Indoor Temperature, Humidity, and Moisture Production in Lightweight Timber-Framed Detached Houses

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ABSTRACT

This paper discusses a study that measured and analyzed the indoor climate conditions in 46 lightweight timber-framed detached houses occupied by single families. This survey was conducted during 2002-2003 in Finland. The main objectives were to analyze the indoor temperature and moisture conditions as well as to determine the internal moisture supply and moisture production. Additionally, the impact of HVAC systems and envelope solutions on the indoor climate were analyzed. The temperature and relative humidity were continuously measured in bedrooms, living rooms, and outdoors. The results showed high indoor temperatures during the summer period and rather unstable temperature conditions during winter, which exceeded acceptable comfort levels in most of the studied houses for a long period of time. During the summer, ventilation systems had significant influence on the indoor temperature levels, humidity levels, and the average daily amplitude of temperature and humidity. The vapor-permeable envelope caused low relative humidity in the winter, and the indoor air was drier for a longer period than in houses with a vapor-tight envelope. The hygroscopic mass showed effect on the average daily amplitude of humidity. Based on the measured indoor and outdoor humidity values, the moisture supply values were calculated. Using those calculated values along with measured air change rate, the moisture production rates are specified.

INTRODUCTION

Due to the cold climate, buildings in Finland are normally designed according to the outdoor climate in winter, whereas outdoor climatic conditions in summer are not usually taken into account. The mechanical cooling systems, air humidifiers, and special shadings for solar protection are seldom found in detached single-family houses in Finland. Therefore, during the summer season, the indoor thermal conditions may exceed acceptable thermal comfort levels. In winter, the continuous heating systems should keep the temperature at the setpoint of thermostats. Nevertheless, the stability and level of the temperature may also cause problems during the heating season. In addition, there are two types of problems with the indoor humidity. First, it may be too high when there is a low ventilation rate and/or a high moisture production rate. This causes potentially serious moisture problems for the building envelope. Second, the humidity level may be excessively low. As a consequence, overheating combined with low outdoor humidity may provoke numerous health symptoms, such as dryness, primarily of the eyes, nasal cavity, and skin. In a cross-sectional study of the Finnish housing stock, Ruotsalainen et al. (1992) observed that the temperature varied from 18°C (64.4°F) to 27°C (80.6°F). The relative humidity ranged from 21% to 65% RH. Information about actual indoor temperature and humidity is important for the assessment of thermal comfort. The performance of the HVAC and control systems should be considered to determine the appropriate moisture design strategies or to prevent moisture problems in buildings and to develop passive methods for handling temperature and moisture conditions.

The impact of the building envelope and building materials on the indoor air humidity level and its fluctuation has been the focus of many studies, either with mathematical models or laboratory experiments. The modeling and experi-

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ments include some uncertainties that may not be present in real life, such as the difficulties in simulating the real air change rate (ventilation, the effect of open windows and doors, air leaks), the hygroscopic mass of the furnishing or that of the indoor textiles, etc. Field measurements are a valuable method of assembling the data to learn how the building envelope influences the indoor climate and to determine the importance of the envelope in the actual use of buildings. The limitation of field measurements is that there are many confounding factors that usually cannot be controlled. In many cases, they can be overcome by increasing the number of studied houses. To date, not many field measurement studies have been conducted on this topic.

In Finland lightweight timber-frame envelopes are most commonly used for detached single-family houses. According to the Finnish building regulations, RakMK C3 (2002), the building envelope's thermal conductance cannot exceed the following values: walls $U \leq 0.25$ W/m^2 K (0.044 Btu/ft^2 h°F); roofs and floors that are connected with the outdoors, $U \leq 0.16$ W/m^2 K (0.0282 Btu/ft^2 h°F); the slab on the ground, $U \leq 0.25$ W/m^2 K (0.044 Btu/ft^2 h°F); and the windows, $U \leq 1.4$ W/m^2 K (0.247 Btu/ft^2 h°F). The most commonly employed building insulation, which is used to comply with the thermal requirements of the building envelope, is mineral wool or cellulose insulation. The remainder of the building envelope assembly generally consists of a plastic air/vapor barrier or bitumen-impregnated paper as an air barrier that is installed on the inner surface of insulation. The sheathing on the external side of the envelope usually consists of wooden fiberboard, plasterboard, or mineral-wool board. A traditional solution to lightweight timber-frame single-family houses is that the external walls are constructed with wood siding or brick cladding systems. Both of the systems involve a ventilation gap, which is installed and used as a drainage system.

In cold climates the concentration of the indoor vapor content normally exceeds the outdoor concentration. To know the critical hygrothermal loads during different seasons is a necessary factor in hygrothermal design. If the envelopes are protected from driving rain, the major moisture problems in the building envelope are usually the outgoing airflows due to air leakage or vapor diffusion through the building envelope. Therefore, it is necessary to know the actual and the critical difference between indoor and outdoor air water vapor content (referred to as the *internal moisture supply* in this study).

In this study field measurements were carried out in 46 single-family timber-framed detached houses during 2002-2003. In total, 78 bedrooms (mainly master bedrooms) and living rooms were under investigation. Other types of rooms (bathrooms, kitchens, dining rooms, laundry rooms) were not studied. Temperature, relative humidity, absolute humidity, internal moisture supply, and moisture production were analyzed in the houses, which were divided according to heating and ventilating systems, different types of envelope assemblies, and different indoor surface materials.

METHODS

Selection of Buildings

The field measurements were carried out in occupied lightweight timber-framed single-family detached houses in the Helsinki and Tampere regions of Finland. The houses were relatively new, meaning that they were generally built less than five years prior to this study. For the purpose of the comparative analysis, some older houses (built about 24 years prior to this study) with natural ventilation systems were also included in the study. Most of the houses (80%) had been occupied for at least one heating season. This is important with regard to the process of drying out construction moisture. The average floor area of the houses was 155 m^2 (1670 ft^2), the average volume was 436 m^3 (15400 ft^3), and the average number of occupants per house was 3.4.

The houses were selected to include houses with mechanical as well as natural ventilation, houses with permeable and vapor-tight envelope structures, and houses with hygroscopic and nonhygroscopic indoor surface materials. In these subgroups, the selection was random. The houses were selected from databases of companies that manufacture and build houses. In the areas close to the universities in Helsinki and Tampere, announcements were published in local newspapers to get homeowners involved in the study. The number of houses in each subgroup is shown in Table 1.

The studied houses had three different types of ventilation systems: passive stack ventilation (referred to as *natural ventilation* in this study), mechanical exhaust ventilation, or mechanical supply and exhaust ventilation (referred to as *balanced ventilation* in this study). There were no houses with mechanical cooling systems, and only one bedroom in this study had a portable humidifier. In all of the studied rooms, occupants were able to open the windows. In the distribution

Table 1. Distribution of Analyzed Houses into Different Subdivisions

	Vapor Tight Envelope	Permeable Envelope	Hygroscopic Surface	Non-Hygroscopic Surface	Total
Natural ventilation	4	1	3	2	5
Exhaust ventilation	9	4	6	7	13
Balanced ventilation	19	9	12	16	28
"Slow" heating syst.	14	8	10	12	22
"Fast" heating syst.	18	6	11	13	24
Total	32	14	21	25	46

of ventilation systems, the number of natural and mechanical exhaust ventilation systems was greater than that in the present building stock. As mechanical supply and exhaust ventilation has been the standard installation in detached houses during the last decade in Finland, it was difficult to find houses with natural or mechanical exhaust ventilation systems.

The heating systems consisted of the following: floor (48%), radiator (37%), ceiling (11%), and air (4%) heating systems. The main heating sources were electricity (65%), oil (19%), district heating (8%), heat pumps (6%), and wood (2%) or combinations. The heating systems were divided into systems with a slow response (referred to as *slow* in this study, e.g., floor heating system or accumulating heating system) and systems with a fast response (referred to as *fast* in this study, e.g., radiator, ceiling, or air heating system). In some houses it was also possible to heat by using the fireplace. Usually the heating systems were not operated during the summer.

