Microclimate in Bathrooms of Multi-Family Buildings

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Abstract. A large number of single-family and multi-family buildings, managed accommodation facilities and institutional buildings both in Poland and throughout Europe are equipped with a natural ventilation system. The operation of this system depends, among other things, on weather conditions, and the system itself is prone to design and operational errors. The analyses of the functional programme of typical flats in multi-family residential buildings as well as of single-family houses indicate that in certain rooms, such as kitchens and bathrooms, the values of the basic microclimate parameters can differ significantly from the parameters’ values of the remaining parts of the flat or building. Kitchens and bathrooms particularly require appropriate ventilation. In their day-to-day operation, these rooms are exposed to a more elevated level of relative humidity than other rooms in the flat or building.

The paper presents the results of the study conducted in autumn and winter in five flats located on different floors in three multi-family buildings in Poland. All the flats under study were fitted with a natural ventilation system with exhaust ducts in their kitchens and bathrooms. The outdoor air was supplied through window vents installed in the window frames in the selected rooms. Special attention was given to the variability in the levels of relative humidity in these rooms. However, the variability in the indoor air temperature as well as the concentration of carbon dioxide were also considered in the analysis. Only buildings with a natural ventilation system and windowless bathrooms were selected for the study. The results of the analysis showed an elevated level of relative humidity persisting in the rooms in focus throughout the entire period of the study. This salient fact should be noted, since the elevated relative humidity levels combined with the relatively high temperature of the indoor air kept in such rooms in winter are conducive to the development of moisture of the partitions, and in extreme cases, to the development of mould fungi on their surface.

1. Introduction

A large number of single-family and multi-family buildings, managed accommodation facilities and institutional buildings both in Poland and throughout Europe are equipped with a natural ventilation system. With the low cost of operation as its unquestionable advantage, this solution also has one fundamental drawback. In order to operate effectively, natural ventilation requires provision of an appropriate stream of ventilation air. And yet, this specific prerequisite for the proper functioning of natural ventilation is not usually met. Despite the fact that the Polish standards [1,2,3] require calculations to be made for such a system, its designers usually ignore it and accept minimum requirements as satisfactory. It is obvious that the adoption of ventilation ducts with the same cross-section, duct inlet grilles with the same area and an identical number of air vents for all the flats is an erroneous assumption. The basic principle of operation of a natural ventilation system says that the value of active pressure depends, among others, on the height of the duct. This very fact implies that
for the flats situated on different storeys, the values of the parameters mentioned above should be selected individually. The lack of such an analysis will consequently result in inefficient room ventilation as well as disturbances in the operation of natural ventilation, even in periods when it should function best, i.e. at low temperatures of outdoor air.

Another significant cause of the faulty functioning of natural ventilation is the improper behaviour of the users. In their attempts to maintain comfortable indoor temperature and reduce the cost of upkeep and maintenance of the buildings, the users limit the volume of the outdoor air stream flowing into the rooms [4,5]. In the autumn/winter period, the temperature of the air stream is quite low, and the tenants close both the air vents and the inlets of the ventilation ducts. This facilitates achieving thermal comfort and reduces the amount of energy necessary to heat the ventilation air stream. However, it limits air exchange at the same time [6,7]. This, in turn, results in an increased level of relative humidity (RH) throughout the flat. The impact of relative humidity on thermal comfort in residential rooms and institutional spaces is usually insignificant, and the elevated HR level is practically unnoticeable to the users. It is the combination of high level of relative humidity (above 70%) and temperature exceeding the level of comfort that causes unfavourable sensations [8].

For a person in light clothes remaining at rest, the comfortable temperature is between 23 – 26°C, whereas for a naked person, it is 28°C [9,10]. The temperature exceeding 25°C was found to be optimum for the growth of mould fungi [11]. In bathrooms, the level of indoor air temperature in the autumn/winter period does not drop below 25°C, so it generates ideal conditions for the development of mould fungi.

The limiting of the ventilation air stream volume by the users is also due to the fact that the perception of temperature is influenced by the velocity of air flow in the given room [8,9]. In Poland, in the majority of buildings equipped with natural ventilation systems, the velocity of air flow does not exceed 0.1 m/s, as shown in the authors’ own research [6, 7, 12]. However, a local increase in air flow velocity, felt as a draught, is possible. This sensation is dependent on the temperature of the air, the surface of the body exposed to the draught and the degree of turbulence. The air flow can be described as pleasant, if the person staying in the room assesses the environment as warm. However, the same air velocity can be evaluated negatively, if the person perceives the thermal environment as cold.

