Influence of building airtightness on the internal thermal comfort and air quality in the single family house

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Abstract. The knowledge of the air exchange and building air-tightness is an indispensable source of information, both on the design and operation stage of the building use. Properly functioning ventilation system affects significantly internal thermal comfort and internal air quality. Infiltration of air determines the proper functioning of the gravitational ventilation, still the most commonly used system in Polish single-family housing. However, the most popular and easy to measure parameter: building airtightness (n50), does not specify the real air exchange in the actual climatic conditions. The real air flow rate may be determined with much more troublesome gas tracing method. Air flow rate, n, is in this method obtained from the decaying curve of gas concentration after injection of tracer gas into the building. This paper presents the results of the airtightness measurements conducted in a single family house with natural ventilation. Both, n50 parameter and building air flow rate n have been measured. The results of the measurements were used as a model calibration tool in the annual computational simulations carried out in the Design Builder program for the Polish climatic conditions. Based on these simulations the authors determined the influence of building airtightness on the internal thermal comfort and the potential scenario of its control.

Keywords: natural ventilation, air tightness, infiltration, thermal comfort, indoor air quality

1. Introduction
The current focus on sustainable construction and energy saving leads to the search for the most effective solutions in every detail of the designed building. Since the exchange of air in the building is associated with large energy losses, it is reasonable to limit these losses to the necessary minimum. The first step in this direction is to obtain effective control over the air exchange in order to adjust it to the obligatory hygiene needs [1]. Hence, in low-energy building, the standard is airtight envelope and mechanical ventilation with heat recovery. Airtight building demands special solutions and materials at design stage, extreme care and special experience at construction stage and experimental testing, finally.

However, low-energy buildings with natural (passive) ventilation, that are significantly cheaper and easier in operation and maintenance, are still being designed. In this case, the process of air exchange is only partially controlled and conflict may occur between the tendency to save energy and the quality of the internal environment. Infiltration is a source of fresh air, and at the same time it may be a cause of the excessive heat losses. High tightness of the building envelope is desirable, but it may lead also to deterioration of air quality [2]. The aim of the article is to prove what effect the air-tightness of the building has on the actual exchange of air and the quality of the environment in a small single-family building with natural ventilation.
2. Measurements of airtightness and air exchange rate

The analysed single family house, figure 1, that was built in 2017, is located in the village Zielonki, in the neighbourhood of Cracow. It is one story building with the unconditioned and non-insulated attic space. Ground floor dimensions are 11.5 m x 7.85 m. External walls are made of the aerated concrete blocs and additionally insulated with 5 cm of expanded polystyrene. The floor below attic and the floor on the ground are insulated with 15 cm of expanded polystyrene. The windows, made of PVC, are triple glazed with low emissivity coating and argon between the panes. The window frames are sealed with the rubber gaskets. The windows are embedded in walls in a standard way, using the assembly PU foam. There is a natural ventilation system in this house, with the two exhaust ducts, 18 cm x 18 cm each, located in the kitchen and in the bathroom. Fresh air supply by means of infiltration. Ventilated volume of the building is 230 m$^3$. Tested building is equipped with ideal gas heating system, that maintains the temperature at a minimum level of 20°C, without setback. There is no cooling system in this building. There are four (2 children), permanently present, inhabitants. Percentage share of glazing areas at the elevations is as follows: N – 7%, S – 30%, E – 20%, W – 3%.

![Figure 1. Tested single family house](image)

2.1. Airtightness

The most popular method of building tightness evaluation is currently the pressure method (blower-door method) [3], according to standard EN 9972 [4]. It allows to assess tightness of the outer building envelope in the artificially created conditions of a considerable pressure difference between the interior and the building's external environment. It is a form of envelope quality diagnostics, but the actual air exchange rate in a building, especially when a gravitational ventilation system was applied, and under the real climatic conditions is still unknown. An approximate way of transition from pressure method to actual air change in time averaged real conditions was developed by Sherman [5] and is also included in EN 13789 [6].

