Development of a Low-Pressure Electrostatic Collection Radon Monitor Resistant to Environmental Temperature and Humidity

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Abstract

The detection efficiency of conventional electrostatic radon monitors is highly susceptible to environmental temperature and humidity. This is primarily because the positively charged 218Po progeny are easily neutralized by OH^- ions, preventing them from being collected. To suppress environmental temperature and humidity interference, a novel low-pressure electrostatic collection radon monitor (LPERM) was developed by reducing the pressure inside the measurement chamber. A hemispherical measurement chamber with a volume of 388 mL was designed, incorporating a gold-silicon surface barrier detector and a pressure regulation system comprising a throttle valve and a vacuum pump. The detection efficiency of the radon measurement chamber was experimentally investigated under different pressure conditions to determine the optimal operating pressure. Experimental results indicate that when the chamber pressure is set to 70.9 kPa, the detection efficiencies under dry (RH $< 10\%$) and high-humidity (RH $> 85\%$) conditions are closest, yielding values of $(12.29 \pm 0.76)\%$ and $(11.17 \pm 0.26)\%$ at 25 °C, respectively. Further experiments at 7 °C showed slightly higher detection efficiencies, but the differences between the two temperature conditions were not statistically significant. The proposed method has the potential advantage of effectively suppressing the influence of ambient temperature and humidity on detection efficiency, thereby maintaining stable measurement performance across a wide range of environmental conditions.

Full Text

Preamble

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Abstract

detection efficiency conventional electrostatic radon monitors highly susceptible environmental temperature humidity. primarily because positively charged progeny easily neutralized ions, preventing being collected. suppress environmental temperature humidity interference, novel low-pressure electrostatic collection radon monitor (LPERM) developed reducing pressure inside measurement chamber. hemispherical measurement chamber volume designed, incorporating gold-silicon surface barrier detector pressure regulation system comprising throttle valve vacuum pump. detection efficiency radon measurement chamber experimentally investigated under different pressure conditions determine optimal operating pressure.

Experimental

results

indicate chamber pressure detection efficiencies under high-humidity conditions closest, yielding values respectively.

Further experiments showed slightly higher detection efficiencies, differences between temperature conditions statistically significant. proposed

method

potential advantage effectively suppressing influence ambient temperature humidity detection efficiency, thereby maintaining stable measurement performance across range environmental conditions.

Keywords

lectrostatic ollection monitors Low-P ressure etection efficiencies

222 Rn

colorless odorless derived decay chain. radon progeny radioactive elements, constituting primary source natural radiation exposure humans. attributable radon accounts approximately natural radiation represents second leading cause cancer [1,2] primary source indoor radon beneath buildings, infiltrating indoors through cracks openings foundations basements [3-5] certain regions radium content soil, water [6,7] natural radium-containing building materials [8-10] serve sources indoor radon.

Owing mobility, stable chemical properties, strong migration capability, radon frequently employed tracer element various physical chemical processes [11-13] different practical purposes, various radon detection instruments based distinct measurement

methods

developed, pulse ionization chambers [14,15] electrostatic collection radon monitors [16,17] scintillation radon monitors [18,19] solid-state nuclear track detectors [20,21] Among these, electrostatic collection radon monitors typically utilize semiconductor detectors measure alpha particles emitted decay radon progeny.

Benefiting collection efficiency electrostatic collection

method

superior energy resolution semiconductor detectors, electrostatic collection radon monitors widely employed radon detection across various scenarios [22-25] Electrostatic collection radon monitors utilize electrostatic collection chamber collect radon progeny.

Typically, voltage applied chamber wall, creating electrostatic field directed toward semiconductor detector surface, which maintained ground potential, potential difference between high-voltage zero-potential detector [26,27] During measurement,

draws radon-containing through drying filter measurement chamber constant rate. decays within chamber, producing positively charged which collected semiconductor detector surface under influence electrostatic field. collected subsequently decays, emitting alpha particles detected detector, generating charge signals.

These charge signals amplified produce voltage pulses, which processed multichannel analyzer obtain alpha particle energy spectrum. counting pulses within specified energy range spectrum, radon concentration calculated. representative electrostatic collection radon

monitor is the RAD7 [28-30] .

Based above principle, detection efficiency electrostatic collection radon monitors primarily depends collection efficiency positively charged

218 Po

which generally susceptible environmental temperature humidity. underlying reason during drift toward detector, produced radon decay undergo recombination negatively charged ions, losing their charge become electrically neutral, failing effectively collected electrostatic field.

