ARTICLE IN PRESS

Journal of Environmental Radioactivity xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration

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ARTICLE INFO

Keywords:
Radon exposure
Environmental indoor parameters
Ventilation system
Thermal retrofit
Numerical assessment

ABSTRACT

For a given radon potential in the ground and a given building, the parameters affecting the indoor radon activity concentration (*IRnAC*) are indoor depressurization of a building and its air change rate. These parameters depend mainly on the building characteristics, such as airtightness, and on the nature and performances of the ventilation system. This study involves a numerical sensitivity assessment of the indoor environmental conditions on the *IRnAC* in buildings. A numerical ventilation model has been adapted to take into account the effects of variations in the indoor environmental conditions (depressurization and air change rate) on the radon entry rate and on the *IRnAC*. In the context of the development of a policy to reduce energy consumption in a building, the results obtained showed that *IRnAC* could be strongly affected by variations in the air permeability of the building associated with the ventilation regime.

1. Introduction

Radon is a radioactive gas originating from the decay of naturally present radium in the earth's crust. Exposure to radon and its decay products is the second leading cause of lung cancer (WHO, 2009). Radon levels outdoors are generally low, and the health risks associated with radon exposure occur mainly in indoor environments. The radon activity concentration indoors depends on many different parameters. First, the ground is the primary cause of radon presence in a building, depending on the nature of the ground (granite, till, clay, etc.) and its air permeability (Sundal et al., 2004; Miles and Appleton, 2005; Diallo et al., 2013; Drolet and Martel, 2016; Chen and Ford, 2016). In addition, some building characteristics, such as the type of foundation and the air exchange rate, also have an impact on *IRnAC* (Sundal et al., 2004; Demoury et al., 2013; Borgoni et al., 2014; Diallo et al., 2015). Indeed, depending on the intensity of radon entry and its dilution indoors, the resulting level of radon indoors could be very important in a region with high ground radon potential. Influencing factors for the indoor presence of gaseous pollutants from the ground are mainly indoor depressurization and the air change rate levels of the building (Arvela et al., 2013; Fronka and Jilek, 2014; Shen and Suuberg, 2016; Vasilyev et al., 2015). For a given configuration of a building and the ground, the intensity of the radon entry is mainly related to the slight indoor depressurization level generated by the stack effect and to the running of different systems (ventilation, heating). In addition, the dilution of *IRnAC* will depend on the air renewal of the building.

Policies are being developed worldwide to reduce energy consumption in existing buildings and in new constructions with a common objective to decrease emissions of greenhouse gases. The work and techniques employed to attain these objectives could impact the indoor environment, such as indoor depressurization levels and air renewal levels, thus modifying the resulting *IRnAC* (Arvela et al., 2013; Ringer, 2014). Recent field studies (Jiranek and Kacmarikova, 2014; Fojtikova and Rovenska, 2015; Pressyanov et al., 2015; Collignan et al., 2016) showed that thermal retrofitted works could cause a decrease in the ventilation rate, inducing an increase in the indoor radon concentration.

In this context, the objective of this study is to analyze the impact of ventilation systems and thermal retrofit works on the mechanisms governing indoor radon concentrations. For that purpose, a simple numerical ventilation model has been used and adapted to take into account radon entry and transport in buildings, especially integrating the radon entry rate laws depending on the indoor pressure level developed based on in situ experimentation (Collignan et al., 2012; Collignan and Powaga, 2014).

2. Materials and methods

The ventilation model SIREN developed at CSTB (Collignan et al., 2012; Millet et al., 1996) has been used to conduct different calculations presented in this paper. Its principles of modeling are summarized below. SIREN is a single-zone nodal numerical model based on the

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https://doi.org/10.1016/j.jenvrad.2017.11.023
Received 18 August 2017; Received in revised form 20 November 2017; Accepted 21 November 2017

