Surface potential uniformity and sensitivity of large-area PTFE electret discs of different thicknesses produced by a modified corona poling rotating system for dosimetry applications

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In this study, large-area (6-cm diameter) Teflon polytetrafluoroethylene (PTFE) discs of different thicknesses (0.2-, 0.5- and 1-mm) were negatively and positively charged by using the “modified single point-to-plane corona poling rotating system”. The effects of some crucial parameters of the PTFE disc as well as the modified corona poling rotating system on the PTFE surface potential uniformity such as: (a) PTFE disc thickness, (b) PTFE disc polarity and (c) needle-to-PTFE disc distance were successfully reported. Accordingly, closer needle-to-PTFE disc distance, positive charging mode and thinner PTFE disc provided a better PTFE surface potential uniformity. However, the effects of PTFE charge polarity and needle distance on the electrostatic charge potential uniformity were much more remarkable in comparison with the effects of PTFE thickness. Additionally, the surface potential distribution profiles of charged PTFE discs were totally flat and independent of the PTFE thickness at 5- and 15-mm needle distances for the negative and positive charging modes, respectively. At the optimized charging conditions, large-area PTFE electret disc (0.5-mm-thick) with positive uniform surface charge potential especially at the edges up to ~ 1.8 kV with stability up to 77 days studied was produced by applying a new multiple heat treatment protocol to the PTFE disc for radon dosimetry. As also observed in this study, the sensitivity of PTFE electret dosimeters to a defined radon gas concentration increases as the PTFE thickness increases. Meanwhile, 0.5-mm-thick PTFE electret disc produced was selected to be used as a high quality electret dosimeter with acceptable and superior parameters for different applications in particular medium-term radiation dosimetry in both low and high dose rate ionizing radiation fields.

Keywords: PTFE electrets; dielectric polarization; surface charge uniformity and stability; electrostatic discharges and measurements; dosimetry.

1. Introduction

In general, electret transducers (hereafter called electret) are made up of different dielectric materials regarding their applications such as PVDF for energy harvesting, polypropylene for air cleaning, parylene HT thin-film polymer for electret power generator and polytetrafluoroethylene (PTFE) for electret microphone and radiation protection dosimetry especially radon detection. The term electret was coined by Heaviside and also the first version of electret material was produced by Eguchi. Teflon PTFE (hereafter used as PTFE) electret is a kind of dielectric material which is electrostatically charged by using some particular methods to uniformly deposit charges and form a quasi-permanent external polarization on the surface of the PTFE disc.

PTFE electret dosimetry is known as a widespread and passive method for detection of ionizing radiations such as alpha, photon, beta and neutron in particular for some radioactive gases like radon. Electret dosimeters consist of a positively or negatively charged PTFE electret disc placed in an air filled conductive ionization chamber for “radon, neutron and alpha” or “photon and beta” dosimetry, respectively. The electret disc has two main roles and acts as a sensor as well as a source of electrostatic field inside the chamber. It is noteworthy that some amount of radon concentration naturally exists in residential houses. For radon detection, electret dosimeter is placed at the special part of a house for a certain period of time. Radon gas flows inside the ionization chamber and ionizes the air volume of the chamber. Accordingly, the electrostatic field of the positively charged electret disc guides the negative ions or electrons toward the electret surface resulting in surface charge potential reduction proportional to the absorbed dose from radon and progeny contained in the air ionization chamber.

High surface charge potential uniformity and stability have been introduced as the most important characteristics of the electret for different applications especially radiation dosimetry. Fluoropolymers such as PTFE films are the most common organic materials for electret dosimeter production on the basis of their high electronegativity,
low dielectric constant, deep charge carrier trap sites and excellent charge storage stability properties.5,8,9,12 According to the Gross theory, there are two different kinds of dielectric polarization named internal and external polarizations which are related to the polarization of the bulk and surface of dielectric materials, respectively. Meanwhile, Maxwell–Wagner, dipolar orientation, ionic and space-charge polarizations have been known as the internal polarizations. However, charge injection from external sources such as corona discharges into the PTFE surface is a prime example of external polarization.4,13

