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Determination of the radon transfer velocity coefficient in water under static and turbulent conditions

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ABSTRACT

The risk associated with the inhalation of radon gas has prompted numerous studies analyzing its behavior and transport from its generating source (soil, water or building materials) to its accumulation in enclosed spaces. In this research, the process of radon gas release from water to air in hermetically sealed equipment and under controlled conditions at laboratory scale is analyzed.

The experimental measurements have been later processed and analyzed by an iterative algorithm, based on the minimization of the squared error, to develop a dynamic model through which the transfer velocity coefficient (k) is obtained in different test conditions. From the experimental results and the dynamic model a coefficient of $(1.4 \pm 0.14)\cdot10^{-3}$ m h^{-1} is obtained for static water conditions and $(2.4 \pm 0.6)\cdot10^{-3}$ m·$h^{-1}$for turbulent water. It is verified that the escape process of radon gas in water is slower when it is in a static state, without turbulence. Finally, the coefficient is validated by calculating the estimated radon concentration evolution in air, which in turn is compared with the experimental results.

1. Introduction

Radon is a noble gas produced during the radioactive decay of uranium and radium. Among the three existing isotopes of radon gas, radon-222 (^{222}Rn) is the most stable, with a half-life of 3.82 days. This gas is found naturally in soil, depending on its composition and type of rock, in some building materials whose raw materials contain radium and uranium and in water, when gas dissolves in underground currents, lakes or wells.

In 1988 radon was classified as a human carcinogen by the International Agency for Research on Cancer (IARC), the World Health Organization (WHO) specialized cancer research agency. Exposure to radon gas leads to an increase in lung cancer cases in the population and contributes significantly to the ionizing radiation dose received by humans (WHO, 2009).

Radon levels vary widely depending on where its concentration is measured. Regardless of its generating source, radon can travel through building materials, pass through slabs, walls or enter through cracks, and tends to accumulate in closed locations without ventilation, increasing the risk associated with its inhalation. While radon average concentration in the open air is around 10 Bq·m^{-3} (UNSCEAR, S., 2000), in homes or workplaces it can reach more than 10,000 Bq·m^{-3} (WHO, 2009). In underground water, radon concentration varies according to the level of uranium in sediments: in contact with crystalline rocks, the radon concentration in water varies between $1\cdot10^2$ and $5\cdot10^4$ Bq·L^{-1} while, in sedimentary rocks or aquifers, the value varies between 1 and 50 Bq·L^{-1}(Cosma et al., 2008). Given its short half-life, radon cannot be transported from great depths by a diffusion system, but it can be transported by a rising gas and bubbles or a water column (Rábago Gómez, 2013). If radon incorporates into the water in the last part of the transport process, before release to the atmosphere, it can be used as a tracer (Burnett and Dulaiova, 2006; Baskaran, 2016).

According to International Commission on Radiological Protection the main pathway for human exposure to radon is its inhalation and to a lesser extent, by ingestion (ICRP 137, Part 3, 2017). Even though radon gas is a chemically inert element, a part of inhaled radon is absorbed from the lungs into the blood stream. Absorbed in the pulmonary blood, it is distributed through the arterial blood to the tissues and subsequently transferred to the venous blood. Finally, it returns to the pulmonary blood from the venous blood where a part of the gas is exhaled, and the rest returns to the arterial blood to continue the cycle. This cycle is defined by the Biokinetic model for systemic radon in ICRP 137 and is used to calculate the dose by inhalation of radon gas. The transfer rate between the blood and the different tissues of the human body depends

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on the blood flow rate, the different tissue and blood volumes, as well as the relative solubility of radon in blood and tissues, which is represented by the coefficients tissue-blood partitioning (ICRP, 2017)..

Regarding ingestion, as radon is soluble in water, if there are high concentrations in drinking water, ingestion can be an important pathway for radon exposure. Radon can be easily absorbed from the alimentary tract into the blood, although the site of absorption has not been established with certainty: stomach or small intestine. Some researchers have considered that it is absorbed in the same proportion in both places (ICRP, 2017).

During the inhalation or ingestion process, the ionizing alpha particles emitted by their short-lived descendants interact with biological tissues causing extensive DNA damage.

The effect of alpha particles on people's health of alpha particle exposure depends on how each individual is exposed. These particles lack the energy to penetrate the outer layer of the skin, so external exposure to the body (or contamination) does not pose a high risk. However, once inhaled or ingested, they can damage sensitive living tissue. They can release high energy, between 10 and 50 cGy in a few cells during the ionization process. In DNA, this type of particle can cause large groups of multiple ionizations, both in nearby DNA and in adjacent molecules, causing severe localized damage (Chauhan et al., 2012).