Please cite this article as: Collignan, B., Journal of Environmental Radioactivity (2017), https://doi.org/10.1016/j.jenvrad.2017.11.023

resolution of the mass balance equation. Each mass air flux $\dot{m}$ between the indoors and outdoors could occur through air leakages of the envelope or through ventilation components. At each time step, the equation to be solved is given as follows:

$$\sum_i \dot{m}_i = 0 \quad (1)$$

where i corresponds to a ventilation component or an air leakage component. Power laws are classically used to express the air exchange as a function of pressure difference on either side of the component (ΔP):

$$\dot{m} = K(\Delta P)^n \quad (2)$$

where K is the flow coefficient and n is the flow exponent. These two coefficients depend on the component considered. The hydrostatic pressure fields indoors and outdoors depend on the ground level pressure, indoor and outdoor temperatures, wind force and wind direction. In the presence of mechanical ventilation, the air supply or/and air exhaust quantity could be added to equation (1). Depressurization of the lower part of a building could occur when the indoor temperature is higher than the outdoor temperature. Because hot air is lighter than cold air, an ascendant movement of air indoors is generated. This well-known phenomenon is called the "stack effect", which is a contributor to the building air exchange rate. In a given building, the intensity of this phenomenon depends on many parameters, principally the following: indoor-outdoor temperature difference (ΔT), wind force and wind direction, building height, air permeability and its repartition on the facade, and the presence and type of ventilation system. Fig. 1 presents schematically indoor and outdoor hydrostatic pressure fields occurring in the presence of the stack effect. The ground indoor pressure P_0^{in} is lower than the ground outdoor pressure P_0^{out}. Hydrostatic pressure fields (in Pa) are expressed as a function of height as follows:

$$P_h^{in} = P_0^{in} - \rho_{in} g h$$

$$P_h^{out} = P_0^{out} - \rho_{out} g h$$

where ρ_{in} (kg m^{-3}) and ρ_{out} (kg m^{-3}) are the indoor and outdoor air densities, respectively. Comparing the pressure difference along the height of the building, it appears that this difference is equal to zero for a given level of the building because $\rho_{in} < \rho_{out}$. This specific height is called the neutral plan (NP) of the building. This indicates that below NP, air enters the building via natural openings or air leakages, whereas above NP, air exits the building. This phenomenon could be amplified or diminished in the presence of wind, which could add or subtract dynamic pressure outdoors on the façade.

Knowing at each time step the meteorological conditions and the indoor temperature and assuming a zero outdoor ground pressure reference, equation (1) could be expressed as a single equation as a function of the indoor ground pressure:

$$f(P_0^{in}) = 0 \quad (3)$$

where P_0^{in} (Pa) is the indoor ground pressure level. Solving equation (3) enables determination of the indoor ground pressure at each time step and rebuilding of each air exchange through different components based on knowledge of the indoor and outdoor hydrostatic pressure fields.

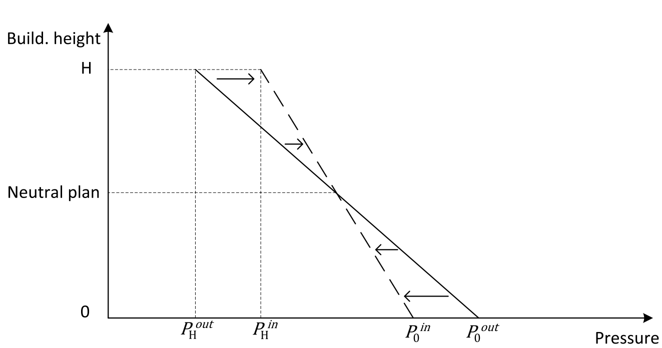

Fig. 1. Indoor and outdoor pressure fields as a function of the height of a dwelling.

The principle of the ventilation model is presented in Fig. 2.

In order to assess the *IRnAC* as a function of time, the following differential equation is solved:

$$\frac{dC_{Rn}}{dt}(t) + \frac{Q_v}{V}C_{Rn}(t) = \frac{\Phi_{Rn}}{V} + C_e\frac{Q_v}{V} \quad (4)$$

where C_{Rn} (Bq m^{-3}) is the *IRnAC*, Q_v (m^3 s^{-1}) is the air change rate calculated using ventilation model SIREN, V (m^3) is the volume considered and Φ_{Rn} (Bq s^{-1} m^{-2}) is the radon entry rate. The outdoor radon activity concentration C_e is neglected in the following study, insofar as we provide only comparative analysis.