Studies identified three primary mechanisms charge recombination positively charged high-energy alpha particles emitted decay radon progeny ionize resulting electrons recombine positively charged water vapor dissociates negatively charged which recombines positively charged electron transfer mechanism, whereby electron affinity, capture electrons molecules ionization energy, nitrogen dioxide, thereby becoming electrically neutral.

Consequently, absolute humidity high, concentration water molecules increases, raising probability recombination between leads positive charge. reduces collection efficiency electrostatic field, ultimately

decreasing the detection efficiency of the radon monitor.

address issue, several

methods

proposed. employs external drying inlet thereby maintaining relative humidity

inside measurement chamber below However,

method

requires periodic replacement desiccant, making unsuitable unattended long-term continuous radon concentration monitoring.

Moreover, considerable volume drying introduces significant volumetric delay effect.

Additionally, using drying before measuring radon concentration alter humidity condition object being measured. accumulative

method

measure radon exhalation rate, radon collection cover typically placed tightly against surface medium. inside cover driven built-in radon monitor, passes through drying measurement chamber radon concentration measurement, returned cover, forming closed-loop circulation circuit During process, drying effect drying causes humidity inside cover continuously decrease.

However, numerous studies shown changes moisture content medium itself significantly affect radon exhalation variations absolute humidity medium surface considerable impact radon exhalation ERS-2-s utilizes temperature-humidity correction curve compensate detection efficiency

method

derives correspondence between collection efficiency temperature humidity based relationship between water vapor concentration concentration Nevertheless, humidity inside measurement chamber high, collection efficiency inevitably decreases, leading reduction detection counts consequently increased statistical fluctuations.

RTM2200 radon monitor adopts design integrating semiconductor detectors small electrostatic collection units, resulting total effective measurement volume reducing volume measurement chamber, collection shortened, thereby decreasing probability recombination before reaching detector, which allows influence high-humidity environments effectively neglected However, approach

results

selling price complex structure detectors signal processing circuits.

suppresses temperature humidity effects using small collection chamber employs CR-39 detector, effectively reducing costs However, CR-39 detector requires post-measurement statistical calculation particle counts allow real-time radon concentration monitoring during measurement process. paper, novel low-pressure electrostatic collection radon monitor LPERM capable mitigating effects ambient temperature humidity developed reducing pressure inside radon measurement chamber, experiments designed validate performance.

results

indicate LPERM effectively suppresses influence ambient temperature humidity detection efficiency.

2.1 Structural

design conventional electrostatic-collection radon monitors, pressure, temperature, humidity inside measurement chamber typically identical those ambient environment.

Within certain temperature range, detection efficiency remains essentially constant relative humidity below specific threshold. essence phenomenon whether probability charge neutralization positively charged during their drift sufficiently significantly affect electrostatic collection efficiency.

Since drift velocity lower their thermal velocity, collision process dominated thermal motion; consequently, collision probability mainly depends concentration charged particles their thermal motion characteristics. pressure inside measurement chamber reduced, density decreases charged particles increases, resulting significant increase drift velocity reduction their transit detector surface. time, decrease pressure

leads reduction water vapor concentration volume, thereby lowering concentration negatively charged (such generated water molecules.

Since collision probability between positively charged negative closely related concentration negative ions, probability charge neutralization during drift process significantly reduced under low-pressure conditions total number collisions experienced during their drift under low-pressure conditions exceed under conditions atmospheric pressure, collection efficiency maintained level comparable higher under atmospheric conditions, high-humidity near-saturated environments. other words, appropriately reducing chamber pressure, collection efficiency comparable under conditions achieved humid environments.

Given relative humidity upper limit, chamber pressure properly adjusted satisfy above condition, detection efficiency remain stable range temperature humidity, thereby effectively suppressing influence environmental variations.

Based above principles, LPERM designed, shown throttle valve installed inlet radon measurement chamber, vacuum pressure connected outlet. adjusting rates throttle valve vacuum pump, pressure inside electrostatic collection measurement chamber precisely regulated desired pressure. pressure within measurement chamber monitored pressure gauge connected series.

