NATURAL VENTILATION PERFORMANCE OF FAMILY BUILDING IN COLD CLIMATE DURING WINDY DAYS

Romana ANTCZAK-JARZĄBSKA[1], Maciej NIEDOSTATKIEWICZ[1]

[1] Gdańsk University of Technology
Faculty of Civil and Environmental Engineering
80-233 Gdańsk, Narutowicza 11/12, Poland
romana.antczak@pg.edu.pl; maciej.niedostatkiewicz@pg.edu.pl

Abstract

Adequately designed natural ventilation is the cheapest and easiest way to effectively remove indoor pollutants and keep the fresh air inside a building. A prediction of performance and effectiveness of ventilation in order to determine the design of a ventilation system can provide real and long term cost savings. The paper presents results of performance (air change rate ACH) and effectiveness (CO_2 concentration in the breathing zone η_v and temperature distribution $\bar{\varepsilon}_t$) of natural ventilation for a building with inlet gap measured for the transitional season (between the heating and the summer season). The measurements were performed during a windy period. The test apartment was located in cold climate. The measurement system measured local climate conditions, indoor climate conditions and air velocities in both vent inlet and outlet.

Keywords: natural ventilation, CO_2 concentration, ACH, wind effect.

WYDAJNOŚĆ WENTYLACJI NATURALNEJ PODCZAS DNI WIETRZNYCH W BUDYNKACH MIESZKALNYCH ZLOKALIZOWANYCH W KLIMACIE CHŁODNYM

Streszczenie

Odpowiednio zaprojektowana wentylacja naturalna jest najtańszym i najłatwiejszym sposobem skutecznego usuwania zanieczyszczeń wewnątrz pomieszczeń oraz utrzymywania świeżego powietrza wewnątrz budynku. Przewidywanie wydajności i skuteczności wentylacji w celu określenia projektu systemu wentylacyjnego może zapewnić rzeczywiste i długoterminowe oszczędności. W pracy przedstawiono wyniki działania (szybkość wymiany powietrza ACH) i efektywność (stężenie CO_2 w strefie oddychania η_v i rozkład temperatury $\bar{\varepsilon}_t$) wentylacji naturalnej w budynku, który posiadał nawiewnik okienny. Badania prowadzone były w sezonie przejściowym (między sezonem grzewczym a letnim). Pomiary przeprowadzono podczas okresu wietrznego. Testowe mieszkanie zlokalizowane jest w klimacie chłodnym. System pomiarowy mierzył lokalne warunki klimatyczne, warunki klimatyczne w pomieszczeniach i prędkości powietrza zarówno na wlocie i wylocie z kanałów wentylacyjnych.

Słowa kluczowe: wentylacja naturalna, koncentracja CO_2, ACH, efekt wiatru.

1. INTRODUCTION

Natural ventilation (NV) is the cheapest strategy for distributing fresh air inside a building. It is still the most popular system found in Poland and other Central and Eastern European countries. Natural ventilation is driven by two physical phenomena, wind [1, 2] and buoyancy (stack effect) caused by temperature difference between indoor and outdoor air temperatures [1, 2]. However, Gładyszewska et al. [6] showed that the NV is mainly affected by wind direction and velocity.

Natural ventilation should work when all or one of natural forces are available. Unfortunately, the two main drivers causing natural ventilation flows are stochastic, therefore natural ventilation may be difficult to control and difficult to predict, analyze and design. Other disadvantages of natural ventilation are the reduced control of air distribution within the building and the lack of its effectiveness in summer conditions with minimal wind. Despite the difficulty in control, natural ventilation is still relied upon to meet the need for fresh air in many buildings. The study [3] shows that natural ventilation has become a new trend in building design in architectural community. Furthermore, natural ventilation has been used in many types of buildings, even in highly controlled indoor climate hospitals [4].

The quality of natural ventilation is usually determined by performance indicators of the ventilation system. Performance means air change rate (ACH) and effectiveness (CO_2 concentration in the breathing zone η_v and temperature distribution

$\bar{\varepsilon}_t$. The ACH measures how quickly the air in the interior space is replaced by air coming from the outside. In turn, ventilation effectiveness is the indicator of the ability of a ventilation system to remove a contaminant. Ventilation performance indicators are to provide information concerning indoor air parameters in a room or a building. Therefore, proper information about realistic climate data of the local climate conditions is important, but usually it is not provided. Generally, we have two different approaches: local climate condition (LCS) at the construction site and climate data in a Typical Meteorological Year (TMY). In the engineering practice, it is not common to take into account the local climate conditions. As we can see in the study [5], the most common practice is to use climate data from the TMY. However, [5] rightly observed that when based on climate data from the TMY, such values are usually slightly overestimated.

In this paper, the performance (air change rate ACH) and effectiveness (CO_2 concentration in the breathing zone η_v and temperature distribution $\bar{\varepsilon}_t$) of natural ventilation for a building with inlet gap measured was performed. A typical residential detached house was chosen for the measurement campaign. The house was located in northern Poland, in a region of cold climate. Field measurements were performed in a test apartment in a family detached house. The measurement campaign started on 2nd of April 2014 at 18:00 and ended on 9th of April 2014 at 18:00. For better knowledge of behavior of natural ventilation in experimental measurement, a windy period of time was chosen. However, April is a month in which primary mechanisms for the transfer of air into a building occur simultaneously. In this paper we focus on the effect of wind on the NV. Therefore, we could not ignore the effect of the bouncy on the results and we also presented the temperature difference in the flow rate in the test apartment. The major contribution of the paper is the experimental determination of the natural (stack) ventilation in a residential apartment with chimney configuration and a window with inlet gap on the air exchange rate and the CO_2 concentration and temperature distribution in the breathing zone.

2. TEST HOUSE

The test building is a two-storey, two-apartment residential house located in Gdansk (northern Poland) in a region of cold climate. The apartment with floor area of approximately 50 m^2 was selected for the measurement campaign (Fig. 1a). The apartment is located on the first floor and consists of a bathroom, bedroom, kitchen, a living room and a corridor. In order to simplify the ventilation system configuration, the bathroom, bedroom and the corridor were excluded from the measurement space and isolated from the rest of the apartment (Fig. 1b). The indoor test space was limited to the living room and the kitchen. The test apartment was inhabited

during the measurement campaign. The residents' activities were registered mainly in the morning and in the evening (after 5:00 pm).

a)

b)
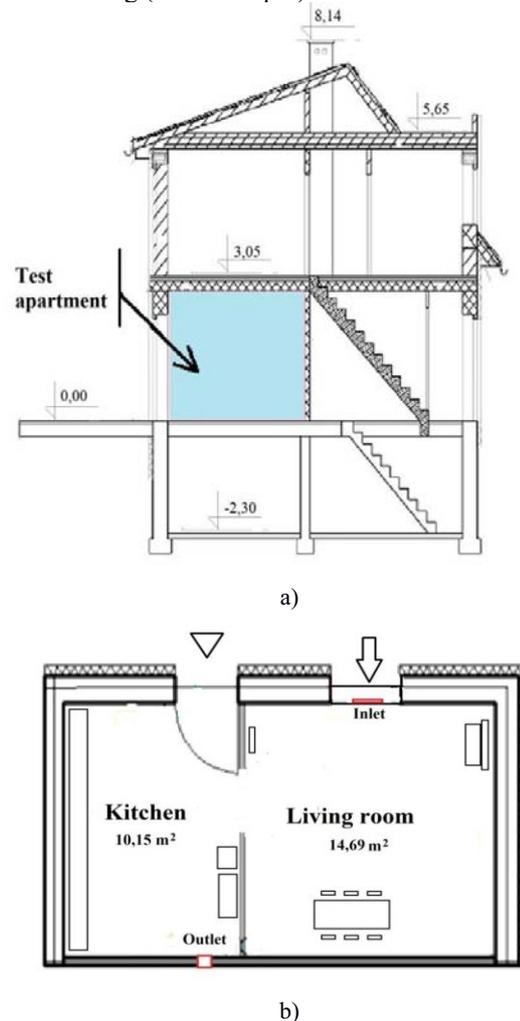
Fig. 1. The residential family detached test house: (a) vertical section and (b) cross-section of the first floor

