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Indoor climate conditions and hygrothermal loads in historic wooden apartment buildings in cold climates

Endrik Arumägi[a*], Targo Kalamees[a], and Urve Kallavus[b]

[a] Department of Structural Design, Chair of Building Physics and Energy Efficiency, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia
[b] Faculty of Chemical and Materials Technology, Centre for Materials Research, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

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Abstract. To design and assess indoor climate, thermal comfort, and the hygrothermal performance of a historic building it is essential to obtain data on the indoor temperature and humidity conditions. This paper analyses indoor climate conditions in historic wooden apartment buildings in Estonia and presents an applicable hygrothermal load model for designers. The average indoor temperature of 41 apartments in historic wooden apartment buildings was 21.0 °C in winter and 24.5 °C in summer. Using the indoor climate category III of the standard EN 15251, it was found that the temperature was outside the target values in 83% of the apartments in winter and in 25% in summer. Throughout the year, the indoor temperature was below the target values during 20% of the time while in winter it was above the target values during 4% of the time. Variations in indoor temperature reflect occupants' main complaints about unstable temperature and cold floors during the winter period. The daily average moisture excess was 3.3 g/m^3 during the cold period and 0.6 g/m^3 during the warm period at the average air change rate of 0.56 h^{-1} and 0.79 h^{-1}, respectively. Moisture generation indoors was 60 g/h at the average living density of 26 m^2/person in the historic wooden apartment buildings. For stochastic analyses in historic wooden buildings, we developed an indoor hygrothermal load model that is in good agreement with measured results.

Key words: building physics, hygrothermal load, indoor climate, moisture excess, historic wooden building.

INTRODUCTION

In the course of time, the use of historic buildings has changed. Today people have different requirements for thermal comfort, energy performance, and functionality of the buildings. Vast quantities of energy are consumed for heating and cooling to ensure standards of thermal comfort acceptable in today's terms (Chappells and Shove, 2005). As the energy prices are rising fast, living in low energy efficiency historic buildings can raise the costs of keeping the thermal comfort at an acceptable level (Arumägi and Kalamees, 2014). The cost of living has increased, and for many people the standard of living is falling in line with a corresponding increase in fuel poverty (Nicol and Stevenson, 2013).

Building users consider thermal comfort to be the most important parameter influencing their overall satisfaction with indoor environmental quality, and thermal comfort is influenced by the type of building, outdoor climate, and season (Frontczak and Wargocki, 2011). Oreszczyn et al. (2006) quantified the variations in the indoor temperatures in the heating season and explained these by the characteristics of the dwelling and the household and by energy efficiency improvements. Some very low indoor temperatures were indicated, which reflect a combination of the efficiency of the heating system and insulation, the capacity (maximum rate of energy consumption) of the heating system, and personal choice/behaviours. In their review

* Corresponding author, endrik.arumagi@ttu.ee

of domestic dwelling temperatures during the heating season, Hunt and Gidman (1982) conclude that the age and the type of the heating system have a strong influence on the temperature model.

Indoor temperature is considered as the most important factor to assess the thermal comfort in a building. In addition, indoor humidity is necessary in the assessment of the building performance. Data on indoor air humidity in buildings are needed for many purposes. Indoor air humidity loads have been investigated in different field studies. Kalamees et al. (2006) presented a thorough literature review about the moisture excess in dwellings, showing a large variance in the results and pointing out short measurement periods. Geving and Holme (2012) studied the mean and diurnal indoor air humidity loads in residential buildings and concluded that measurements of the indoor air humidity should be made on a long-term basis.

A frequent moisture problem in cold climates is related to high indoor humidity levels in winter. In cold climates, excessive indoor humidity can lead to moisture accumulation with its many unwanted consequences, including microbial growth, poor indoor air quality, and potential health problems for the occupants (Bornehag et al., 2004; Glass and TenWolde, 2009). The most often occurring spores are usually also the spores with the highest health risk. Depending on the indoor climate conditions and human response to the irritants, the number of spores in the indoor air need not be very high to cause health problems.

Asikainen et al. (2013) pointed out that large numbers of residences in European countries have mean ventilation rates below the requirements of the national building regulations or codes. The residents play an important role in the ventilation level in their own homes. Surveys of occupants showed that people generally think that ventilation is important, but their understanding of the ventilation systems in their homes is inadequate. The chain of activities from design through execution to use and maintenance, especially those of mechanical ventilation systems, shows weak links. Higher set points required to achieve adequate ventilation are seldom used due to the noisy fans. Thus, poor use and lack of occupants' knowledge seem to be main problems in the under-ventilated homes (Dimitroulopoulou, 2012).

Reasons for low temperatures and air change rates in the historic buildings often lie in the old building systems that have not been upgraded. A relation between the occurrence of mould growth and indoor air humidity levels was shown by Oreszczyn et al. (2006). High levels of humidity and some surface and interstitial condensation may be sufficient for mould growth; these may occur due to water damage from leaks, flooding, and groundwater intrusion or due to construction faults, including inadequate insulation, in combination with poor ventilation (WHO, 2009). Su (2002) found that visible mould growth on indoor surfaces is a relatively common problem in aged residential buildings that lack sufficient insulation. By improving the building envelope with additional insulation, it is possible to increase thermal comfort, save energy, and lower the risk of mould growth and condensation on indoor surfaces. For reasons of preserving architectural appearance, facade changes of historic buildings are often prohibited. Internal insulation is a possible solution when a high value architectural appearance must be preserved. However, internal thermal insulation may cause hygrothermal risks; thus, special requirements are set for the renovation solutions. In addition to the material properties, the boundary conditions are also important (Zhao et al., 2011). To achieve moisture-safe buildings, data concerning deterministic and stochastic indoor humidity loads for the design and risk analysis must be accurate (Hens, 1999; Mjörnell et al., 2012).

