Due to the intention to make more compact design of electric power equipment such as GIS (Gas Insulated Switchgears), the electrical insulation design becomes more important. For the insulation design of the power equipment, solid insulators play the most critical role. In order to improve the insulation performance of the power equipment, we need to control electric field distribution around the solid insulators. However, conventional techniques such as additional electrodes and control of insulator shape lead to more complicated structure of solid insulators and increase in the manufacturing cost [1-3]. Then, it is necessary to propose a new concept on solid insulators with keeping their simple structure and configuration. We have proposed the application of FGM (Functionally Graded Materials) with permittivity distribution to solid spacers for GIS, and made the fundamental investigation of FGM [4-10].

In this paper, we investigated the fabrication and simulation techniques of FGM with various permittivity distributions for GIS spacers.

2 APPLICATION EFFECT OF FGM

2.1 Electric field calculation

In order to confirm the electric field relaxation effect of FGM, we analyzed the electric field around a cone-type FGM spacer in GIS as an application example. Figure 1 shows the calculation model. We arranged the cone-type spacer between HV (100 kV) and GND (0 kV) electrodes in coaxial arrangement. Relative permittivity of uniform spacer is ε_r=6.0. In order to optimize the electric field in coaxial cylinder, we gave the relative permittivity that is proportional to the inverse of radius (1/r) from ε_r=9.0 to ε_r=3.0 for FGM spacer.

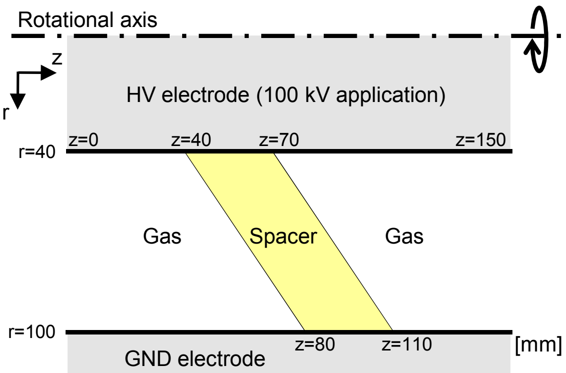


Figure 1: Calculation model for cone-type spacer

2.2 Calculation result

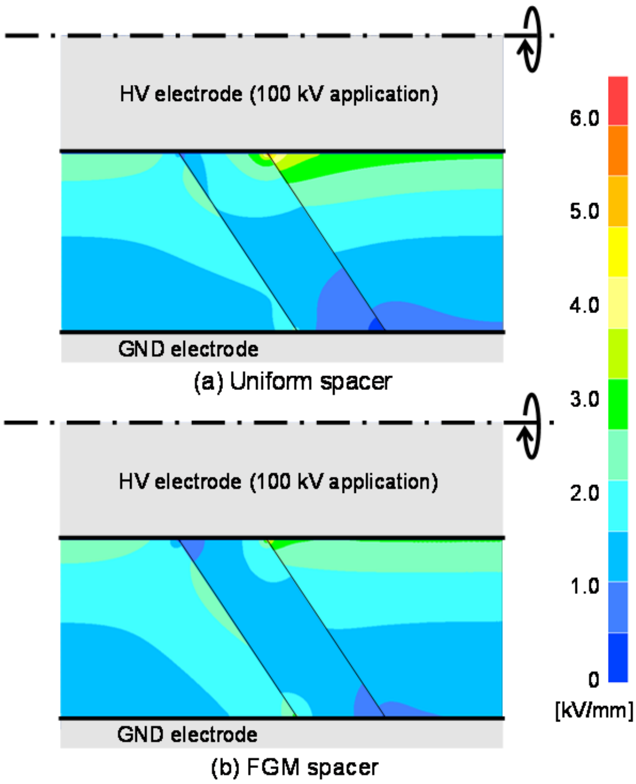
Figure 2 shows electric field distributions of the uniform and FGM cone-type spacers. By the introduction of FGM, the electric field distribution around the spacer is relaxed. Thus, we can control the electric field around the solid insulators by the application of FGM with keeping their simple structure and configuration.

