Field study measurements evaluating radon concentrations under different ventilation scenarios

Janet Gaskin*[1], Yunyi Ethan Li[1], Marcel Brascoupé[2], Liang Grace Zhou[1]

1 National Research Council Canada
1200 Montreal Road
Ottawa, Canada
Presenting author: Janet Gaskin
**Corresponding author: Janet.Gaskin@nrc-cnrc.gc.ca*

2 MB Radon Solutions
75 Pitobig Mikan
Maniwaki, Canada

ABSTRACT

Background: Increasing indoor ventilation has the potential to dilute indoor radon and may be an appropriate first step when measured indoor radon concentrations are close to the mitigation threshold for an existing low-rise house that lacks balanced mechanical ventilation. A ventilation system that includes a heat exchange core is recommended in cold climates to reduce the energy loss associated with replacing stale indoor air with outdoor air that must be either cooled or heated to maintain thermal comfort. A field study of the effectiveness of heat recovery ventilation systems (HRVs) at reducing moderate indoor radon concentration was conducted in 16 houses between 2020 and 2023 in the National Capital Region in Canada.
Methods: The average indoor radon concentration for different HRV settings within a season were compared to estimate the effectiveness of radon reduction. Hourly measurements on lower and upper floors were made using continuous radon monitors and averaged over a one-month period for each HRV setting evaluated: off, running continuously or periodically (typically 20 minutes per hour), and with a fan speed of high or low when running. The effect of the HRV system on indoor radon concentrations was evaluated for sixteen houses, while a comparison of the effect of operating both the passive depressurization system (PSD) for radon mitigation and the HRV was also evaluated for four of the study houses.
Results and Conclusions: The initial radon concentrations measured on the lower floor in the 16 study houses with the HRV off were moderate, ranging from 91 to 312 Bq/m^3, and were roughly lognormally distributed with a geometric mean of 166 Bq/m^3. The arithmetic mean indoor radon was reduced by 40% for continuous HRV operation in the 13 houses with forced air furnace heating systems, with the reduction effectiveness characterized by a normal distribution with a standard deviation of 12%, a minimum reduction of 20% and a maximum of 56%. A higher reduction effectiveness of 80% was observed in the occupied house that had electric baseboard heating and in which an independently ducted HRV was installed. There was an overall trend of higher reduction effectiveness for continuous than periodic fan operation for houses in which more than two HRV settings were assessed. Well designed and installed HRV systems were effective at reducing the moderate indoor radon concentrations measured in these houses that lacked a balanced mechanical ventilation system. In one house, both a passive radon depressurization system and an HRV were required to reduce the indoor radon concentration below the recommended mitigation threshold of 200 Bq/m^3 for existing housing in Canada.

KEYWORDS

Indoor radon, heat recovery ventilation, housing, mitigation,

1 INTRODUCTION

Radon is a naturally occurring radioactive gas that is formed as uranium in the soil decays and that can concentrate indoors as a result of infiltration through the foundations of buildings. The World Health Organization recommends that national radon programs reduce both the population exposure to radon and the exposure of individuals at highest risk (World Health Organization, 2009). Long-term exposure to radon is the second leading cause of lung cancer after smoking in Canada, to which about 3,000 deaths are attributable annually in Canada (Chen et al., 2012; Gaskin et al., 2018). The Health Canada guideline recommends mitigating average annual indoor radon concentrations above 200 Bq/m^3 in existing housing and suggests residents may choose to mitigate lower radon exposures because any reduction in indoor radon will decrease the associated lung cancer risk (Health Canada, 2017).

A balanced mechanical ventilation system that both supplies and exhausts air draws less radon gas through the foundations than a system that has a mechanical exhaust system and relies on the resulting depressurization to draw replacement air through cracks and gaps in the foundation, floors and walls (Arvela et al., 2014). A heat or energy recovery ventilation system includes a heat exchange core to reduce the energy loss associated with replacing stale indoor air with outdoor air that must be either cooled or heated to maintain thermal comfort. Lower indoor radon concentration was reported for low-rise housing that included balanced mechanical ventilation systems compared to those with exhaust only ventilation in Finland, Norway and Sweden (Arvela et al., 2014; Finne et al., 2019; Haanes et al., 2022; Khan et al., 2021; Valmari et al., 2011). Significantly reduced indoor radon was reported for houses built after 2003 in Japan, when a balanced mechanical ventilation system was required by the building code to keep formaldehyde concentrations below the guidelines value and prevent "sick building" syndrome (Suzuki et al., 2010). Improved ventilation in older housing was also associated with decreased indoor radon in two municipalities in Sweden (Tondel et al., 2009). A field study of the effectiveness of heat/energy recovery ventilation systems (HRVs) at reducing moderate indoor radon concentration was conducted in 16 existing houses between 2020 and 2023 in the National Capital Region in Canada.

