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OPTIMIZATION OF STIRRER WITH VARIOUS PARAMETERS IN REVERBERATION CHAMBER

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Abstract—Reverberation chambers are widely used in electromagnetic compatibility test facilities because they provide a large working volume and are cheaper than other types of test facilities. In addition, they provide a statistically uniform field and generate a high maximum electric field within a relatively large volume. The volume of the cavity, the structure of the stirrer, and high tested frequency must be used in the reverberation chamber appropriately. Changing a volume of cavity dimensions and test frequency can be difficult in the reverberation chamber because they were determined already in the design process. In these cases, the stirrer should be changed. We investigated of the effects of various stirrer angles and heights on a reverberation chamber. The optimization of the stirrer with respect to various stirrer parameters was investigated; these parameters are related to field uniformity, the quality factor, stirred efficiency, and electric field polarity. Our results suggest that a reverberation chamber can be successfully operated if careful decisions are made regarding the stirrer design.

1. INTRODUCTION

Modern digital and semiconductor technology has made possible the manufacture of high speed, broadband, and lightweight miniaturized electronic devices. However, these devices can malfunction or be destroyed due to high power electromagnetic waves [1–5]. To protect electronic devices from high power electromagnetic waves, a test simulator is needed to test for electromagnetic compatibility (EMC). Anechoic chambers, TEM/GTEM cell, open-area test sites, and electromagnetic pulse simulators are widely used for this purpose. In addition, the reverberation chamber (RC) becomes increasingly

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popular as an EMC test device. An RC provides a statistically uniform field within a relatively large usable working volume, and generates high maximum electric fields from a potentially noisy ambient environment more effectively than the aforementioned simulators, and at a lower cost [6–13].

A statistically uniform electric field is influenced by the quality factor, the number of excited modes, and the stirred efficiency. The maximum electric field within an RC is considered uniform if the standard deviation is within 3 dB above 400 MHz; within 4 dB at 100 MHz decreasing linearly to 3 dB at 400 MHz; and within 4 dB below 100 MHz [6, 14]. If a uniform electric field degree is satisfied with required tolerances, the electric field in the working volume of an RC can be considered uniform.

The theory of the electric field in an RC has been studied by D. A. Hill et al. [15]. The quality factor, which is defined as the stored energy ability in the chamber, has been studied by L. R. Arnaut et al. [16]. The stirred efficiency has been studied by FOI-Swedish Defence Research Agency and K. Madsen et al. [17, 18]. In contrast, electric field characteristics to the stirrer type variety using genetic algorithm had been studied by J. Clegg, but the trend of electric field characteristics investigation is not thoroughgoing enough to the stirrer parameters such as the stirrer angle, height, the number of the stirrers, the number of the stirrer positions, etc. [19]. The purpose of the present work is to investigate stirrer optimization with respect to the uniform electric field property, quality factor, the number of excited modes, and the stirred efficiency analysis.

2. FORMULATION

The quality Factor Q of a RC is defined as the stored energy ability in the chamber. The Q value is expressed as the ratio of input power to received power as follows:

$$Q = \left(\frac{16\pi^2 V}{\eta_{Rx}\eta_{Tx}\lambda^3}\right)\left(\frac{P_{AveRec}}{P_{Input}}\right)_n \tag{1}$$

where, η_{Rx} and η_{Tx} are the antenna efficiency factors for the Receive (R_x) and Transmit (T_x) antennas, respectively, and V is the RC volume; λ is the free space wavelength at the specific frequency; P_{AveRec} is the averaged received power from the reference antenna; P_{Input} is the chamber input power; and n is the number of antenna locations used to collect the calibration data at the frequency being evaluated. The quality factor bandwidth, BW_Q, is a measure of the frequency bandwidth over which the modes in a RC are correlated. BW_Q is defined as $BW_Q = f/Q$.

The Q value is useful because it allows prediction of the field strength from the input power. If the Q value is high, the maximum electric field in the RC becomes high, but the uniform electric field property declines because the number of excited modes decreases. In contrast, if the Q value is low, then the uniform electric field property improves because the number of excited modes increases; however the maximum electric field in the RC decreases. Here, the number of excited modes M within BW_Q, which is based on the Q value, is computed as follows:

$$M = \frac{8\pi V f^3}{c^3 Q} \tag{2}$$

where c is the velocity of light, V is the volume of the RC, and f is the test frequency.

