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ORIGINAL PAPER

An improved silicon PIN diode based portable radon monitor

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Abstract: A low budget radon monitor has been developed using silicon PIN diode. Sensitivity factor of this monitor is observed to be relatively high over the other similar monitors. This is achieved by incorporation of a hemispherical mesh in the sampling chamber, thereby accelerating the electro-deposition of charged polonium atoms on the detector surface. Its performance has been tested successfully against reference equipment.

Keywords: Radon monitor; PIN diode; Electrostatic collection; Alpha spectroscopy

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1. Introduction

Radon (^{222}Rn), the immediate decay product of ^{226}Ra, is a naturally occurring radioactive gas that emanates from soil and building materials and tends to concentrate in enclosed spaces like underground mines or houses. Radon is the major contributor to the natural radiation dose received by the general population [1]. Reports based on recent results of epidemiological studies [2–4] have stated that radon is the second most important cause of lung cancer in general population next to smoking and recommendations have been made to reduce the reference level in indoor from 300 to 100 Bq m^{-3}.

The increase in awareness of the impact of environmental radon on public health has led to development of more advanced, reliable and easy to use radon measurement systems [5–7]. In the past, emphasis had been given on the development of passive radon measurement systems as they were more economical compared to large scale survey programs [8–11]. However, due to tedious post processing job (etching and counting) associated with these systems, new attempts have been made to develop commercially viable continuous radon monitor. Also, more importance has been stressed upon on the development of fast response and high sensitive radon monitors in order to increase measurement accuracies in a short cycle time. Unlike time-integrated measurement of radon through passive systems, which are mainly limited to dosimetric applications, continuous monitoring provides an insight about spatio-temporal correlations, build-up in confined spaces and most importantly the real time data helps in evolving the control measures to minimize the radon exposure in the environment. In view of above advantages, there is an increasing demand for the development of the Continuous Radon Monitor (CRM).

Radon activity in the environment is generally measured by sampling the ambient air, into a controlled chamber after passing it through a particulate air filter and then detecting the alpha particle emitted from ^{222}Rn and its short lived decay products (^{218}Po and ^{214}Po). Several detectors are available to detect these alpha particles and these can be used to develop a CRM. These are ZnS(Ag) scintillation detector, ion chamber and semiconductor detectors such as silicon PIN diode detectors, etc. Amongst these, silicon detectors are most suitable since they can provide good energy discrimination for alpha particles and are also economically more viable. Besides this, the intrinsic detection efficiency of silicon detectors is close to 100 % for alpha particle. Due to high density, low operating voltage and low power consumption, these detectors are well suited for portable radiation monitoring systems. Several studies related to radon and its decay products and

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development of radon monitors utilizing PIN diodes as detectors have been reported earlier [12–17]. These studies have focused to address the radon concentration measurement for low detection levels at specific laboratory systems. These monitoring systems therefore have employed large volume collection cells and are not suitable for portable monitoring applications.

The present work reports the implementation of PIN diode [18] based portable continuous radon measurement system. The PIN diodes used in this study are locally fabricated in India. A fabrication process based on the technology developed for the silicon strip detectors for the Compact Muon Solenoid (CMS) Experiment at Large Hadron Collider (LHC), CERN has been used for the fabrication of detectors [18]. The radon monitoring system uses a hemispherical metal chamber for active sampling of the environmental air containing the radon gas. Electrostatic collection method has been adapted to deposit the freshly formed, positively charged ^{222}Rn decay products on the detector surface [19] and henceforth the chamber is named as collection cell. Alpha spectroscopy has been employed to estimate the ^{218}Po and ^{214}Po activities deposited on the surface of the detector which is directly related to the radon concentration in the sampled air. The relatively good pulse height resolution provided by the PIN diode has been utilized to eliminate the interference from thoron (^{220}Rn) and its alpha emitting decay products in the sampled air. The alpha particles emitted by ^{218}Po and ^{214}Po are counted by using two individual single channels analyzers (SCA). The influence of electric field inside the collection cell on the electrostatic collection of ^{222}Rn decay products over the detector surface has been studied. The charge state of ^{222}Rn decay products and their electrostatic collection behavior are known to be significantly dependent on the relative humidity. [20–22] The dependence of relative humidity (RH) on performance of the system has also been studied and has been found to be minimum as compared to the other similar system.

