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Temperature and relative humidity measurements and data analysis of five crawl spaces

Anssi Laukkarinen*, Juha Vinha

Tampere University of Technology, Korkeakoulunkatu 10, 33720 Tampere, Finland

Abstract

This paper presents the results of one year long temperature and relative humidity measurements from five cold crawl spaces. The results are presented using a set of indicator values which have been selected to be simple to use and descriptive. Compared to outdoor air conditions, periods of colder temperature and higher moisture content occurred in all the measured crawl spaces. However, not all structures behaved similarly, which can be seen from the indicator values. Based on the analysis the largest differences occurred in the temperature conditions and in the number of condensation risk hours.

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1. Introduction

1.1. General about cold crawl spaces

A cold crawl space is a common floor structure in many countries, in which there is an outdoor air ventilated space between the floor and the ground surface. Some relatively recent temperature and relative humidity measurements of these crawl spaces have been reported for example from Finland [1], Sweden [2,3], Japan [4,5] and USA [6,7]. It seems quite common that there are high values of relative humidity in the crawl spaces during summer, when the cool ground keeps also the crawl space temperature low. Different countries can have substantially different climatic areas and because of that, it is important to use climate specific solutions for the crawl space design.

* Corresponding author. Tel.: +358-50-917-9988

E-mail address: anssi.laukkarinen@tut.fi

1.2. The goals of this study

Despite the problems related to typical solutions used in cold climate areas, cold crawl spaces are still commonly used in Nordic countries. Some of the main reasons or situations for using crawl spaces are construction sites with large ground surface height differences, need to use piles due to low load-bearing capacity of the soil, radon protection and economic price [8]. One of the problems then is that while the advantages have been utilized, the moisture related risks have not been removed. Another big question is that when existing crawl spaces are inspected, it is not always clear when concrete retrofitting actions should be done. Obvious situations of deficiencies in water leakage control and wide-spread mold growth are clear situations to be dealt with, but sometimes high relative humidity can cause mold and microbial growth without being visible.

This study aims to define and test simple indicators to be used when existing crawl spaces are investigated. Temperature and relative humidity measurements are common practice, but the interpretation of results should be made more understandable and easy to communicate even to people outside the building physics sector. Another aim is to represent temperature and relative humidity measurements in such a way, that future comparisons to other similar measurements would be easier. It would be of interest to be able to give a single-valued performance indicator (a “grade”) for a specific structure instead of long time series of temperature and relative humidity. The work is tightly related to the performance-based design discussed e.g. in [9].

The objectives of this study are:

- 1) Measure the temperature and relative humidity conditions inside typical crawl spaces
- 2) Define simple indicator values that could help characterizing the actual heat and moisture behavior of the measured crawl spaces
- 3) Present the measurement results using those indicators
- 4) Identify possibilities to use different indicators for setting design requirements for crawl spaces.

Setting limit values for different deterioration processes is a difficult task. However, if it would be possible to demand that there shouldn't be certain types of conditions at all, we should be on the safe side. In the long run, if more evidence is accumulated that some other limit values would be better, it would be possible to change them. Even then, using objective indicators would help to reduce the variation in the interpretation of the measurement results.

2. Material and methods

2.1. General

The studied cases were five single-family house crawl spaces in southern Finland. Some basic information about the measurements is given in Table 1. The measurements from crawl spaces were done with Rotronic HL-NT2 temperature and relative humidity data loggers with HC2-S sensors. The sensors were tested before the measurements in a climate chamber and approximately half of them after the measurements. Indoor air conditions were measured with Comark Diligence EV N2011 and N2013 data loggers, which were tested before the measurements and only after a longer time after the measurements. The conducted tests against a calibrated reference sensor showed deviations that were within the error limits declared by the manufacturer. Outdoor air conditions were acquired from the closest meteorological weather station. Water vapor saturation content of air was calculated with the equations presented in [10]. All calculations were done using the Python programming language with the jupyter/iPython tools.

2.2. Indicators

There are multiple physical processes affecting the crawl space conditions simultaneously, e.g. water vapor diffusion, capillary water transport, intended and unintentional air flows and heat transport mechanisms. Relative humidity is a key parameter in many moisture-related damaging processes, so it is desired to keep relative humidity values low. However, relative humidity can be difficult to interpret or control directly and because of that, the temperature (°C) and water vapor content (g/m³) values and differences were analyzed.

Table 1. Basic information about the measured crawl spaces.