In the following years, several electret production methods have been developed such as liquid contact,14 electron beam,15 tribo- and corona-charging methods11,16,17 for external polarization and thermo-, photo- and radio-electret formation methods for internal polarization.18 Corona charging systems belong to the most common methods due to their simplicity, self-sufficiency, high speed of charging and availability in any developing laboratories.4,19 Corona discharge is a kind of cold plasma with a low current of ions which is usually produced by using a defined shape of metal electrodes such as needle or wire connected to a negative or positive DC high voltage generator for negative or positive corona charging, respectively. A PTFE disc located at the bottom of the metal needle at a defined distance on an electrode disc is electrically grounded.17

Several types of corona charging methods have been developed for production of electret materials such as “single point-to-plane”,20 “corona triode”,17 “multiple-needle corona poling”18 and “modified single point-to-plane corona poling rotating system” (hereafter called modified corona rotating system).4,5 The modified corona rotating system has been recently invented, constructed and put into operation successfully by us as a highly developed method for production of large-area PTFE electret discs based on a simple manner with some superior characteristics such as excellent surface charge potential uniformity and stability at the electret edges particularly.4,12 In our previous study, this new modified corona rotating system was introduced in addition to production of negative and positive large-area (6- and 14-cm diameters) uniformly charged PTFE electret discs with 0.2-mm thickness (treated based on the pre- and post-charge annealing heat treatment) for different applications especially radiation dosimetry.4 In another study, the effects of PTFE charge polarity and thickness on the surface potential stability of large-area (6-cm diameter) PTFE discs produced at equal charging conditions by using our new modified corona rotating system followed by applying a post-charge annealing heat treatment were reported.5 Accordingly, negatively charged PTFE discs with 0.2-, 0.5- and 1-mm thicknesses were selected to be applicable for a different application especially electret radiation dosimetry while in positive charging mode just 1-mm-thick charged PTFE disc was acceptable for the same applications.5 It should be noted that large-area positively charged PTFE electret discs with 0.2-, 0.5- and 1-mm thicknesses can be applicable for long-, medium- and short-term dosimetry, respectively, in particular for radon monitoring.5,12,21

Among different parameters affecting the surface charge uniformity, lifetime and sensitivity in response of PTFE electret dosimeters, the PTFE disc polarity, PTFE thickness and charging conditions have been considered as the main characteristics.13 Meanwhile, the effects of some important parameters of PTFE disc as well as the modified corona rotating system for instance PTFE thickness, PTFE disc polarity and needle-to-PTFE disc distance on the surface potential uniformity and sensitivity in responses of electret dosimeter are not defined clearly yet. On the other hand, introduction of an efficient charging protocol for production of 0.5-mm-thick positively charged PTFE electret disc by using the modified corona rotating system has been known as the next step of our research as well. Formation of 0.5-mm-thick positive large-area PTFE electret disc with high surface charge potential uniformity and stability especially at the edges is highly desirable to improve the performance of large-area PTFE electret dosimeters to cover and measure all dose ranges from low up to medium and high levels.21 Therefore, absence of such research as well as large-area positively charged PTFE electret discs with 0.5-mm thickness inspired us to conduct this study to fulfill all the described requirements. That is why the purpose of this paper is clearly defined as follows:

1. The effects of PTFE disc thickness (0.2-, 0.5- and 1-mm), PTFE surface potential polarity and needle-to-PTFE disc distance on the PTFE disc surface potential uniformity in particular at the edges.
2. Production of positive large-area PTFE electret disc (0.5-mm thickness, 6-cm diameter) with excellent surface potential uniformity and stability especially at the edges by using the modified corona rotating system based on a new multiple heat treatment charging protocol for medium-term radiation dosimetry applications.
3. The effects of PTFE thickness (0.2-, 0.5- and 1-mm) on the sensitivity of large-area positively charged PTFE electret discs to a defined concentration of radon gas.