2. System description and design

2.1. Fabrication of silicon PIN detector

The silicon PIN detector has been developed by Bhabha Atomic Research Centre (India) using a 4″, class 100, IC fabrication facility. The detector has been designed to have a geometry of 20 mm × 20 mm. The pads are enclosed in two floating field guard rings in order to increase the breakdown voltage and to reduce the leakage currents. N-type, Float-zone, 4″, <111>, 300 μm thick high purity silicon wafers with resistivity of 3–5 kΩ-cm have been used as a starting material for fabricating the detectors. A low leakage current fabrication process developed for the fabrication of Preshower CMS silicon strip detectors was adopted for fabrication of the detectors [18]. The high temperature process and the ion implantation parameters used for the fabrication of detectors have been optimized through a number of process iterations to minimize dead layers and leakage currents and to increase the breakdown voltage of the detector. The processed silicon detectors were mounted on ceramic substrates. The connection to the front side of P^+ region was obtained by bonding a 25 μm (1.0 mil) diameter aluminum wire, while the back side of N^+ electrode contact to the ceramic substrate was obtained by gluing with silver epoxy. The PIN diode detectors were characterized by leakage current I versus voltage V(IV) and capacitance C versus voltage V(CV) measurements using an automated measurement setup. The detectors were characterized using a dual alpha source (^{238}Pu + ^{239}Pu) for estimating the energy resolution. These measurements were carried out by mounting the detector and the source in vacuum. A setup comprising of a charge sensitive preamplifier, spectroscopy amplifier and Multi Channel Analyzer (MCA) has been used for obtaining the histogram with alpha particles. The typical histogram obtained is as shown in Fig. 1. From these measurements, the typical energy resolution of the detectors was observed to be 20–25 keV.

2.2. Design of sampling circuit and collection cell

The design lay out of the collection chamber along with the detector assembly is shown in Fig. 2. A hemispherical aluminum chamber of one litre volume, with a Bakelite plate of 12 mm thickness covering the flat surface serves as the collection cell. The detector (20 mm × 20 mm) is mounted at a depth of 10 mm on the center of the circular plate. An aluminum plate with opening of dimensions 22 mm × 22 mm at the centre is fixed over the surface of the bakelite plate. This assembly is further mechanically fitted to the chamber. In order to improve the sensitivity of the system, a metallic hemispherical mesh of 80 mm diameter having 1 cm side rhombus shaped opening (81 %

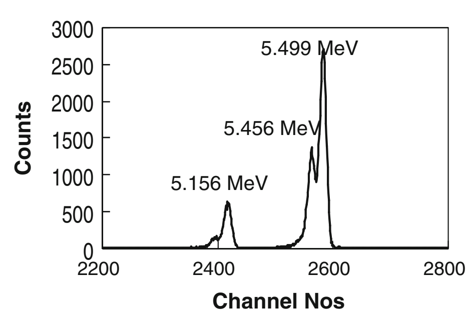

Fig. 1 Alpha histogram of a PIN diode detector for dual alpha source (^{238}Pu + ^{239}Pu) under vacuum

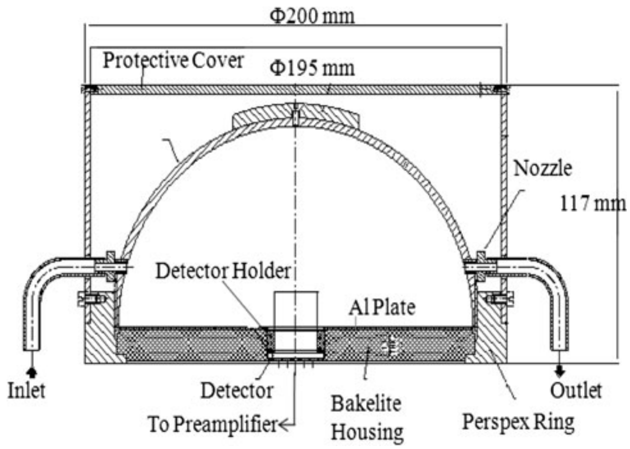

Fig. 2 Design layout of collection cell of the radon monitor

of curved surface) is initially fitted at the centre of bottom aluminum plate. The pins of the detector are taken out of the bottom of plate through a connector for biasing and for charge measurement by using a charge sensitive pre amplifier. Air is sampled in flow mode at a rate of ~ 1 lpm through a drier and filter paper head into the chamber by using software controlled dc pump. A needle valve and a rotameter are incorporated in the sampling circuit for flow adjustment and monitoring. Positive high voltage (HV) is applied to the chamber with respect to the *P* side of the detector so that the positively charged radon progenies get electro-statically collected over the detector surface. The outer surface of the chamber is covered by a reinforced PVC cover for protection.

