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Analysis of indoor climate and occupants' behaviour in traditional Scottish dwellings

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Abstract

Due to the relevance of the internal boundary conditions and the lack of specific data for the Scottish context, an exploration of the internal environment of traditional dwellings is needed. In this study the indoor climate of 24 properties with different levels of insulation and air-tightness was analysed using a combination of quantitative and qualitative data. Temperature and relative humidity were recorded at 15 minutes intervals in two rooms per property. The analysis was complemented with semi-structured interviews with the occupants. Based on temperature and relative humidity, the moisture loads were calculated. Results in non-insulated properties showed indoor temperatures lower than the minimum level of thermal comfort, especially in winter, and high values of relative humidity during the warm season. The humidity levels in upgraded buildings are consistently lower despite the greater variability found in the internal temperatures.

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Keywords: indoor climate; dwellings; traditional buildings; hygrothermal loads; thermal comfort.

1. Introduction

Thermal improvement of traditional and historic buildings, representing around 20% of the total built stock in Scotland [1], is going to play a crucial role in the achievement of established carbon emission targets (80% reduction, respect 1990 levels, by 2050 [2]). However, the long term effect of insulation on the conservation of the solid masonry walls remains unclear. Additionally, there is some uncertainty regarding the rebound effect and the actual reduction of energy consumption. Previous research has shown significant variability in the hygrothermal

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conditions of the living spaces depending on the building age and the level of insulation [3]. The analysis of indoor climate is important both to define reasonable boundary conditions for the hygrothermal simulation of the envelope and to assess the thermal comfort of the occupants.

2. Methods

In this study the indoor climate of 24 traditionally constructed dwellings with different levels of insulation and air-tightness was analysed during 2014-2015 using quantitative and qualitative data. The sample was formed by buildings located in the North-East of Scotland with similar construction characteristics (solid masonry granite walls and pitched roofs covered with slates). Although most of the buildings had some energy related improvements (mainly the substitution of the original single glazed windows), the dwellings were at different levels of conservation; while some of the buildings had kept the original lath and plaster others were completely renovated internally. For analysis, buildings were categorised as "retrofitted" or "non-retrofitted" according exclusively to the insulation of the external wall. Two of the houses were monitored before and after the insulation and therefore were considered as different households, resulting in a total of 26 dwellings.

Temperature and relative humidity were monitored at 15 minutes intervals in two rooms per property (living room and bedroom) along with recordings of external conditions by a dedicated weather station. Air pressure tests were carried out in 9 of the dwellings to measure the permeability of the envelope and its effect on the internal climate. The analysis of the indoor environment was complemented with qualitative information obtained by means of semi-structured interviews with the occupants. The interviews were focused on users' perception of comfort and their energy related patterns. Information regarding the heating, ventilation and moisture production habits was collected in order to achieve a better understanding of the physical measurements.

For analysis, the data was sorted according to seasons. Winter season was analysed using the measurements from December to March, while the summer season only included the measurements from June to September. Based on the measurement of temperature and relative humidity, risk of mould growth and moisture loads were calculated. Using the air permeability values, daily moisture production rates were estimated.

Analysis of the internal temperature in the living spaces was done according to the standard EN 15251:2007 [4]. The design criteria proposed in this standard assumes 3 classes with different levels of predicted percentage of dissatisfied (PPD: <6%, <10%, <15%). Within these classes, the minimum operative temperatures for heating during the winter season (assuming 1 clo) are as follows: Class I, 21°C; Class II, 20°C; Class III, 18°C. Unlike internal temperature, relative humidity is not clearly defined in the standards. CR1752 [5] establishes generic criteria for human comfort and indoor air quality: "*normally few problems occur when the relative humidity is between 30 % and 70 %, assuming that no condensation takes place*". Using the same classes based on the PPD established for the operative temperature, EN 15251 proposes the following levels of humidity for buildings equipped with humidification (or dehumidification) systems: Class I, 30%-50%; Class II, 25%-60%; Class III, 20%-70%. Although the standard acknowledges that humidification or dehumidification is usually only needed in special buildings such as museums, health care facilities, etc. these categories have been used in this paper as they provide a useful framework to interpret the results.