2 METHODS

The recruitment of study houses was restricted to those in which moderate initial radon concentrations were measured. HRV systems were retrofitted in 13 occupied houses in the community that lacked balanced supply and exhaust mechanical ventilation systems. The field study testing also included three National Research Council (NRC) experimental houses in which HRV systems were already installed. Two of the NRC experimental houses were full size, side-by-side, energy efficient duplexes, designed to the R-2000 standard (Natural Resources Canada, 2012), in which typical occupant behaviours such as opening doors were mechanically simulated. The third NRC house was a smaller experimental house. The characteristics of the study houses are described in Table 1, including house type, number of floors (excluding the basement), the presence/absence of a basement, the type of heating system, and whether the house has a passive soil depressurization (PSD) system installed for radon mitigation. All of the houses have a basement, and most have a forced air furnace for heating while two had electric heating. The study houses include one and two-storey detached houses, and two-storey semi-detached and townhouses. Half of the houses have a PSD system installed for radon mitigation.

Table 1: Study house characteristics

House ID	House Type	# floors	Basement	Heating Type	Passive soil depressurization
1	town	2	✓	Forced-air furnace	×
2	town	2	✓	Forced-air furnace	×
3	det	2	✓	Forced-air furnace	✓
4	det	1	✓	Forced-air furnace	✓
5	det	1	✓	Forced-air furnace	×
6	det	2	✓	Forced-air furnace	✓
7	det	2	✓	Forced-air furnace	×
8	det	2	✓	Forced-air furnace	✓

9	det	1	✓	Electric heater	✓
10	semi-det	2	✓	Forced-air furnace	✓
11	semi-det	2	✓	Forced-air furnace	✓
12	det	1	✓	Electric baseboard	✗
13	det	2	✓	Forced-air furnace	✓
14	det	2	✓	Forced-air furnace	✗
15	det	2	✓	Forced-air furnace	✗
16	det	2	✓	Forced-air furnace	✗

Note: # floors excluding basement

The indoor radon concentration was measured every hour on both the lower and upper floors using a continuous radon monitor. The average indoor radon concentration was measured over roughly a one-month period for each HRV setting evaluated in the occupied houses, with testing conducted sequentially within a single season for each scenario. The HRV settings evaluated included the following: off, running continuously or periodically (typically 20 minutes per hour), and with a higher or lower fan speed when running. Shorter two-week periods of radon measurement were conducted in the highly controlled NRC experimental houses for each HRV setting. In four occupied houses in the community, the indoor radon concentrations for different HRV settings were measured both in combination with the operation of the PSD system installed, and without the PSD system operating (stack closed position). The residents were asked to maintain closed house conditions during the testing.

3 RESULTS AND DISCUSSION

The indoor radon concentrations measured in the 16 study houses are presented in Table 2. The initial radon concentrations measured on the lower floor in the 16 study houses with the HRV off were moderate, ranging from 91 to 312 Bq/m^3, and were lognormally distributed with a geometric mean of 166 Bq/m^3. The indoor radon concentrations included in this table were measured with the fan at the design (higher) speed for continuous HRV operation to represent the upper limit for radon reduction under normal occupancy conditions.