The building envelopes were divided into two groups: *vapor-tight* envelopes or vapor-permeable envelopes (referred to as *permeable envelopes* in this study). The vapor-tight envelope represented an envelope that either had a plastic air/vapor barrier placed behind the interior board or polyurethane foam thermal insulation was used. The permeable envelope means that paper was used as the air barrier and no vapor barrier was used (in that case the properties of the internal surface of the envelopes were not considered). In addition, the envelopes were subdivided according to the hygroscopic property of the interior surface: rooms with hygroscopic interior surface material and rooms with fully nonhygroscopic interior surface material. For example, rooms where the walls were covered with hygroscopic surface material and the ceiling was covered with nonhygroscopic material were categorized as a hygroscopic subdivision. The main hygroscopic surface material of the walls was wallpaper made of paper on wood chipboard or on plasterboard and wooden boarding. The major nonhygroscopic surface materials were vinyl wallpaper and paint. All the floors were covered with nonhygroscopic materials.

Measurement Methods

The values of temperature and relative humidity (RH) were measured with data loggers at one-hour intervals from the inside and outside of the building. The data logger's measured temperature range was between –20°C (-4°F) and +60°C (+140°F) with an accuracy of ±0.5°C, and the RH measurement range was between 0% and 97% RH with an accuracy of ±3% RH. The indoor loggers were located on the wall in every master bedroom and in most of the living rooms. The outdoor loggers were located on the north facade and were protected from direct solar radiation and driving rain.

The air change rates were calculated on the basis of the measured return airflows in ventilation ducts and during the winter by using the passive tracer gas air infiltration measurement technique (PFT). The measurement results are shown in Table 2. Additionally air pressure conditions inside the houses were measured by different ventilation loads. The airtightness of each building was measured with the fan pressurization method using blower door equipment. A questionnaire was completed for each house where the structure of the house, type of HVAC system and its use, living habits, opinion of occupants on indoor air quality, etc., were discussed during an interview with occupants. This paper presents only temperature and relative humidity measurement results.

The Period of Time Analyzed

The data that were measured during the summer season and the data measured during the winter season were studied for different purposes.

The summer season analyzed in this study lasted more than two months, from July 1 to September 10. July 1 was chosen because the measurements in all the houses were started before then. September 10 was considered the last day of the summer period because after that the outdoor temperatures began to go down (Figure 1, left). The winter season analyzed in this study was three months, from December 1 to February 28. During that period a couple of times the outdoor temperatures went below the designed temperature range, –26°C (–14.8°F) in Helsinki and –29°C (–20.2°F) in Tampere. Tampere is located 180 km to the north of Helsinki and the climatic conditions are similar. The average number of heating degree-days between 1961 and 1990 is 4366 in Helsinki and 4719 in Tampere (Seppänen 2001). The lowest outdoor temperature in the winter of 2002-2003 was –31.9°C (–25.4°F). The measured data in the Helsinki and Tampere areas were analyzed together as the difference between the average winter outdoor temperatures was only 0.2°C. The average daily outdoor climate data for the winter season from different measured houses are shown in Figure 1, right.

Assessment of Indoor Climate

The Finnish classification of the indoor climate (FiSIAQ 2001) has set the target values for three categories— S1, S2, and S3. For example, with respect to room temperature, the category S1 corresponds to 90% satisfaction. Category S3 is in line with the official quality set by building codes. The classification has the status of a guideline and is widely used by HVAC consultants.

During the summer season, indoor temperature values must range between +23°C (73.4°F) and +26°C (78.8°F) in category S2, which is similar to category B in CR 1752 (1998).

Table 2. Measured Average Air Change Rates in the Analyzed Houses

	From Vent. Ducts [1/h]	With PFT Technique [1/h]
Natural ventilation		0.26
Exhaust ventilation	0.36	0.38
Balanced ventilation	0.42	0.42

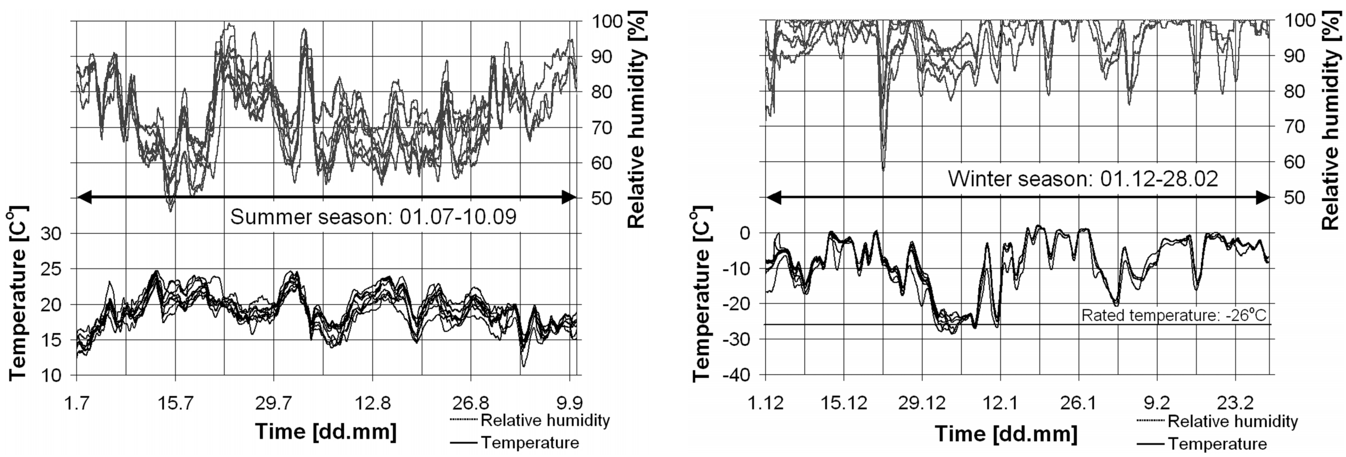


Figure 1 *The daily average outdoor climate in the Helsinki area in the summer (left) and winter (right) from different houses.*

In category S3, the indoor temperature for the summer season must range between +22°C (71.6°F) and +35°C (95°F) (when the outdoor temperature is below +15°C [59°F], the indoor temperature cannot exceed +27°C [80.6°F]). The room temperature may temporarily deviate from the target range of the designed temperatures for a maximum of seven days. The indoor RH values fluctuate during the summer season and are not regulated.

The indoor temperatures during the winter season in category S2 must range between +20°C (68°F) and +22°C (71.6°F). In category S3 temperatures must be between +20°C (68°F) and +23°C (73.4°F). The room temperature may temporarily deviate from the designed temperature for a maximum of seven days of the designed weather conditions. The winter season RH values are regulated only by the S1 category: 25% < RH < 45%. The S1 category is mainly used in the design of office buildings.

In this study, RH values ranging from 20% to 60% were used as a criterion for the acceptable RH range. The main risk factors with low RH are associated with dryness of the skin, nasal cavity, and eyes. The risk factors of having high RH result in either vapor condensation within or on the surfaces of the building envelope (or some other excessive moisture content) or mold growth within or on the building envelope. Fanger (1971) has reported that RH values should not be below 20% because complaints about dry mucous membranes may often be caused by irritants in the air rather than by the dry air. Wyon et al (2002, 2003) have shown that five-hour exposures to low humidity conditions at 22°C (15% and 5% RH) have a measurably negative effect on tear film quality that does not occur above 25% RH. Sterling et al. (1985) suggest that the optimum conditions to minimize the risks to human heath would occur in the narrow range of RH between 40% and 60% at normal room temperatures. According to Viitanen and Ritschkoff (1991), there is no growth of mold fungi below 75% RH within a temperature range of +5°C to +40°C (41°F-104°F).

