Basic Experimental Study on Effect of Bentonite to Efficiency of Wireless Power Transfer Using Magnetic Resonance Coupling Method

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Abstract—**Nuclear power has become one of the significant sources for electricity generation and one crucial issue in operating nuclear power plant is radioactive waste management. Multi Barrier System has been utilized to handle high-level nuclear waste. Several sensors are equipped to ensure the safety condition inside the repository, but with current method, signal cables and power cords have to be drawn to the outside through small hole. To construct Multi Barrier System, the option of completely sealing the repository and transmitting data and power wirelessly has been proposed. Wireless power transfer via magnetic coupling is an attractive method for such application due to its advantage of being able to transfer power across longer distance with high efficiency while being robust to positional shift of antennas and that using repeater antenna can also enable power transmission across even further distance. However, obstacle between antenna, although will not completely disrupt the power transmission, is most likely to have influence on power transfer efficiency. Therefore, in this paper, the efficiency of wireless power transfer with bentonite, which is common component of Multi Barrier System, as transmission obstacle, with and without repeater antenna, is investigated and compared to the efficiency of wireless power transfer with no barrier material.**

Keywords-Wireless Power Transfer; Magnetic Resonance Coupling; Nuclear Waste Management; Multi Barrier System; Bentonite

I. INTRODUCTION

Recently nuclear power has become one of the significant sources for electricity generation. One crucial issue in operating nuclear power plant is nuclear waste management. The current method to handle the high-level nuclear waste is called Multi Barrier System, where nuclear waste is disposed deep underground within several layers of engineered and natural barriers. In order to demonstrate the safety condition within disposal system, the performance of Multi Barrier System will be confirmed by monitoring system. Therefore, various sensors are equipped inside the system for monitoring purpose. Until now, in order to obtain data from sensors, signal cables and power cords connected from sensors are drawn to the outside through small holes. To construct Multi Barrier System, the option of completely sealing the repository and having sensor data and power supply transmitted through wireless power transfer system has been proposed.

Wireless power transfer using magnetic resonance coupling method has been known to have the advantage of being able to transfer power across longer distance with considerably high efficiency and being robust to positional shift of transmitting antenna and receiving antenna. Repeater antennas can also be used to further extend the range of power transmission. Therefore, the mentioned wireless power transfer method is considered an attractive alternative for nuclear waste disposal monitoring system.Substance and material in between antennas such as soil and constructed containers are likely to have some effect on the efficiency of wireless power transfer system, and the possibility of power transfer being disrupted should also not be neglected. However, there have not been many studies available on such effect of substance and material to the wireless power transfer method.

Bentonite clay is a main component in natural barrier, due to its characteristics that it swells when exposed to water and becoming powerful barrier to water flow is utilized. Therefore, in this paper, bentonite clay is used for basis study on the effect of obstacle in wireless power transfer system. In the experiment, antennas of two different sizes are used and transmitting distance, or thickness of bentonite inserted between transmitting and receiving antennas, is varied. The efficiency of wireless power transmission with bentonite as barrier, with and without repeater antenna, is investigated and compared to the efficiency of wireless power transfer with no barrier material.

II. Test Facility

A. Antennas

For this experiment, open-end spiral antennas of two different sizes, as shown in Fig. 1, are used. The antennas are in two sizes, 300mm-diameter and 150mm-diameter antenna; pitch length between centers of wires is 5 mm; the antenna is double layer with distance of 8 mm between layers; and the wire size is 2 mm in diameter. The self-resonant frequency of every antenna used in this experiment is 13.56 MHz. The RLC parameters of each antenna are listed in Table I.

Figure 1. Antennas(left: φ300mm antenna, right: φ150mm antenna).

TABLE I. LCR Parameter of Each Antenna

	Transmitting	Repeater	Receiving	Receiving
Diameter	150 mm	150 mm	150 mm	300 mm
R	2.10 Ω	2.18 Ω	2.21 Ω	2.11 Ω
C	12.14 pF	12.87 pF	19.31 pF	14.58 pF
L	11.35 µH	10.71 µH	7.12 µH	9.49 µH

B. Bentonite Block

For this experiment, bentonite clay was mixed with water with the ratio that makes the specific weight of the mixture 1.3. The mixture was packed into desired shape, which is a short cylinder block with a hole in the middle so that a small antenna can be inserted into the middle of the block. The mixture was then left to dry and harden for one week. The prepared bentonite block is shown in Fig. 2.