The stirred efficiency, r, is defined as the number of independent samples by IEC 61000-4-21 [14]. In order to apply statistics to data obtained from a RC, the number of independent samples must be known. For a given frequency, a stirrer must alter the boundary conditions sufficiently to effect a statistically significant change in the field pattern of the RC. Once such a change has occurred in the field structure, any samples obtained from the fields resulting from the new stirrer position are said to be statistically independent from those of the previous stirrer position. Stirrer performance data must be obtained in order to determine the number of statistically independent samples a given stirrer can provide at a desired frequency. Stirrer performance data is obtained by monitoring the received power at evenly spaced intervals over one stirrer rotation. The stirrer performance can be estimated by calculating the correlation coefficient between stirrer steps. The stirred efficiency is calculated using the correlation coefficients as shown in Eq. (3):

$$r = \frac{\frac{1}{n}\sum\limits_{i=1}^{n}\left(x_i - u_x\right)\left(y_i - u_y\right)}{\sqrt{\frac{\sum\limits_{i=1}^{n}(x_i-u_x)^2}{n-1}} \cdot \sqrt{\frac{\sum\limits_{i=1}^{n}(y_i-u_y)^2}{n-1}}} \tag{3}$$

where y_i is the same distribution as x_i but shifted by one sample for each stirrer step, and n is the number of samples taken over one stirrer rotation. If the number of independent samples increases, the stirred efficiency is improved.

The field uniformity is specified as a standard deviation σ from the normalized mean value of the normalized maximum values obtained at each of the eight locations during one rotation of the stirrer. σ is calculated using data from each probe axis independently and the total data set. σ of the RC is calculated at the standard deviation of the total maximum electric field data as follows:

$$\sigma = \sqrt{\frac{\sum_{m=1}^{m} \sum_{n=1}^{n} \left(E_{m,n} - E_{m\times n}\right)^2}{(m \times n) - 1}} \tag{4}$$

where m is the total position number of the maximum electric field measurement antenna, n is the total coordinate axis number at any position (if components of the maximum electric field strength measured x, y, and z axis, n is 3), and $E_{m\times n}$ is the average maximum electric field. The standard deviation is expressed in dB relative to the mean using the following equation [11, 12]:

$$\sigma\,(\mathrm{dB}) = 20 \log \left(\frac{\sigma + E_{m\times n}}{E_{m\times n}}\right) \tag{5}$$

3. EXPERIMENT

The RC is a rectangular room with conducting metal walls. The dimensions are 3.6 m in length, 2.4 m in width, and 2.3 m in high as shown in Fig. 1. We used a magnetron as an electromagnetic wave source, and the operating frequency was narrow band at $2,467 \pm 1.5$ MHz. The dimensions of the RC and the test frequency are very important for good design because they determine the lowest usable

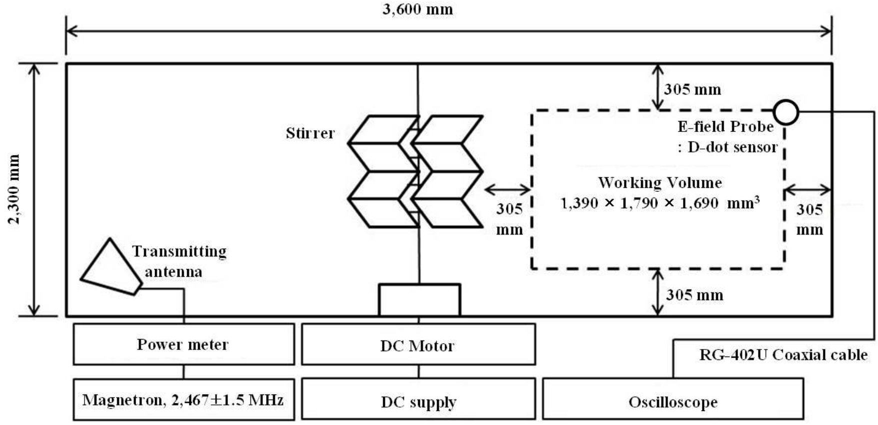

Figure 1. Schematic diagram of the reverberation chamber.

frequency and maximum electric field [6]. The lowest usable frequency in our RC was 246 MHz and the working volume was based on the dimensions of the RC, was 1.39 m in length, 1.79 m in width, and 1.69 m in high.

