Analysis of hygrothermal parameters in Finnish and Lithuanian multi-family buildings before and after energy retrofits

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Abstract

This study focuses on analyzing temperature and moisture related parameters based on data from 45 Finnish and 20 Lithuanian multi-family buildings. The data consist of two rounds of 2-month data-logging (1-hour interval) of indoor temperature and relative humidity at two locations: one representing average occupied zone and the other one nearby the coldest spot of the building envelope. Between the two rounds of data-logging, 37 buildings from Finland and 15 buildings from Lithuania underwent retrofits aiming to improve their energy efficiency. Measurement data were coupled with outdoor data from national weather stations, based on which a temperature factor (f_c) and excess indoor moisture content (Δv) were calculated. Based on the results, f_c was significantly increased in Lithuanian case buildings after the retrofits, whereas no significant differences were observed in Finnish buildings. In addition, Δv was significantly lower in Finnish case buildings after retrofits, whereas an opposite trend was seen in the Lithuanian buildings.

Keywords

Temperature, relative humidity, surface temperature, temperature factor, indoor moisture excess

Introduction

Several measured and calculated parameters are needed to analyze thermal and moisture behavior of building structures. The main measurements include indoor and outdoor temperature (T) and relative humidity (RH) and indoor surface T. These measured parameters can be used to calculate other parameters, such as temperature factor and excess indoor moisture content (Δv). The impacts of energy retrofits on hygrothermal conditions and indoor environmental quality (IEQ) have not been commonly taken into consideration.

High humidity can cause microbial growth and degradation of the building structures due to capillary condensation, or surface condensation if the surface temperature is below dew point (Csoknyai, 2001). According to standard EN ISO 13778 (EN ISO 13788:2012, 2012) there is a risk of mold growth when monthly average surface RH is above 80%. Therefore, decreasing humidity levels and/or increasing surface temperatures can help to prevent both capillary and surface condensation.

Surface T depends on both indoor and outdoor T, surface geometry, airflows, as well as thermal conductivity of each section of the envelope. There are some critical points in the envelope where surface temperatures are typically lower as compared to the other parts of the envelope. Thermal bridges refer to points where thermal conductivity of the envelope is higher due structures (such as timber or steel frames), joints, or degradation of materials, resulting in an overall reduction in thermal insulation. Surface temperatures are also usually lower around the corners of the envelope.

A temperature factor is defined as a difference between internal surface T and external T, divided by the difference between internal T and external T (Equation 1) (EN ISO 10211:2007, 2007) (EN ISO 13788:2012, 2012).

$$f_{Rsi} = \frac{T_{s,min} - T_o}{T_i - T_o} \qquad (1)$$

where $f_{Rs}i$ is temperature factor, $T_{s,min}$ is minimum surface temperature, T_o is outdoor temperature (°C) and T_i is indoor temperature (°C).

Temperature factor has been used more regularly in evaluation of thermal performance and thermal bridges of building envelopes in some countries, such as Finland and UK. In UK the temperature factor and linear thermal transmittance are two key modelling outputs for building regulatory purposes (Ward, Craeme, & Sanders, 2016). These key outputs are used by designers to confirm the adequacy of particular junction details and to improve the thermal performance of junctions. Song and colleagues (Song, Lim, & Song, 2016) studied alternatives for reducing thermal bridges in metal panel curtain wall systems by using both heat loss and lowest indoor surface T obtained through heat transfer simulations. Their assumption was that the closer this value is to 1, the less likely will condensation occur (Song, Lim, & Song, 2016). Finnish Decree 545 (Ministry of Social Affairs and Health, 2015) defines action limits for temperature factor as percentages (i.e. temperature factor multiplied by 100%). These action limits are 81% for walls and 87% for floors.

Different activities generate moisture indoors. These include moisture generation from occupants due to respiratory process, bathing or showering, cooking, dish-washing, laundry, and drying (Zemitis, Borodinecs, & Frolova, 2016). On the other hand, indoor moisture can be removed by ventilation and dehumidification processes.

Maximum moisture content (MC) of air (without condensation) or saturated vapour density is depended on temperature according to an empirical formula (Equation 2) (Nevander & Elmarsson, 1994):

$$V_{sat} = \left[4.85 + 3.47 \times \frac{T}{10} + 0.945 \times (\frac{T}{10})^2 + 0.158 \times (\frac{T}{10})^3 + 0.0281 \times (\frac{T}{10})^4 \right] \times 10^{-3} \quad (2)$$

where V_{sat} = saturated vapour density, g/m^3, and T= temperature, °C. Relative humidity (RH, %) express relation between moisture content in air (V_{air}) and saturated vapour density (V_{sat}) (Equation 3):

$$RH = \frac{V_{air}}{V_{sat}} \times 100\% \quad (3)$$

where V_{sat} (g/m^3) is calculated using Equation 2. After calculating moisture content (V_{air}) (Equation 3) in both indoor and outdoor air, excess indoor MC (resulting from indoor moisture generation) can be calculated (Equation 4):

$$\Delta v = v_i - v_o \quad (4)$$

where Δv is excess indoor MC (g/m^3), v_i indoor air water vapour content (g/m^3) and v_o outdoor air water vapour content (g/m^3). Also terms internal moisture excess or indoor/internal moisture supply are commonly used as synonyms for excess indoor MC.