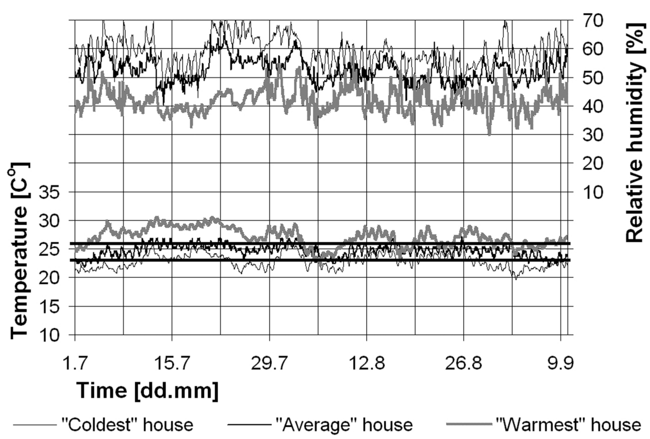


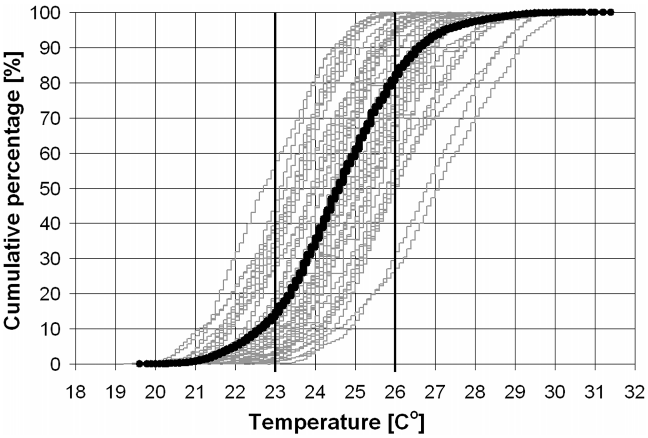
Figure 2 *The indoor climate in three different houses during the summer season.*

RESULTS

Indoor Temperature and Humidity Conditions in Summer

In the summer season the indoor temperatures in all the measured rooms were between +19°C and +32°C (66.2°F and 89.6°F) and the measured RH was between 25% and 80%. The ranges of the indoor temperature and RH in the summer season are shown in Figure 2. Houses have been divided into groups according to the temperature, as the "warmest," "average," and "coldest." The boundary lines +23°C (73.4°F) and +26°C (78.8°F) represent the summer season indoor temperature range in category S2 (FiSIAQ 2001).

All the temperature measurement results and their distribution in the houses with the balanced ventilation system during the summer season are shown in Figure 3, left. Each line represents the measurement result in one room. In the



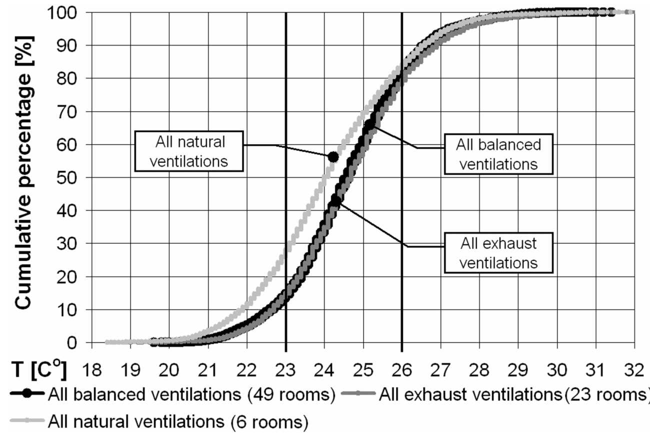


Figure 3 *The distribution of the summer season indoor temperatures in the houses with balanced ventilation (left) and all the results of the subdivision according to the ventilation systems (right).*

thick line, all the temperature measurement values in the current subdivision are sorted in ascending order. A comparison of indoor temperatures with different ventilation systems is shown in Figure 3, right.

The curves with all the temperature values for the houses with a mechanical ventilation system were at the same level. The median values of temperatures in the houses with the natural ventilation system were 0.6-0.7°C lower than the temperatures in the houses with mechanical ventilation. It should be noted that there were only a few houses with natural ventilation (Table 1), and a difference in indoor temperatures between the ventilation systems was not statistically significant. All the values of the absolute indoor humidity (by volume) and their comparison among ventilation systems are shown in Figure 4.

The duration curves of the indoor temperature and the absolute humidity did not show a significant difference in subdivisions of the ventilation systems and envelope assemblies. Therefore, all the differences in the RH duration curves were caused by the differences in temperature.

Figure 5 shows all the absolute humidity (right) and the RH (left) values in the houses grouped according to the indoor surface materials. The darker lines represent the results in the houses with the nonhygroscopic internal surface materials and the brighter ones show the results in houses with the hygroscopic internal surface materials. These subdivisions show only a minor difference in the values of the absolute indoor humidity and the RH. The band of the duration curve of the indoor air absolute humidity in all the rooms was narrower and more stable in the houses with the hygroscopic indoor surface than in those with the nonhygroscopic indoor surface.

When we compare the rooms that have windows facing north (northwest, north, northeast, east) with the rooms that have windows facing south (southeast, south, southwest, west), then it is obvious that during the summer period, rooms with windows facing south have significantly ($P < 0.05$) higher temperatures than in rooms with windows facing north.

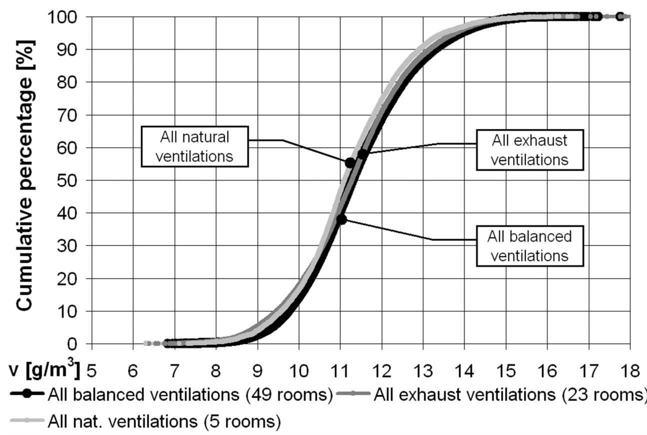
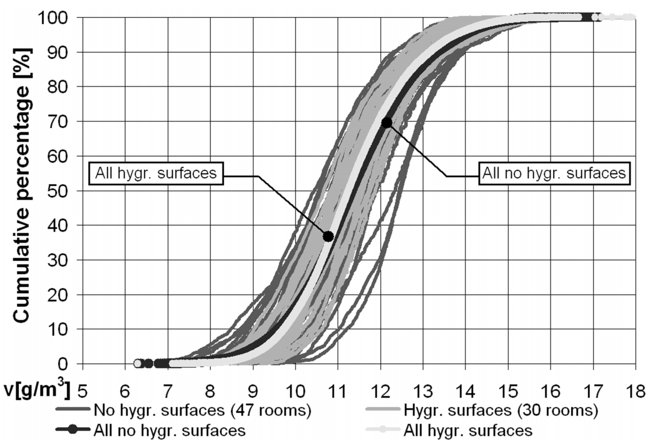


Figure 4 *The distribution of the absolute indoor humidity in the summer season. The comparison between the ventilation systems.*

Indoor Temperature and Humidity Conditions in Winter

In the winter season the indoor temperatures from all the studied houses were measured as being between +7°C (44.6°F) and +32°C (89.6°F) and the measured RH was between 5% and 60%. The indoor temperature and RH in the winter season for the "warmest," the "average," and the "coldest" house are shown in Figure 6. The boundary lines +20°C (68°F) and +22°C (71.6°F) represent the indoor temperature range in category S2 (FiSIAQ 2001) in the winter season.

