

Influence of Electrical Properties of Dielectric Sample to Electromagnetic Field Distribution Inside Solenoid-Type Dielectric Sensor

Chon Ung Kim, Chung Il Kim, Chol Ju Kong

Faculty of Electrical Engineering, Kim Chaek University of Technology, Pyongyang Democratic People's Republic of
Korea

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Abstract-Traditional dielectric sensors such as parallel-plate or coaxial cylindrical metal electrodes have some limitations and disadvantages, including the corrosion of electrode, the occurrence of electrode polarization, the reaction of the sensor material with dielectric samples, etc. This paper aims to investigate the influence of electrical properties of dielectric samples to the behaviors of electromagnetic field distribution inside solenoid-type dielectric sensors and the relationship between the electrical sensor parameters to be measured and material properties of dielectric samples considered, using numerical electromagnetic field analysis method. According to the numerical electromagnetic field analysis, it can be concluded that (i) In the case of high-resistivity dielectric samples such as insulating liquids and powders, the distribution capacitance is more preferable in identifying the dielectric properties of sample to the change of Q-quality; (ii) In the case of high-conductivity dielectric samples such as water and other aqueous solutions, the change of Q-quality is much more sensitive to that of the dielectric properties of sample to the distribution capacitance.

Keywords: Dielectric sensor, Non-contact measurement, Solenoid-type, Numerical analysis

I. Introduction

Since electrical properties of dielectric materials are closely related with their physical and chemical properties, dielectric diagnosis techniques and devices have been widely studied and introduced for the purpose of estimating the quality of materials and monitoring the production processes in many practical applications, including industry, agriculture, biological engineering, medical science, etc.

Especially, as to dielectric sensors, traditional contact-type sensors such as parallel-plate or coaxial cylindrical metal electrode systems have some disadvantages and limitations because of the corrosion of the electrode material, the occurrence of electrode polarization and the reaction of the electrode material with dielectric samples and so on, which may influence the measurement results or negatively affect the sensor performance.

Therefore, various kinds of non-contact dielectric sensors have been long attempted by many researchers all over the world so as to solve such theoretical and practical problems.

One of non-contact dielectric sensors is just the solenoid-type sensor (or induction-type sensor) which is simple in its structure, easy to manufacture and inexpensive. That is why induction-type dielectric sensors have been preferred to use in practical applications rather than any other ones.

Here are some typical application examples for the so-called solenoid-type dielectric sensors:

- Evaluation of dielectric permittivity and dielectric loss tangent for liquids and powders
- Assessment of molecular structure and composition for water and aqueous solutions
- Determination of fat content in milk [8]
- Recognizing bacterial presence in aqueous solutions [8]
- Characterization of carbonized coal [9]

Many researchers have focused their attention on the theoretical and practical issues related with how to improve the structure and measurement accuracy of the solenoid-type dielectric sensors.

Especially, solenoid-type dielectric sensors are non-standard ones, resulting in that the electrical property parameters such as dielectric permittivity, conductivity, dielectric loss tangent of dielectric samples to be measured by using them tend to be non-linear in relation with the measured electrical measurement parameters like the electrical capacitance, resistance and inductive reactance.

What is important in the research of solenoid-type dielectric sensors is to demonstrate the influences of sample properties, sensor geometries, use conditions and other error factors to their performance characteristics.

As well-known, solenoid-type dielectric sensors are used under high frequency condition, and also it may be more or less troublesome or difficult to modify all of the factors giving influences to the sensor characteristics in practice.

Therefore, it is of great significance to apply various useful modeling methods for solving the theoretical and technical problems encountered in the sensor development.

As to the modeling of the electromagnetic sensors such as solenoid-type sensors, there are two kinds of methods, that is, the equivalent circuit method and numerical electromagnetic field analysis method.

The conventional equivalent circuit modeling method has some disadvantages: for example, all of possible factors cannot be reflected in the equivalent circuits because of material, structural, operational and other causes, and also it may be so difficult or even impossible to satisfactorily analyze complex equivalent circuits.

