Mostly dry: current ventilation practice efficiently limits moisture excess in mechanically ventilated apartments

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Abstract. The current Norwegian building code (TEK 17) requires the new residential buildings to have balanced ventilation with heat recovery, in addition to the strict regulations regarding thermal performance and airtightness of the fabric. During the cold winters in the South-East part of the country, the moisture content in the air outdoors is very low and results in a dry climate indoors as well. This study investigates in-situ the moisture excess indoors (Δv) in a series of urban residential apartments that have been built according to TEK 17. In particular, air temperature and relative humidity have been measured in six locations/rooms in each of the monitored apartments. Variations in moisture production as well as in ventilation rates have resulted in different moisture excess levels. The findings reveal that the current practice limits moisture excess and have led to an overall reduction of Δv compared to results found in similar studies performed two decades ago. 90th percentiles of Δv have been calculated as below 2 g/m^3 in all types of rooms, while in bathrooms it has been 2.6 g/m^3. The relative humidity (RH) has been respectively below 30%, with bathrooms being the only exception with RH just over this level. The results from a survey among the occupants showed that most of them complain about fatigue, difficulty in concentrating and a head that feels heavy. In addition, dust and too high air temperature have been identified as the main problems of the indoor environment.

Keywords. indoor moisture excess, relative humidity, residential buildings, mechanical ventilation, Nordic climate.
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1. Introduction

The low or high humidity indoors is closely related to many health problems and it is also linked to energy consumption and durability of construction. Therefore, it is essential to control the relative humidity in order to achieve a healthy and comfortable indoor environment [1]. During the cold and dry winter periods in Nordic climates, the relative humidity can drop down to 10% [2]. The studies revealed correlations between low humidity and health problems such as discomfort in the skin, eye and nose [3]. Besides, the Norwegian Institute of Public Health recommends relative humidity to be over 20% due to the fact that low humidity has an effect on respiratory health [4]. Moreover, in the Norwegian standards, the lower limit of relative humidity in residential apartments was recommended to be at 25% and the upper limit at 60% when humidification and dehumidification systems are installed [5].

With the recent Norwegian building code (TEK 17), residential buildings started to contain balanced ventilation with heat recovery, in addition to the strict regulations regarding airtightness and thermal performance. Despite the very positive results from the energy efficiency point of view, this might cause problems in the indoor environment in Nordic countries, e.g., too low relative humidity. Since the new regulations applied, there are limited studies that have researched the humidity levels in residential buildings. The objective of this study was to determine the indoor environment of modern Norwegian residential buildings in relation to moisture-related parameters.

2. Methods

2.1 Experimental site

The field measurements were conducted in 10 modern dwellings in Oslo, Norway where the large majority of the apartments were located in the project building in the city district Bjerke. In order to utilize the climatic data near the tested apartments, the weather station at Blindern in Oslo was selected as a resource for outdoor climate data such as temperature, RH and pressure.

As this study has a focus on modern Norwegian urban homes, the selection of apartments was done according to the following criteria: the buildings were built/renovated after 2012 and apartments have BRA ≤ 115 m². Summary of building characteristics shown in Tab. 1.

During the field experiments, measurement and monitoring of the time-varying relative humidity (RH), air temperature (T), pressure values and CO_2 levels indoors were monitored and measured utilizing two different sensor types, i.e., Airthings wave mini and Airthings wave plus at 5 minutes interval over a period of 7 days. In order to conduct measurements of each apartment, one set of Airthings sensors, which contains 4 pcs of Wave Mini, 2 pcs of Wave Plus and one Airthings Hub (for the wireless transfer of data) were used. In each testing apartment, placement of the sensors was following; wave plus sensors to the living room and master bedroom, wave mini sensors to bathroom, kitchen, secondary bedroom and entrance.

Tab. 1 - Summary of building characteristics of the 11 apartments included in the research

Apartment	#1	#2A	#2B	#3	#5	#7	#8	#10	#11	#12	#20
Area (m²)	30	60		N/A	45	60	87	90	85	115	67
Number of Occupants	2	3		1	1	1	1	2	4	4	3

Each device was wall-mounted 150-170 cm above the floor level and as a minimum 1 meter / 3 feet away from air supply/exhaust, exterior walls, windows, doors, mechanical fans, heaters or any other noteworthy source of heat gain or loss [7].