Indoor temperatures vary by the building type and the construction. Field data about the indoor climate conditions in historic wooden apartment buildings are scarce. Unless measured conditions are available, realistic estimates of the boundary conditions are needed (Glass and TenWolde, 2009). Indoor temperature and humidity conditions are essential data for the assessment of indoor climate and thermal comfort as well as the hygrothermal performance of the historic buildings.

This paper focuses on indoor climate conditions and problems related to the indoor climate in historic wooden apartment buildings. Based on the long-term indoor temperature and relative humidity measurements, the indoor hygrothermal conditions in the current situation are analysed. In addition, the indoor air quality is assessed based on the CO_2 measurements and air sampling. To find relations between the measured indoor climate parameters and the inhabitants' complaints, the occupants' responses to a questionnaire are analysed. User satisfaction to the living conditions based on this questionnaire is presented. Finally, a hygrothermal load model applicable for stochastic hygrothermal performance analysis is suggested.

METHODS

Studied buildings

The study concentrates on historic wooden apartment buildings (Fig. 1) built before 1940 in Estonia. The average age of the buildings is 98 years. Altogether 29 buildings and 41 apartments were investigated. The focus was on indoor climate studies, measurements, and a survey of the building envelope properties.

The average apartment area is 59.3 m^2 and the average number of inhabitants is 2.3. Typical wall constructions of the buildings consist of horizontal or

Fig. 1. Street view of two studied wooden apartment buildings in Tallinn.

vertical logs with an external wooden cladding or render. The external walls contain no additional thermal insulation. The typical wall thickness is between 150 and 200 mm. Typical wooden-framed windows consist of two panes. Original heating systems are wood burning stoves, and ventilation is by the natural passive stack.

In general, the discharge takes place through the chimneys and the compensation through the building body, which means that the air change rate in the studied buildings depends on their air tightness. The reason is in the absence of fresh air valves in the majority of cases. The average air leakage rate at 50 Pa (q_{50}) pressure difference was 10.5 $m^3/(h \cdot m^2)$ (varied from 4 to 18 $m^3/(h \cdot m^2)$) and the air change rate (n_{50}) was 12.5 h^{-1} (varied from 5 to 24 h^{-1}).

Measurements

Technical conditions were inspected visually for each building (Klõšeiko et al., 2011). In addition, a questionnaire was conducted for each building to obtain information about the occupants' habits, typical complaints, and symptoms related to indoor air quality.

Temperature and relative humidity (RH) were measured continuously with data loggers (measurement range –20 to +70 °C, 5–95% RH, accuracy respectively ±0.35 °C and ±2.5% RH). Temperature and RH inside the bedroom and outside the building were recorded at one-hour intervals. The indoor loggers were located on separating walls in the master bedroom or in the living room and in reference measurement points. Loggers to measure outdoor temperature were placed on the north side of the building, protected from direct solar radiation.

The moisture excess $\Delta\nu$ (g/m^3) (the difference between the indoor and the outdoor air water vapour content) was calculated on the basis of the indoor and outdoor temperature and RH measurements:

$$\Delta\nu = \nu_i - \nu_e = \frac{G}{q_v} \ (g/m^3), \tag{1}$$

where ν_i is the indoor air water content, g/m^3; ν_e is the outdoor air water content, g/m^3; G is the moisture production indoors, g/h; and q_v is the ventilation air flow, m^3/h.

To analyse the dependence of the moisture excess on the outdoor climate and to determine the critical moisture excess values, the data were sorted according to the outdoor air temperature, using a 1 °C step of the outdoor temperature. The sorted values were used to calculate average, maximum, minimum, and 10% critical levels.

The levels of CO_2 in the bedrooms were measured during the winter and summer periods to assess the air change in the apartments. The CO_2 levels were measured at 10-min intervals during 2 to 3 weeks using CO_2 monitors with data loggers (measurement range 0–10 000 ppm, with an accuracy of ±5% of the reading or 50 ppm).

The air change calculations were based on the measurements of indoor CO_2 levels and estimated CO_2 emissions from the inhabitants (Guo and Lewis, 2007):

$$C_{i,t} = C_e + \frac{E}{R_a} - \left(C_e + \frac{E}{R_a} - C_{i,0} \right) \cdot e^{-\frac{R_a}{V} \cdot t}, \tag{2}$$

where $C_{i,t}$ is the CO_2 concentration at time t (ppm); C_e is the CO_2 concentration of the outdoor air (ppm); E is the CO_2 generation rate (13 L/(h·pers); R_a is the ventilation and infiltration airflow (m^3/s); $C_{i,0}$ is the CO_2 concentration at the beginning of the time period (ppm); V is the effective volume of enclosure (m^3); t is the time (s), and e is Euler's number. We used the measurement results from the night-time (23:00–7:00) in our calculations.

Air sampling was used to assess the quality of the indoor air in the buildings. A Biotest HYCON Air sampler RCS was used to take the air samples. For sample collection Y and F sampling stripes and 4-min sample times were used. The incubation time was 8 days at the temperature of 21 °C for later analysis. No mould species were detected in the incubated air samples. In this study the samples were collected during winter months (January and February) when the outdoor temperature prevails below 0 °C and the concentration of the spores in the outdoor air is very low. Our results are expressed as colony forming units (cfu) per volume of air (for air samples).