The test apartment was equipped with the natural ventilation system in configuration with air inlets and chimneys ducts. Air inlets are small appliances mounted in the casement or window frame, which allow for controlling fresh air inflow to the room. They were invented and introduced in the 1960s in Scandinavian countries [8]. In Poland, this type of inlet gaps (Fig. 2) is obligatory in the case of usage of stack ventilation in configuration with multi-chimneys ducts. The air inlet into the chimney duct was equipped with controllable vent grill, which was located 0.15 m below the room ceiling. The measurement system was limited to the two rooms (Fig. 1b) with a usable area of 24.84 m^2 and an air volume of 63.34 m^3. The configuration with one air inlet (rectangular inlet gap in a window frame) and one air outlet (a chimney duct in the kitchen) let reduce the unknown parameters influencing the air exchange process. During the measurement time-period, all windows were closed. The doors inside the test apartment were closed during the night-time and during the residents' work-time. The test house

is a heavy-weight building. The floor slabs are made of concrete. Stone materials are used for both sides of the cavity walls. The building was erected in the 1950s and thermally renovated in 2012. Table 1 provides the U-values overview of the main structural components.

Fig. 2. Typical inlet gaps in Poland

Table 1. Overview of construction details for the base case building from 2012

Element	Details	U-value
External wall	Cavity wall with (inside to outside): limestone inner layer, thermal insulation, brick outer layer	0.18 W/(m^{2}K)
Internal wall	Limestone wall	-
Door	Wood	1.10 W/(m^{2}K)
Windows	Double panel glazing	0.90 W/(m^{2}K)

3. Measurement setup and equipment

The measurement system was designed for the constant monitoring of indoor climate conditions, ambient climate conditions and airflow velocity in vent inlets and outlets. It included sensors, port data acquisition modules, network switch and a PC computer (Fig. 3). All sensors were wire-connected directly to the data acquisition modules which registered the measured data and were connected to the PC computer via a 16-port Ethernet Switch. The measurement data management software LBX 2012 of LAB-EL [12] was installed on the PC computer. The data collected in the module data acquisition was automatically transferred to the SQL database located on a PC computer. The sensors and the data acquisition modules worked in a real-time mode, while the data management software was synchronized with the data acquisition module at each probe time step.

The test apartment was divided into the rooms with lightweight internal walls. The door between the rooms was open. Air velocity and temperature were registered in the vent inlet (A1 and T1) and outlet (A4 and T4). In the indoor zone, indoor climate conditions were monitored and measured. Air temperature was measured at 2 points of the test apartment: (T2) in the living room and (T3) in the kitchen, with air relative humidity measured at the same 2 points as the temperature: (W2) in the living room and (W3) in the kitchen. Barometric pressure was registered at 1 point in the living room (B2). All

sensors were located in the rooms at the height of 1.6 m from the floor level. Many Researchers have been using the information about indoor carbon dioxide (CO_2) concentration to evaluate the effectiveness of ventilation and Indoor Air Quality Control (IAQC) [13, 14]. When trying to estimate the contaminant (CO_2 or other) or natural effectiveness proposed by [15], it is necessary to know the system flow parameters, such as the supply, lead off and average CO_2 concentration in the breathing zone. During the research, carbon dioxide indoors was measured at 4 points. The CO_2 sensors were located in the living room: 1 in the inlet (C1) and 1 in the breathing zone in the room (C2). The CO_2 sensors were located in the kitchen: 1 in the outlet (C4) and 1 in the breathing zone in the kitchen (C3). Ventilation performance indicators are to provide information concerning indoor air parameters in a room or a building. Thus, proper information about realistic climate data of the local climate conditions is of importance here. In that instance, a local climate station was built. The climate station measured wind velocity W [m/s], wind direction WD [°], pressure P [Pa], relative humidity H [%] and temperature of the ambient air $Tamb$ [°C] as well as solar radiation $Tsol$ [W/m^2].
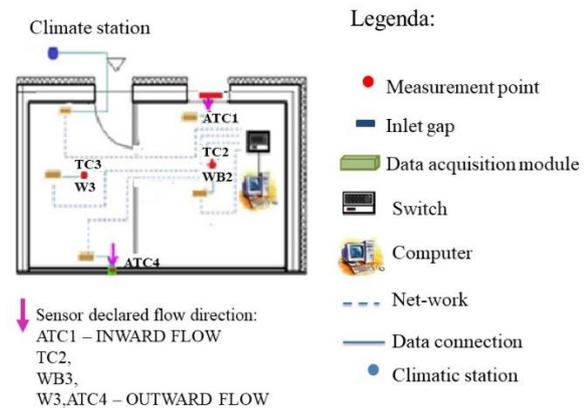
Fig. 3. The measurement system in the test building

To perform the measurements, components of the LAB-EL products line [12] were used. At the climate station, the omnidirectional wind anemometer LB-747 with the measurement range of 0.5 m/s to 90 m/s and accuracy of 2% was used. The omnidirectional wind anemometer LB-747 of the climate station was located on the roof of the building at the height of 9.69 m above the ground level and 2.05 m above the roof ridge. Barometric pressure was measured with LB-716, which worked in the absolute pressure mode within the range of 2-200 kPa and accuracy of ±0.5 kPa. Temperature and relative humidity were measured with the thermo-hygrometer LB-710R. Its temperature range was -40-85°C with the accuracy of ±0.1°C and its relative humidity range was 99% with the accuracy of ±2.0%. In the study the visible radiation sensor type LB-901 was used, with the measurement range of 0

W/m^2 to 2000 W/m^2 and accuracy of 5%. In the indoor zones barometric pressure was measured with LB-750, which worked in the absolute pressure mode within the range of 0.1-120 kPa and the accuracy of ±0.1 kPa. The CO_2-concentration was measured with LB-854 sensors. They measured the range of the CO_2-concentration of 0-10000 ppm (accuracy ±5%) and of the temperature of -15-100°C (accuracy ±0.2°C). Air velocity and temperature were registered in the vent inlet and outlet. Due to complex airflow characteristics in the vent inlet (long rectangular shape) and potential flow direction changes, the air velocity measurement was difficult. In this measurement campaign, the thermo-anemometers LB-801A and LB-801C were installed in a double-sensor configuration. Both thermo-anemometers were based on a hot-wire concept. The first thermo-anemometer LB-801A worked in an analog mode and measured low velocity. The sensor was capable of measuring the indoor convection air velocity between 0.05-10 m/s with the accuracy of ±0.05 m/s. The second thermo-anemometer LB-801C worked in a digital mode and was used to detect airflow direction. The airflow direction detection function was designed by a modification of the LB-801C sensor. The sensor was modified by closing its airflow channel from one side and re-calibrating its characteristics for two opposite flow directions. The new characteristics were recorded in its EPROM memory. Both sensors were installed as an integrated measurement point. The measurement data management software LBX 2012 registered flow direction and air velocity. All sensors were calibrated by the LAB-EL Laboratory in Poland before their installation and commissioning. The sensors were confirmed by means of suitable calibration certificates. Before the start of the measurements, several days of testing preceded.