The stirrer structure was a common rotating vertical type as shown in Fig. 2. It was rotated using a direct current (dc) motor, and the rotating rate was fixed at 30 rpm. The stirrer angles and heights were the stirrer optimization parameters to be varied as shown in Table 1.

To measure the field in the RC, we used an E-field probe (PRODYN, AD-80) to measure the amplitude of the electromagnetic field in three orthogonal directions. The IEC 61000-4-21 standard recommends measuring the electric field at eight positions around the working volume. We measured the field at fifteen positions to improve accuracy as shown in Fig. 3.

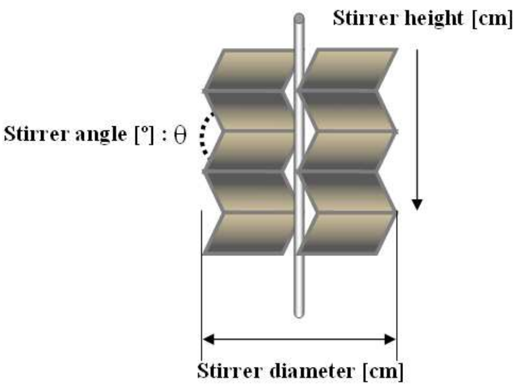

Figure 2. Structure of the stirrer.

Table 1. Various parameters of the stirrers.

Stirrer angle	60°	90°	120°	180°
Stirrer height	20 cm	20 cm	20 cm	20 cm
	40 cm	40 cm	40 cm	40 cm
	60 cm	60 cm	60 cm	60 cm
	80 cm	80 cm	80 cm	80 cm
	100 cm	100 cm	100 cm	100 cm
Stirrer diameter	80 cm	80 cm	80 cm	80 cm

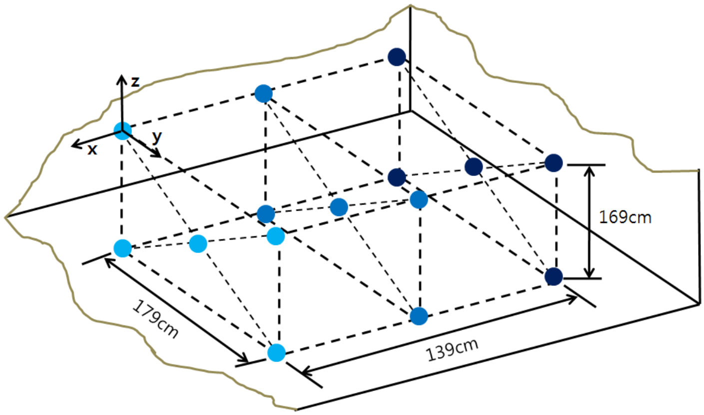

Figure 3. *E*-field probe positions for measuring the electric field.

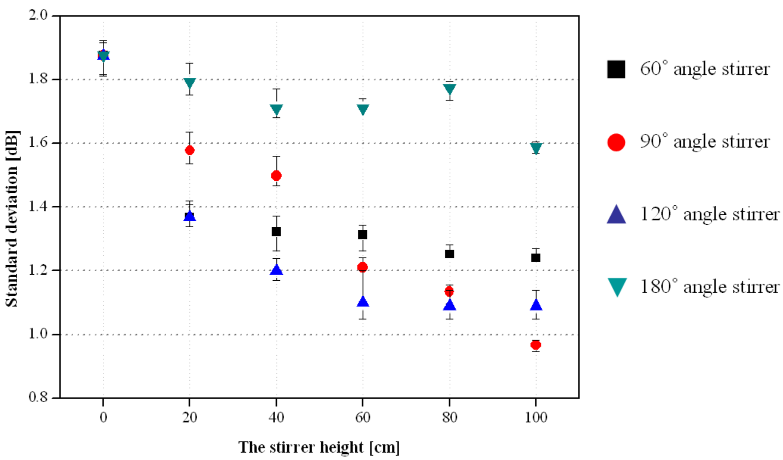

Figure 4. Field uniformity with various stirrer parameters.