To quantify the effect of damage caused by radon gas and its decay products, it is necessary to analyze the dose received. For this purpose, the ICRP 137 provides revised dose coefficients for occupation intakes of radionuclides for both ingestion and inhalation. These coefficients are updated regularly and depend on each age group, differentiating between men and women.

Due to radon dangerousness, in the las few decades, numerous researchers have studied and analyzed radon transport from different sources as soil, building materials or water until its release to air (Soniya, S.R. et al., 2021; Chakraverty, S et al., 2018; Ye, Y.J et al., 2014). The transport of radon is given by two processes: diffusion and advection. The diffusion process is the predominant process given by the gradient in concentration between the initial migration point and the end point. However, the advection (convection) process is given by a pressure difference. Diffusive transport is determined by the properties of the medium in which the transfer occurs such as the diffusion length, which is the distance that radon can travel before disintegrating. This distance varies greatly depending on the diffusion material: in air, this length can reach 2.2 m (IAEA, 2013) and in water, between 0.2 and 0.3 m (Singh et al., 1993; Hassan et al., 2009). It should be noted that, as radon gas is also water soluble, its transport up to 5 km is possible in underground flowing streams. Radon remains dissolved in water until a gas phase is introduced, for example by turbulence or pressure difference. In pure water, for example, convection generated by the thermal gradient and transport by microbubbles could be one of the main radon transports (Varhegyi et al., 1992).

Given the transport properties of radon, one of the most important processes to analyze is its release from water since the risk associated with its exposure is mainly due to inhalation, when the gas is released into the air, and not due to drinking water ingestion. Some investigations have analyzed the release of radon at the surface of an aquifer (Klein et al., 1995; Monnin and Seidel, 1997) while others have assessed radon exposure from different water sources (Bernhardt,1996). In all these cases, radon escapes from the water through the water-air interface until it reaches the air. However, transport at the interface water-air, has not been extensively studied, despite the availability of some research in which the transfer between both media is modeled (Calugaru and Crolet, 2002). The radon flux at the interface is defined as a function of its concentration in both phases, considering two constants: the Ostwald coefficient ($\boldsymbol{\alpha}$) and the transfer velocity coefficient ($\boldsymbol{k}$). The Ostwald coefficient represents the relation under equilibrium conditions between the concentration of radon in water and in air, which defines the solubility of radon in water, and it varies between 0.157 at 40 °C and0.525 at 0 °C. The radon transfer velocity coefficient represents the ease for radon to transfer from water to air and ranges from 10^{-4} m s^{-1} (Vinson et al., 2008) and 10^{-6} m s^{-1} (Ongori et al., 2015). It is an important parameter to consider during the study of human exposure to radon gas inhalation in locations where its release from water to air occurs.

The main objective of this research is to determine the radon transfer velocity coefficient at the water-air interface under static and turbulent water conditions. For this purpose, experimental equipment is designed to perform measurements under controlled conditions at laboratory scale and a dynamic mathematical model has been developed to model the gas transfer process.

2. Methods and materials

This section describes the methodology followed in the research: the experimental procedure, the dynamic equations that model the behavior of radon gas as well as the procedure followed for this modeling.

The experimental methodology aims to simultaneously analyze the concentration of radon in water and in air. For this, tests are carried out in a 120 L high-density polyethylene deposit, impermeable to radon and hermetically sealed. Its tightness has been validated by applying the protocol detailed in ISO 11665-13. The obtained leak constant was set at $\lambda_p = 0.000579\, h^{-1}$, lower than the acceptable value according to ISO ($\lambda_p = 0.00358\, h^{-1}$) (Noverques Medina, 2022). The experimental setup consists of a metal support, located 605 mm from the base, on which the air radon detector is placed, and a tap, located 240 mm from the base, which allows the extraction of water samples.

Initially, the deposit is filled with 25 L of radon-free water and a natural radium source (0.27 ± 0.27 kBq) is immerse in a hermetic bag. The bag, water impermeable, prevents entry of the water and favors the diffusion of radon to water. The gas diffusion from the source to the water produces an increase in the concentration of radon in water. Once a certain concentration is reached, according to previous tests (Noverques Medina, 2022), the source is removed by opening the deposit quickly. Inevitably, there is the loss of a small concentration of radon. However, once closed, the release of radon from the already enriched water to the air continues to be monitored during decay.