2.3. Electronics modules

The schematic diagram of the continuous radon monitoring system is shown in Fig. 3. The PIN diode detector is reverse biased at 40 V. A charge sensitive pre-amplifier based on a low noise and low distortion operational amplifier is used for processing the output signal provided by the detector. The output from the preamplifier is further fed to a spectroscopy amplifier, the output of which is simultaneously fed to two individual Single Channel Analyzer (SCA). The amplifier is adjusted to provide a conversion ratio of around 1 V/MeV. SCA windows are set such that the 6 MeV ^{218}Po and 7.687 MeV ^{214}Po alpha pulses would fall within the respective voltage threshold levels. A temperature and humidity sensor is provided at the sample exit side of the detector cell. The TTL (Transistor Transistor Logic) output generated by SCA is fed to a Si-Lab make 8 bit micro controller board. The system is equipped with an alphanumeric LCD display unit which is used to provide a visual interface to the software and also displays the measured radon concentration. The system can be also interfaced serially with a computer for transfer of measured data. The modules for generating all the voltage supplies are housed inside the instrument. A compact rechargeable battery is housed inside the equipment for required power supply. Facility to store/recall 170 data sets from SCAs output counts along with real time tag is also provided in the system. The corresponding radon concentration, temperature and humidity are logged for each data set in nonvolatile memory. The complete system weighs 3.2 kg.

3. System characterization

Subsequent to development of the radon monitoring system, various experiments were carried out using standard source of radon (Activity of 110 kBq as on March 1996, PYLON Make, Canada) and the calibration chamber available at Bhabha Atomic Research Centre, India, in order to characterize the system. These experiments mainly include alpha spectrum generation and isotopic channel identification, optimization of collection voltage, humidity interference test and calibration of the system. The experimental procedures and results of above studies are described in the subsequent sections.

3.1. Alpha spectrum studies and channel setting

Radon concentration (~ 10 kBq m^{-3}) was introduced into the collection cell of the radon monitoring system. The inlet and outlets of the system were sealed. A collection voltage of positive 2 kV was applied to the metallic collection cell. A preliminary alpha spectrum of radon decay products, electro-deposited on the detector surface, was acquired by a MCA. The energy resolution of the detector is adequate to identify the alpha energies of the radon decay products (^{218}Po and ^{214}Po). A typical spectrum obtained during the experiment is shown in Fig. 4.

The associated measurements for channel setting were carried out after 3 h delay to get equilibrium counts in the two channels of SCA. Sliding window method was applied to set windows of SCAs for the alpha energies corresponding to radon daughters namely, ^{218}Po and ^{214}Po. The count rates were recorded for every 100 mV increment in the baseline voltage with a widow width of 100 mV from 4 V up to 7.5 V. The plot of count rate versus baseline voltage (LLD) gives differential pulse height spectrum of ^{218}Po and ^{214}Po electro-statically collected by the detector inside the collection cell. The windows for ^{218}Po (channel A) and ^{214}Po (channel B) were set manually.