3. Results

3.1. Internal temperature and relative humidity

Figure 1 shows the results of the internal temperature as a function of the external temperature for summer and winter. In summer the average internal temperature was 19.8°C for non-treated houses, with minimum and maximum values of 13°C and 28.6°C respectively, and 18.8 °C for retrofitted buildings (min=15.5°C; max=28.5°C) (Fig 1a). The internal temperature was strongly dependent on the external conditions, especially in non-retrofitted buildings. For external values under 15°C, retrofitted buildings fell below the lower threshold of Class III (18°C). Class I was only achieved by non-retrofitted buildings and only when the external temperature exceeded 17 °C. The results are homogeneously distributed between the percentiles 10 and 90. The lines are almost parallel and the difference between them is around 4 °C (Fig. 1a).

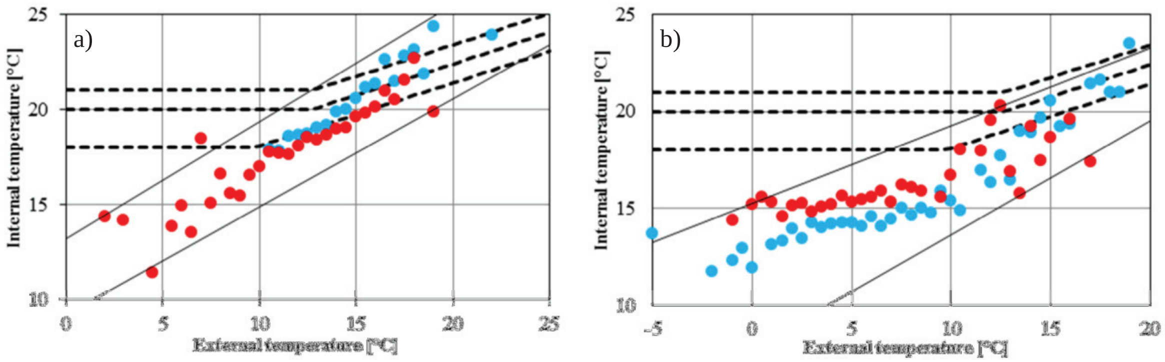

Fig. 1. Internal temperature as a function of the external temperature for (a) summer and (b) winter. Each dot represents the average hourly value of the room's temperature in dependence of the daily average external temperature. Blue dots represent non-retrofitted dwellings, whereas red dots summarise the results for the retrofitted buildings. Thin black lines represent percentiles 10 and 90 for the whole sample. The dashed lines represent the lower limits of the three classes proposed in the standard EN 15251:2007.

In winter the internal conditions changed and the temperature in non-retrofitted buildings was lower than in retrofitted buildings (Fig. 1b). The average temperature for non-insulated houses was 14.4°C (min =5.5°C; max=24.6°C) while in insulated dwellings it reached 15.4°C (min=3.5°C; max=28.5°C). Despite the higher temperature monitored in retrofitted buildings, both non-insulated and insulated dwellings were consistently colder than the lower limit of the least restrictive class (Class I, 18°C). The internal temperature increased by 2°C for an external variation of 10°C. Due to the low number of warm days in winter, not enough data was obtained to establish any clear relationship between internal and external conditions when the outdoor temperatures increased beyond 10°C. In figure 1b the difference between the percentiles 10 and 90 indicates greater variation within internal temperatures during the cold season, resulting in a wide range of internal temperatures.