The tape sampling technique was used to identify mould taxa in the buildings where discoloration of surfaces or mould growth was detected during visual inspection. Samples were taken in kitchens, bedrooms, or washing rooms or if mould growth was detected, in living rooms. Adhesive tape lift samples were collected using 3M Crystal Clear Tape.

Assessment

Target values from the indoor climate category III (CR 1752, 1999; EN 15251, 2007) were used to assess indoor thermal conditions: 18–25 °C during winter months and 22–27 °C during summer months. Indoor climate category III represents an acceptable moderate level of expectation used for existing buildings. In the thermal evaluation, an hourly criterion is used, based on the calculation of the percentage of time when the criteria are met or are outside a specified range.

The ventilation rates required are specified as an air change per hour for each room, and/or outside air supply, and/or required exhaust rates (bathroom, toilets, and kitchens) or given as an overall required air-change rate (EN 15251, 2007). According to the indoor climate category III, the required overall air-change rate should be 0.5 h^{-1} or 4 L/s per person or 0.6 L/s per m^2 of the bedroom.

Air sampling results are expressed as colony-forming units (cfu) per volume of air (for air samples). Singh et al. (2010) presented the levels recommended in Great Britain. Husman et al. (2002) provided the limits for the quantity of fungal spores in the indoor air used in Finland. The levels in these two studies differ by an order of magnitude. As the relation between dampness, microbial exposure, and health effects cannot be quantified precisely, no quantitative health-based guideline values or thresholds can be recommended for acceptable levels of contamination with microorganisms (WHO, 2009). As no limits have been set in Estonia, the Finnish standard was used in our comparison because of similarities in Estonian and Finnish climates. The quantity of fungal spores in the indoor air was compared with the hazard classes presented in the WHO (2009) guidelines.

RESULTS

Indoor hygrothermal conditions

To determine the temperature and humidity loads, the dependence of the indoor temperature and moisture excess on the outdoor temperature was analysed (Fig. 2). The average indoor temperature during the winter period was 21.0 °C (SD 2.3 °C, min 13.3 °C, and max 24.8 °C) and during the summer period 24.5 °C (SD 1.1 °C, min 22.7 °C, and max 26.7 °C). During winter the indoor temperature was outside the category III (EN 15251, 2007) target values in 83% of the apartments and during summer in 25% of the apartments. Throughout the year the indoor temperature was below the target values on average for 1731 h in winter and for 20 h in summer and above the target values on average for 345 h in winter and for 49 h in summer.

The diurnal moisture excess during the cold period ($t_e \leq +5$ °C) was 3.3 g/m^3 (SD 1.1 g/m^3) and during the warm period ($t_e \geq 15$ °C) it was 0.6 g/m^3 (SD 0.7 g/m^3).

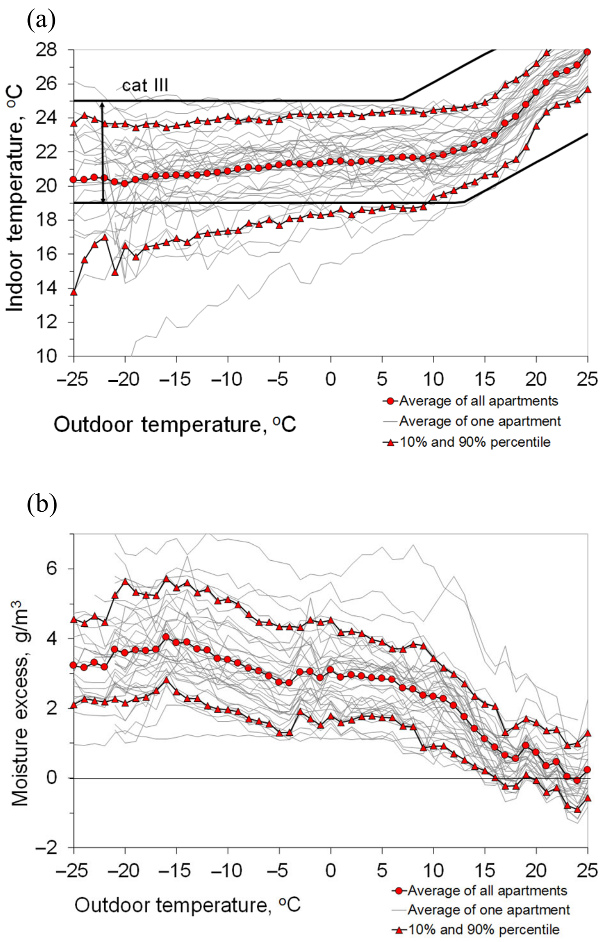

Fig. 2. Dependenc of indoor temperature (a) and moisture excess (b) measurement results on the outdoor temperature (Sanders, 1996).

The average of 90% percentile from the diurnal moisture excess during the cold period was 5.1 g/m^3 and during the remaining time 3.0 g/m^3. Weekly average moisture excess values were 3.0 g/m^3 (SD 1.1 g/m^3) and 0.7 g/m^3 (SD 0.7 g/m^3), average of 90% percentile 4.3 g/m^3 and 1.9 g/m^3, respectively.

