Effects of Heat Recovery Ventilation Systems on Indoor Radon

***Keramatollah Akbari*[a], *Jafar Mahmoudi*[b]**

[a]*TDI researcher at ACECR, Iran and Mälardalen University, PhD student, School of Sustainable Development of Society and Technology, Västeras, Sweden*
keramatollah.akbari@mdh.se

[b]*Mälardalen University, Adj Professor at School of Sustainable Development of Society and Technology, Västeras, Sweden* *jafar.mahmoudi@mdh.se*

Abstract

A heat recovery ventilation system enables us to control indoor conditions such as ventilation rate, temperature, relative humidity and pressure difference. These environmental conditions affect indoor radon levels.

Computational fluid dynamics (CFD) is a powerful tool for predicting and visualizing radon content and indoor air quality and is cost effective in comparison with other methods such as full scale laboratory and gas trace techniques.

In this study a mechanically balanced ventilation system and a continuous radon monitor (CRM) were used to measure the indoor ventilation rate and radon levels. In a numerical approach the FLUENT CFD package was used to simulate radon entry into the building and effects on indoor air conditions.

The effects of different ventilation rates, indoor temperature and relative humidity on indoor radon concentrations were investigated in a one family detached house in Stockholm. Results of numerical studies indicated that changes of ventilation rate, indoor temperature and moisture by means of ventilation systems have significant effects on indoor radon content. Ventilation rate was inversely proportional to indoor radon concentration. Minimum radon levels were estimated in the range of thermal comfort, i.e. at 21℃ and relative humidity between 50-70%.

The analytical solution was used to validate numeric results at 3 distinct air change rates. Comparisons between numerical and analytical results showed good agreement but there was poor agreement between simulations and measurement results due to the short measuring period.

Keywords:

Numerical modeling, Radon mitigation, Balanced Ventilation, Residential buildings

Nomenclature

A	surface (m^2)
C	radon concentration $(\mathrm{Bq}.m^{-3})$
D	diffusion coefficient
D_h	hydraulic diameter
E	radon exhalation rate $(\mathrm{Bq}m^{-2}h^{-1})$
G	source term
K	turbulence kinetic energy
Pa	Pascal
T	temperature (℃)
V	volume of the house (m^3)
U_r	equivalent room velocity
ρ	density $(\mathrm{kg}.m^{-3})$
ε	energy dissipation rate
λ_v	air change rate (h^{-1})
λ_{Rn}	radon decay constant $(2.1 \times 10^{-6}\ s^{-1})$
ν	air kinematic viscosity $(1.1 \times 10^{-5} m.s^{-1})$
ATD	alpha track detector
CFD	computational fluid dynamics
CRM	continuous radon monitor
HRV	heat recovery ventilation system
Re	Reynolds number
RH	relative humidity