It is generally considered that Δv is relatively constant during the colder part of the heating season (T_o < 0 °C) and it decreases when the outdoor temperature increases (Geving & Holme, 2012). According to International Energy Agency Annex 24, the critical level for Δv is suggested as a safety margin (1.1) not be exceeded in more than 10% of the cases (corresponds to 90th percentile) when performing hygrothermal simulations. Several field studies have been performed to define typical Δv. Geving (Geving & Holme, 2012) measured 85 Norwegian dwellings (mainly detached and semi-detached houses) for one week during heating season and calculated Δv in living rooms, bedrooms and bathrooms. The 90th percentile values were 3.2 g/m^3 and 3.0 g/m^3 for weekly average outdoor temperatures below and above +5 °C, respectively. Kalamees et al. (Kalamees, 2006) concluded that the average Δv in living rooms during winter is between 2 and 3 g/m^3. They also performed full-year measurements in detached houses with low to medium occupancy (average 42 m^2/person), and concluded that critical level for Δv is about 4 g/m^3 during the cold period (T_{out} < +5 °C) and about 1.5 g/m^3 during the warm period (T_{out} ~ +15 °C). The average values were 1.8 and 0.5 g/m^3 for the cold and warm periods, respectively. Ilomets et al. (Ilomets, Kalamees, & Vinha, 2017) measured indoor hygrothermal loads in 237 dwelling units in Estonia and concluded that average Δv is 2.8 g/m^3 during the cold period (outdoor T≤ 5 °C) and that occupancy, cooking and type of ventilation (air change rate) impacts on Δv.

This study utilizes data collected from 45 Finnish and 20 Lithuanian multi-family buildings as a part of INSULAtE project. The purpose of the whole project was to assess impacts of energy retrofits on indoor environmental quality (IEQ) and occupant satisfaction with IEQ and health, and to develop a common methodology on assessment of these impacts both on the building and national levels. In our previous papers, we assessed impacts of energy retrofits on ventilation rates and indoor carbon dioxide (CO_2) concentrations as well as air pressure differences across building envelope (Leivo, et al., 2017)) and indoor thermal environment (Leivo, et al., 2018). In this paper, we present further analyses focused on temperature and moisture related parameters.

Materials and Methods

Case study buildings

Selected buildings were volunteering multi-family buildings that were planned to be retrofitted during the project. Also some buildings, which were not retrofitted during the project, were included as controls. Majority of the selected buildings were built in 1960-1980 (Figure 1). An average of five apartments per building were targeted to participate in the measurements.

