An airflow pulse ionization chamber system supported with FPGA-based electronic technique for measurement of alpha-radioactivity in atmosphere

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A homemade airflow pulse ionization chamber system was inexpensively made for the measurement of alpha-radioactivity in atmosphere. The signal electrode of the ionization chamber was divided into two for the reduction of common-mode noises, and pulse signals from each electrode were treated with electronic circuits based on a field programmable gate array (FPGA). Multichannel pulse-height analyzers, multichannel scalers and other related electronic modules were constructed for the analysis of alpha-radioactivity in the FPGA. The symmetrical structure of the electrodes of the ionization chamber was effective in the cancellation of common-mode noises induced by commercial electricity, mechanical vibration and others. An alpha-ray source ($^{241}$Am) was set inside the ionization chamber for the monitoring of air conditions. It was confirmed from an experiment with a mantle containing thorium ore that radon alpha-radioactivity in air could be well measured with this system.

Key words: airflow pulse ionization chamber, alpha-radioactivity measurement, radon monitoring, FPGA, humidity effect

1. Introduction

Radon is a gaseous alpha-radioactive element distributed in nature and easily enters in a lung of a human being. The exposure to radon and its progenies is inevitable and increases the risk of suffering from lung cancer$^{1-3}$. Thus, radon concentration in atmosphere is the subject of growing interest in the world. In addition, the measurement of alpha-radioactivity in air is also necessary for the safety confirmation in a nuclear fuel facility. Thus monitoring alpha-radioactivity in air is one of the very important topics in the radiation safety management.

There are several types of instruments for continuously monitoring alpha-radioactivity in atmosphere. Such instruments with elaborate ionization chambers and moreover silicon detectors or scintillation detectors for the energy analysis of alpha-rays have very good quality and are commercially available, although they are fairly expensive. Then, in this work, we have tried to monitor alpha-radioactivity with a simpler and more inexpensive airflow ionization chamber.

An ionization chamber is generally used as a detector for large fluxes of radiation and its average current proportional to radiation flux is measured with an electrometer, which results in low radiation sensitivity. Then in order to sensitively monitor alpha-radioactivity in air, we have tried to measure every current pulse induced in an airflow ionization chamber by alpha-rays. We have made a twin-type airflow ionization chamber with symmetrical electrode structure and moreover have improved several electronic circuits by the use of a field programmable gate array (FPGA) for small and slow pulse signals from the ionization chamber.

The purpose of this paper is to show the homemade airflow pulse ionization chamber with FPGA-based electronic circuits for the monitoring of alpha-radioactivity in atmosphere. At first, this paper describes the outline of the system and then shows results of its performance tests.

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2. Materials and Method

2.1 Airflow pulse ionization chamber

Figure 1 shows the construction of the homemade airflow pulse ionization chamber and the experimental arrangement for the measurement of alpha-radioactivity in air. Parallel plate electrodes for the bias (high) voltage and for the detection of current pulses were formed in an acrylic plastic box of which size was 340 mm × 180 mm × 180 mm. As the electrodes, thin copper sheets (thickness; 0.3 mm) were conveniently stuck on the inner walls of the acrylic plastic box. As shown in Fig. 1, the signal electrode was divided into two for the purpose of the reduction of common-mode noises, and the area of each signal electrode was the same (150 mm × 120 mm). Such twin signal electrodes were surrounded with grounded guard electrodes to prevent leakage current from coming in. Moreover, the acrylic plastic box was covered with aluminum plates for the shield against electromagnetic noises. A compact circuit board of a charge sensitive amplifier (CSA) was located immediately above each signal electrode across the acrylic plastic insulation plate for the reduction of the input capacitance, which degrades signal-to-noise ratio in the measurement of alpha-ray-induced current pulses. The ionization chamber covered with aluminum plates was supported on a rubber plate which reduced vibration.

An alpha-ray source (²⁴¹Am) was set inside the ionization chamber and was used for the examination of changes in its response characteristics affected by air condition. The bias voltage was kept as high as possible for the shortening of the charge collection time in the ionization chamber, although too high voltage caused dielectric breakdown. The electrode for the bias voltage had a 1mm φ hole, through which ²⁴¹Am alpha-rays passed. The counting rate of ²⁴¹Am alpha-rays was about 40 cps. Pulse height distributions of the ionization chamber for ²⁴¹Am alpha-rays were measured under different conditions of the distance between the bias voltage and signal electrodes. The optimum distance between both the electrodes was determined from the comparison among the pulse height distributions for ²⁴¹Am alpha-rays.

An electric fan injected air into the ionization chamber through air-filters. The electric fan was connected to the ionization chamber by the use of a soft tube which decreasingly transmitted the vibration. The airflow rate (0~3 l/min) was monitored with an airflow sensor (AWM 2100V) placed at a branch to the outlet. Humidity and temperature sensors were also housed together with an electromagnetic shield in the acrylic plastic box.