LPERM enable radon measurement chamber withstand certain pressure, chamber designed hemispherical shape, structure shown hemispherical electrostatic collection radon measurement chamber consists stainless steel hemisphere, polycarbonate cover, gold-silicon surface barrier detector, preamplifier shielding enclosure, black silicone gasket, aluminum foil. stainless steel hemisphere outer diameter inner diameter thickness chamber volume Holes drilled through center hemisphere side,

respectively, quick-connect fittings installed inlet outlet. withstand pressure, cover fabricated polycarbonate material diameter thickness preamplifier placed inside aluminum shielding enclosure, which connected signal ground amplifier detector shield against external electromagnetic interference. gold-silicon surface barrier detector fixed cover shielding enclosure. black silicone gasket light shielding, sealing, supporting aluminum foil. aluminum adhered black silicone gasket electrical contact stainless steel hemisphere high-voltage connection. edges chamber filled silicone rubber ensure airtightness. factor affecting detection efficiency electrostatic collection radon monitors probability recombination between positively charged negatively charged during electrostatic collection.

Increasing voltage between measurement chamber semiconductor detector enhance drift velocity electrostatic field, thereby shortening collection reducing probability recombination ions, which improves detection efficiency.

However, chamber voltage exceeds 2000 V, further increases voltage yield limited improvement collection efficiency Therefore, paper, chamber aluminum cover connected high-voltage output terminal high-voltage module, maintaining potential while detector shares common ground high-voltage module. configuration establishes electrostatic field within measurement chamber directed chamber cover toward detector surface.

LPERM employs GM-30 gold-silicon surface barrier detector (China Nuclear Control Systems Engineering Ltd.) outer diameter effective diameter alpha particle detector. multichannel

analysis

module consists analog-to-digital converter AD9220 (Analog Devices, Inc.) microcontroller STM32F407

(STMicroelectronics N.V.) pulse signals generated detector first amplified preamplifier, sampled digitized AD9220. digital signals subsequently processed STM32F407 generate energy spectrum, which transmitted computer serial display analysis. system signal processing shown Experimental

methods

Experimental Setup under Ambient Pressure better evaluate effectiveness low-pressure electrostatic collection radon monitor suppressing influence temperature humidity detection efficiency, ambient pressure experimental system designed, shown system, pressure regulation device low-pressure electrostatic collection radon monitor removed, allowing measurement chamber operate under ambient pressure. measurement chamber connected series RAD7, detection efficiency measured under different temperature humidity conditions. ambient pressure experimental system mainly consists washing bottle containing built-in radon source, humidity control device, electrostatic collection radon measurement chamber, washing bottle built-in temperature humidity meter, RAD7.

Since incorporates built-in L/min, additional provided system. humidity control device comprises Valve Valve Valve Valve drying tube, umidity Control Bottle water saturated solutions, enabling adjustment different humidity levels. environment required measurement chamber, Valve Valve opened, while Valve Valve closed, allowing dried passing through drying

tube. high-humidity environment required measurement chamber, Valve Valve opened, while Valve Valve closed. replacing different saturated solutions umidity Control Bottle employing bubbling method, humidity output controlled.

During measurement process, built-in first draws radon released radon source mixed After being adjusted desired humidity humidity control device, passes through filter remove radon progeny enters electrostatic collection radon measurement chamber.

Inside measurement chamber, progeny produced radon decay collected detector surface under influence electrostatic field.

After leaving measurement chamber, radon-containing sequentially flows through umidity Control Bottle equipped temperature humidity meter enable real-time monitoring system' s temperature humidity. passes through second drying further drying again through filter remove radon progeny, ensuring accurately measures radon concentration within system.

Finally, returned radon source, forming closed loop.

Experimental Setup under Ambient Pressure measure detection efficiency low-pressure electrostatic collection radon monitor, low-pressure experimental system designed, shown low-pressure experimental system mainly consists washing bottle containing built-in radon source, humidity control device, throttle valve, electrostatic collection radon measurement chamber, vacuum pressure gauge, vacuum pressure pump, washing bottle built-in temperature humidity meter, RAD7. control

method

humidity control device described above. During measurement process, under action vacuum pressure pump, radon-containing first drawn washing bottle containing built-in radon source.

After being adjusted desired humidity humidity control device, passes through throttle valve filter before entering radon measurement chamber. pressure inside measurement chamber regulated combined action throttle valve vacuum pressure pump:

intake controlled rotating throttle valve, while vacuum pressure continuously extracts thereby achieving stable control chamber pressure. vacuum pressure gauge connected between radon measurement chamber vacuum pressure monitor pressure inside chamber time. entering radon measurement chamber extracted vacuum pressure flows through washing bottle equipped built-in temperature humidity meter monitor temperature humidity during system operation.