The implicit Euler scheme is used to solve equation (4), neglecting C_e:

$$C_{Rn}^t = \frac{C_{Rn}^{t-1} + \Delta t\frac{\Phi_{Rn}(t)}{V}}{1 + \Delta t\frac{Q_v(t)}{V}} \quad (5)$$

where C_{Rn}^t is the *IRnAC* (Bq m^{-3}) at the given time t and C_{Rn}^{t-1} is the *IRnAC* (Bq m^{-3}) at the previous time (t-1), Δt is the time step in seconds.

Previous experimental studies (Collignan et al., 2012; Collignan and Powaga, 2014) enabled the determination of the radon entry rate empirical laws for dwellings. The radon entry rate law Φ_{Rn} (Bq s^{-1}) has the following shape:

$$\Phi_{Rn}(\Delta P_G) = K_r(\Delta P_G)^{n_r} \quad (6)$$

where ΔP_G ($= P_0^{out} - P_0^{in}$) is the pressure difference between outdoors and indoors at ground level, K_r is the radon flow coefficient and n_r is the radon flow exponent. These two last coefficients depend on a given situation of the radon ground potential, the type of building and the type of foundation. Using this entry rate law in the SIREN model enables the calculation of *IRnAC* as a function of time, taking into account the slight depressurization of the building ΔP_G, which depends on dwelling characteristics and local meteorological data. If a calculation is conducted during one year, the result obtained is the variation of *IRnAC* all along this year. It is then possible to calculate the annual averaged *IRnAC*. This value is relevant to compare different configurations because it corresponds to the value considered in the field of risk assessment.

The coefficients K_r and n_r could be determined experimentally (Collignan and Powaga, 2014). From this knowledge, for the calculations presented in this study, a medium radon entry rate has been considered with $K_r = 12$ and $n_r = 0.7$.

However, it appeared in preliminary sensitivity studies that the values of these coefficients have no influence on the qualitative analysis results presented in this paper. These preliminary calculations are not shown to avoid overloading the presentation.

A typical individual dwelling on two levels is considered as a test case to perform the calculations. The ground surface is 80 m^2. Depending on the calculations, different air leakage levels and different ventilation systems could be considered.

The air leakage level is generally expressed in France using the I_4 parameter (m^3 h^{-1} m^{-2}), which corresponds to an air flow through air leakages under a depressurization of 4 Pascal relative to the surface of the façade. For a conventional dwelling, the following relationship is valid: $I_4 = n_{50}/4$; this relationship involves the more recognized parameter n_{50}, which defines the air change rate (h^{-1}) under 50 Pa of depressurization.

To address the needs of sensitivity studies undertaken, 4 values of I_4 were chosen; these values could correspond to various thermal retrofit works, as described in Table 1.