Table 2: radon concentrations measured on upper and lower floors with HRV off compared to operated continuously

House #	Season	Time period	PSD installed & operating	Radon (Bq/m3) L floor HRV off	Radon (Bq/m3) L floor HRV cont.	Radon (Bq/m3) U floor HRV off	Radon (Bq/m3) U floor HRV cont.
1	winter	2020-12-23/ 2021-03-03	✗	125 ± 8	77 ± 6	125 ± 8	70 ± 6
2	winter	2020-12-23/ 2021-03-13	✗	91 ± 7	73 ± 6	75 ± 6	57 ± 5
3	winter	2021-01-16/ 2021-03-15	✗	127 ± 8	97 ± 7	123 ± 8	99 ± 7
3	spring	2021-04-19/ 2021-06-15	✓	26 ± 3	17 ± 3	-	-
4	spring	2021-01-29/ 2021-04-07	✗	208 ± 12	101 ± 7	156 ± 10	77 ± 6
4	fall	2021-11-06/ 2022-01-01	✓	110 ± 8	61 ± 5	78 ± 6	49 ± 4
5	spring	2021-01-28/ 2021-04-02	✗	104 ± 7	57 ± 5	98 ± 7	52 ± 5
6	spring	2021-02-17/ 2021-04-19	✗	309 ± 17	162 ± 10	174 ± 11	140 ± 9
6	summer	2021-05-19/	✓	119 ± 8	43 ± 4	80 ± 6	34 ± 4

		2021-07-26					
7	spring	2021-03-19/ 2021-05-26	✗	109 ± 7	58 ± 5	54 ± 5	24 ± 3
8	summer	2021-05-17/ 2021-07-16	✓	134 ± 9	57 ± 5	108 ± 7	50 ± 5
9	winter	2021-02-10/ 2021-04-07	✗	312 ± 18	171 ± 7	299 ± 17	160 ± 7
10	winter	2021-01-08/ 2021-02-19	✗	166 ± 10	95 ± 7	181 ± 11	92 ± 7
11	winter	2021-01-08/ 2021-02-19	✗	184 ± 11	65 ± 5	-	-
12	spring	2021-03-26/ 2021-05-27	✗	259 ± 15	68 ± 5	150 ± 10	14 ± 3
13	fall	2021-10-29/ 2021-12-24	✓	217 ± 13	164 ± 10	174 ± 11	150 ± 10
14	winter	2022-11-04/ 2023-01-06	✗	220 ± 13	108 ± 7	217 ± 13	91 ± 7
15	winter	2022-11-21/ 2023-01-16	✗	241 ± 14	177 ± 11	183 ± 11	94 ± 7
16	winter	2022-11-29/ 2023-02-11	✗	104 ± 7	61 ± 5	50 ± 5	37 ± 4

The effectiveness of the radon reduction was calculated from the indoor radon concentration with the HRV operating compared to the HRV turned off as described in Equation 1:

$$\text{effectiveness} = 100\,(1 - C_{HRV\_on} / C_{HRV\_off}) \tag{1}$$

where:
C_{HRV_on} – average indoor radon concentration with HRV in operation
C_{HRV_off} – average indoor radon concentration with HRV off

The indoor radon concentration was reduced by the continuous operation of the HRV system in every study house. The average effectiveness of the HRV at reducing indoor radon when operated continuously, for the 13 study houses that had forced air furnace heating and measurements on both lower and upper floors, was normally distributed (see Figure 1) with an arithmetic mean of 40% and a standard deviation of 12% (see Table 3). The highest effectiveness at reducing radon was for the occupied house with electric baseboard heating, at 80%, where the independently ducted HRV supplied outdoor air to the main living area and exhausted basement air. While the arithmetic mean radon reduction was the same on the lower and upper floors measured in the 14 houses that had a forced air furnace when an HRV was operated continuously at the higher design fan speed, there was wider distribution for the upper than the lower floor.

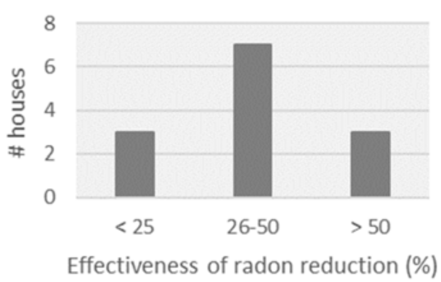

Figure 1: Histogram of HRV effectiveness

Table 3: HRV effectiveness

Radon reduction effectiveness	**House average (%)**	**Lower floor (%)**	**Upper floor (%)**
arithmetic mean	40	40	40
standard deviation	12	12	15
minimum	20	20	14
maximum	56	57	58

The average radon reduction of 40% measured in this study is consistent with the results of a Finnish study, which reported that indoor radon concentrations were 20 to 47% lower in houses with mechanical supply and exhaust ventilation systems with heat recovery than in houses with mechanical exhaust only (Arvela et al., 2014). The average effectiveness of radon reduction may be a little higher for houses in this study because it was determined from indoor radon concentrations measured before and after the recent installation and balancing in each study house of an HRV system operated continuously at the design fan speed.