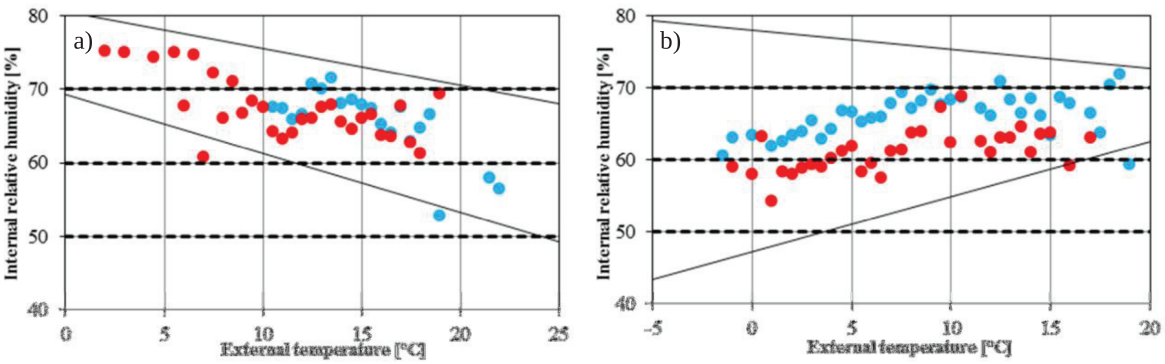

Fig. 2. Internal relative humidity as a function of the daily average external temperature for (a) summer and (b) winter. Blue dots represent averaged hourly values in non-retrofitted dwellings, whereas the red dots stand for the retrofitted buildings. Thin black lines represent percentiles 10 and 90 for the whole sample. The dashed lines represent the upper limits of the three classes proposed in the standard EN 15251:2007.

Figure 2a shows internal values for relative humidity in summer as a function of the external temperature. In summer the relationship on the external conditions was negative with lower relative humidity values at higher external temperature. The internal climate in summer was similar for both samples with average values of 68% (min=44%; max=90.6%) for non-insulated and 65.7% (min=42.8%; max=86.2%) for insulated houses. Compared to the standards [4,7], those results correspond to Class III or a high occupancy/moisture load scenario. The relative humidity dependence on the external temperature during the cold season (figure 2b), although not very strong, was positive. This relationship with the exterior became almost negligible for external temperatures beyond 10 °C.

Internal relative humidity fell within Class III most of the time except for retrofitted buildings at outdoor temperatures below 5°C when it went down to Class II (fig. 2b). Average internal humidity was 65.8% (min=31.3%; max= 89.7%) for non-retrofitted buildings and 59.6% (min=26.4%; max=90.0%) for insulated buildings. As observed for the internal temperature, the dispersion of internal relative humidity was greater in winter than in summer. The difference between percentiles 10 and 90 in summer (fig. 2a) oscillated between 10% (for external temperatures of 0°C) to 15 % (at 20°C). In winter (fig. 2b) this difference increased significantly as the external temperature went down (over 30% for external temperatures around 0 °C).

3.2. Mould growth risk

In this paper, the model developed by Hukka and Viitanen [8] for the prediction of mould growth risk on wooden materials was used to assess the internal climate. The curve resulting from the application of the model indicates the critical levels of relative humidity (Fig 3a). Internal conditions in the dwellings were favourable for the initiation of mould growth in 6.8% of the monitored time. As for the effect of the insulation, non-retrofitted buildings were at risk 8.0% of the time while retrofitted dwellings were over the threshold only 4.1% of the time. Regarding the seasonal effect, results for summer and winter were similar (4.4% and 4.9% respectively) whereas during the intermediate months (April, May, October and November) the time at risk rose up to 11.2%. The frequency distribution plotted in figure 3b shows that the time at risk of mould growth for non-retrofitted buildings was similar in living rooms and bedrooms. In retrofitted buildings this risk was mainly present in living rooms. The distribution also shows that the majority of the events when the conditions were favourable for the initiation of mould growth were recorded when the external daily average temperature was between 9 and 14°C.

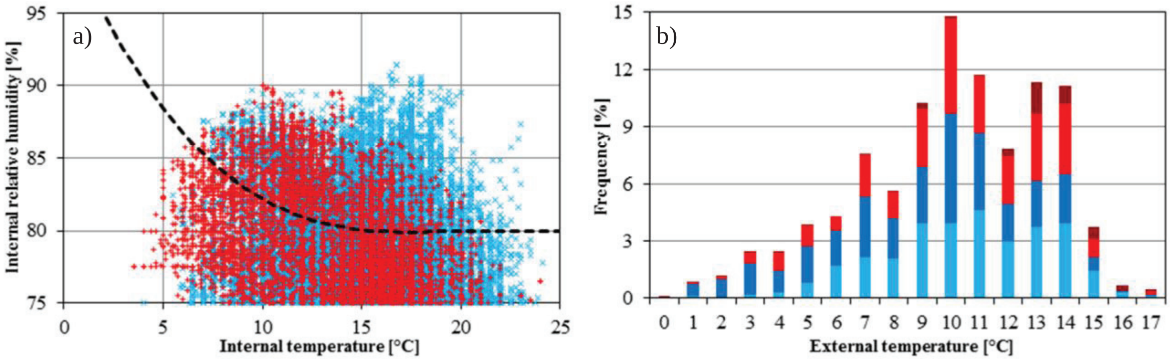

Fig. 3. (a) Internal RH as a function of internal temperature; (b) frequency distribution of the time (in percentage) when RH >RH_{crit} as a function of the daily average external temperature. In both charts blue stands for non-retrofitted buildings and red for retrofitted. In chart (a) the dashed line represents the threshold for mould growth according to Hukka and Viitanen. In the second plot (b), light colours represent the living rooms while the darker colours stand for the bedrooms.

