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Comparison of indoor moisture excess in three different terraced housing projects

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Abstract. In this study three neighbourhoods of terraced houses have been investigated. In 16 to 29 houses of each project, indoor temperature and indoor humidity have been measured, inhabitants have been interviewed and Blower-Door Tests have been performed. PSG is a project with 91 similar, very airtight detached houses. More than 29 of these houses have been investigated. TES is a low-rise high-density project with 46 single family houses built in 1974. The measuring results of 20 houses with very poor airtightness have been analysed. APW is a project with 26 terraced houses built in 2012, which have mechanical ventilation systems. From APW 16 houses have participated in the study. It will be illustrated that the airtight houses of PSG have the highest absolute indoor humidity, the TES houses with the poor airtightness have medium absolute indoor humidity and the APW with the mechanical ventilation systems have the lowest absolute indoor humidity. Box plots of the moisture excess in the diagram with the humidity classes from EN ISO 13788 [1] show that the boxes do not overlap.

1. Introduction

Indoor humidity is a significant boundary condition for the durability of constructions. Distributions of indoor climate are a necessary input parameter for a probabilistic assessment. Indoor absolute humidity depends on factors like external absolute humidity, indoor moisture production and airing.

In this study absolute indoor humidity has been measured in three neighbourhoods of terraced houses over three winter periods. 208 monthly mean values were analyzed in the end. This article includes a brief description of the three different housing projects, a summary of the investigations that were conducted, the actual measurement results (indoor temperature, indoor relative humidity, airtightness and if applicable, air volume flow of the mechanical ventilation system), some data analysis (for instance comparison of the results and depiction of the calculated moisture excess in the humidity classes of EN ISO 13788 [1]) and conclusions.

The collected data will be used to improve the recently presented model [2] for the prediction of the indoor absolute humidity based on questionnaires. The resulting distributions of each neighbourhood will be used for probabilistic assessment of the durability of building components.

A lot of publications dealt with indoor humidity. Künzel [3] determined a connection between outdoor temperature and indoor humidity by measuring ten living spaces. Künzel suggested a model with three humidity classes. Janssens and Vandepitte [4] measured 39 detached houses, semi-detached houses and apartments built around 1990 in Belgium. The higher vapor pressure in the social dwellings was considered to relay on the bigger geometry of the private houses. Vinha et al. [5] measured 100
Finish detached houses and distinguished into vapour tight and vapour permeable envelopes. The houses with vapour permeable envelopes showed lower moisture excess but the difference was small and not significant. Tariku et al. [6] compared measurements with calculations and figured out, that at least the inner layer of the building envelope is important due to its buffering effects. De Place Hansen and Møller [7] measured 500 Danish dwellings during summer and winter. A substantial influence of the building type (non timber-framing 1910, Brick 1911-1959, Brick 1960-1979, wooden houses, etc.) was not identified. Ilomets et al. [8] measured 237 dwellings and figured out, that at least the inner layer of the building envelope is important due to its buffering effects. De Place Hansen and Møller [7] measured 500 Danish dwellings during summer and winter. A substantial influence of the building type (non timber-framing 1910, Brick 1911-1959, Brick 1960-1979, wooden houses, etc.) was not identified. Ilomets et al. [8] measured 237 dwellings and figured out, that at least the inner layer of the building envelope is important due to its buffering effects. De Place Hansen and Møller [7] measured 500 Danish dwellings during summer and winter. A substantial influence of the building type (non timber-framing 1910, Brick 1911-1959, Brick 1960-1979, wooden houses, etc.) was not identified. Ilomets et al. [8] measured 237 dwellings and figured out, that at least the inner layer of the building envelope is important due to its buffering effects. De Place Hansen and Møller [7] measured 500 Danish dwellings during summer and winter. A substantial influence of the building type (non timber-framing 1910, Brick 1911-1959, Brick 1960-1979, wooden houses, etc.) was not identified. Ilomets et al. [8] measured 237 dwellings and figured out, that at least the inner layer of the building envelope is important due to its buffering effects. De Place Hansen and Møller [7] measured 500 Danish dwellings during summer and winter. A substantial influence of the building type (non timber-framing 1910, Brick 1911-1959, Brick 1960-1979, wooden houses, etc.) was not identified. Ilomets et al. [8] measured 237 dwellings and figured out, that at least the inner layer of the building envelope is important due to its buffering effects. De Place Hansen and Møller [7] measured 500 Danish dwellings during summer and winter. A substantial influence of the building type (non timber-framing 1910, Brick 1911-1959, Brick 1960-1979, wooden houses, etc.) was not identified. Ilomets et al. [8] measured 237 dwellings and figured out, that at least the inner layer of the building envelope is important due to its buffering effects.

All these publications dealt with user behavior and almost all with the influence of the envelope. Totally equal buildings have not been investigated in any of these studies.