4. RESULTS AND DISCUSSIONS

Field uniformity, with various stirrer parameters as shown in Table 1, is shown in Fig. 4. For various angles and increasing stirrer height, field uniformity greatly improved compared to an empty RC (only the E-field probe in the cavity). The improvement rate of normalized field uniformity was the lowest to 180° angle stirrer. In the cases of 20 cm to 80 cm stirrer height, normalized field uniformities of 120° stirrer angle were the lowest. This means that 120° stirrer angle is the best uniformity. In cases of 20 cm and 40 cm stirrer height, 60° stirrer angle was slightly good uniformity than 90° stirrer angle. However, for increasing the stirrer heights 60 cm and 80 cm, 90° stirrer angle was slightly good uniformity than 60° stirrer angle. Furthermore, 90° stirrer angle, in the case of 100 cm stirrer height, was the best uniformity. At this condition, the standard deviation value was less than 1 dB. Field uniformity was influenced by the stirrer height and angle. From field uniformity result, the conditions of the stirrer optimization parameters were investigated that the stirrer height was 100 cm and the stirrer angle was 90°.

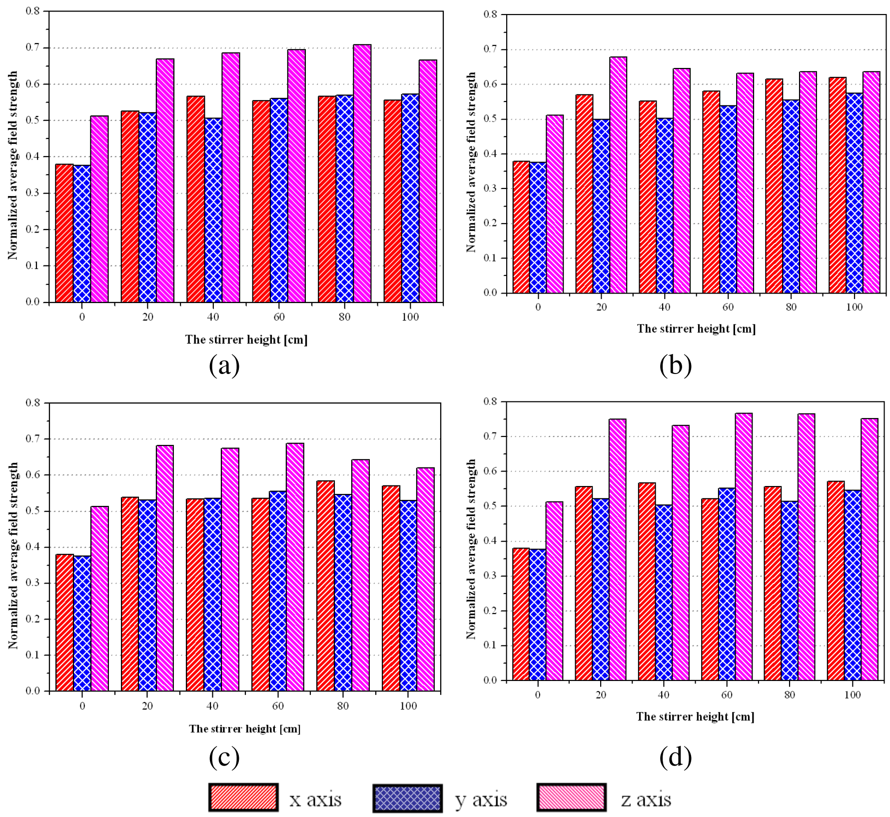

Figure 5. The x, y, and z axis average electric field with various stirrer parameters. (a) The x, y, and z axis average electric field with various stirrer heights in 60° angle stirrer. (b) The x, y, and z axis average electric field with various stirrer heights in 90° angle stirrer. (c) The x, y, and z axis average electric field with various stirrer heights in 120° angle stirrer. (d) The x, y, and z axis average electric field with various stirrer heights in 180° angle stirrer.