The heating systems have the main effect on indoor temperature level and stability in winter. A comparison of indoor temperatures in rooms with different heating systems is shown in Figure 7, left. Each line is the measurement result from one room. The darker lines represent the results from



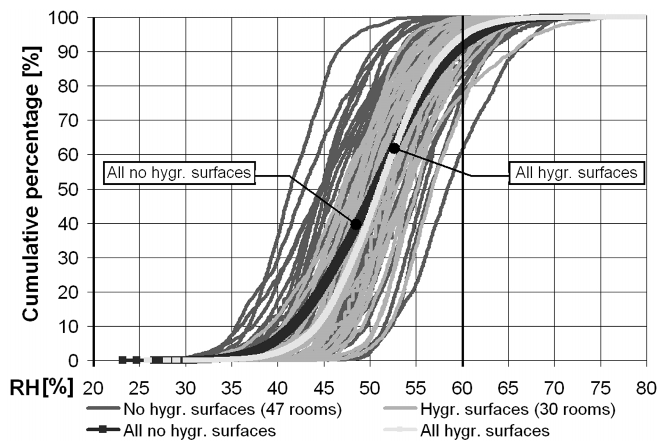


Figure 5 *The distribution of the absolute indoor humidity (left) and RH (right) in the summer season. Ae comparison of the indoor surface materials.*

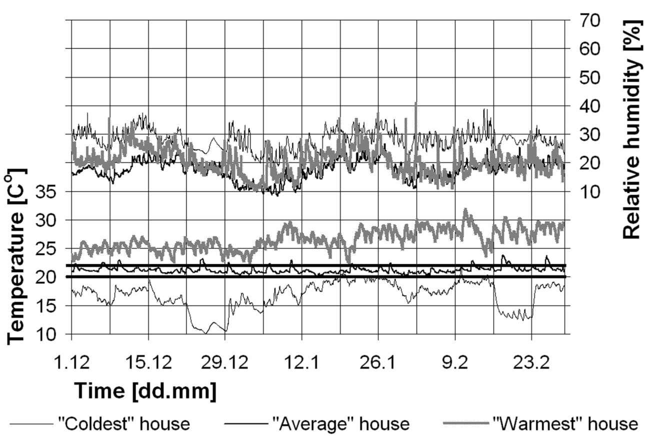


Figure 6 *The winter season indoor climate in three different houses.*

houses with "fast" heating systems and the brighter lines from houses with "slow" heating systems. In the thick line, all temperature measurement values in the current subdivision are sorted in ascending order. A comparison of winter season indoor temperatures among ventilation systems is shown in Figure 7, right.

There was a difference in the indoor temperatures between heating systems with fast and slow response in the S2 category. The slow heating systems were, on average, 0.3ºC warmer than the fast heating systems.

The indoor temperatures satisfied the indoor classification category S2 in 45% of the measured time in the houses with the slow heating systems and in 40% of the measured time in houses with the fast heating systems. The category S3 requirements were met in 69% of the measured time in the houses with the slow heating systems and in 64% of the measured time in houses with the fast heating systems.

The indoor humidity depends mainly on moisture production, the air change rate, and the outdoor humidity. During the winter, there is a relatively high vapor pressure difference over the building envelope in a cold climate. The permeable envelope may, therefore, have a lower humidity rate than that in houses with the vapor-tight envelope. A comparison of indoor absolute humidity and RH between different envelope assemblies in the winter season is shown in Figure 8. The darker lines represent the results from the houses with the vapor-tight envelopes and the brighter lines from the houses with the permeable envelopes.

In the houses with the permeable envelope, the indoor air was drier than in the houses with the vapor-tight envelope. During winter, relative humidity was less than 20% in the houses with the permeable envelope for 41% of the time and in the houses with the vapor-tight envelope for 29% of the time. The lower RH can be partially explained by higher temperature, but the absolute humidity curves show a lower humidity rate in the houses with the permeable envelope at a low range of humidity.

Average Daily Amplitude of Temperature, RH, and Absolute Humidity by Volume

To study the fluctuation of temperature, RH, and absolute humidity, the amplitudes of 24 hours, i.e., the difference between the daily maximum and minimum values, were calculated. An average value of these daily values over all the summer and winter period is considered as a measure of the fluctuation of the parameter studied. The values of the average daily amplitude in all subdivisions during summer and winter seasons are shown in Table 4.

During summer, the daily average amplitudes of the temperature were significantly lower (and showed the lowest variation) in rooms with balanced ventilation compared to rooms with natural ventilation ($P < 0.0001$) and mechanical

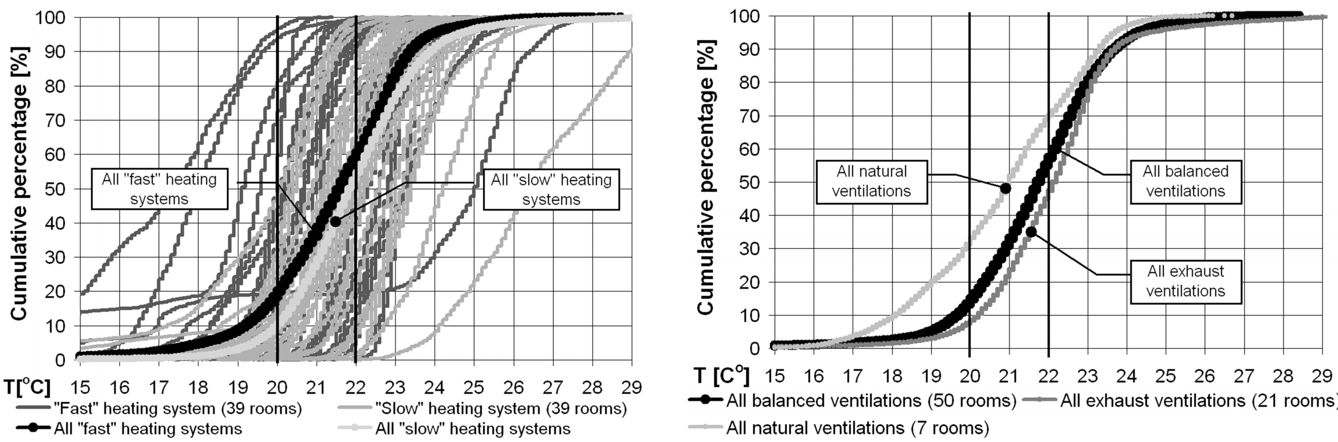


Figure 7 *Distribution of winter season indoor temperatures. A comparison between the heating systems (left) and ventilation systems (right).*

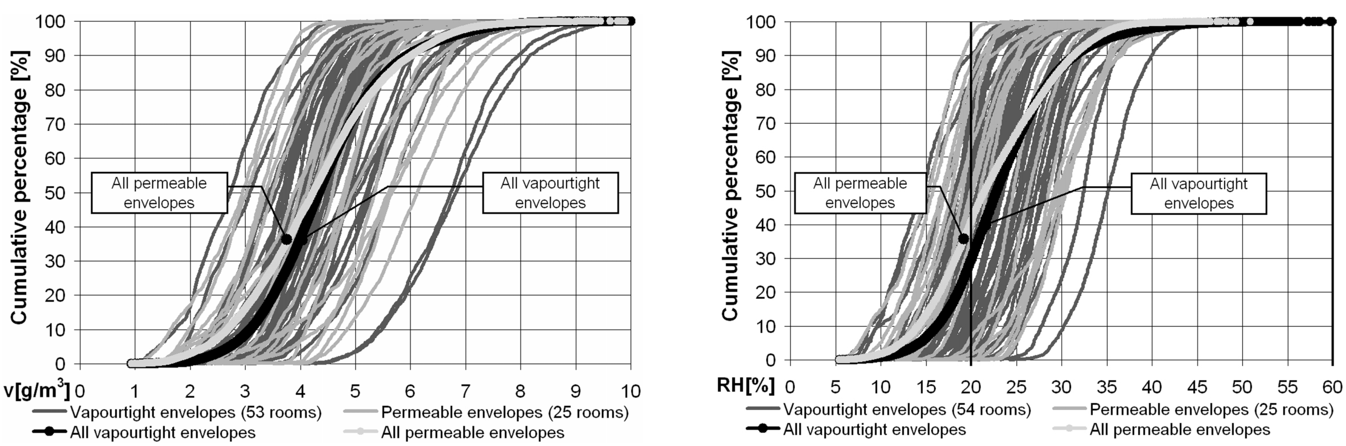


Figure 8 *The distribution of the indoor air absolute humidity (left) and RH (right) in the winter season. Comparison is between the envelope assemblies.*

Table 3. Average Values of Temperature (T), RH, and Absolute Humidity (v) in All Subdivisions During Summer (S) and Winter (W) Seasons