2. Material and Methods

PTFE® sheets (Teflon PTFE, DuPont Co.) are used for production of large-area (6-cm diameter) electret discs with 0.2-, 0.5- and 1-mm thicknesses.4,5,9,12,22 One side of each PTFE disc is covered with a 1-mm-thick aluminum disc as applied in other related dosimetry studies.4,5,23–25 The surface of the PTFE discs was carefully cleaned by acetone and monitored with an optical microscope to detect dust, other external residues and surface defects which all can result in a probable charge de-trapping.4,24

All PTFE discs were charged by using the modified corona rotating system (Fig. 1).4,5 This new modified system was well described before for PTFE electret disc charging of
different thicknesses and sizes with high surface potential stability and uniformity especially at the edges for different practical applications in particular radiation dosimetry.\textsuperscript{4,5} The modified corona rotating system in brief consists of a moveable nickel-plated steel corona needle (hereafter called a needle) located on top of a heatable rotational disc electrode at a specified distance as connected to a direct current high voltage (0–5 kV) with a stable output. The rotational disc electrode is electrically grounded and also acts as a corona ion collector which rotates around the self-center at \( \sim 360 \) rotations per minute. The needle also acts as an ionizing element and automatically scans and exposes a constant current of corona ions to a defined diameter of the PTFE disc which is attached concentric to the heatable (up to 500°C) rotational disc electrode for a period of time (Fig. 1).\textsuperscript{4,5} The surface temperature of the PTFE disc was accurately measured by a commercial noncontact infrared thermometer (Hioki FT3700) with \( \pm 0.1^\circ \text{C} \) resolution. The needle movement is controlled using a digital counter device to be fixed at a specified and constant speed (\( \sim 5.5 \times 10^{-3} \) m s\(^{-1}\)).\textsuperscript{5}

As shown in Fig. 2, to measure the electret surface charge potential based on a nondisruptive method, an electrostatic probe (TREK, model 3450) placed at 3-mm distance above the PTFE disc is connected to a Keithley electrometer (model 6514) via a noncontacting electrostatic voltmeter (TREK, model 341).\textsuperscript{4,26–33} Accordingly, surface charge potential distribution profiles of PTFE discs were obtained by monitoring 25 positions, 2.5 mm apart from each other, along a defined diameter of the PTFE disc immediately after PTFE charging to avoid post-charging decays.

Homo charge stability of the charged PTFE discs was evaluated according to the different standard methods such as long-term surface potential monitoring, thermally stimulated discharge (TSD) and isothermal surface potential decay (ISPD).\textsuperscript{5,11,13,23} According to open circuit conditions, each charged PTFE disc was stored in a closed dark aluminum metal box for a 77 days period for long-term surface potential monitoring.\textsuperscript{19,20,34} The laboratory environment was kept stable at around 26 \( \pm 1^\circ \text{C} \) temperature and 29 \( \pm 1\% \) relative humidity during charge potential measurements and storing of the PTFE electret discs.

3. Results

The effects of PTFE disc thickness, PTFE surface charge polarity and needle-to-PTFE disc distance on the PTFE disc surface charge potential uniformity especially at the edges are given below. For the first time, large-area positively charged PTFE electret discs (0.5-mm thickness) with high surface potential stability and uniformity especially at the edges were produced by the modified corona rotating system based on a new multiple heat treatment protocol for different applications in particular medium-term radon monitoring. Furthermore, the effects of PTFE thickness (0.2, 0.5 and 1 mm) on the sensitivity of large-area uniformly charged positive PTFE electret discs to a defined concentration of radon gas were studied in detail.
3.1. Effects of PTFE thickness, charge polarity and needle-to-PTFE disc distance

Of all the crucial parameters, surface charge potential uniformity especially at the edges is the most important characteristic of large-area PTFE electret discs required for the related applications especially ionizing radiation dosimetry.\(^5,33\) In order to study the effects of the PTFE thickness, charge polarity and needle-to-PTFE disc distance on the PTFE surface potential uniformity, different thicknesses (0.2-, 0.5- and 1-mm) of large-area PTFE discs were negatively and positively charged by using the modified corona rotating system. The charging temperature, needle bias voltages and its scanning duration were selected to be \(\sim 220^\circ\text{C}, \pm 4\) kV (for negative or positive charging) and 4 min, respectively.\(^5,24,26,27\) The needle-to-PTFE disc distances were 13, 21 or 29 mm for positive and 5, 13 or 21 mm for negative corona charging modes, as are usually applied by us in our previous studies.\(^4\) Immediately after charging each PTFE disc, it was rapidly cooled down to \(\sim 16^\circ\text{C}\) using a Peltier cooling device to avoid any probable PTFE surface potential decay due to TSD phenomenon.\(^4,24,27,28\)

It is noteworthy that all electret dosimeters have a defined work limitation and therefore electret with voltages less and more than 100 V and 2.5 kV, respectively, are not allowed to be used in radiation dosimetry due to this matter that more and less electret voltages than the mentioned range bring about a nonlinearity in the electret dosimeter responses which is not applicable for radiation dosimetry.\(^4,5,12\) Based on our previous studies, 4 kV has to be selected as the optimized corona needle voltage and by applying voltages more than 4 kV to corona needle the electret voltage exceed the allowed maximum electret potential (2.5 kV) and such an electret is not applicable to be used for radiation dosimetry purposes.