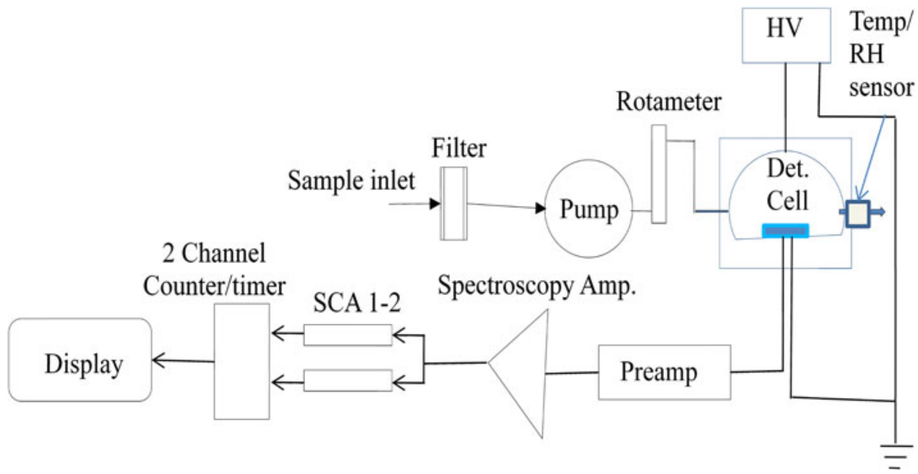

Fig. 3 Schematic diagram of continuous radon monitoring system

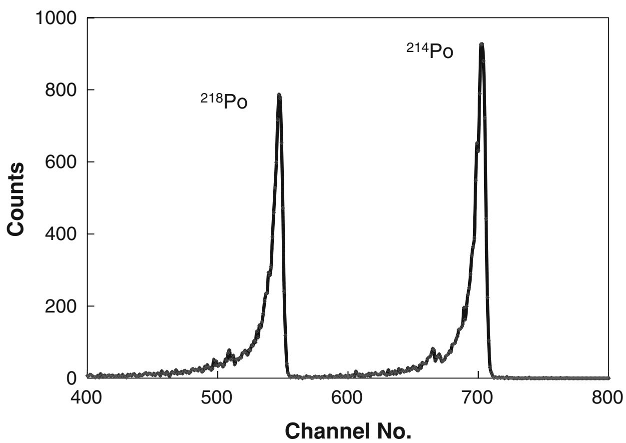

Fig. 4 Typical spectrum at a collection voltage of 1,750 V, temperature 27 °C and RH 8 %

3.2. Optimization of collection voltage and sensitivity

Studies were carried out to optimize the collection voltage so as to maximize collection efficiency for radon decay products on the detector surface. Standard Radium source of activity 6 kBq from National Institute of Standards and Technology, US Department of Commerce was used to generate radon gas inside the chamber during these studies. Radon gas from a standard chamber was sampled through a dehumidifier and activity was assessed by the radon detector RAD7 (Durridge, USA) [23]. The same sample was filtered and circulated through the collection cell and returned back to the chamber. A USB based MCA was employed to acquire the alpha spectrum at various collection voltages after three hours of continuous sampling for an acquisition period of 30 min. The total counts of ^{218}Po and ^{214}Po were obtained from the corresponding energy windows of the acquired spectrum. The humidity inside the cell was maintained at less than 15 % throughout the experiment. The response of the diode detector setup is compared with the standard radon detector. The experimental arrangement is shown in Fig. 5. Figure 6 shows the variation of sensitivity (cph/Bq.m^{-3}) as a function of applied collection voltage. The sensitivity attains a near saturation beyond an applied collection voltage of 1,500 V and for normal noise free operation it can be set at 1,750 V as an optimum option. The sensitivity at 1,750 V collection voltage and 9 % RH was found to be 0.26 cph/Bq.m^{-3} for ^{218}Po α counts. An attempt was made to increase the electric field intensity and thereby improve the collection efficiency by introducing a hemispherical mesh above the base aluminum plate of the collection cell which encloses a volume of 134 cc. Experiment was repeated with the modified collection cell to estimate the sensitivity. It was observed that the introduction of the hemispherical mesh within the collection cell led to 40 % increase in the sensitivity of the system at the same operating conditions. The upper limit of the applied collection voltage was established on the basis of the electrostatic field developed across *P* side of the detector and chamber wall, detector cell design and associated processing electronics. It was found that operating collection voltage beyond 2,000 V was not desirable as it lead to significant increase of noise pulse. The performance of the system was found to be dependent on the RH of the sampled air. When RH varied from 7 to 63 % the sensitivity was found to vary from 0.37 to 0.14 cph/Bq.m^{-3}. However, the variation of the sensitivity was found to be marginal (<5 %) for the RH below 15 %. In view of this, it is required to dry the sampled air before entering to the collection cell to ensure RH is below 15 % which will make uniqueness of the sensitivity factor of the instrument throughout the measurement period. Figure 7 shows the variation of sensitivity with RH within the operating Humidity range.