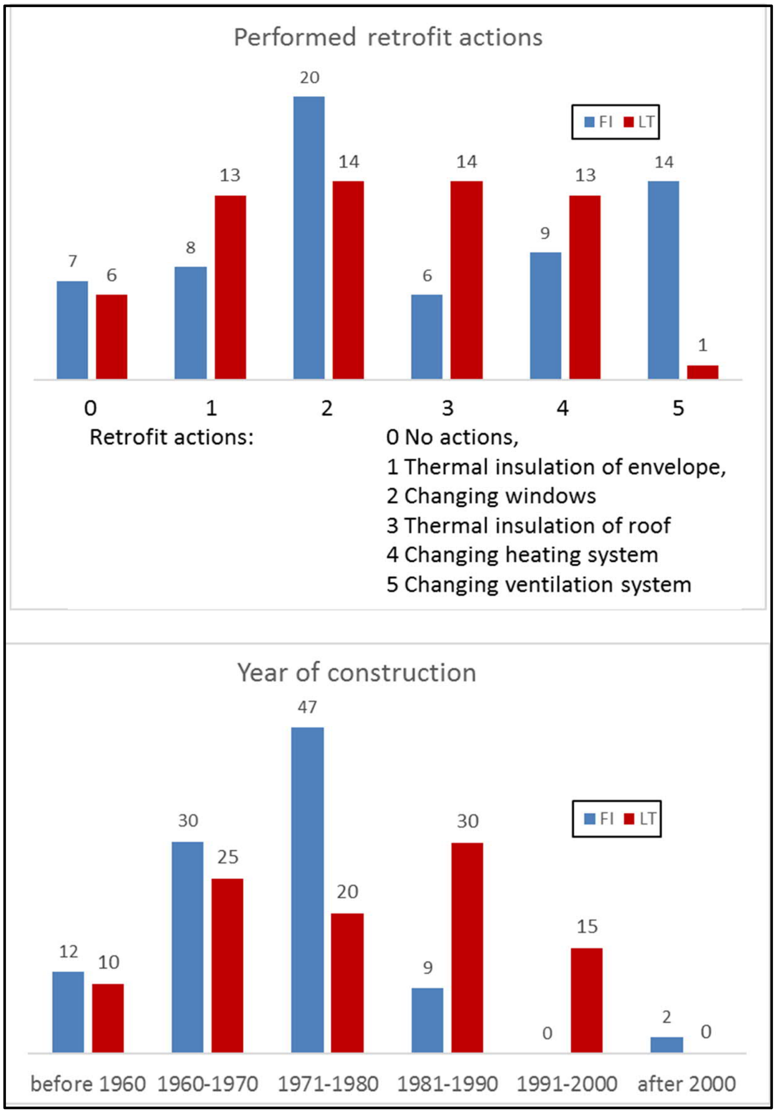

Figure 1. Year of construction and performed retrofit actions in Finland (FI) and Lithuania (LT).

The studied buildings in both countries are quite comparable in terms of construction type and common building materials. The external walls were commonly made of prefabricated concrete elements (with thermal insulation in between the panels) in both countries. It was also noticed that the average size of the apartments was almost the same in both countries, and the majority of the buildings were built in 1960-1980.

In Finland, the final sample included 45 multi-family buildings: 37 were retrofitted (CASE) and eight were not retrofitted (CONTROL) buildings. Majority of the measured buildings (about 92% of apartments) had a mechanical exhaust ventilation system, with or without heat recovery units. The ventilation systems are typically operated so that more efficient exhaust is turned on for two hours once or twice a day, in the morning (10 am to 2 pm) and in the afternoon (4 pm to 6 pm). Average floor area per person was 41.7 m^2 (range 17.7 m^2 - 113 m^2 per person). Majority of the apartments had glazed balconies. Typical U-values of the structures before retrofits were: outer walls U= 0.40 … 0.28 W (m-2 K-1), roof 0.40 … 0.36 W (m-2 K-1), floors 0.40 … 0.29 W (m-2 K-1), and windows 2.1 W (m-2 K-1).

In Lithuania, the final sample consisted of 20 multi-family buildings, including 15 retrofitted (CASE) and five not-retrofitted buildings (CONTROL). Majority of the buildings had natural ventilation, which in 44% of the apartments had been improved with occupant-controlled fan driven exhaust in the kitchen and natural/mechanical exhaust in the bathroom. The average floor area per person was 23.9 m^2 before, and 22.3 m^2 after the retrofits (range 12 m^2 - 83 m^2 per person). Typical U-values before the retrofits were: outer walls U=1.27…0.88 (m-2 K-1), roof 0.85 (m-2 K-1), floors 0.71 (m-2 K-1).

In Finland, majority of the case buildings underwent focused energy retrofits (FER), where only one retrofit action was performed. Some 11% of the cases underwent deep energy retrofits (DER), involving several retrofit actions. Few of the case buildings had already completed some retrofit actions prior to the study. As shown in Figure 1, the most common retrofit action in Finland was replacing windows (new U-value 1.0 W (m-2 K-1)) and/or installing heat recovery to the existing exhaust ventilation system, which then became mechanical ventilation with heat recovery (MVHR).In Lithuania, about 87% of cases underwent deep energy retrofits, most commonly involving adding thermal insulation to the wall (new U-value 0.20 W (m-2 K-1)) and roof (new U-value 0.16 W (m-2 K-1)), replacing windows (new U-value 1.4 W (m-2 K-1)) and glazing of balconies, but did not typically include changes in the ventilation systems.

Measurement methods

Selection of the measurement methods were limited to non-destructive and cost-effective methods, which were accurate enough to detect meaningful differences between pre and post retrofit conditions.

Temperature (T) and relative humidity (RH) was continuously monitored with data loggers (model DT-172, T range -40 - +70 °C, accuracy ± 1 °C; RH range 3 - 100%, accuracy ± 3%) for two months during the heating season, with 1-hour measurement interval. In each apartment, one data logger was placed nearby the coldest spot (usually on the floor by the balcony door), i.e. place where coldest inner surface temperature was detected by thermographic camera (ThermaCAM B2, FLIR Systems AB, measurement range -15…+45 C, accuracy +-2°C or 2%) or IR-thermometer (Testo 830 T1 infrared temperature meter with 1-point laser, range -30...+400 °C, accuracy 0.5 °C), presented as T_c and RH_c. Temperature nearby the coldest spot of the building envelope better reflects risk of condensation or microbial growth. Another logger was placed in the occupied zone, e.g., middle of the living room (height of 1.2-1.5 m above ground, i.e. human breathing zone as seated), presented as T_w and RH_w. All units used in the study were new and recently calibrated by the manufacturer. The measurements loggers were placed in the same spot both before and after retrofits in each apartment. Therefore, the values are comparable on the apartment and building levels.

Outdoor T and RH data during the measurement period were obtained from local weather monitoring stations, i.e. several regions (Tampere, Hämeenlinna, Lappeenranta, Helsinki, Porvoo, Kuopio) in Finland (by Finnish Meteorological Institute under the Ministry of Transport and Communications) and Kaunas region in Lithuania (by Lithuanian Hydrometeorological Service under the Ministry of Environment).