Measurements of the building airtightness have been conducted on October 13, 2018, by means of the Blowerdoor set with the digital controller Retrotec 3000 and Fantestic program for data collection. Tests were conducted in two pressure states: pressurization and depressurization [4] in the following weather conditions: external air temperature 18°C, wind speed in Beaufort scale: 1, air temperature inside the building 22°C. Final result of the test was equal to $n_{50}=1.85$ h$^{-1}$.

2.2. Air infiltration rate

The actual air exchange rate in natural conditions can be measured using gas tracer concentration decay method standardized in EN ISO 12569 [7]. Despite the simple physical principle of this method, it is not easy to achieve the high precision of measurements due to the problems with uniform mixing of tracer gas and air in a multi-room apartment or building. The practical aspects and problems connected with the tracer gas concentration decay method were discussed in [8]. This measurement method was described in numerous publications [9, 10, 11]. The method is based on the analysis of the
rate of decay of tracer gas concentration in the internal air. Carbon dioxide is one of the natural compounds of atmospheric air that can be used also as a tracer gas. It is an odourless, colourless non-flammable and non-toxic gas, heavier than the air [12].

The test measurements of building infiltration in the analysed building, by means of gas tracing method, were conducted for five times in different climatic conditions.

The serious difficulty in conducting the measurements was connected with the assumption of a single zone measurement in case of multi-space building [8]. According to the European standard the uniformity of concentration within the tested space is obligatory. The concentration of tracer gas should not fluctuate more than 10% from the average value within the tested zone. To meet this assumption forced mixing of air within the building is necessary and in multi room zone data should be recorded separately in each room.

Two CO₂ detectors were located in the living room and kitchen being one open space. The third detector was in the bedroom. CO₂ concentration was generated from the cylinder with the compressed gas. Data have been gathered and stored at 10 minute intervals. Air was initially mixed with CO₂. The results from the two detectors located in the living room met the requirement of the standard but the results from the third one must have been rejected as the fluctuations were still beyond the acceptable range of 10%.

The specific airflow rates were calculated separately for each day of measurements by means of the two point decay method [7]. Measurements of the airflow rate were performed with the windows closed and the internal doors open. The results of the initial measurements are presented in table 1.

| Date       | Specific airflow rate n [1/h] | External temperature [°C] | Wind speed [m/s] |
|------------|-------------------------------|---------------------------|-----------------|
| 24.07.2018 | 0.029                         | 26                        | 3.4             |
| 25.07.2018 | 0.031                         | 28                        | 2.4             |
| 03.08.2018 | 0.011                         | 27                        | 1.0             |
| 29.01.2019 | 0.096                         | -4                        | 1.5             |
| 17.02.2019 | 0.102                         | 6                         | 5.7             |

The measured values of the actual air exchange in the building were very low and did not meet the required hygienic requirements. The maximum measured air change rate occurred in February and was equal to 23 m³/h (0.102 · 230 m³), while the hygienic requirements for this building (2 adults and 2 children) can be estimated as 100 m³/h. It is to be expected that air quality in this building will be very low. Residents have already reported problems related to excessive humidity in the interior. Initial research, shown in this article, concerned the tightness of the housing and air exchange. Further tests will include measurements of humidity and the natural concentration of CO₂ in this object.

It can be expected that in the summer period with moderate external air temperature, opening windows in the building can help improve the quality of indoor air, and will also act as a protection against overheating. However, in the transition periods in this well-insulated and heavily glazed building, severe space overheating and poor air quality must be expected. On hot summer days, with as high external air temperature as during the measurements, windows opening would increase the internal overheating. In these conditions, with windows closed, natural ventilation practically does not work.

In this situation, building tightness and infiltration rate, which is in this case the main factor of air exchange, has a significant impact on the thermal comfort and indoor air quality.