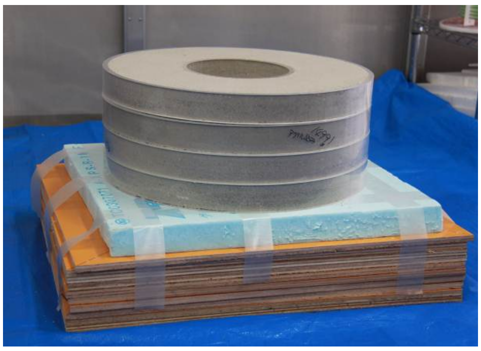


Figure 2. Bentonite block.

III. Antenna Characteristics

Antenna characteristics, of how much power efficiency can be transferred at each transmitting distance and for antenna of each size, was measured by vector network analyzer (VNA) for reference. The setup for characteristics measurement is shown in Fig. 3. S-parameter values, reflected wave ratio named S_{21} and transmitted wave ratio named S_{21}, are read directly from the VNA. Efficiency coefficient η_{11} and η_{21} are then derived by equation (1) and (2).

$$\eta_{11} = |S_{11}|^2 \times 100[\%] \quad (1)$$

$$\eta_{21} = |S_{21}|^2 \times 100[\%] \quad (2)$$

where

η_{11} = power reflection ratio

η_{21} = power transmission ratio.

The results of power transmitting characteristics of each antenna sizes are displayed in Fig. 4.

The maximum efficiency of wireless power transfer using the prepared antenna is approximately 95% for 300mm-diameter antenna and 85% for 150mm-diameter antenna.

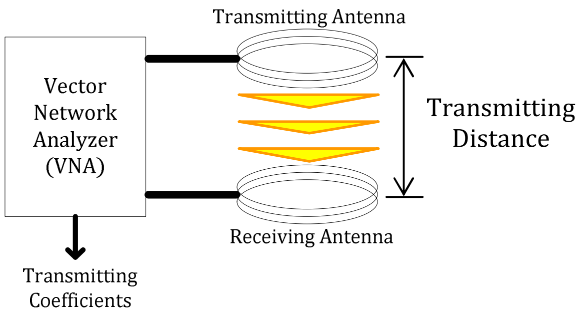
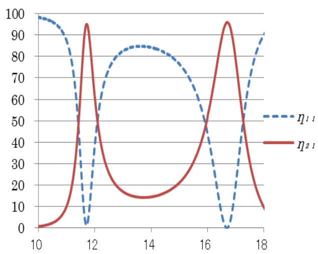
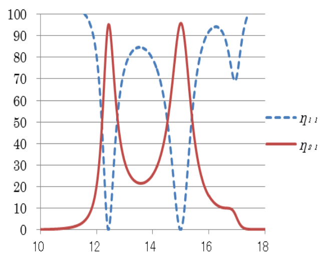


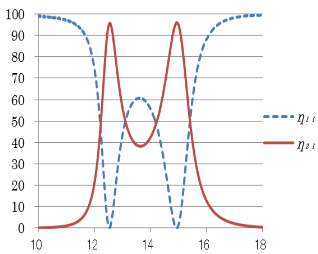
Figure 3. VNA setup.



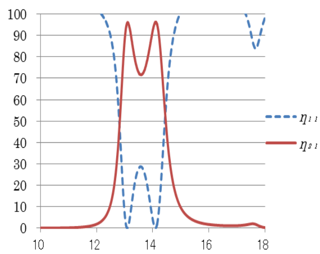
(a) φ300mm antenna, transmitting distance = 50 mm.



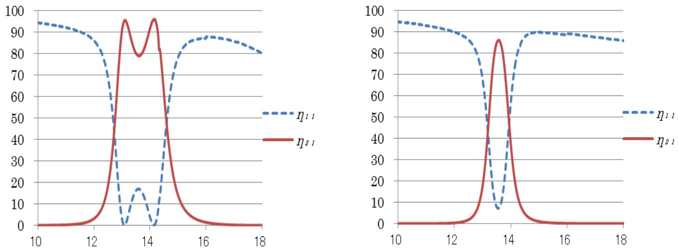
(d) φ150mm antenna, transmitting distance = 50 mm.



(b) φ300mm antenna, transmitting distance = 100 mm.



(e) φ150mm antenna, transmitting distance = 100 mm.



(c) φ300mm antenna, transmitting distance = 150 mm.