Numerical electromagnetic analyses based on the well-known finite element method (FEM) are so effective and useful enough to investigate the behaviors of the electromagnetic field distribution without preparing any real objects to be considered, but only with virtual models visually and in more details than analogous equivalent circuit methods that they have been regarded as powerful tools necessary to the researches of electromagnetic sensors.

To our best knowledge, the investigation of solenoid-type dielectric sensors have been performed mainly based on analogous equivalent circuit methods, and a few researchers have paid attentions to the application of numerical analysis methods.

This paper aims to investigate the influence of electrical properties of dielectric samples to the behaviors of electromagnetic field distribution inside solenoid-type dielectric sensors and the relationship between the electrical sensor parameters to be measured and material properties of dielectric samples considered, using numerical electromagnetic field analysis method.

Numerical analysis experiment

Finite element method was used to investigate the influence of dielectric material properties to the electromagnetic field distribution inside the solenoid-type dielectric sensor,

Fig 2 represents FEM model of the solenoid-type dielectric sensor cell model for numerical electromagnetic field analysis.

The AC/DC module of COMSOL Multiphysics 5.4 was adopted as a tool for FEM analysis of the electromagnetic field analysis.

The geometric and material parameters of the solenoid sensor model necessary for FEM analysis are shown in Table 1. All the material parameters in Table 1 correspond to room temperature conditions.

The excitation voltage used for the electromagnetic field distribution analysis was 1 V and the frequency was taken as 2 MHz.

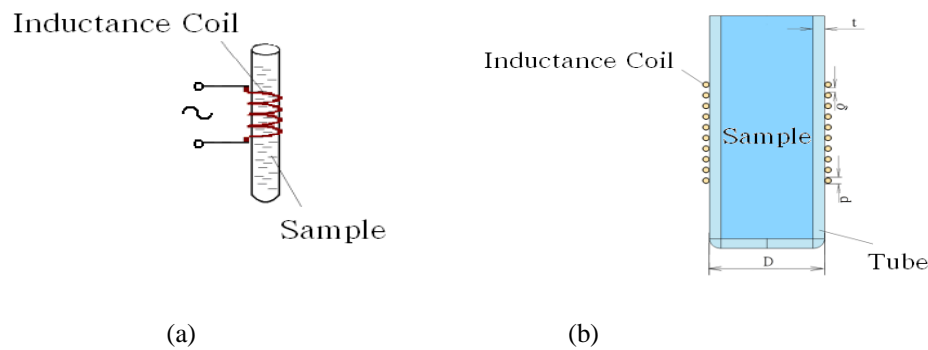


Fig 1: Solenoid dielectric sensor structure (a) and its FEM analysis model (b)

Table 1: Geometrical and material parameters of the solenoid sensor model

parameter	symbol	unit	value
Number of coil turns	N	-	17
Pitch of coil	δ	mm	0
Inner diameter of solenoid	D	mm	7.35
Diameter of wire conductor	d	mm	0.51
Insulation thickness of wire conductor	t_{ena}	mm	0.025
Thickness of sample tube wall	t	mm	0.5
Height of sample tube wall	h	mm	28.56
Relative permittivity of sample tube material	ϵ_{rtube}	-	5.5
Specific resistivity of sample tube material	ρ_{tube}	$\Omega \cdot m$	10^{12}

Relative permittivity of sample	ϵ_{rs}	-	1~80
Conductivity of sample	γ	S/m	0~10 ⁻²

First, the behaviors of the changes of electromagnetic field distribution with the dielectric permittivity and conductivity of the dielectric sample were analyzed to investigate the electric and magnetic field distributions inside the solenoid sensor, respectively.