Note that these values do not correspond to real feedback, and they

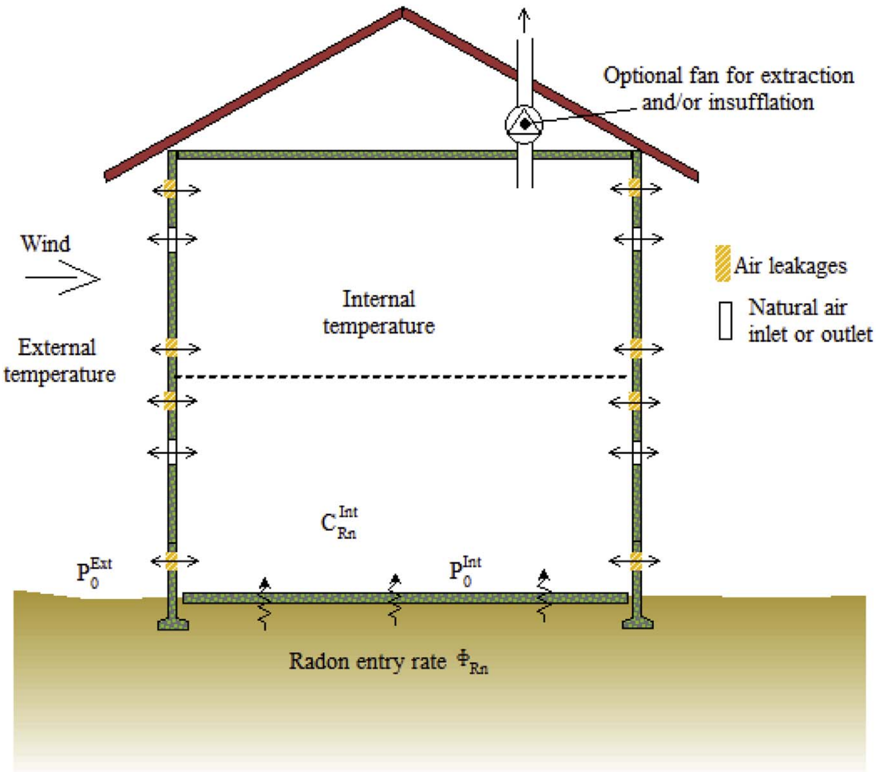

Fig. 2. Principle of the ventilation model SIREN.

Table 1
Values of I_4 parameter considered in thermal retrofit works.

I_4 ($m^3\ h^{-1}\ m^{-2}$)	Type of works
1.6	Reference case
1.2	Changing windows
1.0	Changing windows and inside thermal insulation
0.8	Changing windows and outside thermal insulation

claim only to represent a trend. In this manner, the outside thermal insulation is considered to have a greater effect on the building airtightness than the inside thermal insulation.

The ventilation systems used and modeled for this study represent the most used ventilation systems in France, as described with the results of national campaign of indoor air measurements in dwellings conducted by French Indoor Air Quality Observatory (Lucas et al., 2009). There are the following:

No ventilation system: Air renewal of the dwelling is only generated through air leakage sites.

Natural ventilation system (NVS): this type of ventilation system induces natural air inlets and outlets in low and high positions of the façade for humid rooms. This system was classically used in France before the hygienic regulation of 1969. Classical rules of dimensioning used in France are followed to model the system (size of openings in humid rooms).

Mechanical exhaust ventilation system (MEVS): air enters naturally in living rooms (bedrooms and living rooms) through natural air inlets and then is transferred into the dwelling before being extracted mechanically in humid rooms (kitchen, bathroom and toilets). Regulation requirements and classical rules of dimensioning used in France are followed to model the system (the level of air flows extracted mechanically and the dimensions of natural air entry).

Mechanical balanced ventilation system (MBVS): air enters mechanically in living rooms (bedrooms and living rooms) and then is transferred into the dwelling before being extracted mechanically in humid rooms (kitchen, bathroom and toilets). The same requirements as those of the *MEVS* are followed for mechanical extraction flows. The same values of incoming air are also imposed to balance the system.

Mechanical supply ventilation system (MSVS): air enters mechanically in living rooms (bedrooms and living rooms) and then is transferred into the dwelling before being extracted through natural outlets in humid rooms (kitchen, bathroom and toilets).

Note that in the calculations presented, the impact of occupant behavior (windows opening) is not taken into account. For all the annual ventilation calculations, a typical French weather database (Nancy town) were used (outdoor temperature, wind strength and wind direction). This weather database, with hourly time step, is provided by METEONORM, a global weather database software developed by CSTB.

To study the impact of the air leakage level and the ventilation system on the indoor ground pressure and the *IRnAC*, three sensitivity studies were conducted, as presented below.

2.1. 1st sensitivity study

First, stationary calculations were realized to highlight the impact of predominant parameters as stack effect, type of ventilation system and air permeability level of the building envelope, on the indoor depressurization level. To undertake different stationary calculations using SIREN, stationary meteorological conditions were used.

2.2. 2nd sensitivity study

Second, one year calculations were undertaken to compare the impact of two different ventilation systems (*MEVS* and *MSVS*) on indoor environmental conditions, with the same air exchange rate.

2.3. 3rd sensitivity study

Last, one-year calculations were undertaken to compare the impact of four conditions of ventilation (no ventilation system, *NVS*, *MEVS* and *MBVS*) associated with four levels of airtightness on the indoor environmental conditions and the annual averaged *IRnAC*.