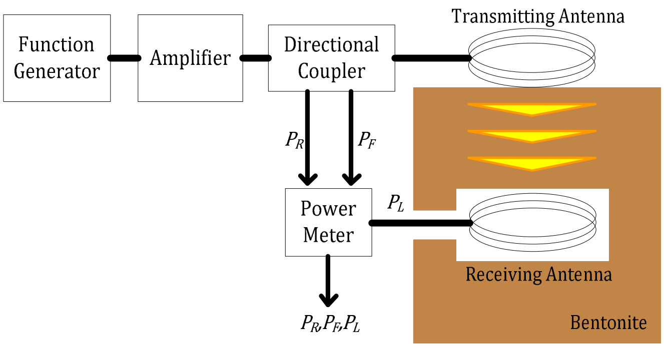
(f) φ150mm antenna, transmitting distance = 150 mm.

Figure 4. Antenna Characteristics.

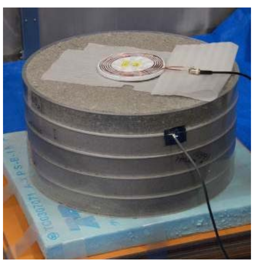
IV. EXPERIMENTAL SETUP

A. *Bentonite without Repeater Antenna*

For experimental setup in the case without repeater antenna, the transmitting antenna is inserted inside the stack of bentonite block and the receiving antenna is placed on the top of bentonite stack. The transmitting antenna is connected to the power amplifier which received input signal from a function generator. The receiving antenna is connected directly to the power meter where power that actually goes into load or load power (P_L) will be read. The directional coupler is inserted between the amplifier and the transmitting antenna and also connected to the power meter. The directional coupler can separate power signal into power that returns to source or reflected power (P_R), and power that has actually been transmitted from the transmitting antenna or forward power (P_F). Therefore the signal that can be read from the power meter with this setup is P_R, P_F and P_L. The experimental configuration is shown in Fig. 5.



(a) Experimental configuration diagram.



(b) Photo of experimental setup with bentonite.

Figure 5. Experimental setup with no repeater antenna.

B. *Bentonite with Repeater Antenna*

The experimental configuration of this case is setup in the same way as the case without repeater antenna, except that one more antenna of diameter of 150 mm is inserted inside the bentonite stack as a repeater antenna. The experiment has been conducted for only at transmitting distance of 150 mm both between transmitting antenna and repeater antenna and between repeater antenna and receiving antenna. The experiment configuration is displayed in Fig. 6.

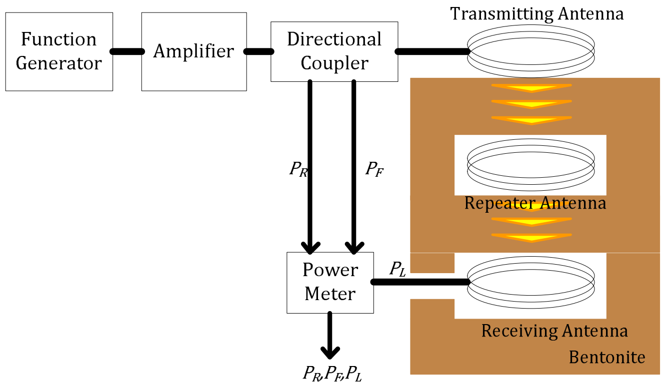


Figure 6. Experimental setup with a repeater antenna.

For the configuration described in both section A and B, the experiment is conducted by, at each transmitting distance, sending input power of different levels (20W, 40W, 60W, 80W and 100W) into the transmitting antenna, measuring the efficiency for each power input level and use the average efficiency as a representing efficiency for the that transmitting distance.

V. EXPERIMENTAL RESULT

In this section, the efficiency measured from the experiment will be presented. As described in the previous section, reflected power (P_R), forwarded power (P_F) and load power (P_L) are measured. The efficiency of power transmission, η_{21} is defined by equation (3)

$$\eta_{21} = \frac{P_F}{P_L} \times 100[\%] \quad (3)$$

Equation (3) is be used to calculate the result efficiency of the experiment with bentonite block based on the values read from the power meter. Note that although the self-resonant frequency of the antenna is 13.56 MHz, for the purpose of examining the maximum possible transmission efficiency, the frequency of interest in this experiment is the point where transmission efficiency is the highest for each transmitting distance. Therefore, referring to Fig. 4, power transfer efficiency at each transmitting distance is measured at the frequency of the peak in each plot.