Taking into account that the solenoid-type dielectric sensor is known to be taken as a sample sensor in Q meter method, the complex impedance values of the sensor without and with the dielectric sample to be measured were taken from FEM electromagnetic field analysis, and then the changes of resonant capacitance and quality factor were calculated using Equation 1 and Equation 2.

$$C = \frac{1}{\omega X} \tag{1}$$

$$Q = \frac{X}{R} \tag{2}$$

where X is the inductive reactance of the solenoid sensor, R is its resistance, C is the capacitance and Q is the quality factor.

Considering that the resonant capacitances and Q-factors of the solenoid sensor with and without dielectric sample are C₁, C₀ and Q₁, Q₀, respectively, then the changes of the resonant capacitance and the Q-factor can be express as follows:

$$\Delta C = C_1 - C_0 \tag{3}$$

$$\Delta Q = Q_1 - Q_2 \tag{4}$$

The parameters ΔC and ΔQ given in Equation 3 and Equation 4 were taken as characteristic indices of the solenoid-type non-contact dielectric sensor to be considered.

II. Result and Discussion

A. In the case of high-resistivity dielectric sample

Fig 2 and Fig 3 represent the behaviors of the magnetic and electric field distributions inside the solenoid-type dielectric sensor without and with the high-resistivity dielectric sample ($\rho = 10^{13} \Omega \cdot m$), respectively.

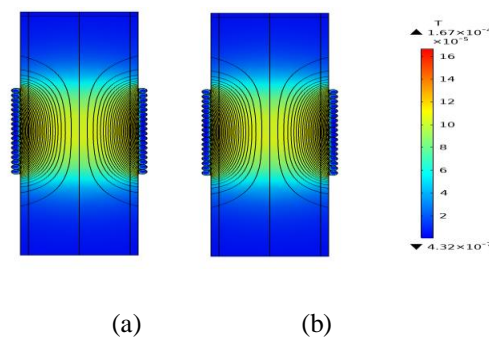


Fig 2: The magnetic field distribution behaviors inside the solenoid-type dielectric sensor without (a) and with (b) the dielectric sample ($\epsilon_r = 20$)

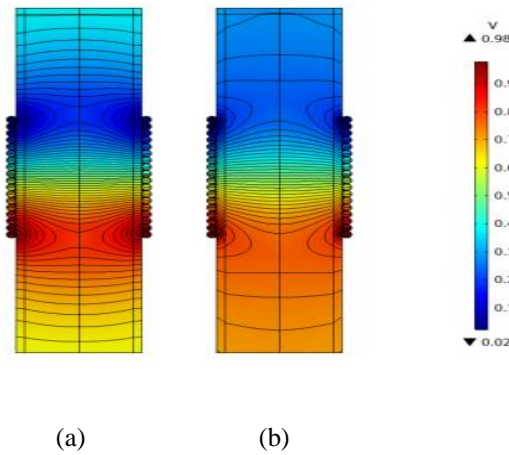


Fig 3: The electric field distribution behaviors inside the solenoid-type dielectric sensor without (a) and with (b) the dielectric sample ($\epsilon_r = 20$)

As can be clearly seen in Fig 2 and 3, the magnetic field distribution of the solenoid-type dielectric sensor is independent of the existence of the dielectric sample inside it, whereas there exists a significant change in the electric field distribution, which means that the dielectric permittivity of dielectric samples gives an influence to the electric field distribution inside the sensor and its distribution capacitance (Fig 4).

Fig 4 and 5 show the FEM analysis results on the variation of the sensing capacitance and Q-factor of the solenoid-type sensor with dielectric constant of the insulating material sample, from which the distribution capacitance and Q-factor of the sensor tend to non-linearly increase with the dielectric permittivity increasing.

However, considering that the resolution of Q-meter used is generally 0.01pF in capacitance and 0.01 in Q-factor, it can be concluded that the variation of Q-factor of the sensor with dielectric permittivity of the sample can be neglected and that only the distribution capacitance of the solenoid-type dielectric sensor is practically available for the measurement of dielectric permittivity for high-resistivity samples.

