Altendorf, D., **Wienkenjohann, H.**, **Berger, F.**, Dehnert, J., Grünewald, H., Naumov, D., **Trabitzsch, R.**, **Weiß, H.** (2024):
Successful reduction of indoor radon activity concentration via cross-ventilation: experimental data and CFD simulations
Isot. Environ. Health Stud. **60** (1), 74 - 89

https://doi.org/10.1080/10256016.2023.2282686

Successful reduction of indoor radon activity concentration via cross-ventilation: Experimental data and CFD simulations

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Abstract

Advanced computational fluid dynamics (CFD) simulations are essential for predicting airflow in ventilated spaces and assessing indoor air quality. In this study, a focus was set on techniques for the reduction of indoor radon-222 activity concentration [Rn], and it is demonstrated how true-to-scale 3D CFD models can predict the evolution of complex ventilation experiments. A series of ventilation experiments in an unoccupied flat on the ground floor of a residential block in Bad Schlema (Saxony, Germany) were performed. Specifically, the 'Cross-ventilation 100 %' experiment resulted in room-specific [Rn] reductions from ~ 3000 Bq m^{-3} down to ~ 300 Bq m^{-3}. We quantitatively interpreted the results of the ventilation experiment using a CFD model with a k–ε turbulent stationary flow model characterised by the used decentralised ventilation system. The model was coupled with a transient transport model simulating indoor [Rn]. In a first approach the model overestimated the decrease in the starting of the experiment and the steady state. Adjusting the model parameters inflowing radon and inlet velocity the model results are in a good agreement with the experimental values. In conclusion, this paper demonstrates the potential of CFD modelling as a suitable tool in evaluating and optimising ventilation systems for an effective reduction of elevated [Rn].

Keywords: Bad Schlema, Germany; FD simulation; decentralised ventilation; indoor radon mitigation; natural radioactivity; radio ecology; radon-222

1. Introduction

Indoor exposure to radon-222 is identified as health risk for humans. Depending on the duration and the level of radon exposure, the risk of lung cancer increases [1,2]. High radon activity concentrations, here after referred as [Rn], especially in living and work spaces where people spend long periods of time, increase the risk. Regional case studies worldwide reveal heterogeneous indoor [Rn] distribution patterns, varying in both range and absolute [Rn], e.g. 30–1000 Bq m^{-3} in Ann Arbor (Michigan, USA) [3], 200-1000 Bq m^{-3} in Albany (New York, USA) [4], 300–7000 Bq m^{-3} Schneeberg (Saxony, Germany) [5], and 7000–14,000 Bq m^{-3} in Bad Schlema (Saxony, Germany) [6].

Two main factors are influencing the [Rn] in indoor environments: (i) the regional geology at the site, and (ii) the entry pathways of radon from the subsurface into buildings [7]. These pathways might include cracks in the base plate, cable ducts, or the connection to the sewage system [8]. To minimise the health risk for the public, the European Union (EU) has adopted an enactment for a European Basic Standards Directive 2013/59/EURATOM [9]. Consequently, a reference value of 300 Bq m^{-3} for the annual mean of radon-222 activity concentration at indoor workplaces and living spaces was defined by the Federal Government in Germany [10].

Structurally engineered solutions, such as the extraction of radon-rich soil air next to/below the building, or the installation of a radon-impermeable barrier are difficult to realise, especially in existing buildings [11]. However, techniques such as sealing cracks and gaps in foundations or implementing radon-impermeable barriers have achieved effective indoor [Rn] reductions [12,13].

One of the most promising solutions with comparatively little technical effort is installing a ventilation system. In particular, ventilation systems with heat recovery can prevent significant heat losses due to arbitrary ventilation. For this purpose, an automatic ventilation control system based on the control parameter [Rn] is currently being developed as part of an ongoing project RadonVENT [11,14].

Within RadonVENT, hourly measured [Rn] values are used to change the ventilation modes automatically and to turn the system on and off based on a certain [Rn] threshold value (100 or 300 Bq m^{-3}). In the first results published in a previous work [14], the installation of a decentralised ventilation system with heat recovery, guided by real-time [Rn] measurements, in an unoccupied flat located in a high risk area resulted in a significant reduction of indoor [Rn], decreasing from 7000 to 300 Bq m^{-3}.