Figure 5 shows the x, y, and z axis average electric field which was calculated to normalize the measured maximum electric field. In case of a 180° angle stirrer and empty RC as shown in Fig. 5(d), the z axis average electric field showed a remarkable difference of about 22% compared with the x and y axis average electric field. This effect was maintained even if the stirrer heights were longer. In the case of 60°, 90°, and 120° angle stirrers shown in Figs. 5(a) to (c), the gap of x, y, and z axis average electric fields was on the decrease with increasing stirrer height. However, in the case of 90° angle stirrer, the gap of x, y, and z axis average electric fields was closer than other angle stirrers. In other words, the average electric field polarity characteristic of each axis was a relaxation. Furthermore, the average electric field in the RC with a stirrer increased compared to an empty RC.

This result shows that the RC is a useful simulator for an EMC test. Many electronic systems are located within metal enclosures with apertures, slots, and lines to the interior enclosure [1, 20]. Coupled voltage and current can cause a malfunction or destruction of an electronic system. For such cases, the analysis of electromagnetic waves is necessary, and an RC can be a useful substitution for an EMC test simulator facility [21, 22].

The quality factor decreased with increasing stirrer height; therefore, the number of excited modes increased as shown in Figs. 6 and 7. The ability of an RC to store energy is determined by the losses present in the RC. The dominant losses in an empty RC are the RC walls [14]. However, the dominant losses in an RC with a stirrer increased in the RC wall, the stirrers, the gear box with motor for revolving the stirrer, the supporting structure for the stirrer, etc.

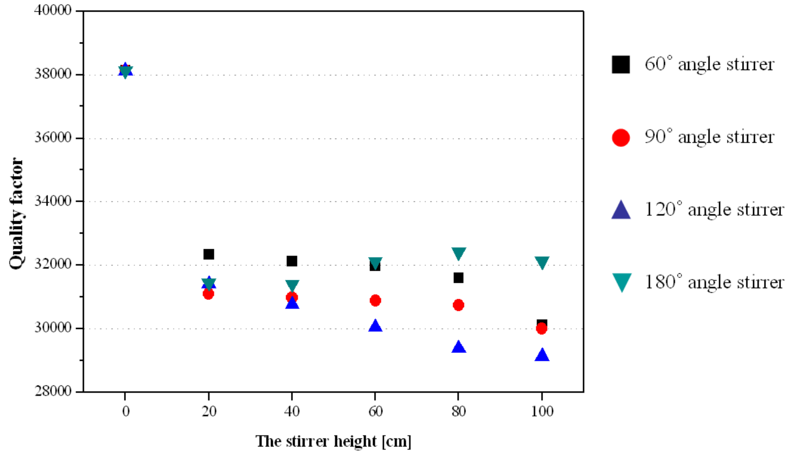

Figure 6. Quality factor with various parameters stirrer.

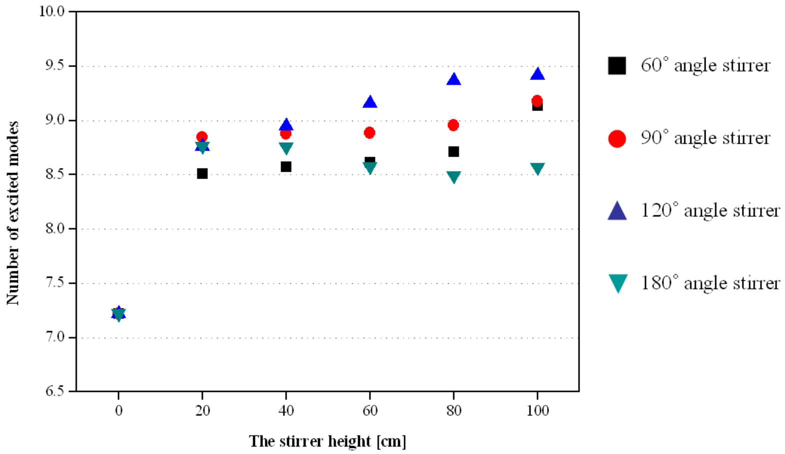

Figure 7. The number of excited modes with various parameters stirrer.

Thus, the quality factor was on the decrease with increasing stirrer height because losses in an RC increased in the stirrers. The number of excited modes is influenced the quality factor as well as the tested frequency, as described by Eq. (2). The frequency can influence to the number and density of the modes increases. The frequency is increased the number and density of the modes increases. This means that high frequency is a useful way to generate electric field uniformity.