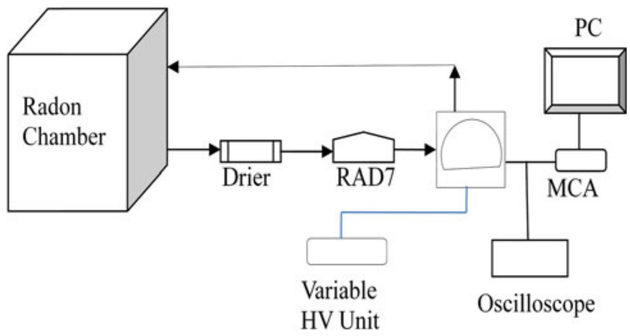

Fig. 5 Experimental setup for collection voltage optimization

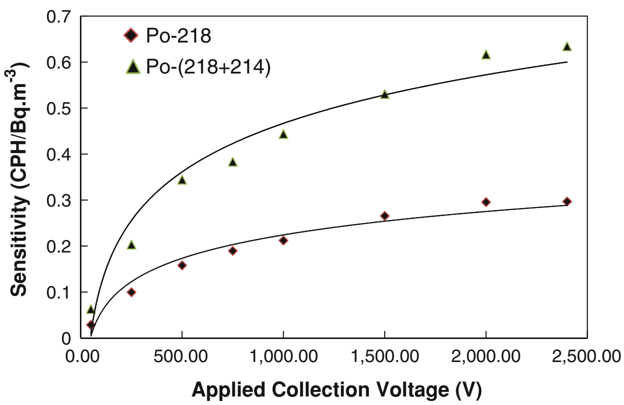

Fig. 6 Sensitivity variation with different applied collection voltages. RH < 15 %, Temperature 26–29 °C

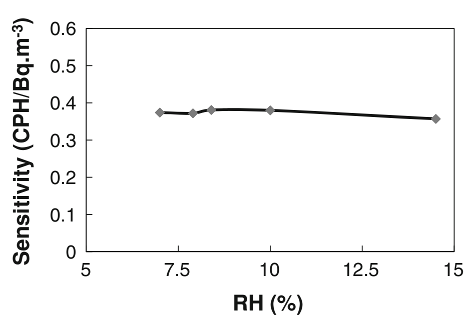

Fig. 7 Variation of Sensitivity with RH within the operating humidity range

3.3. Calibration of the system

The system was calibrated at the radon calibration facility available at Bhabha Atomic Research Centre, India. The calibration facility has a radon test chamber (0.5 m^3) with arrangement of generating known radon concentration in the chamber volume using standard radon source (PYLON, Canada). The RAD7 system was considered as the reference standard instrument for the calibration. A similar arrangement as used in collection voltage optimization experiment was repeated for carrying out the calibration of the system. Initially, the counts data from the ^{218}Po and ^{214}Po channels were recorded over a period of 15 min subsequent to start of the sampling process. The plot of counts data of ^{218}Po and ^{214}Po with time (collection profile) is shown in Fig. 8. It was observed that ^{218}Po activity attained 67 % of sampled radon activity at end of 15 min, 98 % at end of 30 min and 99 % at end of 45 min. In contrast, ^{214}Po activity attained 67 % of sampled radon activity at end of 1 h, 98 % at end of 2 h and 99 % at end of 3 h. At the end of 4 h, the HV of the system was switched off and count profile was followed. It was observed that about 95 % of the ^{218}Po activity was decayed at end of 30 min, while ^{214}Po took about two and half hours for the same percentage of decay. From this observation, we may conclude that counting cycle of 30 min is sufficient to report the radon activity concentration using the counts data from ^{218}Po channel so that there will not be any interference from residual activity of ^{218}Po. Similarly a counting cycle of 3 h is sufficient to report radon activity concentration utilizing the counts from both ^{214}Po and ^{218}Po channels. The first approach mentioned may be referred to as the fast mode, while the second method can be called as the sensitive mode. For low level radon concentrations measurement, monitor may be operated in sensitive mode while for the measurement of varying radon concentrations, the monitor may be operated in fast mode utilizing the counts from ^{218}Po channel alone.