Since the driving forces in natural ventilation are temperature and wind, the outdoor conditions constitute an important factor when discussing natural ventilation. In this instance, the study was based on real climate conditions. The measurement campaign was conducted in the month of April. Fig. 4 shows the driving forces in natural ventilation measured on the construction site. The most unpredictable conditions during the entire year for natural ventilation were caused by wind effect. We already know how strong an impact the wind has on the air change rate in buildings [26]. Besides, we also know that the stack effect is reduced significantly while the impact of wind gusts is significant. Therefore, in that case, the wind effect could not be ignored. Thus, the major contribution of the paper is the experimental determination of the stack effect on the air exchange rate for natural ventilation with inlet gap subject to the wind effect.
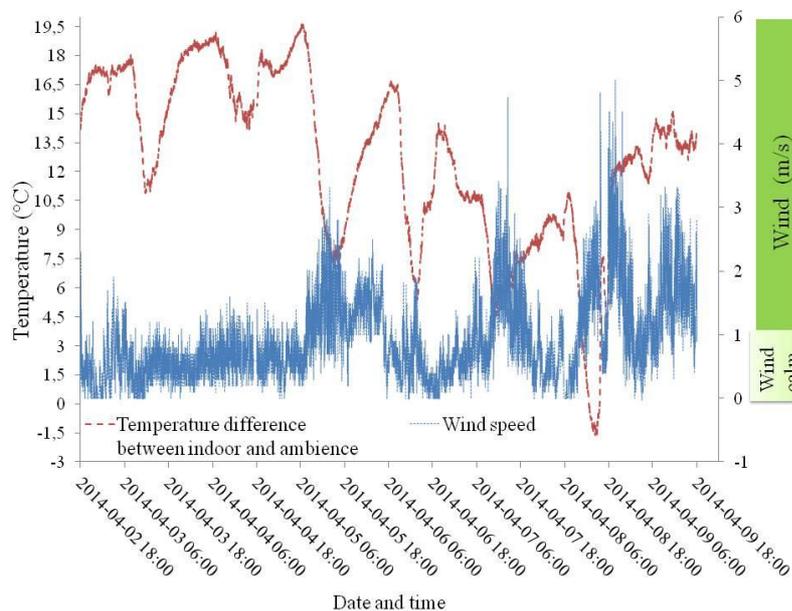
Fig. 4. Driving forces in natural ventilation measured at the construction site

During the whole period of time, air velocity in the inlet (A1) was strongly dependent of wind velocity. Figure 5 presents the inlet air velocity at point (A1) in relation to wind velocity for the windward. The windward direction was defined by the geographic range of (270°-90°). A higher wind velocity would result in a higher flow rate in the building. It should be noted that the wind direction in the experiment was 75% normal on the outside surface of the building. However, the wind velocity was not significant, as its maximum value was 5 m/s.
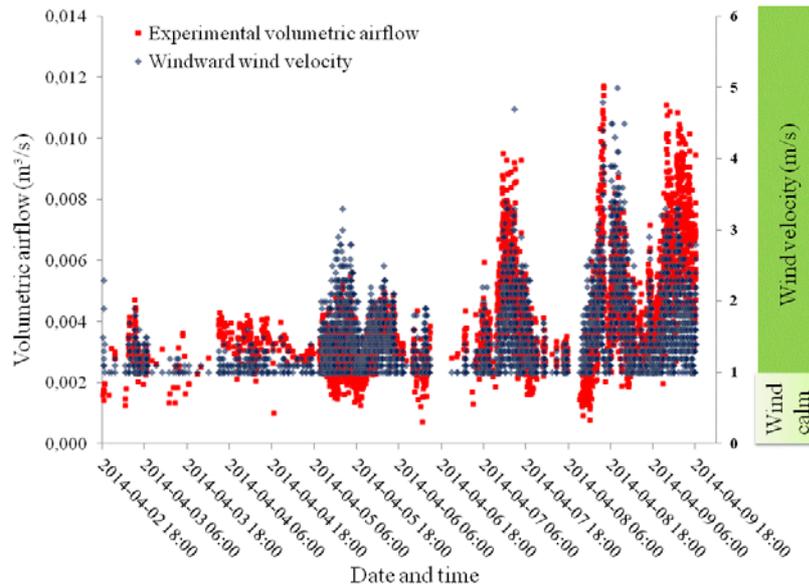
Fig. 5. Measured flow rate and related wind velocity for windward opening

4. THE AIRFLOW MODEL

Simultaneous measurements of air velocities provide a stringent and unique check on the overall accuracy of the technique, in the sense that the measured mass flow rates should satisfy the continuity equation (conservation of mass). In our investigations, the ambient temperature varied significantly and exceeded the indoor temperature. Both zones were free-connected to each other with an inlet gap to the chimney. The mean value of the mass flow rate in the vent outflow calculated was based on:

$$\dot{m}_{out} = \rho(A_{eff}\ U_{out}) \qquad (1)$$

Where ρ is the air density, A_{eff} is the effective area of the air outlet to the chimney ducts and U_{out} is the mean air velocity measured in point ACT4.

The mean value of the mass flow rate in the vent inlet calculated was based on:

$$\dot{m}_{int} = \rho(A_{eff}\ U_{int}) \qquad (2)$$

Where ρ is the air density, A_{eff} is the effective area of the air outlet to the chimney ducts and U_{out} is the mean air velocity measured at point ACT1.

Density difference between the zones were relatively small (fig. 6) and can be ignored. Maximum air density difference between the zones did not exceed 2%. It leads to the conclusion that the small inlet gap in the window frame had a slight effect on the airflow characteristics. The mean measured value for air density in the living room was 1,190 kg/m^3 with standard deviation (SD) of 0,00432, whereas the mean measured value for air density in the kitchen was 1,191 kg/m^3 with standard deviation (SD) of 0,00460.
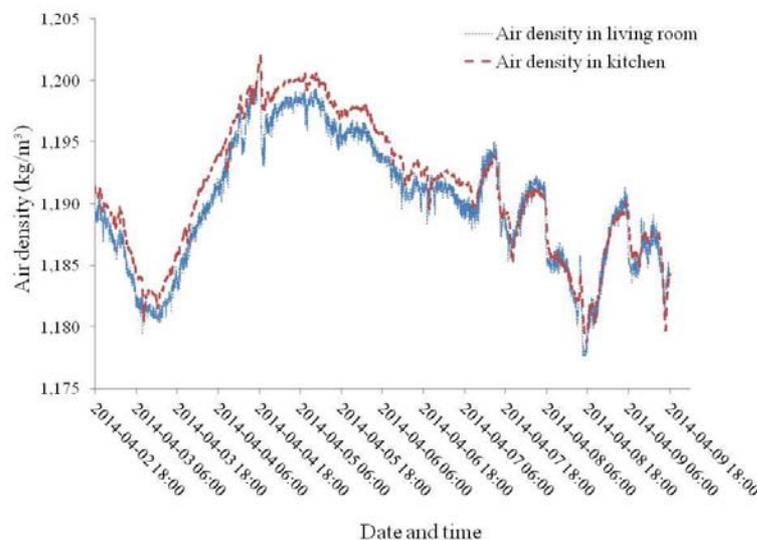
Fig. 6. Time-variation of spatially-averaged indoor air density in the living room and the kitchen

The model apartment is divided into two zones (kitchen and living room), in which the temperature and density are assumed to be homogeneous. The pressure distribution within a zone is assumed to be hydrostatic [17]. The air is treated as an incompressible fluid. The general equations governing the mass conservation in each zone can be written as follows:

$$\frac{d\rho_i V}{dt} =$$
$$\rho_{inlet}(A_{eff\,inlet}\,U_{inlet}) +$$
$$\rho_{outlet}(A_{eff\,outlet}\,U_{outlet}) + \rho_{leak}q_{leak} = 0 \qquad (3)$$