	T, [°C]		RH, [%]		v, [g/m^3]	
	S	W	S	W	S	W
Natural ventilation	24.2	20.8	51.9	26.4	11.2	4.68
Exhaust ventilation	24.7	22.1	50.1	22.4	11.3	4.48
Balanced ventilation	24.6	21.7	50.7	22.9	11.4	4.35
Slow heating syst.em		21.9		23.1		4.45
Fast heating system		21.4		23.3		4.39
Permeable envelope	24.7	22.1	50.2	22.2	11.3	4.34
Vapor-tight envelope	24.6	21.0	50.8	23.5	11.4	4.45
Hygroscopic surface	24.4	21.5	51.3	23.2	11.4	4.34
Nonhygroscopic surface	24.8	21.7	50.1	23.4	11.4	4.46
All data	24.6	21.7	50.6	23.2	11.4	4.42

Table 4. Values of Average Daily Amplitude of Temperature (T), RH, and Absolute Humidity (v) in All Subdivisions During Summer (S) and Winter (W) Seasons

	T, [°C]		RH, [%]		v, [g/m^3]	
	S	W	S	W	S	W
Natural ventilation	2.5	2.2	9.2	5.4	2.0	1.2
Exhaust ventilation	2.1	1.5	9.6	6.1	2.2	1.5
Balanced ventilation	1.6	1.5	8.0	5.2	2.0	1.3
"Slow" heating syst.		1.6		6.1		1.4
"Fast" heating syst.		1.5		5.6		1.3
Permeable envelope	1.8	1.5	9.2	6.4	2.1	1.4
Vapor-tight envelope	1.8	1.6	8.3	5.6	2.0	1.3
Hygroscopic surface	1.8	1.5	8.0	5.5	1.9	1.3
Non-hygr. surface	1.8	1.6	9.0	6.0	2.1	1.4
All data	1.8	1.6	8.6	5.9	2.0	1.3

exhaust ventilation ($P < 0.001$). Balanced ventilation showed a significantly lower variation of RH ($P < 0.0003$) and absolute humidity ($P < 0.006$) than mechanical exhaust ventilation. The vapor tightness of the envelope did not show any significant difference in daily average amplitudes of temperature, RH, and absolute humidity. In rooms with hygroscopic indoor surfaces, the daily average amplitude of the RH ($P < 0.05$) and absolute humidity ($P < 0.05$) was significantly lower than in rooms with nonhygroscopic indoor surfaces.

During winter, the daily average amplitudes of the temperature were significantly higher in rooms with natural ventilation than in rooms with balanced ventilation ($P < 0.004$) and mechanical exhaust ventilation ($P < 0.009$).

The heating systems with slow and fast response should differ by response time when outdoor temperature is changing. According to FiSIAQ (2001), in winter the S2 category allows the temporary deviation of ±1°C from the set temperature and S3 allows ±2°C. Mean values of the indoor temperature daily amplitude were 0.3°C higher in houses with slow heating systems (massive floor heating, accumulating heating) it than in houses with fast heating systems (radiator, ceiling, and air heating), Figure 9 left. Comparisons of winter season indoor temperature daily amplitudes between different ventilation systems are shown in Figure 9, right.

A comparison of the average daily amplitude of the absolute indoor humidity between the different indoor surface materials in the summer (left) and winter (right) is shown in Figure 10.

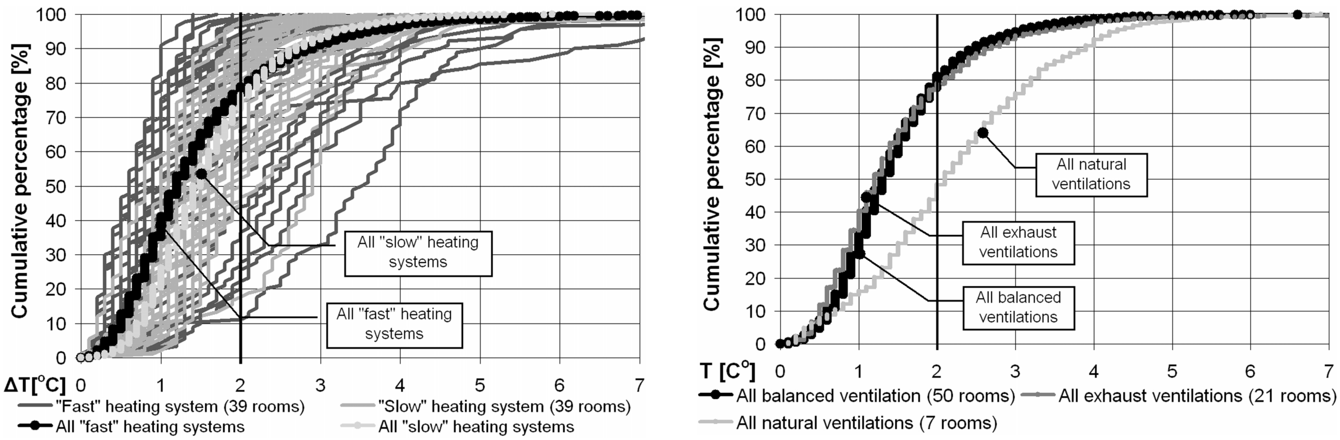


Figure 9 *Distribution of the indoor temperature daily amplitude over the winter season. Comparisons between heating (left) and ventilation (right) systems.*

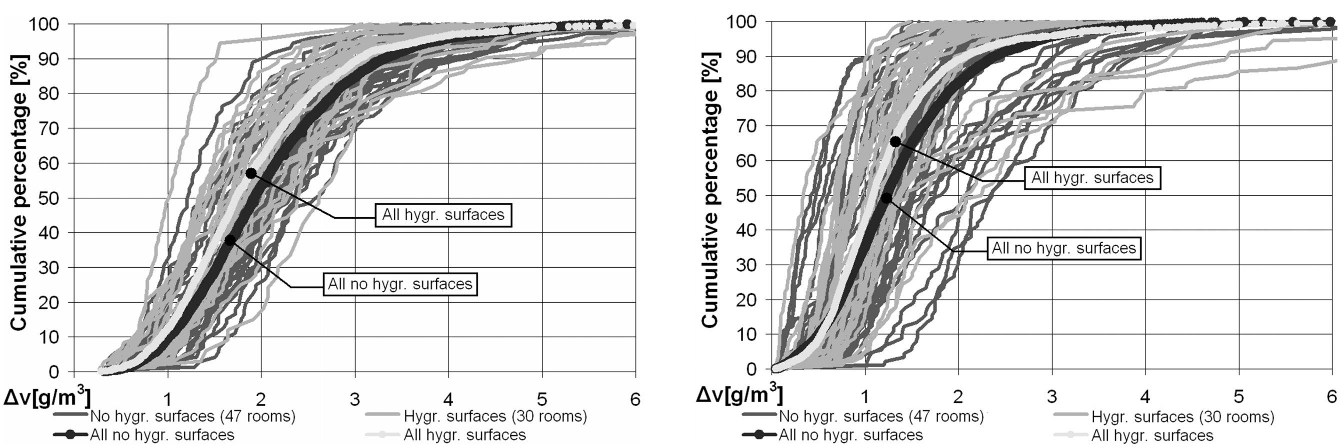


Figure 10 *The distribution of the average daily amplitude of the absolute humidity of the air in summer (left) and winter (right). Comparison between the indoor surface materials.*

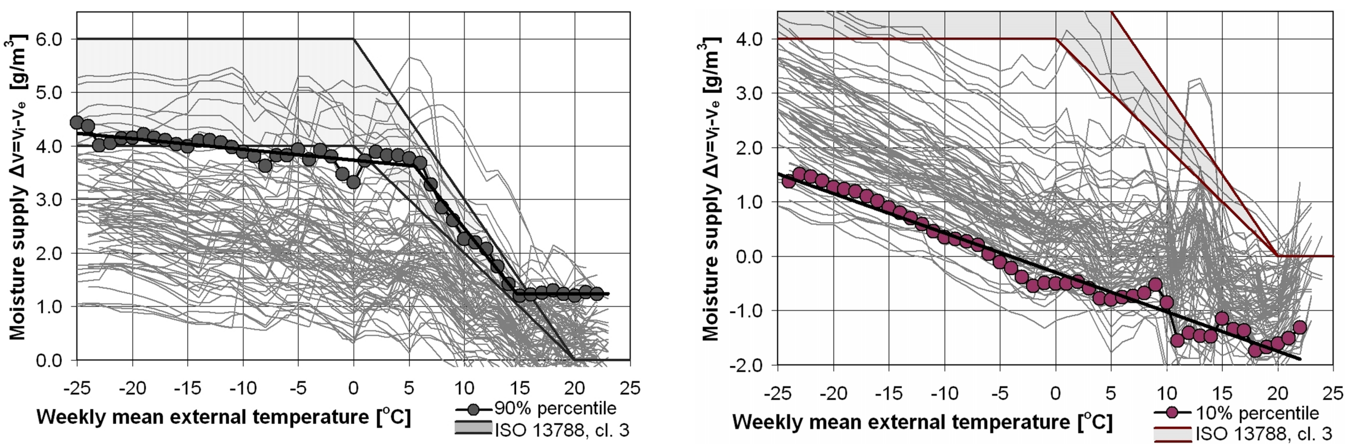


Figure 11 *The internal moisture supply (90% percentile at left and 10% percentile at right) as a function of weekly mean outdoor temperature.*