In order to interpret the influence of a decentralised ventilation system on indoor radon behaviour quantitatively, a selected ventilation experiment performed in the flat was reproduced in a three-dimensional computational fluid dynamics model, short CFD model. In contrast to compartment models [15], CFD simulations offer the advantage of precisely modelling complex geometric environments while simultaneously capturing turbulent flows and complex flow patterns. They provide the flexibility to adapt parameters and boundary conditions for various scenarios. Furthermore, the visualisation of flow patterns contributes to improved comprehensibility and communication of results, especially in complex fluid analysis projects.

CFD models are instrumental to describe indoor and outdoor airflow patterns as well as concentration distributions of indoor air pollutants [16,17]. Several studies utilizing CFD models investigated the indoor radon distribution influenced by different radon exhalation rates inside rooms [18–21] or from building materials [22,23]. In addition, indoor radon distribution due to radon entry through cracks between floor and wall was modelled in Spotar et al. [24].

While many studies focused on radon accumulation indoors [18,20,24], research regarding the influence of ventilation, particularly decentralised ventilation, has been relatively scarce in the literature. Nonetheless, the following three studies have addressed related issues. Akbari et al. [16] employed a 3D steady-state model with various air exchange rates and their impact on indoor radon levels. In addition, Xie et al. [21] provided a detailed study focusing on the impact of varying inlet air velocities during unsteady conditions in a single room. Agarwal et al. [25], on the other hand, examined the effect of ventilation rates on thoron (radon-220) levels in a test house.

The work presented here aims to contribute to this knowledge gap. Therefore, the purpose of this research was to determine the potential of lowering [Rn] in indoor environments via cross-ventilation quantitatively with CFD simulations. The room-specific measured [Rn] before the experimental mode 'Cross-ventilation 100 %', was used as a starting point for the true-to-scale CFD simulation to explore the complex spatio-temporal dynamics of indoor radon reduction with ventilation in the flat.

2. Material and methods

A series of ventilation experiments, each with a duration of seven days, were set up with an installed decentralised ventilation system with heat recovery (inVENTer, Löberschütz, Germany). Generally, a decentralised ventilation system comprises of multiple smaller ventilation devices strategically positioned throughout a building. For the installed system here, two ventilation devices form a ventilation unit, creating distinct and individually controllable ventilation zones (VZs). The experiments were performed inside an unoccupied ground floor flat in Bad Schlema (Saxony, Germany) in order to determine the decrease in indoor radon. Furthermore, this flat has a partial basement located directly below the living room, while all other rooms have a direct contact with the subsoil. With the installed ventilation devices, three VZs are created inside the flat: (I) the bathroom, (II) the living room, and (III) the bedroom, the corridor, and the kitchen. Each VZ includes a ventilation device (iV14-Zero®) that supplies air (inlet) and a ventilation device (iV14-Zero®) that extracts air (outlet). An exception exists in the bathroom, where a different ventilation device the iV-Twin+® was installed. The iV-Twin+® combines two ventilation devices in one casing, creating a single ventilation unit with vertically separated air volume flows. Figure 1 shows the 3D model of the unfurnished flat, which also served as the basis for the CFD simulation, with all the defined VZ, inlets and outlets. For all performed ventilation experiments, the internal room doors are also closed and also in the CFD model of the flat. The wooden doors are relatively airtight. Nevertheless, notable gaps, approximately 3 cm in width, are present between the floor and the bottom of the door, as well as gaps up to 1 cm between the door frame and the door itself and the keyholes. The VZ III, however, is an exception, because three circular holes each with a diameter of 0.085 m were drilled in the bedroom and kitchen doors to ensure an air flow (so-called overflow area).

For this study, among all of the performed experiments, the experimental mode 'Cross-ventilation 100 %' was chosen for representation and recreation in a CFD model. In 'Cross-ventilation 100 %' mode, the defined inlets and outlets remain fixed, resulting in a preferred airflow direction.

As previously described in [14], we used a Radon Scout Plus® and Smart Radon Sensors® (SARAD, Dresden, Germany) for permanent recording of the [Rn] in all rooms including the basement and on the balcony. The measured [Rn] are a combination of the diffusive and advective radon transport, with the advective component being more dominant [26]. For the CFD modelling, the diffusive component is implemented using the measured radon emanation rate for each room (see Table 1), whereas the advective component (hereafter referred to as slope) is estimated. This slope is determined through a linear regression analysis, capturing the indoor radon rebound that occurred after the ventilation system was turned off for the first 72 hours.