Based on both indoor air and outdoor data, temperature factors were calculated using Eq. 1 and Δv using Eq. 2-4. The temperature factor was used because it takes into account outdoor temperature, and therefore allows for better comparison between pre and post retrofit values. Due to the measurement technique used (i.e. using data loggers rather than surface temperature measurements), the calculated temperature factor is not strictly corresponding to f_{Rsi} as defined in Eq. 1, and is therefore referred to as f_c.

In addition to the descriptive analysis, the associations between retrofitting and both f_c and Δv were studied using linear mixed modelling (LMM). First, a null model was studied, which included only the outcome variables without any predictors, order to examine the variance between country, building and apartment levels, and to calculate the intra class correlation (ICC) (i.e. proportion of the total variance accounted for by the clustering). Secondly, the selected independent variables were included in the models. Retrofit status was based on case/control and before/after retrofits (pre/post) variables, so that the reference group was case buildings at first measurement (pre-retrofit), and the other groups included case buildings at second (post-retrofit) measurement as well as control buildings at first and second measurements. In addition, the fixed effects included country (Finland/Lithuania), as well as ventilation rate and number of occupants for Δv. (Results related to ventilation rates are reported by Leivo et al. 2017). The estimation was based on the Restricted Maximum Likelihood (REML) method and the Expected Maximum (EM) algorithm. The building and apartment codes were used as subject variables, and the covariance type was identity (covariance structure for a random effect with only one level). Only main effects were studied, while the factorial design with interaction effects were not used. In addition to studying models among the whole population sample, the models were also run for both Finnish and Lithuanian buildings separately. Finally, the effects of level of retrofitting (deep / focused) were studied among the case buildings.

Results and discussion

Temperature factors

Calculated temperature factors in DER, FER and CONTROL buildings are presented in Table 1. Based on the results, f_c appear to be somewhat higher in the Lithuanian buildings, which is surprising given that previously used building codes in Finland have had higher requirements for insulation than what has been used in Lithuania. One possible explanation could be related to the placement of data loggers.

Table 1. Temperature factors f_c in Finnish and Lithuanian apartments.

Finland	DER		FER		Control	
	1st	2nd	1st	2nd	1st	2nd
N	23	17	147	91	30	13
Average	0.85	0.88	0.89	0.88	0.90	0.90
SD	0.05	0.08	0.06	0.08	0.05	0.06
Median	0.85	0.85	0.90	0.89	0.90	0.90
25th	0.81	0.82	0.85	0.84	0.87	0.84
75th	0.88	0.91	0.93	0.94	0.93	0.94
5th	0.78	0.79	0.77	0.73	0.81	0.81
95th	0.94	1.02	0.97	1.00	0.97	0.97
Lithuania	**DER**		**FER**		**Control**	
	1st	2nd	1st	2nd	1st	2nd
N	57	50	9	5	23	8
Average	0.92	0.94	0.85	0.83	0.93	0.88
SD	0.07	0.05	0.11	0.20	0.07	0.11
Median	0.94	0.94	0.88	0.92	0.95	0.89
25th	0.89	0.92	0.74	0.75	0.90	0.82
75th	0.98	0.98	0.95	0.97	0.97	0.97
5th	0.82	0.86	0.69	0.56	0.85	0.72
95th	1.00	1.00	0.96	0.98	0.99	0.99

Table 2 presents LMM model for f_c, expressed as %. Based on the model estimates, estimated mean f_c was 3.5% lower in Finnish apartments as compared to Lithuanian apartments. In the country specific analyses, f_c was significantly higher (2.3 %) in Lithuanian case buildings after the retrofits, whereas significant differences were not observed in the Finnish buildings. Based on the results, temperatures near cold surfaces were increased in Lithuanian buildings, as would be expected after adding thermal insulation on the building envelope. Only a few Finnish buildings added insulation, which is consistent with the findings.

The calculated f_c seems to be a useful indicator in assessments of effects of energy retrofits. Its applicability is best in apartment and building level where loggers are placed in exactly same location before and after retrofits. Based on this study, comparability between countries may not be as good; placement of the loggers may require additional testing and instructions for consistency among field investigators. Long measurement period, one to two months in heating season improves reliability of the results.

Excess indoor moisture content

Results related to excess indoor moisture content are presented in Table 3. Based on the results, average Δv values are higher in Lithuanian buildings, which could be related to differences in occupancy and ventilation characteristics.

Table 3. Excess indoor moisture contents Δv in Finnish and Lithuanian apartments.