3 FABRICATION TECHNIQUES OF FGM

3.1 Concept of FGM

3.1.1 FGM with grading to higher permittivity along centrifugal direction (GHP-FGM)

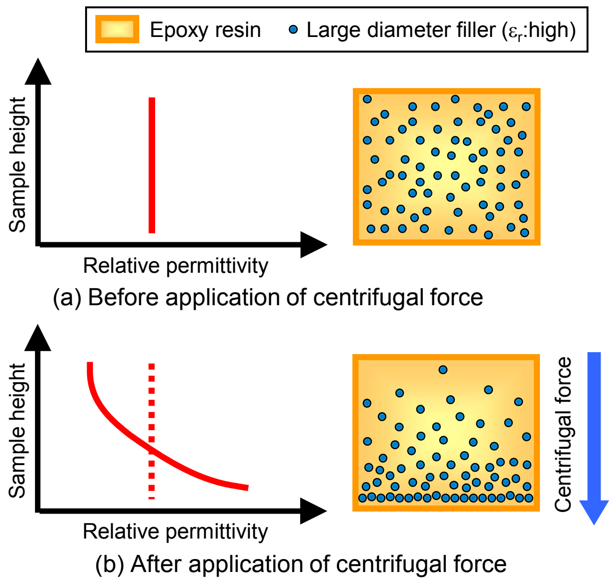
We used centrifugal force technique to fabricate FGM. GHP-FGM is the basic fabrication technique of FGM. Figure 3 shows the concept of GHP-FGM. We load with 1 kind of filler with permittivity higher than that of epoxy resin and applied centrifugal force. Then, we can obtain graded filler distribution along the centrifugal direction. GHP-FGM can be applied for post-type spacer. When we apply high permittivity part of GHP-FGM spacer to the high voltage electrode, we can reduce the electric field around the high voltage electrode.



(a) Uniform spacer

(b) FGM spacer

Figure 2: Electric field distributions



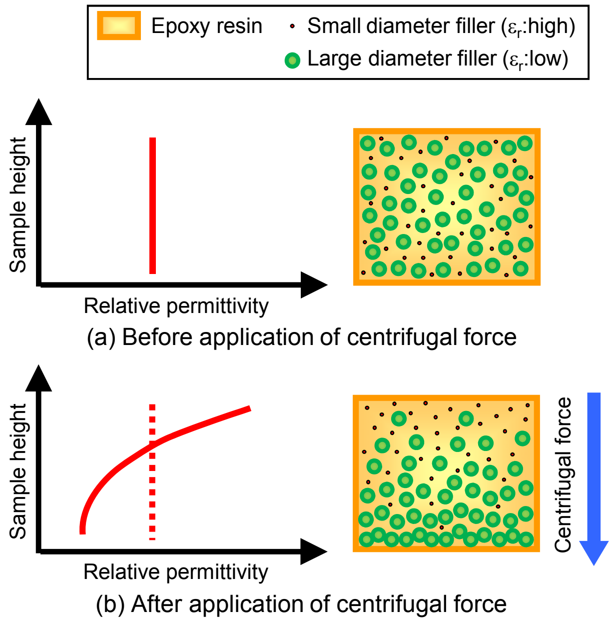
(a) Before application of centrifugal force

(b) After application of centrifugal force

Figure 3: Concept of GHP-FGM

3.1.2 FGM with grading to lower permittivity along centrifugal direction (GLP-FGM)

GLP-FGM can be applied to optimize the electric field distribution of disk-type spacer. Figure 4 shows the fabrication concept of GLP-FGM. We load with 2 kinds of fillers in the epoxy resin uniformly. One filler has small diameter and high permittivity, and the other has large diameter and low permittivity. By centrifugal force application, the filler with large diameter and low permittivity moves to the centrifugal direction. Accordingly, the filler with small diameter and high permittivity moves to the upper part of the sample instead. As the result, we can obtain GLP-FGM.