Moreover, measurement of the air flow supply rates and mechanical exhaust ventilation air flows were conducted by utilizing two different equipment sets where first set was consisted of Kimo K35 measuring funnel and Velocicalc® Air Velocity Meter 9545 anemometer with hot wire and the second one was consisted of Swemaflow 125 air flow hood. For the measurements of the ventilation airflow rates, one sample apartment from each project area was selected and the measured values were used as a reference for all tested apartments in the same project areas. Apart from Apartment #1, all other tested apartments were located in the same project area which includes 4 buildings with similar characteristics. Thus, Apartment #1 and Apartment #2 were selected as sample apartments for the ventilation airflow rates measurements.

Furthermore, the calibration processes of the devices called Airthings Wave Plus and Wave Mini were performed in SINTEF Community laboratory by utilizing a climate chamber called Termarks KB 8400 F/L.

2.3 From experiment to data

The hourly averaged absolute humidity levels were calculated from logged data of indoor temperature, relative humidity and pressure along with the outdoor temperature, relative humidity and pressure data collected from the nearest meteorological station. The indoor moisture excess levels were calculated using the equation (2).

$$\Delta v = v_i - v_e \; [g/m^3] \tag{2}$$

2.4 Questionnaire

The online questionnaire consists of 26 questions related to occupancy level, moisture sources, characteristics of the apartment, occupant behaviours and health symptoms related to indoor environment. A multiple-choice, yes-no and scaled choices as “Never, Sometimes and Often” were used to record the responses to the questions. All responses to the questionnaires were stored anonymously. Moreover, a permission from Norwegian centre for research data [8] were granted to perform the surveys.

3. Results

3.1 Measurement period and overall climate

The defined experiment period for this study was February 14, 2021 – April 22, 2021. During the experiment period, the average outdoor temperature was 1.87 °C; this was 0.08°C cooler than the 30-year average of 1.95°C recorded at the Oslo Blindern weather station for the period of February to April 1990-2021.

3.2 Participating households

In this study a total number of 10 households was participated. The detailed characteristics of participating households are shown in Table 2 [6]. It must be noted that Apartment #2 was tested two times in different time periods and presented as Apartment #2A and #2B, where A stands for the period of the measurements without a humidifier, B stands for the period of the measurements with a humidifier. Since, it was the same households, to avoid confusion the details of the Apartment #2B was not counted in the mean value calculations except for the row showing the owning humidifier(s).

Tab. 2 - The characteristics of participating households

	Mean values (Range)
Total household members	2.4 (1-4)
Age of household members	41.73 (26-60)
Rooms in home	3.2 (2-5)
Floors in building	6.5 (6-7)
BRA (m²)	72.6364 (30-115)
Can turn heat on and off	
Yes	10 (%100)
No	0 (%0)
Own humidifier(s)	
Yes	2 (%18.2)
No	9 (%81.8)

Note. Adapted from [6]

3.3 Ventilation air flow rates

The measured air supply and air extraction rates in aforementioned apartments and a comparison with the design values recommended in TEK 17 [9] are shown in Tab. 3 [6]. It is obvious that the obtained values differ from the recommended values.

3.4 Relative humidity, temperature and indoor moisture excess

The air temperature and relative humidity values in the bathroom, kitchen, master bedroom, living room and secondary bedroom of each apartment which were measured over a period of 5-13 days are presented as boxplot graphs according to room types, respectively, in Fig. 4, Fig. 5, Fig. 6, Fig. 7. In boxplot graphs, the top of the box (upper quartile) represents 90th percentile while the bottom (lower quartile) stands for 10th percentile.