In this experiment, only the antenna of 150 mm diameter is be used as transmitting antenna and repeater antenna, while antennas of both sizes, 150 mm and 300 mm diameter, are used as receiving antennas.

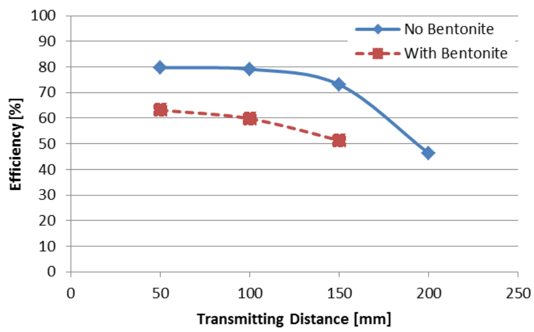
A. Without Repeater Antenna

For the configuration where transmitting antenna is 150 mm in diameter and receiving antenna is 300 mm in diameter or 150mm-300mm configuration, the efficiency after including bentonite block reduced to approximately 74.9% of the efficiency when transmitting power without bentonite. For the 150mm-150mm configuration, where both transmitting and receiving antenna are 150 mm in diameter, the efficiency with bentonite reduced to 70.8% of initial efficiency. The result plots are shown in Fig. 7.

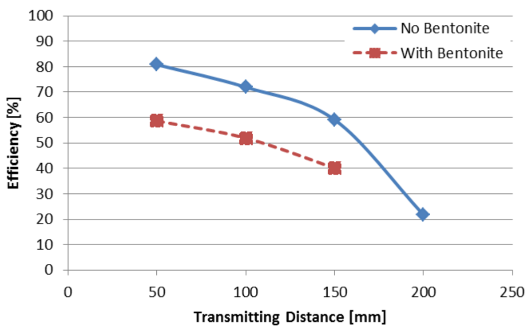
Besides the antenna efficiency, the ratio of power that is actually transferred through the antenna is also examined by investigating the ratio between reflected power and forwarded power, $P_R{:}P_F$. The reflected power increases in both 150mm-300mm and 150mm-150mm configuration, especially at the small transmitting distance. The results are shown in Fig. 8.

B. With Repeater Antenna

For 150mm-150mm-150mm configuration with bentonite, overall efficiency is approximately 51%, and for 150mm-150mm-300mm configuration with bentonite block, overall efficiency is approximately 49%. The decreased efficiency is believed to be caused by 70-75% reduction in efficiency in each stage, according to data from section A of transmission efficiency by two antenna configuration.

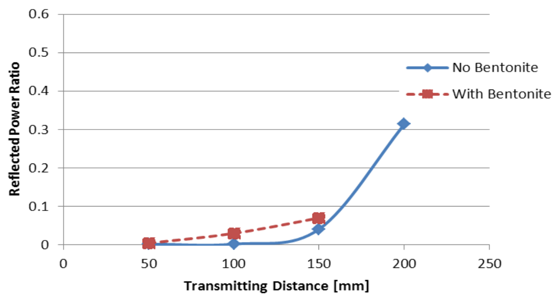


(a) Efficiency of 150mm-300mm configuration.

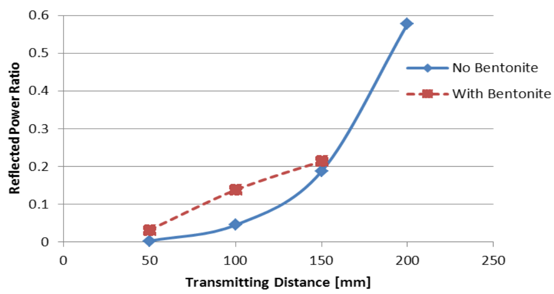


(b) Efficiency of 150mm-150mm configuration.

Figure 7. Efficiency comparison.



(a) $P_R{:}P_F$ for 150mm-300mm configuration



(b) $P_R{:}P_F$ for 150mm-150mm configuration

Figure 8. Ratio between reflected power and forwarded power.

VI. Conclusion

According to this experiment, the effect of bentonite on the efficiency of wireless power transfer is 30% decrease for all the transmitting distance of 50mm to 150 mm. This numerical result is based on the transmission coefficients, η_{21}, calculated from the values read directly from power meter. For further investigation of the cause of the power loss, the electromagnetic analysis will be carried out. However, the permittivity and conductivity value of bentonite clay, which depends on density and frequency, is in the process of measurement and therefore will be include in future research.

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