VALIDATION OF THE INDOOR EXPOSURE MODEL FOR DWELLING LIFE CYCLE ASSESSMENT

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ABSTRACT

Damage to human health as a result of exposure to contaminants emitted to indoor air is poorly addressed in life cycle assessment tools for dwellings. A new model is available to calculate damages to human health caused by contaminants emitted from building materials, using a multizone indoor airflow and exposure model. Ventilation rates and radon concentrations have been simulated for the Dutch reference dwelling and are compared with measurement data from the Dutch Ecobuild houses and from average ventilation rates and radon concentrations in dwellings in the Netherlands. The ventilation rates and radon concentrations as simulated with the indoor exposure model have the same order of magnitude as the ventilation rates and radon concentrations measured in the Ecobuild dwellings and in both radon surveys, except for the crawl space, where the modelled ventilation rates are overestimated and the radon concentrations are underestimated. Overall, the indoor airflow and exposure model gives a good reflection of actual ventilation rates and radon concentrations, but for the crawl space, the model needs to be adjusted, and the effects of mechanical ventilation on the model results need to be tuned to practice.

INTRODUCTION

Damage to human health as a result of exposure to contaminants emitted to indoor air is poorly addressed in life cycle assessment tools for dwellings. In a recent study, a methodology was developed to calculate health damages as a result of emissions from building materials to indoor air (Meijer et al., 2005a,b). The results of this study showed that these health damages have the same order of magnitude as the health damages associated with the production and waste disposal phase of the building materials. This methodology is used as basis for a new framework to take into account indoor exposure in life cycle impact assessment (LCIA) (Hellweg et al., 2009).

The methodology needs to be validated against measurement data. As health effects are taken from the generic LCIA methods and are also difficult to measure, the focus of the validation is on the emission and exposure part of the methodology. Exposure to radon is considered in this research, because radon is emitted mostly from stony building materials and from the soil, and occupant behaviour has little influence on the radon levels in the dwelling. In this research, radon exposure levels calculated with the new methodology are compared with measurement data from two Dutch radon surveys and from the Ecobuild project (Stoop et al., 1998; Hasselaar, 2002; Blaauboer et al., 2008).

METHODOLOGY

Simulation

In the LCA methodology, characterisation factors can be used to calculate the combined environmental damage occurring in the life cycle of a product (Heijungs and Hofstetter 1996). For radon emitted from building products, characterisation factors can be used to link the total amount of radon exhaled during the lifetime of the building material to human health damage. The damage score for the use phase of building material *p* as a result of emission of radon is expressed in terms of Disability Adjusted Life Years (DALY), which is the weighted sum of Years Lived Disabled (YLD) and Years of Life Lost (YLL), and can then be calculated by:

$$DS_{p,u} = \sum_r M_{r,p} \cdot Q_r \qquad (1)$$

$$Q_r = \sum_j \left(F_{r,j} \cdot \sum_k E_{r,k,j} \cdot D_{r,k} \right) \qquad (2)$$

where $DS_{p,u}$ is the damage score associated with the use phase of 1 kg building material p (DALY·kg^{-1}); $M_{r,p}$ is the total amount of radon exhaled during the lifetime of building material p (Bq·kg^{-1}); Q_r is the characterisation factor of radon (DALY·Bq^{-1}); F_r is the fate factor of radon for impact category j (Sv·Bq^{-1}); $E_{r,k,j}$ is the effect factor of radon for impact category j for human health damage category k (cases·Sv^{-1}); and $D_{r,k}$ is the damage factor of radon for human health damage category k (DALY·case^{-1}).

The total amount of radon exhaled during the lifetime of building material p can be calculated by:

$$M_{r,p} = ER_{r,p} \cdot LT_p \cdot df_p \qquad (3)$$

where $ER_{r,p}$ is the radon exhalation rate of building material p ($Bq \cdot kg^{-1} \cdot h^{-1}$); LT_p is the lifetime of building material p (h); and df_p is the distribution factor for building material p (-).

The distribution factor df_p reflects the distribution of the emissions over the compartments. When a building material is applied in a wall between two compartments (e.g. the floor between the first and second floor), half of the radon emission is attributed to one of the compartments and half to the other, assuming an equal radon emission rate at both sides of the construction dividing the compartments. Similarly, when a building material is applied in a wall between a compartment and outdoor space, half of the radon emission is attributed to the compartment and half of the concentration is regarded as an emission directly to outdoor air.