Where $\frac{d\rho_i}{dt}$ is the air density change of the indoor air during the time step dt, ρ_{inlet} is the air density in the inlet gap, $A_{eff\,inlet}\,U_{inlet}$ is the volumetric flow rate in the inlet, ρ_{outlet} is the air density of indoor air flow in the outlet, $A_{eff\,outlet}\,U_{outlet}$ is the volumetric flow rate in the outlet, ρ_{leak} is the air density of leakage and q_{leak} is the flow rate of the leakage. In the study it is assumed that V is constant and equal to the total volume of the test apartment which is 63,34 m^3. Opposite to the natural ventilation, the infiltration rate refers to the air change rate through unintentional leakage areas of the building envelope when doors and windows are closed. As the types of cracks in a specific building are unknown, the air leakage is difficult to be estimated. In order to estimate the leakage flow rate, a measured volume was used to detect it: the time-average flow rate in the air outlet ($A_{eff\,outlet}\,U_{outlet}$) and the time-average flow rate in the air inlet ($A_{eff\,inlet}\,U_{inlet}$) (fig.7).
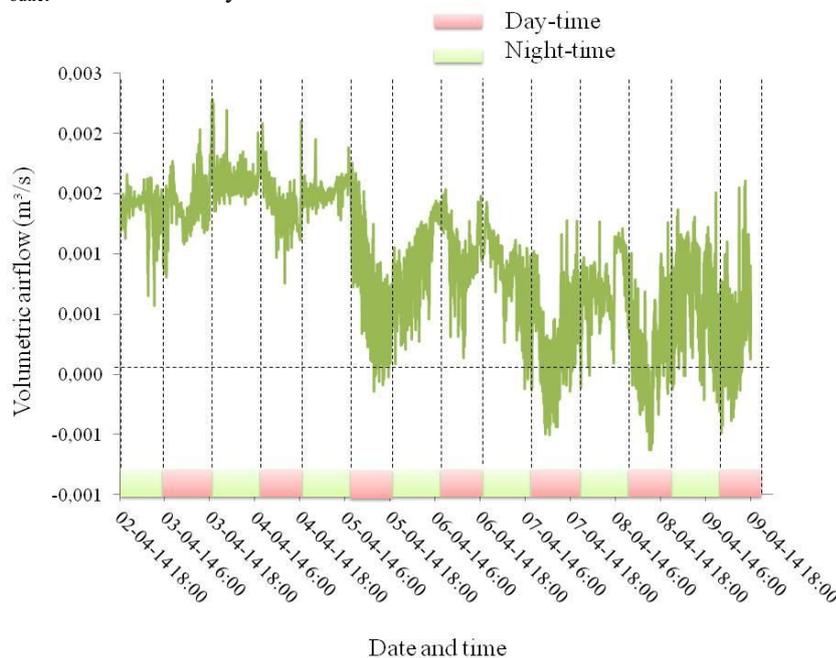
Fig. 7. Time – variation of leakage flow rate in the test apartment

The main problem with infiltration is estimating how much air will leak into a building through leakage [16]. Features of the building which can affect the infiltration are listed as follows: construction year, building orientation, floor area and the number of rooms. An uncontrolled air leakage may be significant in the air exchange process. Jokisalo et al. [4] showed that the average building leakage air flow of all the 170 houses studied was 3,7 (1/h). The authors concluded that airtightness was significant in terms of leakage value. An example of the leakage rate of a massive building was estimated at 2,3 (1/h), while the average of timber frame and log houses was 3,9 (1/h) and 5,8 (1/h) respectively. Thus, in that case, the leakage air flow may not be ignored. In order to study the actual leakage in the test building, a simple system test was defined. In the test building one inlet and one outlet were isolated. In the test building, air pressure testing was not performed. One way to measure the amount of uncontrolled air flow (also known as air leakage) within a property as a result of unsealed gaps or cracks within the thermal

envelope is by pressure testing. Unfortunately, pressure testing does not provide characteristics for all ranges of pressure difference. In Figure 6 it is shown that the uncontrolled air leakage is not significant in the air exchange process in our experiment. The maximum leakage rate of the studied house was 0,023 (m^3/s) which resulted in the air exchange rate of 0.13 [1/h]. Shi et al. showed in [16] study that the leakage rate slightly depends on the age of the building. The authors concluded that leakage rate for residences constructed before 1990 is in the range of 0,06 to 0,82 [1/h]. It is in agreement with the present study, as the average leakage rate for apartment was 0,06 [1/h].

It should be noted that leakage flow rate can be estimated on the basis of the Regulation of the Ministry of Infrastructure and Development [18]. The leakage flow rate V_{leak} (m^3/s) for building without tightness test or experiment test can be estimated as follows:

$$V_{leak} = \frac{0.2\ V}{3600} = \frac{0.2*63.34}{3600} = 0.0035\ \left(\frac{m^3}{s}\right) \quad (4)$$

This is a simple method of the leakage flow rate estimation which is usually applied in an overall energy demand prediction. The estimated leakage flow rate is comparable with eq. (4). Unfortunately, this method does not consider variable and time-dependent air flow conditions. Thus, the method is not able to estimate the instantaneous leakage flow rate in the entire range of air flow conditions.

5. NATURAL VENTILATION (η_v) PERFORMANCE INDICATORS

The quality of natural ventilation indices used in this study are performance and effectiveness indicators. Performance means air change rate (ACH) (indicator 1) and it is the measure of how many times the air within a defined space is replaced. Air change rates are often used as a principle with broad application that is not intended to be strictly accurate or reliable for every situation in ventilation design. The ventilation effectiveness can be related to other parameters influencing the environmental indoor comfort such as: CO_2 concentration in breathing zones η_v (indicator 2) and the rate of temperature distribution homogeneity $\bar{\varepsilon}_t$ (indicator 3).

5.1. Air change rate (ACH) (indicator 1)

The air change rate per hour (ACH) is calculated based on the ratio of total air supply $((A_{eff\ inlet}\ U_{inlet}) + V_{leak})$ into a zone (i.e. a room or space) in relation to the volume of this zone room volume (V_R) [19]. During the study airflow direction was not reversed. It leads to the assumption that the sum of the air supply measured at point ATC1 and positive V_{leak} (fig. 7) constitute the total air supply into an apartment. The total air supply $((A_{eff\ inlet}\ U_{inlet}) + V_{leak})$ will be named $\dot{V}(t)$. It is generally expressed as air change per hour [h^{-1}] or [ACH]. The ACH is defined by the ASHRAE as:

$$ACH\ (t) = (\dot{V}(t) * 3600)/V_R \quad (5)$$

Where:

ACH(t) - is the ventilation rate or air change rate, h^{-1}

$\dot{V}$(t) - is the total air supply into a room, m³/h

V_R - is the room's volume, m³

The exchange processes that take place during the measurement period are assumed to be temporally invariant. The air supply rate $\dot{V}$ (t) and, thus, the air change rate ACH (t) are constant. $\dot{V}$ (t) and ACH (t) can be replaced by $\dot{V}$ and ACH. For the air change rate, which is designed to calculate the performance of ventilation, the following simplifying assumptions have been made:

- the air is considered to be completely mixed throughout the measurements. Inside the room there are no concentration gradients, i.e. the concentration of air at a given time is the same for the whole room,

- the rooms presents in (fig.1) are considered a single zone system.

5.2. Effectiveness based on temperature distribution $\bar{\varepsilon}_t$ (indicator 2)

Information about ventilation effectiveness dates back to mid-1900s and was a measure of the ability of a ventilation system to remove contaminants. The most popular tasks of a ventilation system are to control air quality, comfort, contaminant and energy performance [20]. In 1986 [21] published a new type of measure, using the age of the air. This way a method was introduced with which the ability of a ventilation system to exchange air in a room could be quantified. In 1992 [22] worked on air distribution and ventilation effectiveness based on numerical study. They concluded that displacement ventilation performs better than mixing ventilation in terms of ventilation effectiveness. In 1998 [23] proved that ventilation effectiveness for heat distribution for displacement ventilation is almost twice the value for mixing ventilation. Awbi proved it by experimental and numerical investigation.