A temperature and humidity load model for hygrothermal design can be derived from the measurement results. The indoor temperature and moisture load design curves for the historic wooden apartment buildings are presented in Fig. 3 (described by Eqs 3 to 6). Indoor temperatures show a turning point at the outdoor temperature of +15 °C. The average indoor temperature curve rises from 20 °C to 22 °C during the heating season when outdoor temperatures range from –25 °C to +15 °C. After the outdoor temperature level of +15 °C, the incline of the curve is steeper and the indoor temperature rises from 22 °C up to 28 °C. The moisture excess curve shows turning points at the outdoor temperatures 5 °C and 20 °C. During the cold period ($t_e \leq +5$ °C), the average moisture excess curve stays at the level of 3.3 g/m^3 and during the warmer period ($t_e \geq +20$ °C) at the level of 0.6 g/m^3. The moisture excess curve shows a linear change between the turning points at the outdoor temperatures 5 °C and 20 °C.

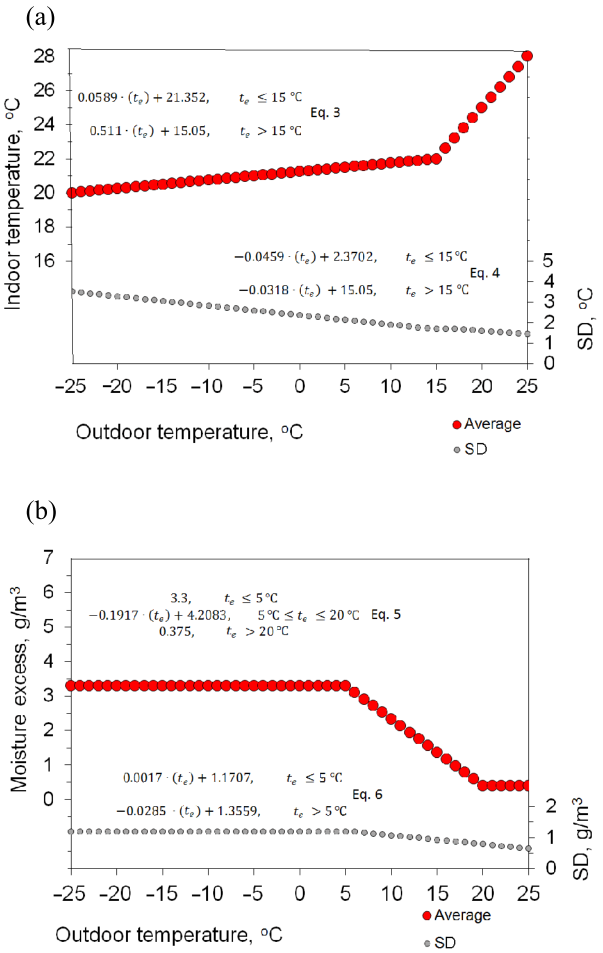

Fig. 3. Indoor temperature (a) and moisture load design curves (b) for historic wooden apartment buildings.

The dependence of the standard deviation on the outdoor temperatures describes variations in the average values. In stochastic analyses, the distribution of values is needed. The difference demonstrates possible variations in occupants' habits on the one hand and the differences in the heating capacities and thermal resistance on the other hand. The standard deviation curve of indoor temperature, on the contrary, remains opposite in relation to the indoor temperature. The standard deviation shows a linear correlation on the outdoor temperature, the curve declines from the value 3.5 at –25 °C to the value 1.5 at +25 °C. Standard deviations of moisture excess show a linear correlation on the outdoor temperature; the curve declines from the value 1.2 at the outdoor temperatures –25 °C to +5 °C and declines to the value 1.5 at +25 °C (see Fig. 3).

The indoor relative humidity (RH) was calculated with the indoor temperature and moisture excess models to test the conformity of indoor RH conditions to those in reality. The indoor RH was calculated for the number of cases equal to the number of apartments where the indoor climate was measured. A model using random sampling was applied to calculate RH. First, knowing the outdoor temperature (t_e), the average indoor temperature (t_i), moisture excess (Δv), and standard deviations (σ_{ti}, $\sigma_{\Delta v}$) were calculated by Eqs 3–6 in Fig. 3. As the next step, assuming normal distribution and using the average values and standard deviations, random sampling was done. Knowing the outdoor RH and temperature, the indoor air vapour content was calculated using Eq. 1. The indoor RH was calculated using the indoor air vapour content and saturation content at the corresponding indoor temperature. As the last step, the calculated values of indoor RH and indoor temperature were averaged using a 24-h running average.

There was good agreement between the measured and the calculated indoor RH values (Fig. 4a). The cumulative distributions of the measured and the calculated results from five outdoor temperatures (–25 °C, −10 °C, 0 °C, +5 °C, and +15 °C) were compared. Even at good agreement between the measured and calculated RH values, the calculated results show slightly larger aberrancy at higher outdoor temperatures (Fig. 4b). Generally, the calculated RH levels are higher than the measured RH levels at an equal number of calculated and measured values.