For five common building material categories, average radon exhalation rates and total radon emitted during the lifetime of the material are given in Table 1 (Bosmans 1996). The radon exhalation rates are given using a distribution factor df_p of 1 and a material lifetime LT_p of 75 year, unless stated otherwise.

With the fate factor, exposure levels of occupants to radon are calculated as a result of an emission of radon to indoor air. The effect and damage factors are used to calculate health damages from the exposure levels. For the validation of the indoor exposure model, these factors are left out of the comparison, because they are taken from generic LCIA models.

The exposure levels to radon emitted to indoor air are calculated with a multizone indoor airflow and exposure model (Meijer et al., 2005a,b). The dwelling is divided into three compartments (see Figure 1). It is assumed that the concentrations in the rooms of one compartment are similar. As convective transport has the dominating effect on concentrations in dwellings (Nazaroff et al., 1985), diffusive transport is not included in the fate factor calculations. Furthermore, in these calculations average Dutch meteorological conditions and ventilation behaviour are assumed.

The human dose in indoor air as a result of radon exhaled from building material p situated in dwelling compartment a can be calculated by:

$$F_{Rn,a,i} = \frac{CF_d}{f_{e,a}} \cdot N_a \tag{4}$$

where $F_{Rn,a,i}$ is the fate factor, representing the conversion of the emission of radon to the indoor air of compartment a to dose received by the occupants ($Sv \cdot Bq^{-1}$); CF_d is the dose conversion factor ($Sv \cdot y^{-1} \cdot Bq^{-1} \cdot m^3$); $f_{e,a}$ is the effective outgoing airflow for an emission to compartment a ($m^3 \cdot h^{-1}$); and N_a is the number of persons living in the dwelling (-).

The effective outgoing airflow $f_{e,a}$ is the weighed sum of the airflows leaving all compartments regarding an emission in compartment a. It reflects the radon transport between the compartments and the time fraction the occupants spend in the compartments. It can be calculated as follows:

$$f_{e,c} = \frac{vr_c}{t_c + t_1 \cdot \frac{f_{c1}}{vr_1} + t_2 \cdot \frac{f_{c1}}{vr_1} \cdot \frac{f_{12}}{vr_2}} \tag{5}$$

$$f_{e,1} = \frac{vr_1}{t_1 + t_2 \cdot \frac{f_{12}}{vr_2}} \tag{6}$$

$$f_{e,2} = \frac{vr_2}{t_2} \tag{7}$$

where $f_{e,c}$ is the effective outgoing airflow of an emission to the crawl space (-); vr_c is the total ventilation rate of the crawl space ($m^3 \cdot h^{-1}$); t_c is the time fraction spent in the crawl space (-); t_1 is the time fraction spent at the first floor (-); f_{c1} is the airflow from the crawl space to the first floor ($m^3 \cdot h^{-1}$); vr_1 is the total ventilation rate of the first floor ($m^3 \cdot h^{-1}$); t_2 is the time fraction spent at the second floor (-); f_{12} is the airflow from the first floor to the second floor ($m^3 \cdot h^{-1}$); vr_2 is the total ventilation rate of the second floor ($m^3 \cdot h^{-1}$); $f_{e,1}$ is the effective outgoing airflow of an emission to the first floor (-); and $f_{e,2}$ is the effective outgoing airflow of an emission to the second floor (-).

The total ventilation rates of the different compartments can be calculated by:

$$vr_c = f_{oc} + f_{mv,c} \tag{8}$$

$$vr_1 = f_{o1} + f_{c1} + f_{mv,1} \tag{9}$$

$$vr_2 = f_{o2} + f_{12} + f_{mv,2} \tag{10}$$

where f_{oc} is the airflow from outside to the crawl space ($m^3 \cdot h^{-1}$); $f_{mv,c}$ is the airflow induced by the mechanical ventilation in the crawl space ($m^3 \cdot h^{-1}$); f_{o1} is the airflow from outside to the first floor ($m^3 \cdot h^{-1}$); $f_{mv,1}$ is the airflow induced by the mechanical ventilation at the first floor ($m^3 \cdot h^{-1}$); f_{o2} is the airflow from outside to the second floor ($m^3 \cdot h^{-1}$) ; and $f_{mv,2}$ is the airflow induced by the mechanical ventilation at the second floor ($m^3 \cdot h^{-1}$). The airflows induced by mechanical ventilation are derived from building legislation in the Netherlands.