Subsequent to characterization of fast and sensitive mode of the system, the calibration exercise was carried out for both fast and sensitive mode of operation. In this experiment, RAD7 was operated in auto mode and cycle of 1 h, with thoron ON, so that the pump will remain ON continuously. The variation of sensitivity with radon concentrations was studied after initial setting the window

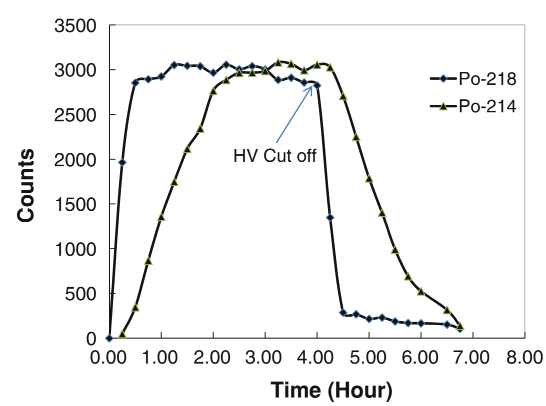

Fig. 8 Collection profile of ^{218}Po and ^{214}Po, RH varied from 7 to 10 %, Temperature 27–29 °C

width of SCA. An optimum collection voltage of 1,750 V was applied as it ensured the absence of satellite peaks and also minimized the electronic noise which otherwise was observed to be higher for higher collection voltages. The counts measured at the end of four hours for each radon concentration were considered for obtaining the calibration parameters in order to avoid any error in the sensitivity factor due to the collection behavior of radon daughter products. The ^{218}Po and the total (^{218}Po + ^{214}Po) counts were plotted against the corresponding radon concentration measured by the RAD7 detector system (Fig. 9). The sensitivity at the set collection voltage and RH < 10 % was found to be 0.36 cph/Bq.m^{-3} in fast mode and 0.75 cph/Bq.m^{-3} in the sensitive mode. The response of the presently developed system was compared with the RAD7 system for the radon activity generated in the calibration chamber. The system response was observed to give good linearity in response ($r^2 = 0.99$) to radon concentration. The instrument can be used for environmental radon monitoring using the sensitivity factor of 0.75 cph/Bq.m^{-3} when operated in sensitive mode. Measurements using the instrument in sensitive mode could reliably estimate the variation in environmental radon concentration as 4–20 Bq.m^{-3}.

3.4. Inter-comparison

Subsequent to the calibration of the system, simultaneous measurement of radon concentration was carried out to get an inter comparison between RAD7 and present PIN diode detector based CRM. Radon gas was sampled from a calibration chamber in which the concentration was varied by inserting radon gas from a standard source (PYLON, Canada). Time correlated readings from both the systems in the range 2–45 kBq/m^3 were plotted (Fig. 10). A very good one to one correlation was observed with slope 1.01.

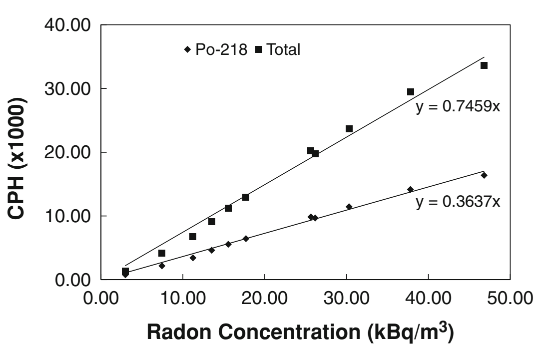

Fig. 9 Calibration graph for the PIN diode detector based continuous radon monitor, RH < 10 %, Temperature 26–29 °C

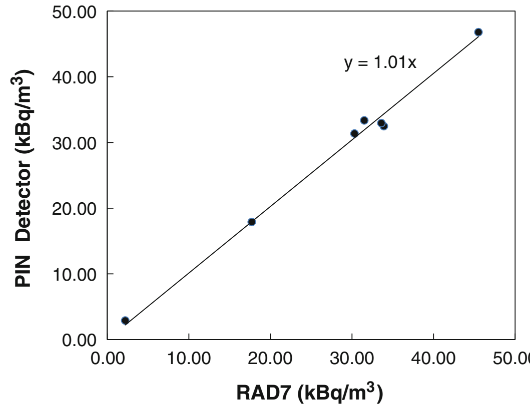

Fig. 10 Inter-comparison graph between the readings of RAD-7 and PIN detector based radon monitoring system

4. Conclusions

A PIN diode detector based continuous radon monitor has been developed for Indian radon research program. Its response and sensitivity has been characterized using the standard radon source. The novelty of the monitor is the substantial increase of the sensitivity factor due to incorporation of a hemispherical mesh inside the collection chamber of the monitor. Its performance has been tested against commercially available radon monitor and it has been observed that the measurements from both the systems are comparable with each other.

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