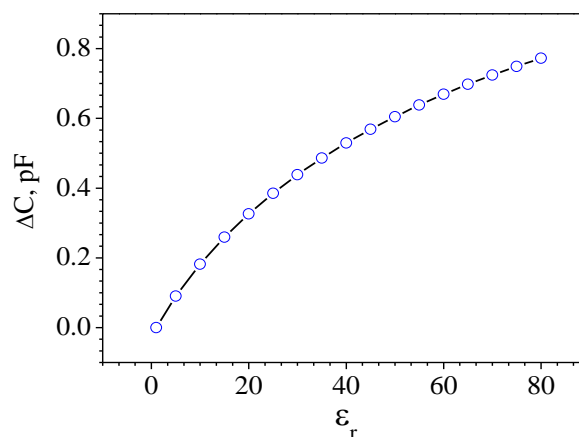


Fig 4: The plot of the distribution capacitance of the solenoid sensor versus the dielectric constant of dielectric samples

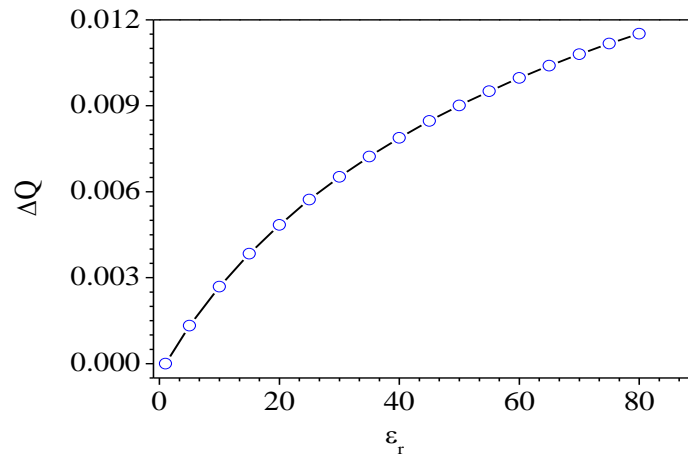


Fig 5: The plot of Q-factor of the solenoid sensor versus the dielectric constant of dielectric samples

B. In Case of high-conductivity sample

For highly conductive samples, including water and aqueous solutions, the variation of conductivity of dielectric sample results in that of the impedance of the solenoid sensor, which implies the change in the electromagnetic field distribution inside the sensor.

For FEM simulation, the dielectric constant was fixed as 80, and the electrical conductivity of the sample was taken in the range from 10^{-4} to 100S/m, which corresponds to the conductivity values of water and other aqueous solutions.

Fig 6 and Fig 7 represent the simulation results of the magnetic and electric field distributions inside the solenoid-type dielectric sensor with the dielectric samples different in the conductivity values, respectively.