Based on the experimental results of radon concentration in water, the transfer velocity coefficient, $\boldsymbol{k}$, will be calculated from the developed numerical model. Likewise, by results of air radon concentration, measured simultaneously inside the deposit, the coefficient and, therefore, the developed model will be validated.

The tests are carried out firstly in static water and secondly in turbulent water conditions. In the first case, the water remains stagnant while in the second, an aquarium submersible pump has been installed, setting a flow rate of 300 L h^{-1}. The tests have been carried out at different times, the water has not been reused and both experiments have been done separately.

Fig. 1 shows the two experimental setups for static water and turbulent water. In both cases, the water is already enriched, and its release into the air occurs. It is also observed the metal support on which the air radon detector is located and the tap through which the water samples are extracted.

Water radon concentration is analyzed by scintillation detector *Hidex 600 SL*. The detector measures low-intensity light that is produced when the water sample, which contains radon emitting alpha and beta radiation, is mixed with liquid scintillation Maxilight. The light is collected on the photocathodes of the photomultiplier tubes (PMT) inside the Hidex 600SL and is transformed into an electrical signal, as a spectrum, which determine the water radon concentration (Hidex 600 SL Manual, 2021). In the tests, 8 mL of water are introduced into a Teflon vial containing 12 mL of liquid scintillation. The water must be introduced into the liquid, avoiding the formation of bubbles and the loss of radon gas. The sample is shaken for 1 min and analyzed after 3 h, until the

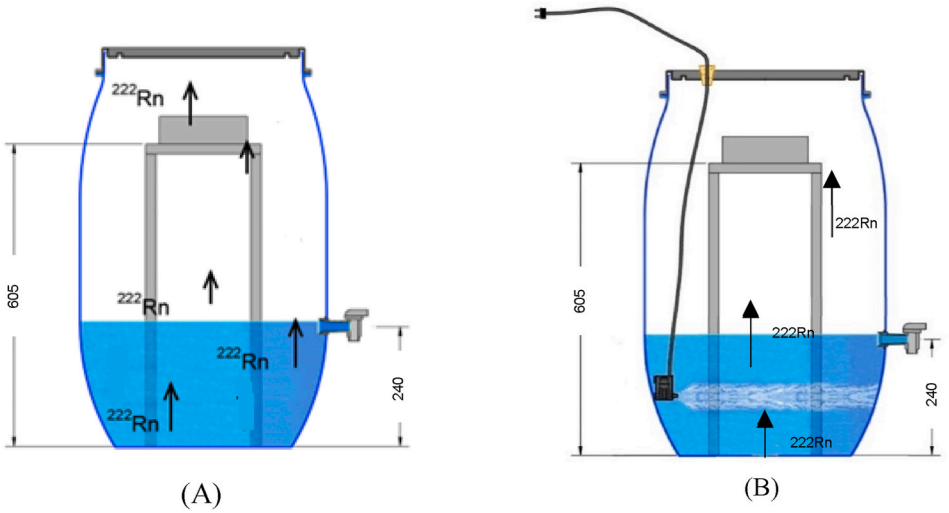

Fig. 1. Experimental equipment for the analysis of radon gas decay. (A) Water under static conditions. (B) Water under turbulent conditions.

radon reaches equilibrium with its progeny.

Radon concentration in air is measured by the Radon Scout Plus a continuous detector. It is a solid-state silicon detector with a diffusion chamber that quantifies the alpha particles emitted by radon decay products. Due to its small size, of 175 x 135 x 55 mm and a weight of 800 g, it is widely used. At a range between −10 °C and 40 °C, the measurement range varies from 0 to 2 MBq·m^{-3}. The uncertainty is set below 10% (User Manual Radon Scout Plus, 2017). This detector allows continuous measurement, hour by hour.

In turbulent water conditions, the experimental procedure followed is the same as in static water conditions, but a submergible pump is added to maintain a continuous agitation during the whole process of measuring radon in water and air.

2.1. Modelling of radon accumulation in water

In this research, a single mathematical model has been proposed to analyze radon release from water to air, regardless water conditions (static or turbulent). This is because the velocity radon transfer coefficient (k) includes two components: diffusivity (static transfer velocity) and the convective component (due to fluid motion). When the fluid is static, the transfer velocity coefficient (k) and the diffusivity coincide. The effect of turbulence is given by the convective part, which is included in the value of k. Therefore, the same mathematical model is valid for static and turbulent conditions, just changing the contributions of diffusion and convective part of the transfer velocity coefficient, k.