The calculation of the airflows between the different compartments of the dwelling and between the outdoor air and the compartments is described by Meijer et al. (2005a,b). The airflows between the outdoor and indoor air are calculated using stack pressures and wind pressures. The airflow between the compartments is calculated using pressure differences and properties of cracks and gaps in the floors. The calculation of the effect and damage factors is also described by Meijer et al. (2005a,b).

Validation

For the validation of the model, the focus is set on the radon exhalation $M_{r,p}$ in equation (1) and on the fate factor $f_{r,j}$ in equation (2). The radon concentrations are calculated for a Dutch reference dwelling, a two-floor single-family row house in the Netherlands (Novem 1998, W/E Adviseurs 1999). The walls between the dwellings and the floors are made of concrete, and the façades are made of sand-lime bricks and clay bricks. The windows are double paned. Parameter values used in this methodology are given by Meijer et al. (2005a,b). Ventilation rates and radon concentrations have been calculated for houses both without and with mechanical ventilation. In practice, most new houses in the Netherlands have mechanical ventilation systems, but often the ventilation rates of these ventilation systems are in practice lower than designed.

For the reference dwelling, the total radon emission rate in compartment *a* is calculated by:

$$M_{r,a} = \sum_{p} \left(X_{p,a} \cdot ER_{r,p} \cdot df_{p,a} \right) \tag{11}$$

where $M_{r,a}$ is the total radon emission rate in compartment a ($Bq \cdot h^{-1}$); $X_{p,a}$ is the total amount of building material p in compartment a (kg); and $df_{p,a}$ is the distribution factor for building material p in compartment a (-). The total radon emission rates for the different compartments in the Dutch reference dwelling (Novem 1998, W/E Adviseurs 1999) are given in Table 2 (Meijer et al. 2005b)

The radon concentration in compartment a can then be calculated by:

$$C_{r,a} = \frac{M_{r,a}}{vr_a} \tag{12}$$

where $C_{r,a}$ is the radon concentration in compartment a ($Bq \cdot m^{-3}$). The ventilation rates vr_a can be calculated using equations (8-10). The airflows used to calculate the vantilation rates vr_a are given in Table 2.

Case studies

The results of the indoor airflow and exposure model are compared with measurement data from three case studies.

The first case study is the Ecobuild dwellings of the Energy Research Centre of the Netherlands in Petten, the Netherlands. Four test dwellings have been built for energy performance measurements (Figure 2). The dwellings are single-family row houses, built in a similar way and with a similar division as the Dutch reference dwelling (Novem, 1998). Two dwellings have a concrete skeleton (dwellings A and B), and two of them a wooden skeleton (dwellings C and D). Dwelling A has mechanical exhaust ventilation, and dwellings B, C and D have balanced ventilation with heat recovery. Hasselaar (2002) carried out measurements of ventilation rates and radon levels in the Ecobuild dwellings.

The second case study is the radon survey carried out in 1998 by the National Institute for Public Health and the Environment (RIVM) in the Netherlands (Stoop et al., 1998). In this survey, ventilation rates and radon levels have been measured in 1000 single-family and multi-family dwellings (mostly single-family) in 52 municipalities in the Netherlands. The dwelling that have been measured have been built between 1985 and 1993.

The third case study is the radon survey carried out in 2006 by the National Institute for Public Health and the Environment (RIVM) in the Netherlands (Blaauboer et al., 2008). In this survey, ventilation rates and radon levels have been measured in 700 single-family dwellings in 20 municipalities in the Netherlands. The dwelling that have been measured have been built between 1994 and 2003.

RESULTS AND DISCUSSION

In Table 3, the ventilation rates and radon exposure levels are given for each compartment, as calculated with the indoor exposure model and as given in the case studies.

The ventilation rates in each compartment have the same order of magnitude for the model results and the case studies. For the crawl space, the model yields a ventilation rate that is three times higher than measured in the radon survey 1998. For the ventilation rate at the first floor, the model results without mechanical ventilation are similar to the ventilation rates as measured in the Ecobuild dwellings. The ventilation rate at the first floor with mechanical ventilation is about three times higher, and is close to the ventilation rates at the first floor as found in both radon surveys. The same holds for the ventilation rates at the second floor.