Figures 3(a)–3(c) illustrate the surface charge potential uniformity profiles of the negatively charged PTFE discs with 0.2-, 0.5- and 1-mm thicknesses, respectively, as a function of distance of the measuring probe from the disc center for three different needle distances (5, 13 or 21 mm).

Different positively charged PTFE discs were also produced based on the similar charging conditions as stated above. Figures 4(a)–4(c) show the surface charge potential uniformity responses of the positively charged PTFE discs with 0.2-, 0.5- and 1-mm thicknesses, respectively, as a function of distance of the measuring probe from the disc center for three different needle distances (13, 21 or 29 mm).

In general, surface charge uniformity profiles of the charged PTFE discs in all 0.2-, 0.5- and 1-mm PTFE thicknesses are almost symmetrical with respect to the center of the disc and having highly flat responses at 5- and 13-mm distances for negative and positive corona charging, respectively (Figs. 3 and 4). Such observations are in good agreement with other studies.\(^4,5\) However, for other distances (13 or 21 mm for negative and 21 or 29 mm for positive charging), the responses are partially flat in the middle and non-uniform near the edges (Figs. 3 and 4).
To be precise, the percentages of surface potential non-uniformity of negatively (Fig. 3) and positively (Fig. 4) charged PTFE discs with 0.2-, 0.5- and 1-mm thicknesses for different needle distances (13, 21 or 29 mm for positive and 5, 13 or 21 mm for negative corona charging) are reported in Table 1.

According to Table 1, Figs. 3 and 4, the percentage of PTFE surface potential nonuniformity at a defined charging mode and needle distance depends on the PTFE disc thickness which decreases as the PTFE thickness decreases. Moreover, the surface potential nonuniformity of the charged PTFE discs at a specified PTFE thickness and charging mode is highly dependent on the needle-to-PTFE-disc distance which decreases as the needle distance decreases (Table 1). By making a comparison in Table 1, it can be concluded that the PTFE surface potential uniformity is much more dependent on the needle-to-PTFE disc distance than the PTFE disc thickness. From Table 1, Figs. 3 and 4, it can also be observed that the surface charge potential uniformity is independent of the PTFE thickness at 5- and 13-needle-to-PTFE-disc distances for negative and positive charging modes, respectively. Therefore, 5- and 13-mm distances of the needle were selected as optimum values for charging PTFE discs of different thicknesses at this stage of development.

As can be seen in Figs. 3, 4 and also Table 1, the surface charge distribution responses at a specified PTFE disc thickness and needle-to-PTFE disc distance are highly dependent on the charge polarity. In this case, the surface charge potential distribution for positive charging mode having more uniformity than negative corona charging mode (Figs. 3, 4 and Table 1). Such observation can be explained on the basis

Table 1. Percentage of surface potential nonuniformity of negatively and positively charged PTFE discs with 0.2-, 0.5- and 1-mm thicknesses for different needle distances as stated above.