2. The subject and scope of the study
The study was conducted in an autumn/winter period in five flats situated on different floors in three multi-family buildings. All the flats under study were fitted with a natural ventilation system with exhaust ducts in the bathroom, kitchen and/or separate toilet. The outdoor air was supplied through window vents installed in the window frames of the selected rooms. The characteristics of the flats under analysis are shown in table 1.

During the measurements, the variability in the basic indoor microclimate factors, i.e., the concentration of CO₂, the temperature and the relative humidity of the indoor air, were recorded. The airflow velocity at the exhaust ducts’ inlets was also recorded. This enabled the determination of the direction of the flow and the volume of the ventilation air stream. Three series of measurements were performed for each of the flats, one in November, one in December and one in January. Each measurement series lasted two weeks, and the measurement interval was 5 minutes.
Table 1. Characteristics of the flats under analysis

| Symbol of the flat | M1       | M2       | M3       | M4       | M5       |
|--------------------|----------|----------|----------|----------|----------|
| Area of the flat [m²] | 58.00    | 64.00    | 50.20    | 48.50    | 58.0     |
| Number of exhaust ducts [pcs] | 2 | 3 | 2 | 2 | 3 |
| Number of vents [pcs] | 2 | 2 | 1 | 1 | 1 |
| Maximum stream of outdoor air fed through the vents [m³/h] | 100 | 100 | 30 | 50 | 50 |
| Number of users [persons] | 3 | 2 | 2 | 3 | 5 |
| Gas appliance | Gas range cooker | Gas range cooker | Gas range cooker | Gas range cooker | Gas range cooker |
| Method of warm water provision | From the municipal supply system | From the municipal supply system | From the municipal supply system | From the municipal supply system | From the municipal supply system |
| Bathroom window | none | none | none | none | none |

The measurements of the parameter values for outdoor air were conducted simultaneously, along with the measurements of the parameters for the microclimate in the flats under study. A local meteorological station, located 1.8 – 4.5 km in a straight line from the residential buildings under study, was used for this purpose. The values of the outdoor air temperature were from -11°C to +9°C, the relative humidity was in the range of 62% ÷ 99%, the concentration of carbon dioxide was from 416 ppm to 580 ppm, and the wind speed was 0.00 ÷ 6.10 m/s. The mean daily values of the parameters for outdoor air in the testing period are shown in table 2.

Table 2. Average daily outdoor air parameters in the period under investigation

| Parameter                  | November       | December      | January       |
|----------------------------|----------------|---------------|---------------|
| Temperature [°C]           | 0 ÷ 10         | -2 ÷ 5        | -3 ÷ 6        |
| Relative humidity [%]      | 68 ÷ 99        | 73 ÷ 99       | 70 ÷ 99       |
| Atmospheric pressure [hPa] | 992 ÷ 1016     | 986 ÷ 1011    | 989 ÷ 1015    |
| CO₂ concentration          | 427 ÷ 456      | 422 ÷ 481     | 429 ÷ 463     |

3. Test results

The analyses of the obtained test results clearly showed that in all the bathrooms under study, the variability amplitude of the measured microclimate parameters had the same character. On the days when the bathrooms were used, the RH level fluctuated continually, with an upward trend of this parameter observed in the daytime. At night, the relative humidity decreased gradually to reach the minimum values in the early morning hours. During bathing, taking a shower or drying the laundry in the bathrooms, the level of relative humidity increased rapidly to the maximum values, and then began to drop to the initial values (Figure 1). The time needed to arrive at the initial value depended on the type of activity. The longest time was recorded during laundry drying, while the shortest time was observed in the case of taking a shower. This was obviously related to the duration of the effect of the additional moisture load.

Figure 1 presents a plot of daily variability of microclimate parameters for one of the bathrooms selected for the study. The analyses of the relative humidity values shown in the graph indicated their quick rise by ca. 10 ÷ 20% at shower time (tests no. 10 and 51), and then their lowering. The time necessary to arrive at the initial, pre-shower values varied, depending on the bathroom, and ranged from 20 minutes to 1.5 hours for a shower lasting approximately 5 minutes. During a bath taken for about 30 minutes, the relative humidity of air grew by 20 ÷ 30%, and the time needed to reach the pre-bath value of the parameter was up to 2.5 hours. Drying the laundry in the bathroom also brought about an increase in the HR values in this room. After the laundry had been hung to dry, a rapid growth of relative humidity values was observed (test no. 6, Figure 1). However, a much longer time was necessary to arrive at the initial relative humidity values. Depending on the bathroom under
analysis, it ranged from a few to a dozen hours or so for about 4 kg of dry laundry. When manual washing of single pieces of clothes and their drying were done, the changes in relative humidity did not exceed several per cent and were practically unnoticeable.