Crawl space	Construction year	Start of one year analysis period	Average indoor air temperature	Description of the outdoor air ventilated crawl spaces
A	1978	2011-01-01	21.2	The load-bearing beams are made of aerated concrete (250mm) with 60mm of EPS-insulation on top. Ground is mostly covered with a plastic foil. The crawl space is ventilated through L-pipes. $U_{\text{fl}} \approx 0.3\text{W}/(\text{m}^2\text{K})$
B	1984	2011-01-01	23.5	Timber joists with mineral wool insulation in between. There is a 50mm covering sand protecting a plastic sheet, which spread over at least part of the soil. The crawl space is ventilated through openings in the foundation wall.
C	2001	2011-01-01	23.6	Hollow-core slab 265 mm with 175 mm EPS-insulation on top. Ground surface has a mixed gravel/sand ground layer. The crawl space is ventilated through L-pipes. $U_{\text{fl}} \approx 0.2\text{W}/(\text{m}^2\text{K})$
D	2007	2011-01-01	25.6	The floor is made of timber joists with 200mm mineral wool insulation, on top of large concrete beams. There is coarse gravel on ground surface, with a plastic foil covering approximately 75 % of the ground. The crawl space is ventilated through openings in the foundation wall. $U_{\text{fl}} \approx 0.19\text{W}/(\text{m}^2\text{K})$
E	2008	2011-02-28	24.7	Timber floor with total insulation thickness 300mm. Leca on ground surface. The crawl space is ventilated directly through openings in the foundation walls. $U_{\text{fl}} \approx 0.13\text{W}/(\text{m}^2\text{K})$

For this study, the following temperature-related indicators were chosen:

- 1) Yearly average temperature difference between the crawl space air and outdoor air, which describes the basic temperature conditions inside the crawl space.
- 2) Decrease in the yearly crawl space temperature amplitude compared to outdoor air, which describes the thermal connectedness of the crawl space to outdoor air.
- 3) The time lag in crawl space temperature compared to outdoor air temperature, which describes the relationship between different heat flows and the effective thermal mass.
- 4) Number of hours in a year when the air temperature inside the crawl space is lower than in the outdoor air, calculated from the hourly measurement data. It describes the amount of potentially harmful conditions mainly during summer-time.
- 5) Same as number 4, but calculated from the fitted sine curves (explained in the next paragraph). The fitted values are more easily available for the whole year due to the possibility to use shorter-than-year measurement time, but the fitting procedure causes loss of information.

The indicator values 1–3 were calculated by first fitting a sine curve (Eq. 1) both to the measurement data and then subtracting the parameter values from different fitted functions.

$$T(t) = \bar{T} + \hat{T} \cdot \sin\left(2\pi \frac{t-t_0}{8760}\right) \quad (1)$$

Where $T(t)$ is the temperature as a function of time ($^{\circ}\text{C}$), \bar{T} is the yearly average temperature ($^{\circ}\text{C}$), \hat{T} is the yearly temperature amplitude ($^{\circ}\text{C}$) and t_0 is the phase (h).

The following vapor content related and other indicators were chosen:

- 6) The yearly mean and standard deviation of water vapor excess inside the crawl space compared to outdoor air. These values describe the combined effect of moisture production from the soil and crawl space ventilation.
- 7) The number of hours in a year, when the water vapor content inside the crawl space is higher than in the outdoor air, calculated from the hourly measurement data. It describes the duration of moisture evaporation from the soil (versus the soil acting as a moisture sink).

- 8) Number of hours in a year, when the outdoor air water vapor content is higher than the saturation water vapor content of the crawl space air, calculated from the hourly data. It describes the risk of moisture condensation to the crawl space surfaces.
- 9) Coefficient of determination (R^2) for the correlation between the change in consecutive values of wind speed at nearest meteorological weather station and water vapor excess in crawl space ($\Delta v_t - \Delta v_{t-1}$ vs $ws_t - ws_{t-1}$). It describes the susceptibility of the crawl space structure to the microclimatic wind conditions. The idea is that when the wind speed increases from one time step to another, it should make the water vapor excess smaller.
- 10) Number of hours in a year, when the relative humidity is over 80 %RH or 90 %RH
- 11) Mold index calculated both for outdoor air and crawl space conditions, with the Finnish mold growth model (updated model with material sensitivity classes, see e.g. [11,12]). Calculations are started from January 1st. Sensitivity class “very sensitive” and mold index decline coefficient of 0.5 were used for all cases.

3. Results

Based on Table 1, it is interesting to notice that the newer buildings had higher average indoor air temperature than the older buildings. It should be noted that the sample size is small, so definite inferences should be done with caution.

Table 2 shows the numeric values for temperature-related indicators 1–5.