| Charging mode | PTFE thickness (mm) | Needle-to-PTFE disc distance (mm) | Charge potential nonuniformity (~%) |
|---------------|---------------------|----------------------------------|----------------------------------|
| Negative      |                     |                                  |                                  |
| charging      | 0.2                 | 5                                | 0                                |
|               |                     | 13                               | 15                               |
|               |                     | 21                               | 33                               |
|               | 0.5                 | 5                                | 0                                |
|               |                     | 13                               | 16                               |
|               |                     | 21                               | 34                               |
|               | 1                   | 5                                | 0                                |
|               |                     | 13                               | 18                               |
|               |                     | 21                               | 36                               |
| Positive      | 0.2                 | 13                               | 0                                |
| charging      |                     | 21                               | 9                                |
|               | 0.5                 | 13                               | 0                                |
|               |                     | 21                               | 10                               |
|               |                     | 29                               | 24                               |
|               | 1                   | 13                               | 0                                |
|               |                     | 21                               | 11.4                             |
|               |                     | 29                               | 26                               |
of the physical nature of corona discharge. That is to say that the positive corona beam provides more uniform ion flux distribution on the PTFE disc surface than the negative polarity of corona discharge. Accordingly, positive charging mode was selected to be used as an optimized charging polarity for the production of large-area uniformly charged PTFE electret disc with 0.5-mm thickness for medium-term radiation dosimetry especially radon monitoring. Moreover, it should be noted that the positive polarity of PTFE electret disc is just applicable to be used in radon detection based on the universal radiation protection dosimetry theory.\(^5,12\)

3.2. Production of large-area positively charged PTFE electret disc based on a multiple heat treatment protocol

Surface homo charge stability of the charged PTFE disc over an extended period of time is known as another crucial parameter of electrets for different applications in particular radiation dosimetry.\(^5,12,32\) However, depending on the PTFE disc thickness and its mechanical stability, several PTFE treatment protocols as a part of corona charging conditions have been proposed to increase deep charge trap sites in PTFE disc and improve surface charge potential stability. These treatment protocols include post-charge annealing heat treatment, multiple heat treatment and pre- and post-charge annealing heat treatment for thick PTFE discs in the range of few millimeters.\(^4,5,25,34-37\) Other methods such as plasma and chemical treatments are applicable for thin PTFE films in the micrometer thickness range.\(^32,38\) In radiation dosimetry, thick PTFE electret discs (e.g., millimeter) are commonly used due to their better good mechanical stability during charging, handling and also their electrostatic potential measurement.\(^4,23,24\) According to our previous studies, production of a large-area positively charged PTFE electret disc (0.5-mm thickness, 6-cm diameter) by using the modified corona rotating system was unsuccessful (i.e., 41.9\% decay of charge over 77 days) based on the pre- or post-charge annealing heat treatment energy and deep trap sites.\(^39,40\) Therefore, in this study, a multiple heat treatment protocol was selected to be used for dramatic improvement of surface potential stability of 0.5-mm-thick PTFE discs for radiation dosimetry applications. Positive large-area PTFE electret discs with 0.5-mm thickness is highly desirable for different practical applications especially radiation dosimetry.\(^39,40\) Therefore, in this study, a multiple heat treatment protocol was selected to be used for dramatic improvement of surface potential stability of 0.5-mm-thick PTFE discs for radiation dosimetry applications. Positive large-area PTFE electret discs with 0.5-mm thickness is highly desirable for different practical applications especially medium-term radiation dosimetry in particular radon monitoring.\(^5,12\)

In order to apply this multiple heat treatment protocol, large-area (6-cm diameter) PTFE discs with 0.5-mm thickness were positively charged under a same condition as explained above.\(^5,26-28\) According to Fig. 4(b), the needle-to-PTFE disc distance was optimized to be 13 mm to uniformly deposit positive corona ions on the PTFE disc surface with an almost flat profile especially at the edges. In this study, the multiple heat treatment protocol includes different steps such as multiple charging of PTFE disc, post-charge annealing heat treatment (160°C for 150 min)\(^5,25,34,35\) and isothermal charge decay (180°C for 2.5 h)\(^7,41\) which are needed to be applied for several times to the positively charged PTFE discs. In fact, heat treatment and charging can be repeated again and again to de-trap charges with low activation energy, so that, finally, an extremely stable positively charged PTFE electret disc is obtained.\(^37\) Therefore, three samples of the PTFE discs were treated and positively charged up to ~1.8 kV as follows:

(1) Sample 1 was positively charged under described corona charging conditions followed by a post-charge annealing heat treatment.
(2) Sample 2 was charged and treated similar to sample 1 followed by applying an isothermal charge decay, the second charging round and a post-charge annealing heat treatment to the charged PTFE disc, respectively.
(3) Sample 3 was charged and treated at the same procedure as applied to the sample 2 followed by applying an isothermal charge decay, the third charging round and a post-charge annealing heat treatment, respectively.