Finland	DER		FER		Control	
	1st	2nd	1st	2nd	1st	2nd
N	23	23	147	101	30	21
Average	0.83	0.68	1.34	1.19	1.26	0.94
SD	0.87	0.88	1.26	1.05	0.76	0.66
Median	0.63	0.50	0.98	0.98	1.07	0.78
25th	0.04	-0.05	0.42	0.50	0.72	0.53
75th	1.25	0.92	1.89	1.73	1.51	1.10
5th	-0.18	-0.33	-0.16	-0.23	0.34	0.11
90th	1.89	1.79	3.17	2.24	2.48	1.99
95th	2.22	2.55	3.82	3.05	2.49	2.33
Lithuania	DER		FER		Control	
	1st	2nd	1st	2nd	1st	2nd
N	57	50	9	5	23	8
Average	3.47	4.16	3.50	3.53	3.45	2.68
SD	1.61	1.76	0.91	1.26	1.09	1.40

Median	3.27	3.93	3.50	3.76	3.59	2.59
25th	2.58	2.72	3.27	2.89	2.64	1.98
75th	4.76	5.22	4.21	4.36	4.06	3.44
5th	0.78	1.90	2.15	1.97	1.91	0.81
90th	5.63	7.27	4.36	4.70	4.96	4.52
95th	5.91	7.38	4.61	4.82	5.02	4.53

Figure 2 shows the calculated 10% critical Δv (i.e. 90th percentile values), divided by types of ventilation and retrofit action. The critical Δv was 3.0 and 2.1 g/m^3 before and after retrofits in apartments with mechanical exhaust ventilation in Finland. The critical Δv was 2.1 and 2.7 g/m^3 before and after retrofits in apartments with natural ventilation, respectively. In the control buildings, the critical Δv was 2.5 and 2.3 g/m^3 in the first and second measurement, respectively. In Lithuania, the critical Δv was 5.6 and 6.6 g/m^3 before and after the retrofits in apartments with mixed ventilation, while it was 5.5 and 7.3 g/m^3 before and after the retrofits in apartments with natural ventilation. In the control buildings, the critical Δv was 5.0 in the first and 4.5 g/m^3 in the second measurement in buildings with natural ventilation, and 4.1 and 2.9 g/m^3 in buildings with mixed ventilation, respectively.

These results indicate that different critical levels for Δv may be needed for hygrothermal simulations, depending on location of the buildings, type of ventilation, and retrofit status.

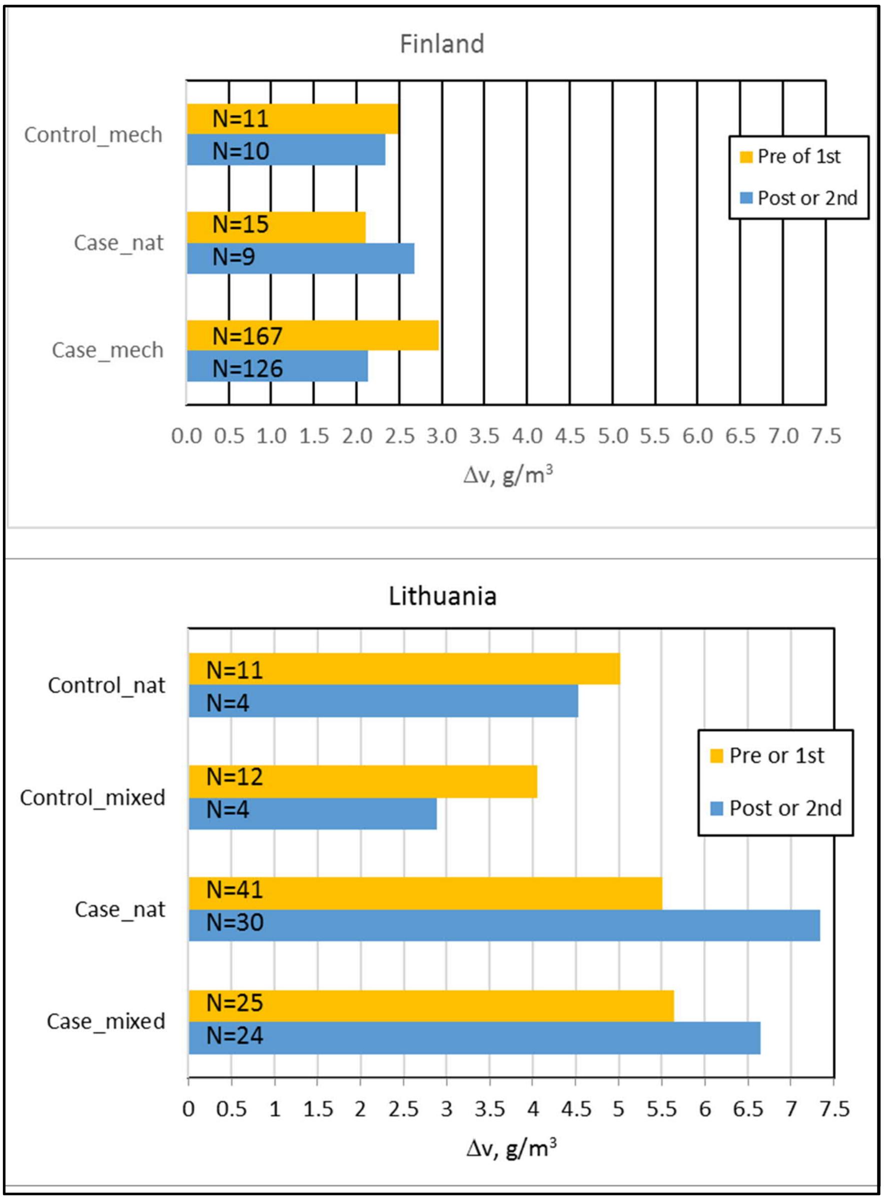

Figure 2. Calculated critical Δv in Finnish and Lithuanian apartments.