Table 2. Values of the numeric indicator 1-5 and the root mean square error (RMSE) between the first year of measured data and the fitted sine functions.

Indicator	A	B	C	D	E
1) Yearly average temperature difference	5.0	2.0	4.1	3.2	1.4
2) Decrease in temperature amplitude	-9.4	-5.8	-8.6	-5.1	-4.1
3) Phase difference between crawl space and outdoor air temperature	827	319	673	162	192
4) Number of hours when the crawl space is colder than outdoor air (based on hourly data)	2424	2847	2672	2127	2854
5) Number of hours when crawl space is colder than outdoor air (based on sine curve fit)	2922	3452	3110	2576	3470
RMSE, hourly crawl space temperature and sine curve fit	0.4	2.0	0.5	1.4	2.0
RMSE, hourly outdoor air temperature and sine curve fit	5.2	5.6	5.1	5.6	4.6

Values from indicators 1–3 are also presented in Figure 1, which shows the correlation between crawl space and outdoor air temperature fitting function parameters.

Based on Figure 1, there seems to exist a correlation between the yearly average temperature difference, amplitude and lag: Compared to outdoor air conditions, the higher the average temperature difference is, the smaller the temperature amplitude and larger the time lag becomes. This means that the crawl space temperature shifts away from the outdoor air temperature and closer to the indoor air temperature.

Further analysis of indicators 4 and 5 shows that the number of colder hours either by calculating them directly from the hourly data or from the sine curve fit correlate clearly, but the values from the fitted function are 438-616 hours larger than the values calculated directly from the hourly data. The difference becomes the bigger, the larger the number of the colder hours is.

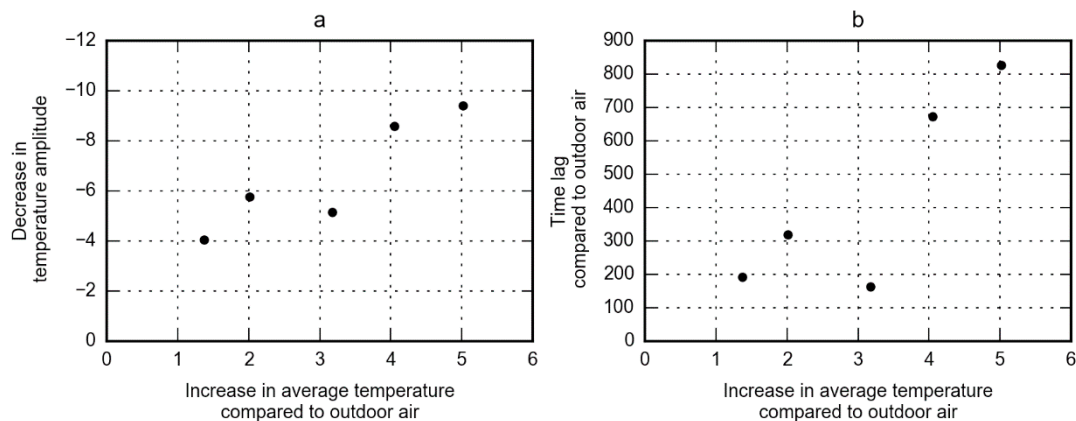


Figure 1. Comparison of temperature conditions inside the crawl spaces compared to outdoor air conditions. a) Between yearly average temperature rise and decrease in temperature amplitude and b) between yearly average temperature rise and time lag. One point represents one crawl space (five in total).

The results for indicators 6–11 are presented in Table 3.

Table 3. Values of numerical indicators 6–11 for each measured crawl space.

Indicator	A	B	C	D	E
6) Mean and standard deviation of water vapor excess in crawl space, based on hourly values, g/m^3	0.4, 1.6	0.3, 1.0	2.9, 1.9	1.0, 1.0	0.5, 0.9
7) Number of hours in a year, when the vapor content inside crawl space is higher than in outdoor air, calculated from hourly data	5979	5587	8087	7638	6367
8) Number of hours in a year, when the outdoor air vapor content is higher than crawl space saturation vapor content	796	571	593	156	144
9) Impact of wind speed on moisture excess, R^2	0.003	0.002	0.003	0.002	0.008
10) Number of hours in a year, when the relative humidity is over 80 % RH or 90 % RH	2760, 1241	3307, 1967	8752, 6801	3707, 884	3554, 335
11) The maximum value of one-year mold index for outdoor air and crawl space, calculated for the very sensitive class	5.5, 3.3	4.7, 5.7	3.1, 6.0	4.7, 3.6	3.1, 1.7

The yearly average vapor excess for different crawl spaces was 0.3–2.9 g/m^3 . The crawl space with the biggest vapor excess had relative humidity over 85 % all year around and e.g. visibly moist ground surface and condensation at thermal bridges during winter.