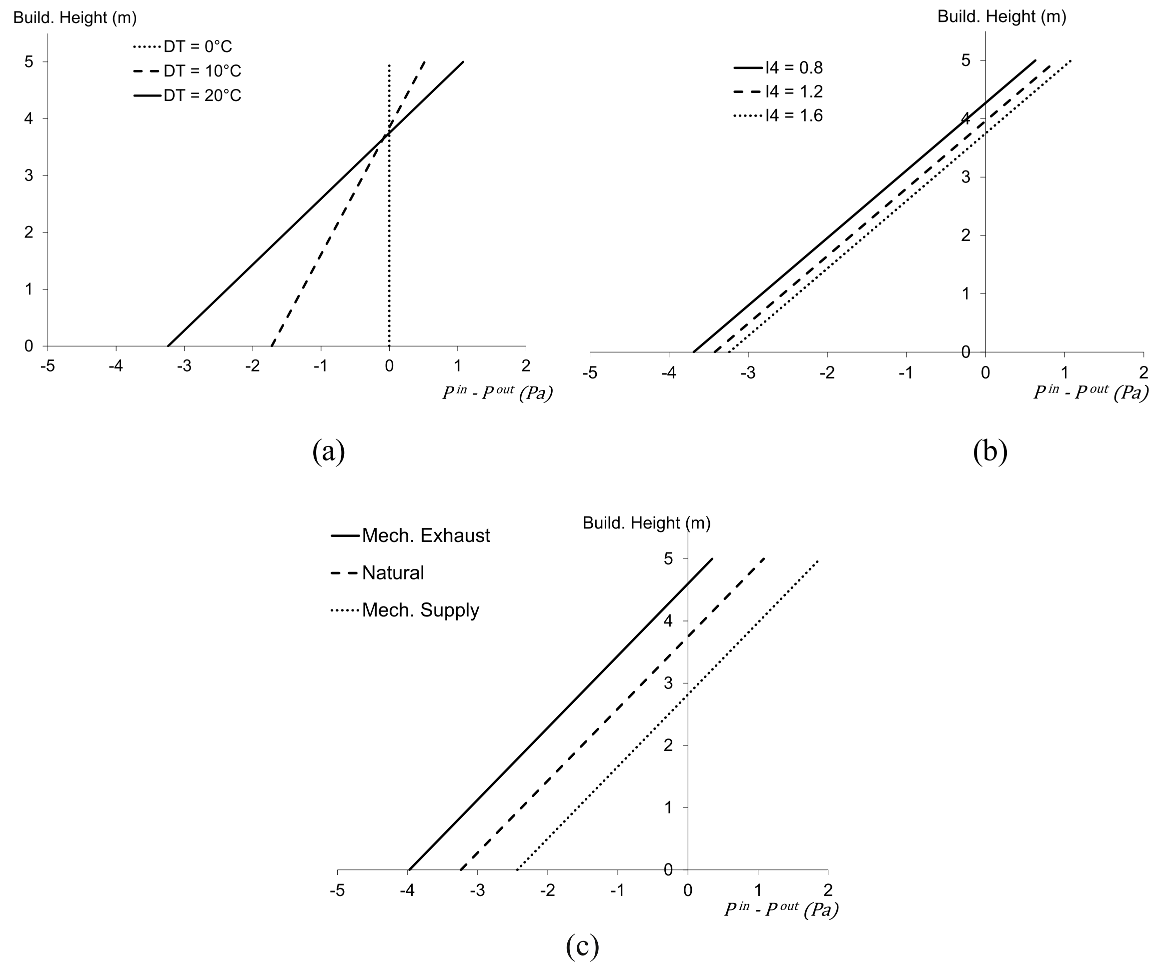

Fig. 3. Impacts of different parameters on the stationary indoor pressure field (relative to outdoor pressure field) as a function of the height of a dwelling.

As mentioned in introduction, it is well known that *IRnAC* varies along time, depending on many parameters. For this reason, it is relevant to use the annual averaged *IRnAC* to compare different configurations. Furthermore, it corresponds to the value considered in the field of risk assessment.