The radon transfer process inside the experimental device is shown in Fig. 2, considering its release from water to air as well as radon decay in both sites.

Considering the aqueous medium as the control volume, the mass balance follows equation (1)

$$\frac{dC_W}{dt} = -\frac{S\,F(t)}{V_W} - \lambda C_W(t), \tag{1}$$

Where $C_w(t)$ is the radon concentrations in water (Bq·m^{-3}); S is the contact surface of water-air interface (m^2); $F(t)$ is the radon gas flux (Bq·m^{-2}·h^{-1}); V_W the water volume (m^3) and λ, the radon decay constant (h^{-1}). The flux is defined as followed in equation (2)

$$F(t) = k[C_w(t) - \alpha C_a(t)], \tag{2}$$

being (k) the transfer velocity coefficient(m·s^{-1}); α the Ostwald coefficient and $C_a(t)$ the radon concentrations in air (Bq·m^{-3}).

equation (2) is substitute into equation (1) according to equation (3)

$$\frac{dC_W}{dt} = -\frac{S\,k[C_w(t) - \alpha C_a(t)]}{V_W} - \lambda C_W(t). \tag{3}$$

By readjusting the terms and integrating in a time interval between T_0 and T_1 it is obtained equation (4), which models the evolution over time of radon concentration in water, considering its disintegration and air transfer

$$C_w(T_1) = C_w(T_0)\, e^{-\left(\frac{S\,k}{V_W}+\lambda\right)(T_1-T_0)} + \frac{S\,k\,\alpha}{V_w}\left[\frac{C_{a\,exp}(T_1)e^{\left(\frac{S\,k}{V_W}+\lambda\right)T_1} + C_{a\,exp}(T_0)e^{\left(\frac{S\,k}{V_W}+\lambda\right)T_0}}{2}\right] e^{-\left(\frac{S\,k}{V_W}+\lambda\right)T_1}. \tag{4}$$

Being $C_w(T_1)$ and $C_w(T_0)$ radon water concentration (Bq·m^{-3}) at the instant of iteration (T_1) and at the previous instant (T_0) and $C_{a\,exp}(T_1)$ and $C_{a\,exp}(T_0)$ radon in air concentration measured experimentally (Bq·m^{-3}) at the same instants.

This equation allows to calculate the transfer rate coefficient, (***k***), which determines how the release of radon gas from water to air occurs, i.e., the rate of transfer from one medium to another (Vinson et al., 2008;

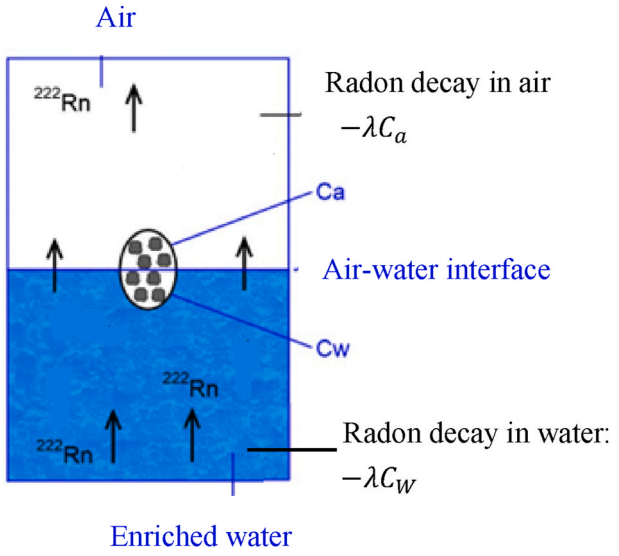

Fig. 2. Radon transfer from water to air.

Lindsay et al., 2015). The coefficient k is calculated by minimizing quadratic errors between the estimated (iterative) radon concentration and the experimental radon concentration, according to *Matlab* function, a nonlinear programming solver that finds the minimum of unconstrained multivariable function using derivative-free method.

The value of ($\boldsymbol{k}$) can be determined through the iterative process from a single initial value of radon concentration in water, initially considering that the concentration in air is zero. This process is a great advantage over water and air sampling that requires a large volume of experimental data.