1.Introduction

Understanding indoor radon transport and distribution is a priority, and for this it is important to be able to predict indoor air quality and the exact value of radon level at different points and areas, especially in breathing zones in residential buildings.
Indoor radon distribution and treatments have been studied through measurements and full scale laboratory and tracer gas models. These methods are rather expensive and time consuming. Analytical methods are also limited to varying ventilation rates, and radon measurements are generally expressed as average monthly or annual levels.
A numerical modeling approach using computational fluid dynamics (CFD) techniques may be a powerful and cost-effective tool to study and predict indoor radon distribution. Numerical models can be used to estimate the importance of specific factors for radon entry. These models also can provide a cost-effective test bench for improved designs of radon prevention systems [1,2].
CFD techniques are based on solving the transport equations iteratively and are employed to solve equations involving velocity, temperature and species transport numerically in a finite volume. They describe the processes in the ventilated room, including the conservation of mass, energy, momentum and species such as radon [3, 4].
Numerous studies have used CFD to study the distribution of indoor air flow and radon concentration in two and three dimensions. Some of these studies are described in the following paragraphs.
Zhuo [5] used CFD to study the concentrations and distributions of indoor radon in three dimensions. According to the results of this simulation, the distribution of radon in a ventilated room is uniform except at locations near air diffuser vents. He showed that the results of simulations of activities and their distributions agreed well with experimental results in a laboratory.
Feng and Persily [6] performed computer simulations of airflow and radon transport in a large building using the multi-zone airflow and pollutant transport model CONTAM88. This study investigated ventilation system factors including the operation of exhaust fans and variations in outdoor air intake.
Wang and Ward [7] used the CFD package FLUENT to develop a model of multiple radon entry in a house with a cellar. In order to develop the model, they applied methods such as using a subroutine to specify the radon generation rate in the soil cells and designed appropriate boundary conditions. The model was verified by a grid-independency test and convergence behavior analysis. The inter-model validation technique and comparison with analytical solutions were also used to validate the model.
Cohilis [8] suggested the use of a numerical code based on the finite difference method. Based on the results and the code validation, they concluded that this method was a powerful tool that could predict and evaluate the performance of subfloor ventilation strategies.
Rota [9] compared the results of numerical simulations and experiments. The results showed good agreement, but the simulation results showed elevated concentrations in the region with low ventilation rates compared to the experiments. Unlike the previous cited works, this study focuses on indoor radon concentration, in this case the diffusion and advection forces are considered and there is not any radon decay and generation rate.

1. Material and Methods

In this study a continuous radon monitor (CRM) and alpha track detectors (ATD) were used to measure indoor radon concentrations. A one family detached house with a rotary heat exchanger ventilation system was used in a case study. Numerical methods, measurement and analytical calculations were used to estimate radon levels, as detailed in the following section.
The house consists of eight rooms with a total volume of $12\times9\times2.4$ m^3. Each room has its own vent except for Room 8, which shares a vent with Room 6. All doors are kept open. A rotary heat exchanger is placed in Room 4. The effect of the heat exchanger is ignored and an outlet vent is considered in Room 4 to play the role of the heat exchanger. Figure 1 shows the geometry of the house plan.

2.1. Numerical method

In the numerical approach the commercial CFD package including GAMBIT was used to define the geometry, and FLUENT 6.3 [10] was used as the solver for calculations to simulate radon entry into the building and ventilation effects.
The selected 3dimentional model was: species transport, pressure base and steady state, k–ε turbulence, and the SIMPLE algorithm were used to calculate and predict radon concentration at all grid locations numerically.

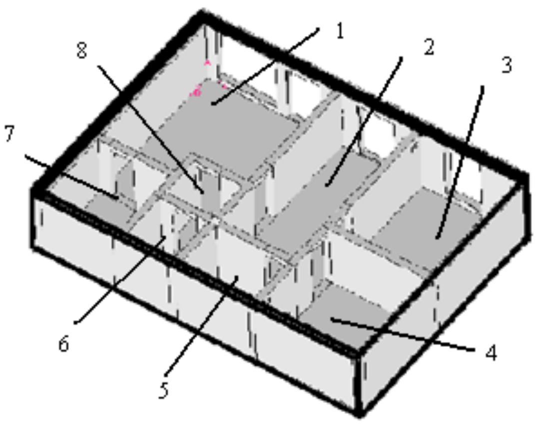

Fig.1. The geometry of the house plan

The model is meshed with 376238 hexahedral cells with 10 cm vertices in order to solve the conservation equations of various fluid properties within each cell. These equations are flow, energy, turbulence, radon and humidity.
Three criteria were considered to confirm the model convergence. The first criterion was the residuals of equations residuals could not change drastically through iterations and the residuals of all the conservation equations had to be less than 1×10^{-7}.
The second criterion was that the concentration of radon in one of the rooms (Room 1) could not change through iterations. The third criterion concerned the rate of radon passing through the outlet. As the model is solved for the steady state, all radon which is generated in the floor must also pass through the outlet, i.e. radon rate from the outlet must be equal to the radon generation rate. Specifically, radon rate through the outlet must be 2 bq/s and 3 bq/s for 1 Pa and 2 Pa pressure differences respectively. In order to avoid residual instability and oscillations, under relaxation factors were adjusted to speed up the convergence.
The results of using 376238 and 752476 cells were compared to ensure that the grid cells were sufficiently small to ensure accurate results.