In this article the system effectiveness of natural ventilation was calculated on the basis of equations [20] where $\bar{\varepsilon}_t$ is ventilation efficiency, defined as temperature difference.

$$\bar{\varepsilon}_t = (T_{outlet} - T_{inlet})/(T_{average} - T_{inlet}) \quad (6)$$

Where:

T_{outlet} - is the average temperature for the indoor air mixture at the outlet, °C

$T_{average}$ - is the average temperature for the indoor air mixture all over the breathing zone, °C

T_{inlet} - is the average temperature for the indoor air mixture at the inlet, °C

The temperatures are calculated by the following equations:

$$T_{average} = \left(\int_{A_z} T\ dA\right) / A_z \quad (7)$$

$$T_{outlet} = \left(\int_{Sr} T\ dS\right) / S_r \quad (8)$$

$$T_{inlet} = \left(\int_{Ss} T\ dS\right) / S_s \quad (9)$$

Where:

A_z - is the area of the breathing zone, m^2

S_r - is the outlet surface, m^2

S_s - is the inlet surface, m^2

T - is temperature at the point of (x, y), °C

5.3. Effectiveness based on CO_2 concentration in the breathing zone η_v (indicator 3)

Another index refers to contaminant distribution which is defined as the pollution of air within a room and called ventilation effectiveness for contaminant removal [24]. The indoor air quality is investigated in terms of ventilation effectiveness, which is based on the CO_2 concentration in the breathing zone. The ventilation effectiveness η_v [25] is a measure of how the airflow supply mixes within the breathing zone for a removal of CO_2 or other pollutants:

$$\eta_v = (C_r - C_s)/(C_z - C_s) \qquad (10)$$

Where:

C_r - is the average CO_2 return concentration, [ppm]

C_s - is the average CO_2 supply concentration, [ppm]

C_z - is the average CO_2 concentration in the breathing zone, [ppm].

C is the CO_2 concentration at the point of (x, y). The average CO_2 concentrations C_r, C_s and C_z are computed from:

$$C_z = \left(\int_{A_z} C \, dA\right) / A_z \qquad (11)$$

$$C_r = \left(\int_{S_r} C \, dS\right) / S_r \qquad (12)$$

$$C_s = \left(\int_{S_s} C \, dS\right) / S_s \qquad (13)$$

The quality of natural ventilation indices used in this study is performance and effectiveness indicators. Performance means air change rate (ACH) and it is the measure of how many times the air within a defined space is replaced. Air change rates are often used as a principle with broad application that is not intended to be strictly accurate or reliable for every situation in ventilation design. The ventilation effectiveness can be related to some other parameters influencing the environmental indoor comfort such as: CO_2 concentration in breathing zones (indicator 2) and the rate of the temperature distribution homogeneity (indicator 3).

6. DISCUSSING RESULTS

In cold climate conditions of northern Poland ventilation works in a winter regime from November to March. January is the coldest month in Poland. The average temperature is about -4°C but it can fall as low as -35°C. On the other hand, in the summer months of June, July and August, the temperature average is about 18°C and the maximum summer temperature is 40°C. All other time periods can be called Transient Climate Conditions (TCC). In the article the TCC are characterized by a day temperature difference between the indoor and ambient temperature in the range of about (20°C, -2°C). They are the most unfavorable conditions during the entire year. This is due to the stack effect being reduced significantly, while the impact of wind gusts is very random and dependent upon ventilation configuration. However, the time period of transient climate conditions is very advantageous for field investigations of a quality of natural ventilation.

In this study, the test apartment was equipped with one air inlet gap located in the living room. According to the national regulations and standards [9, 10], the active flow area of fully open air-inlet should be designed to enable the airflow in the range from 20 to 50 (m³/h) for pressure difference of 10 Pa on both sides of the opening. In the test apartment, the inlet gap was located only in the living room and was being in contact with the ambient air. When fully opened, it should ensure an air exchange rate of 0.8 [1/h]. The chimney duct of 14x14 cm² (min. 0.016 m²) was located in the kitchen. The active area of the air inlet to the chimney duct was 0.008 m². During measurements the test apartment was occupied by two adults at the same times of the day: before work (6:00-7:00 am) and after work (5:00-8:00 pm).

6.1. Indicator 1

For better knowledge of the influence of wind on the ACH in the building, the study includes a windy period with wind velocity higher than 3 m/s. The ventilation performance was investigated as the air change rate per the apartment total volume during 1h (ACH). The results were compared with the requirements of the industry standard [9] (natural ventilation in the test apartment should exchange 50 m³/h of air during the day-time and 30 m³/h during the night-time). Fig.8 shows the wind effect for a windy period on the flow rate in the apartment. For wind velocity higher than 3 m/s the night-time flow rate was fulfilled at 90% of that time while the day-time flow rate was fulfilled at only 22% of that time. Fig.8 shows that during the windy period, the flow rate is significantly dependent on the wind velocity normal to the inlet. Despite the fact that temperature differences between indoor and ambience was 14 °C, the ACH was at a relatively low level. It was probably caused by temporary radiation, which weakened the influence of driving forces in natural ventilation.
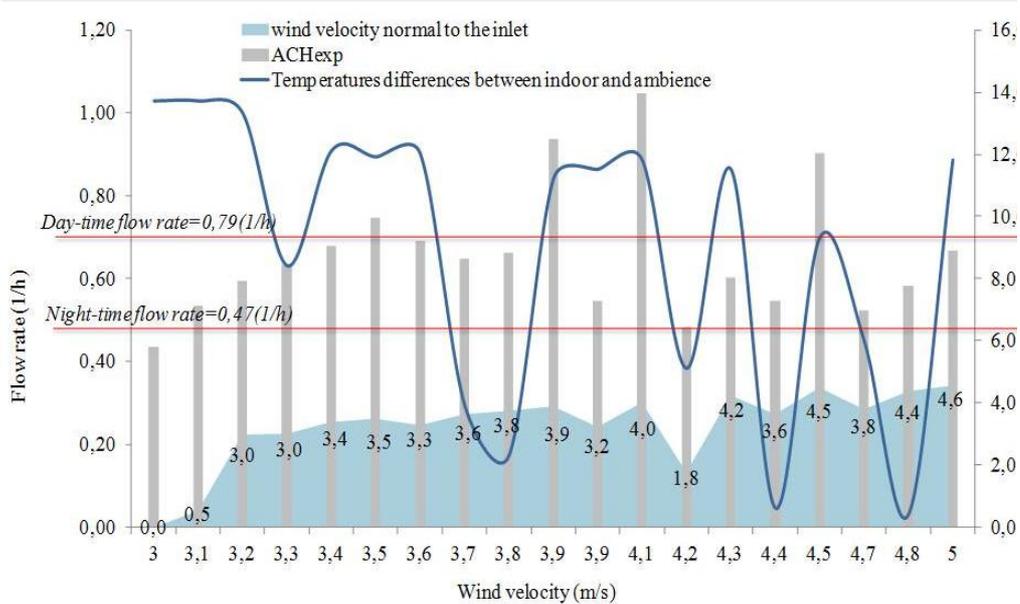
Fig. 8. Measured flow rate and related wind velocity for the test apartment during the windy period

Figure 8 shows a large time-variation of the ACH during a windy period typical for the cold climate in Poland. Considering this time-variation, the air change rate in the experiment varied between the minimum of ACH ≈ 0,44 h^{-1} and the maximum of ACH ≈ 1,06 h^{-1}. The mean measured air change rate for the windy period was 0,67 with the significant standard deviation (SD) of 0,71.