Another possibility of presenting indoor humidity loads is through the indoor moisture production and the ventilation rate (Eq. 1). During winter the average ventilation airflow in the bedrooms was 0.43 L/(s·m^2) (varied between 0.1 and 1.5 L/(s·m^2)), and the average

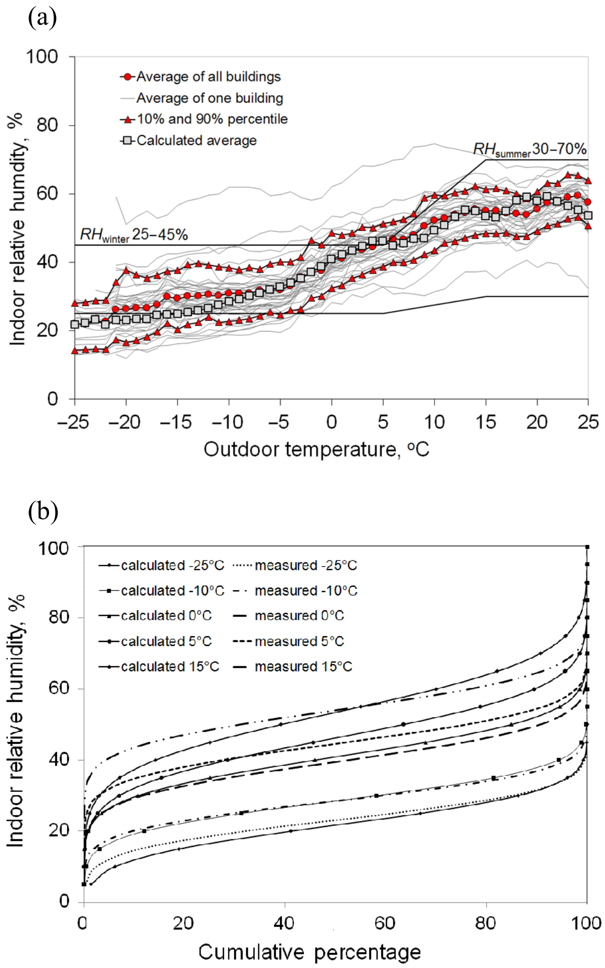

Fig. 4. Indoor air relative humidity measurement results (a) and comparison of measured and calculated values (b) at different outdoor temperatures.

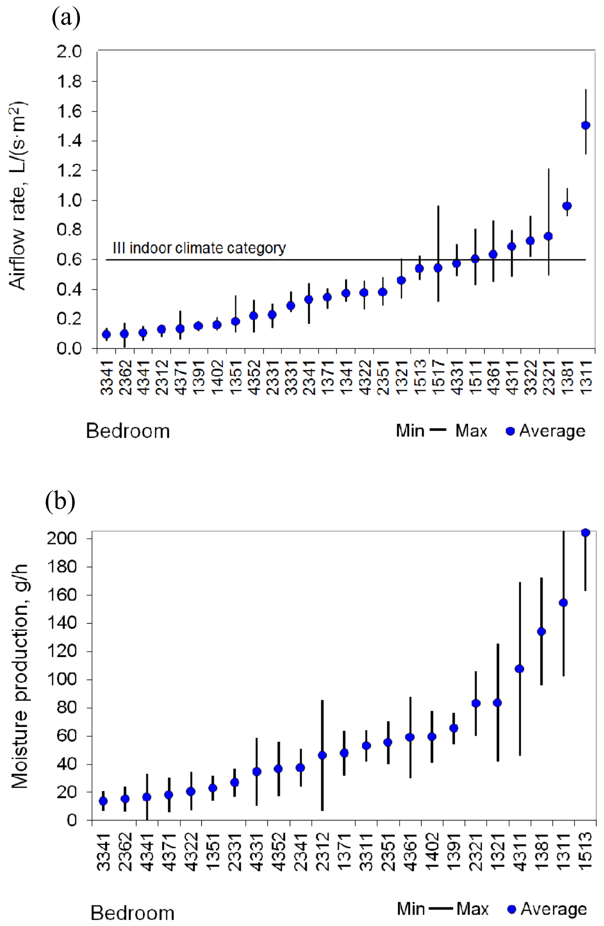

Fig. 5. Airflow rate (a) and moisture production (b) in bedrooms during winter period.

air-change rate in the bedrooms was 0.56 h^{-1} (varied between 0.1 and 2.0 h^{-1}) (Fig. 5). During summer the average air-change rate in the bedrooms was 0.79 h^{-1} (varied between 0.1 and 2.2 h^{-1}). The average air-change rate satisfies the target value for indoor climate category III. The minimum required air change is met in 44% of the bedrooms. However, in terms of airflow per floor area, only 26% of the bedrooms complied with the target value of climate category III.

The average moisture production in the bedrooms during night was 60 g/h (variation between 14 and 200 g/h). The calculated moisture production shows mainly moisture from inhabitants and common household activities as the ventilation airflow rate and moisture excess values are measured during the night-time. These values include also moisture transport between the room air and the building fabric. The presented moisture production values can be used as input values for the indoor climate of a whole building, and energy simulation programs targeted to moisture transfer between the room air and the building fabric are neglected. When advanced numerical hygrothermal tools are used in the simulation programs covering the whole building and the moisture transfer between the room air and the building fabric is taken into account, the corresponding moisture production value should be larger than the measured average production during night in the bedrooms. Based on moisture buffering studies (Svennberg et al., 2004; Rode and Grau, 2008), moisture buffering mainly influences daily variations in the range from 10% to 40%, depending on the furnishing and building fabric.

Indoor air quality

Indoor CO_2 concentrations were used as one of the indicators of indoor air quality because occupants are the main pollution source in dwellings. During our measurements, the peak values varied between 1287 ppm and 3999 ppm in the wintertime. During the winter period, the average value of all the bedrooms (occupied) was 1084 ppm (varied between 537 and

1972 ppm) in the night-time. During the summer period, the average value of all the bedrooms was 1062 ppm (varied between 614 and 1565 ppm). The measured CO_2 concentrations were above 1000 ppm for 51% of the measurement time in the winter period and for 45% of the measurement time in the summer period. The measured CO_2 concentrations were above 1500 ppm for 18% of the measurement time both in winter and summer periods.