3.2.1. PTFE surface charge potential stability

After producing all three samples as stated above, the homo charge stability of samples was investigated by means of TSD, ISPD and long-term surface potential monitoring experiments.\(^5,11,13,23\)

Accordingly, all three samples were subjected to the TSD experiment. Figure 5 illustrates the normalized surface potential of the positively charged PTFE samples 1, 2 and 3 produced by using the modified corona rotating system as a function of the PTFE temperature monitored up to 300°C every other 10°C promptly after applying the multiple heat treatment protocol to the samples as stated above. The temperature of the PTFE discs was increased linearly with a heating rate of 5°C·min\(^{-1}\) from room temperature up to 300°C. As seen from Fig. 5, the \(T_{1/2}\), which is the temperature where the surface potential decays to half of its initial value, was increased from 240°C \((T_{1/2} \text{ of sample 1})\) to 260°C and 300°C for samples 2 and 3, respectively. Accordingly, it is obvious that the multiple heat treatment protocol indeed improved the surface charge potential stability of samples 2 and 3 by increasing the charges with high activation energy and deep trap sites.

As can be concluded from Fig. 5, the surface charge potential of samples begins to fall at around 180°C. Therefore, the temperature of 180°C was chosen for ISPD test in order to accelerate the charge decay for assessing the surface potential stability of produced samples at a short-time. As an ISPD test, Fig. 6 shows the normalized surface potential of the positively charged PTFE samples 1, 2 and 3 produced by using the modified corona rotating system as a function of the storage duration at 180°C monitored up to 2.5 h after the
multiple heat treatment protocol applied to the samples as stated above. Figure 6 clearly demonstrates that the treated samples can still retain 58% and 78% of their initial surface potential for samples 2 and 3, respectively, after 2.5 h at such a high temperature, at which the charges on sample 1 are reduced to 43% of initial surface potential. Therefore, the surface charge potential stability of treated sample 3 was improved remarkably in comparison with samples 1 and 2 which are in good agreement with the data presented in Fig. 5.

Figures 5 and 6 confirm to conduct a long-term surface potential monitoring to make sure either these treated samples can be a good candidate over a long period of time for different applications in particular radiation dosimetry or not. Figure 7 shows the normalized surface potential of the positively charged PTFE samples 1, 2 and 3 produced by using the modified corona rotating system as a function of the storage duration at 26 ± 1°C and 29 ± 1% relative humidity monitored up to 77 days every other 6 ± 1 days after the multiple heat treatment protocol applied to the samples as stated above.

As can be seen in Fig. 7, the surface electrostatic charge potential decreases rapidly at early days of storage in particular for samples 1 and 2 and then decreases with time which is in good agreement with those of others.5,32,42,43
However, in sample 3, the surface charge potential reaches to almost a steady state value.

As shown in Fig. 7, the surface charge potential of sample 3 is highly stable compared to the samples 1 and 2; i.e., 6%, 25% and 42% decay of charges over 77 days storage period for samples 3, 2 and 1, respectively. While 6% decay for the positively charged PTFE disc over such a long period of 77 days is acceptable, the 25% and 42% decay for samples 2 and 1 are extremely unacceptable for many applications in particular radiation dosimetry. Variations in stability of charges such as 7.7% and 6.5% over 77 days for PTFE electret discs have been reported for radiation protection dosimetry applications.

3.3. Effects of PTFE thickness on the sensitivity of large-area positively charged PTFE electret discs to the radon gas

Electret passive environmental radon monitoring is known as one of the most effective and common methods for radon dosimetry indoors and outdoors. Sensitivity of electret dosimeters to the ionizing radiations in particular radon gas is highly dependent on some parameters such as PTFE electret thickness, electret diameter and volume of ionization chamber. Among these characteristics, thickness of PTFE electret has been known as the most important parameter for production of PTFE electret dosimeters with low, medium and high sensitivities for long-, medium- and short-term measurements of dose, respectively.