The stirred efficiency was defined as the number of independent samples. Fig. 8 shows the number variation of independent samples for various stirrer parameters. The number of independent samples was on the increase with increasing stirrer height and angle stirrer. In particular, 180° angle stirrer created number of independent samples mostly. Nevertheless, the field uniformity was the lowest compared to other angle stirrers because the number of excited modes was generated fewest as shown in Fig. 7. As a result, the number of excited modes is a more important parameter to the improvement of field uniformity than the stirred efficiency.

Field uniformity in an RC depends on the volume of the RC, the tested frequency, the stirrer position, and the stirrer design. Generally, the RC and the stirrer are constructed from electrically-conductive material which alters the electromagnetic boundary conditions. If the electromagnetic boundary conditions are altered, the height and the number of stirrers change. However, increasing the stirrer height is a difficult matter because of the limited volume of the RC. In additions, increasing the number of stirrers is different problems because the electromagnetic field density is decreased by loss increasing. Thus, we must improve field uniformity within the limited volume of the RC. We set up two different types of stirrers that add to reflectors at right angles, as shown in Fig. 9. Additional reflectors were designed the 0.5λ and 1λ high metal plates on 90° angle stirrer of equal width and material respectively. λ is the free space wavelength of the test frequency.

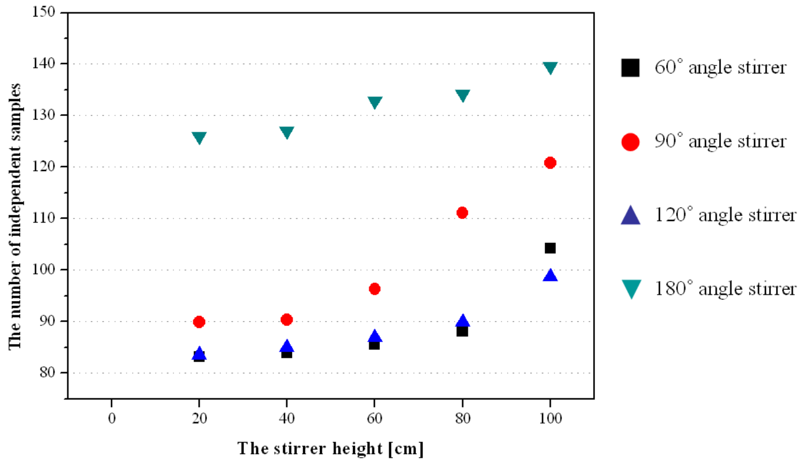

Figure 8. The stirred efficiency with various stirrer parameters.

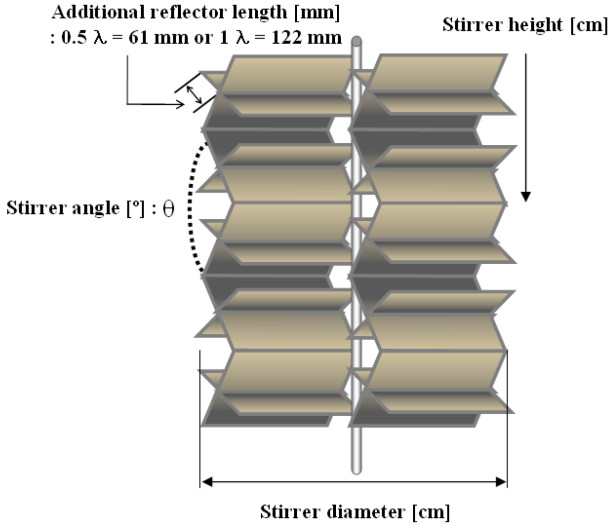

Figure 9. Structure of the stirrer with additional reflectors.

Figures 10 to 13 show the field uniformity, quality factor, the number of excited modes, and the stirred efficiency, respectively, with various parameters between a 90° angle stirrer and 90° angle stirrers with additional reflectors. The quality factor decreased slightly in the 90° angle stirrers with the additional reflectors because the dimensions of the stirrers were increased. The number of excited modes and the stirred efficiency increased slightly in the 90° angle stirrers with additional reflectors. These effects were obviously investigated 90° angle stirrers with the addition of 1λ high metal plate reflectors than 90° angle stirrers with 0.5λ additional reflectors. Theses results showed that field uniformity was slightly improved using 90° angle stirrers with the addition of 1λ high metal plate reflectors.