3. Results and discussion

To illustrate the impact of different parameters on the indoor ground depressurization, some stationary calculations were conducted with the SIREN model. To simplify the illustration, calculations were undertaken without wind. Fig. 3 (a) shows that for a given configuration of building using *NVS*, the indoor-outdoor temperature difference (ΔT) has a strong impact on the indoor ground depressurization. The higher ΔT is, the greater is the indoor ground depressurization. In addition, the natural air exchange rate is more important in the presence of the stack effect. The resulting *IRnAC* will depend on the intensity of the incoming radon entry rate, which is related to the level of indoor depressurization and radon dilution indoors with air renewal. However, generally, in the presence of the stack effect, the higher the value of ΔT is, the higher is the resulting *IRnAC*.

The results shown in Fig. 3 (b) illustrate the impact of air permeability on the indoor ground pressure. The more airtight the building is, the more it is depressurized when the neutral plan is slightly higher. In Fig. 3 (c), based on the hydrostatic indoor pressure field generated by a *NVS*, the impact of adding a mechanical exhaust air flow is observed. Ground depressurization is accentuated, and the neutral plan is elevated. Inversely, if a mechanical supply air flow is imposed, then both ground depressurization and the level of neutral plan are reduced.

To go further, a one-year calculation was performed on the same dwelling to compare the indoor environment generated with the use of *MEVS* and *MSVS* to analyze more closely their impact on the indoor pressure and the radon concentration. For these calculations, $I_4 = 1.2$. In addition, the radon entry power law has been added to assess the indoor radon entry rate incoming over time as a function of indoor depressurization and the *IRnAC*. The same air flow is imposed for the mechanical exhaust and for the mechanical supply. As a result, the average air renewal is approximately equivalent for the two calculations and is approximately 0.35 h^{-1}. However, some differences in air renewal could be observed over time due to the impact of the variations of the meteorological conditions on the ventilation.

Fig. 4 presents a comparison of the indoor ground pressure level histogram relative to outdoor pressure using two different ventilation systems.

The building depressurization generated using the *MEVS* is more important than that using the *MSVS*. As a consequence, the incoming indoor radon entry rate over time is more important for the *MEVS* than for the *MSVS*. Finally, the ratio between the annual averaged *IRnAC* using the *MSVS* and that using the *MEVS* is 0.47 in our calculations. In conclusion, the use of the *MSVS* is more effective in protecting a building against radon than the use of the *MEVS*. However, the technique should be implemented with caution because it is known that the *MSVS* or the unbalanced *MBVS* could induce long-term risk of moisture load in a house structure (Arvela et al., 2013), enhancing the indoor overpressure and air exfiltration though air leakage sites. In addition, a recent study (Belleudy et al., 2016) demonstrated that when air exfiltrates from air leakages, the building material can store moisture. This potential problem is particularly relevant in cold weather and high

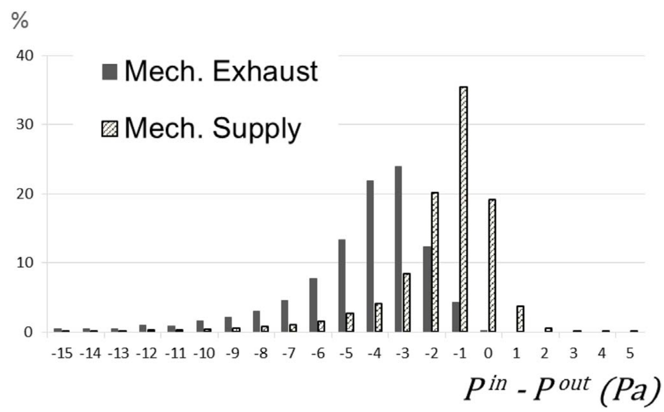

Fig. 4. Comparison of the indoor ground pressure level histogram relative to the outdoor pressure for one-year calculation, considering two different ventilation systems.

Table 2
Annual averaged *IRnAC* relative to the reference case (in bold with gray box).