3.3. Moisture excess

The moisture load or moisture excess (difference between indoor and outdoor water vapour concentration) for each room was calculated based on the records of temperature and relative humidity. Average of daily mean values plotted in figure 4a show a moisture load of less than 4 g/m^3 at an external temperature of 0°C. This value corresponds to the humidity class 2 (dwellings with normal occupancy and ventilation) of the standard EN 13788:2012. The higher 10% critical level [6] was calculated for each of the independent samples (insulated and non-insulated). The moisture load is consistently higher in non-retrofitted buildings. The difference became even more evident for external temperatures over 10°C, as the dependence on the external temperature was much higher in the retrofitted buildings than in those non-insulated. The relationship between moisture load and external temperature allowed for a linear regression to be used to define new design curves (figures 4b and 4c).

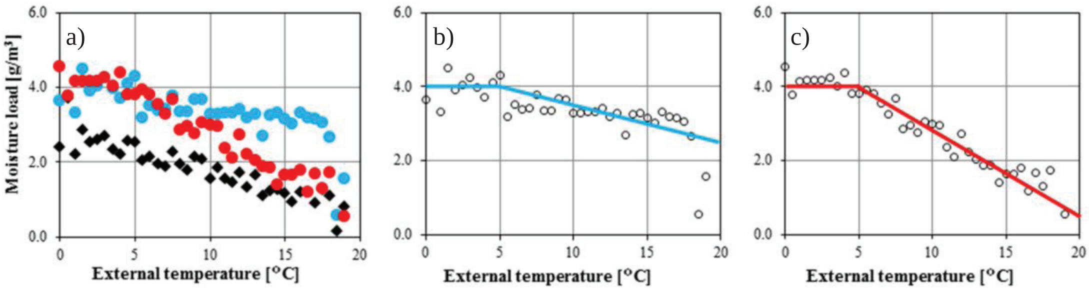

Fig. 4. (a) Daily mean value of measured moisture load in dependence of external temperature. Black squares represent average values while dots show the percentile 90 for non-retrofitted (blue) and retrofitted (red) buildings. Design curves are calculated for (b) non-retrofitted and (c) retrofitted using a linear regression of the results.

The average values of internal temperature for the whole year (figure 5a) were directly related to external temperatures. This dependence on the external weather was stronger for non-insulated properties. The positive linear relationship had a turning point for both non-retrofitted and retrofitted buildings at 10 °C, when the internal temperatures were similar. When plotting the same graph (figure 5b) for the internal relative humidity, another turning point could be seen at the same temperature. In this case, the relationship after the turning point becomes negligible, or slightly negative, for both types of buildings. The moisture load curves (fig. 5c) are in consonance with EN 13788:2012 [9]. The results fall slightly above the humidity class 2 (dwellings with normal occupancy and ventilation), although there are some discrepancies when comparing the results with the standard. The turning point is at 5 °C instead of 0 °C and the humidity load at 20 °C for non-retrofitted buildings would be around 2.5 g/m^3.

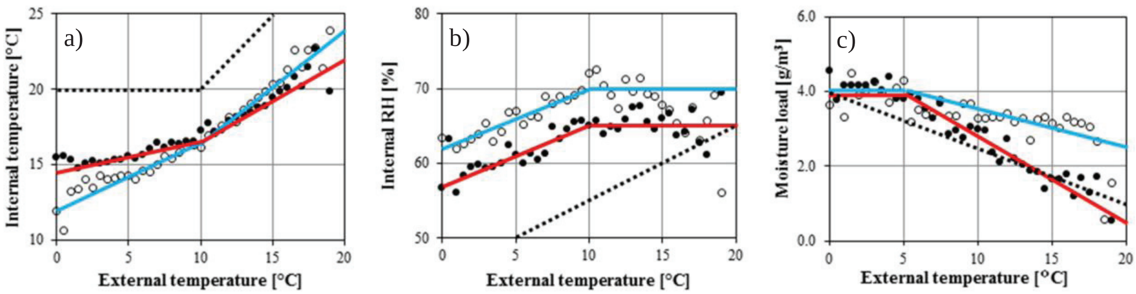

Fig. 5. Regression lines of (a) temperature, (b) relative humidity and (c) moisture load as a function of the external temperature. Non-retrofitted buildings are represented by white dots and blue lines and retrofitted buildings are rendered as black dots and red lines. Dash lines represent the boundary conditions proposed in the Annex A of EN 13788:2012.