### 3. Building simulation model

The aim of the building simulations was to determine the influence of infiltration rate on the thermal comfort in the building interior. The calculations were carried out in the Design Builder v.3. Actual air exchange rate between the analysed building and external environment was in simulation based on the measured n₅₀ parameter and calculated by means of the simplified input procedure of EnergyPlus called: ZoneInfiltration:DesignFlowRate [13]. In the balance equation of infiltration a set of coefficients used
in the BLAST program was applied. This makes it possible to take into account the effect of temperature difference and wind speed in simulations. The measured building airtightness, treated here as a model calibration parameter, is equal to $n_0=1.85$ l/h (section 2.1.). It was also assumed, in accordance with the conditions that had been kept during the tracer gas tests, that the internal doors between the rooms were constantly open.

The simulations were conducted for the Polish climatic conditions (building located in Zielonki close to Cracow). Visualization of the building simulation model is presented in figure 2.

Figure 2. Simulation model of the single family house

The results of the measurements of the actual air exchange in the building (2.2.) can be used only for rough estimation of the simulation model. It is not possible to accurately compare the monthly average values of the air exchange, figure 3, with the measured instantaneous values, table 1. It can only be stated that the average values obtained from simulations and winter measurement results are close to each other, and the results of the simulations confirm the very low air exchange rate in this building. One of the many reasons of the expected result discrepancies can be protection of the existing building against wind due to the slope of the area and the dense vegetation. As it results from the tests carried out, table 1, and the calculated values of ventilation during the year, figure 3, air change intensity is not very sensitive to the variability of thermal conditions, and more sensitive to the effects of wind.

Figure 3. Average monthly values of the simulated air change rate
4. Simulations and evaluation of thermal comfort

The thermal comfort simulation results presented in the article concern the two transition periods (April-May and September-October). The average air changes in these months are similar, equal to 0.15 l/h – figure 3. In April hourly values of the internal air temperature in the entire building are between 22°C and 26°C and at the end of May the mean values exceed 34°C. While in April the PMV factor is close to the acceptable comfort range, since 10th of May it increases gradually and then it is higher than 2 for most of the time (figure 4a and 4b). These inconvenient conditions last for the entire days and do not change significantly during the nights. These microclimate conditions exceed the recommended range of \(-0.5 < \text{PMV} < +0.5\). The similar conditions can be observed in the analysed autumn months. In September average temperature inside is ca. 30°C and at the end of October it decreases to 21°C. At the beginning of September PMV exceeds 2 but then it lowers to the acceptable range in October.

The simulations proved that there is a problem with overheating since May up to September. The external temperature is within the range of 4°C and 22°C in May and 6°C and 23°C in September and it can be expected that a more intensive air exchange would in this period efficiently cool down the space.

In the second stage of modelling the mechanical ventilation system was used to prove the influence of the more intensive air exchange on the thermal comfort conditions. The results are presented in figure 4a and 4b. The noticeable improvement of the PMV factor in the analysed transition periods can be observed however overheating was not completely removed.

**Figure 4a, 4b.** Thermal comfort evaluation for natural and mechanical ventilation systems.  
4a – April and May; 4b – September and October
5. Conclusions

In the buildings with the gravitational ventilation there is an obvious conflict between the desire to save energy and the quality of the internal environment. In the analyzed, new single-family house, due to the good tightness of the outer shell and wind shielding effect provided by the surrounding slope and trees, the ventilation air exchange is insufficient, even in winter conditions with a large temperature difference. In the transition periods, in this building with a large glazing and very low air exchange rate, there is also a significant overheating of the interior.

The investors and building users should be made aware of the problems that may be associated with the natural ventilation system. For the benefit of the designers and users, the infiltration quality of the housing and the quality of the internal environment may be controlled by the different passive measures, as suggested below.

To reduce overheating in such buildings the controlled increase of infiltration intensity using passive measure (operable trickle vents) would be a reasonable solution. The next step of passive operation, during the periods with moderate external temperature during the day, window opening would be a sufficient measure to keep the required conditions. Finally, during the hottest periods night cooling of thermal mass could be an effective way of overheating protection.

This article presents the preliminary measurements of the building, more advanced analysis and tests regarding air quality and moisture build up are being planned.

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