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Thermal Insulation of Radon Systems to Avoid Freezing

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ABSTRACT
Radon (Rn) stacks, with or without an inline Rn fan, are designed to extract damp soil gas from under basement concrete slabs of homes. Along with Rn gas, moisture vapor also travels up through the Rn stacks. The amount of moisture in the vent pipes can, depending on the circumstances, be significant. In extremely cold weather, this moisture can condense, freeze, form ice and clog the vent pipe at the exit point. In this study, COMSOL Multiphysics was used to examine the amount of insulation required to avoid ice build-up in the Rn vent pipe located in unheated attic space under different outdoor weather conditions. The effects of different parameters on the air temperature in a Rn stack were studied; specifically, (i) air velocities in the vent pipe, (ii) thermal insulations, (iii) different lengths of vent pipe in unheated attic space. The boundary conditions for the model, including the relative humidity, inlet air velocity, and the inlet air temperature in the stack, as well as the temperature in the attic and outdoors were determined based on the data from the Canadian Centre for Housing Technology. Based on the results obtained from numerical simulations, recommendations for insulation to avoid freezing of Rn stack at the exit were proposed. Thereafter, a Rn mitigation system was designed and installed in a home in Ottawa, based on the recommendations. Data was collected from the in-situ experiment during the winter of 2017. This stack was then modeled using the hypothesis used in the predictive simulations, and the model was benchmarked against the data collected from the experiment. The benchmarking results indicated that no freezing was observed using the recommended level of insulation on the Rn vent pipe in an unheated attic and above roof.

KEYWORDS
Radon Stacks, COMSOL Multiphysics, Numerical Simulations, In-situ Measurements

INTRODUCTION

Radon (Rn, atomic weight 222) is a naturally occurring radioactive colorless and odorless gas, which can be found in varying amounts in all types of soil and bedrock. Recent research by Health Canada estimates that 16 per cent of lung cancer deaths among Canadians are attributable to indoor Rn exposure (HC, 2010; HC 2014). Since December 2014, provisions in the British Columbia Building Code have required the installation of a full size passive vent pipe (i.e. passive stack) that extends through the building and terminates outside, in high Rn risk areas. A schematic of such a system is depicted in Figure 1.

Seasonal variation of external and indoor environmental conditions (e.g. temperature, RH, air pressure, wind speed and wind direction) may significantly influence the effectiveness of a passive stack. Previous experimental data from the Canadian Centre for Housing Technology demonstrated that the Relative Humidity (RH) of soil gas within the Rn stacks was close to 100%. The amount of moisture being extracted from under a home can be very significant. At lower temperatures air losses its capacity to retain moisture. In cold climates, condensation within an uninsulated vent pipe is inevitable. However, condensation within the pipe can freeze if the temperature inside the stack remains consistently below the freezing point.

Hence, the clogging of Rn stacks due to the formation of ice in the vent pipe can occur in extreme cold climates.

This paper provides a description of numerical simulations using a COMSOL Multiphysics software platform to predict the temperatures and relative humidity of air along the length of a Polyvinyl chloride (PVC) vertical stack used to exhaust Rn gas from beneath a typical Canadian home with an attic, a main floor, and a basement. Different scenarios for insulation thicknesses, insulation material, in-stack air speed, vent lengths in attic and outdoor temperatures were investigated. Based on the numerical results, a suggestion for required insulation was made for an in-situ test to avoid freezing. The results from tests then were compared with the results from the simulations.

METHODS

A 2D axis-symmetric COMSOL Multiphysics model was employed to examine the temperature profile of soil gas inside a PVC pipe having an outer diameter of 11.43 cm and inner diameter of 10.16 cm (4 inches). Soil gas at 18 °C with the RH of 50%-100% enters the pipe and rises vertically from the basement through the building, into the unheated attic and thereafter is expelled to the exterior atmosphere beyond the roof line. The building other than the attic is generally conditioned and the temperature maintains approximately at 20 °C, which does not appear to affect the temperature in the stack significantly. Therefore, this portion of the stack is not considered in this study. The exposed length of the pipe to outdoor temperature was 30 cm. Different lengths (1 m, 1.5 m, 2 m and 2.7 m) of the part in the attic were studied. Ambient exterior temperatures of -25 °C and -30 °C with the corresponding attic temperatures of -13 °C and -17 °C were considered. Two insulation materials with the thermal conductivities of 0.02 W/(m•K)] and 0.04 W/(m•K)] were used in the simulations to achieve R7 and R14 insulation. On the outer wall of the pipe located in the attic, natural convection heat transfer coefficient of h = 10 [W/(m2•K)] was considered; whereas, the convective heat transfer coefficients on the outer surface of the pipe above the roof were calculated using an average wind speed of 21.5 km/h (6 m/s) and an insulation thickness of 2.54 cm (1 inch), resulting in a forced convection heat transfer coefficient of 30.9 [W/(m2•K)] based on the equations from Incropera et al. (2011).