Worth to mention are site-specific elevated [Rn] in the outdoor air, which have to be considered later in the modelling approach [27]. The high outdoor air [Rn] are partly due to the immediate vicinity of the residential block to a remediated uranium mining heap, for further details see [14].

3. Modelling approach

The impact of the ventilation on the [Rn] was simulated with COMSOL Multiphysics v6.1. The modelling was carried out in two steps. Firstly, using a stationary flow model the steady-state indoor flow field generated by the ventilation was computed. Secondly, the transport behaviour of the radon based on the flow field was simulated. All details about the model geometry, the governing equations, the boundary conditions, and the input parameters are provided in the following sections.

3.1. Model geometry and mesh quality

This study considers a three-dimensional domain, in which the rooms and fans are placed accordingly to their configuration at the Bad Schlema test site. As shown in Figure 1, the 3D model of the unfurnished flat consisted of three individual VZs. All VZs have an inlet and outlet, which is a fan with a diameter of 0.194 mm in zone I and a diameter of 0.154 m in zones II and III, placed accordingly to their built-in positions. A different type of fan, however, is installed in the bathroom. In accordance with the technical design of the iV-Twin+® device (inVENTer, Löberschütz, Germany), the inlet and the outlet are semicircles. Furthermore, for the most realistic representation of the model room, the plastic square inner covers of the fans are also included (see Figure 2). In order to represent the overflow area in the model, for simplification, the three existing circular holes located in the lower part of the bedroom and kitchen doors were assumed to be a rectangular horizontal gap at the doorsill. As a result, both doors have a height of only 1.78 m instead of 1.90 m, allowing the air exchange as ‘shortened doors’ in VZ III.

The solution domain uses a mesh consisting of 21,515 mesh vertices with a total number of 102,877 domain tetrahedral elements. Furthermore, the mesh was refined at the fans and at the inner covers of the fans (Figure 2), since steep velocity gradients are likely to occur in these areas.

3.2. Governing equations

Flow in general is described by the Navier-Stokes equations. COMSOL Multiphysics uses the finite element method (FEM) for solving these equations.

While the air flow inside an flat is usually turbulent [28] and a Reynolds number greater than 2000 was calculated, a standard k–ε turbulent flow model [29] was used here. This model uses Reynolds-averaged Navier–Stokes (RANS) equations, with k as turbulent energy and ε as the dissipation of turbulent energy.

The air flow was assumed to be incompressible because only minor pressure and temperature variations occurred in the rooms of the flat. Thus, for incompressible flow, the equations of motion for airflow are the continuity equation (conservation of mass):

$$\rho \nabla \cdot u = 0, \tag{1}$$

where ρ is the density of air (kg m^{-3}), and u is the velocity field and its components (m s^{-1}), and the momentum equation (conservation of momentum):

$$\rho (u \cdot \nabla) u = \nabla \cdot [-p + \mu_e], \tag{2}$$

where p is the pressure (N m^{-2}), and μ_e is an effective viscosity term, which can be mathematically expressed as [20,25]:

$$\mu_e = (\mu + \mu_T), \tag{3}$$

in which μ is the dynamic viscosity (N s m^{-2}), and μ_T is the turbulent viscosity (N s m^{-2}).

The standard k–ε model regulates the effect of turbulence on the flow field and the transport equations for the turbulent kinetic energy k and dissipation rate ε read as:

$$\rho(u \cdot \nabla)k = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon \tag{4}$$

$$\rho(u \cdot \nabla)\varepsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_E}\right)\nabla \varepsilon\right] + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}, \tag{5}$$

where the turbulent viscosity μ_T is linked to the turbulent kinetic energy k and dissipation rate ε as:

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}, \tag{6}$$

in which C_μ is a constant with the value 0.09. The equations also contain some other empirical constants, namely: $\sigma_k = 1.00, \sigma_\varepsilon = 1.30, C_{\varepsilon 1} = 1.44,$ and $C_{\varepsilon 2} = 1.92$ [29].