The model was solved for four different air change rates. Specifically, Ach=0.05, 0.25, 0.5 and 1.2. Temperature and relative humidity were assumed to be fixed at 30 °C and 30% respectively in these cases. The difference pressure was set at 1kPa.

2.1.1. Initial values and boundary conditions

The materials used in the model are air, water vapor, radon as a fluid in a mixture and light concrete for the floor, dense concrete for walls, windows material and main door as solid materials. Internal doors are left open. Properties of radon are given in the previous sections. Properties of the other materials are as shown in Tables 1 and 2.

Table 1. Properties of Fluids

Properties	Air	Water Vapor	Radon
Density (kg/m^3)	1.225	0.5542	9.73
C_p (j/kg-k)	1006.43	2014	96.35
K (w/m-k)	0.0242	0.026	0.0036
Viscosity(kg/m.s)	1.7894×10^{-5}	1.34×10^{-5}	1.8×10^{-5}
M_W (kg/kmol)	28.966	18.0153	222

Table 2. properties of Solids

Material	Density kg/m^3	C_p j/kg-k	K w/m-k
Light concrete	1200	1000	0.4
Dense concrete	2100	840	1.4
Windows	2700	880	0.8
Main Doors	720	1250	0.16

Boundary conditions in the model are: 7 vents in rooms, outer surfaces, floor zone, outlet, walls zones and room zones. Characteristics of these boundaries are as follows.

The vent in each room is defined as the velocity inlet boundary. Specifications which must be defined for this type of boundary are velocity, hydraulic diameter, temperature and mass fraction of radon and mass fraction of water vapor.

2.2. Measuring method

Radon concentrations were measured continuously during winter and spring, both with a continuous radon meter (CRM) and an alpha track detector (ATD). The air change rates in the house also were measured by the heat recovery ventilation (HRV) system.

2.3. Analytical method

Indoor radon content can be calculated as

$$C = \frac{EA}{V(\lambda_{Rn}+\lambda_v)} = \frac{E}{h(\lambda_{Rn}+\lambda_v)} \qquad (1)$$

Where $C(\mathrm{Bq}m^{-3})$ is indoor radon concentration at the steady state, $E\ (\mathrm{Bq}m^{-2}h^{-1})$ is radon exhalation rate, $A\ (m^2)$ is the radon exhalation surface (in this study the house floor), $V\ (m^3)$ is the volume of the house, $\lambda_{Rn}\ (2.1 \times 10^{-6}\ s^{-1})$ is the radon decay constant and $\lambda_v\ (h^{-1})$ is the air change rate in the house and h=2.4 m is the height of the house.

For $E = 65\ \mathrm{Bq}m^{-2}h^{-1}$ (11) and the given data of the case study house, Equation (1) gives indoor radon levels for different ventilation rates (0, 0.25, 0.5 and 1).

3. Results and discussion

3.1. Numerical results

Graphical presentations of the three dimensional simulation data were prepared using FLUENT contours. These contours are a good tool for qualitative comparisons. From the FLUENT report, it is also possible to determine the numeric data for quantitative comparisons. This study investigated the effects of: *1. Ventilation rate, 2. Temperature, 3. Relative humidity, and 4. Pressure difference*

1.Ventilation rate:

Contours of radon concentration in the house plan at position y=210 cm from the floor for various air change rates are shown in Figure 4. This figure shows qualitative comparisons of radon concentrations at four different hourly air change rates ranging from 0.05 to 1.2 Ach.