Another indicator of indoor air quality studied was occurrence of fungal spores in tape lift samples. No fungal spores were found in half of the samples (Table 1). The largest numbers of spores found in the indoor air belonged to the genera *Cladosporium* and *Phoma* found in 13% and 10% of the samples, respectively (Table 1). Spores of other identified genera of fungi occurred in 2–3% of the samples. The spores most frequently found in apartments are the spores with the highest health risk (Singh, 2000). Moreover, the number of spores in the indoor air need not be very high to cause health problems.

No relevant correlation (low R^2) was found between the numbers of spores in the indoor air and the average indoor temperature in the apartments. Indoor RH (moisture excess, moisture production) and air change rate (ventilation, air tightness) in the apartments showed a higher correlation with mould growth: the higher were the moisture excess and the RH, the higher was the number of spores in the indoor air. In case the average moisture excess was over 6 g/m^3 and the RH was over 60%, the numbers of spores in the indoor air were higher than the acceptable level 500 cfu/m^3 (Fig. 6).

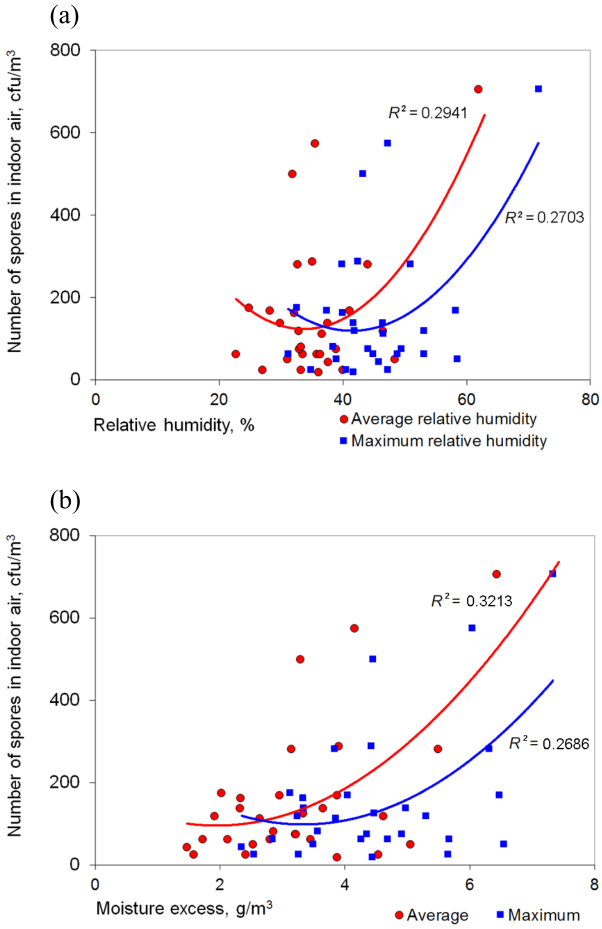

Fig. 6. Dependence of the number of spores in the indoor air on the indoor air relative humidity (a) and moisture excess (b).

User satisfaction

A questionnaire was conducted in each building to survey occupants' habits, typical complaints, and symptoms related to the indoor air quality. To ensure reasonable data collection about the inhabitants' opinions in a simple context, the questions concerned seriousness and frequency of the problems. Considering the cold outdoor climate, most questions were targeted to the indoor conditions during the heating period when the heating and ventilation systems are of critical importance. The main problems indicated by inhabitants were unstable temperature, cold floors, and stuffy air during the winter period (Fig. 7).

The occupants' responses were used to find relations between the measured indoor climate parameters and the inhabitants' complaints. Despite the fact that the average temperature in most of the buildings was on an acceptable level, inhabitants complained about the unstable indoor temperature. Indeed, the diurnal temperature variations were great and the indoor temperature was prevailingly outside the target levels. Inhabitants complained about the unstable temperature during the winter-time if the average daily temperature variation was 3.8 °C; which is 1 °C higher than in the buildings with no complaints ($p = 0.045$). Besides, periods with the indoor temperature outside the target levels were 26% longer in buildings with complaints. The

Table 1. Occurrence of fungal spores of different genera in tape lift samples

Find	% of occurrence
Chaetomium	2
Cladorrhinum	2
Cladosporium	13
Echinobotryum	2
Epicoccum	2
Exophiala	3
Phoma	10
Ulocladium	3
Unidentified spores	10
Unidentified mycelium	3
No spores (soot, dust)	50
Total	100