The transient advection–diffusion–reaction equation for simulating the displacement and decay of radon in the flat reads as:

$$\frac{\partial c}{\partial t} = S + \nabla \cdot (D\nabla c) - \nabla(uc) - \lambda c, \tag{7}$$

where c is the radon activity concentration in the domain volume (Bq m^{-3}), S represents the radon source term (Bq s^{-1}) and is expressed as $S = JA$ with the radon flux J (Bq m^{-2} s^{-1}) emanating from the surfaces, and A is the area (m^2) of the surfaces, D is the diffusion coefficient for radon in air ($2.11 \cdot 10^{-5}$ m^2 s^{-1}) [30], and λ is the radon decay constant ($2.1 \cdot 10^{-6}$ s^{-1}).

The governing equations were solved in COMSOL Multiphysics v6.1 using a coupling approach including the physics interfaces ‘Turbulent Flow, k–ε’, ‘Transport of Diluted Species’ and ‘Chemistry’.

3.3. Boundary conditions and input parameter

For the modelled representation of the ventilation experiment ‘Cross-ventilation 100 %’, the air volume flow is 58.0 m^3 h^{-1} for the iV-14-Zero device and 22.0 m^3 h^{-1} for the iV-Twin+® device in the bathroom. Considering the diameter of 0.154 m (0.194 m for iV-Twin+®), the average flow velocity in the pipe is 0.86 m $s^{-1}$and 0.41 m s^{-1} respectively, which are used as inlet velocities. The outlets are defined as pressure-driven with suppress backflow. Overall, for the incompressible turbulent k–ε flow model, a no slip boundary condition for the wall treatment is used. Moreover, a reference pressure of 1,013 hPa (1 atm) and reference temperature of 293.15 K (≙ 20 °C) were applied as initial conditions.

The initial [Rn] for each room was equivalent to the measured [Rn] right before the start of the ventilation experiment and was reported in Table 1. Furthermore, the measured radon exhalation rate and the assumed slope were used as a room-specific influx boundary condition (general inward flux), which was assigned to the surfaces at the bottom of the flat, i.e. the floor of each individual room. This boundary condition represents the inflow of radon gas from the underlying bedrock into the flat. For the representation of the elevated [Rn] in the outdoor air an additional radon influx was defined for all inlet boundary conditions. The defined influx of 75.7 Bq m^{-2} h^{-1} represented the mean value of the measured [Rn] in the outdoor air during the experimental period of seven days.

In Table 2, an overview of the various input parameters defined for the COMSOL Multiphysics simulation is summarised.

4. Results

4.1. Flow pattern in individual rooms

Figure 3 shows the horizontal and vertical differentiation of the developed stationary flow field with corresponding streamlines for VZ III. For each room, a horizontal and vertical heterogeneity was observed. The highest velocities are found at the inlets. By taking a closer look, it is apparent that the incoming air, through the inner covers, does not enter the room directly, but rather is directed radially to the side and towards the floor.

The lowest velocities were found in the bathroom, corridor and kitchen. In the bathroom, this can be explained by the design of the installed fan and the associated lower inflow velocity. While there is no installed ventilation unit inside the corridor and the kitchen has only a pressure-driven outlet, the simulation results seem consistent.

The flow path of the air is represented by streamlines, which here originate at the inlet inside the bedroom. From there, they move to the defined outlet (kitchen) and thus follow the preferred airflow direction specified in the 'Cross-ventilation 100 %' experiment. Especially for VZ III, where the so-called overflow area is realized, they show the flow between the associated rooms.

4.2. [Rn] decrease due to the ventilation experiment

4.2.1. Comparison between the measured [Rn] at 'Cross-ventilation 100 %' and the CFD model

Throughout the 'Cross-ventilation 100 %' ventilation experiment a room-specific radon reduction from ~3000 to ~300 Bq m^{-3} was achieved (see [Rn] measured in Figure 4). Thereby, the reduction of [Rn] is constantly accompanied by inflowing radon, diffusively and advectively into the flat. And, in the special case here, it is also influenced by the inflow of radon from the elevated [Rn] in the outdoor air. Based on the directly measured [Rn] before the start of the ventilation experiment the initial radon content for each room of the flat was implemented as Rn_{ini} (Table 1).

With the first modelling approach *'Model: emanation and slope with influx at inlet'* the previous described boundary conditions and input parameters (see 3.3) for each room were implemented. As can be seen in Figure 4, the first CFD simulation results showed a rather fast radon reduction. So, after four hours of ventilation, respectively six hours for the bathroom, all radon inside the rooms was gone.