As evident from Figure 5, different ventilation rates have distinct effects on indoor concentration in Room 1. The quantitative comparisons are plotted in Figure 6, which shows that the radon concentration levels were inversely proportional to outdoor flow rate at steady state.

Numerical simulations were performed at different Reynolds numbers. The Reynolds number in the house was calculated using Equation (2):

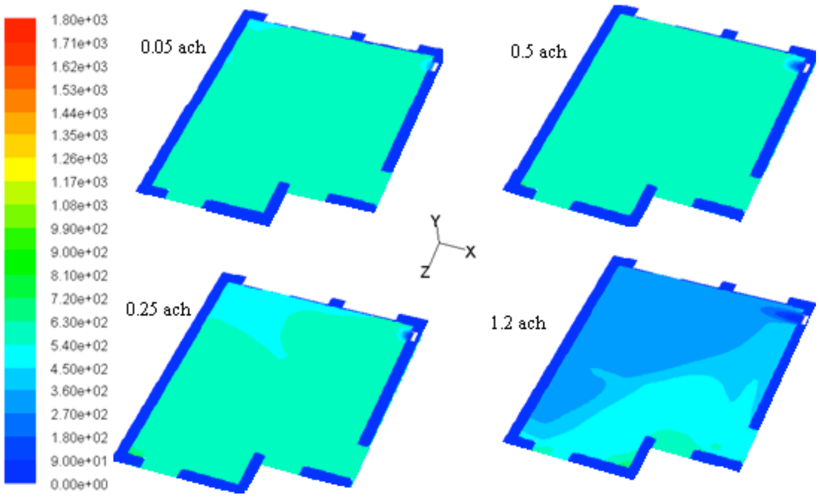

Figure 4. Contours of radon concentration in the house plan (Room1) with air change rates 0.05-1.2 Ach

$\mathrm{Re} = D_h \times U_r/\nu$ (2)

where D_h is the hydraulic diameter of room and is defined as: $2WH/(W+H)$ (W = width, H = height), U_r is the equivalent room velocity (flow rate/cross-sectional area) and ν $(1.1 \times 10^{-5} m/s)$ is the kinematic viscosity of air [3]. The Reynolds numbers were 2×10^4 and greater than 2×10^5, corresponding to ventilation rates of 0.05 and greater than 0.5 Ach.

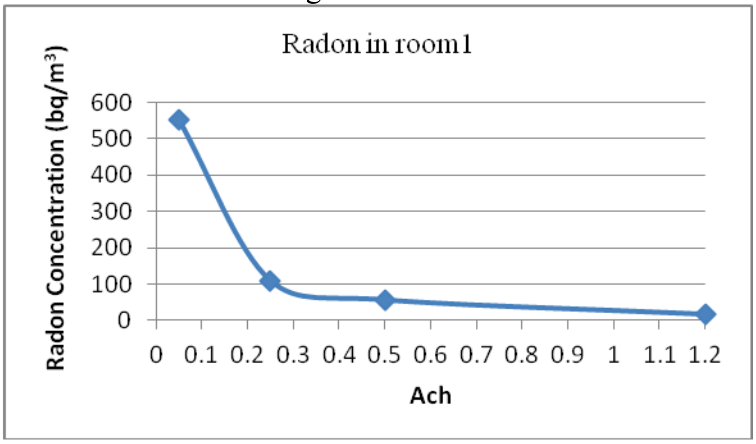

Figure 5. Radon concentrations in Room1 versus air change rate

2. Temperature:

In order to investigate the effects of temperature changes on radon concentration, air change and relative humidity were fixed and indoor temperature was varied between 15 °C to 25 °C. Air change and relative humidity were maintained at 0.5 and 30% respectively. The temperature effects are shown qualitatively in Figure 6. Indoor radon levels were inversely proportional to indoor temperature. This is because of the direct correlation between temperature and pressure as stated by the constant gas law. Thus, increasing temperature increases the pressure, and since the indoor radon concentration is driven by pressure, the amount of radon driven into the room decreases. From another perspective, increasing the house temperature increases indoor pressure and the outside acts a vacuum cleaner and sucks away the indoor air. This phenomenon is referred to as the "stack effect"[12].