The differences of the ventilation rates at the first and second floor between the Ecobuild dwellings and the dwellings in both radon surveys may be explained by the higher airtightness of the Ecobuild dwellings compared to the older dwellings in the radon surveys. The ventilation rates at the first and second floor as calculated with the model are underestimated when no mechanical ventilation is assumed. When mechanical ventilation is included, the calculated ventilation rates are higher, but may be overestimated because the mechanical ventilation system is in practice working with a lower than maximum airflow rate. For the crawl space, the modelled ventilation rates are higher than measured in the radon survey 1998, because the size of the ventilation grate may be overestimated in the reference dwelling.

As a consequence of the overestimation of the modelled ventilation rate in the crawl space, the modelled radon concentration in the crawl space is 50-125 times lower than the measured radon concentrations. This difference is larger than the difference in ventilation rates. This may be caused by the exclusion from the model of radon emissions from the soil and of the background radon concentration in outdoor air.

The modelled radon concentrations at the first floor without mechanical ventilation have the same order of magnitude as the measured radon concentrations, although the radon concentrations found in the radon survey 1998 are three times higher. The modelled radon concentration at the first floor with mechanical ventilation is up to 10 times smaller than the measured radon concentrations at the first floor, mainly caused by the overestimation of the ventilation rate. For the second floor, modelled radon concentrations without mechanical ventilation have the same order of magnitude as measured radon concentrations, while the modelled concentrations with mechanical ventilation are 2-5 times lower.

CONCLUSION

The ventilation rates and radon concentrations as simulated with the indoor exposure model have the same order of magnitude as the ventilation rates and radon concentrations measured in the Ecobuild dwellings and in both radon surveys, except for the crawl space, where the modelled ventilation rates are overestimated and the radon concentrations are underestimated. The differences in radon concentrations are up to a factor of 10. The modelled ventilation rates without mechanical ventilation are generally lower than the measured ventilation rates, while the modelled ventilation rates with mechanical ventilation are generally higher.

Overall, the indoor airflow and exposure model gives a good reflection of actual ventilation rates and radon concentrations, but for the crawl space, the model needs to be adjusted. Furthermore, the effects of mechanical ventilation on the model results need to be tuned to practice. Comparison with other measurement data, with results of other models such as COMIS, and validation for houses in other countries may further improve the accuracy and usability of the model.

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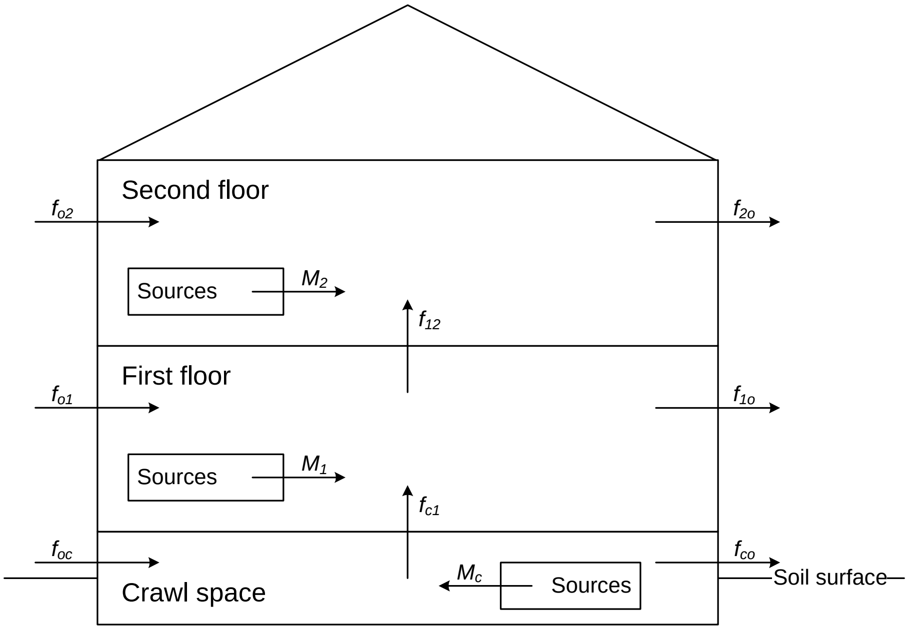

Figure 1 Overview of the different compartments of the single-family row house

Figure 2: The Ecobuild dwellings (Energy Research Center of the Netherlands)

Table 1

Average total radon exhalation of common building material categories (Bosmans 1996)