Relative humidity

For each type of apartments without a humidifier, 90% of the measured values of RH levels indoors were below 32% while the mean values were lower than 23% (25% is the lowest limit for “Category II” according to the NS-EN 16798-1:2019 [5]). While, 10% of the RH levels indoors measurement results were even lower than 15%. Although, the mean values of the RH indoors for the apartments with humidifier was between 32-43%. Additionally, RH peaks were lower in Apartment #10 and #12 compared to other apartments. The highest measured RH indoors was observed in Apartment #11, nevertheless some attention-grabbing high values were also observed in Apartments #1, #2B and #7. Moreover, the measured highest RH levels were observed in bathrooms and bedrooms of the apartments regardless of owning humidifier(s). Besides, the RH levels in the bathrooms of Apartments #1, #2B, and #11 display larger interquartile ranges which comprise higher RH values than the others. However, the median RH value in the bathroom of Apartment #11 was still between 15-25%, likewise all apartments excluding Apartments #1 and #2B.

Tab. 3 – The ventilation rates measured in Apartments #1 and #2 and design targets from TEK 17 [9]

Room Type	Apartment #1		Apart-ment #2		Design Targets	
	S* [m³/h]	Ext* [m³/h]	S* [m³/h]	Ext* [m³/h]	S* [m³/h]	Ext* [m³/h]
Bathroom	-	25		100	-	54
Master Bedroom	37	-	18	-	26	-
Living room Kitchen	37	-	25	21	-	36
Small Bedroom	-	-	11.5	-	26	
Total (Apartment #1)	**74**	**25**			**36**	**54**
Total (Apartment #2)			**54.5**	**121**	**72**	**90**

Abbreviations: S*, Supply; Ext*, Extract.
Note. Adapted from [6]

The maximum measured RH levels in master bedrooms were observed in Apartment #1 and followed by Apartment #2. However, this only observed for one time roughly 20 minutes about 15:20 during one monitoring day, correspondingly an increase was observed in RH levels every day roughly around 15:20. Moreover, some findings were also observed in Apartment #11, even though the median RH value of Apartment #11’ master bedroom was observed as 21.49%, it was exposed to higher levels of RH as far as 38% and after some days of the measurement period, it was reduced till 15% levels while at the same time there was a decrease observed in its CO_2 levels.

The minimum mean RH value was monitored in living rooms. Except for Apartment #2, the median RH values were observed as below 25% in all other apartments’ living rooms.

The maximum RH level measured in kitchens was observed as 43.53%, however 90% of the monitored RH levels were down below 29.66%. Moreover, comparing to the others, the highest number of weekly cooking events were observed in apartments

#2 and #11, according to the survey data.

Temperature

The mean indoor temperature values of the monitored apartments were observed as between 21-27 °C. It was found that 10% of the monitored indoor temperature values were above 23 °C, which considered as higher than the recommended value in TEK 17 and required value in NS-EN 16798-1:2019 [5,9].

The lowest mean temperature value was observed in master bedrooms. While the mean temperature in the bedrooms of most of the monitored apartments was between 20-23 °C except for three apartments (#8, #10 and #12) where higher values were observed.

The maximum mean temperature value was observed in bathrooms as 38.99 °C in Apartment #20. Moreover, when compared to others, significantly lower temperatures were observed in Apartment #3 and #12' bathrooms.

Although the maximum reached temperature in kitchens was 29.01 °C, 90% of the measurement results were below 25.9 °C. In addition, the findings show that the temperatures measured from the kitchens were considerably higher ($p < 0.05$) compared to the monitored living rooms and bedrooms, without making discrimination of with or without humidifier(s) [6].

Furthermore, considering the effect of outdoor temperature on indoor temperature, as shown in Fig. 1, the correlations were only observed in Apartment #1 and #10 which shows an increase in indoor temperature together with the outdoor temperature.

Absolute Humidity

The hourly average absolute humidity values from kitchen and living rooms were at their maximum in the evenings (approximately 3 pm – 10 pm) when the majority of the people from Norway are generally at home. Also, 80% of the hourly average absolute humidity values from bedrooms were at their maximum between evening and night hours (approximately 6 pm – 3 am). Moreover, as shown in Fig. 2, outdoor absolute humidity levels were generally low during the whole experiment period with an exception for Apartment #1 and #2A' period of measurement.