When the transfer rate coefficient has already been calculated, the radon concentration in air can be estimated. By integrating equation (3), analogously to the procedure followed for C_w, the radon concentration in air is

$$C_a(T_1) = C_a(T_0)\, e^{-\left(\frac{S}{V_a}\frac{k}{\alpha}+\lambda\right)(T_1-T_0)} + \frac{S}{V_a}\frac{k}{\alpha}\left[\frac{C_{w\ exp}(T_1)e^{-\left(\frac{S}{V_a}\frac{k}{\alpha}+\lambda\right)T_1} + C_{w\ \ exp}(T_0)e^{-\left(\frac{S}{V_a}\frac{k}{\alpha}+\lambda\right)T_0}}{2}\right] e^{-\left(\frac{S}{V_a}\frac{k}{\alpha}+\lambda\right)T_1}, \quad (5)$$

when $C_a(T_1)$ and $C_a(T_0)$ are radon in air concentration (Bq·m^{-3}) at the instant of iteration (T_1) and at the previous instant (T_0) respectively; V_a air volume (m^3) and $C_{w\ exp}(T_1)$ and $C_{w\ \ exp}(T_0)$ radon water concentration measured experimentally (Bq·m^{-3}), at the same instants.

2.2. Procedure for modeling the experimental results

The procedure is based on processing the experimental data of water radon concentration to obtain, using the developed dynamic model, the transfer rate coefficient. The steps followed are detailed:

- ***Processing*** of the experimental data of radon in water: only decay period values are selected.

▪***Calculation*** of the transfer rate coefficient ($\boldsymbol{k}$) according to equation (4), starting with an initialization parameter of ($\boldsymbol{k}$). The algorithm allows a fast convergence. From the experimental data, the best approximating numerical solution is found by minimizing the sum of the square of the residuals, calculated as the difference between estimated and experimental data.

▪***Validation*** of the transfer rate coefficient ($\boldsymbol{k}$): the value of the coefficient is used to calculate the estimated concentration of radon in air through equation (5). This concentration is compared with the experimental air concentration values measured in the laboratory.

For both estimated radon concentrations in water and air, upper and lower limits are calculated with 95.5% confidence (±2 σ).

The following Fig. 3 shows a flowchart of the iterative process procedure.

Initially, the water volume and the Ostwald coefficient are known. With these parameters and an initial value of radon water concentration ($C_{w\ experim.}(t_0)$) the modeling begins according to equation (4). The radon concentration in water ($C_{w\ estimated}$) and the transfer rate coefficient, k, are iteratively obtained by *Matlab* simulation. The estimated concentration of radon in water is compared with the experimental results to verify if the obtained k coefficient is accurate.

Subsequently, from the volumes of water and air, the Ostwald coefficient, the k coefficient as well as the experimental water radon concentration and just one value of air radon concentration ($C_{a\ experim.}(t_0)$), the estimated values in air are obtained according to the modeling of equation (5). Also, the estimated air radon concentrations ($C_{a\ estimated}(t)$) are compared with experimental ones to verify model fitting.