There was also a need to account for the condensation that occurs on the inner surface of the pipe. To simplify the problem, condensation was modelled as a surface heat source at the wall. Both the exit temperature and the condensation amount were unknown but correlated. Hence, an iterative approach was taken to determine both these values. For the first iteration, the heat release from the heat source was assumed to be zero and a simulation was conducted. Based on the outlet temperature, the amount of heat source was calculated as the input for the second iteration. This procedure was continued until the values from two consecutive simulations converged; this usually occurred after three to four iterations.

In order To find the amount of water vapour at each temperature, there was first a need to calculate the saturation vapour pressure of water in air. Monteith and Unsworth (2008) provided Tetens' correlation for temperatures above 0 °C and Murray (1967) provided Tetens' equation for temperatures below 0 °C:

$$P = 0.61078 exp\left(\frac{17.27T}{T+237.3}\right) \qquad T > 0\,℃ \tag{1}$$

$$P = 0.61078 exp\left(\frac{21.875T}{T+265.5}\right) \qquad T < 0\,℃ \tag{2}$$

Figure 1. The schematic of system modeled (Left), Temperature sensor in the stack in the attic (Middle), and insulation around the stack in the attic (right).

Where T is the temperature in degrees Celsius. P is the saturation pressure in kilopascals (kPa). The humidity ratio, ω, is defined as the ratio of the mass of the water vapor, m_v, to the mass of dry air, m_a, and can be calculated knowing the air pressure and saturation:

$$\omega = 0.622 \frac{P_v}{P - P_v} \tag{3}$$

Hence, given the average air temperature at each cross section, the saturation pressure and water vapor pressure could be calculated in relation to the RH and humidity ratio. Calculating the mass flow rate of the inlet air, the water vapor content at the inlet and outlet of the pipe could then be determined. The difference in the water vapor content between the inlet and the outlet of the pipe determined the amount of condensation. Using the latent heat of condensation, the heat source term could be established. Figure 2 shows the Control Volume (CV) that was analyzed.

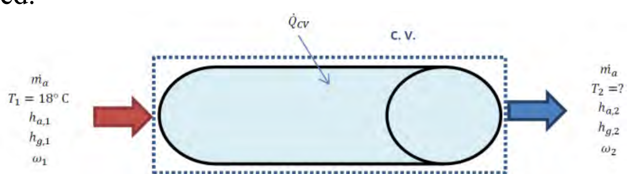


Figure 2. Thermodynamics analysis of the control volume

This analysis can be written as:

$$\dot{Q}_{CV} + \dot{m}_a\left[(h_{a,1} - h_{a,2}) + \omega_1 h_{g,1} + (\omega_2 - \omega_1)h_w - \omega_2 h_{g,2}\right] = 0 \tag{4}$$

Where $\dot{Q}_{CV}$ accounts for heat transfer to the surrounding cold environment; $\dot{m}_a(h_{a,1} - h_{a,2})$ represents the sensible heat carried by the air, which can be written as $C_p(T_1 - T_2)$; $\dot{m}_a(\omega_2 - \omega_1)h_w$ accounts for the sensible heat released by the condensed water; and $\dot{m}_a(\omega_1 h_{g,1} - \omega_2 h_{g,2})$ is the amount of water that condensed. The first two terms in the bracket were calculated in the simulations, whereas the last two terms were calculated after the aforementioned source heat term was established. An excel sheet was created to input the corresponding heat being transferred to the surrounding for each outlet condition.

RESULTS

Numerical simulations — Extensive simulations were conducted to determine the insulation requirement to minimize the risk of stack ice clogging. Two RH levels in the soil gas were considered, 100% and 50%. It was found that the worst case scenario when freezing is the most likely to occur near the pipe outlet is the case with 50% RH at the inlet. When the RH of the air at the inlet is 50%, condensation is delayed until the air reaches a temperature where the air becomes saturated with moist. The air velocities at the pipe inlet were assumed to be 0.05 m/s, 0.1 m/s and 0.15 m/s. It has been observed that the heat source term decreases as the velocity of the soil gas reduces, and the risk for freezing will thus increase in these instances. Using insulating materials with greater thermal resistances around vent pipe can reduce the overall diameter of the pipe and consequently reduce the overall area exposed to cold temperature, which is preferred.