As shown in Fig. 2, in addition, a window together with a fitted lid was prepared in the side of the ionization chamber and a small pocket was attached on the inside of the acrylic plastic box. A radioactive sample was put in the pocket through the window, and gaseous alpha-radioactivity from the sample was measured with the pulse ionization chamber.
2.2 Electronic circuits

In the airflow ionization chamber, electrons produced by the ionization effect of radiation are easily attached to oxygen or water molecules and are transformed into negative ions\(^5\). The drift velocity of ions is much smaller than that of electrons in air, which results in the formation of slow current pulses in the airflow pulse ionization chamber. The ion collection time is on the whole a millisecond order for the airflow pulse ionization chamber. Thus, the feedback time constant \(R_fC_f\) of a CSA to integrate current pulses was set to 10 msec, i.e. the capacitance \(C_f\) of 1 pF and resistance \(R_f\) of 10 GΩ as shown in Fig. 3.

A differential amplifier effectively reduced common-mode noises from a pair of CSAs connected to the twin electrodes of the airflow ionization chamber. The output signals of the differential amplifier were fed into a linear amplifier with a \(CR-RC^2\) shaping time of 1 msec. This shaping amplifier was also effective in the reduction of high frequency (>1 kHz) noises.

In the present electronic circuits, the FPGA (Cyclone EP1C3, ALTERA Corp.) played an important role in the processing of pulse signals. Two multichannel pulse-height analyzer (MCA) modules, four multichannel scaler (MCS) modules, a digital low-pass filter (DLPF) and a digital pulse divider (DPD) were constructed in the FPGA. The differential amplifier outputted positive and negative pulses for the right ionization chamber and for the left one in Fig. 1, respectively. The output pulses from the shaping amplifier were digitized with a free-running ADC (AD9225, Analog Devices; 12 bits, 20 MSPS). The digitized signals were at first fed into the DLPF with a cut-off frequency of 2 kHz. And then the signals were divided into positive and negative groups by the baseline, and negative signals were inverted for the pulse-height analysis here in the DPD. As for the MCA, the triggering and peak-detecting for pulse signals were independently performed in the FPGA\(^6\). Pulse-height distributions of the right and left pulse ionization chambers in Fig. 1 for alpha-rays were measured with the MCA-1 and MCA-2, respectively. The four MCSs were mainly used for the measurement of the decay curve of alpha-radioactivity, i.e. the change in counting rate of alpha-rays. The discrimination levels of the lower-level discriminator (LLD) and upper-level discriminator (ULD) for the alpha-ray detection, the dwell time and time span for the MCSs were set up from the personal computer (PC). The dwell time for the MCS was adjustable from 10 msec to 10 min. In the present system, the change in counting rate of alpha-rays can be independently measured for four different pulse-height regions, i.e. energy regions.

Data acquired in MCA and/or MCS modes were sequentially sent to the PC via a microcomputer and Local Area Network (LAN). Sensors of humidity, temperature and airflow were led to amplifiers and were finally connected to the PC via an ADC.

![Diagram of FPGA-based electronic circuits](image-url)
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and input/output module (USB-6008, National Instruments). Measured data on the humidity, temperature and airflow were recorded in the PC together with PHA and/or MCS data. This system is applicable to the long time monitoring of alpha-radioactivity in air.

3. Results and Discussion

3.1 Pulse shape observation

Figure 4 shows examples of output pulse shapes of the CSA-1 for the detection of $^{241}$Am alpha-rays in the pulse ionization chamber filled with air. A digital oscilloscope was effectively used for the measurement of the pulse shapes of output signals from the CSA-1. Every output pulse shape for the alpha-ray detection was superimposed at the same timing, and the smoothed data on the output pulse shape were stored in the digital oscilloscope followed by the PC. This averaging method was effective in the reduction of random noises. The rise time of the pulse shape was 1.8 msec for the bias voltage of $-3$ kV. It was confirmed from the pulse shape observation that slow pulses due to the ion drift were formed by alpha-ray detections in the pulse ionization chamber filled with air. Under normal air condition, no dielectric breakdown took place until $-3$ kV.

As for the common-mode noises, for example, a periodic noise of about 60 mV peak-to-peak was induced by the mechanical vibration at the output of each CSA when the electric fan was worked near the ionization chamber. Also a sine curve noise of several tens of mV peak-to-peak was often induced by commercial electricity at the output of each CSA in case that the electromagnetic shield for the ionization chamber was insufficient. However, they were common-mode noises, and the differential amplifier effectively reduced them by one or two order.

3.2 Measurement of pulse height distributions

Figure 5 shows an example of pulse height distributions of the air-filled ionization chamber for $^{241}$Am alpha-rays. This distribution, of which energy resolution was 24%, was obtained under the following conditions: Temperature of 22°C, humidity of 36%, bias voltage of $-3$ kV and electrode gap of 4 cm. According to the charge calibration, the peak position in Fig. 5 corresponded to $1.4 \times 10^{-14}$ C.