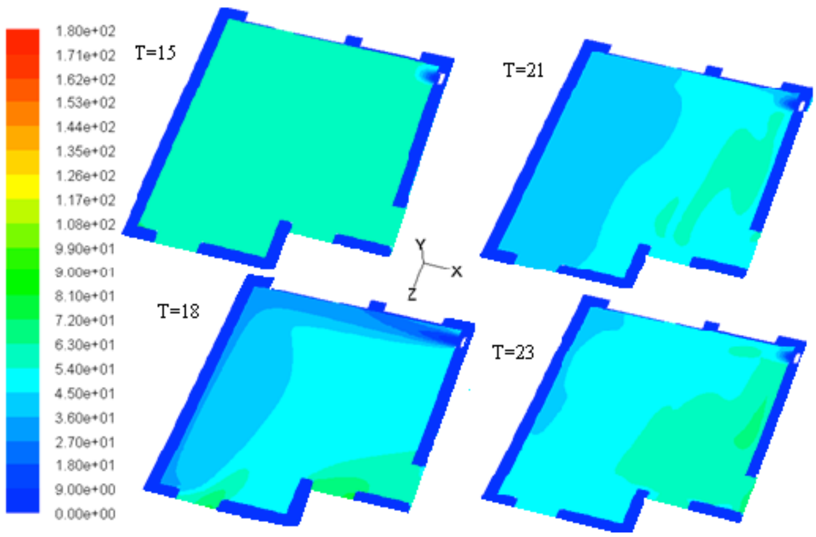

Figure 6. Contours of radon concentration in Room 1 at different temperatures

Figure 7 shows the contours of radon concentration at y=120 cm from the floor for various temperatures.

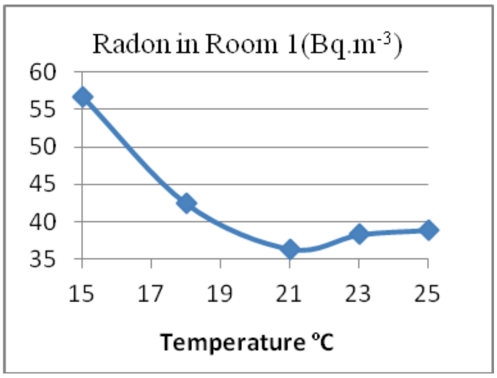

Fig.7. Radon concentrations in Room1 versus temperature

3. Relative humidity

The effect of varying relative humidity on radon concentration in Room 1 is shown in Figure 8. Relative humidity is varied between 30 to 80% and temperature and air change are maintained at 18ºC and 0.25 respectively.

Figure 8 indicates that radon concentration decreases from RH 30% to 70%, and increases when RH rises from above 70%.

This is because increasing humidity from zero to a defined quantity below 50% increases the pressure gradient in air. This increases the driving force that draws the radon out of the ground. However, higher RH levels result in denser air, and radon is unable to rise to high altitudes. Increased moisture in air also decreases diffusion coefficient and hence reduces the diffusion length of radon, which reduces transfer of radon to areas of low radon concentration.

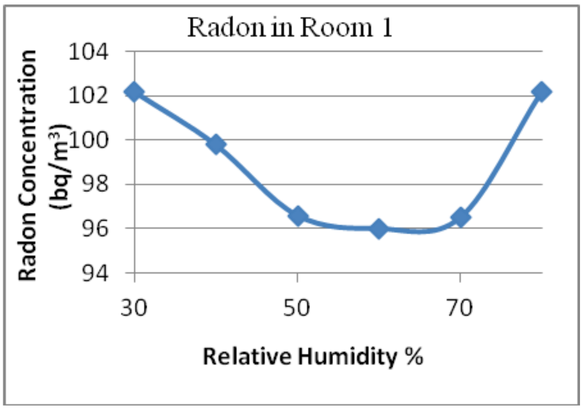

Fig. 8. Radon concentrations in Room1 versus relative humidity

4. Pressure difference

The model was solved for 1 Pa and 2 Pa difference pressures. Radon entry rate varies with pressure difference. Previous work in the field has established entry rates of 2 Bq/s and 3 Bq/s for pressure differences of 1 Pa and 2 Pa respectively [1].