This rather significant discrepancy between the first results and the actual measurements indicate that the model either overestimates the ventilation or underestimates the inflowing radon.

In order to improve the model fit, first of all the inflowing radon was modified *'Model: varied slope I'* (see Table 3). With this implementation, all rooms show a significantly better approximation to the steady-state range reached after approximately four to six hours in the experiment. The slope of the [Rn] decrease, however, does not improve. Nevertheless, especially for the bathroom, this modelling approach led to a good agreement between the experimental values and the simulation results.

Secondly, the inlet velocity was reduced by half, while the previously adopted slope was maintained *'Model: varied slope I with halved inlet velocity'*. Here it is important to mention that the reduction of the inlet velocity within the turbulent flow model reduces the velocities without affecting the indicated flow direction.

With slower inlet velocities of 0.43 m s^{-1} and 0.2 m s^{-1}, the CFD simulation results show a significantly better consistency for the first hours. In contrast, radon is overestimated during the steady state. This is particularly evident in the bathroom, where the radon doubles during the steady state part of the simulated experiment (see Figure 4A).

Since with the reduced inlet velocity the level of the modified inflowing radon is too high, it was modified further *'Model: varied slope II with halved inlet velocity'* (exception: bathroom). In the bathroom, the input parameters are the same for models *'Model: varied slope I'* and *'Model: varied slope II with halved inlet velocity'*, accordingly both show an identical curve in Figure 4A.

Especially, for the bedroom and kitchen, as part of the VZ III, this approach reproduces both the first hours and steady state very well. For the corridor, on the other hand, the simulated radon is overestimated within the first two hours, but afterwards the results also show a very good consistency. Table 3 provides an overview of the adjusted values for the inflowing radon (varied slope values).

In summary, the different steps taken to improve the model have demonstrated that an increase in inflowing radon (diffusive and advective) improves the steady-state achieved by ventilation, while a reduction in inlet velocity respectively air exchange rate improves the initial non-steady hours of the CFD model. Accordingly, the modelling approach with a varied slope and halved inlet velocities achieves the best agreement.

4.2.2. Radon transport model

Figure 5 shows an exemplary horizontal modelled radon distribution at about one hour and ten hours inside the flat (*'Model: varied slope II with halved inlet velocity'*).

In general, the model shows the highest [Rn] in the bathroom and the lowest in the living room, while the other rooms (VZ III) show [Rn] values in between. This is consistent with the behaviour of the rooms on site and the measured [Rn] values.

As with the flow model, horizontal and vertical differentiations can also be observed here. Thus, the modelled [Rn] show higher values near the ground level than near the room ceiling. The vertical distribution of the modelled [Rn] is relatively uniform for all rooms except the bathroom and kitchen. By taking a closer look into the bathroom as well as the kitchen, not only the horizontal differentiation but also the vertical differentiation of the radon distribution in the room can be seen. Both rooms show higher simulated radon activity concentrations near the left wall of the room. For the bathroom, the values differ between the left wall from 2200 to 1400 Bq m^{-3} on the right wall. Similarly, in the kitchen, radon values vary between the left wall (2,200 Bq m^{-3}) and right wall (1,600 Bq m^{-3}).

5. Discussion

The results of the ventilation experimental mode ‘Cross-ventilation 100 %’ showed different [Rn] reductions, which are influenced by (i) the initial indoor radon values before and at the start of the experiment, (ii) the ventilation setup, and (iii) the building's technical properties combined with the radon entry points. All these properties also play an important role in the representation of the CFD-model.

Looking at all the radon measurement plots for the experiment, it can be seen that the lowest reductions were achieved in the bathroom with measurement values of 600 to 900 Bq m^{-3}. While in the other rooms, with the exception of the kitchen (values between 300 and 500 Bq m^{-3}), the measured values during the experiment were between 100 and 300 Bq m^{-3} and consequently showed the pursuit value.

According to the necessary adjustments described in 4.2.1, a good representation of the ventilation experiment in a CFD model could be achieved.

5.1. Ventilation zone I

Inside the bathroom, the highest [Rn] can be found. This applies to both the measured [Rn] and the associated initial radon value (2982 Bq m^{-3}) as well as the simulated CFD results over 24 hours (Figures 4 and 5). Compared to the other rooms, the first model approach already provides a good agreement between the actual radon reduction and the CFD model, especially within the first three hours.