The Internal Moisture Supply

The values of the internal moisture supply (the difference between water vapor content of indoor and outdoor air) were calculated, based on measured results of the indoor and outdoor temperatures and RH, as the average difference in the absolute humidity during the reference time period. In the EN ISO 13788 (2001) the reference time period is one month. The reference period in this study was one week as it allowed us to calculate more values and to study the outdoor temperature dependency in more detail. A shorter reference time was not used because in the case of a very short period the results may significantly deviate from the representative average value of a longer period due to the dynamic behavior of heat and moisture transfer.

Moisture supply values are calculated as the average values for each week. Then weekly average values are sorted according to the outdoor air temperature, using 1°C steps for the outdoor temperature. From these sorted values, maximum and minimum values are calculated and shown as one thin line for each house in Figure 11. From all values of current outdoor temperatures, the 10% critical levels for moisture supply are calculated. These values are compared with EN ISO 13788 (2001) internal humidity class 3 (dwellings with a low occupancy) in Figure 11. The moisture supply is not a constant value over a year—its dependence on the outdoor temperature is clearly visible. During the warm season, the smaller moisture production (less indoor living activities) and higher air change rate (open windows and doors, possibly higher fan speed) decrease the value of the moisture supply.

From Figure 11 we can see the following disagreement between the trend of measured results and the EN ISO 13788 (2001) graph.

- Moisture supply does not nullify at temperatures above +20°C (68°F), as in the EN ISO 13788 graph. The positive moisture supply was also measured during the summer season.
- The deflection points of the moisture supply are not +20°C (68°F) and ±0°C (−32°F), as in the EN ISO 13788 graph, but +15°C (59°F) and +6°C (42.8°F).
- At low temperatures (<+6°C, 42.8°F) the moisture supply is not completely constant as in the EN ISO 13788.

During a warm and humid summer, it is possible that the indoor air is drier than the outdoor air and humidity moves from outdoors to indoors. To assess the possible summertime condensation due to the inward vapor drive, the negative internal moisture supply, as well as driving rain and solar radiation, should be taken into account. The distribution of the minimum internal moisture supply at a 10% critical level is given in Figure 11, right.

For hygrothermal calculations and sensitivity analysis, it is necessary to know the distribution of different moisture supply levels over the whole outdoor temperature range. The different internal moisture supply curves are calculated from the measurement results and shown in Figure 12, left. The curves are calculated so that during the cold period (<+6°C, 42.8°F) the average values of internal moisture supply are the following: +1 g/m^3, +2 g/m^3, +3 g/m^3, +4 g/m^3, and +5 g/m^3. The curves are limited to the positive values of the internal moisture supply.

The internal moisture load has been researched in many field studies (Van der Kooi and Knorr 1973; Hens 1992; Tolstoy 1994; Jenssen et al. 2002) through numerical analysis (Janssens and Hens 2003). A comparison of the current study with other studies and with EN ISO 13788 (2001) standard is shown in Figure 12, right.

The building interior may have significant hygrothermal mass that can influence the indoor climate. Materials absorb

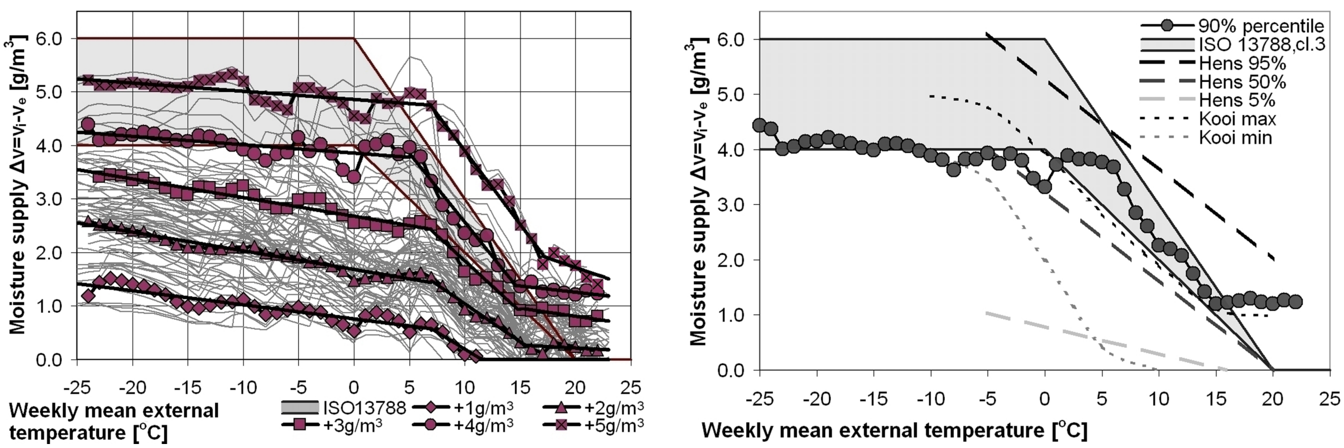


***Figure 12** The internal moisture supply at different levels at left and a comparison of present results with those of other studies (Van der Kooi and Knorr 1973; Hens 1992) at right.*

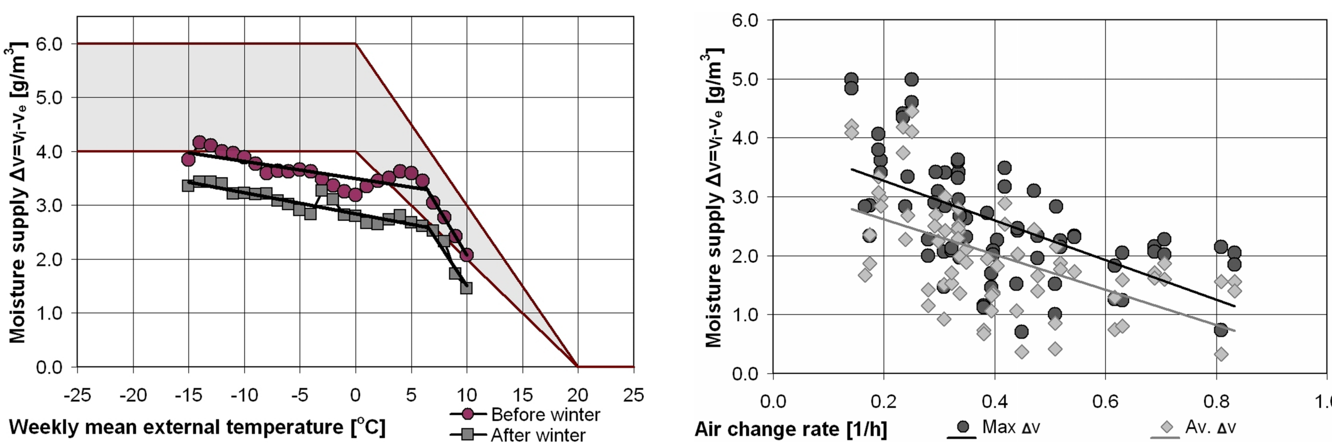


***Figure 13** Comparison of internal moisture supplies (90% percentile) during autumn and spring (left) and the effect of the air change rate on the maximum and average internal moisture supply during winter (right).*

the moisture when the RH increases and desorb it when the RH decreases. Over a year the indoor RH is low during the heating season and is higher in the summer season. The moisture supply hysteresis over a year is shown in Figure 13, left. During the period when the external temperature was between −15°C and +10°C (5°F and 50°F), the moisture supply during autumn was, on average, 0.6g/m^3 higher than during spring. Before the winter begins, the building envelope surfaces and other interior hygroscopic masses release the moisture that has been stored in the room during the summer; therefore, the moisture supply is higher than after the winter, even though the external conditions are similar. Right after winter, the envelope is dried out and may begin to absorb moisture from the air again, hence, decreasing the internal moisture supply. Therefore, the moisture capacity has an impact on the indoor humidity. The same phenomenon can be observed when looking at the simulation results (Janssens and Hens 2003).