The trends in indoor radon reduction by HRV setting was plotted in Figure 2 for the 8 study houses in which more than two HRV settings were assessed. An overall trend of higher reduction effectiveness for continuous than periodic fan operation and for higher than lower fan speed was evident, although in some houses there was little difference in indoor radon concentration between lower or higher fan speed for continuous HRV operation.

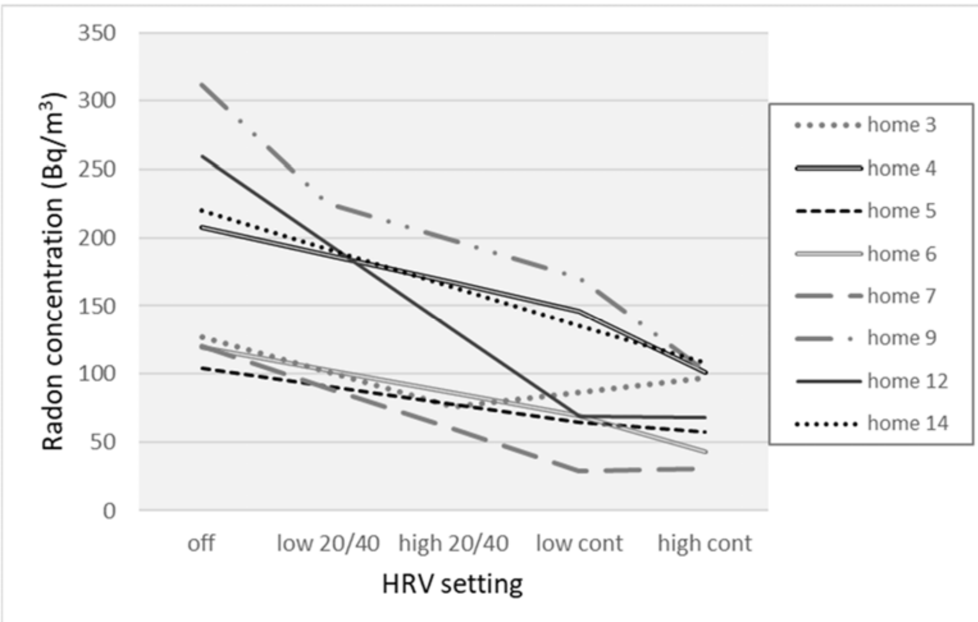

Figure 2: Trends in lower floor radon concentration with HRV setting

The indoor radon concentrations in houses when the HRV was operated in combination with the PSD radon mitigation system are presented in Table 4. The indoor radon concentration was much lower in each floor in every study house when the passive radon depressurization mitigation system was operating. As before, the operation of the HRV system always reduced the indoor radon concentration, both used with and without a PSD radon mitigation system. In three houses, a somewhat higher effectiveness in radon reduction was observed on each floor from the continuous operation of the HRV system when the PSD system was operating also, but in the fourth house the opposite was observed. A similar average radon reduction was observed for continuous HRV operation with and without the PSD radon mitigation system, at 42% and 40% on the lower floor, respectively, and 36% and 27% on the upper floor, respectively. This observation of similar effectiveness of radon reduction for HRV operation with and without a PSD system operating is consistent with the independent operation of the two systems, where the sub-slab depressurization system reduces the ingress of radon indoors from the soil and the HRV system subsequently reduces indoor radon concentration by dilution. The indoor radon concentrations measured in study house 13 during both shoulder seasons for different HRV settings (fall and spring) were included in this table due to the relatively small number of homes used to compare the effectiveness of radon reduction using HRV with and without the PSD system operating. In study house #13, both a passive radon depressurization system and an HRV were required to reduce the indoor radon concentration below the recommended mitigation threshold of 200 Bq/m^3 for existing housing in Canada. This result was consistent with Norwegian studies that reported significantly lower indoor radon and separate effects identified in multivariate regression for balanced mechanical supply and exhaust ventilation with heat recovery and for a passive radon depressurization system in houses built after the 2010 building code change in Norway (Finne et al., 2019; Haanes et al., 2022).