For better knowledge of the natural ventilation performance during the unfavorable climate conditions, a short-term date was selected (fig. 9). Figure 9 shows the time-variation of the ACH for the temperature differences between the indoors and the ambience -0,7 ÷ 2,3 °C. It should be noted that at this time the ACH significantly (by 83%) deviates from the minimum required standard value [16]. The results show that despite normal wind velocity to the inlet it has a significant influence on air flow rate in the apartment. However, it sometimes occurs that despite normal wind velocity to the inlet, the ACH is weakening. This is due to radiation. It was shown in fig. 9 in the instance of wind velocity at 2,2 m/s. Radiation raised the temperature of the inlet air at point ATC1. This weakened the force of natural ventilation.
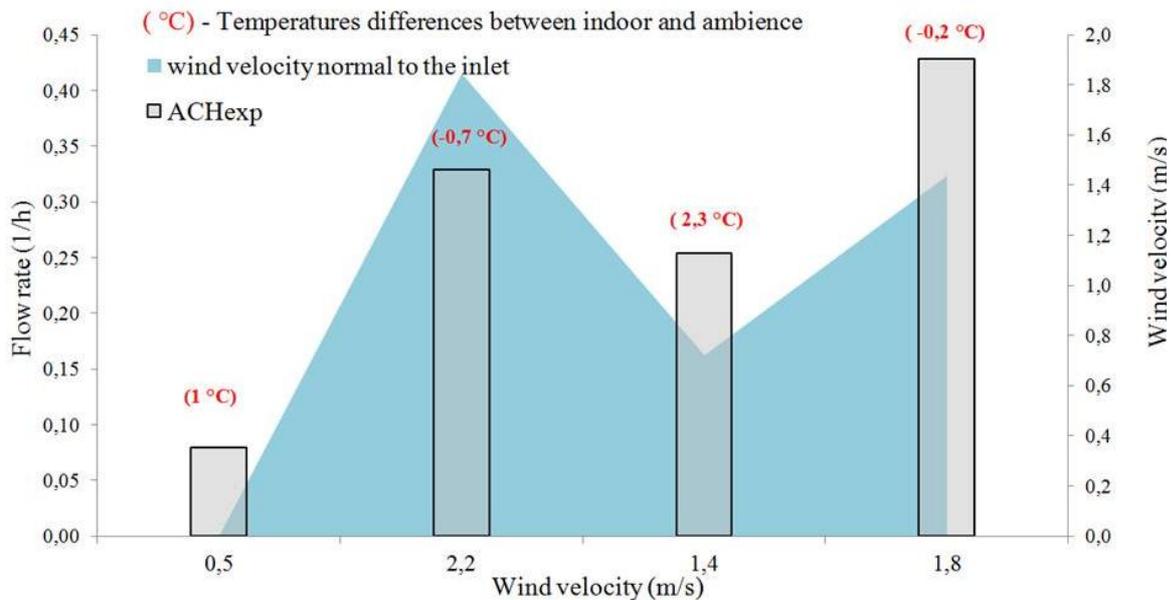
Fig. 9. Ventilation performance in the test apartment with respect to air change rates (ACH) in the instance of term of date was selected

6.2. Indicator 2

In the year 1856 Max von Pettekofer, suggested setting the upper limited value of CO_2 concentration at the level of 1 000 ppm by volume in the indoor air in rooms meant for people. Such amount was considered to be the highest acceptable norm for people concentration in air. As Targowski (2005) [35] noticed, due to the atmospheric carbon dioxide concentration in the middle of the 19th century, Pettenkofer considered admissible triple increase of CO_2 content in the indoor air in relation to the fresh air. In that case Targowski prepared the carbon dioxide influence effects on human organism:

CO_2 concentration in air influence effect on human:

- 350 – 450 ppm - fresh atmospheric air, ideal conditions
- Under 600 ppm - acceptable air quality in office and living indoor spaces
- Under1000 ppm - minimum hygienic requirement in Pettenkofer scale
- 10 000 ppm - slight respiration rate increase
- 15 000 ppm - maximum dosage tolerated for workers in specific working conditions, under medical control (breweries, submarines, spacecrafts)

The ventilation effectiveness is verified by its ability to remove waste air and decrease pollutants concentration [30,31]. This research is limited to the parameters of CO_2 concentration. The CO_2-concentration was monitored at four points: in the inlet (ATC1), in the outlet (ATC4) and one in the room (ATC2) and one in the kitchen (ATC3) (Fig.10). The CO_2-concentration in the test apartment was high, the maximum value was 1908 ppm and the minimum value was 428 ppm. The CO_2-concentration at ATC1, ATC2 and ATC3 was at a similar level, with the mean value respectively: 712 ppm, 617 ppm, 678 ppm. The highest differences were measured in the outlet (ATC4). The maximum value at ATC4 was 1908 ppm, based on World Health Organization scale it means that the air quality was dangerous for human health. The mean measured CO_2-concentration was 738 with the standard deviation (SD) of 164. At ACT4 the peak of CO_2-concentration increased from 500 ppm up to 1900 ppm. It was observed after 6:00 pm. It can be explained by the apartment being suddenly exploited by the residents. That agrees with the study of Lugg's et al. [32]. The authors concluded that CO_2-concentration increased from 300 ppm up to 3500 ppm during the occupied periods. They investigated the ventilation effectiveness in two classrooms over two days.
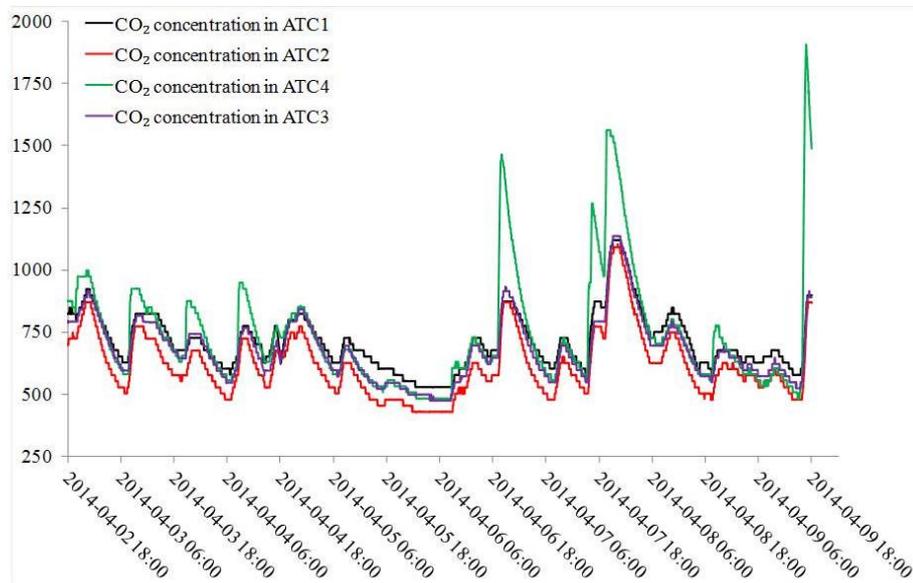
Fig. 10. Measured CO2-concentration in the test apartment

The measurement of the ventilation effectiveness is described extensively in a related work by [33]. If complete mixing of air and pollutants occurs there, the ventilation effectiveness is $\eta_v = 1$. It has also been confirmed in the study [34]. In the building test the ventilation effectiveness η_v was in the range of 0,18 ÷ 0,74 (-) (fig.11). The mean measured value for ventilation effectiveness η_v was 0,55 (-) with standard deviation (SD) of 0,0565. In fig. 11 it is shown that when the apartment was occupied, the natural ventilation effectiveness suddenly dropped. The lowest value of η_v was observed during the peak apartment expatiation (example: cooking).
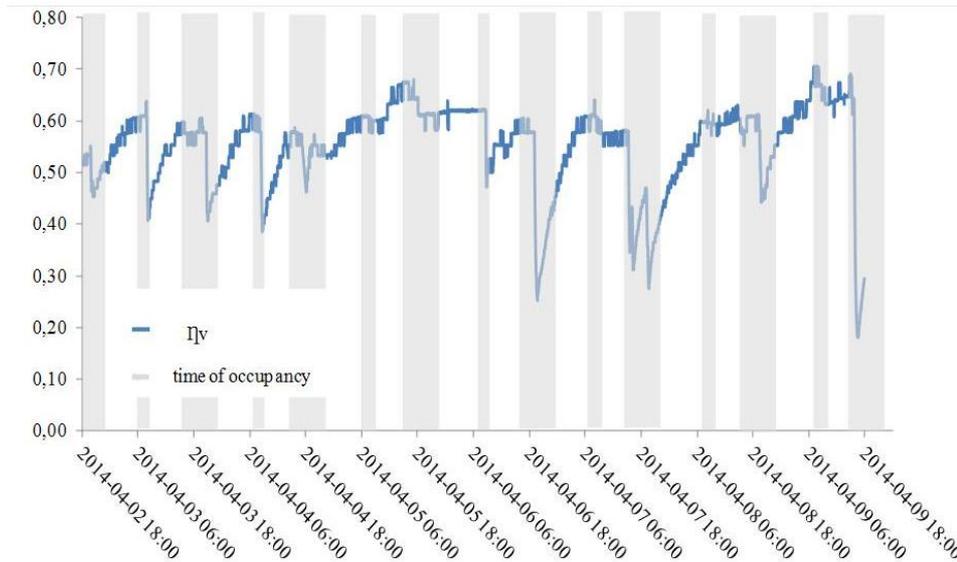
Fig. 11. Time-variations of overall ventilation effectiveness for CO_2

6.3. Indicator 3

In order to present the overall ventilation effectiveness, the temperature distribution is presented at three points: ATC1, ATC4 and the mean value from ATC2/3 (Fig.12). The most homogeneous temperature was in the apartment (kitchen T3 and living room T2). The mean temperature at ATC2/3 was 19,5 °C÷22 °C. The highest difference was observed at ATC1 during the measurement time period. The maximum value was 23 °C during day time and the minimum was 9,4 °C in the early morning. Surprisingly, the peaks were observed at ATC4. Probably, the peaks were generated by the residents. The highest peak temperature was 31,1 °C and it was observed in the afternoon.