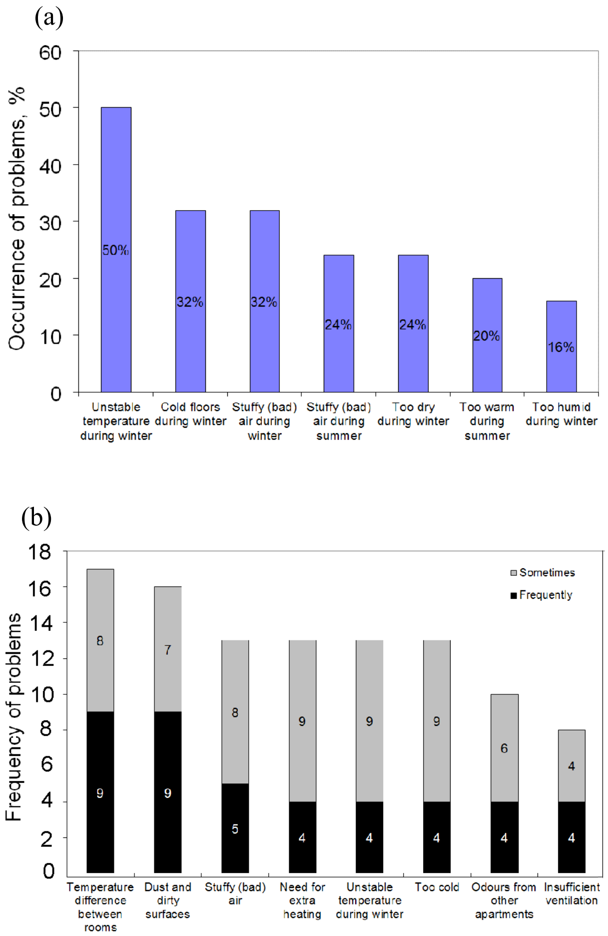

Fig. 7. Occurrence (a) and frequency (b) of the problems based on the questionnaire.

survey showed that complaints about the indoor temperature concerned 42% and absence of complaints 16% of the time, which is not in compliance with the indoor climate category III.

Problems with cold floors during winter ($p = 0.019$) occurred in apartments with unstable temperature. The reason probably lies in the infiltration and low thermal resistance of the constructions or in an insufficient power of the heating system. Buildings with larger temperature variations and cold floors during winter were much leakier and had a higher air-change rate n_{50} ($p = 0.036$) and larger energy consumption ($p = 0.047$) than buildings with no occupants' complaints.

DISCUSSION

International standards like ISO 7730 (2005) and ASHRAE 55 (2013) have derived substantially from the studies of thermal comfort, to guide the built environment professions to design and maintain comfortable indoor thermal environments (de Dear, 2004), but in reality the indoor climate conditions may differ considerably in historic buildings.

Our results show that while the average indoor temperature during the winter period was 21.0 °C, large variations occurred in indoor temperatures. Because of large heat losses and insufficient heating capacities, the measured indoor temperatures were lower during the heating period. At lower outdoor temperatures, the scattering in the measured results showed almost two times larger deviation than at warmer outdoor temperatures. Large variations in the indoor temperature can be explained by the characteristics of a particular building, such as low thermal transmittance of building constructions, large air leakages, and insufficient power of heating systems, as well as by the behaviour of the occupants (Becker and Paciuk, 2009).

For hygrothermal dimensioning of the building envelopes, sufficiently critical humidity loads should be considered. Sanders (1996) recommended the use of 10% percentile as the critical level. This means that hygrothermal loads higher than their normative value should not appear in more than 10% of the cases. Another approach would be a stochastic analysis taking into account more realistic conditions. This paper presents the average values with distributions.

The hygrothermal design curve for the buildings with low occupancy (average 43 m^2/person) was presented by Kalamees et al. (2006), showing the maximum moisture excess 4 g/m^3 during the cold period ($t_e \leq +5$ °C), 1.5 g/m^3 during the warm period ($t_e \geq 15$ °C), and a linear change between the cold and the warm period. Geving and Holme (2012) proposed design curves that depend on the occupancy and the moisture production as 'low' (low occupancy <0.02 person/m^2), 'medium' (medium/high occupancy >0.02 person/m^2), and 'high' (bathrooms and laundry rooms). Moisture excess values to design curves during cold periods ($t_e \leq +5$ °C) are 2.5 g/m^3 (low), 4 g/m^3 (medium), and 6 g/m^3 (high). Moisture excess values to design curves during warm periods ($t_e \geq 15$ °C) are 0.5 g/m^3 (low), 1.5 g/m^3 (medium), and 3 g/m^3 (high). Between the cold and the warm period there is a linear change. In this study the average occupant density was 26 m^2 per person (0.04 person/m^2). The level of the moisture excess model curve derived from our measurement results appears to be the same as the 10% critical level in other studies. The moisture excess level is higher than in (Kalamees et al., 2006) and (Geving and Holme, 2012), which correlates with higher occupant density and lower ventilation air-change rate.

Metabolic CO_2 can be used as an indoor air quality indicator. Indoor CO_2 concentrations above 1000 ppm are generally regarded as an indicator of inadequate ventilation. In Nordic residential buildings, ventilation rates below half an air change per hour are considered too low, which may lead to high concentrations of pollutants and cause health problems (Wargocki et al., 2002; Sundell et al., 2011). Indoor humidity is influenced by the ventilation rate. Ventilation usually reduces indoor moisture levels. Older buildings and the use of natural ventilation are associated with increased frequency of dampness indicators as well as with increased frequency of complaints on bad indoor air quality (Hägerhed et al., 2002).

In the studied buildings, the frequency of overall appearance of spores in the indoor air is distributed unevenly. The largest numbers of spores found in the indoor air of the wooden apartment buildings are also the spores with the highest health risk (Singh, 2000). Depending on the inhabitants' response, the number of spores in the indoor air need not be very high to cause health problems. The number of spores in the indoor air of more than 50% of the studied wooden apartment buildings was lower than 150 cfu/m^3 and was smaller than the numbers of different fungal genera in the indoor air in the brick and concrete-element apartment buildings (Kalamees, 2011). According to our results, ventilation in wooden apartment buildings is inadequate as the presented air-change values include also air change between rooms when the communicating door is open. In spite of the high living density and poor thermal transmittance of the buildings, air samples with the number of spores lower than 150 cfu/m^3 were found in more than half the buildings. The result seems good and it is in correlation with the number of air samples with no spores. The main reason is that there are fewer critical thermal bridges in wooden apartment buildings than, for example, in brick and prefabricated reinforced concrete large-panel element apartment buildings (Ilomets et al., 2014).