In order to better determine a threshold for the ice accretion at the end of the pipe, the average temperature at the end cross section was calculated. If the average temperature is above 0 °C, it can be assumed that ice accretion or blockage at the end of the pipe is unlikely to occur. The average air temperatures at the end of the pipe for each case were calculated when outdoor temperature was -25 °C, and the results are shown in Figure 3 (a) and (b), corresponding to k = 0.04 W/(m•K) and k= 0.02 W/(m•K) respectively. It can be seen when R7 insulation is used along the entire length of pipe, the average temperature at the end of the pipe can reach below the freezing point when the inlet velocity is 0.05 m/s regardless of the insulation material. As mentioned before, this is the worst case scenario where the vent stack air velocity is minimal (0.05 m/s) and the RH is only 50%; hence, the minimum amount of heat from condensation is added to the control volume. The results also showed that using R14 insulation all along the entire length of pipe is more than sufficient to avoid freezing, however it is also more costly.

Figure 4 depicts the temperature contours along the pipe for the case when R7 was applied to the outer perimeter of the stack in the unheated attic and R14 was used around stack above the roof. We used k = 0.02 W/(m•K), V=0.05 m/s, inlet RH= 50% and the length in attic = 2 m in our simulation and the outdoor temperature was -25 °C. It can be seen that, with the R7/R14 insulation combination, the core of the air flow is still warm at the pipe end and freezing is unlikely to occur. Hence, it is recommended that R7 insulation be used along the pipe section located in the attic and R14 insulation for that section exposed to outdoor conditions.

<u>Validation of simulation using experimental results</u> — The recommendations for Rn vent stacks insulation based on simulation results have been taken by a field study conducted between December 2017 and February 2018 in the National Capital Region of Canada. An outdoor temperature of -26 °C occurred on 28 December, 2017, which was chosen to benchmark the simulation results. The velocity of the vent stack was measured as 0.15 m/s and the RH was 100% at the pipe inlet. The 150 cm of the stack was located in the attic and having R7 insulation. 40 cm of pipe, insulated with R14 insulation, was above the roof line. The air temperature was measured at 86 cm from the pipe inlet and was used to benchmark the simulation. The average temperature derived from the simulation was 13.4 °C, and an average temperature of 13.25 °C was measured from the test. These results confirm that the method used to model the condensation as the surface heat source was rational. The temperature contours for the simulation are shown in Figure 5. It can be seen that the soil gas remains warmer than 0 °C even at the end of the pipe using the suggested insulation. The in-situ observations also confirmed that no freezing developed at the pipe exit.

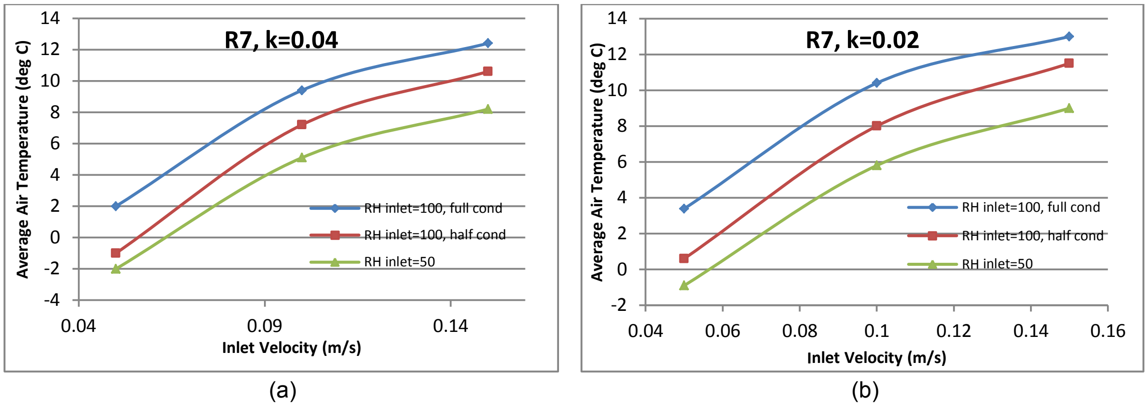


Figure 3. Average temperature at the outlet cross section of the pipe for R7 and (a) k=0.04 W/(m.K) insulation, (b) k=0.02 W/(m.K) insulation with an outdoor temperature of -25 °C