2. Investigated housing projects

2.1. PSG

PSG is a low-rise high-density housing project in Austria. 91 almost identical two-story detached houses were built within a social housing project in 2009. Each house has dimensions of 4.75 m by 11.00 m, which leads to a gross floor area (GFA) of 52 m². The net floor area of both floors amounts to 84 m². Most of the houses have unheated cellars which can be seen in the cross section of Figure 1.

The houses consist of a timber frame construction with an inside gypsum board. The external finish of the walls is either an external thermal insulation composite system (ETICS) or a ventilated curtain-wall facing. The flat roof covering is a rear ventilated Foil (Ethylene-Propylene-Dien Group M (EPDM)). There is no controlled domestic ventilation system installed in the houses but there are fans in the toilets and in the bathrooms. Furthermore, the bathrooms have two big windows each. A detailed description of PSG as well as measurement results can be found in [2] and [11] and [12].

2.2. TES

The low-rise high-density project TES was built in Austria between 1972 and 1974. The 46 terraced houses are single-story plus unheated cellars (Figure 2). The L-shaped houses have overall dimensions of 15.25 m by 13.40 m. Gross floor area therefore results in 151 m² whereas the net floor area of the main floor is approximately 130 m². The houses have brick walls and a concrete slab on top with a ventilated flat wooden roof. In 1974 no thermal insulation was applied, neither at the facade nor in the roof. The houses have large window areas. The internal bathrooms have light domes. The houses are not equipped with central mechanical ventilation systems. Most of the houses have undergone several renovations. The TES housing project and measurement results are described in detail in [13].
Figure 2. Site plan (black … investigated houses), floor plan, cross section (TES).

2.3. APW
APW consists of 26 terraced houses which were approximately built in the year 2012 in Austria. Each house has overall dimensions of about 9.50 m by 7.50 m. All the houses have four stories: an attic, an upper floor, a ground floor and a cellar (Figure 3). Only four of the 16 investigated houses have a heated attic included in the living space. Twelve cellars are heated but they are mostly only of minor use like storage space, gym, sauna, etc. Each floor has a gross floor area of 63 m² and a net floor area of approximately 60 m² respectively. So, most of the houses offer a living space of about 120 m², some 180 m² or 240 m².

Figure 3. Site plan (black … investigated houses), floor plans, cross section (APW).

The houses are built of brick walls with an external thermal insulation composite system (ETICS). All houses have steep roofs with roofing tiles. The cellars are totally under the ground. The houses are connected at the gable wall. The houses have windows to the northeast and southwest only. Kitchens, bathrooms and toilets have windows. Each house has a mechanical ventilation system. Its main unit is situated in the cellar. There are inject outlets in the sleeping rooms and in the living room. The extraction outlets are in the bathroom, kitchen, toilet and cellar.

3. Evaluations

3.1. PSG
Questionnaires regarding moisture production and ventilation behavior were distributed to all 91 households in October 2012. By the end of March 2013, 39 completed questionnaires were returned, 34 Blower-Door Tests were realized and temperature and relative humidity in 29 houses were measured throughout the whole winter. In PSG 29 houses were equipped with two data loggers each in November 2012. One logger was mounted on the ground floor in the center of the open plan kitchen living at head height. The other logger was placed on the upper floor in the bedroom or sometimes in the second
upstairs room (nursery, study, etc). Most inhabitants stated that the interior doors were always open, so it was assumed that the house was one hygrothermal zone. Blower-Door Tests were conducted in these 29 houses and five additional houses.

3.2. TES
20 houses in TES were equipped with one data logger each. The employed logger collected temperature and relative humidity in the living room for the period 1 November 2019 to 1 March 2020. In 15 houses Blower-Door Tests were performed. The inhabitants of precisely these 15 houses and one additional house returned one questionnaire each.

3.3. APW
16 houses were investigated over the course of winter 2017/2018. One data logger was placed in each living room to gather information about temperature and relative humidity in the building. The inhabitants of all those houses also returned one questionnaire each. The air volume flow produced by the mechanical ventilation system has been measured at each outlet using a vane anemometer. The measured volume flow has been compared with the settings of the mechanical ventilation’s main unit. Additional Blower-Door Tests were not conducted in these houses. It was considered, that infiltration has no substantial influence compared to the high mechanical ventilation rates.

3.4. Measurement equipment
Temperature and humidity have been measured using data logger from T&D (RTR), HOBO and BluSensor. The T&D (RTR) have an accuracy of +/- 0.3 °C and +/- 5% relative humidity. The HOBO have have an accuracy of +/- 0.35 °C and +/- 2.5% relative humidity. The BluSensor have an accuracy of +/- 0.2 °C and +/- 2% relative humidity. Blower-Door Tests have been performed with Minneapolis Blower-Door devices. Air volume flows at the outlets have been measured using a TESTO 417 vane anemometer with a funnel. The TESTO has an accuracy of +/- 0.1 m/s + 1.5% of measurement reading.

4. Measurement results of each project

4.1. PSG
Monthly average temperatures vary between 18 °C and 24 °C in the living rooms (Figure 4).

![Figure 4](image-url) Histograms of measured monthly mean temperature (left) and relative humidity (right) within December 2012 and February 2013 (PSG) (the horizontal axis shows the mean value of the category).