MATERIAL CATEGORY	RADON EXHALATION RATE *($Bq \cdot kg^{-1} \cdot h^{-1}$)*	TOTAL RADON EXHALATION DURING LIFETIME *($Bq \cdot kg^{-1}$)*
Bricks, cement, mortar and ceramics[a]	$7.07 \cdot 10^{-3}$	$4.7 \cdot 10^{3}$
Concrete cellular[b]	$6.58 \cdot 10^{-3}$	$4.3 \cdot 10^{3}$
Concrete other[c]	$8.32 \cdot 10^{-3}$	$5.5 \cdot 10^{3}$
Gypsum[d]	$6.78 \cdot 10^{-3}$	$3.6 \cdot 10^{3}$
Sand-lime bricks[e]	$9.01 \cdot 10^{-3}$	$5.9 \cdot 10^{3}$

[a] ρ (density) = 1498 $kg \cdot m^{-3}$; thickness = 0.05 m; [b] ρ = 593 $kg \cdot m^{-3}$; thickness = 0.10 m; [c] ρ = 2375 $kg \cdot m^{-3}$; thickness = 0.20 m; [d] ρ = 843 $kg \cdot m^{-3}$; thickness = 0.07 m, lifetime = 60 y; [e] ρ = 1748 $kg \cdot m^{-3}$; thickness = 0.08 m

Table 2
(Assumed) value for several parameters used in the indoor airflow and exposure model

PARAMETER	DENOTATION	VALUE	LITERATURE
$M_{r,c}$	Total radon emission rate in crawl space	140 $Bq \cdot h^{-1}$	a,b
$M_{r,1}$	Total radon emission rate in crawl space	325 $Bq \cdot h^{-1}$	a,b
$M_{r,2}$	Total radon emission rate in crawl space	523 $Bq \cdot h^{-1}$	a,b
f_{oc}	Airflow from outside to the crawl space	153 $m^3 \cdot h^{-1}$	a
f_{o1}	Airflow from outside to the firs floor	31.9 $m^3 \cdot h^{-1}$	a
f_{o2}	Airflow from outside to the second floor	16.0 $m^3 \cdot h^{-1}$	a
f_{c1}	Airflow from the crawl space to the first floor	0.074 $m^3 \cdot h^{-1}$	a
f_{c2}	Airflow from the first floor to the second floor	0.074 $m^3 \cdot h^{-1}$	a
$f_{mv,c}$	Airflow induced by mechanical ventilation in crawl space	0 $m^3 \cdot h^{-1}$	
$f_{mv,1}$	Airflow induced by mechanical ventilation in first floor	75 $m^3 \cdot h^{-1}$	
$f_{mv,2}$	Airflow induced by mechanical ventilation in second floor	75 $m^3 \cdot h^{-1}$	

[a] Meijer et al., 2005a,b; [b] Novem 1998

Table 3
Comparison between model results and measurement data for ventilation rates and radon concentrations in Dutch single-family dwellings

	INDOOR EXPOSURE MODEL		ECOBUILD DWELLINGS				RADON SURVEY 1998	RADON SURVEY 2006
	WITHOUT MECHANICAL VENTILATION	WITH MECHANICAL VENTILATION	A	B	C	D		
Dwelling skeleton	Concrete	Concrete	Concrete	Concrete	Wood	Wood	Mostly concrete	Mostly concrete
Ventilation system	Natural	Mechanical exhaust	Mechanical exhaust	Balanced	Balanced	Balanced	Varies	Varies
Ventilation rate crawl space ($m^3 \cdot h^{-1}$)	153	153	n/a	n/a			41.5	n/a
Ventilation rate first floor ($m^3 \cdot h^{-1}$)	32	107	20-84 [a]	20-28			85.9 [a]	114 [a]
Ventilation rate second floor ($m^3 \cdot h^{-1}$)	16	91	28-48 [b]	12-24 [b]			n/a	74 [b]
Radon concentration crawl space ($Bq \cdot m^{-3}$)	0.92	0.92	82	56	115	48	72.5	45.4
Radon concentration first floor ($Bq \cdot m^{-3}$)	10.2	3.0	10.4 [a]	6.8 [a]	7.2 [a]	3.6 [a]	30.3 [a]	12.9 [a]
Radon concentration second floor ($Bq \cdot m^{-3}$)	32.6	5.7	n/a	n/a	n/a	n/a	29 [b]	11.5 [b]

n/a: Not available
[a] Living room
[b] Bedroom(s)