Overall, the majority of the occupants in the historic wooden buildings did not complain about the indoor climate conditions. In our study, most of the complaints concerned unstable temperature and low temperature of the floor during the winter period rather than the air quality or noise problems. The reason is that the occupants rank thermal comfort as more important than good air quality and acoustic comfort (Frontczak and Wargocki, 2011). Another reason may be that human adaptation is more active in naturally ventilated buildings and that the zone of equal thermal sensation for naturally ventilated building occupants is generally broader than for those in heated and ventilated and air-conditioned buildings. In naturally ventilated buildings, the thresholds are broad due to the occupant-adaptive behaviour in the presence of outdoor climate (Zhang et al., 2011). In most of the studied buildings, inhabitants have control over the environment, and this has been seen as an indoor environment improvement factor (Frontczak and Wargocki, 2011). Because of the peculiarities of historic buildings, their occupants tend to tolerate deficiencies characteristic of apartments in such buildings to a considerably greater extent than those of more recent buildings.

CONCLUSIONS

The focus of this study was on the indoor climate conditions of historic wooden apartment buildings. Altgether 29 buildings and 41 apartments were investigated.

The measured indoor temperatures revealed a linear dependence on the outdoor temperatures, showing a twice as large deviation at lower outdoor temperatures as at higher outdoor temperatures. Indoor temperature was outside the category III target values in 83% of the apartments in winter and in 25% of the apartments in summer. Indoor temperature variations reflect also the complaints concerning the unstable temperature and cold floors during the winter period.

The indoor climate conditions differ from those in more recently built apartment buildings and it is necessary to improve their indoor thermal comfort. Even though most of the time the thermal comfort was outside the acceptable moderate level of expectations, the building occupants showed overall satisfaction with the living environment in historic wooden apartment buildings.

Typically, to assess the hygrothermal performance and the moisture risks of the constructions the deterministic approach is used in the design process. The reliability can be defined as the probability for a solution to function without failure during a given period of time. The reliability concept requires the assessment of probabilities, calling for the application of probabilistic methodologies rather than deterministic techniques (Janssen, 2013). For the hygrothermal analysis of the building envelope, the modelling curves of the indoor temperature and moisture excess were derived from the measurement results. The curves of the indoor temperature and moisture excess reveal their dependence on the average value and standard deviation of the outdoor temperature. The presented curves can be used for dynamic simulations of hygrothermal performance.

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Sisekliimatingimused ja niiskuskoormused ajaloolistes puitkorterelamutes

Endrik Arumägi, Targo Kalamees ja Urve Kallavus

Et projekteerida ja hinnata sisekliimat, soojuslikku mugavust või niiskustehnilist toimivust ajaloolises hoones, on oluline teada ruumide sisetemperatuuri ning suhtelise niiskuse tingimusi hoones. Hindamaks uuritavate hoonete sisekliimat, tehti pikaajalised sisetemperatuuri, suhtelise niiskuse ja CO_2 mõõtmised 29 ajaloolise puitkorterelamu 41 korteris. Lisaks sisekliimatingimuste analüüsile on esitatud uuritud hoonetüübile rakendatav niiskuskoormuste mudel. Analüüsitud 41 korteri mõõtmisandmete põhjal oli korterite keskmine sisetemperatuur talvel 21,0 °C ja suvel 24,5 °C. Sisekliima mõõtmised näitasid, et korterite sisetemperatuur oli väljaspool sisekliima III klassi piirsuurusi talvel 83% ja suvel 25% ajast. Sisetemperatuuri kõikumised peegeldavad hästi elanike kaebusi muutuva sisetemperatuuri ja külmade põrandate osas talvisel ajal. Vaadates talvist perioodi, oli sisetemperatuur madalam alumisest piirsuurusest 20% ajast ja kõrgem ülemisest piirsuurusest 4% ajast. Välis- ja sisekliima mõõtmiste põhjal arvutati ruumide niiskuslisa. Külmal perioodil oli päevane keskmine niiskuslisa 3,3 g/m^3 ja soojal perioodil 0,6 g/m^3. Ruumides tehtud CO_2 mõõtmiste põhjal arvutatud keskmine õhuvahetus oli talvel 0,56 h^{-1} ja suvel 0,79 h^{-1}. Arvestades arvutuslikku õhuvahetust ja keskmist asustustihedust 26 m^2 inimese kohta, oli korterites hinnanguline keskmine niiskustoodang 60 g/h. Ajalooliste puitkorterelamute sisekliimatingimused erinevad oluliselt tänapäevaste korterelamute sisekliimast, mis näitab tehnosüsteemide ja hoone välispiirete renoveerimise vajadust.

Mõõtmistulemuste põhjal koostati sisetemperatuuri ja niiskuslisa modelleerimise mudel, mis võimaldab stohhastilist analüüsi. Sisetemperatuuri ja niiskuslisa suurused on kirjeldatud sõltuvuses välistemperatuurist läbi keskmiste suuruste ning tõenäosuslike hajuvustega. Koostatud mudelit saab kasutada hoonepiirete niiskustehnilise toimivuse analüüsiks.