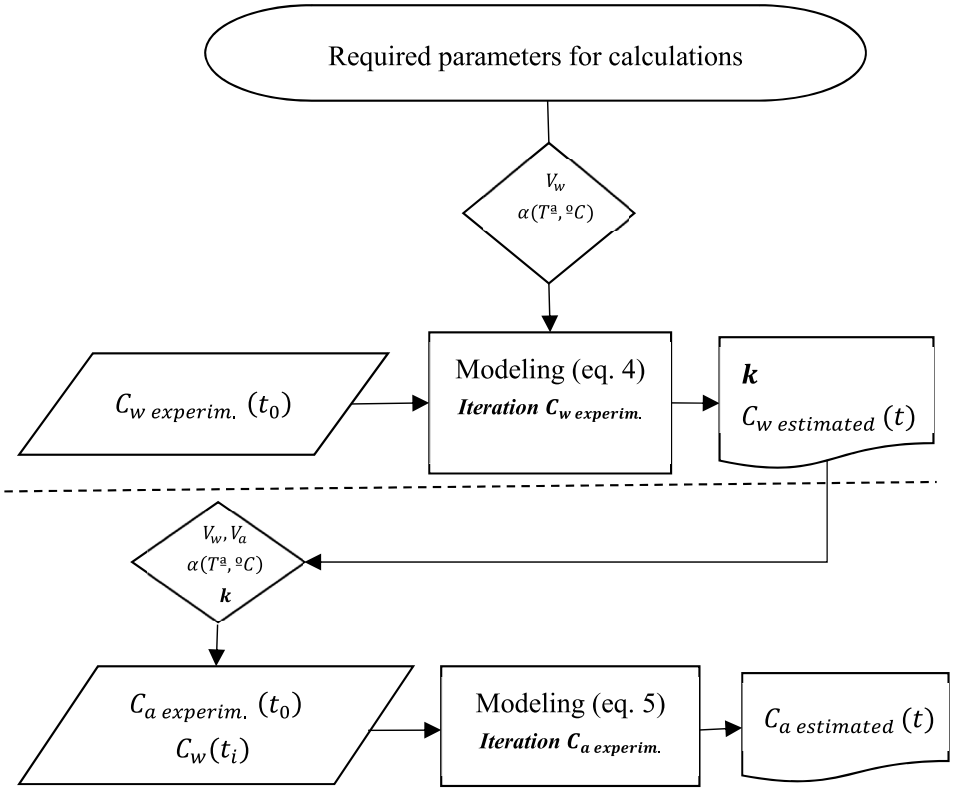

Fig. 3. Flowchart of the radon concentration estimation process for the determination of the k coefficient.

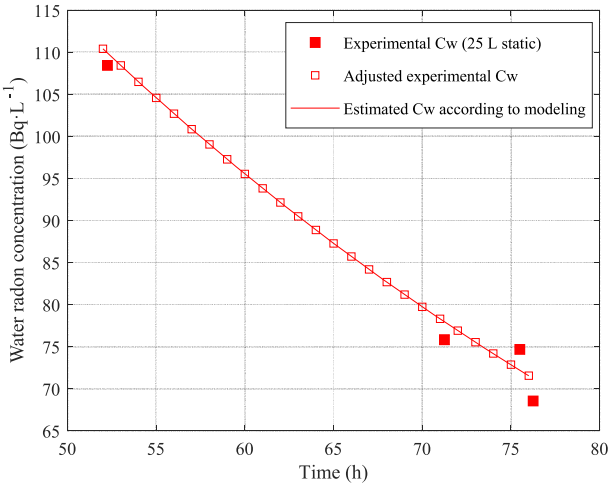

Fig. 4. Water radon concentration results. Static water conditions.

3. Results

The results obtained for the determination of the water-air radon gas transfer coefficient, both in static and turbulent water conditions are presented.

3.1. Results for static water conditions

The determination of the radon transfer velocity coefficient (***k***) is based on the experimental measurement of radon in water and air carried out at the laboratory. Once the radium source is removed from water. Furthermore, the initial point for modelling has been selected avoiding the oscillations observed in the concentration of radon in water and in air at the beginning of the decay process.

Fig. 4 shows the experimental water radon concentration measured at laboratory by Hidex 600 SL detector as well as these experimental data adjusted for hourly values and the estimated radon concentration in water calculated according to equation (4).

The adjustment of the experimental values used in the iterations and the values estimated from equation (7) fit with high accuracy and overlap as shown in Fig. 4. Thus, the value of the coefficient (***k)*** is accurately determined.

The iteration of the equation allows obtaining a low deviation of the residuals that validates the least squares technique and the calculation of the coefficient. The upper and lower limits are almost equal to the estimated radon concentration value in water, with 95.5% confidence.

From these experimental results, the transfer velocity coefficient is obtained by iteration, considering equation (4) when the water is in static conditions: $\boldsymbol{k} = (1.4 \pm 0.14)\cdot 10^{-3}$ m h^{-1}.

This value indicates that the release or transfer of radon gas from the water surface is a relatively slow process. According to the bibliography, in watertight conditions, the transfer rate ranges from $1.98\cdot 10^{-4}$ m h^{-1} to $6.33\cdot 10^{-3}$ m h^{-1} (Calugaru and Crolet, 2002). In this case, the coefficient obtained analytically is in the same range, for similar test conditions.

To validate the obtained coefficient, the estimated radon concentration in air is calculated according to equation (5) using the value of (***k***). Fig. 5 shows the experimental values of radon in air measured with the Radon Scout Plus; the estimated radon concentration in air calculated according to the model developed from equation (5) and the upper and lower limits with a confidence of 95.5%

It is verified that 85% of the experimental data is within the calculated limits with 95.5% confidence. Thus, the radon transfer velocity coefficient is validated, as well as the described exponential model for estimating radon concentrations.