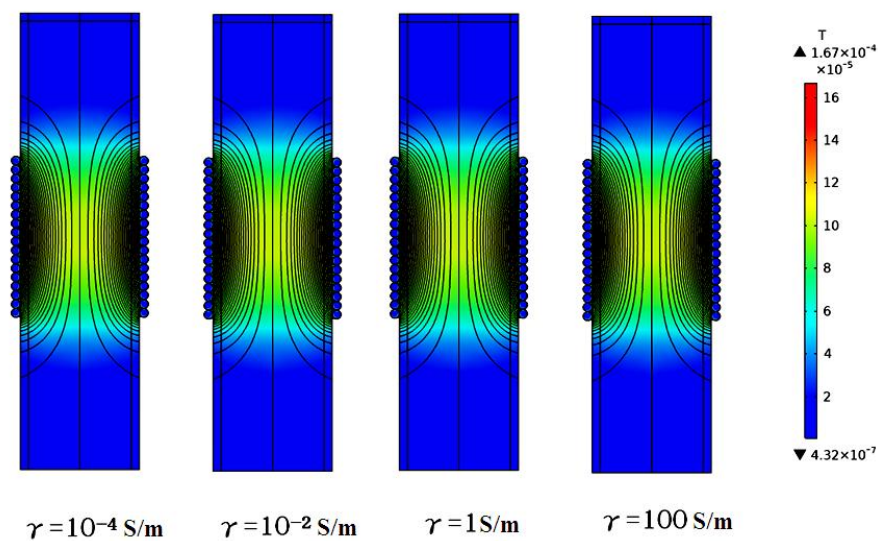


Fig 6: Behaviors of magnetic field distribution for dielectric sensors with different conductivity values ranged between 10^{-4} to 100S/m

As can be seen in Fig 6, no change in the magnetic field distribution inside the sensor is also observed in the conductivity range of 10^{-4} to 100S/m.

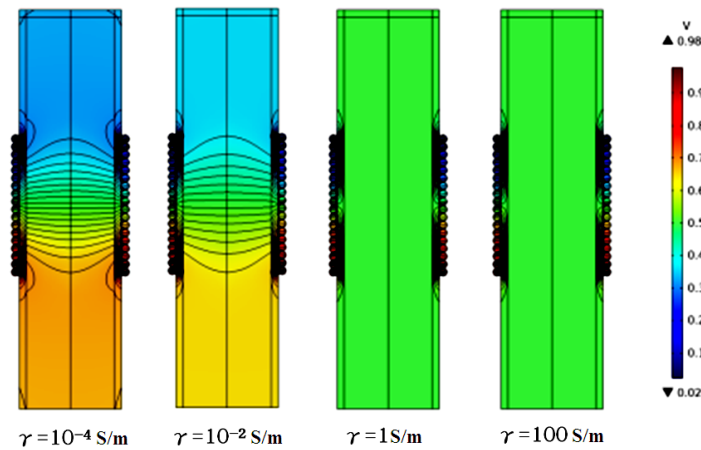


Fig 7: Behaviors of electric field distribution for dielectric sensors with different conductivity values ranged between 10^{-4} to 100S/m

However, the variation in the conductivity value of the sample is observed to cause the change of the electric field distribution inside the sensor in the low conductivity range, whereas not in the high conductivity range over 10^{-2}S , which may be attributed to that too high conductivity of the dielectric sample causes the electric field distribution inside the sensor to show nearly the same with that in metallic materials, that is, there exists no electric field distribution inside the sensor as shown in Fig 7(c) and (d).

Considering that water and aqueous solutions met in the practical applications have the conductivity values below 1S.m , only the variation of electric field distribution is also found to be related with that of dielectric permittivity (or capacitance) of the dielectric sample to be considered.

Fig 8 and Fig 9 show the variation of the distribution capacitance and Q-factor of the solenoid sensor with the dielectric permittivity and conductivity for highly conductive samples in the conductivity range of 10^{-4} to 10^{-2}S/m .

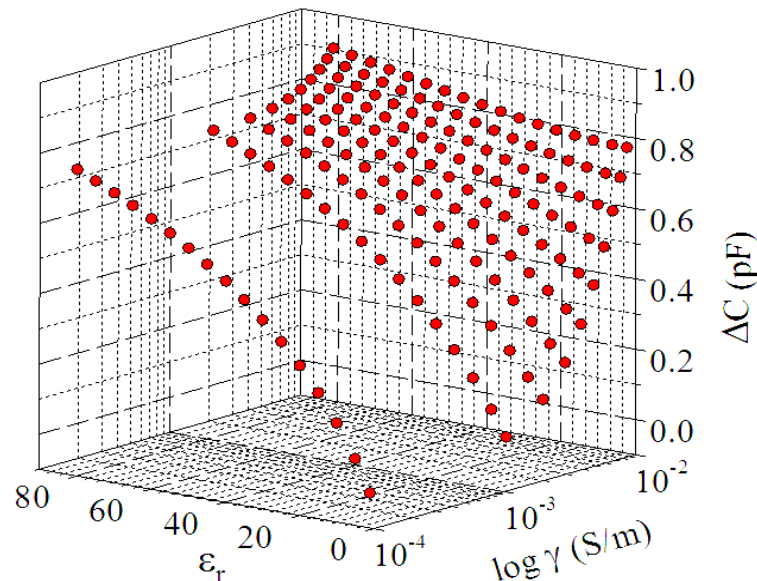


Fig 8: The influence of conductivity on the permittivity dependence of the distribution capacitance for the solenoid-type sensor with high-conductivity sample inside it