Based on the air temperature in the test apartment, the overall ventilation effectiveness for the temperature distribution $\bar{\varepsilon}_t$ was presented (fig.12). Ventilation effectiveness for temperature distribution during the experiment was in the range of 0,62÷0,87. The mean measured value for ventilation effectiveness $\bar{\varepsilon}_t$ was 0,764 (-) with standard deviation (SD) of 0,039. It means that the temperature homogeneity level is satisfactory. Analyzing the above results it can be seen that natural ventilation with an inlet gap can maintain a satisfying thermal comfort level. In fig. 13 local fluctuations were observed. These fluctuations corresponded with the temperature fluctuations measured at ATC4 in fig. 12. It was observed that when the temperature fluctuations increase then the ventilation effectiveness fluctuations decrease.
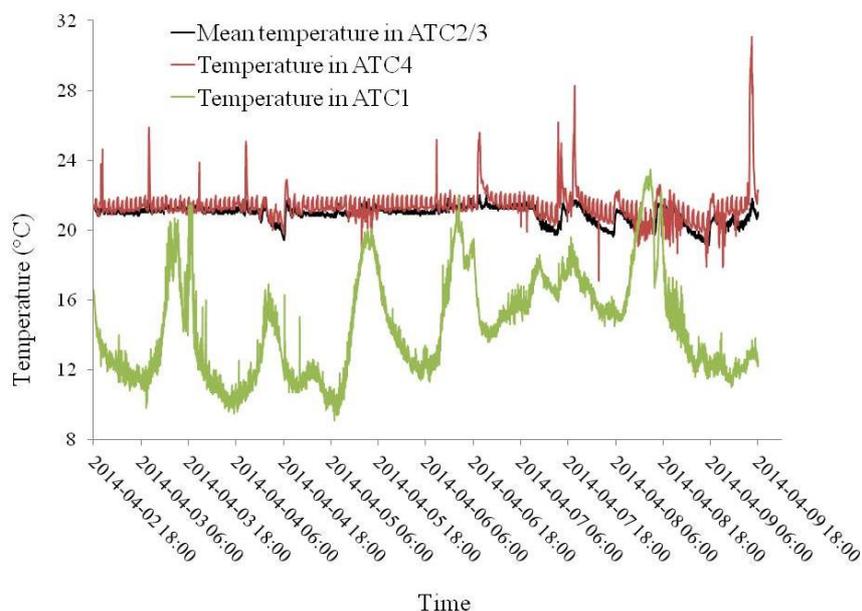
Fig. 12. Time-variations of temperature distribution in the apartment
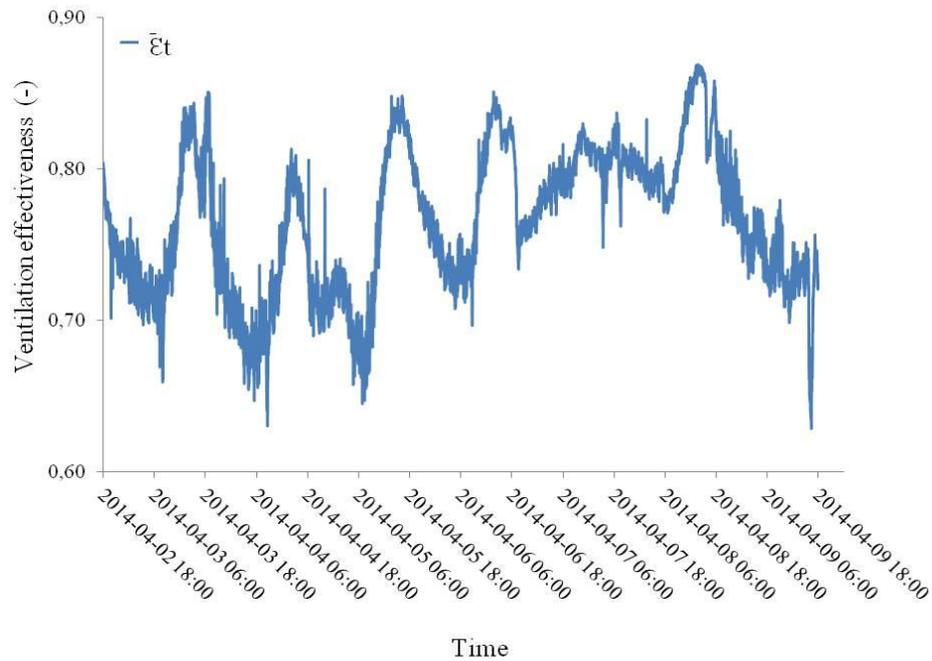
Fig. 13. Time-variations of overall ventilation effectiveness for temperature distribution $\bar{\varepsilon}_t$
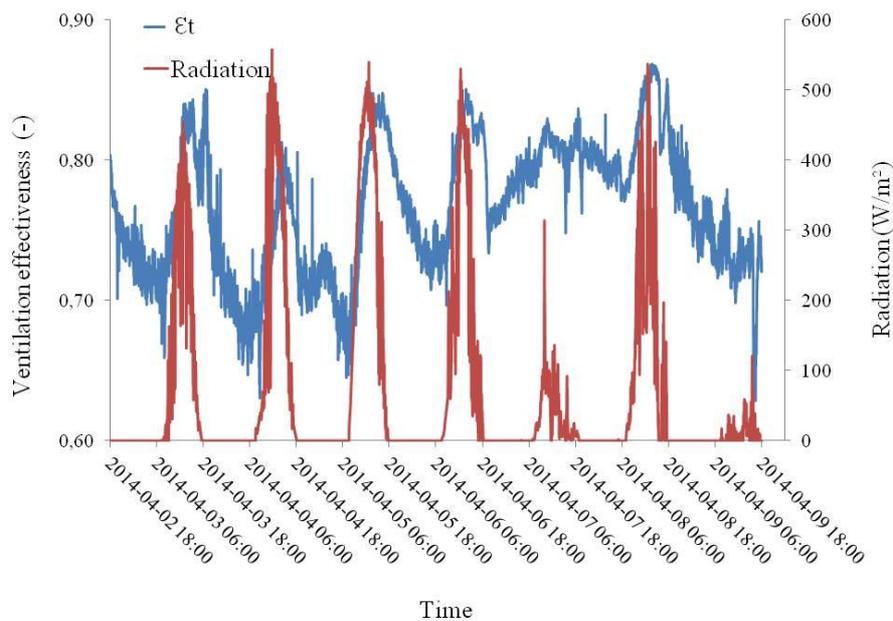
Fig. 14. Comparison of temperature distribution to radiation time variations

The peaks on the ventilation effectiveness $\bar{\varepsilon}_t$ time variations can be explained when comparing $\bar{\varepsilon}_t$ with the solar radiation time variations (Fig.14). The peaks of $\bar{\varepsilon}_t$ were strongly related with the occurrence of solar radiation which disturbed the airflow around the house and, consequently, the airflow through the inlet gap in the window.

7. CONCLUSIONS

The field investigations of prediction of air flow rate, CO_2 concentration and temperature distribution in the apartment with natural (stack) ventilation with

an inlet gap in a window were performed. The measurements were carried out in a test apartment of a family detached house located in a cold climate. The measurement campaign was conducted in transient climate conditions.