Figure 3 presents Δv corresponding to various outdoor temperatures. The two internal humidity classes: 2 (offices, dwellings with normal occupancy and ventilation) and 3 (buildings with unknown occupancy), determined on standard EN ISO 13778 (EN ISO 13788:2012, 2012), are shown for comparison. As seen in the plots, Δv values were usually below class 2 humidity values in Finnish apartments, while there were more variation in Lithuanian apartments.

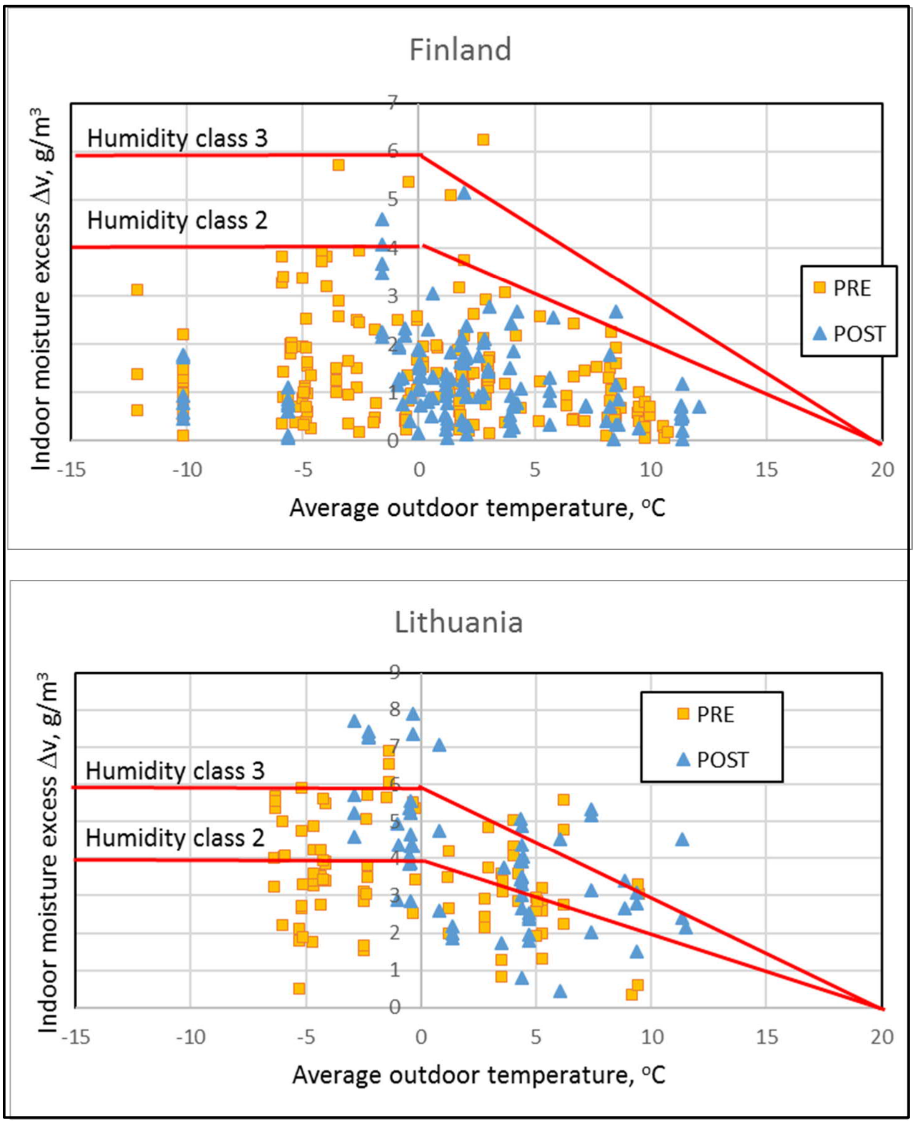

Figure 3. Indoor *Δv* corresponding to various outdoor temperatures.

Based on LMM, significant associations were observed between Δ*v* and both ventilation rate and number of occupants. However, estimated mean Δ*v* is significantly lower in Finnish buildings even after the type of ventilation and number of occupants are included in the models (Table 4). In Finnish buildings, there were differences between case and control buildings, however, no differences were observed in the retrofitted buildings. In Lithuanian buildings, Δ*v* was significantly higher in the case buildings after the retrofits, whereas it was lower in the control buildings based on the second measurement. It appears that internal moisture loads may increase after energy retrofits in some buildings (e.g. deeply retrofitted building relying on natural ventilation).