Since vacuum pressure (approximately L/min) greater built-in (approximately L/min), directed entirely RAD7, built-in might damaged excessive pressure. prevent issue, connector connect washing bottle built-in temperature humidity meter, drying inlet RAD7, inlet radon source. configuration, after exits washing bottle built-in temperature humidity meter, portion drawn built-in measure radon concentration system ultimately returned radon source outlet. remaining directly returned radon source through pipeline, thereby forming closed loop.

Since total amount closed-loop system fixed, pressure inside radon measurement chamber lower atmosphere, amount within under ambient pressure, while amount other parts system increases correspondingly, resulting pressure higher atmosphere. affects accurate measurement relative humidity hygrometer cause water vapor saturation condensation under high-humidity conditions, thereby interfering experiment. eliminate these effects, connector installed pipeline parallel RAD7, slender connected atmosphere.

During initial startup vacuum pressure pump, valve opened release system pressure. reading vacuum pressure gauge stabilized, valve

closed, ensuring system remained stable during experiment.

discussion

Radon progeny energy spectrum measurement Radon-containing introduced LPERM, energy spectrum obtained measurement shown comparing positions energy spectrum energies spectrum conforms characteristic features progeny spectrum.

analysis

indicates energy calibration coefficient radon monitor approximately width maximum (FWHM) characteristic channels. maximize retention effective counts radon progeny while excluding

background

interference, counting intervals measurement based positions radon progeny energy spectrum.

Specifically, counting interval channel 1050, counting interval channel

220 Rn

present environment important interfering factor accuracy radon monitors.

Effectively eliminating interference fundamental achieving accurate radon concentration measurements. verify radon

monitor developed paper distinguish between energy spectrum, thereby eliminating interference mixture

220 Rn

introduced measurement chamber testing. After period measurement, obtained energy spectrum shown observed figure energy spectrum peaks progeny progeny exhibit clear separation.

Based counting intervals 214 Po, progeny accurately excluded, thereby preventing radon

monitor from being affected by 220 Rn interference.

Detection efficiency under different atmospheric pressure conditions detection efficiency radon monitor defined ratio number alpha particles detected decay specific radon progeny number decays radon progeny actually occurring measurement chamber. decay radon within measurement chamber reaches equilibrium, expressed denotes number alpha particles decay actually detected radon monitor denotes atmospheric pressure (kPa) denotes pressure (kPa), denotes actual radon concentration measurement chamber radon monitor denotes volume measurement chamber radon monitor denotes measurement radon

monitor (s) .

3.2.1 Detection

Efficiency Radon Measurement Chamber under Ambient Pressure Relative humidity affected ambient temperature, which variation saturated water vapor pressure different temperatures.

Under relative humidity, higher ambient temperature

results

higher concentration water molecules First, detection efficiency hemispherical electrostatic collection radon measurement chamber under ambient pressure experimentally determined under different humidity conditions.

During measurement, measurement cycle radon measurement chamber minutes, allowing radon monitor start measurements synchronously. sniff mode, which radon concentration calculated solely based counts radon measurement chamber counted events energy interval, ensuring counts obtained radon monitor paper corresponded radon concentration measured time.

After reached equilibrium, collected, detection efficiency radon measurement chamber under ambient pressure calculated using Equation experimental

results

shown Table different relative humidity levels

Table observed under ambient pressure, detection efficiency radon measurement chamber highly sensitive ambient humidity, decreasing relative humidity measurement system increases. humidity inside measurement chamber below average detection efficiency however, humidity exceeded average detection efficiency dropped representing pronounced difference. investigate effect different temperatures detection efficiency radon measurement chamber under ambient pressure, experiments conducted ambient temperature under conditions relative humidity below above experimental shown Table different relative humidity levels shown Table ambient temperature humidity inside chamber below average detection efficiency humidity exceeded average detection efficiency because lower ambient temperatures, actual water vapor content (absolute humidity) relative humidity lower.

Therefore, compared high-temperature environments, overall detection efficiency radon measurement chamber increases temperatures.

Meanwhile, although difference detection efficiency between high-humidity conditions narrows, efficiency reduction caused humidity remains significant.