Air change rate, temperature and relative humidity are maintained at 0.25, 18 ºC and 40% respectively.

Contours of radon concentration in a plane at y=120 cm from the floor are shown in Figure 9, and clearly show that pressure difference affects indoor radon levels.

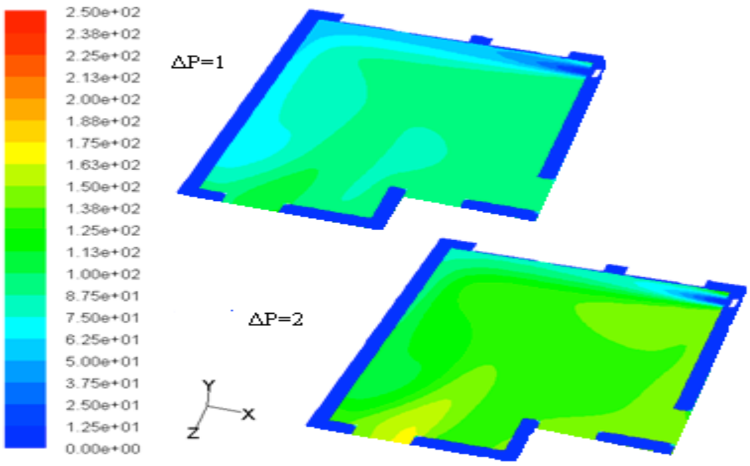

Figure 9. Contour of radon concentration for Δp=1Pa and 2 Pa

3.2 Measuring results

The results of measurements are shown in Table 3. In order to show the impact of ventilation rate on radon level, radon concentrations were measured at three different ventilation rates. Figure 10 shows the results at three different air change rates, measured with a CRM. The figure shows that measured radon levels were inversely proportional to air exchange rate.

Continuous radon measurements using a CRM also confirmed that in the indoor temperature range, fluctuating radon levels in the house have a strong indirect correlation with temperature (Figure 11).

Table 3. Measured indoor radon levels (Bq.m^{-3})

Date and period	ATD	CRM	Ventilation rate	Ventilation type	Remedial action
2008-2 (2weeks)	3580 380	------	0.25	Extract fan	No action
2010-1 (3months)	1280 160	1580 158	0.25	HRV	Radon sump &sealing
2010-04 (3 weeks)	100 20	------	0.5	HRV	3connected sumps
2010-3 (12days)	-------	97 10	0.5	HRV	3connected sumps
2010-3 (12days)	-------	65 6	0.5	HRV	3connected sumps
2010-4 (12 days)	-------	36 4	1	HRV	3connected sumps

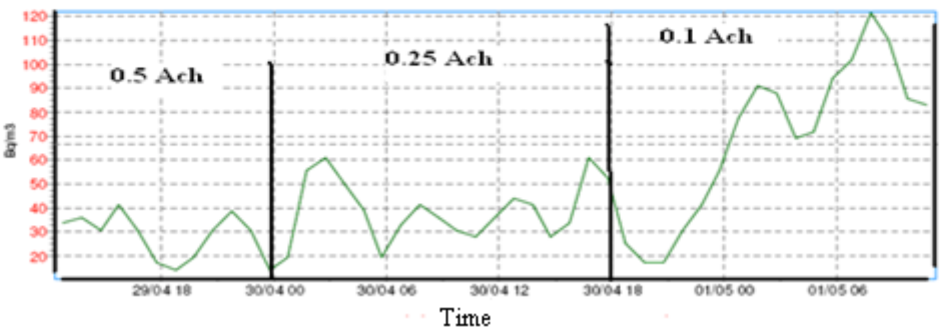

Fig.10. Measured radon level measurements versus ventilation rate

3.3. Analytical results

As previously mentioned, Equation (1) was used for analytical calculation and air change rates were set at 0.25, 0.5, and 1.2 h^{-1}. The results are shown in Table 4.