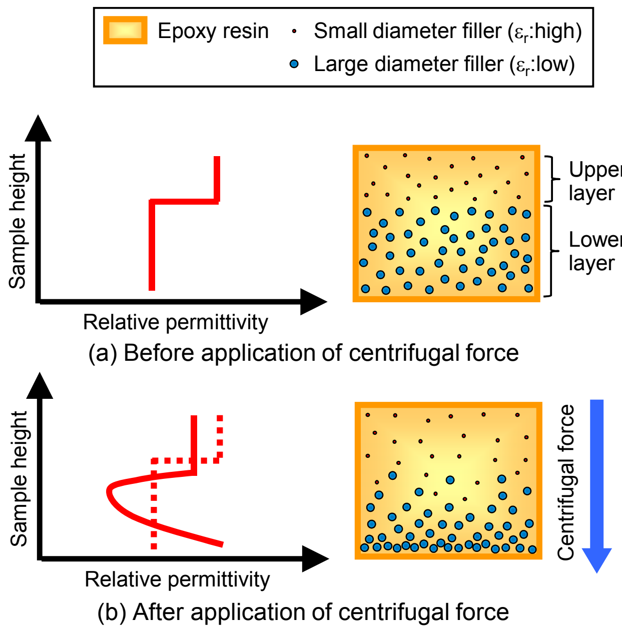
(a) Before application of centrifugal force

(b) After application of centrifugal force

Figure 4: Concept of GLP-FGM

3.1.3 FGM with U-shape permittivity distribution (U-FGM)

Figure 5 shows the fabrication concept of U-FGM. U-FGM is suitable for the relaxation of electric field on the HV and GND electrode surface in contact with post-type spacer [9]. We load with small diameter and high permittivity filler at the upper layer of the sample, and large diameter and low permittivity filler at the lower layer, respectively. Under centrifugal force application, the large diameter filler moves to the centrifugal direction. On the other hand, the small diameter filler does not move so much. Then, the permittivity becomes high at the lower part of the sample where the filler density of large diameter is increased. Consequently, U-shape permittivity distribution can be obtained.



(a) Before application of centrifugal force

(b) After application of centrifugal force

Figure 5: Concept of U-FGM

3.2 Application process of FGM

Figure 6 shows the flowchart of application process of FGM to power equipment. Firstly, we carry out electric field analysis of the objective equipment. Then, we obtain the optimum permittivity distribution for minimizing the electric field distribution in and around the solid insulator by computer-aided optimization technique [6]. For the practical use of FGM, a permittivity distribution is expected to be evaluable when we give a fabrication condition before actual fabrication. Thus, it is necessary to establish a simulation technique for FGM fabrication.

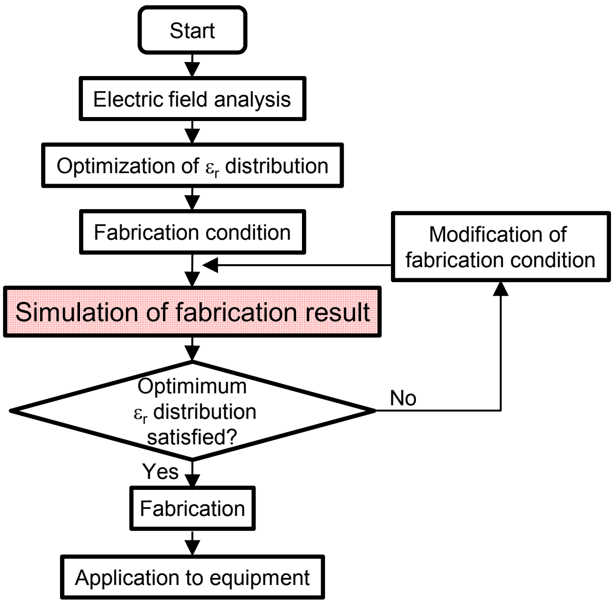


Figure 6: Flowchart of application of FGM

3.3 Simulation technique

We introduced a calculation model to simulate the filler particle movement in viscous fluid (epoxy resin mixed with hardener) under centrifugal force. Figure 7 shows the calculation model of centrifuging process. We used 1 dimensional model and calculated the flow of particle density in each region of the sample under centrifugal force. In the calculation, we considered the balance of 3 forces against a filler particle; centrifugal force, buoyancy and drag force, given by the following equation:

$$M\frac{dv_r}{dt} = Mr\omega^2 - Mr\omega^2\frac{\rho_f}{\rho_p} - F_D \tag{1}$$

Here M is mass of filler particle, v_r is relative velocity of filler particle, r is radius of rotation, ω is angular speed, ρ_f and ρ_p are specific gravity of fluid and particle, F_D is viscous force.

Given dv_r / dt = 0, the terminal velocity (v_t) of filler particles is given as follows:

$$v_t = \frac{GD_p^{\,2}(\rho_p - \rho_f)}{18\eta} \tag{2}$$

Here G is acceleration of centrifugal force, D_p is diameter of filler particle, η is viscosity of epoxy resin mixed with filler particles.

In the calculation, the estimation of viscosity η is important. We considered the interaction between particles by the viscosity. In order to estimate the viscosity of epoxy resin loaded with fillers, we extended Brinkman equation that gives the relative viscosity η_r of epoxy resin loaded with one kind of filler [7,10].

In the case of GHP-FGM, we simulated the movement of Al_2O_3 particles. In the case of GLP-FGM, we simulated the movement of SiO_2 particles with larger diameter in the condition that the filler content (vs. epoxy) of TiO_2 was constant, because TiO_2 particles with smaller diameter do not move by centrifugal force application. And in the case of U-FGM, we simulated the movements of both TiO_2 and Al_2O_3 particles.

In order to estimate relative permittivity ε_r of epoxy resin loaded with fillers, we extended Bruggeman equation that gives ε_r of epoxy resin loaded with one kind of filler [7,10]. Figure 8 shows the results of relative permittivity estimation and measurement.

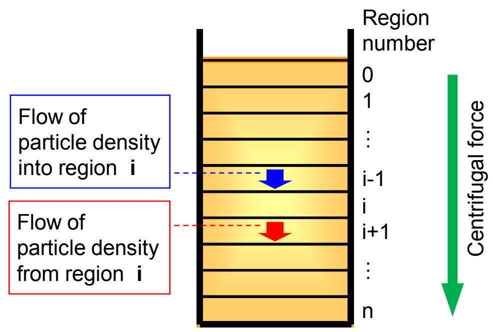


Figure 7: Calculation model of centrifuging process

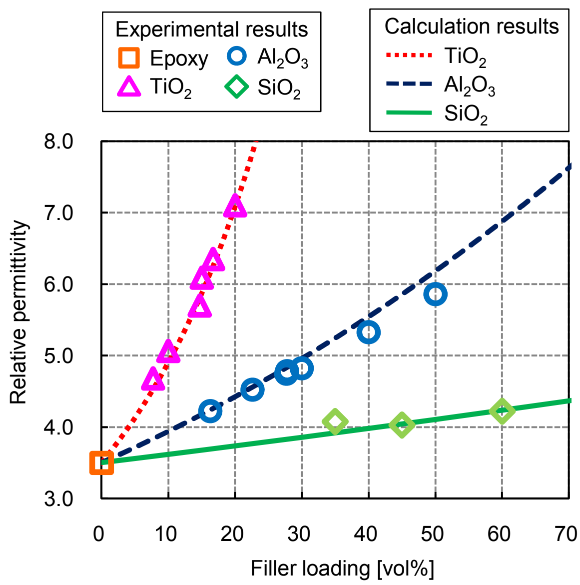


Figure 8: Relative permittivity of epoxy resin loaded with fillers

For each filler, the estimation result of ε_r agreed well with the measurement one. With this equation, we can calculate ε_r for each region based on the filler loadings after centrifuging process.