Effect of level of retrofit on f_c and Δv

Further analyses were conducted among the case (retrofitted) buildings in order to evaluate the effect of level of retrofit on f_c and Δv. These analyses are restricted due to small number of buildings undergoing deep energy retrofits (DER) in Finland, and focused energy retrofits (FER) in Lithuania.

With respect to f_c, there were some differences between FER and DER buildings at the baseline, in Finland f_c was 3.2 % lower in DER buildings whereas in Lithuania, it was 6.9 % higher (Table 5). After the retrofits, the difference between Finnish DER and FER buildings was diminished, whereas in Lithuania, f_c in DER buildings was further increased. These results support the findings that the level of retrofit (which could be attributed to insulation activities), is likely to impact temperature factors (corresponding to increased surface temperatures in DER buildings). Thermal factor is a therefore a potential indicator for future assessments related to effects of improved energy efficiency on IEQ and thermal comfort.

With respect to Δv, once again, there was a significant difference between FER and DER buildings at the baseline (Table 6). Among Finnish buildings, Δv was 0.51 g/m^3 smaller in DER buildings, and after retrofits the difference was further increased. In Lithuania, an increased Δv was seen in DER buildings after the retrofits, although the difference was not statistically significant. These results indicate that the level of retrofit could results in changes in internal moisture loads, the effects of which could be not completely explained by differences in ventilation rates and occupancy. Also Δv appears to be a useful indicator to be included in the future assessments.

It should be noted that occupant behavior has significant impacts on building energy performance as well as indoor thermal conditions and IEQ. A comprehensive literature review of current state of occupant behavior research was presented by Hong et al. (Hong, Yan, D'Oca, & Chen, 2017). Energy related occupant behavior, also reviewed by Hong et al. (Hong, Taylor-Lange, D'Oca, & Corgnati, 2016) includes adjusting indoor temperature, opening/closing windows, dimming/switching lights, pulling up/down blinds, turning on/off HVAC systems and movement between spaces, affects also on IEQ. With respect to our study, occupants' satisfaction with IEQ and health as well as changes in their behavior (such as window opening) before and after retrofits will be reported elsewhere (Haverinen-Shaughnessy, submitted paper 2017).

Conclusions

The estimated mean temperature factor was significantly higher in Lithuanian case buildings after retrofits as compared to the situation before the retrofits, whereas there were no significant differences in Finnish case buildings. The results also indicated that the level of retrofit could results in changes in internal moisture loads, the effects of which could be not completely explained by differences in ventilation rates and occupancy. Both temperature factor and excess indoor moisture content are useful indicators to be included in the future assessments of effects of energy retrofits on indoor environmental quality.

Acknowledgements

This study is part of the INSULAtE project (ENV/FI/000573), funded by EU Life+ programme and Finnish Energy Industry. The authors wish to thank the building owners and occupants participating in the project as well as the whole INSULAtE project group.

References

Asumisterveysohje. Oppaita 2003:1 Finnish Housing Health Guide. (2003). Ministry of Social and Health, Finland.

Csoknyai, T. (2001). Surface temperature at thermal bridges. *J. Therm. Envel. Build. Sci., 25*(1), 67-81.

EN ISO 10211:2007. (2007). *Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations.*

EN ISO 13788:2012. (2012). *Hygrothermal performance of building components and building elements. Internal surface temperature to avoid critical surface humidity and interdtitial condensation. Calculation method.*

Geving, S., & Holme, J. (2012). Mean and diural indoor air humidity loads in residential buildings. *J. Build. Phys., 35*(4), 392-421.

Hong, T., Taylor-Lange, S. C., D'Oca, S., & Corgnati, S. P. (2016). Advances in research and applications of energy-related occupant bahavior in buildings. *Energy and Buildings*, 694-702.

Hong, T., Yan, D., D'Oca, S., & Chen, C.-f. (2017). Ten questions concerning occupant behavior in buildings: The big picture. *Building and Environment*, 518-530.

Ilomets, S., Kalamees, T., & Vinha, J. (2017). Indoor hygrothermal loads for the deterministic and stochastic design of the building envelope for dwellings in cold climates. *Journal of Building Physics*. Sage. doi:10.1177/1744259117718442

Kalamees, T. (2006). Indoor humidity loads and moisture production in lightweight timber-frame detached houses. *J. Build. Phys., 29*(3), 219-246.

Leivo, V., Prasauskas, T., Du, L., Turunen, M., Kiviste, M., Aaltonen, A., . . . Haverinen-Shaughnessy, U. (2018). Indoor thermal environment, air exchange rates, and carbon dioxide concentrations before and after energy retro fits in Finnish and Lithuanian multi-family buildings. *Science of the Total Environment*.