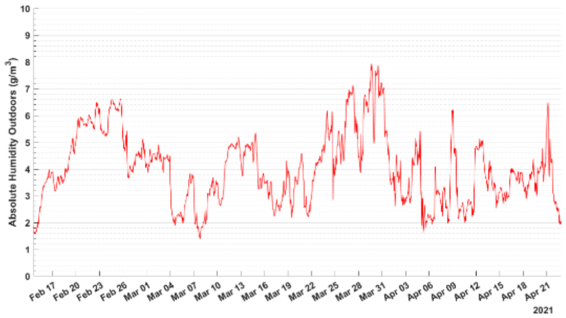

Fig. 2 - Absolute humidity outdoors expressed in g/m3, during the experiment period [6].

Moisture Excess

The maximum mean internal moisture excess value was observed as 1.3565 g/m^3 in bathrooms of the apartments without humidifiers. And this was followed by kitchens as 0.896 g/m^3. As for the apartments with humidifier(s), the maximum mean internal moisture excess value was observed in the secondary bedroom as 5.44 g/m^3 and it was followed by bathroom as 4.77 g/m^3.

For the apartments without humidifier(s), the minimum mean Δv has been calculated as 0.59 g/m^3 in bedrooms and followed by living rooms as 0.69 g/m^3. Besides, 90th percentiles of Δv have been calculated as below 2 g/m^3 for all types of rooms of the apartments without humidifier(s) except for bathrooms which were calculated as 2.6 g/m^3.

As concerns the highest hourly average values in bedrooms, 50% of them were observed through the night-time whereas the rest were observed afternoon and evenings (around 12 pm – 7 pm).

Regarding kitchens, 90% of the estimated Δv values were below 1.862 g/m^3 and the highest estimated Δv was 4.33 g/m^3. While the mean estimated Δv from kitchens of the apartments which did not own humidifier(s) was 0.896 g/m^3. Furthermore, the

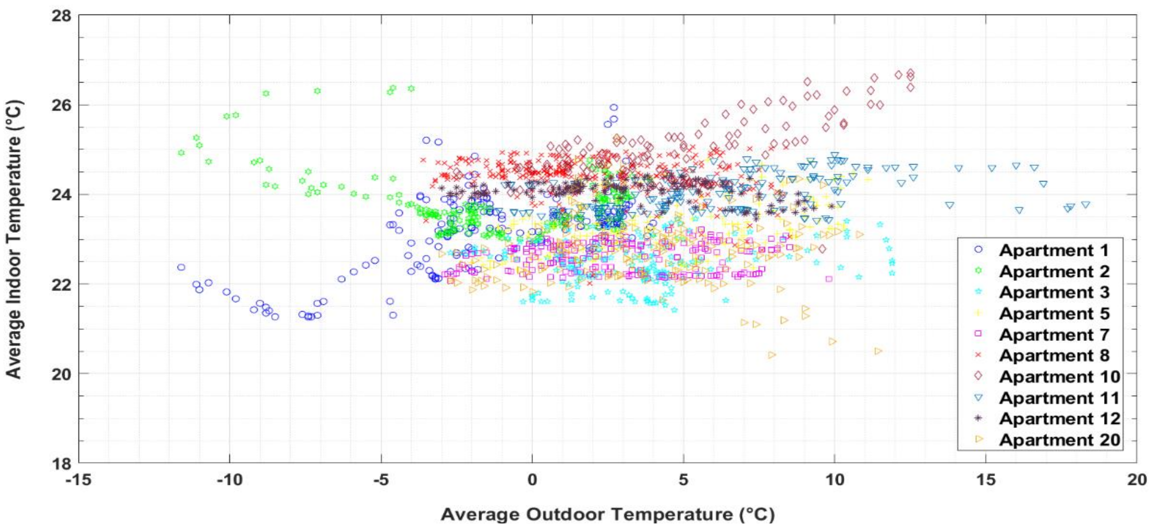

Fig. 1 - The correlation between indoor and outdoor temperatures, average values per house [6].

apartments (2,7,10,11,12 and 20) with more occupancy levels and claimed to have more dinner activities compared to others, had generally higher internal moisture excess from their kitchen.

As to bathrooms, the minimum mean moisture excess in bathrooms was observed as 0.36 g/m^3 in Apartment #3. However, the median Δv values for seven of eleven measurements (Aparments 5,7,8,10,11,12 and 20) were between 0.8 – 2 g/m^3. Furthermore, the maximum Δv have been calculated as 9.13 g/m^3 was from bathrooms of the apartmens without humidifier(s).