4. Defined Functions

In our estimates, radon concentrations are given in $bq.m^{-3}$, whereas the FLUENT package gives molar concentration of radon in $kmol.m^{-3}$. We therefore define a Custom Field Function to calculate radon concentration ($bq.m^{-3}$) in term of molar radon concentration as follows:

$$C_{Rn}\left(\frac{bq}{m^3}\right) = \frac{C_{Rn,molar}\left(\frac{kmol}{m^3}\right) \times M_{Rn}\left(\frac{kg}{kmol}\right)}{1.75\times10^{-19}\left(\frac{kg}{bq}\right)} \qquad (3)$$

Where M_{Rn}= 222 $\frac{kg}{kmol}$ is the molecular weight of radon.

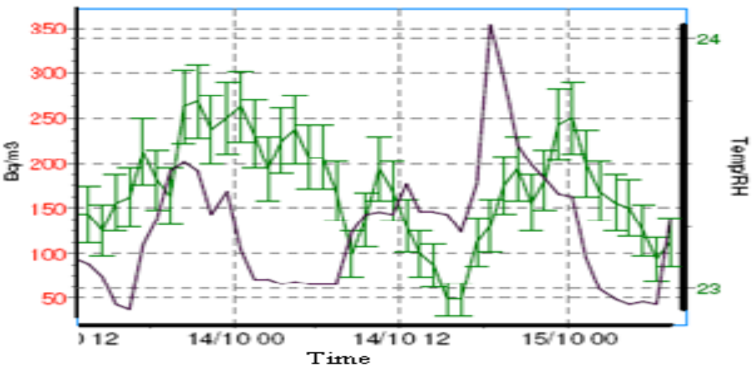

Fig.11. Radon level (green) versus temperature (black)

5. Model Validation

Model validation was performed using analytical solution. The numeric differences between numerical simulation and analytical calculation results are shown in Table 4.

For quantitative comparisons, the percentage difference between the results of estimation by FLUENT and the analytical calculations were computed at each ventilation rate. The maximum difference was found to be below 10%. Measurement data were not suitable for comparison, because the measuring period was too short to obtain an acceptable average radon level.

Table 4.Indoor radon concentrations result in $Bq.m^{-3}$

Ach	Measurement	Analytic	Numeric
0.0	3580	3582	-----
0.25	90	106	107
0.5	45	53	55
1.2	25	22	20

6. Conclusion

The models were developed in FLUENT with simulated radon entry through the floor into a one family house in three dimensional models. The results support the hypothesis that indoor radon concentrations are indoor temperature and moisture dependent.
The verification of the model and its performance indicate that radon entry to the house and the effects of temperature and moisture have been well defined physically and numerically. The performance and sensitivity of the model was confirmed by varying input parameters and boundary conditions. The effects of different parameters of indoor air such as ventilation rate, indoor-outdoor pressure difference, indoor temperature and relative humidity on indoor radon concentrations were investigated. The value of mass flow rate at the air inlet outlet affected the distribution patterns of indoor radon, both qualitatively and quantitatively.
Discrepancies were found here between CFD simulation, numerical calculations and measurement data. These may have resulted from insufficiently detailed representation of boundary conditions and inaccuracies of measured data due to the short measurement period.
In conclusion, CFD is a powerful research tool for predicting the factors that influence indoor radon distribution. However, further improvement of the accuracy of the quantitative estimations of radon concentration will require more detailed consideration of turbulence, near wall effects, grid refinement near the vents, and development of a robust validation method.

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