In order to study the effects of PTFE thickness on the sensitivity of electret discs to the radon concentration, large-area (6-cm diameter) PTFE electret discs (0.2-, 0.5- and 1-mm thicknesses) with high surface potential uniformity and stability were produced at described optimized corona charging conditions. Accordingly, PTFE discs were positively charged by using the modified corona rotating system on which some heat treatment protocols such as pre- and post-charge annealing heat treatment, multiple heat treatment (as stated above) and post-charge annealing heat treatment were applied to the PTFE discs with 0.2-, 0.5- and 1-mm thicknesses, respectively. It should be noted that the production of large-area (6-cm diameter) positively charged PTFE electret discs of 0.2- and 1-mm thicknesses with acceptable parameters was well described in our previous studies for radiation dosimetry applications. In summary, for a 0.2-mm-thick positively charged PTFE electret disc, a pre-charge annealing with a heating rate $1^\circ \text{C} \cdot \text{min}^{-1}$ from room temperature up to 250$^\circ \text{C}$ followed by a quenching temperature at 16$^\circ \text{C}$ has been applied in addition to a post-charge annealing heat treatment at 160$^\circ \text{C}$ for 60 min. However, only the same post-charge annealing heat treatment has been applied to the 1-mm-thick PTFE electret disc. All these large-area positively charged PTFE electret discs have high quality with acceptable charge potential uniformity and required stability especially at the edges to be applied for electret dosimetry applications in particular radon monitoring.

Produced electret discs were stored in a sealed radon box environment with high and stable $^{222}\text{Rn}$ (radon) gas concentration of about $\sim 25 \pm 1.1 \text{kBq} \cdot \text{m}^{-3}$ for 6 days period of time. Figure 8 illustrates the normalized surface charge potential of large-area PTFE electret discs positively charged by using the modified corona rotating system as a function of storage duration in radon box environment at $26 \pm 1^\circ \text{C}$ and 25–30% relative humidity monitored up to 6 days every other 2 days after the heat treatment protocols applied to the charged PTFE discs with 0.2-, 0.5- and 1-mm thicknesses as stated above.

By taking Fig. 8 into consideration, it can be concluded that the surface electrostatic potential of electret discs decreases linearly with time and therefore all these electrets are suitable for radiation dosimetry and radon detection which is in line with other studies. However, the profile of 1-mm-thick electret is not linear at the end of the storage duration which is due to inability of electrostatic field and also low surface potential of electret to fully collect all negative ions produced in the radon box environment. The surface charge potential decay over a period of 6 days was about 19%, 53% and 94% for...
0.2-, 0.5- and 1-mm thicknesses of the positively charged PTFE electret discs, respectively (Fig. 8). Therefore, the sensitivity in responses of electret discs to a defined radon concentration increases as the PTFE thickness increases; in good coordination with those of others.47 Accordingly, PTFE electret disc with 1-mm thickness is sensitive to the radon ambient the most, while 0.2-mm-thick electret disc illustrates the least sensitivity which is both suitable to be applied for short- and long-term dosimetry in low and high dose rate radiation fields, respectively. Interestingly, the sensitivity of 0.5-mm-thick PTFE electret disc to the radon concentration demonstrates that this thickness of electret can be ideal for the medium-term radiation dosimetry in both low and high dose rate ionizing radiation fields in particular $^{222}$Rn gas ambient.

4. Discussion

The results indicated that the surface potential uniformity of the charged PTFE discs produced by using the modified corona rotating system depends on the needle-to-PTFE disc distance, PTFE thickness and charge polarity. According to Table 1, Figs. 3 and 4, it can be claimed that at a defined PTFE disc thickness, the surface potential nonuniformity of the charged PTFE discs decreases dramatically as the needle-to-PTFE disc distance decreases for both negative and positive charging modes. Such an observation has been rooted in this reality that by reducing the needle distance, the corona charge distribution width and deposition on the surface of rotating PTFE disc decreases causing a reduction in PTFE surface potential nonuniformity variations.48,49 However, charge potential nonuniformity for 0.2-, 0.5- and 1-mm PTFE thicknesses at 21-mm needle distance and negative charging mode are 33%, 34% and 36%, respectively, which are extremely unacceptable for radiation dosimetry applications (Table 1).27,33

At a specified needle-to-PTFE distance and charging mode, the surface charge potential nonuniformity of PTFE disc decreases slightly as the PTFE thickness decreases (Table 1, Figs. 3 and 4). This observation seems to be due to this matter that the thicker PTFE discs have lower capacitance and also faster charging speed than the thinner discs which both result in a smooth reduction of corona discharge equilibrium and uniform distribution of ion flux on the PTFE surface.