The dependency of the moisture supply on the actual ventilation rate was possible to determine, as the air change rate was measured from each house by the PFT measurement technique during the winter. The relationships between air change rate and the weekly maximum and average moisture supply are shown in Figure 13, right.

Moisture Production

Based on the indoor and outdoor humidity and the air change rate, the moisture production G (kg/day) during winter was calculated:

$$G = q_v \cdot \Delta v \text{ , [kg/day]} \qquad (1)$$

where Δv indicates the moisture supply [kg/m^3], and q_v is the air change rate (m^3/day).

Table 5. Average (AV) and Maximum (MAX) Weekly Moisture Production During Winter in the Analyzed Houses

	Daily Moisture Production, [kg/d]			
	$\Delta v < 3g/m^3$ (29 house)		$\Delta v > 3g/m^3$ (13 house)	
	AV	MAX	AV	MAX
≤3 pers.	4.7	13.8	6.1	14.5
>3 pers.	5.0	18.6	7.0	14.3

Table 6. Typical Average Moisture Production Rates

Activity	kg/d
People	0.9
Dog/cat	0.4/0.1
Cooking, dishwashing	0.2/person
Plants	0.4/five plants
Shower	0.3/time
Sauna	1/time
Washing/drying clothes	1/time

The weekly moisture production values are shown in Table 5. The moisture production was calculated only for the winter because the air change rate was measured with the PFT technique during that period. The actual air change rates during the summer were not known because these depend a lot on the use of window airing. As the air change rate was measured for the whole building, the indoor humidity values used for calculating the daily average moisture supply were the average values of the bedroom and living room measurements.

The moisture production values calculated from the air change rate and the moisture supply were compared to the expected values, which were determined based on data from the occupant questionnaire and on specific moisture production rates from the literature review (Angell 1988; BS 1989; Koch et al. 1986; prEN 2002; Sanders 1996; Sedlbauer 2002; Straube 1999), which are listed in Table 6. Winter season calculated moisture production rates (based on measurements of indoor and outdoor humidity and air change rate) are compared with the predicted moisture production rates (based on occupant behavior and Table 6) in Figure 14.

DISCUSSION

This study measured and analyzed indoor temperatures and RH in houses, and the results were compared according to the different types of building envelopes and heating/ventilating systems. When the indoor climate parameters were compared, some limitations and uncertainties were taken into account. The architecture, orientation, and surroundings of the buildings were different in every case. Especially during summer, solar radiation had the main influence on the indoor temperatures. As the temperature and the RH sensors were located in the master bedroom of all the houses and, in addition, in the living rooms of most houses, the orientations of these rooms played an important role. As all the houses were different and situated in different areas, urban or natural surroundings, the neighboring houses or trees may have had a direct influence on the indoor conditions. Additionally, the occupants' behavior may have played an important role, for example, on the temperature level. These factors may have caused large differences between individual houses.

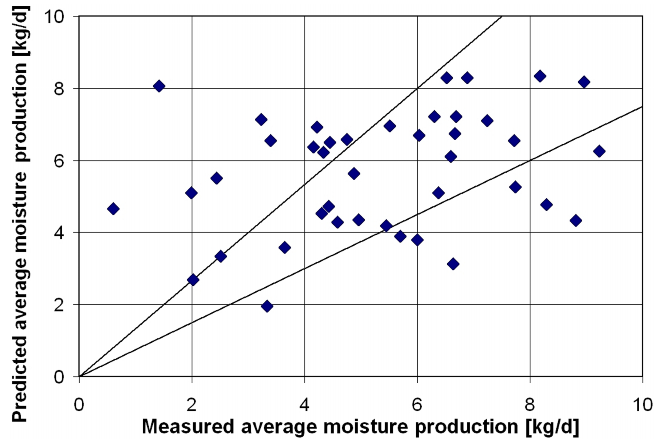


Figure 14 Comparison of measured daily average moisture production and the expected moisture production values. Lines on the figure indicate ±75% accuracy.

During the summer the difference in the daily amplitude of the indoor humidity was only slightly smaller in rooms with hygroscopic envelopes on the indoor surfaces, 8.0% vs. 9.0% (see Table 4). This difference was less than the dynamic simulations showed (Simonson et al. 2002a, 2002b; Kurnitski et al. 2003). According to Kurnitski et al., the daily average amplitude of the indoor RH was about 5% in the rooms with hygroscopic and permeable surfaces and about 15% in rooms with nonhygroscopic and vapor-tight surface (both of the values apply the ventilation rate at 4 L/s and 6 L/s per person). Such a difference between measurements and simulation may simply occur due to the fact that in real life ideal nonhygroscopic houses do not exist. Besides, the envelopes also contain other hygroscopic mass, such as that of textiles, furniture, or other furnishings, which are present in real houses. These additional hygroscopic masses probably smooth the seasonal fluctuation of the indoor air humidity and reduce the differences between the hygroscopic and nonhygroscopic subdivisions. Another reason explaining the different results in the hygroscopic cases is that the hygroscopic houses in the field measurements did not have as many hygroscopic surfaces and highly hygroscopic materials as have been used in simulations.

In this study it was difficult to divide buildings into the hygroscopic and the nonhygroscopic ones. A clear performance or parameter for the hygroscopic case was not possible to use. Such a single parameter to express the moisture buffer performance of materials is under development in the Nordtest project (Rode 2003), but it is much more complicated to classify real houses. In this study, the only possible way was to use a simple definition—the room was defined as hygroscopic if the majority of the surfaces were covered with hygroscopic material. In this study the hygroscopic surface materials were wallpaper on wood chipboard or plasterboard and unfinished wooden boarding. Other surface materials, including painted surfaces and lacquered wood, were classified as nonhygroscopic. Classifying painted surfaces as nonhygroscopic is, of course, problematic because the moisture permeability of paints varies from permeable whitewash and tempera paints to thick and almost impermeable enamel paints. The paint systems may have a moisture capacity that could not be neglected (Svennberg 2003). The moisture absorption of the paint systems depends strongly on the number of paint layers (Svennberg and Harderup 2002). However, such systematic classification was used because in the field inspection it was not possible to know the correct paint type and the number of paint layers.

The vapor-tight building envelopes were divided according to that of the special vapor barrier layer, and the internal surface of the envelopes were not considered. So it means that the subdivision of vapor-permeable envelopes may also contain the houses where the envelope is quite vapor tight because the inner surface was, for example, painted with impermeable paint.

The room temperatures were assessed according to the Finnish classification of the indoor climate (FISIAQ 2001). This classification defines the range and the allowed excess of temperature for each indoor climate category. For example, in category S2 the room temperature may temporarily deviate from the target range for a maximum of seven days in winter and summer. Seven days may mean $7 \times 1 = 7$ hours or $7 \times 24 = 168$ hours. Another problem is that the length of the climatic season in not explicitly defined. It would be clearer and more flexible if we allowed the excess to be a certain percentage of the studied time. For example, 5% of the exceeded time is seven days during five months. In the present form, the criterion seems not suitable for the long-term evaluation of the room temperature as the majority of the houses did not meet even the requirements of the lowest category, S3.

The internal moisture supply values show a clear dependence on the outdoor air temperature. At the higher outdoor air temperatures, this dependency may be explained by the higher summer ventilation rates and probably by the occupants having spent more time outdoors. At the low outdoor air temperatures, there is no clear explanation of this dependency. For a more detailed analysis, the same measurements are planned to be carried out during the year (2003-2004), allowing the analysis of the data during two years.