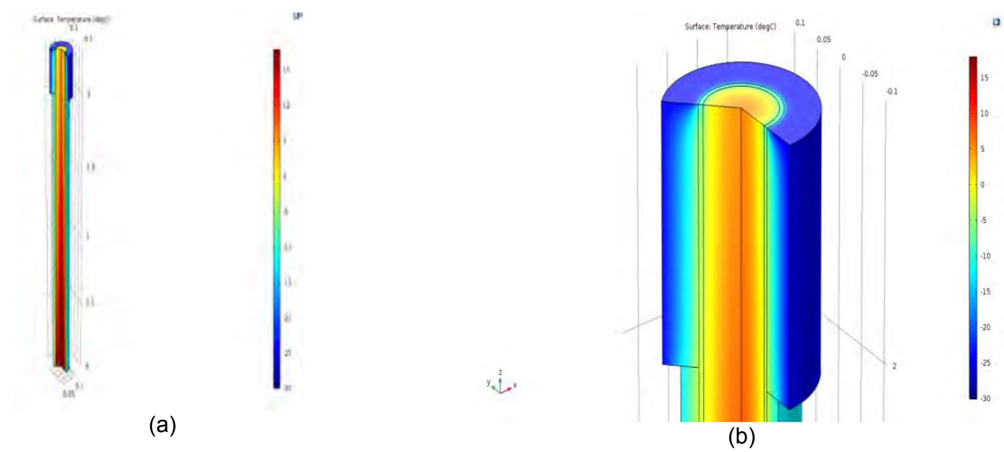
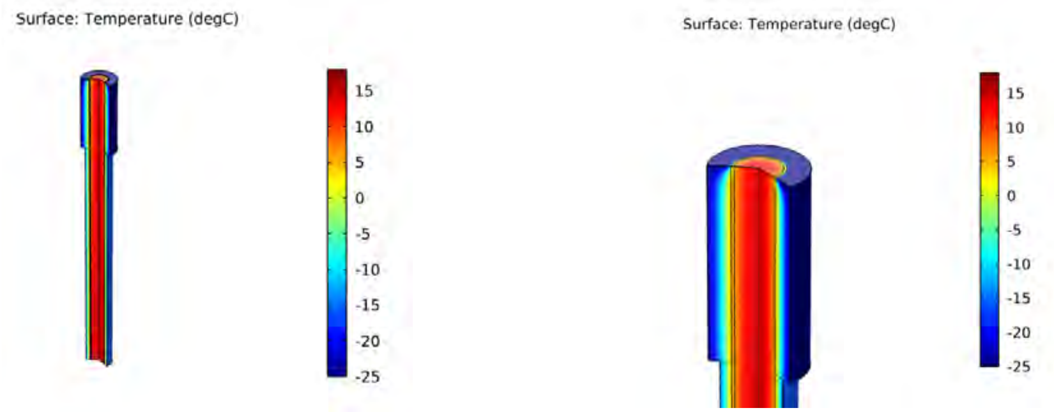


Figure 4. Temperature contours for the combined R7/R14 insulation using K=0.02 W/(m.K), V=0.05 m/s, inlet RH= 50% and the length in attic= 2 m (a) along the pipe (b) at the end of the pipe

DISCUSSIONS

Using the COMSOL Multiphysics package, a study was undertaken to determine the level of insulation required to the avoid freezing and ice clogging of Rn stacks in Canadian winters. Different air velocities in the pipe, lengths of vent pipe, insulation level and thickness, and outdoor conditions were investigated. The following outcomes were derived from the simulations:

- Soil gas flow in the stack was found to be vulnerable to freezing; the lower the air velocity is in the pipe, the more likely freezing occurs.
- Using insulation materials with lower thermal conductivity for the same thermal resistance can reduce the surface area exposed to the cold temperature and thereby reduce the freezing risk.
- Minimizing the length of pipe located in the attic and outdoors can reduce the exposure to low temperatures and hence reduce the freezing risk.
- A Rn stack was installed in a Canadian home by applying R7 insulation around the pipe in the attic and R14 insulation around pipe above roof line, as suggested by the simulation results. The combined insulation appeared to avoid freezing of the Rn stack vent effectively, even when the outdoor temperature dropped to -26 °C.



(a) (b)

Figure 5. Temperature contours for the combined R7/R14 insulation using K=0.02 W/(m.K), V=0.15 m/s, inlet RH= 100% and the pipe length in attic= 1.5 m (a) along the pipe (b) at the end of the pipe

CONCLUSIONS

This study presents a numerical model to determine the required insulation level around Rn stacks in unheated attic space and above roof, in order to minimize the risk of ice blockage at the exit of the stack. Simulation results provided guidance on insulating a stack in a field study home in cold climate. The soil gas temperature measured from one point in the pipe was compared with the results from simulation. The difference is only 1.2%. This demonstrates the model benchmarking is successful. These results confirm the validity of the assumptions made for the numerical model as well as the recommendations for the insulation level. No freezing in the Rn stack occurred during the coldest days of the test period using the R7/R14 insulation combination. Future field testing from other regions of Canada will demonstrate further whether the combined R7/R14 insulation suggested by simulation work described in this paper is sufficient for Rn stacks to avoid ice blockage at the exit, in cold Canadian winter.

ACKNOWLE DGEMENT

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