The mean value is 20.8 °C whereas the median is 21.0 °C. Monthly average relative humidity in all 29 houses amounts to percentages between 35 % and 64 %. The mean value is 52 %, the median is 51 %. The outdoor climate was measured on site with two different devices and is provided in Table 1. The weather station at a distance of 8 km showed comparable values.
Table 1. Monthly mean values of outside climate during measuring period.

| Temperature (°C) | Relative humidity (%) | Absolute humidity (g/m³) |
|------------------|-----------------------|--------------------------|
| December 2012    | 0.8                   | 79                       | 4.2                       |
| January 2013     | 0.4                   | 77                       | 3.9                       |
| February 2013    | 1.2                   | 73                       | 3.8                       |

The next Figure (Figure 5) shows the measured $n_{50}$ values in PSG. In this paper the boxes include 50% of all values. The whiskers include all values from the lowest to the highest.

![Figure 5. Box plot of the measured $n_{50}$ values (PSG).](image)

4.2. TES

The observation period for most houses was between October 2019 and March 2020. The analysis has been carried out with the values from December to February to make an appropriate analogy to the other two projects. Monthly average temperatures vary between 15 °C and 25 °C in the living rooms (Figure 6). The mean as well as the median value is 20.7 °C. Monthly average relative humidity in all 20 houses fluctuates between 34% and 59%. The mean value is 46%, the median is 45%. The outdoor climate was taken from a weather station at a distance of 2 km and is presented in Table 2.

Table 2. Monthly mean values of outside climate during measuring period.

| Temperature (°C) | Relative humidity (%) | Absolute humidity (g/m³) |
|------------------|-----------------------|--------------------------|
| December 2019    | 3.1                   | 83                       | 5.0                       |
| January 2020     | 1.2                   | 87                       | 4.4                       |
| February 2020    | 5.4                   | 73                       | 5.2                       |

Figure 7 depicts the measured $n_{50}$ values in TES.
4.3. APW

Monthly average temperatures fluctuate between 21 °C and 25 °C in the living rooms (Figure 8). The mean value is 23.4 °C whereas the median is 23.5 °C. Monthly average relative humidity in all 16 houses varies between 25 % and 43 %. The mean value as well as the median is 32 %. The outdoor climate was taken from a weather station at a distance of 3 km and is shown in Table 3.

Figure 8. Histograms of measured monthly mean temperature (left) and relative humidity (right) within December 2017 and February 2018 (APW) (the horizontal axis shows the mean value of the category).

### Table 3. Monthly mean values of outside climate during measuring period.

|                | Temperature (°C) | Relative humidity (%) | Absolute humidity (g/m³) |
|----------------|------------------|-----------------------|--------------------------|
| December 2017  | 1.7              | 84                    | 4.5                      |
| January 2018   | 3.8              | 85                    | 5.3                      |
| February 2018  | -1.1             | 79                    | 3.7                      |

Figure 9 depicts the air volume flow produced by mechanical ventilation system in the APW houses. Each house has five to nine inject outlets and four to nine extraction outlets. The air volume flow was measured at each outlet. The volume flows of all inject outlets were added up and all the volume flows of the extraction outlets were totalled too. The grey bars in Figure 9 show the mean value of those two sums. The error bars show the maximum and minimum possible value when adding/subtracting the accuracy according to the datasheet of the TESTO vane anemometer (+/- 0.1 m/s + 1.5 % of reading) to the volume flow measured at each outlet. The more outlets, the higher the error bars. In most houses, the main unit of the ventilation system shows lower air flows than those actually measured using a vane anemometer.
5. Comparison of measurement results

By using the measured temperatures and relative humidities, absolute humidities have been calculated. The indoor moisture excess is determined by subtracting the outdoor absolute humidity from the indoor absolute humidity. This calculation has been performed for each house using monthly mean values. These monthly mean values for the moisture excess are depicted in box plots and drawn into the humidity classes in EN ISO 13788 [1] (Figure 10).

Figure 10 shows the monthly mean values of PSG from December 2012 to March 2013, TES from November 2019 to February 2020 and APW from December 2017 to February 2018.

Figure 10 demonstrates that the PSG houses have the highest indoor humidity level, the TES houses have medium indoor humidity and the APW houses have the lowest indoor humidity. Figure 10 also illustrates that the boxes do not overlap.
6. Conclusion
The PSG houses prove to have the highest indoor humidity due to their high airtightness, although they are detached. The TES houses turn out to have poor airtightness which leads to medium indoor humidity. The TES houses are terraced and merely have a ground floor which is a common form of low-rise high-density. The TES and APW houses are considered to be much better wind shielded than the PSG houses, which are free-standing in a lowland. The lowest absolute indoor humidity has been measured in the APW houses equipped with the mechanical ventilation system.

The distribution of the moisture excess in each housing project for each month under observation can be examined in the box plots and is caused by user behavior. In spite of this, the type of the house itself seems to have the highest influence.

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