The research began with performing studies on the influence of the leakage. In this study the leakage distribution did not have significant effect which agreed with the Polish act [18].

The indicator 1 was investigated under steady climate conditions in a windy period. The top influence on the ACH in the apartment was the wind velocity normal to the inlet. The minimum value which fulfilled the day-time flow rate requirement

was wind velocity normal to the inlet and equal to 3,5 m/s. At the top temperatures the differences between the indoors and the ambience were even up to 14 °C, as the natural ventilation performance can be weakened by temporary radiation.

The effectiveness of natural ventilation at which carbon dioxide is generated (indicator 2) in a space strongly depends on the activity of people in the space. During the study conditions dangerous for human health occurred. The results of ventilation effectiveness for the removal of contamination also showed that during the study sudden activity of residents reduced natural ventilation effectiveness.

The heat removal effectiveness for ventilation systems (indicator 3) is generally satisfactory. Based on the study it has been concluded that the main influence on natural ventilation effectiveness by temperature distribution was recorded for the occurrence of solar radiation. This agrees with study [36]. In the article [36] the authors found that heat removal effectiveness for the NV is mainly affected by convection and radiation.

REFERENCES

1. LBNL, 2007, EnergyPlus Engineering Reference, November 6, 2007:384-381.
2. Jarząbska-Antczak R, Niedostatkiewicz M. Projektowanie i diagnostyki wentylacji grawitacyjnej. Wybrane problemy. Polskie Centrum Budownictwa Difin i Muller sp. z o.o., 1-80, Warszawa, 2017.
3. Krishan A. Climate responsive architecture: a design handbook for energy efficient buildings, Tata McGraw-Hill Pub. Co., New York, 2001.
4. Clarke D. A breath of fresh air, Hospital Development. 32(11), (2001): 13-17.
5. Okisalo J, Kurnitski J, Korpi M, Kalamees T, Vinha J. Building leakage, infiltration, and energy performance analyses for Finnish detached houses. Building and Environment 2009; 44:377-387.
6. Gładyszewska-Fiedoruk K, Gajewski A. Effect of wind on stack ventilation performance. Energy and Buildings 2012; 51: 242-247. http://dx.doi.org/10.1016/j.enbuild.2012.05.007.
7. Krzaczek M, Florczuk J, Tejchman J. Field investigations of stack ventilation in a residential building with multiple chimneys and tilted window in cold climate, Energy and Buildings, 2015; 103:48-61. http://dx.doi.org/10.1016/j.enbuild.2015.06.034.
8. Bülow-Hübe H. Energy-Efficient Window Systems. Doctoral Dissertation. ISSN 1103-4467. Lund University, Lund Institute of Technology, Lund 2001.
9. PN-83/B-03430 (including revision A3:2000). Ventilation in collective dwelling places and public buildings – requirements, (in Polish).
10. Dutton S, Shao L and Riffat S. Validation and parametric analysis of energy plus: air flow. Network model using Contam. Third National Conference of IBPSA-USA. Berkeley, California. July 30 – August 1, 2008.
11. Stephen RK, Parkins LM and Woolliscroft M. Passive stack ventilation systems: design and installation. BRE Information Paper, July 1994.
12. LAB-EL Elektronika Laboratoryjna s.j. Available from www.label.pl.
13. Chung KC, Hsu SP. Effect of ventilation pattern on room air and contaminant distribution. Building and Environment 2001;36:989-98.
14. Fisk WJ, Faulkner D, Sullivan D, Bauman F. Air change effectiveness and pollutant removal efficiency during adverse mixing conditions. Indoor Air, 1997; 7:55-63.
15. Lawrence TM, Braun JE. Evaluation of simplified models of CO_2 concentrations in small commercial buildings. Building and Environment 2006; 41(2):184-94.
16. Shi S, Chen C, Zhao B. Air infiltration rate distributions of residences in Beijing, Building and Environment, 2015; 92: 528-537, http://dx.doi.org/10.1016/j.buildenv.2015.05.027 .
17. Mora L, Gadgil AJ, Wurtz E. Comparing zonal and CFD model predictions of isothermal indoor airflows to experimental data, Indoor Air, 2003; 13: 77-85.
18. Regulation of the Minister of Infrastructure and Development. Calculation methodology of building energy characteristics and method of preparing and patterns of energy characteristic certificates. Warsaw 2014 (in polish).
19. Axley J. Introduction to the design of natural ventilation system loopequation, Proc. 19th AIVC Conf. Ventilation Technologies Urban Areas, 1998: 47-56.
20. Cao G, Awbi H, Yao R, Fan Y, Siren K, Kosonen R, Zhang J. A review of the performance of different ventilation and airflow distribution systems in buildings. Buildings and Environment, 2014: 171-186. http://dx.doi.org/10.1016/j.buildenv.2013.12.009.
21. Sandberg M. Efficiency of general ventilation systems in residential and office building-concepts and measurements. In: Goodfellow HD, editor. Ventilation 85. Elsevier Science Publishers B.V. Amsterdam-Printed in The Netherlands; 1986.
22. Awbi H, Gan G. Simulation of Solar Induced Ventilation, Second World Renewable Energy Congress. Solar and Low Energy Architecture, September 1992, Pergamon Press, Oxford.
23. Awbi H. Energy efficient room distribution. Renew Energy 1998;2:293-9.
24. Sandberg M. What is ventilation efficiency? Build Environ 1981; 16:123-35.
25. Lawrence TM, Braun JE. A methodology for estimating occupant CO_2 source generation rates from measurements in small commercial buildings. Building and Environment, 2007; 42:623-639.
26. Awbi H. Ventilation of buildings, Chapman & Hall, 1991.
27. Dascalaki E, Santamouris M, Bruant M, Balaras CA, Bossaer A, Ducarme D, Wouters P. Modeling large openings with COMIS, Energy and Buildings, 1999, 30: 105-115.
28. Brown WG, Solvason KR. Natural convection through rectangular opening in partitions. 1. Vertical partitions. Heat and Mass Transfer 1962; 5: 859-868.
29. Tan G, Glicksman LR. Application of integrating multi-zone model with CFD simulation to natural ventilation prediction, Energy and Buildings, 2005, 37: 1049-1057.
30. Wegner J. Untersuchungen des natürlichen Luftwechsels in ausgeführten Wohnungen, die mit sehr fugendichten Fenstern ausgestattet sind, Gesundheits-Ingenieur, 1983; 1: 1-5.

31. Roulet CA. Ventilation and Airflow in Buildings: Methods for Diagnosis and Evaluation, Earthscan Publications Ltd, London, 2008.

32. Lugg AB, Batty WJ. Air Quality and Ventilation Rates in School Classrooms. I. Air Quality Monitoring, Building Services Engineering Research & Technology (BSERT), 1999; 20(1): 13-21.

33. Roos A. The air exchange efficiency of the desk displacement ventilation concept-Theory, measurements and simulations, Proc. Roomvent'98, Stockholm, Sweden.1998; 1: 249-256,.

34. Novoselac A, Srebric J. Comparison of air exchange efficiency and contaminant removal effectiveness as IAQ indices. ASHRAE Trans, 2003, 109: 339-349

35. Targowski L. http://www.wentylacja.com.pl/ciekawostki/ciekawostki.asp?ID=4145, 2005 (in Polish).

36. Heiselberg P, Sandberg M. Convection from a slender cylinder in a ventilated room, Roomvent 90', 1990, Norway.

Romana ANTCZAK-JARZĄBSKA, MSc Eng – is a graduate of the Gdańsk University of Technology, where she studied at the Faculty of Civil and Environmental Engineering, scientific fields of interests concern among building engineering physics, building's internal environment conditions and air ventilation.

Maciej NIEDOSTATKIEWICZ, Ph.D., D.Sc. is an associate professor and Head of Department of Concrete Structures, Gdansk University of Technology. His scientific interests are related to the subject of diagnostics by means of non-invasive methods and reinforcement of structural elements of general construction and issues of building physics.