The increase of the slope (360 Bq m^{-2} h^{-1}), in order to represent the inflowing radon through one of the main radon source, the sewage system, clearly contributes to the model improvement.

5.2. Ventilation zone II

On the contrary the lowest measured [Rn] and initial radon values (1085 Bq m^{-3}) were found inside the living room. When looking at the measured [Rn] curve, a more linear trend can be observed for the first four hours. This as well as the outlier in the seventh hour are not represented in any of the model approaches. One possibility for the outlier is a time-limited increased radon influx into the living room due to a wind-induced negative pressure on the façade of the house.

With an increased slope of 144 Bq m^{-2} h^{-1} and a reduced inlet velocity the CFD model matches quite good with the real results.

5.3. Ventilation zone III

Unlike the bathroom and the living room, which both represent a single ventilation zone, VZ III consists of three rooms: the bedroom, the corridor and the kitchen.

While the bedroom (2840 Bq m^{-3}) and the kitchen (2786 Bq m^{-3}) show similar initial values, the corridor is characterised by a lower initial radon value of 1749 Bq m^{-3}. The achieved reduction of indoor [Rn] through the ventilation experiment varies between the three rooms.

As shown in the turbulent flow model (see chapter 4.1), the air flow develops from the inlet in the bedroom through the overflow area in the corridor to the outlet in the kitchen. This air flow field's influence is particularly evident in the kitchen. The ‘fresh’ air enters the kitchen via the overflow area and creates a flow path towards the right wall. In this kitchen area with direct air flow, the [Rn] are lower than in areas with less or hardly present flow and air circulation. As the simulation time progresses, this heterogeneity remains.

Like for the living room, the model with the adjusted slope and the reduced inlet velocity shows the best agreement. With an inflowing radon of about 360 Bq m^{-2} h^{-1}, the simulated radon curve in the bedroom corresponds very well with the experimental result. Whereas for the corridor, radon is overrepresented within the first two hours. One possible explanation could be the onward transport of the radon-rich air from the bedroom into the corridor, along the developed turbulent air flow.

For the kitchen, however, a significantly higher slope of 1080 Bq m^{-2} h^{-1} had to be assumed. As in the bathroom, one reason for this high adjustment may be the direct connection to the sewage system, which is known for a major source for radon. Moreover, the kitchen is the extraction room of the VZ, which leads to higher [Rn] of the inflowing air and to less dilution of the polluted air in the room.

5.4. Additional aspects influencing ventilation efficiency

Considering the simulated decay curves of the first CFD model (‘*Model: emanation and slope with influx at inlet’*), it becomes evident that either the ‘effective’ air volume flow of the ventilation units is lower or the inflowing radon is significantly higher than assumed.

While the increase of the inflowing [Rn] led to a model improvement especially in the steady state part of the ventilation experiment, the halving of the inlet flow velocity, on the other hand, led to an improvement of the agreement for the first hours of the ventilation experiment.

Furthermore, the tightness of the flat or house can influence the behaviour of the indoor radon [23]. With the help of a blower door test, numerous leakages were found inside the flat. These include the sockets in the exterior walls, cable penetrations of the ceiling lights, or gaps on the floor to exterior and interior walls. In summary, the leakages are distributed very inhomogeneously throughout the flat with the worst airtightness in the bathroom. The determined leakage rate at a pressure difference of 50 Pa for the bathroom was 115 $m^3 h^{-1}$, and thus corresponds to an air exchange rate of 9.45 h^{-1} (n_{50}).

These leakages of the building envelope can have effects in both directions, so that additional pathways for the reduction of the [Rn] or on the other hand pathways for the entry of radon can be created. All leakages that were found are not reproduced in the CFD model and can thus contribute to explaining the differences between reality and the CFD model.

Also, the heterogeneous radon distribution inside the flat as well as inside the individual rooms plays an important role. Thus, especially in the kitchen, in areas which are less influenced by the turbulent flow field, significantly higher [Rn] could be observed. These findings are consistent with other studies, in which the [Rn] are lower in the areas of the flow field [18,20,21]. While increased [Rn] therefore can be found mainly in the corners of the rooms, which are less affected by the flow field.