3.4 Survey results

The survey responses to some health problems were shown in Tab. 4. The occupants have reported little but some issues with health problems for instance headache, fatigue, difficulty in concentrating and dizziness. As shown in Table 4, "often" was used only once as a response to a dizziness by Apartment #7. Besides, majority of the occupants responded as "sometimes" to difficulty in concentrating, fatigue and heavy in the head.

Tab. 4 – The survey responses to some health problems

Apart-ment	1	2 A	2 B	5	7	8	10	11	12	20
Dizzi-ness	N	S	S	N	O	N	N	N	N	S
Head-ache	S	S	S	N	N	N	N	N	S	S
Fatigue	S	S	S	S	N	N	N	S	S	N
Diffi-culty in concen-trating	S	S	S	S	S	N	N	S	S	N
Heavy in the head	S	S	S	S	S	N	S	N	S	N

Note. Adapted from [6].

Further, Fig. 3 shows the survey responses related to the thermal environment. As shown in Figure 3, 90% of the households responded that they never felt too low room temperature, while only 10% responded that they felt sometimes too low room temperature which was in phase with the field measurement results that showed indoor temperatures being often high and rarely being too low. However, 30% of the participants reported often too high room temperatures and 40% reported sometimes too high room temperatures. As to varying room temperature, 30% of the participants responded as "sometimes" and 70% of the participants never felt any varying room temperature.

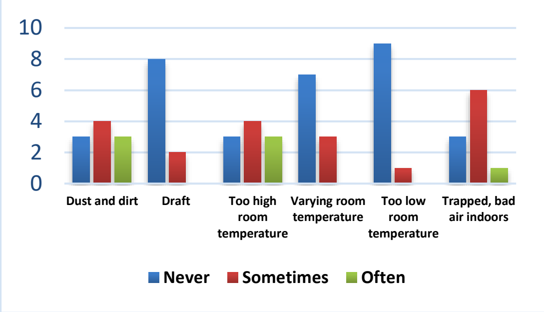

Fig. 3 - Survey responses correlated with the thermal environment [6].

As concerns humidity related problems, except for the occupants of the apartments with humidifier(s), all other participants responded that the perceived indoor air was dry. The majority of the participants were responded as "often" to questions about an irritated, stuffy or runny nose. As to hoarseness / dry throat, 60% of the participants responded as "Sometimes" and 20% as "Often" and the rest as "Never". While each participant reported at least one humidity related problem, the participant from Apartment #8 responded as "Never" to all questions even though he/she expressed the perceived air as dry.

4. Discussion

4.1 Ventilation airflow rates

The air supply and extraction rates monitored in apartments were far away from the recommended values of TEK 17 [9]. The measured air supply rate in Apartment #1 was higher than its extraction rate resulting in under pressurisation, while the exact opposite situation was occurred in Apartment #2 resulting in over pressurisation. It must be noted that the aforementioned rates were only measured once for a small period of the measurement periods in each mentioned apartment, therefore, no certainty can be provided that the data obtained during the small period of the measurement remains unvaried throughout the entire measurement.

4.1 Relative humidity, temperature, and indoor moisture excess

The low RH levels might occur mostly during winter period, due to various factors such as high indoors temperatures, excess air conditioning, high ventilation exhaust air rates, and so on. The low levels of RH peaks in the Apartments #10 and #12 were presumed to be due to higher ventilation rates, since these two apartments had the largest BRAs. The high monitored levels of RH in Apartment #1' bathroom, is assumed to be because of under ventilation.

In the majority group of bedrooms, the RH levels were usually lower through the period between morning and evening-time while these periods also low CO_2 levels (approx. 400 ppm) were observed. However, higher levels of RH were observed in the

Tab. 5 – The survey responses to humidity related problems.