CONCLUSIONS

The high indoor temperatures of the summer period exceeded the acceptable comfort levels in most of the studied houses. Due to the high indoor temperatures during the summer season, only 12% of the rooms met the requirements of the category S2 (FiSAQ 2001). All other rooms fell into the S3 category with lower requirements for indoor temperature in summer. The uncontrolled temperatures indicated that thermal comfort during summer had not been considered in the design process.

The effectiveness of ventilation and heating systems play the most important role in the indoor climate. The room's orientation had an influence on the room temperatures. However, rooms with windows to the south had, on average, only 0.4°C higher temperatures in summer than rooms with windows to the north.

During the winter only 9% of the houses followed the category S3 (FiSIAQ 2001) requirements. No houses met category S2 due to the strict requirements for temporary temperature deviation from the defined range. The temperature was below +20°C (68°F) in 45% of the winter season and above +23°C (73.4°F) in 19% of the winter season. The temperatures were within the range of S2 in 43% of the winter season and within the range of S3 in 67% of the winter season.

The effect of the hygroscopic materials was possible to show by the average daily amplitude of the absolute humidity and RH during summer and winter. However, the dampening effect was remarkably less than the dynamic simulations show in previous studies. This indicates that in reality ideal nonhygroscopic houses do not exist despite the use of completely nonhygroscopic materials. The actual air change rate (ventilation, infiltration, opening the windows and doors) and the hygroscopic mass of furniture and indoor textiles probably play a significant role in forming the indoor humidity amplitude. The moisture-permeable air/vapor barrier did not decrease the daily amplitude of relative humidity in the setup of this study.

Vapor-tightness had an effect on the RH level during the winter. The houses with the permeable envelope were drier during winter. The time during winter when the RH < 20% was 41% in the permeable case vs. 29% in the vapor tight-case.

For the hygrothermal design of the building envelope, the critical values of the moisture supply were calculated using the measurements of temperature and relative humidity. The maximum moisture supply on the 10% critical level on the amount of houses during the cold period ($T_{out} < +6$°C,42.8°F) was close to +4 g/m^3. During the warm period ($T_{out} > +15$°C, 59°F) the moisture supply was higher than +1.2g/m^3. For the sensitivity analysis and hygrothermal calculations, the different levels of the moisture supply values and their dependence on the outdoor temperature are given. The measurement results also show a negative load of the moisture supply, which may be 0 g/m^3 at −5°C and may linearly decrease to –2.0 at +23°C. To provide a safety margin, these values should be multiplied by at least 1.10 as is suggested in EN ISO 13788 (2001).

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REFERENCES

Angell, W.J. 1988. Home moisture sources. CD-FS-3396-1988, University of Minnesota.

BS 5250. 1989. *British Standard Code of practice for control of condensation in buildings*. British Standard Institution.

CR 1752. 1998. *Ventilation for buildings: Design criteria for the indoor environment*. CEN, Brussels.

EN ISO 13788. 2001. *Hygrothermal performance of building components and building elements—Internal surface temperature to avoid critical surface humidity and interstitial condensation—Calculation methods*.

Fanger, P.O. 1971. *Air humidity, comfort and health*, pp. 1-5. Lundby, Denmark: Technical University of Denmark.

FiSIAQ. 2001. Classification of Indoor Climate 2000. Espoo: Finnish Society of Indoor Air Quality and Climate.

Hens, H. 1992. Indoor climate classes. Heat, air and moisture transfer in insulated envelope parts (HAMTIE). Internal Report IEA-Annex 24 T2-B-92/02. International Energy Agency.

Janssens, A., and H. Hens. 2003. Development of indoor climate classes to assess humidity in dwellings. *Proceedings of the 24th AIVC-Conference, Ventilation, humidity control and energy, Washington DC*, pp. 41-46.

Jenssen, J.A., S. Geving, and R. Johnsen. 2002. Assessments on indoor air humidity in four different types of dwelling randomly selected in Trondhein, Norway. *Proceedings of the 6th Symposium on Building Physics in the Nordic Countries, Trondheim, Norway, June 17th-19th, 2002*, pp. 729-735.

Koch, A.P., et al. 1986. Fugt i boligen. Danish Technological Institute.

Kurnitski J., A. Suursoho and J. Palonen. 2003. The effect of structures on IAQ and thermal comfort. P*roceedings of ISIAQ 7th International Conference on Healthy Buildings, 11th December 2003, Singapore*.

prEN 14788. 2002. Ventilation for buildings - Design and dimensioning of residential ventilation systems. Draft.

RakMK C3. 2002. Rakennuksen lämmöneristys. Suomen rakentamismääräyskokoelma, Helsinki, Ympäristöministeriö.

Rode, C. 2003. Nortest workshop on moisture buffer capacity–Summary Report. DTU, Lygnby, Denmark, August.

Ruotsalainen, R., R. Rönnberg, J. Säteri, A. Majanen, O. Seppänen, and J.J.K. Jaakkola. 1992. Indoor climate and the performance of ventilation in Finnish residences. *Indoor Air* 2: 137-145.

Sanders, C.H. 1996. Environmental Conditions: Final Report, Task 2. Energy conservation in buildings and community systems, Annex 24, Heat, air and moisture transfer in insulated envelope parts (HAMTIE). International Energy Agency (IEA).

Sedlbauer, K. 2002. Prediction of mould fungus formation on the surface of and inside building components. Ph.D. dissertation, Fraunhofer Institute for Building Physics, University of Stuttgart.

Seppänen, O. 2001. Rakennusten lämmitys. Suomen LVI-liitto ry. Gummerus kirjapaino Oy, Jyväskylä.

Simonson, C.J., M. Salonvaara, and T. Ojanen. 2002. The effect of structures on indoor humidity—Possibility to improve comfort and perceived air quality. *Indoor Air* 12: 243-251.

Simonson, C.J., M. Salonvaara, and T. Ojanen. 2002. Humidity, comfort and air quality in a bedroom with hygroscopic wooden structures. *Proceedings of the 6th Symposium on Building Physics in the Nordic Countries, Trondheim, Norway, June 17th-19th, 2002*, pp. 743-750.

Sterling, E.M., A. Arundel, and T.D. Sterling. 1985. Criteria for human exposure to humidity in occupied buildings. *ASHRAE Transactions* 91(1).

Straube, J.F. 1999. Moisture fundamentals and mould. OBEC Seminar, Etobicoke, Ontario, November 17.

Svennberg, K., and L.-E. Harderup. 2002. Time-dependent moisture properties for plasterboard with surface coating. *Proceedings of the 9th International Conference on Indoor Air Quality, Indoor Air 2002, Monterey, CA, USA*, Vol. IV, pp. 66-72.

Svennberg, K. 2003. Determination of moisture properties for materials exposed to the indoor air. Lunds University, Dept. of Building Physics, Research Reports: TVBH-3042.

Tolstoy, N. 1994. *The condition of buildings, Investigation methodology and applications.* Royal Institute of Technology, Stockholm.

Van der Kooi, J., and K.T.H. Knorr. 1973. De temperatuur en vochtigheid in woningen (Temperature and humidity in dwellings, in Dutch). *Klimaatbeheersing* Vol. 2: 490-496.

Viitanen, H., and A.-C. Ritschkoff. 1991. Mould growth in pine and spruce sapwood in relation for air humidity and temperature. Swedish University of Agricultural Sciences, Department of Forest Products, Uppsala. Report No 221.

Wyon, D.P., L. Fang, and P.O. Fanger. 2003. Low winter humidity indoors has a negative effect on the performance of office work. *Proceedings of the 4th International Conference on Cold Climate, Trondheim, Norway, June 15th to 18th*, CD-ROM.

Wyon, D.P., L. Fang, H.W. Mayer, J. Sundell, C.G. Weirsoe, N. Sederberg-Olsen, H. Tsutsumi, T. Agner, and P.O. Fanger. 2002. Limiting criteria for human exposure to low humidity indoors. *Proceedings of the 9th International Congress on Indoor Air Quality, July 2-6, 2002, Montery, CA, USA*.