Leivo, V., Prasauskas, T., Turunen, M., Kiviste, M., Aaltonen, A., & Martuzevicius, D. H. (2017). Comparison of air pressure difference, air change rates, and CO2 concentrations in apartment buildings before and after energy retrofits. *Building and Environment*, 85-92.

Nevander, L.-E., & Elmarsson, B. (1994). *Moisture handbook, theory and practise*. Svensk Byggtjänst.

Song, J., Lim, J.-H., & Song, S.-Y. (2016). Evalutaion of alternatives for reduicing thermal bridges in metal panel curtain wall systems. *Energy Build., 127*, 138-158.

Ward, T., Craeme, H., & Sanders, C. (2016). *BRE Guide 497. Conventions for calculation linear thermal transmittance and temperature factors.* BRE Publications.

Zemitis, J., Borodinecs, A., & Frolova, M. (2016). Measurements of moisture production caused by various sources. *Energy Build., 127*, 884-891.

Table 2. Linear mixed model for f_c.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	91.59	90.01	93.16	***	87.92	86.80	89.04	***	91.14	89.21	93.07	***
Country												
Finland	-3.48	-5.60	-2.08	***								
Lithuania	0[a]	.	.									
Retrofit status												
Control; 2nd measurement	-.21	-3.25	2.84		1.22	-2.62	5.06		-2.32	-7.58	2.94	
Case; 2nd measurement	.86	-.16	1.89	†	.17	-.98	1.32		2.33	.27	4.39	*
Control; 1st measurement	1.45	-1.09	3.98		1.65	-1.96	5.25		1.64	-2.09	5.36	
Case; 1st measurement	0[a]	.	.		0[a]	.	.		0[a]	.	.	

[a] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table 4. Linear mixed model for Δv.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper	***		Lower	Upper			Lower	Upper	
Intercept	2.56	2.08	3.05		0.76	.38	1.14	***	2.25	1.37	3.14	***
Country												
Finland	-1.98	-2.31	-1.65									
Lithuania	0[a]	.	.		0[a]	.	.		0[a]	.	.	
Retrofit status												
Control; 2nd measurement	-.48	-.99	.04	†	.32	-.22	.87		-.98	-1.93	-.03	*
Case; 2nd measurement	.15	-.01	.31	†	-.08	-.23	.07		.65	.30	.99	***
Control; 1st measurement	-.15	-.57	.27		.60	.08	1.11	*	-.39	-1.09	.30	
Case; 1st measurement	0[a]	.	.		0[a]	.	.		0[a]	.	.	

Ventilation rate	-.01	-.03	-.00	*	-.018	-.03	-.01	**	.00	-.04	.05	
Number of occupants	.49	.32	.65	***	.42	.23	.60	***	.52	.25	.80	***

[a] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table 5. Linear mixed model for f_c among retrofitted buildings.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	91.76	88.99	94.53	***	88.45	87.22	89.68	***	85.19	80.35	90.04	***
Country												
Finland	-3.77	-6.43	-1.11	**								
Lithuania	0[a]	.	.		0[a]	.	.		0[a]	.	.	
Retrofit status												
DER; 2nd measurement	1.84	-.94	4.61		-.62	-4.20	2.96		9.11	3.85	14.38	**
FER; 2nd measurement	-.15	-1.48	1.18		-.29	-1.56	.97		.54	-6.16	7.24	
DER; 1st measurement	-.66	-3.33	2.00		-3.62	-6.81	-.44	*	6.91	1.67	12.15	**
FER; 1st measurement	0[a]	.	.		0[a]	.	.		0[a]	.	.	

[a] This parameter is set to zero because it is redundant. *p<0.05 **p<0.01 ***p<0.001 †p<0.1

Table 6. Linear mixed model for Δv among retrofitted buildings.

	All				Finland				Lithuania			
Parameter	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.	Estimate	95% CI		Sig.
		Lower	Upper			Lower	Upper			Lower	Upper	
Intercept	2.96	2.29	3.62	***	1.01	.60	1.42	***	2.14	.80	3.47	**
Country												
Finland	2.26	-2.73	-1.80	***								
Lithuania	0[a]	.	.		0[a]	.	.		0[a]	.	.	
Retrofit status												
DER; 2nd measurement	.06	-.38	.50		-.77	-1.21	-.34	**	.76	-.31	1.83	
FER; 2nd measurement	-.05	-.25	.14		-.04	-.20	.12		-.17	-1.48	1.14	
DER; 1st measurement	-.40	-.83	.03	†	-.51	-.90	-.13	**	.05	-1.02	1.12	
FER; 1st measurement	0	.	.		0	.	.		0	.	.	

Ventilation rate	-.02	-.03	-.00	*	-.02	-.04	-.01	***	.01	-.04	.06	
Number of occupants	.48	.30	.65	***	.36	.17	.56	***	.54	.22	.86	**

[a] This parameter is set to zero because it is redundant. *$p<0.05$ **$p<0.01$ ***$p<0.001$ †$p<0.1$