The x, y, and z axis average electric fields with various parameters between two different types of 90° angle stirrers with additional reflectors are shown in Fig. 14. The gap of x, y, and z axis average electric fields was on the decrease 90° angle stirrers with 1λ height metal plate additional reflectors than 0.5λ additional reflectors. In addition, the average electric field polarity characteristic of each axis, in the case of 90° angle stirrers with 1λ height metal plate additional reflectors, was a relaxation compared to 90° angle stirrers as shown in Fig. 5.

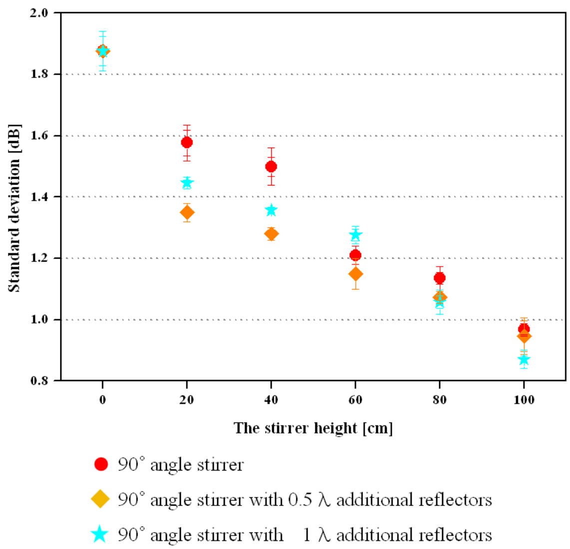

Figure 10. Field uniformity with various parameters between 90° angle stirrer and 90° angle stirrers with additional reflectors.

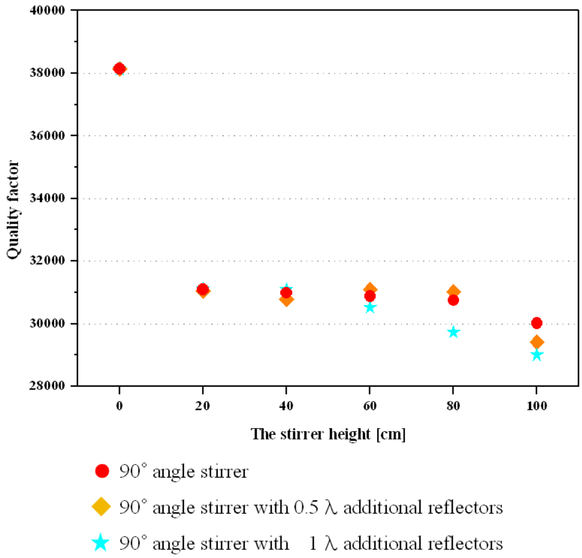

Figure 11. Quality factor with various parameters between 90° angle stirrer and 90° angle stirrers with additional reflectors.

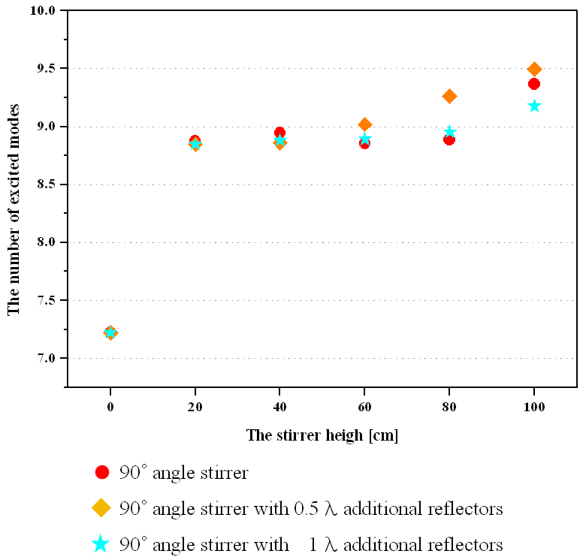

Figure 12. Number of excited modes with various parameters between 90° angle stirrer and 90° angle stirrers with additional reflectors.