Table Table represented their values, comparison using Y-error plots performed Origin software.

results

shown experimental obtained under ambient pressure verify ambient temperature humidity significant impact measurements conventional radon monitors based electrostatic collection method. pressure different temperature humidity conditions

3.2.2 Determination

Pressure Parameters Low-Pressure Radon Monitor determine optimal operating pressure minimizes influence ambient temperature humidity radon monitor, comparative experiments

conducted ambient temperature During experiments, relative humidity circuit adjusted using humidity control device, while pressure inside radon measurement chamber precisely regulated using throttle valve conjunction vacuum pump. detection efficiency measured under high-humidity conditions chamber pressures 70.9, 60.8, 50.7, detailed measurement

results

presented Tables

high-humidity environment (RH $>$ 85%)

Table observed under high-humidity conditions detection efficiencies radon measurement chamber under different low-pressure conditions remain essentially consistent close environment under ambient pressure temperature.

Notably, compared detection efficiency under ambient pressure temperature humidity, detection efficiency radon monitor under low-pressure conditions shows relative improvement approximately fully demonstrates reducing pressure inside measurement chamber effectively overcome interference water vapor significantly enhance detection efficiency radon monitor high-humidity environments.

environment (RH $<$ 10%)

Experiment

Table observed environment reducing pressure inside measurement chamber positive effect improving detection efficiency.

However, pressure continues decrease, actual amount within chamber correspondingly diminishes, leading increase relative statistical fluctuation counts, which ultimately

results

greater uncertainty detection efficiency. pressure conditions different humidity environments Tables averaged compared using Y-error plots,

results

shown Although reducing pressure radon

measurement chamber continuously improves detection efficiency environments, effect enhancing efficiency high-humidity environments quite limited.

Consequently, pressure further decreases, difference detection efficiency between high-humidity conditions tends widen.

Based comprehensive data, chamber pressure difference detection efficiency under extreme humidity conditions reaches minimum.

Therefore, measurement chamber pressure LPERM developed paper

3.2.3 Detection

Efficiency LPERM under Different Temperature Humidity Conditions detection efficiency LPERM under different humidity conditions measured ambient temperature experimental

results

presented Table Table observed ambient temperature detection efficiency radon measurement chamber exhibits slight overall decreasing trend increasing relative humidity. range detection efficiency decreases slightly stabilizes approximately 11.0%. relative humidity further rises above

detection efficiency Overall, maximum variation detection efficiency LPERM under different humidity conditions approximately percentage points, relative change about Except condition 10%), differences detection efficiency under moderate humidity conditions within standard deviations considered consistent. indicates LPERM effectively suppress influence ambient humidity measurement results. investigate effect temperature detection efficiency LPERM, measurements conducted under high-humidity conditions ambient temperature

results

shown Table Tables further comparison LPERM under conditions, detection efficiency lower temperature slightly higher higher temperature. detection efficiency which higher observed detection efficiency higher observed

result

indicates ambient temperature decreases, absolute concentration water molecules under relative humidity condition reduced, thereby weakening inhibitory effect electrostatic collection process consequently increasing detection efficiency

measurement chamber. LPERM under different temperature humidity conditions Tables averaged compared using Y-error plots,

results

shown clearly observed differences detection efficiency humidity points under temperature conditions within standard deviations, indicating these differences statistically significant.

Taken together experimental under different humidity conditions these

results

demonstrate LPERM maintain stable detection efficiency across range ambient temperature humidity conditions, thereby effectively suppressing influence variations ambient temperature humidity measurement results.

4. Conclusion

address issue detection efficiency electrostatic collection radon monitors susceptible ambient temperature humidity, novel low-pressure radon monitor developed. detection efficiency radon measurement chamber under different pressure conditions experimentally investigated.

results

showed detection efficiency radon measurement chamber under high-humidity conditions closest chamber pressure 70.9kPa thereby determining optimal operating pressure LPERM Under operating pressure, effects ambient temperature relative humidity detection efficiency LPERM further studied.

Experimental

results

indicated relative humidity increased detection efficiency exhibited slight overall decreasing trend. average detection efficiency moderate humidity range detection efficiency stabilized approximately 11.0%; detection efficiency Except extremely humidity condition, differences detection efficiency under other humidity conditions within standard deviations, demonstrating consistency.

Comparison revealed detection efficiency lower temperature slightly higher under relative humidity, differences between temperature conditions within statistical uncertainty.

Overall, detection efficiency LPERM developed paper remained stable, indicating instrument effectively suppress influence variations ambient temperature humidity measurement results, thereby exhibiting environmental adaptability measurement stability.

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Declaration Generative During preparation work, authors ChatGPT-5.3 DeepSeek-V3.1 purpose language editing grammar checking only. improve readability clarity text.

After using tool, authors reviewed edited content needed responsibility content published article. generate scientific data, perform analysis, formulate conclusions.

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Note: Figure translations are in progress. See original paper for figures.