As an important outcome, it can be concluded that the effects of charge polarity and needle-to-PTFE disc distance on the PTFE surface potential uniformity are much more remarkable than the PTFE disc thickness (Table 1, Figs. 3 and 4).

According to the TSD curves of the treated PTFE discs, it was apparent that the $T_{1/2}$ of samples 2 and 3 was higher than sample 1 by 20°C and 60°C, respectively (Fig. 5). Moreover, the ISPD test illustrates that about 57%, 42% and 22% decay of charges were observed for samples 1, 2 and 3, respectively, after 2.5 h at 180°C (Fig. 6). Therefore, the results of ISPD and TSD measurements are in good agreement with each other and confirm the surface potential stability improvement of sample 3 in comparison with samples 1 and 2. Additionally, as can be observed in Fig. 7, the surface potential of sample 3 is highly stable compared to samples 1 and 2 over 77 days period of time. This means that the half-life time for sample 3 is around 1.78 years to reach the 50% of its initial surface potential. Therefore, the treated sample 3 exhibits a quasi-permanent electrical polarization which justifies its use for radiation dosimetry and other applications. This observation is in good agreement with those of others for positive PTFE electret discs.5,13,44 According to Figs. 5–7, it can be claimed that by applying the multiple heat treatment protocol to sample 3, shallow charge trapping sites have decreased so that the deep trap sites have been allocated to the holes or positive ions with high activation energy.

Referring to Fig. 8, it is obvious that the sensitivity of electret discs to radon concentration increases as the PTFE thickness increases over a period of 6 days. This is due to this matter, the thicker electret disc has higher capacitance and illustrates more voltage drop than thinner electret by collecting a defined charge density resulting from the interaction of alpha particles emitted from radon with the air.12,47 Additionally, at equal corona charging conditions, thicker electret discs have higher surface charge potential than thinner discs and that is why they produce a stronger external electrostatic field inside the ionization chamber.4,5 Therefore, thicker positively charged electret discs have been associated with a better good efficiency in comparison with thinner electrets to collect all electrons and negative ions resulting from the interaction of alpha particles emitted from radon and progeny with the active volume of air in the ionization chamber. In this study, produced PTFE electret discs with 0.2-, 0.5- and 1-mm thicknesses were selected as high quality electret dosimeters with low, medium and high sensitivities for long-, medium- and short-term radiation dosimetry, respectively (Fig. 8). Meantime, electret dosimeters with 0.2- and 1-mm PTFE thicknesses are applicable to be used in high and low dose rate radiation fields respectively while 0.5-mm-thick electret can be used in ionizing radiation fields with both low and high dose rates (Fig. 8). Such a characteristic makes the performance of large-area PTFE electret dosimeter (0.5-mm thickness) comprehensive.

5. Conclusion

The effects of PTFE thickness, PTFE disc polarity and needle-to-PTFE disc distance on the surface potential uniformity of charged PTFE discs produced by the modified corona rotating system, as required for different applications in particular electret radiation dosimetry were carefully studied.

The multiple heat treatment protocol was selected as an effective method for production of large-area positively
charged PTFE electret discs (0.5-mm thickness) with high surface potential stability and uniformity for radiation dosimetry and other purposes. This new treatment method has some superior characteristics over other existing protocols such as chemical and plasma treatments. These characteristics include low cost, ease of conducting in a developing laboratory and high efficiency. However, the multiple heat treatment protocol has also some disadvantages such as being lengthy process and applicable just for thick PTFE discs (at least 0.5-mm thickness) with high mechanical stability against deformation due to the long period of annealing. In spite of such limitations, the advantages outweigh the drawbacks.

The sensitivity of large-area uniformly charged positive PTFE electret discs to a defined concentration of radon gas is highly dependent on the PTFE thickness; i.e., the electret sensitivity increases as the PTFE thickness increases. The produced PTFE electret disc with 0.5-mm thickness as a high quality large-area electret dosimeter has some superior characteristics over other PTFE electret thicknesses (0.2- and 1-mm) such as medium sensitivity for medium-term dose measurements and also radiation dosimetry in both low and high dose rate ionizing radiation fields especially radon ambient.

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