Apartment	Is the indoor air perceived as dry, humid?	Itchy burning/ irritation in the eyes	Irritated, stuffy, or runny nose	Hoarse-ness / dry throat	Dry or red skin on the face	Cough	Dandruff/ itching of the scalp/ears	Dry, irritated/ red skin on the hands
1	Dry	Sometimes	Often	Sometimes	Often	Never	Never	Often
2A	Dry	Sometimes	Often	Often	Never	Sometimes	Never	Never
2B	Humid	Never	Sometimes	Sometimes	Never	Never	Never	Never
5	Dry	Sometimes	Never	Never	Never	Never	Sometimes	Sometimes
7	Humid	Often	Often	Often	Often	Often	Often	Never
8	Dry	Never	Never	Never	Never	Never	Never	Never
10	Dry	Never	Often	Sometimes	Never	Sometimes	Never	Sometimes
11	Dry	Never	Often	Sometimes	Sometimes	Never	Never	Sometimes
12	Dry	Never	Never	Sometimes	Sometimes	Sometimes	Never	Sometimes
20	Dry	Sometimes	Often	Sometimes	Never	Sometimes	Sometimes	Often

Note. Adapted from [6].

night-times, meanwhile high levels of CO_2 (above 700 ppm) have occurred. Based on these observations, it was concluded that the occupancy rate and/or window opening and closing activities in the bedrooms from morning to evening caused low relative humidity rates. It has also been hypothesized that the peaks of RH levels and indoor moisture excess in bedrooms during the daytime were due to short-term use of bedrooms, i.e., children's nap time and/or usage of the bedroom as a home office.

Furthermore, it was assumed that the higher RH levels and temperatures observations from the living rooms and kitchens were due to higher occupancy rate leading more cooking events and/or less window opening activities, taking into consideration that all monitored apartments had an open kitchen design. Besides, the observed low air temperatures in the kitchens and/or living rooms were assumed as due to small BRA of the apartments, low occupancy rates leading to low numbers of cooking activities. The low air temperature in bedrooms were assumed due to window opening activities and/or low occupancy rates through the day time.

In addition, it was presumed that the higher peak temperature values in bathrooms (apartments #1, #2 and #5) have occurred due to hot and long showering events while, as to apartment #20, it was assumed to be high-temperature settings of floor heating in-line with the dryer usage whereas low levels of RH were observed meanwhile air temperatures were in their peaks. Also, the small interquartile ranges indicate the occurrence of stable temperature values in the bathrooms. And it was assumed that the stable temperatures were due to the normal showering temperatures and keeping the bathroom door closed.

As concerns correlations between indoor and outdoor temperatures, as shown in Fig. 1, it gave the impression that changes in indoor temperature were not a result of outdoor temperature.

The outdoor absolute humidity's effect on indoor moisture loads were noteworthy. The low absolute humidity outdoors together with high temperatures indoors were assumed to be a cause of the dry indoor environment. However, as for indoor moisture excess, many factors play a role, such as occupancy rates, dinner activities, occupant behaviours, BRA, ventilation rates and so forth. The higher ventilation rates compared to total supply rates, low RH levels, overheating and large BRA, which minimise the effect of moisture-generating activities in the environment, was assumed to be a reason for the low median moisture excess values as well as negative moisture loads. Moreover, without making discrimination of with or without humidifier(s), it was assumed that the cause of the observed peak Δv values in bathrooms were due to warmer temperatures together with high RH levels which resulted by showering events. However, the minimum Δv values observed in Apartment #3' bathroom were result of low temperature and RH levels which might be caused by several factors such as short-cold showering, keeping the door open most of the time, which were supported by the logged data showing an air exchange between bathroom and corridor after showers.

The ventilation exhaust air rate was probably effective in drawing polluted air such as CO_2 and humid air out of the apartments. The higher CO_2 concentrations in bedrooms compared to kitchen/livingroom and bathrooms were assumed to caused due to bedrooms not having an outlet. While, not enough fresh air inlet might be a cause for some of the health related problems which participants claimed to have. Moreover, gradually varying temperatures could explain why the participants were not feeling varying temperatures but rather high temperatures.

5. Conclusion

The indoor climate conditions in 10 selected apartments from modern Norwegian residential buildings were assessed considering the following parameters; temperature, RH, outdoor air supply/extract, CO_2 concentration, indoor moisture excess. The research indicated that monitored ventilation rates deviated from the required values in Norwegian building regulations (TEK 17) [9].