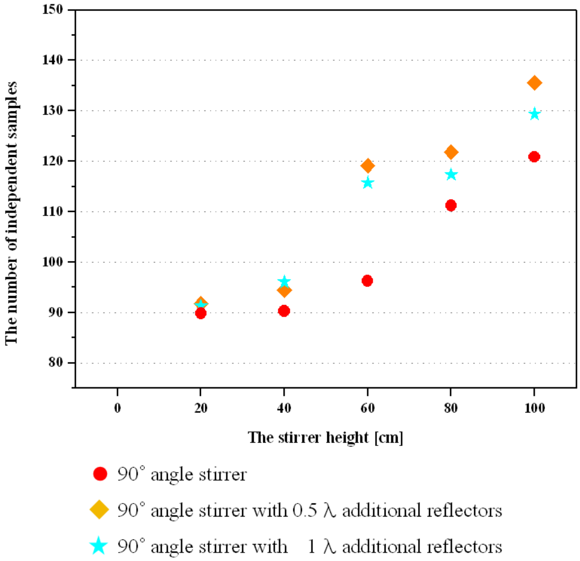

Figure 13. Stirred efficiency with various parameters between 90° angle stirrer and 90° angle stirrers with additional reflectors.

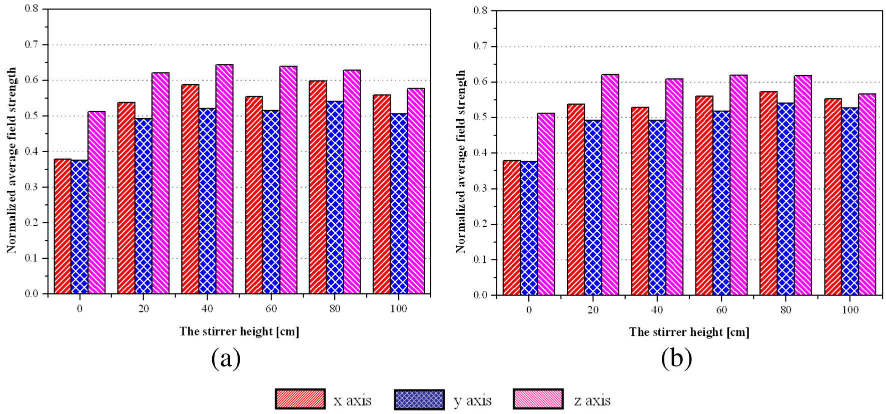

Figure 14. x, y, and z axis average electric field with various parameters for 90° angle stirrers with metal plate additional reflectors with heights of 0.5λ and 1λ. (a) The x, y, and z axis average electric fields with various stirrer heights for 90° angle stirrer with additional reflectors (metal plate of height 0.5λ). (b) The x, y, and z axis average electric fields with various stirrer heights for 90° angle stirrer with additional reflectors (metal plate of height 1λ).

5. CONCLUSION

We investigated reverberation chamber stirrer optimization with respect to parameters including the angle and the height of the stirrers. The field uniformity, quality factor, number of excited modes, and stirred efficiency were analyzed with respect to stirrer optimization. Stirrer optimization conditions were investigated for a stirrer angle of 90°, and stirrer height of the stirrer was greater than 80 cm. It is impractical to change the limited volume of the reverberation chamber, so that two different types of stirrers were designed. We set up two different types of stirrers that add to reflectors at right angles. Additional reflectors were designed the 0.5λ and 1λ high metal plates on 90° angle stirrer respectively. In this paper, the conditions of stirrer optimization parameters were investigated that the angle of stirrer was 90° and the height of stirrer was above 80 cm with 1λ height metal plate additional reflectors at the right angles. The IEC 61000-4-21 standard recommends that the evaluation items for the design of a reverberation chamber are the field uniformity, quality factor, number of excited modes, and stirred efficiency factors. Furthermore, the information about the polarity characteristic of each axis average electric field is substantially included in the standard deviation for individual field components as well. If the normalized field uniformity is within 3 dB, the RC can be considered uniform though a deviation of each axis average electric field is wide variations. In this study, the polarity characteristic of each axis average electric field was considered with the field uniformity for the stirrer design. Our results suggest that a reverberation chamber can be successfully operated if careful decisions are made regarding the stirrer design.

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