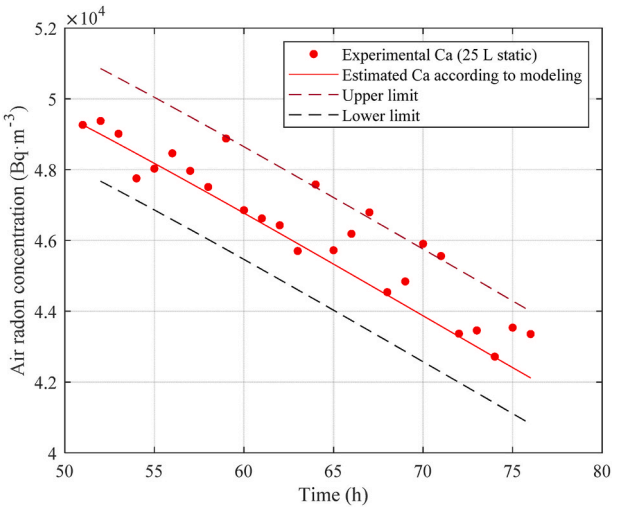

Fig. 5. Air radon concentration results, including upper and lower limits. Static water conditions.

3.2. Results for turbulent water conditions

Following the same procedure as in the previous section, the value of the radon transfer velocity coefficient under turbulent water conditions is calculated using the same iterative algorithm. As in static conditions, the iterative process requires the calculation of the estimated radon concentration in water, through an iterative process, minimizing the residual between this data and the experimental value, as shown in Fig. 6.

As shown in Fig. 6, the two experimental values measured by the Hidex detector differ slightly from the estimated values. This may be due to the water sampling, which is not performed continuously hour by hour as estimated according to the modeling.

These results confirm the need to carry out new tests, with longer exposure periods (t > 60 h) and shorter sampling times. The low temporal resolution of passive detectors such as the Hidex 600 SL tend to smooth out changes in concentrations by underestimating or overestimating concentrations (Grossi et al., 2022). For this reason, in future tests the sampling periods have been reduced, to have an optimal fit.

To verify this fitting, the transfer velocity coefficient obtained under turbulent water conditions should be applied to equation (5) to check the estimated values in air deviate from the experimental values measured by the Radon Scout detector, as shown in Fig. 7.

From the experimental results obtained and considering equation (4)

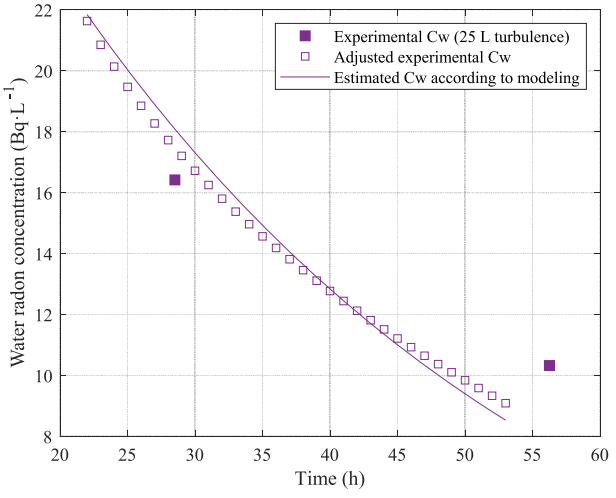

Fig. 6. Water radon concentration results. Turbulent water conditions.

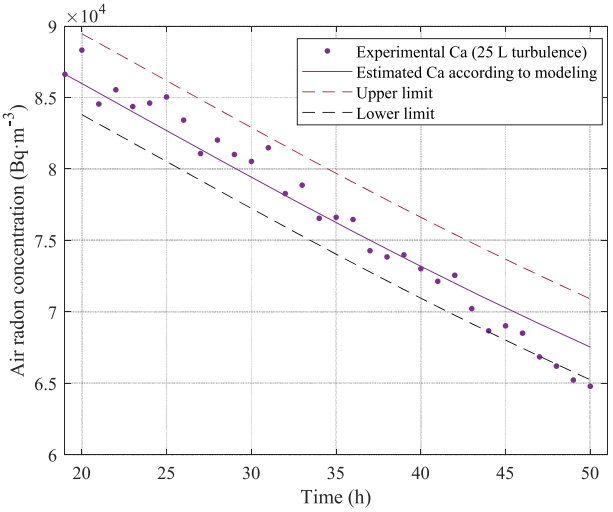

Fig. 7. Air radon concentration results, including upper and lower limits. Turbulent water conditions.

the radon transfer velocity coefficient is calculated under water in turbulence conditions: $\boldsymbol{k} = (2.4 \pm 0.6)\cdot 10^{-3}$ m h^{-1}.