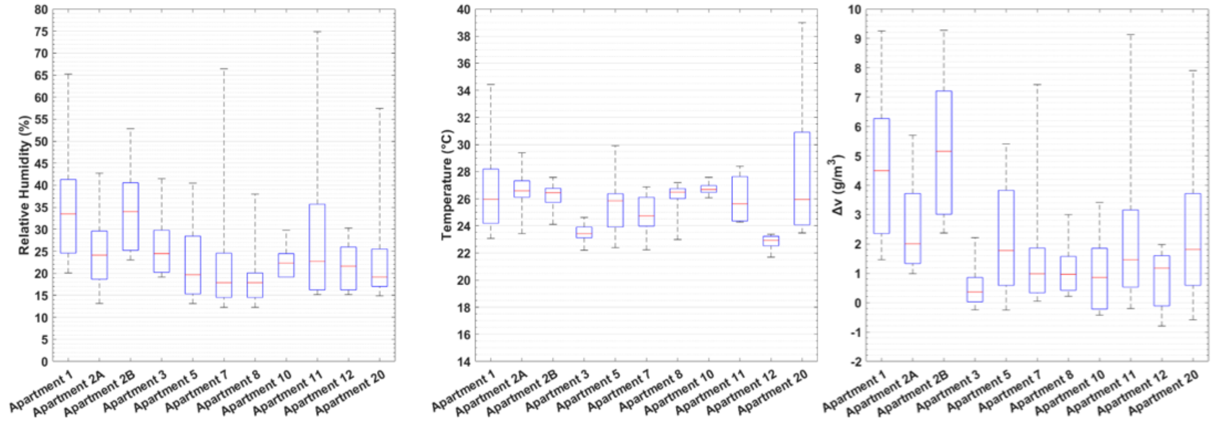

Fig. 4 - Measurements of RH, air temperature and Δv values from the bathroom of each tested apartment.

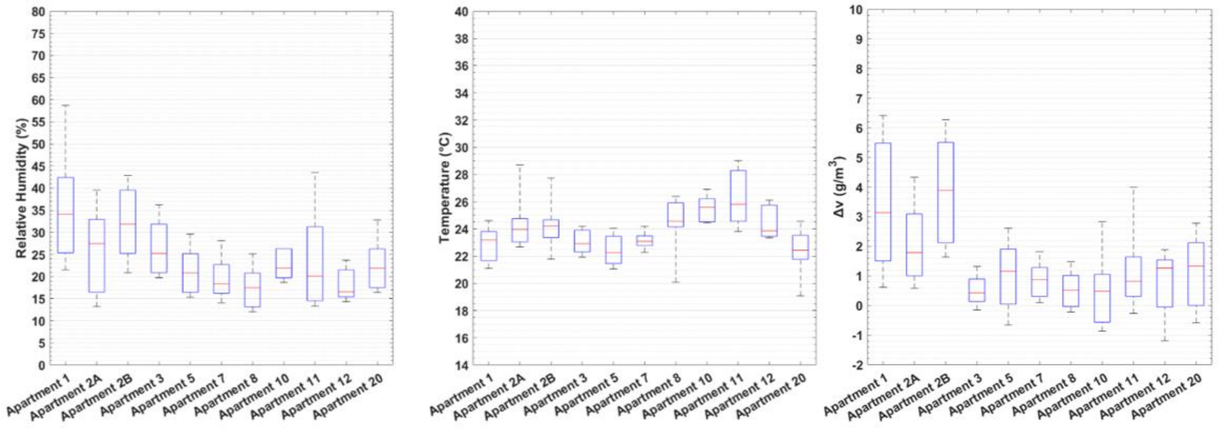

Fig. 5 - Measurements of RH, air temperature and Δv values from the kitchen of each tested apartment.