![Figure 1. Daily amplitudes of variability of microclimate parameters in one of the bathrooms under study.](image)

Throughout the study, in all the flats and for almost all measurement periods, the mean relative humidity values in the analysed bathrooms varied by a few to as much as 20 ÷ 40%, compared to the remaining parts of the flats (Figure 2). Exceptions to the regularity were the situations in which the bathroom door was left open after a bath, a shower or during laundry drying. In such cases, the level of the relative humidity in the bathroom affected the level of this parameter in other rooms. The maximum RH values recorded in the bathrooms reached even 90%. However, it should be noted that these were temporary values. The minimum and the maximum values of the measured parameters for the individual bathrooms are given in table 3.

| Table 3. Minimum, maximum and standard deviation values of the measured parameters in the bathrooms under study |
|------------------------------------------|
| Rooms | CO₂ [ppm] | Temp. [°C] | RH [%] | CO₂ [ppm] | Temp. [°C] | RH [%] | sCO₂ [ppm] | sTemp. [°C] | sRH [%] |
|------|---------|----------|-----|---------|---------|-----|----------|----------|-------|
| Bathroom 1 | 3933 | 29.4 | 85.3 | 441 | 25.9 | 49.2 | 517.2 | 0.51 | 6.04 |
| Bathroom 2 | 4350 | 28.6 | 83.7 | 575 | 23.2 | 51.4 | 625.5 | 1.10 | 4.64 |
| Bathroom 3 | 3917 | 27.9 | 86.8 | 408 | 23.5 | 45.8 | 465.9 | 0.76 | 4.72 |
| Bathroom 4 | 4106 | 28.3 | 86.1 | 492 | 24.9 | 52.2 | 582.7 | 0.91 | 4.86 |
| Bathroom 5 | 3519 | 29.5 | 90.2 | 463 | 26.3 | 50.5 | 478.3 | 0.64 | 5.28 |
Given the character of the performed activities as well as the minimum air temperature values for individual rooms stipulated by the standard [13], the recorded temperature values in the analysed bathrooms were higher by approximately 1.0 ÷ 5.3°C for the kitchen and 3.6 ÷ 6.2°C for the remaining parts of the flats (Figure 3).

**Figure 2.** Plot of weekly variability of the relative humidity in individual rooms of the selected flat (start at 5 p.m., measurement interval 5 minutes)

**Figure 3.** Plot of weekly temperature variability in the rooms of one of the flats under study (start at 5 p.m., measurement interval 5 minutes)
However, converse situations were observed, i.e., when the values of indoor air temperature in the bathrooms were considerably lower than in the neighbouring rooms. In the flats, where the stream of ventilation air turned out to be insufficient, the function of the element delivering outdoor air was taken over by one of the exhaust air ducts. This caused low-temperature outdoor air to be forced into the room in which the duct had its inlet. The temperature of the air forced through the duct was dependent on the storey on which the flat was located. For instance, for the flat on the 3rd floor, with an outdoor air temperature of 0°C, an air stream at the temperature of 13 ÷ 15°C was forced into the flat through the ventilation duct at a velocity of 0.05 ÷ 0.8 m/s (Figure 6). In the case of the flat situated two storeys below, the temperature was higher by ca. 1.5°C. Regardless of the storey level on which the flats were located, the indoor temperature fell significantly in the rooms under study. This phenomenon also caused a decrease in the temperature of the surface of the wall over the ventilation ducts (Figure 4). Whether the phenomenon occurred in the kitchen or in the bathroom, the users of the flats experienced general lack of thermal comfort in the rooms. Combined with a high level of relative humidity present in the analysed bathrooms, the occurrence of backdraught in the bathroom ventilation ducts resulted in the condensation of water vapour on the surface of the walls covering the ventilation ducts (Figure 5). Such situations took place in three out of the five flats under study and concerned the dwellings in which only one air vent with a capacity of 30 m³/h or 50 m³/h was installed.