The number of condensation risk hours (indicator 8) shows a decreasing trend when compared to construction year. Also, the number of hours when the relative humidity was over 90 % RH was smaller in newer crawl spaces than in older ones. However, no clear correlation is visible regarding the number of hours for relative humidity over 80 % RH or one-year maximum value of mold index. This would mean that although the amount of severe conditions was lower in newer buildings, they still experience long period of mold-susceptible conditions. Vapor excess in crawl spaces didn't correlate with wind speed, which means that the vapor excess didn't depend at least directly from wind speed.

4. Conclusion

Continuous hourly temperature and relative humidity measurements were done in five traditional cold crawl spaces. A group of indicators were defined to help describing and comparing their heat and moisture behavior. Based on the data analysis, conditions susceptible for mold growth and condensation occurred in all measured crawl spaces.

The closer the crawl space conditions were to outdoor air conditions, the less severe moisture related conditions occurred, such as condensation risk hours. However, in all measured cases there was still a large amount of conditions of colder temperature, higher vapor content and high relative humidity. To remove these conditions, crawl space design should be changed to minimize thermal lagging due to soil thermal capacity, keep vapor excess in a low level and at the same time allow temperature to rise compared to outdoor air.

Different crawl spaces behaved differently during the measurement period, which would imply that there are measurable differences between them. Larger measurement sample would allow more robust study of the impact of different parameters, such as indoor air temperature, building materials, ventilation arrangements and shorter measurement periods. The presented indicators can be used to help analyzing measurement data and to set limit values for them.

The limit values used in actual building projects depend essentially on building regulations and on the views of the client. One possibility for design requirements could be however, that there shouldn't be any condensation risk hours and in the long run there shouldn't be any mold growth either. This requires that both temperature and moisture conditions are equally considered in the crawl space design.

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References

- [1] Kurnitski J. Crawl space air change, heat and moisture behaviour. *Energy & Buildings* 2000;32:19-39.
- [2] Bok G, Hallenberg N, Åberg O. Mass occurrence of *Penicillium corylophilum* in crawl spaces, south Sweden. *Building and Environment* 2009;44:2413-7.
- [3] Johansson P, Svensson T, Ekstrand-Tobin A. Validation of critical moisture conditions for mould growth on building materials. *Building and Environment* 2013;62:201-9.
- [4] Iwamae A, Matsumoto M. The Humidity Variation in Crawl Spaces of Japanese Houses. *Journal of Thermal Envelope and Building Science* 2003 Oct 1;27(2):123-33.
- [5] Toyoumi A, Horisawa S, Yoshimura T, Doi S, Imamura Y. The effect of different foundation systems on the fungal flora in the crawl space of a new wooden Japanese house. *Building and Environment* 2010;45:1054-1060.
- [6] Hales D, Lubliner M & Gordon M. Vented and Conditioned Crawlspace Performance in Marine and Cold Climates of the Pacific Northwest. *Buildings Conference 2010 Clearwater Beach, Florida*; 2010.
- [7] Zoeller W, Williamson J, Puttagunta S. Sealed Crawl Spaces with Integrated Whole-House Ventilation in a Cold Climate. 2015;23 p.
- [8] Burke S. Crawl spaces in wood framed single family dwellings in Sweden: Unwanted yet popular. *Structural survey* 2007;25(1):51-60.
- [9] Hens, Hugo S L C. *Performance Based Building Design 1: From Below Grade Construction to Cavity Walls*. 1st ed. : Wilhelm Ernst & Sohn; 2012.
- [10] SFS-EN ISO 13788:2012. *Hygrothermal performance of building components and buildings elements. Internal surface temperature to avoid critical surface humidity and interstitial condensation. Calculation methods*. 2012.
- [11] Viitanen H, Vinha J, Salminen K, Ojanen T, Peuhkuri R, Paajanen L, et al. Moisture and Bio-deterioration Risk of Building Materials and Structures. *Journal of Building Physics* 2010;33(201):201-24.
- [12] Ojanen T, Viitanen H, Peuhkuri R, Lähdesmäki K, Vinha J & Salminen K. Mold growth modeling of building structures using sensitivity classes of materials. *Proceedings of Thermal Performance of the Exterior Envelopes of Whole Buildings XI, ASHRAE, DOE, ORNL; December 5–9.; Clearwater Beach, Florida, USA; 2010.*