Accordingly, this radon remains longer in the room, but is nevertheless exchanged sooner with a constant and permanently running ventilation than in 3.8 days (decay process of radon).

These heterogeneities result in different radon curves at different model points. This may influence the results discussed here because they are based on the model points representing the locations of the radon measuring devices in the room. Assuming that there are areas in the room with more or less radon, it might be useful to average the measured values in the model room over the volume integral.

6. Conclusion

We used an advanced CFD model to reproduce the ventilation experimental mode 'Cross-ventilation 100 %'. Thereby, the different room-specific [Rn] and the resulting radon behaviour caused by the ventilation experiment posed a particular challenge.

For this purpose, a true-to-scale three-dimensional model of a flat affected by elevated indoor [Rn] was built and important features such as the position of the fans as well as their inner covers were included as accurately as possible.

The initial modelling approach displayed a significant decrease in indoor radon levels that occurred much more rapidly than observed in the actual ventilation experiment. After adjusting the model parameters inflowing radon (slope) and inlet velocity the CFD model results are in a good agreement with the experimentally derived values of the flat.

Similar errors occurred in modelling the 'Cross-ventilation 75 %' ventilation experiment, not discussed in this paper, using the same CFD model. Here, too, the previously described modifications led to an improvement of the model. While the CFD model is designed to be as accurate as possible, there could still be systematic errors in the model setup. One possibility for such errors is the absence of room leakage in the

CFD model, which can lead to increased air exchange or radon input. Further investigations will be necessary to explore this issue more thoroughly in the future.

Acknowledgements

The authors acknowledge the infrastructure and support of SARAD GmbH in Dresden, inVENTer GmbH in Löberschütz, Bergsicherung Schneeberg GmbH & Co. KG, the Gebäude- und Wohnungsverwaltung GmbH Schlema and the Staatliche Betriebsgesellschaft für Umwelt und Landwirtschaft in Chemnitz.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding details

This work was supported by the German Federal Ministry for Economic Affairs and Climate Action on basis of a decision by the German Bundestag under Grant ZF4315809PR9 and ZF4115006PR9.

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Tables

Table 1. Parameters used as input for the numerical CFD model (* copied value from corridor).

Room	VZ	Inlet/Outlet	Area (m^2)	Volume (m^3)	Initial [Rn] before experiment (Bq m^{-3})	Radon exhalation rate (Bq m^{-2} h^{-1})	Slope (Bq m^{-2} h^{-1})
Bathroom	I	Inlet/Outlet	5.2	12.2	2,982	2.2*± 0.1	114.9
Living room	II	Inlet/Outlet	21.9	51.2	1,085	5.3± 1.1	23.9
Bedroom	III	Inlet	14.3	33.5	2,840	2.7± 1.4	85.0
Corridor	III	-	6.2	14.4	1,749	2.2± 0.1	49.6
Kitchen	III	Outlet	8.3	19.4	2,786	5.0± 0.4	97.5

Table 2. Input parameters.

Name	Expression	Description
Inlet U0_100	0.86 m s^{-1}	Inflow velocity at iV-14-Zero® device (living room and bedroom)
Inlet U0_100_Twin	0.41 m s^{-1}	Inflow velocity at iV-Twin+® device (bathroom)
Outlet		Pressure-driven
D_radon	2.11×10^{-5} m^2 s^{-1}	Diffusion coefficient of radon in air [30]
Lambda_radon	2.1×10^{-6} s^{-1}	Decay constant of radon
Influx_Exp	75.7 Bq m^{-2} h^{-1}	Additional radon influx placed at all three inlet boundary conditions

Table 3: Overview of the modified inflowing radon at the floor (slope) with U_0 – inlet velocity, $U_0/2$ halved inlet velocity and CV – 'Cross-ventilation 100 %'.

Room	Slope (Bq m^{-2} h^{-1})	Varied Slope I with U_0 and with $U_0/2$	Varied slope II with $U_0/2$ for CV 100 %
Bathroom	114.9	360 (3-times)	360 (3-times, U_{Twin})
Living room	23.9	252 (10-times)	144 (6-times)
Bedroom	85.0	720 (8-times)	360 (4-times)
Corridor	49.6	540 (10-times)	360 (7-times)
Kitchen	97.5	1728 (17-times)	1080 (11-times)