Table 4: initial radon concentrations and effectiveness of radon reduction on upper and lower floors from HRV operated continuously, with and without passive radon mitigation system operating

House #	**Season**	**Time period**	**PSD operating**	**Initial radon (Bq/m^3) L floor HRV off**	**Reduction effectiveness (%) L floor HRV cont.**	**Initial radon (Bq/m^3) U floor HRV off**	**Reduction effectiveness (%) U floor HRV cont.**
3	winter	2021-01-16/ 2021-03-15	✗	127 ± 8	24%	123 ± 8	20%
3	spring	2021-04-19/ 2021-06-15	✓	26 ± 3	35%	-	-
4	spring	2021-03-07/ 2021-05-07	✗	146 ± 9	31%	128 ± 8	40%
4	fall	2021-11-06/ 2022-01-01	✓	110 ± 8	45%	78 ± 6	37%
6	spring	2021-02-17/ 2021-04-19	✗	309 ± 17	48%	174 ± 11	20%
6	summer	2021-05-19/ 2021-07-26	✓	119 ± 8	64%	80 ± 6	58%
13	heating	2021-09-28/ 2022-03-01	✗	593 ± 32	56%	348 ± 19	29%
13	fall	2021-10-29/ 2021-12-24	✓	217 ± 13	24%	174 ± 11	14%

Note: the HRV was operated continuously at low speed for House #4 but at the higher design speed for the other houses, for house #6 the heating season measurements were of one month duration each but not measured consecutively.

This study estimated the upper limit of the effectiveness of HRV systems to reduce indoor radon concentrations. The residential HRV systems were recently installed and balanced by a certified individual, and therefore did not incorporate any changes over time due to differences in maintenance activities, such as the frequency of filter and duct cleaning. The HRV settings evaluated were measured during consecutive periods within a season to reduce confounding from other factors that can influence indoor radon concentration. The design, installation, commissioning, operation and maintenance lower have all been reported to affect ventilation effectiveness by the Canadian Mortgage and Housing Corporation, and can result in problems ranging from poor ventilation to complete system failure (CMHC, 2017). Residents may also choose to operate their HRV systems intermittently and at lower fan speeds to reduce energy consumption, and this should be considered before extrapolating the results of this study to the general population. The impact of residential HRV operation modes on energy consumption and effectiveness of indoor radon reduction have recently been evaluated (Jiránek and Kačmaříková, 2020).

Improving the energy efficiency of housing is an important part of Canada's plan to address climate change and to meet its 2030 and 2050 commitments to reduce emissions (Environment and Climate Change Canada, 2020). New energy efficient housing designs that incorporated adequate balanced mechanical ventilation systems have been reported to have lower indoor radon than conventional housing having mechanical exhaust only ventilation (Arvela et al., 2014; McCarron et al., 2020; Ringer, 2014). The presence of balanced mechanical ventilation systems with heat recovery may be sufficient to prevent an increase in indoor radon in housing undergoing energy efficiency retrofits (Du et al., 2019; Jiránek and Kačmaříková, 2020). Future studies will be conducted to evaluate the effectiveness as a radon control measure of HRV systems incorporated into housing undergoing energy efficiency retrofits and HRV systems included in new energy efficient housing designs in Canada.

4 CONCLUSIONS

The arithmetic mean average indoor radon was reduced by 40% with a standard deviation of 12% for continuous HRV operation in the 13 study houses with forced air furnace heating systems, ranging from a minimum reduction of 20% to a maximum of 56%. An overall trend of more effective reduction was observed for continuous than periodic fan operation for houses in which more than two HRV settings were assessed. In the eight study houses with a passive radon depressurization mitigation system, a similar average radon reduction was observed for continuous HRV operation with and without the passive radon depressurization system operating. Well designed and installed HRV systems were effective at reducing the moderate initial indoor radon concentrations measured in these houses that lacked a balanced mechanical supply and exhaust ventilation system. In one house, both a passive radon depressurization system and an HRV were required to reduce the indoor radon concentration below the recommended mitigation threshold of 200 Bq/m^3 for existing housing in Canada.

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