**Figure 4.** A cooled wall over ventilation ducts – a thermographic image and a Figuregraph.

**Figure 5.** Condensation of water vapour on the surface of the wall over the cooled ventilation ducts.
The recorded values of carbon dioxide concentration confirm the improper organisation of air exchange in the flats under study. The mean CO₂ level in the analysed rooms ranged from 941 ÷ 1280 ppm. Since there are no national legal requirements regulating the values of this parameter in residential buildings, the requirements of ASHRAE Standard 2016 [14] and the standard [15] were used as a baseline for the comparison and analysis of the obtained results. Taking into account the average concentration of carbon dioxide in the outdoor air, which was ca. 450 ppm in the area of the premises under study, the values measured in the rooms were within the limit specified in ASHRAE Standard 2016. It exceeds the CO₂ concentration in the outdoor air by 750 ppm, so for the site under study, the acceptable level for the rooms was 1200 ppm. However, the comparison of the obtained results with the requirements specified in the standard [15] showed that the air quality could only be classified as category IDA 3, that is as “moderate”. The exhaustive analysis of the amplitude of variability of CO₂ concentration in the individual rooms revealed that for a large part of the analysis, the concentration level of that parameter was much higher. These values exceeded 1200 ppm and reached up to 5000 ppm (Figure 7). The maximum values were only temporary values, and usually pertained to the kitchens. This was due to the use of gas appliances (gas cooker). Depending on the flat and the measurement series, the value exceeding 1200 ppm lasted for 34 ÷ 71% of the measurement period for the kitchens and the bathrooms, and from 18% to 31% of the measurement time for the remaining rooms.
Figure 7. Plot of weekly variability of carbon dioxide concentration in the rooms of one of the flats under study (start at 5 p.m., measurement interval 5 minutes)

4. Conclusions
The obtained test results indicate clearly that the values of the basic microclimate parameters in the bathrooms differ significantly in comparison to the remaining parts of the flats. This is mainly manifested by the elevated level of relative humidity in the bathrooms, but also very frequently by high concentration of carbon dioxide. The study showed that the elevated level of relative humidity persisted in the bathrooms during bathing or taking a shower, and remained at that level long afterwards. A similar situation occurred during drying the laundry in the bathrooms. The time recorded by the authors, necessary to obtain the initial value of relative humidity in these rooms, i.e., the time before a shower/bath was taken or the laundry was dried, depended on the type of the performed activity. For a 30-minute bath, it amounted up to 2.5 hours, whereas for a 5-minute shower, the time was from 20 minutes up to 1.5 hours. The longest time the elevated level of relative humidity persisted in the bathrooms was observed during laundry drying. For the laundry load weighing ca. 4kg, the time was up to 19 hours. The maximum time values referred to the situations when the bathroom doors were closed after the users had left the place. The elevated RH level resulted from both the activities performed in the bathrooms and the inadequate stream of outdoor air delivered to the houses under study, i.e., insufficient air exchange. This was evidenced by the high concentration of carbon dioxide, considered an outdoor air quality index, recorded in all the rooms of the flats under study. In the spaces, where window vents had been installed (rooms), the observed levels of CO₂ concentration were relatively low and remained in the range of 500 ÷ 2500 ppm. Nevertheless, for a significant part of the measurement period, they exceeded the limits recommended by ASHRAE standards. On the other hand, in the kitchens and the bathrooms, the observed values of carbon dioxide concentration were considerably higher and frequently reached the level of 5000 ppm. The exceedances of the level recommended for these rooms by ASHRAE persisted for 34 ÷ 71% of the measurement period.

Backdraught in the ventilation ducts was another phenomenon that proved an improper organisation of air exchange and was accountable for the elevated RH level in the rooms under study. In the flats, in which only 30 ÷ 50m³ of outdoor air was supplied in an organised manner within one hour (one window vent), the function of the element supplying outdoor air was taken over by one of the exhaust ducts. Usually, it was the duct located in the kitchen; however, this phenomenon was also observed in bathroom ducts. This caused significant cooling of the rooms. Besides, it brought about
condensation of water vapour on the surface of the bathroom walls in which the ventilation ducts had been installed.

In conclusion, it should be stated that in multi-family residential buildings, the proper functioning of the natural ventilation system requires an in-depth analysis as early as the design stage. Faulty or improper design of the elements supplying outdoor air and removing indoor air is the cause of multiple disturbances in the operation of the natural ventilation system. Bathrooms are the rooms that need to be focused on. Due to the elevated level of relative humidity resulting from the functions they perform, bathrooms are particularly vulnerable to exceeding the limit values as well as the values recommended for the microclimate of that type of rooms. The recorded high relative humidity values along with the high temperature maintained in bathrooms create conditions conducive to the growth of mould fungi on the surface of the partition walls, which can consequently lead to the development of the sick building syndrome in the buildings.

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