In order to determine the optimum distance between the signal and bias voltage electrodes in the pulse ionization chamber, we made an examination of a relation between the electrode gap and the pulse-height distribution for $^{241}$Am alpha-rays. Measured results are summarized in Fig. 6. The best energy resolution and the largest peak channel (position) were obtained for the electrode gap of 4 cm and 3 cm, respectively. The electrode gap of the pulse ionization chamber was settled to be 4 cm because more importance was attached to the energy resolution. For the larger electrode gap, the peak channel shifted to the lower side, which was considered to be due to the lower charge collection efficiency or the recombination. For the smaller electrode gap, the peak channel also shifted to the lower side, which was considered to be due to the lower charge production by $^{241}$Am alpha-rays. The range of $^{241}$Am alpha-rays in air is about 4.2 cm.

![Fig. 4 Examples of output pulse shapes of CSA-1 for detection of $^{241}$Am alpha-rays in pulse ionization chamber filled with air](image1)

![Fig. 5 Example of pulse height distributions of air-filled ionization chamber for $^{241}$Am alpha-rays](image2)
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Figure 7 shows a relation between humidity and response characteristics of the pulse ionization chamber for $^{241}$Am alpha-rays. The humidity varied from 33% to 73% in the ionization chamber. The peak channels corresponding to the amount of collected pulse charge and energy resolutions were obtained from measured pulse height distributions. There was no large change in the peak channel and resolution in the humidity range below 62%. Thus precise control of humidity seems to be unnecessary for the alpha-ray measurement with the air-filled ionization chamber, although the humidity needs to be kept as low as possible for the prevention of local dielectric breakdown.

3.3 Detection of $^{220}$Rn-related alpha-rays

A mantle containing thorium ore was set in the air-filled pulse ionization chamber as described in Section 2.1 and Fig. 2, and its response to alpha-rays from the mantle was examined. Alpha-rays from $^{220}$Rn and its progenies were measured with the pulse ionization chamber. Figure 8 shows a comparison of pulse-height distributions between for $^{220}$Rn-related alpha-rays and for $^{241}$Am alpha-rays. The pulse-height distribution for $^{220}$Rn-related alpha-rays broadened as compared with that for $^{241}$Am alpha-rays. This is because $^{220}$Rn-related alpha-rays cause ionization at various positions in the pulse ionization chamber. Also the energy of alpha-rays from $^{220}$Rn and its daughter nuclide $^{216}$Po is fairly larger than that from $^{241}$Am.

Next, the decay curve of the $^{220}$Rn alpha-radioactivity was measured with this pulse ionization chamber. The mantle was kept for about 10 min in the pocket of the ionization chamber, and the counting rate of alpha-rays was measured in the MCS mode soon after the mantle was taken out of the ionization chamber. The mantle was tied with a thread and could be quickly pulled out of the ionization chamber by the thread.

Figure 9 shows the change in the alpha-ray counting rate measured with this system. The discrimination level of the LLD was set to the position of channel number 100 in Fig. 8, and the dwell time was set to 2.0 sec. With the aim of the improvement
of the counting statistics, the MCS measurement for 5 min was repeated 15 times in the same way, and measured data on the counting rate were superimposed at the same timing. The measured result on the decay curve was in good agreement with the well-known half life (55.6 sec) of $^{220}$Rn. It was confirmed from this experiment that the counting rate of alpha-rays from radon in air could be well measured with the present system.

3.4 Monitoring of alpha-radioactivity in atmosphere

The pulse ionization chamber was placed in a small room that linked to a basement. This detector measured the change of alpha-radioactivity in the room when the entrance door of the basement was opened. Fig. 10 shows an example of the variation of the alpha-ray detection rate from the detector. The average alpha-ray detection rate in the room increased from about 1.7 cpm to about 7.7 cpm after the door of the basement had been opened. This increment was considered to be due to an influx of air with higher radon concentration from the basement. According to results measured with a commercially available radon monitor (Radium 3A Radon Monitor) set near the pulse ionization chamber, the average radon concentration in the room was about 38 Bq/m$^3$ before and 180 Bq/m$^3$ after the opening of the door, respectively. The results (alpha-ray detection rate) measured with the pulse ionization chamber was relatively in good agreement with the results (radon concentration) measured with the radon monitor.

4. Conclusion

The airflow pulse ionization chamber system was inexpensively made for the monitoring of alpha-radioactivity in atmosphere. The electrode gap in the airflow pulse ionization chamber with a bias voltage of $-3$ kV was set to 4 cm in consideration of the pulse-height distribution of the air-filled pulse ionization chamber for $^{241}$Am alpha-rays. The signal electrode of the pulse ionization chamber was divided into two and pulse signals from each electrode were treated with the FPGA-based circuits. The symmetrical structure of the pulse ionization chamber was effective in the cancellation of common-mode noises induced by commercial electricity, mechanical vibration and others. With the aim of the analysis of alpha-radioactivity, the MCAs, MCSs and other electronic modules were constructed in the FPGA. The alpha-radioactivity of the mantle containing thorium ore was well analyzed by the use of the MCA and MCS in the FPGA. It was confirmed that radon alpha-radioactivity in air could be well monitored with this system.

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