3.4 Fabrication method

The FGM samples were fabricated based on epoxy resin. The specifications of materials are shown in Table 1. Figure 9 shows diameter distributions of the applied fillers. The fabrication process has the following five steps:

(1) Epoxy resin is mixed with hardener and fillers.
(2) The mixed sample with fillers is poured into a test tube.
(3) The sample is degassed enough for removal of bubbles.
(4) Centrifugal force is applied at 30˚C for certain time duration depending on the case.
(5) The sample is cured at 100˚C in the oven.

Table 2 shows the fabrication conditions. GHP-FGM is epoxy composite filled with Al_2O_3 28.6 vol%. GLP-FGM is loaded with 2 kinds of fillers, TiO_2 10 vol% and SiO_2 40 vol%. To obtain U-FGM, epoxy composite filled with Al_2O_3 28.6 vol% is poured into the test tube for the lower layer and epoxy composite filled with TiO_2 16.7 vol% is poured for the upper layer.

Table 1: Specifications of applied materials

	Epoxy resin	Hardener	Filler		
Chemical structure	BPA epoxy resin	Anhydride - type	Al_2O_3 spherical	TiO_2 rutile crystal	SiO_2 crystal
Relative permittivity (1kHz,30℃)	3.5 (at mixed condition)		9.3	114	4.5
Specific gravity [g/ml]	1.19 (at mixed condition)		3.95	4.2	2.65
Viscosity [Pa*sec](30℃)	1.7 (at mixed condition)		—	—	—
Mean diameter [μm]	—		3.21	0.672	5.89

Table 2: Specifications of fabrication conditions

FGM sample	Filler loading (vs.total) [vol%]			Centrifugal condition	
	Al_2O_3	TiO_2	SiO_2	Centrifugal force [G]	Time duration [min]
GHP-FGM	28.6	—	—	2900	10
GLP-FGM	—	10	40	4000	60
U-FGM	28.6 (Lower layer)	16.7 (Upper layer)	—	2900	10

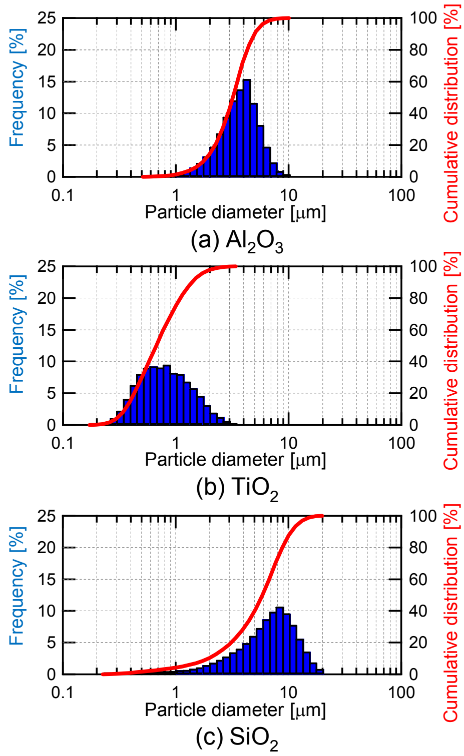


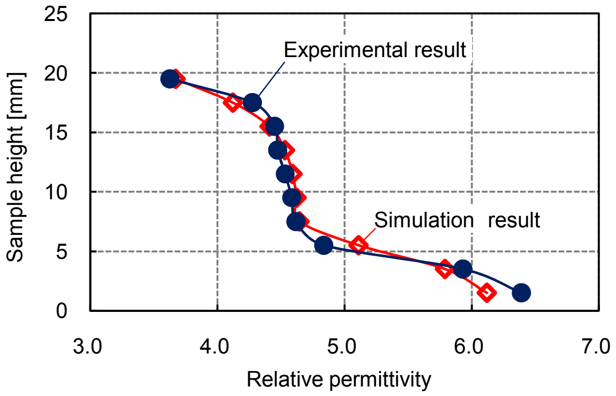
Figure 9: Diameter distributions of applied fillers