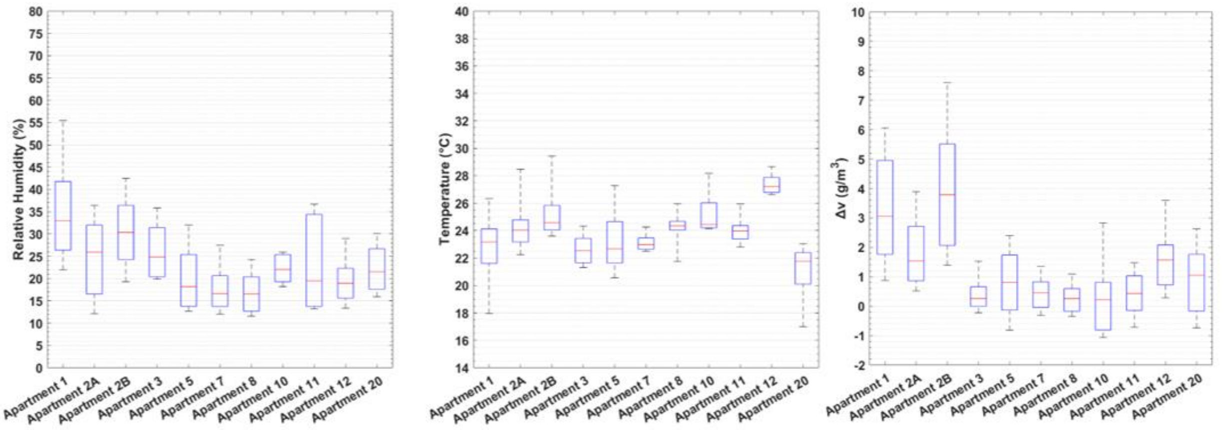

Fig. 6 - Measurements of RH, air temperature and Δv values from the living room of each tested apartment.

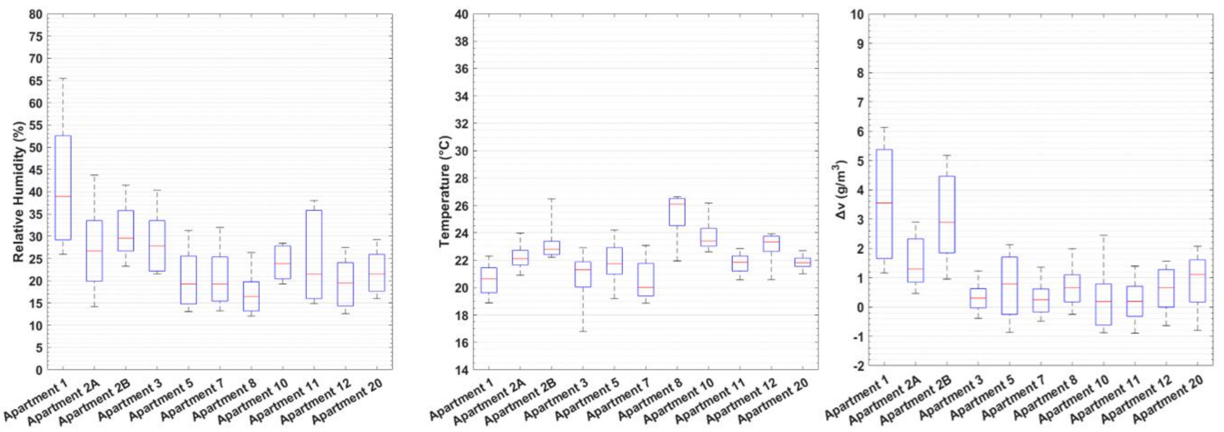

Fig. 7 – Measurements of RH, air temperature and Δv values from the master bedroom of each tested apartment.

Generally, the causes of low moisture excess were presumed to be high ventilation rates, low absolute humidity and low internal moisture supply. Also, the findings reveal that there is an overall reduction of Δv compared to the results found in similar studies [10–14].

The monitoring period is also noteworthy for assessing moisture conditions indoors. The study showed that the low outdoor absolute humidity during the monitoring of the majority group of apartments caused low moisture levels indoors when combined with high indoor temperatures. Moreover, the findings revealed that indoor temperatures were very often exceed 20 °C which is the temperature value assumed for simulating moisture conditions.

Furthermore, the survey findings indicated that majority of the participants perceived air as dry. Substantial number of participants complain about fatigue, difficulty in concentrating and a head that feels heavy. Besides, 70% of the participants claimed to expose to high indoor temperatures and 60% of the participants reported feeling of bad, trapped air indoors.

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