3.4. Moisture production

An estimation of the moisture production (Table 1) was made considering the values for air leakage obtained with the air pressure tests as the only source of air renovation. Bearing in mind that the calculations do not consider the air renovation due to ventilation, it can be observed that moisture production in some of the untreated households (dwellings 3, 7 and 9) was relatively high for single occupancy flats [6]. The air pressure tests carried out in 9 of the properties revealed a great difference between retrofitted and non-retrofitted dwellings. The average n_{50} values were 22.1 ach for non-treated buildings and 13.0 ach for insulated buildings. The difference could be even greater if considering that all the non-retrofitted buildings analysed were tenements with less envelope area than the insulated houses in the sample. Interestingly, results obtained in dwelling 5 (n_{50} = 2.1 ach) differ greatly from the rest. The tenant of this rented property undertook a full draught proofing of the dwelling by sealing all the gaps between floor boards, around window and door frames and behind kitchen cabinets and bathroom units.

Table 1. Air permeability and moisture production.

#	House Type	Insulation	Occupants	Volume [m3]	Air leakage [ach]	Moisture load (g/m^3)	Production (kg/day)	
							Summer	Winter
3	Flat	No	1	111	1.57	1.9	6.4	10.8
5	Flat	No	1	180	0.1	2.4	1.2	1.5
6	Flat	No	1	102	0.95	1.2	2.4	7.4
7	Flat	No	1	111	1.25	2.4	8.9	9.6
9	Flat	No	1	111	1.65	1.8	7.9	10.7
19	Semi-det	Yes	2	212	0.62	0.3	0.5	4.7
20	Detached	Yes	2	199	0.71	1.0	3.3	6.4
21	Detached	Yes	4	240	0.43	2.2	3.5	10.1
22	Detached	Yes	3	329	0.45	0.9	2.8	7.3

4. Discussion

The use of qualitative information gathered during the interviews can help to explain the results obtained in this study. Despite the fact that most of the rooms fell below the minimum level proposed in the standard, the level of thermal comfort reported by the occupants was reasonable high. Just 3 households were using the heating over the summer and most of the occupants reported to not have any difficulty to achieve adequate levels of thermal comfort during the warmer months. Even in winter, when the internal temperature was between 2.6 and 3.6 °C lower than the least restrictive threshold, most of the occupants described the temperature as comfortable. Therefore it is clear that there is an important discrepancy between the recommended internal temperature in the standards and the actual thermal preferences of the occupants. Effects of seasonality on the ventilation and moisture production patterns were fairly limited. Interviews have shown that the daily habits for airing rooms, cooking or laundry drying are linked to the personal preferences and do not change over the year. This is especially true in the buildings that have not been upgraded. As a result, the moisture load in those buildings in summer is higher than the forecasted in the standard.

An important finding of this study is the disagreement between the standard boundary conditions [9] and the design curves resulting from the measurements (Fig. 5). Besides the differences in the internal temperature, internal relative humidity obtained higher values and a turning point at 10°C, instead of 20°C. Moreover, while the moisture load in the insulated properties decreased towards 0 g/m^3 when approaching an external temperature of 20°C (similarly to [6]), the non-insulated sample remained above 2 g/m^3 independent of the external conditions.

5. Conclusions

The boundary conditions proposed in EN 13788:2012 for hygrothermal calculations are not representative of the internal climate in Scottish traditional buildings. Indoor environment in retrofitted buildings, that are supposed to perform in the manner of modern construction, is more similar to the boundary conditions but there are still some important disagreements in the internal temperature and relative humidity of these buildings that need to be further investigated. Understanding the role of users' behaviour and their comfort perception is necessary for an accurate description of this particular type of construction.

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