3.5 Fabrication and simulation results

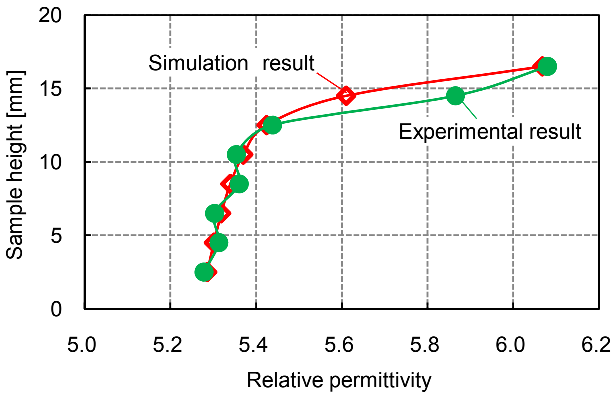
The fabrication results of relative permittivity distributions are shown in Figures 10 for (a)GHP-FGM, (b)GLP-FGM and (c)U-FGM, respectively. Figure 10 shows that we could fabricate GHP-FGM with ε_r from ε_r=3.6 to ε_r=6.4 by the graded distribution of Al_2O_3 particles. We could also obtain GLP-FGM with ε_r from ε_r=6.1 to ε_r=5.3 by the graded distribution of SiO_2 particles. U-FGM with ε_r from ε_r=5.8 to ε_r=6.3 through ε_r=4.5 was also fabricated. Thus, we could establish the fabrication techniques of FGM with various permittivity distributions.

Simulation results of ε_r distributions are also shown in Figure 10 with the experimental ones. From these figures, simulation results agreed well with the experimental ones for various fabrication conditions and permittivity distributions. As the result, we could develop the simulation technique for fabrication of FGM and establish the effective technique for application of FGM to power equipment.

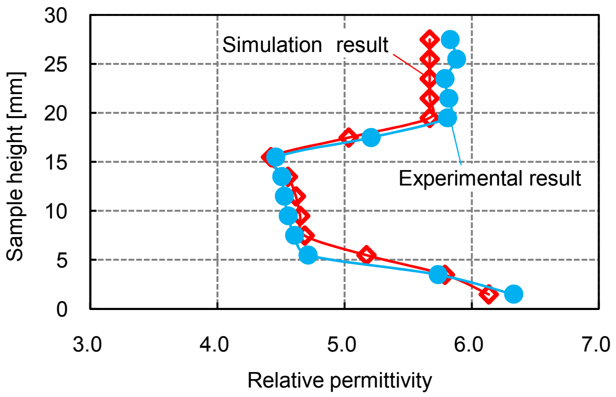
Consequently, the fabrication and simulation techniques for application of FGM with various relative permittivity distributions to GIS spacer were successfully obtained



(a) GHP-FGM



(b) GLP-FGM



(c) U-FGM

Figure 10: Experimental and simulation results of relative permittivity distributions for various FGM

4 CONCLUSION

For the compact design and reliability enhancement of power equipment, we proposed the application of FGM with various permittivity distributions to solid insulators. In this paper, we investigated fabrication feasibility of FGM for GIS spacers from both experimental approach and numerical calculation.

The results are summarized as follows:

(1) We investigated a simulation technique for FGM fabrication by numerical calculation. We introduced a calculation model to simulate the filler particle movement in viscous fluid.

(2) We fabricated FGM with various permittivity distributions. We fabricated GHP-FGM with ε_r from 3.6 to 6.4, GLP-FGM with ε_r from 6.1 to 5.3 and U-FGM with ε_r from 5.8 to 6.3 through 4.5.

(3) Simulation results of relative permittivity distributions agreed well with the experimental ones.

Consequently, the fabrication and simulation techniques for FGM with various permittivity distributions were established for power equipment with gas / solid composite insulation system.

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