Air permeability of dwelling I_4 ($m^3\ h^{-1}\ m^{-2}$)	I_4 = 1.6	I_4 = 1.2	I_4 = 1.0	I_4 = 0.8
No ventilation system	1.78	2.38	2.86	3.57
Natural ventilation system (*NVS*)	**1**	1.25	1.44	1.71
Mechanical exhaust ventilation system (*MEVS*)	0.87	0.96	1.01	1.09
Mechanical balanced ventilation system (*MBVS*)	0.56	0.63	0.66	0.72

indoor humidity conditions (TenWolde and Rose, 1996; Janssens and Hens, 2003).

Finally, a sensitivity study was conducted referring to the four classical ventilation types associated with four air permeability levels of the dwelling. These levels could represent the initial state of the air permeability of the dwelling and the impact of three types of thermal retrofit works, as mentioned in Table 1. Table 2 shows the annual averaged radon activity concentration calculated for different cases relative to the reference case, which is chosen as the dwelling with *NSV* and I_4 equal to 1.6 $m^3\ h^{-1}\ m^{-2}$. A reference case has been chosen to highlight the impact of different configurations and to avoid showing absolute radon level. For this reason, the values taken for the coefficients K_r and n_r, have no influence on qualitative results shown, as explained previously. The only impact on results are the levels of depressurization of building along year in the different configurations.

For a non-retrofitted dwelling (I_4 = 1.6), the beneficial impact of ventilation is observed. In addition, *MEVS* is more efficient than *NVS* because the constant exhaust air flow imposed induces a better air exchange rate over the year. Moreover, the *MBVS* is more efficient than the *MEVS* for an equivalent air renewal. This difference is due to the lower indoor depressurization using the *MBVS*, which does not increase the radon entry rate compared to the *MEVS*.

For all types of ventilation, when the dwelling becomes more airtight, the *IRnAC* increases. This increase occurs because a decrease of air permeability has an initial impact on a decrease of air exchange rate of the dwelling and particularly for the cases with “no ventilation system” and for the *NVS*. Next, as shown in Fig. 3 (b), a decrease in the air permeability could increase the indoor depressurization and, as a consequence, increase the radon entry rate. However, when the ventilation system is efficient (*MEVS* or *MBVS*), the increase of the annual averaged *IRnAC* with the decrease in air permeability is relatively low because of the efficient dilution generated by the air exchange rate. It can be concluded that when thermal retrofitting is undertaken in a dwelling, it is crucial to associate with this work an efficient ventilation system to avoid a significant enhancement of radon exposure for the occupants.

Note that these calculations are illustrative and do not take into account occupant behavior, which could impact the air renewal via management of the opening of windows.

Another method of reading Table 2 is examination of an airtight dwelling (I_4 = 0.8) with an efficient ventilation system (*MEVS* or *MBVS*), which could represent recent dwellings. For this dwelling, if, for some reason, the ventilation fails because of poor dimensioning or maintenance, the resulting *IRnAC* could increase significantly (last column of Table 2). In comparison, for a more leaky dwelling (the first column of Table 2 and I_4 = 1.6) the impact of ventilation failure on the *IRnAC* is less important. This last point highlights the need to install and to maintain an efficient ventilation system in new airtight buildings.

4. Conclusions

This study presents the results of a numerical sensitivity analysis that highlights the impact of some environmental parameters on radon entry into the building and on the resulting indoor radon activity concentration (*IRnAC*).

It appears that for a given configuration of radon potential in the ground and building characteristics (typology, type of foundation), the *IRnAC* depends on the meteorological conditions, the air permeability of the building, the type of ventilation system and the level of air change rate. These parameters could impact, on one hand, the level of depressurization indoors that determines the radon entry intensity and, on the other hand, the levels of dilution indoors.

Based on annual calculations, these results also show that the thermal retrofit process must be associated with the relevant ventilation system to avoid a significant increase of *IRnAC*. In addition, for an airtight new building, it is shown that if the ventilation system fails, then the *IRnAC* could be enhanced.

Finally, this study presents a numerical tool adapted to the assessment of *IRnAC* as a function of the prevailing parameters. This tool could assist in the decision making process by conducting sensitivity studies and revealing the impact of some of the involved building characteristics on the *IRnAC*.

Acknowledgements

This work was supported by the French housing ministry.

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