As shown in Fig 8, as the conductivity of the high-conductivity sample increases in the considered conductivity range, the variation of the distribution capacitance with its dielectric permittivity tends to be close to zero, which hints us at that the distribution capacitance may be useless in distinguishing dielectric materials from each other when the values of conductivity get higher and higher for high-conductivity samples.

Meanwhile, the higher the conductivity of high-conductive dielectric sample samples is, the more apparent the variation in Q-factor with the dielectric permittivity is.

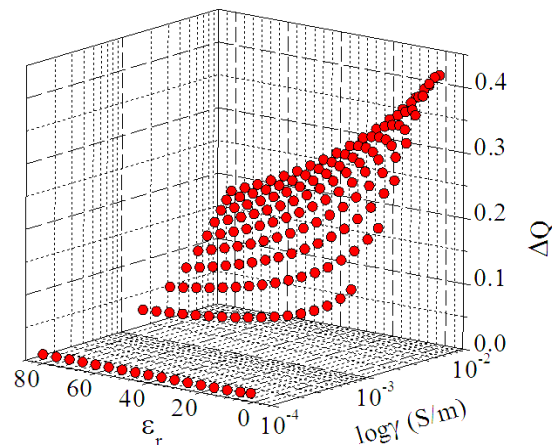


Fig 9: The influence of conductivity on the permittivity dependence of the Q-factor of the solenoid sensor with high-conductivity sample inside it

It can be deduced from the above-mentioned FEM analytical results that for estimating the dielectric permittivity values of high-conductivity dielectric samples such as water and various aqueous solutions the distribution capacitance is more available rather than the Q-factor as the conductivity is lower, whereas the Q-factor is more available as the conductivity is higher.

III. Conclusion

This paper has been dealt with both the influence of electrical conductivity of dielectric samples to the electromagnetic field distribution inside the solenoid-type non-contact dielectric sensor and the dependences of its distribution capacitance and Q-factor versus dielectric permittivity on the conductivity of dielectric samples, based on FEM electromagnetic field distribution analysis.

The followings have been found based on the FEM numerical analysis of the electromagnetic characteristics for the solenoid-type dielectric sensor:

- (i) The dependence of the distribution capacitance and Q-factor of the solenoid-type non-contact dielectric sensor mentioned in this paper on the dielectric permittivity of the dielectric sample to be considered can be obtained from FEM electromagnetic field distribution analysis, based on which, it is possible to effectively measure the dielectric permittivity values of high-resistivity or high-conductivity dielectric materials without any negative influences such as electrode polarization, electrode contamination and corrosion, etc.
- (ii) Irrespective of the electrical conductivity values of the dielectric samples properties contained in the solenoid-type non-contact dielectric sensor in the conductivity range of 10^{-4} to 10^{-2} S/m, their dielectric permittivity give the considerable

influences only to the electric field distribution, indicating that its mechanism of measurement of dielectric permittivity is only related to the electric field distribution characteristics inside it;

(iii) In the case of high-resistivity dielectric samples such as insulating oils and powders, the distribution capacitance of the sensor is more preferable in identifying the dielectric properties of sample to its Q-quality;

(iv) In the case of high-conductivity dielectric samples such as water and other aqueous solutions, as the conductivity is increased in the above-mentioned conductivity range, Q-quality is much more sensitive to that of the dielectric properties of sample to the distribution capacitance.

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