This coefficient ($\boldsymbol{k}$) indicates that the release process is higher compared to the one obtained with static water conditions, as it would be expected because agitation of water favors transfer of radon to the air. This value presents the same order of magnitude compared to researches in which there is low turbulence during the tests, whose velocity coefficient is $(5.04 \pm 0.72)\cdot 10^{-3}$ m h^{-1} (Ongori et al., 2015). The variation between the two coefficients may be due to the degree of water agitation.

To validate the value of the transfer rate coefficient under turbulent water conditions, the radon concentration in air estimated according to equation (5) is calculated. Fig. 7 shows the experimental air radon concentration measured by Radon Scout Plus, the estimated air radon concentration (equation (5)) as well as the upper and lower limits with 95.5% confidence.

Fig. 7 shows the experimental radon concentration values as well as the estimated concentration ones, calculated according to equation (5), considering the transfer coefficient in turbulent conditions.

The experimental values are distributed on both sides of the straight line of the estimated concentration and 87.5% of these data are within the limits, calculated with 95.5% confidence.

After 45 h, a slight deviation is observed with respect to the proposed model, even though this model includes both the concentration of radon in the air, while decay, and the contribution of radon from the water. It is considered that this deviation is due to the adjustment of the experimental data of radon in water (Fig. 6), which underestimates the experimentally measured concentration. These results of radon concentration in air confirm the importance of making measurements in water more continuously, with shorter periods of time to obtain a better fit during modeling.

From the results obtained in both static and turbulent water, it is observed that, in decay processes, from an initial value of radon concentration in water considering some parameters such as the water volume and the Ostwald coefficient and according to equation (4), the value of the transfer velocity coefficient ($\boldsymbol{k}$) can be obtained for these specific test conditions. Likewise, if the value of the coefficient ($\boldsymbol{k}$) is known, the previous calculation is not necessary and the concentration of radon in air can be estimated, only from an initial value of air radon concentration and some values of water radon concentration $C_w\,(t_i))$, being $i \simeq 5$ points in intervals of 2–3 days.

These simulations allow very precise concentrations of radon in air to be obtained without the need to carry out a high volume of field measurements.

4. Conclusions

In this research, the radon gas transfer rate coefficient has been determined under static and turbulent water conditions.

For this purpose, an experimental equipment has been designed to simultaneously analyze the radon concentration in water and air. A passive detector, the Hidex 600 SL, has been used for water measurements, while a continuous detector, Radon Scout Plus, has been used for air radon measurements.

Moreover, a dynamic *Matlab* model has been developed to calculate the ($\boldsymbol{k}$) coefficient through an iterative process that minimizes the quadratic sum of errors. In this algorithm, the estimated evolution of radon concentration in water is also determined. Finally, considering this coefficient and the experimental results of radon in water and air, the radon concentration evolution in air is estimated.

In static and turbulent water conditions the transfer coefficient is $(1.4 \pm 0.14)\cdot 10^{-3}$ and $(2.4 \pm 0.6)\cdot 10^{-3}$ m h^{-1}, respectively. It is verified that the ($\boldsymbol{k}$) coefficient at turbulence conditions is twice as under static conditions and, therefore, much more radon is released into the air. Compared with other research, it is observed that both are between the ranges established for zero and low turbulence.

Finally, the ($\boldsymbol{k}$) coefficient is validated by calculating the estimated radon concentration in air, which is compared with the experimental values measured in the laboratory. In this case, it is also verified that both experimental and estimated values are within the established limits.

In this research, the procedure to calculate the transfer velocity coefficient in different test conditions has been validated. Likewise, based on the dynamic model developed, it is shown that air radon concentrations can be predicted in locations where there is radon in water.

From the experimental results obtained and the modeling carried out, possible improvements of the developed methodology have been observed. There is a clear need for experimental equipment to analyze the radon concentration in water continuously, to be able to compare these experimental values with those estimated according to the modeling, as is the case with the radon in air tests.

This research and the results obtained are a first step to potentially use the generated algorithm in field measurements situations. The procedure followed in this work is a reliable and accurate concentration estimation process that will be transferred to real field studies such as caves or *spas* where radon tends to accumulate in air, reaching high concentrations.

Author statement

Noverques, A.: Conceptualization, Methodology, Software, Validation, Investigation, Writing - Original Draft.

Juste, B.: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision.

Sancho, M.: Conceptualization, Methodology, Validation, Writing - Review & Editing, Supervision.

Verdú, G.: Software, Validation, Supervision, Writing - Review & Editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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